Corrosion Cost and Preventive Strategies in the United States

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U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
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FOREWORD

It is known that the corrosion of metallic structures has a significant impact on the U.S. economy, including infrastructure, transportation, utilities, production and manufacturing, and government. A 1975 benchmark study by Battelle-NBS calculated the cost of corrosion to be $70 billion per year, which was 4.2 percent of the nation's gross national product (GNP). Other studies, both in the United States and abroad, have addressed the cost of corrosion as well.

A need was identified to carry out a systematic study to estimate the current impact of metallic corrosion on the U.S. economy and to provide strategies to minimize the impact of corrosion. Through discussions between NACE International (The Corrosion Society), members of Congress, and the U.S. Department of Transportation (U.S. DOT), an amendment for the cost of corrosion was included in the Transportation Equity Act for the 21st Century (TEA-21), which was passed by the U.S. legislature in 1998. In the period from 1999 to 2001, CC Technologies conducted the research, in a cooperative agreement with the Federal Highway Administration (FHWA).

In this study, the total direct cost of corrosion was determined by analyzing 26 industrial sectors in which corrosion is known to exist and extrapolating the results for a nationwide estimate. The total direct cost of corrosion was determined to be $276 billion per year, which is 3.1 percent of the U.S. gross domestic product (GDP). Indirect costs to the user (society costs) are conservatively estimated to be equal to the direct costs. This means that the overall cost to society could be as much as 6 percent of the GDP. Often, the indirect costs are ignored because only the direct costs are paid by the owner/operator.

New technologies to prevent corrosion continue to be developed and cost-based corrosion management techniques are available to further lower corrosion costs. However, cost-effective methods are not always implemented. Better corrosion management can be achieved using preventive strategies at every level of involvement (owner, operator, user, government, Federal regulators, and general public).

The preventive strategies include: (1) increase awareness of large corrosion costs and potential savings, (2) change the misconception that nothing can be done about corrosion, (3) change policies, regulations, standards, and management practices to increase corrosion cost-savings through sound corrosion management, (4) improve education and training of staff in recognition of corrosion control, (5) advance design practices for better corrosion management, (6) advance life prediction and performance assessment methods, and (7) advance corrosion technology through research, development, and implementation.

This report will be of interest to government regulators and policy-makers involved in materials-related issues, the general public, and practicing engineers concerned with materials of construction and process design.

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Research and Development

NOTICE

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16. Abstract

This report describes the annual total cost of metallic corrosion in the United States and preventive strategies for optimum corrosion management. In 1998, an amendment for a Cost of Corrosion study was included in the Transportation Equity Act for the 21st Century (TEA-21) and was approved by Congress. In the period from 1999 to 2001, CC Technologies conducted the research in a cooperative agreement with the Department of Transportation Federal Highway Administration (FHWA) and NACE International (The Corrosion Society).

The total direct cost of corrosion is estimated at $276 billion per year, which is 3.1 percent of the 1998 U.S. gross domestic product (GDP). This cost was determined by analyzing 26 industrial sectors in which corrosion is known to exist and extrapolating the results for a nationwide estimate. The sectors were divided among five major categories: infrastructure, utilities, transportation, production and manufacturing, and government. The indirect cost of corrosion is conservatively estimated to be equal to the direct cost (i.e., total direct cost plus indirect cost is 6 percent of the GDP). Evidence of the large indirect corrosion costs are lost time, and thus lost productivity because of outages, delays, failures, and litigation. It was found that the sectors of drinking water and sewer systems ($36 billion), motor vehicles ($23.4 billion), and defense ($20 billion) have the largest direct corrosion impact. Within the total cost of corrosion, a total of $121 billion per year is spent on corrosion control methods and services.

The current study showed that technological changes have provided many new ways to prevent corrosion and there has been improved use of available corrosion management techniques. However, better corrosion management can be achieved using preventive strategies in non-technical and technical areas. These preventive strategies include: (1) increase awareness of large corrosion costs and potential savings, (2) change the misconception that nothing can be done about corrosion, (3) change policies, regulations, standards, and management practices to increase corrosion cost-savings through sound corrosion management, (4) improve education and training of staff in recognition of corrosion control, (5) advance design practices for better corrosion management, (6) advance life prediction and performance assessment methods, and (7) advance corrosion technology through research, development, and implementation.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
in²	square inches	645.2	square millimeters	mm²
ft²	square feet	0.093	square meters	m²
yd²	square yards	0.836	square meters	m²
ac	acres	0.405	hectares	ha
mi²	square miles	2.59	square kilometers	km²

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft³	cubic feet	0.028	cubic meters	m³
yd³	cubic yards	0.765	cubic meters	m³

NOTE: Volumes greater than 1000 l shall be shown in m³.

MASS

Symbol	When You Know	Multiply By	To Find	Symbol
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C

ILLUMINATION

Symbol	When You Know	Multiply By	To Find	Symbol
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m²	cd/m²

FORCE and PRESSURE or STRESS

Symbol	When You Know	Multiply By	To Find	Symbol
lbf	poundforce	4.45	newtons	N
lbf/in²	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
mm²	square millimeters	0.0016	square inches	in²
m²	square meters	10.764	square feet	ft²
m²	square meters	1.195	square yards	yd²
ha	hectares	2.47	acres	ac
km²	square kilometers	0.386	square miles	mi²

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m³	cubic meters	35.71	cubic feet	ft³
m³	cubic meters	1.307	cubic yards	yd³

MASS

Symbol	When You Know	Multiply By	To Find	Symbol
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F

ILLUMINATION

Symbol	When You Know	Multiply By	To Find	Symbol
lx	lux	0.0929	foot-candles	fc
cd/m²	candela/m²	0.2919	foot-Lamberts	fl

FORCE and PRESSURE or STRESS

Symbol	When You Know	Multiply By	To Find	Symbol
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in²

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

EXECUTIVE SUMMARY

INTRODUCTION

Previous studies have shown that corrosion is very costly and that it has a major impact on the economies of industrial nations. A 1975 benchmark study by Battelle-NBS pointed out the severe impact on the United States economy. The estimates based on the Battelle-NBS study are that the cost of corrosion in the United States alone was approximately $70 billion, which was 4.2 percent of the gross national product (GNP). A limited study in 1995 updating the 1975 cost numbers estimated the total cost of corrosion at approximately $300 billion.

Through discussions between NACE International (The Corrosion Society), members of Congress, and the U.S. Department of Transportation (U.S. DOT), an amendment for the cost of corrosion was included in the Transportation Equity Act for the 21st Century (TEA-21), which was passed by the U.S. legislature in 1998. The amendment requested a study be conducted in conjunction with an interdisciplinary team of experts from the fields of metallurgy, chemistry, economics, and others, as appropriate. Subsequently, the Federal Highway Administration (FHWA) initiated a systematic study to estimate the total economic cost of metallic corrosion and to provide preventive strategies to minimize the impact of corrosion. In the period 1999 to 2001, CC Technologies conducted the study in a cooperative agreement with FHWA and NACE International (The Corrosion Society).

OBJECTIVES AND SCOPE

The primary objectives of this study were to:

(1) develop an estimate of the total economic impact of metallic corrosion in the United States, and

(2) identify national strategies to minimize the impact of corrosion.

The work to accomplish these objectives was conducted through the following main activities:

- determination of the cost of corrosion based on corrosion control methods and services,
- determination of the cost of corrosion for specific industry sectors,
- extrapolation of individual sector costs to a national total corrosion cost,
- assessment of barriers to progress and effective implementation of optimized corrosion control practices, and
- development of implementation strategies and recommendations for realization of cost savings.

REVIEW OF PREVIOUS STUDIES

A critical review of previous national studies was conducted. These studies have formed the basis for much of the current thinking regarding the corrosion costs to the various national economies. The earliest study was reported in 1949 by Uhlig, who estimated the total cost to the economy by summing materials and procedures related to corrosion control. The 1949 Uhlig report, which was the first to draw attention to the economic importance of corrosion, was followed in the 1970s by a number of studies in various countries, such as the United States, the United Kingdom, and Japan. The national study by Japan conducted in 1977 followed the Uhlig methodology. In the United States, Battelle-NBS estimated the total direct cost of corrosion using an economic input/output framework. The input/output method was adopted later by studies in two other nations, namely Australia in 1983 and Kuwait in 1995. In the United Kingdom, a committee chaired by T.P. Hoar conducted a national study in 1970 using a method where the total cost was estimated by collecting data through interviews and surveys of targeted economic sectors.

Although the efforts of the above-referenced studies ranged from formal and extensive to informal and modest, all studies arrived at similar estimates of the total annual cost of corrosion ranging from 1 to 5 percent of each country's GNP.

APPROACH

In the current study, two different approaches were taken to estimate the total cost of corrosion. The first approach followed a method where the total cost is determined by summing the costs for corrosion control methods and services. The cost of materials were obtained from various sources such as the U.S. Department of Commerce Census Bureau, existing industrial surveys, trade organizations, industry groups, and individual companies. The data collection for corrosion control materials and products relied heavily on surveys of relevant web sites. Data collection of corrosion control services such as engineering services, research and testing, and education and training was obtained primarily from trade organizations, educational institutions, and individual experts.

The second approach followed a method where the cost of corrosion was first determined for specific industry sectors and then extrapolated to calculate a national total corrosion cost. Data collection for the sector-specific analyses differed significantly from sector to sector depending on the availability of data and the form in which the data were available. In order to determine the annual corrosion costs for the reference year of 1998, data were obtained for various years in the last decade, but mainly for the years 1996 to 1999. Generally, for many of the public sector categories, such as infrastructure and utilities, much of the information is public and could be obtained from government reports and other publicly available documents. In many cases, the advice of experts in the specific industry sectors was sought in order to obtain specific relevant information. Discussions with industry experts provided the basis of the industry sector data collection. Corrosion-related cost information from the private industry sectors was more difficult to obtain directly. This stemmed from the fact that either the information was not readily available or could not be released because of company policies. In this case, information from publicly available industry records on operation and maintenance costs was obtained, and with the assistance of industry experts, corrosion-related costs were estimated.

The industry sectors for corrosion cost analyses were selected in order to achieve as broad a cross-section of the U.S. economy as possible. The sectors were divided among five sector categories, i.e., infrastructure, utilities, transportation, production and manufacturing, and government. The industry sectors represented approximately 27 percent of the U.S. gross domestic product (GDP). In the sector category of *Infrastructure*, the following industry sectors were analyzed: highway bridges, gas and liquid transmission pipelines, waterways and ports, hazardous materials storage, airports, and railroads. In the sector category of *Utilities*, the analyzed industry sectors were: gas distribution, drinking water and sewer systems, electrical utilities, and telecommunications. For the sector category *Transportation*, the analyzed industry sectors included: motor vehicles, ships, aircraft, railroad cars, and hazardous materials transportation. For the sector category of *Production and Manufacturing*, some major industry groups were selected. Although not all industries could be included, the analyzed industry sectors were: oil and gas exploration and production; mining; petroleum refining; chemical, petrochemical, and pharmaceutical; pulp and paper; agricultural; food processing; electronics; and home appliances. For the sector category of *Government*, the analyzed industry sectors were: defense and nuclear waste storage.

ECONOMIC ANALYSIS

The total cost of corrosion was estimated by determining the percentage of the GDP of those industry sectors for which direct corrosion costs were estimated, and subsequently extrapolating these numbers to the total U.S. GDP. The direct cost used in this analysis was defined as the cost incurred by owners or operators. The following elements were included in these costs:

- additional or more expensive material used to prevent corrosion damage,
- labor attributed to corrosion management activities,

- equipment required because of corrosion-related activities,
- loss of revenue due to disruption in supply of product,
- loss of reliability, and
- lost capital due to corrosion deterioration.

For all industry sectors studied in this report, the direct corrosion costs were determined. However, for one industry sector, highway bridges, a life-cycle cost analysis was performed in which both the direct and indirect costs of corrosion were addressed. Indirect costs are incurred by individuals other than the owner or operator of the structure. Measuring and valuing indirect costs are generally complex assessments, and several different methods can be used to evaluate potential indirect costs. Owners or operators can be made to assume the costs through taxation, penalties, litigation, or paying for clean-up of spills. In such cases, these expenses become direct costs. In other cases, costs are assumed by the end user or overall economy. These indirect costs, such as traffic delays in the case of bridge repair, are more difficult to turn over to the owner or operator of the structure. Once assigned a dollar value, the indirect costs are included in the cash flow of the corrosion management of the structure and are treated the same way as all other costs.

RESULTS

The two methods used in the current study to estimate the cost of corrosion to the United States are based on: (1) the cost of corrosion control methods and services and (2) corrosion costs of specific industry sectors. Past studies have indicated that the second method is more likely to incorporate all costs and that the first method is likely to miss the significant cost of corrosion management, the cost for direct services related to the owner/operator, and the cost of loss of capital due to corrosion.

Method 1 – Corrosion Control Methods and Services

With this method, the total annual direct cost of corrosion was estimated by adding the cost of control methods and services. The corrosion control methods that were considered include protective coatings, corrosion-resistant alloys, corrosion inhibitors, polymers, anodes, cathodic protection, and corrosion control and monitoring equipment. Other contributors to the total annual direct cost that were reviewed in this report are corrosion control services (i.e., non-owner/operator services), corrosion research and development, and education and training.

Protective Coatings - Both organic and metallic coatings are used to provide protection against corrosion of metallic substrates. These metallic substrates, mostly carbon steel, will corrode in the absence of the coating, resulting in the reduction of the service life of the steel part or component.

According to the U.S. Department of Commerce Census Bureau, the total amount of organic coating material sold in the United States in 1997 was 5.56 billion L (1.47 billion gal), at a value of $16.56 billion. The total sales can be broken down into architectural coatings, product original equipment manufacturers (OEM) coatings, special-purpose coatings, and miscellaneous paint products. A portion of each of these was classified as corrosion coatings for a total estimate of $6.7 billion. It is important to note that raw material cost is only a portion of a total coating application project, ranging from 4 to 20 percent of the total cost of application. When applying these percentages to the raw materials cost, the total annual cost of coating application ranges from $33.5 billion to $167.5 billion.

The most widely used metallic coating method for corrosion protection is galvanizing, which involves the application of metallic zinc to carbon steel for corrosion control purposes. Hot-dip galvanizing is the most common process, and as the name implies, it consists of dipping the steel member into a bath of molten zinc. Information released by the U.S. Commerce Department in 1998 stated that about 8.6 million metric tons of hot-dip galvanized steel and 2.8 million metric tons of electrolytic galvanized steel were produced in 1997. The total market for metallizing and galvanizing in the United States is estimated at $1.4 billion. This figure is the total material cost of the metal coating and the cost of processing, and does not include the cost of the carbon steel member being galvanized/metallized.

Metallizing is defined as the application of very thin metallic coatings for either active corrosion protection (zinc or aluminum anodes) or as a protective layer (stainless steels and alloys). Application can be by flame spraying or electroplating. Other advanced processes such as plasma arc spraying can be used for exotic refractory metals for very demanding applications, but most of the advanced processes are not used for corrosion control. The metallizing anode market ranges from $5 million to $10 million annually, and is also growing due to the recognition by government agencies that life-cycle costs are significant if corrosion mitigation is not specified from the start.

Corrosion-Resistant Alloys – Corrosion-resistant alloys are used where corrosive conditions prohibit the use of carbon steels and protective coatings provide insufficient protection or are economically not feasible. Examples of these alloys include stainless steels, nickel-base alloys, and titanium alloys. According to U.S. Census Bureau statistics, a total of 2.5 million metric tons of raw stainless steel was sold in the United States in 1997. With an estimated cost of $2.20 per kg ($1 per lb) for raw stainless steel, a total annual (1997) production cost of $5.5 billion was estimated. It is assumed that all production is for U.S. domestic consumption. The total consumption of stainless steel also includes imports, which account for more than 25 percent of the U.S. market. Thus, the total consumption of stainless steel can be estimated at $7.3 billion.

Where environments become particularly severe, nickel-base and titanium alloys are used. Nickel-base alloys are used extensively in the oil production and refinery and chemical process industries, where conditions are aggressive. Furthermore, there is an increased use of these alloys in other industries, where high temperature and/or corrosive conditions exist. With the average price for nickel-base alloys at $13 per kg in 1998, the total sales value n the United States was estimated at $285 million.

The primary use of titanium alloys is in the aerospace and military industry, where the high strength-to-weight ratio and resistance to high temperatures are properties of interest. However, titanium and its alloys are also corrosion-resistant in many environments, and have therefore found application in oil production and refinery, chemical process, and pulp and paper industries. In 1998, it was estimated that 65 percent of the titanium mill products were used for aerospace and 35 percent for non-aerospace applications. The total annual consumption cost for titanium and titanium alloys for corrosion control applications is estimated at $150 million.

The total 1998 consumption cost of the corrosion-resistant metals and alloys is estimated at $7.7 billion.

Corrosion Inhibitors - A corrosion inhibitor may be defined, in general terms, as a substance which when added in a small concentration to an environment effectively reduces the corrosion rate of a metal exposed to that environment. Inhibition is used internally with carbon steel pipes and vessels as an economic corrosion control alternative to stainless steels and alloys, coatings, or non-metallic composites. A particular advantage of corrosion inhibition is that it can be implemented or changed *in situ* without disrupting a process. The major industries using corrosion inhibitors are the oil and gas exploration and production industry, the petroleum refining industry, the chemical industry, heavy industrial manufacturing industry, water treatment facilities, and the product additive industries. The largest consumption of corrosion inhibitors is in the oil industry, particularly in the petroleum refining industry. The total consumption of corrosion inhibitors in the United States has doubled from approximately $600 million in 1982 to nearly $1.1 billion in 1998.

Engineering Plastics and Polymers - In 1996, the plastics industry accounted for $274.5 billion in shipments. It is difficult to estimate the fraction of plastics used for corrosion control, because in many cases, plastics and composites are used for a combination of reasons, including corrosion control, light weight, economics, strength-to-weight ratio, and other unique properties. While corrosion control is a major market for many polymers, certain polymers are used mostly, if not exclusively, for corrosion control purposes. The significant markets for corrosion control by polymers include composites (primarily glass-reinforced thermosetting resins), polyvinyl chloride (PVC) pipe, polyethylene pipe, and fluoropolymers. The portion of polymers used for corrosion control is estimated at $1.8 billion.

Cathodic and Anodic Protection - The cost of cathodic and anodic protection of metallic structures subject to corrosion can be divided into the cost of materials and the cost of installation and operation. Industry data have provided estimates for the 1998 sales of various hardware components totaling $146 million. The largest share of the cathodic protection market is taken up by sacrificial anodes at $60 million, of which magnesium has the greatest market share. Major markets for sacrificial anodes are the water heater market and the underground storage tank market. The costs of installation of the various cathodic protection (CP) components for underground structures vary significantly depending on the location and the specific details of the construction. For 1998, the average total cost for installing CP systems was estimated at $0.98 billion (range: $0.73 billion to $1.22 billion). The total cost for replacing sacrificial anodes in water heaters and the cost for corrosion-related replacement of water heaters was estimated at $1.24 billion per year; therefore, the total estimated cost for cathodic and anodic protection is $2.22 billion per year.

Corrosion Control Services - In the context of this report, services are defined as companies, organizations, and individuals that are providing their services to control corrosion, while excluding corrosion-related activities that owners/operators may do in-house. By taking the NACE International membership as a basis, a total number of engineers and scientists who provide corrosion control services may be estimated. Based on a 16,000 membership in 1998 and the assumption that 25 percent provides corrosion control services, a total services cost of $1.2 billion was estimated.

Research and Development - It has been observed that over the past few decades less funding has been made available for corrosion-related research and development, which is significant in light of the cost and inconvenience of dealing with leaking and exploding underground pipelines, bursting water mains, corroding storage tanks, aging aircraft, and deteriorating highway bridges. In fact, several government and corporate research laboratories have significantly reduced their corrosion research staff or even have closed down their research facilities. Moreover, less research and development funding has been available, both from government and private sources. An estimate of an annual academic budget of $20 million was made; no estimates were made of the cost of corporate or industry corrosion-related research, which is likely to be much greater than the annual academic budget.

Education and Training - Corrosion-related education and training in the United States include degree programs, certification programs, company in-house training, and general education and training. A few national universities offer courses in corrosion and corrosion control as part of their engineering curriculum. Professional organizations such as NACE International (The Corrosion Society) and SSPC (The Society for Protective Coatings), offer courses and certification programs that range from basic corrosion to coating inspector to cathodic protection specialist. NACE International offers the broadest range of courses and manages an extensive certification program. In 1998, NACE held 172 courses with more than 3,000 students, conducted multiple seminars, and offered publications, at a total cost of $8 million.

Summary - A total annual direct cost of corrosion by summing the costs of corrosion control methods and services was estimated at $121 billion, which is 1.38 percent of the U.S. GDP of $8.79 trillion in 1998. The largest portion (88.3 percent) of this cost is the organic coatings group at $107.2 billion. Notably, the categories of research and development and education and training indicated unfavorably low numbers.

Method 2 – Industry Sector Analysis

For the purpose of this study, the U.S. economy was divided into five different sector categories. Each of the sector categories were then divided into specific industry sectors for a total of 26 sectors, as follows:

Infrastructure:	Highway Bridges Gas and Liquid Transmission Pipelines Waterways and Ports Hazardous Materials Storage Airports Railroads

Utilities:	Gas Distribution Drinking Water and Sewer Systems Electrical Utilities Telecommunications
Transportation:	Motor Vehicles Ships Aircraft Railroad Cars Hazardous Materials Transport
Production and Manufacturing:	Oil and Gas Exploration - Production Mining Petroleum Refining Chemical, Petrochemical, and Pharmaceutical Pulp and Paper Agricultural Food Processing Electronics Home Appliances
Government:	Defense Nuclear Waste Storage

Infrastructure – The U.S. infrastructure and transportation system allows for a high level of mobility and freight activity for the nearly 270 million residents and 7 million business establishments. In 1997, more than 230 million motor vehicles, ships, airplanes, and railroad cars were used on 6.4 million km (4 million mi) of highways, railroads, and waterways connecting all parts of the United States. The transportation infrastructure also includes more than 800,000 km (approximately 500,000 mi) of oil and gas transmission pipelines, 8.5 million tanks for hazardous materials storage, and 18,000 public and private airports. The annual direct cost of corrosion in the infrastructure category is estimated at $22.6 billion.

Highway Bridges: Based on the National Bridge Inventory Database, there are 586,000 bridges in the United States. Of this total, 435,000 bridges are made from steel and conventional reinforced concrete, 108,000 bridges are constructed using prestressed concrete, and the balance is made using other materials of construction. Approximately 15 percent of the bridges are structurally deficient, primarily due to corrosion of steel and steel reinforcement. The dollar impact of corrosion on highway bridges is considerable. The annual direct cost of corrosion for highway bridges is estimated to be $8.3 billion, consisting of $3.8 billion for the annual cost to replace structurally deficient bridges over the next 10 years, $2.0 billion for maintenance and cost of capital for concrete bridge decks, $2.0 billion for maintenance and cost of capital for concrete substructures (minus decks), and $0.5 billion for maintenance painting of steel bridges. Life-cycle analysis estimates indirect costs to the user due to traffic delays and lost productivity at more than 10 times the direct cost of corrosion.

Gas and Liquid Transmission Pipelines: There are more than 528,000 km (328,000 mi) of natural gas transmission and gathering pipelines, 119,000 km (74,000 mi) of crude oil transmission and gathering pipelines, and 132,000 km (82,000 mi) of hazardous liquid transmission pipelines. For all natural gas pipeline companies, the total investment in 1998 was $63.1 billion, from which a total revenue of $13.6 billion was generated. For liquid pipeline companies, the investment was $30.2 billion, from which a revenue of $6.9 billion was generated. At an estimated replacement cost of $643,800 per km ($1,117,000 per mi), the asset replacement value of the transmission pipeline system in the United States is $541 billion; therefore a significant investment is at risk with corrosion being the primary factor in controlling the life of the asset. The average annual corrosion-related cost is estimated at $7.0 billion, which can be divided into the cost of capital (38 percent), operation and maintenance (52 percent), and failures (10 percent).

Waterways and Ports: In the United States, 40,000 km (25,000 mi) of commercial navigable waterways serve 41 states, including all states east of the Mississippi River. Hundreds of locks facilitate travel along these waterways. In January 1999, 135 of the 276 locks had exceeded their 50-year design life. The oldest operating locks in the United States are Kentucky River Locks 1 and 2. U.S. ports play an important role in connecting waterways, railroads, and highways. The nation's ports include 1,914 deep-water (seacoast and Great Lakes) and 1,812 along inland waterways. Corrosion is typically found on piers and docks, bulkheads and retaining walls, mooring structures, and navigational aids. There is no formal tracking of corrosion costs in these structures. Based on cost numbers obtained from the U.S. Army Corps of Engineers and the U.S. Coast Guard, an annual corrosion cost of $0.3 billion could be estimated. It should be noted that this is a low estimate since the corrosion costs of harbor and other marine structures are not included.

Hazardous Materials Storage: There are approximately 8.5 million regulated and non-regulated aboveground storage tanks (ASTs) and underground storage tanks (USTs) for hazardous materials (HAZMAT) in the United States. While these tanks represent a large investment, and good maintenance practices would be in the best interest of the owners, federal and state environmental regulators are concerned with the environmental impact of spills from leaking tanks. In 1988, the U.S. Environmental Protection Agency set a December 1998 deadline for UST owners to comply with the requirement to have corrosion control on all tanks, as well as overfill and spill protection. Thus, tank owners face considerable costs related to clean-up and penalties imposed by the government if they would not be in compliance. It is estimated that the annual cost of corrosion for ASTs is $4.5 billion and for USTs is $2.5 billion, resulting in a total annual direct corrosion cost of $7.0 billion.

Airports: The United States has the world's most extensive airport system, which is essential to national transportation and the U.S. economy. According to 1999 Bureau of Transportation Statistics figures, there were 5,324 public-use airports and 13,774 private-use airports in the United States. A typical airport infrastructure is complex, and components that might be subject to corrosion include the natural gas distribution system, jet fuel storage and distribution system, deicing storage and distribution system, vehicle fueling systems, natural gas feeders, dry fire lines, parking garages, and runway lighting. Generally, each of these systems is owned or operated by different organizations or companies; therefore, the impact of corrosion on an airport as a whole is not known or documented. However, the airports do not have any specific corrosion-related problems, that have not been described elsewhere in this report.

Railroads: In 1997, there were nine Class I freight railroads (railroads with operating revenues of more than $256.4 million). These railroads accounted for 71 percent of the industry's 274,399 km (170,508 mi) of railroad. There were 35 regional railroads (those with operating revenues between $40 million and $256.4 million and/or operating at least 560 km (350 mi) of railroad). The regional railroads operated 34,546 km (21,466 mi) of railroad. Finally, there were 513 local railroads operating more than 45,300 km (28,149 mi) of railroad. The elements that are subject to corrosion include metal members, such as rail and steel spikes; however, corrosion damage to railroad components are either limited or go unreported. Hence, a corrosion cost could not be determined.

Utilities – Utilities form an essential part of the U.S. economy by supplying gas, water, electricity, and communication. All utility companies combined spent $42.3 billion on capital goods in 1998, an increase of 9.3 percent from 1997. Of this total, $22.4 billion was used for structures and $19.9 billion was used for equipment. The total annual direct cost of corrosion in the utility category is estimated to be $47.9 billion.

Gas Distribution: The natural gas distribution system includes 2,785,000 km (1,730,000 mi) of relatively small-diameter, low-pressure piping, which is divided into 1,739,000 km (1,080,000 mi) of distribution main and 1,046,000 km (650,000 mi) of services. There are approximately 55 million services in the distribution system. A large percentage of the mains (57 percent) and services (46 percent) are made of steel, cast iron, or copper, which are subject to corrosion. The total annual direct cost of corrosion was estimated at approximately $5.0 billion.

Drinking Water and Sewer Systems: According to the American Waterworks Association (AWWA) industry database, there is approximately 1,483,000 km (876,000 mi) of municipal water piping in the United States. This number is not exact, since most water utilities do not have complete records of their piping system. The sewer system consists of approximately 16,400 publicly owned treatment facilities releasing some 155 million m^3 (41 billion gallons) of wastewater per day (1995). The total annual direct cost of corrosion for the nation's drinking water and sewer systems was estimated at $36.0 billion. This cost was contributed to by the cost of replacing aging infrastructure, the cost of unaccounted-for water through leaks, the cost of corrosion inhibitors, the cost of internal mortar linings, and the cost of external coatings and cathodic protection.

Electrical Utilities: The electrical utility industry is a major provider of energy in the United States. The total amount of electricity sold in the United States in 1998 was 3,240 billion GWh at a cost to the consumers of $218 billion. Electricity generation plants can be divided into seven generic types: fossil fuel, nuclear, hydroelectric, cogeneration, geothermal, solar, and wind. The majority of electric power in the United States is generated by fossil and nuclear supply systems. The total annual direct cost of corrosion in the electrical utility industry in 1998 is estimated at $6.9 billion, with the largest amounts for nuclear power at $4.2 billion and fossil fuel at $1.9 billion, and smaller amounts for hydraulic and other power at $0.15 billion, and transmission and distribution at $0.6 billion.

Telecommunications: The telecommunications infrastructure includes hardware such as electronics, computers, and data transmitters, as well as equipment shelters and the towers used to mount antennas, transmitters, receivers, and television and telephone systems. According to the U.S. Census Bureau, the total value of shipments for communications equipment in 1999 was $84 billion. An important factor for corrosion cost is the additional cost of protecting towers and shelters, such as painting and galvanizing. In addition, corrosion of buried copper grounding beds, as well as galvanic corrosion of the grounded steel structures, contributes to the corrosion cost. For this sector, no corrosion cost was determined because of the lack of information on this rapidly changing industry. Many components are being replaced before physically failing because the technology has become obsolete in a short period of time.

Transportation - The transportation category includes vehicles and equipment, such as motor vehicles, aircraft, railroad cars, and hazardous materials transport, that make use of the U.S. highways, waterways, railroads, and airports. The annual cost of corrosion in the transportation category is estimated at $29.7 billion.

Motor Vehicles: U.S. consumers, businesses, and government organizations own more than 200 million registered motor vehicles. Assuming an average value of $5,000, the total investment Americans have made in motor vehicles can be estimated at more than $1 trillion. Since the 1980s, car manufacturers have increased the corrosion resistance of vehicles by using corrosion-resistant materials, employing better manufacturing processes, and by designing corrosion-resistant vehicles. Although significant progress has been made, further improvement can be achieved in the corrosion resistance of individual components, such as fuel and brake systems, and electrical and electronic components. The total annual direct cost of corrosion is estimated at $23.4 billion, which is divided into the following three components: (1) increased manufacturing costs due to corrosion engineering and the use of corrosion-resistant materials ($2.56 billion per year), (2) repairs and maintenance necessitated by corrosion ($6.45 billion per year), and (3) corrosion-related depreciation of vehicles ($14.46 billion per year).

Ships: The U.S. flag fleet can be divided into several categories as follows: the Great Lakes with 737 vessels at 100 billion ton-km (62 billion ton-mi), inland with 33,668 vessels at 473 billion ton-km (294 billion ton-mi), ocean with 7,014 vessels at 563 billion ton-km (350 billion ton-mi), recreational with 12.3 million boats, and cruise ship with 122 boats serving North American ports (5.4 million passengers). The total annual direct cost of corrosion to the U.S. shipping industry is estimated at $2.7 billion. This cost is divided into costs associated with new construction ($1.1 billion), with maintenance and repairs ($0.8 billion), and with corrosion-related downtime ($0.8 billion).

Aircraft: In 1998, the combined aircraft fleet operated by U.S. airlines was more than 7,000, of which approximately 4,000 were turbojets. The fleet includes the Boeing 707, DC-9, Boeing 727, DC-10, and the early versions of the Boeing 737 and 747. At the start of the jet age (1950s to 1960s), little or no attention was paid to corrosion and corrosion control. One of the concerns is the continued aging of the airplanes beyond the 20-year design life. Only the most recent designs (Boeing 777 and late version 737) have incorporated significant improvements in corrosion prevention and control in design and manufacturing. The total annual direct cost of corrosion to the U.S. aircraft industry is estimated at $2.2 billion, which includes the cost of design and manufacturing ($0.2 billion), corrosion maintenance ($1.7 billion), and downtime ($0.3 billion).

Railroad Cars: In 1998, 1.3 million freight cars and 1,962 passenger cars were reported to operate in the United States. Covered hoppers at 28 percent make up the largest portion of the freight-car fleet, with tanker cars making up the second largest portion at 18 percent. The type of commodities transported range from coal (largest volume) to chemicals, motor vehicles, farm products, food products, and metallic and non-metallic ores and minerals. Railroad cars suffer from both external and internal corrosion. It is estimated that the total annual direct cost of corrosion is approximately $0.5 billion, divided over external coatings ($0.25 billion) and internal coatings and linings ($0.25 billion).

Hazardous Materials Transport: According to U.S .Department of transportation, there are approximately 300 million hazardous materials shipments of more than 3.1 billion metric tons annually in the United States. Bulk transportation of hazardous materials includes overland shipping by tanker truck and rail car, and by special containers that are loaded onto vehicles. Over water, ships loaded with specialized containers, tanks, and drums are used. In small quantities, hazardous materials require specially designed packaging for truck and air shipment. The total annual direct cost of corrosion for hazardous materials transport is more than $0.9 billion. The elements of the annual corrosion cost include the cost of transporting vehicles ($0.4 billion per year), the cost of specialized packaging ($0.5 billion per year), and the direct and indirect costs ($0.5 million per year and an unknown value, respectively) of accidental releases and corrosion-related transportation incidents.

Production and Manufacturing - This category includes industries that produce and manufacture products of crucial importance to the U.S. economy and the standard of living in the United States. These include oil production, mining, petroleum refining, chemical and pharmaceutical production, and agricultural and food production. The total annual direct cost of corrosion in this category was estimated to be $17.6 billion.

Oil and Gas Exploration and Production: Domestic oil and gas production can be considered to be a stagnant industry, because most of the significant available onshore oil and gas reserves have been exploited. Oil production in the United States in 1998 consisted of 3.04 billion barrels. The significant recoverable reserves left to be discovered and produced are probably limited to less convenient locations such as in deep water offshore, remote arctic locations, and difficult-to-manage reservoirs with unconsolidated sands. The total annual direct cost of corrosion in the U.S. oil and gas production industry is estimated at $1.4 billion, made up of $0.6 billion for surface piping and facility costs, $0.5 billion in downhole tubing expenses, and $0.3 billion in capital expenditures related to corrosion.

Mining: In the mining industry, corrosion is not considered to be a significant problem. There is a general consensus that the life-limiting factors for mining equipment are wear and mechanical damage rather than corrosion. Maintenance painting, however, is heavily relied upon to prevent corrosion, with an annual estimated expenditure for the coal mining industry of $0.1 billion.

Petroleum Refining: Petroleum is the single largest source of energy for the United States. The nation uses twice as much petroleum as either coal or natural gas. The U.S. refineries represent approximately 23 percent of the world's petroleum production, and the United States has the largest refining capacity in the world, with 163 refineries. In 1996, U.S. refineries supplied more than 18 million barrels per day of refined petroleum products. The total annual direct cost of corrosion is estimated at $3.7 billion. Of this total, maintenance-related expenses are estimated at $1.8 billion, vessel turnaround expenses at $1.4 billion, and fouling costs are approximately $0.5 billion annually.

Chemical, Petrochemical, and Pharmaceutical: The chemical, petrochemical, and pharmaceutical industries play a major role in the U.S. economy by providing a wide range of products. The chemical industry includes those manufacturing facilities that produce bulk or specialty compounds by chemical reactions between organic and/or inorganic materials. The petrochemical industry includes those manufacturing facilities that create substances from raw hydrocarbon materials such as crude oil and natural gas. The pharmaceutical industry formulates, fabricates, and processes medicinal products from raw materials. The total annual direct cost of corrosion for this industry sector is estimated at $1.7 billion per year (8 percent of total capital expenditures). No calculation was made for the indirect costs of production outages or indirect costs related to catastrophic failures. The costs of operation and maintenance related to corrosion were not readily available; estimating these costs would require detailed study of data records of individual companies.

Pulp and Paper: The $165 billion pulp, paper, and allied product industry supplies the United States with approximately 300 kg of paper per person per year. More than 300 pulp mills and more than 550 paper mills support its production. The total annual direct cost of corrosion is estimated at $6.0 billion, with the majority of this cost in the paper and paperboard-making industry, and calculated as a fraction of the maintenance costs. No information was found to estimate the corrosion costs related to the loss of capital.

Agricultural: Agriculture operations are producing livestock, poultry, or other animal specialties and their products, and producing crops, including fruits and greenhouse or nursery products. According to the National Agricultural Statistics Service, there are approximately 1.9 million farms in the United States. Based on a 1997 census, the total value of farm machinery and equipment is approximately $15 billion per year. The two main reasons for replacing machinery or equipment include upgrading old equipment and substituting because of wear and corrosion. Discussions with people in this industrial sector resulted in an estimate of corrosion costs in the range of 5 percent to 10 percent of the value of all new equipment. The total annual direct cost of corrosion in the agricultural production industry is estimated at $1.1 billion.

Food Processing: The food processing industry is one of the largest manufacturing industries in the United States, accounting for approximately 14 percent of the total U.S. manufacturing output. Sales for food-processing companies totaled $265.5 billion in 1999. Because of quality-of-food requirements, stainless steel is widely used. Assuming that the stainless steel consumption and cost in this industry is entirely attributed to corrosion, a total annual direct cost of corrosion is estimated at $2.1 billion. This cost includes stainless steel usage for beverage production, food machinery, cutlery and utensils, commercial and restaurant equipment, appliances, aluminum cans, and the use of corrosion inhibitors.

Electronics: Corrosion in electronic components manifests itself in several ways. Computers, integrated circuits, and microchips are now an integral part of all technology-intensive industry products, ranging from aerospace and automotive to medical equipment and consumer products, and are therefore exposed to a variety of environmental conditions. Corrosion in electronic components are insidious and cannot be readily detected; therefore, when corrosion failure occurs, it is often dismissed as just a failure and the part or component is replaced. Particularly in the case of consumer electronics, devices would become technologically obsolete long before corrosion-induced failures would occur. However, capital-intensive industries, with significant investment in durable equipment with a considerable number of electronic components, such as the defense industry and the airline industry, tend to keep the equipment for longer periods of time, and corrosion is likely to become an issue. Although the cost of corrosion in the electronics sector could not be estimated, it has been suggested that a significant part of all electronic component failures are caused by corrosion.

Home Appliances: The appliance industry is one of the largest consumer product industries. For practical purposes, two categories of appliances are distinguished: "Major Home Appliances" and "Comfort Conditioning Appliances." In 1999, a total of 70.7 million major home appliances and a total of 49.5 million comfort conditioning appliances were sold in the United States, for a total of 120.2 million appliances. The cost of corrosion in home appliances includes the cost of purchasing replacement appliances because of premature failure due to corrosion. For water heaters alone, the replacement cost was estimated at $460 million per year, using a low estimate of 5 percent of the replacement being corrosion-related. The cost of internal corrosion protection for all appliances includes the use of sacrificial anodes ($780 million per year), corrosion-resistant materials (no cost estimate), and internal coatings (no cost estimate). The cost of external corrosion protection using coatings was estimated at $260 million per year. Therefore, the estimated total annual direct cost of corrosion in home appliances is at least $1.5 billion.

Government - Federal, state, and local governments play important roles in the U.S. economy with a 1998 GDP of approximately $1.1 trillion ($360 billion federal, $745 billion state and local). While the government owns and operates large assets under various departments, the U.S. Department of Defense (DOD) was selected for analysis because of its significant impact on the U.S. economy. A second government sectors elected is nuclear waste storage under the U.S. Department of Energy (DOE).

Defense: The ability of the DOD to respond rapidly to national security and foreign commitments can be adversely affected by corrosion. Corrosion of military equipment and facilities has been, for many years, a significant and ongoing problem. The corrosion-related problems are becoming more prominent as the acquisition of new equipment is decreasing and a large degree of reliability of aging systems is expected. The data provided by the military services (Army, Air Force, Navy, and Marine Corps) indicate that corrosion is potentially the number one cost driver in life-cycle costs. The total annual direct cost of corrosion incurred by the military services for both systems and infrastructure was estimated at $20 billion.

Nuclear Waste Storage: Nuclear wastes are generated from spent nuclear fuel, dismantled nuclear weapons, and products such as radio pharmaceuticals. The most important design item for the safe storage of nuclear waste is effective shielding of radiation. Corrosion is not considered a major issue in the transportation of nuclear wastes due to the stringent packaging requirements and the relatively short duration of the transport. However, corrosion is an important issue in the design of the casks used for permanent storage with a design life of several thousand years. A 1998 total life-cycle cost analysis by DOE for the permanent disposal of nuclear waste in Yucca Mountain, Nevada, estimated the total repository cost by the construction phase (2002) at $4.9 billion, with an average annual cost (from 1999 to 2116) of $205 million. Of this cost, $42.2 million is corrosion-related.

Summary of Total Cost - The cost of corrosion was estimated for the individual economic sectors discussed above. The total cost due to the impact of corrosion for the analyzed sectors was $137.9 billion per year. Since not all economic sectors were examined, the sum of the estimated costs does not represent the total cost of corrosion to the entire U.S. economy. By estimating the percentage of U.S. GDP of the sectors for which corrosion costs were determined and extrapolating the cost numbers to the entire U.S. economy, a total cost of corrosion of $276 billion was estimated. This is approximately 3.1 percent of the nation's GDP. The indirect corrosion costs (i.e., the costs incurred by other than owners and operators as a result of corrosion) are conservatively estimated to be equal to the direct cost; giving a total direct plus indirect cost of $552 billion (i.e., 6 percent of the GDP). Evidence of the large indirect corrosion costs are: (1) lost productivity because of outages, delays, failures, and litigation; (2) taxes and overhead on the cost of corrosion portion of goods and services; and (3) indirect costs of non-owner/operator activities.

The current study showed that the technological changes have provided many new ways to prevent corrosion, as well as the improved use of available corrosion management techniques. However, better corrosion management can be achieved using preventive strategies in non-technical and technical areas. These preventive strategies include: (1) increase awareness of large corrosion costs and potential savings, (2) change the misconception that nothing can be done about corrosion, (3) change policies, regulations, standards, and management practices to increase corrosion cost-savings through sound corrosion management, (4) improve education and training of staff in recognition of corrosion control, (5) advance design practices for better corrosion management, (6) advance life prediction and performance assessment methods, and (7) advance corrosion technology through research, development, and implementation.

While corrosion management has improved over the past several decades, the United States is still far from implementing optimal corrosion control practices. There are significant barriers to both the development of advanced technologies for corrosion control and the implementation of those technological advances. In order to realize the savings from reduced costs of corrosion, changes are required in three areas: (1) the policy and management framework for effective corrosion control, (2) the science and technology of corrosion control, and

(3) the technology transfer and implementation of effective corrosion control. The policy and management framework is crucial because it governs the identification of priorities, the allocation of resources for technology development, and the operation of the system for implementation.

Incorporating the latest corrosion strategies in industry management and government policies, as well as advances in science and technology, are required. It is necessary to engage a larger constituency comprised of the primary stakeholders, government and industry leaders, the general public, and consumers. A major challenge involves disseminating corrosion awareness and expertise that is currently scattered throughout government and industry organizations. In fact, there is no focal point for the effective development, articulation, and delivery of corrosion cost-savings programs.

Therefore, the following recommendations are made:

1. Form a committee on "corrosion control and prevention" under the National Research Council.
2. Develop a national focus on corrosion control and prevention.
3. Improve policies and corrosion management.
4. Accomplish technological advances for corrosion cost-savings.
5. Implement effective corrosion control.

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LIST OF ACRONYMS

AAPA	American Association of Port Authorities
AAR	Association of American Railroads
AASHTO	American Association of State Highway and Transportation Officials
ABS	Anti-locking Braking System
ACAP	Automotive Corrosion and Prevention Committee
AD	Airworthiness Directives
ADT	Average Daily Traffic
AF&PA	American Forest and Paper Association
AGA	American Gas Association
AIChE	American Institute of Chemical Engineers
AMC	American Motor Company
AP	Anodic Protection
APB	Acid-Producing Bacteria
API	American Petroleum Institute
ARS	Agricultural Research Service
ASCE	American Society of Civil Engineers
ASIP	Air Force Structural Integrity Program
AST	Aboveground Storage Tank
ASTM	American Society for Testing and Materials
ATA	Air Transportation Association
AV	Annualized Value
AWWA	American Water Works Association
AWWC	American Water Works Company
BCA	Benefit-Cost Analysis
BWR	Boiling Water Reactor
CAPEX	Capital Expenditures
CARC	Chemical Agent Resistance Coating
CCW	Condenser Circulating Water
CDM	Corrosion Data Management
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
CFRP	Carbon Fiber Reinforced Plastics
CHD	Catalytic Hydro-Desulfurization
CIC	Corrosion-Inhibiting Compounds
CIP	Capital Improvement Project

LIST OF ACRONYMS (continued)

CMA	Calcium Magnesium Acetate
CMA	Chemical Manufacturers Association
CP	Cathodic Protection
CPC	Corrosion Preventative Compounds
CPCP	Corrosion Prevention and Control Programs
CRA	Corrosion-Resistant Alloys
CRSI	Concrete Reinforcing Steel Institute
CSE	Copper Sulfate Electrode
DCF	Discounted Cash Flow
DM	Deutschmarks
DOD	Department of Defense
DOE	Department of Energy
DOT	Department of Transportation
DRA	Drag Reducing Agents
DTM	Direct-to-Metal
ECF	Elemental Chlorine Free
EIA	Energy Information Administration
ELPO	Electrodeposition
EPA	Environmental Protection Agency
EPDM	Ethylene Propylene Dione Monomer
EPRI	Electric Power Research Institute
EVA	Ethylene Vinyl Acetate
FAA	Federal Aviation Administration
FBE	Fusion-Bonded Epoxy
FCC	Fluid Catalytic Cracking
FDA	Food and Drug Administration
FERC	Federal Energy Regulatory Committee
FFS	Fitness-for-Service
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FRP	Fiber-Reinforced Plastics
GDP	Gross Domestic Product
GNP	Gross National Product
GRI	Gas Research Institute
GRP	Glass-Reinforced Plastic
GSA	Government Services Administration
GW	Gigawatt
GWh	Gigawatt hours
HAC	Hydrogen-Assisted Cracking
HAZ	Heat-Affected Zone
HAZMAT	Hazardous Materials
HCA	High Consequence Areas

LIST OF ACRONYMS (continued)

HDPE	High-Density Polyethylene
HIC	Hybrid Integrated Circuits
HIC	Hydrogen-Induced Cracking
HLW	High-Level Waste
HMIS	Hazardous Materials Information System
HMMWV	High Mobility Multi-Purpose Wheeled Vehicle
HMPE	Hazardous Materials Program Evaluation
HMR	Hazardous Materials Regulations
HPI	Hydrocarbon Processing Industry
HPOAS	High-Purity Oxygen-Activated Sludge
HT	High Tensile
HVL	Highly Volatile Liquids
IATA	International Air Transportation Association
IC	Integrated Circuits
ICCP	Impressed Current Cathodic Protection
ID	Inside Diameter
IGA	Intergranular Attack
IGSCC	Intergranular Stress Corrosion Cracking
ILI	In-Line Inspection
IO	Input/Output
IRC	Institute for Research Construction
kW	kilowatt
kWh	kilowatt hours
LCC	Life-Cycle Costing
LCR	Lead and Copper Rule
LLW	Low-Level Waste
LMC	Latex-Modified Concrete
LMC	Liquid Metal Cracking
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gases
LPG	Liquid Propane Gas
LPR	Linear Polarization Resistance
LWR	Light-Water Reactor
MAOP	Maximum Allowable Operating Pressure
MAPI	Maintenance Association of the Paper Industry
MCRT	Mean Cell Residence Time
MFL	Magnetic Flux Leakage
MGD	Million Gallons per Day
MIC	Microbiologically Induced Corrosion
MLSS	Mixed Liquor Suspended Solids
MMBD	Million Barrels per Day
MO	Magneto-Optic

LIST OF ACRONYMS (continued)

MSHA	Mine Safety and Health Administration
MTI	Materials Technology Institute
MTV	Medium Tactical Vehicle
MW	Megawatt
MWh	Megawatt hours
NAC	Naphthenic Acid Corrosion
NACE	National Association of Corrosion Engineers
NAECA	National Appliance Energy Conservation Act
NASA	National Aeronautics and Space Administration
NASS	National Agricultural Statistics Service
NBI	National Bridge Inventory
NBS	National Bureau of Standards
NCHRP	National Cooperative Highway Research Program
NDE	Nondestructive Examination
NDI	Nondestructive Inspection
NDT	Nondestructive Testing
NEC	National Electrical Code
NGL	Natural Gas Liquid
NIST	National Institute of Standards and Technology
NRC	Nuclear Regulatory Commission
NWT	Nominal Wall Thickness
O&M	Operation and Maintenance
OD	Outside Diameter
OEM	Original Equipment Manufacturers
OHMS	Office of Hazardous Materials Safety
OPEC	Organization of Petroleum Exporting Countries
OPS	Office of Pipeline Safety
OSHA	Occupational Safety and Health Administration
OUST	Office of Underground Storage Tanks
PC	Personal Computer
PC Boards	Printed Circuit Boards
PCS	Personal Computer Systems
PDM	Program Depot Maintenance
PDV	Present Discounted Value
PhRMA	Pharmaceutical Research and Manufacturers of America
ppb	parts per billion
PSM	Process Safety Management
PTI	Post-Tensioning Institute
PVC	Polyvinyl Chloride
PWR	Pressurized Water Reactor
RBA	Risk-Based Assessment
RBI	Risk-Based Inspection
RBM	Reliability-Based Maintenance

LIST OF ACRONYMS (continued)

RC	Responsible Care
RCRA	Resource Conservation Recovery Act
RMP	Risk Management Program
ROW	Right-of-Way
RSPA	Research and Special Programs Administration
SAE	Society of Automotive Engineers
SCC	Stress Corrosion Cracking
SDWA	Safe Drinking Water Act
SHRP	Strategic Highway Research Program
SIC	Standard Industrial Classification
SJV	San Joaquin Valley
SMYS	Specified Minimum Yield Stress
SPCC	Spill Prevention Countermeasure and Control
SRB	Sulfate-Reducing Bacteria
SSPC	Steel Structures Painting Council
STB	Surface Transportation Board
STI	Steel Tank Institute
SVI	Sludge Volume Index
SWTR	Surface Water Treatment Rule
TAACOM	Tank Automotive and Armaments Command
TAN	Total Acid Number
TAPPI	Technical Association of the Pulp and Paper Industry
TAPS	Trans-Alaska Pipeline System
TCF	Totally Chlorine Free
TCR	Total Coliform Rule
TFS	Tin-Free Steel
TRB	Transportation Research Board
TRI	Toxics Release Inventory
TVA	Tennessee Valley Authority
UAN	Urea Ammonia Nitrate
USDA	U.S. Department of Agriculture
UST	Underground Storage Tanks
UT	Ultrasonic Testing
UT	Ultrasonic Tools
UV	Ultraviolet
VCR	Video Cassette Recorder
VIN	Vehicle Identification Number
VIUS	Vehicle Inventory and Use Survey
VOC	Volatile Organic Compounds
WIDB	Water Industry Database
WIN	Water Infrastructure Network
WTI	West Texas Intermediate

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CORROSION COSTS AND PREVENTIVE STRATEGIES IN THE UNITED STATES

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INTRODUCTION

Previous studies have shown that corrosion is very costly and has a major impact on the economies of industrial nations. A 1975 benchmark study by Battelle-NBS pointed out the severe impact of corrosion on the U.S. economy.⁽¹⁾ The estimates based on the Battelle-NBS study report that the annual cost of corrosion in the United States alone was approximately $70 billion, which was between 4 and 5 percent of the gross national product (GNP). A limited study in 1995, updating the 1975 cost numbers, estimated the total annual cost of corrosion at approximately $300 billion.⁽²⁾ This staggering total corrosion loss resulted from equipment and structure replacement, loss of product, maintenance and repair, the need for excess capacity and redundant equipment, corrosion control, designated technical support, design, insurance, and parts and equipment inventories. During the same time period that the original Battelle-NBS study was conducted, other national studies, such as in the United Kingdom,⁽³⁾ Japan,⁽⁴⁾ Australia,⁽⁵⁾ and Kuwait,⁽⁶⁾ investigated their respective corrosion costs. While all these studies emphasized the financial losses due to corrosion, no systematic study was conducted to investigate preventive strategies with cost-benefit considerations.

Through discussions between NACE International (The Corrosion Society), members of Congress, and the U.S. Department of Transportation (U.S. DOT), an amendment for the cost of corrosion was included in the Transportation Equity Act for the 21st Century (TEA-21), which was passed by the U.S. legislature in 1998. The amendment states:

> IN GENERAL – The Secretary shall make a grant to conduct a study on the costs and benefits of corrosion control and prevention. The study shall be conducted in conjunction with an interdisciplinary team of experts from the fields of metallurgy, chemistry, economics, and others, as appropriate.

Subsequently, the Federal Highway Administration (FHWA) initiated a systematic study to estimate the total economic cost of metallic corrosion and to provide preventive strategies to minimize the impact of corrosion. A major focus of this study was on various economic sectors, with an emphasis on infrastructure, utilities, transportation, production and manufacturing, and government.

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BACKGROUND

Review of Previous Studies (Appendix A)

In this section of the report, a critical review of previous national studies on the cost of corrosion is presented. These studies have formed the basis for much of the current thinking regarding the cost of corrosion to the various national economies, and have led to a number of other national studies(7-9) that are currently being performed. A detailed description of these national studies is given in Appendix A.

In the past, cost of corrosion studies have been undertaken by several countries. The earliest study was reported in 1949 by Uhlig,(10) who estimated the total cost of corrosion to the economy by summing material and procedure costs related to corrosion control. The 1949 Uhlig report, which was the first to draw attention to the economic significance of corrosion, was followed in the 1970s by a number of studies in various countries, such as the United States,(1) the United Kingdom,(3) and Japan.(4) The national study by Japan conducted in 1977 followed the Uhlig methodology. In the United States, the Battelle-NBS study estimated the total direct cost of corrosion using an economic input/output framework. The input/output method was adopted later by studies in two other nations, namely Australia in 1983(5) and Kuwait in 1995.(6) In the United Kingdom, a committee chaired by T.P. Hoar conducted a national study in 1970 using a method similar to the one used by Uhlig. The Hoar study estimated the total cost of corrosion by collecting data through interviews and surveys of targeted economic sectors.

Although the efforts of the above-referenced studies ranged from formal and extensive to informal and modest, all studies estimated the total annual cost of corrosion as ranging from 1 to 5 percent of each country's GNP.

In the following sections, the three main methods used by the previous studies are described:

1. The cost of corrosion protection products and services with indirect costs (costs to others) included - United States, 1949 (Uhlig study)(10) and Japan.(4)
2. The direct cost of corrosion products and services by sectors (no indirect costs included); data were based on surveys and experts judgments - United Kingdom, 1970 (Hoar study).(3)
3. Input/output analysis - United States, 1978 (Battelle/NBS study),(1) Australia,(5) and Kuwait.(6)

These previous studies are important in that they confronted the difficult problems in assessing the cost of corrosion and subsequently arrived at judgments regarding the most helpful approach. They each contributed to the current knowledge of estimating the cost of corrosion.

1. Corrosion Protection Products and Services

The 1949 study, "The Cost of Corrosion in the United States" by H.H. Uhlig,(10) was the earliest effort to estimate the U.S. national cost of corrosion. This study attempted to measure the costs of corroding structures to both the owner/operator (direct cost) and to others (indirect cost). The total cost of corrosion to owners/operators was estimated by summing the cost estimates for corrosion prevention products and services used in the entire U.S. economy, such as coatings, inhibitors, corrosion-resistant metals, and cathodic protection, and multiplied these totals by their respective prices. Three items were selected as examples to estimate the cost to private consumers/users: domestic water heater replacement, automobile internal combustion engine repairs, and replacement of automobile mufflers. Adding up both direct and indirect costs, the annual cost of corrosion to the United States was estimated to be $5.5 billion or 2.1 percent of the 1949 GNP.

This method was adapted in a later study to estimate the total cost of corrosion in Japan. That study estimated the national cost of corrosion at $9.2 billion (1974), which was equivalent to 1 to 2 percent of the Japanese GNP.

2. Direct Cost of Corrosion Products and Services by Sectors

The Hoar study (United Kingdom, 1970)(3) took a different approach from the Uhlig method to determine the national corrosion cost in the United Kingdom. The study identified the sources for the cost of corrosion by sectors of the economy. It estimated the direct expenditures (costs to owner/operator) in each economic sector. Indirect costs were not included in the study. Information was gathered by interviewing corrosion experts who worked in companies and agencies, and by surveys on expenditures for corrosion protection practices. Corrosion experts estimated corrosion costs and the potential savings based on their experiences for major economic sectors. The costs by sector were totaled for the whole economy. The study estimated the annual total corrosion cost in the United Kingdom to be approximately 3.5 percent of their GNP.

3. Input-Output Analysis

The Battelle-NBS study (United States, 1978)(1) used an economic input/output analysis to estimate the cost of corrosion for the United States. In the input/output model, the U.S. economy was divided into 130 industrial sectors. For each industry sector, estimates were made on the costs of corrosion prevention, as well as for the cost of repair and replacement due to corrosion.

The following direct costs (cost to owner/operator of the structure) were included in the study:

- replacement of equipment or buildings,
- loss of product,
- maintenance and repair,
- excess capacity,
- redundant equipment,
- corrosion control, such as inhibitors, and organic and metallic coatings,
- engineering research and development testing,
- design,
- insurance, and
- parts and equipment inventory.

The input-output analysis was invented by Wassily Leontief, who received a Nobel Prize in 1973 for developing the model. The input-output model is a simplified general equilibrium model of an economy showing the extent to which each sector uses inputs from the other sectors to produce its output – and thus showing how much each sector sells to other sectors. The input-output model shows the increase in economic activity in every other sector that would be required to increase the net production of a sector. For example, if a certain amount of paint were required for corrosion prevention, the input-output model would show the total activity through all the sectors in order to produce this amount of paint. Since a U.S. input-output matrix was constructed by the Department of Commerce from the census of manufacturers, it represented the actual structure of the U. S. economy. The economic input-output analysis explicitly accounts for all the inputs within the sector and the rest of the economy inputs to produce a product or service by using the input-output matrices of a national economy.

The standard annual input-output matrix has embedded in it the cost of corrosion in a specific year. The study identified the elements of various sectors that represented corrosion expenditures, such as coatings for steel pipelines. The coefficient of coatings for the steel pipelines were then modified so that, for example, pipelines spent nothing on coatings since the only purpose of coatings is to prevent corrosion. Once the particular coefficients in the steel pipeline column were modified, the column was re-normalized to add up to one. This new matrix represented the world without corrosion. With the new matrix, the level of resources used to produce the GNP in a world of corrosion would produce a higher GNP than in a world without corrosion.

The Battelle-NBS study collected data on corrosion-related changes in resources (material, labor, energy, required value added to produce a product or service), capital equipment and facilities, and replacement rates for capital stock of the capital items. The total cost of corrosion was defined as "the increment of total cost incurred because corrosion exists." The study therefore asked, "what cost would not be incurred if corrosion did not exist?" It developed three "worlds" for its analysis as follows:

World I:	real world of corrosion (year 1975 was modified to full employment level of economic activity),
World II:	hypothetical world without corrosion (to establish a baseline), and
World III:	hypothetical world in which the economically most effective corrosion prevention is practiced by everyone.

The input-output model was constructed to describe these three economies. The total national cost of corrosion was defined as the difference between the GNP of World I and the GNP of World II. In terms of the Battelle-NBS study, the standard input-output matrix represents World I.

The Battelle-NBS study divided the total cost into avoidable and unavoidable costs. The avoidable cost of corrosion is the difference between the GNP of World I and the GNP of World III, or it is the "cost which is amenable to reduction by the most economically efficient use of recently available corrosion control technology." Unavoidable cost of corrosion is the difference between the GNP of World II and the GNP of World III or "the cost that is not amenable to reduction by presently available technology."

The final results of the Battelle-NBS study, after adjustments by NBS to the Battelle report, for the base year of 1975 were:

- the total U.S. cost of metallic corrosion per year was estimated to be $70 billion, which comprised 4.2 percent of the GNP in 1975, and
- 15 percent or $10 billion was estimated to be avoidable by the use of the most economically effective presently available corrosion technology.

An uncertainty of ±30 percent for the total corrosion cost figure was estimated, while greater uncertainty was estimated for the avoidable costs.

OBJECTIVES AND SCOPE

The objectives of the current cost of corrosion study were to:

(1) develop an estimate of the total economic impact of metallic corrosion in the United States, and

(2) identify national strategies to minimize the impact of corrosion.

The scope of the study is restricted to metallic corrosion. The study provides an overall estimate of the total cost of corrosion in the United States and discusses the economic effects of corrosion prevention strategies. Furthermore, the study provides detailed descriptions of individual industry sectors that have a significant impact on the U.S. economy.

The work involved to accomplish the above-stated objectives was conducted through the following main activities:

- determination of the cost of corrosion based on corrosion control methods and services,
- determination of the cost of corrosion for specific industry sectors,
- extrapolation of individual sector costs to a national total corrosion cost,
- assessment of barriers to progress and effective implementation of optimized corrosion control practices, and
- development of implementation strategies and recommendations for realization of cost-savings.

Total Cost of Corrosion: The total cost of corrosion in the United States is estimated by using two entirely different methods. The first method estimates the cost of corrosion by adding the costs of corrosion control methods and services. The second method estimates the total cost by extrapolating the corrosion costs of representative industrials sectors to the entire U.S. economy. Past studies have shown that the second method is more likely to incorporate all costs and that the first method is likely to miss the significant cost of corrosion management, the cost for direct services related to the owner/operator, and the cost of loss of capital because of corrosion.

Corrosion Costs for Specific Industry Sectors: The costs for individual industry sectors are examined, and estimates are made for total annual direct corrosion costs for the sectors as well as for individual aspects within the sectors. The sectors are divided among five sector categories: Infrastructure, Utilities, Transportation, Production and Manufacturing, and Government.

Barriers to Progress and Effective Implementation: The various strategies and policies that are or can potentially be relevant to corrosion control and management are examined. The importance of subjects such as education, training, corporate and public awareness, and tax policies as related to corrosion is discussed.

Implementation and Recommendations: Suggestions are made to implement the findings of the research to improve corrosion control and management practices in a cost-effective manner.

APPROACH

Various aspects of the previous studies are relevant to the current study, such as the methods to determine the total cost of corrosion and the cost elements that make up the total cost. Elements and approaches from the Battelle-NBS report (United States, 1975),(1-2) the Hoar report (United Kingdom, 1971),(3) and the Uhlig report (United States, 1952)(10) were used to define the approach for the current study.

In order to achieve the objectives of the project, a systematic approach to data collection, sector selection, and economic analysis was adopted. The data collection and analysis served both the total costs of corrosion and the specific sector studies.

Data Collection

In the current study, two different approaches were taken to estimate the total cost of corrosion. The first approach followed the Uhlig method where the total cost was determined by summing the costs for corrosion products and services. The second approach consisted of data collection for specific economic sectors.

The costs of corrosion control products and services were obtained from various sources such as the U.S. Department of Commerce, Census Bureau, existing industrial surveys, trade organizations, industry groups, and individual companies. The data collection for corrosion control products relied heavily on surveys of relevant web sites. Data collection of corrosion control services, such as engineering services, research and testing, and education and training, was obtained primarily from trade organizations, educational institutions, and individual experts.

Data collection for the sector-specific analyses differed significantly from sector to sector depending on the availability of data and the form in which the data were available. In order to determine annual corrosion costs, it was attempted to obtain data for the years 1996 to 1999, with an emphasis on 1998. Generally, for many of the public sectors, such as infrastructure and utilities, much of the information is public and can be obtained from government reports and other publicly available documents. In many cases the advice of experts in the specific sectors was sought in order to obtain relevant information. Discussions with industry experts provided the basis of the industry sector data collection. Corrosion-related cost information from the private industry sectors was more difficult to obtain directly, because either the information was not readily available or could not be released because of company policies. In this case, information from publicly available industry records on operation and maintenance costs was obtained and, with the assistance of industry experts, corrosion-related costs could be estimated.

In a few cases, very detailed industry data formed the basis for data collection. For example, in the case of the electric utility industry, specific information on the corrosion fractions of capital and operation/maintenance could be obtained from one specific utility. These detailed data could be extrapolated to the entire utility industry using published industry data. A separate project with the Electric Power Research Institute allowed for this detailed data collection approach.(11)

Economic Analysis Methods (Appendix B)

The cost of corrosion can be defined in different ways depending on what is included and who is affected. In past studies, different definitions of the cost of corrosion have been used, and have therefore arrived at different estimates. In the current study, the total direct corrosion cost for each sector was estimated and major components contributing to this cost were analyzed. In addition, preventive strategies for corrosion control were described for the individual sectors. The objective of the current study was to obtain a measure of the cost of corrosion for the target year 1998. The cost of corrosion is defined as the corrosion fraction of design, manufacturing, operation and maintenance, technology development, and asset value loss.

While emphasis is placed on current corrosion costs, in some cases, changes in the cost of corrosion could be addressed by examining changes in corrosion control practices over the last few decades. This allows placing current practices into perspective within the sector's history and demonstrating achievements to date.

For other sectors, the economic analysis demonstrated how the current cost of corrosion may be lowered by implementing optimal corrosion management practices. Where possible, data on alternative designs, materials, and maintenance practices were gathered and analyzed, as well as data on the service life of structures.

Three important concepts that are frequently used in the analysis of the results are corrosion management, life-cycle costing (LCC), and cost-benefit analysis. Corrosion management includes all activities through the lifetime of a structure that are performed to prevent corrosion, repair its damage, and replace the structure. These activities include design, manufacturing, maintenance, inspection, repair, rehabilitation, and removal. The LCC of a structure is defined as the cost that includes all cash expenditures to the end of the structure's life, including construction cost, the cost of maintenance, and the cost of outages. The design with the lowest life-cycle cost will provide the service at the lowest cost. A cost-benefit analysis goes a step further than the life cycle cost analysis, because it includes the benefit generated by spending money on corrosion issues. In some cases, prevention of corrosion failures is justified at a very high cost, while in other cases, a corrosion failure may have minimal impact and simply replacing a part at a low cost is the most economical solution. Cost-benefit analysis considers both sides of this economic balance.

The annual cost of corrosion consists of both direct costs and indirect costs. The direct costs related to corrosion are made up of two main components:

1. The costs of design, manufacturing, and construction:
    - material selection, such as stainless steel to replace carbon steel,
    - additional material, such as increased wall thickness for corrosion allowance,
    - material used to mitigate or prevent corrosion, such as coatings, sealants, corrosion inhibitors, and cathodic protection, and
    - application, including the cost of labor and equipment.
2. The cost of management:
    - corrosion-related inspection,
    - corrosion-related maintenance,
    - repairs due to corrosion,
    - replacement of corroded parts,
    - inventory of backup components,
    - rehabilitation, and
    - loss of productive time.

Using highway bridges as an example, the optimized contribution of each of the contributing components is calculated through life-cycle cost analysis and characterized by the annualized value. The selection of alternative approaches to controlling the cost of corrosion is therefore based on annualized values of initial or capital costs as well as maintenance over the life of the structure and its replacement. Typically, an owner/operator will base decisions on a direct-cost analysis.

Indirect costs are incurred by others than just the owners or operators of the structure. Measuring and determining the value of indirect costs are generally complex assessments; however, several methods, such as risk-based analyses, can be used to evaluate these costs. Owners and operators can be made to assume the costs through taxation, penalties, litigation, or paying for clean-up of spilled products. In such cases, the costs become direct costs. However, there are some indirect costs, such as traffic delays due to bridge repairs and rehabilitation that are more difficult to turn over to the owner or operator of the structure. These become indirect costs to the user, but can have a significant impact on the overall economy due to lost productivity.

Once assigned a dollar value, the indirect costs are included in the cash flow of the corrosion management of the structure and are treated in the same manner as all other costs. Including indirect cost into the life-cycle cost analysis of alternative corrosion control approaches is important so that the cost of corrosion to the whole society can be minimized. If only direct costs are included, the design with the lowest cost to the owner may not necessarily be the one with the lowest cost to society. (See Appendix D, Highway Bridges, for an example cost analysis including indirect costs.)

Method for Determination of the Cost of Corrosion in Industry Sectors

While a general approach for corrosion cost calculations was followed, it was recognized that each of the individual industry sectors had its own economic characteristics, specific corrosion problems, and methods to deal with these problems. For example, in one sector, the corrosion mechanisms may be well understood, but this know-how is not sufficiently implemented. For some sectors, a multitude of reports were found describing the mechanisms of corrosion in detail for that particular area. However, the multitude of mechanisms may be hard to generalize, and cost data were not available. In those cases, a "best estimate" had to be made based on experts' opinions. In other cases, a convenient multiplier was determined, and a cost per unit was calculated. By multiplying the cost per unit by the number of units used or made in a sector, a total cost could be determined. It was found that by analyzing each sector individually, a corrosion cost could be determined using a calculation method appropriate for that specific industry sector. After the costs were calculated, the components of the cost determined which Bureau of Economic Analysis (BEA) industry category would be the best match for correlating that industry sector to a BEA subcategory.

Correlation Between BEA Categories and Industry Sectors in the Current Study

The basic method used for extrapolating the cost analysis performed in the current study to the entire gross domestic product (GDP) was to correlate categories defined by the BEA to the industry sectors that were analyzed in the current study. For clarification, BEA "categories" and "subcategories" are used to specify BEA classifications, and "industry sectors" is used to classify industries that were analyzed for the current study.

BEA Categories

Each BEA category represents a portion of the U.S. Gross Domestic Product (GDP). In 1998, the total GDP was $8.79 trillion, divided into the major BEA categories as follows: Services (20.90 percent), Finance, Insurance, and Real Estate (19.22 percent), Manufacturing (16.34 percent), Retail Trade (9.06 percent), State and Local Government (8.48 percent), Transportation and Utilities (8.28 percent), Wholesale Trade (6.95 percent), Construction (4.30 percent), Federal Government (4.10 percent), Agriculture (1.45 percent), and Mining (1.20 percent). These figures are summarized in table 1 and graphically shown in figure 1.

Table 1. Distribution of 1998 U.S. gross domestic product for BEA industry categories.

	GDP	
	$ x billion	**percentage**
Services	1,837.2	20.90
Finance, Insurance, and Real Estate	1,689.4	19.22
Manufacturing	1,435.9	16.34
Retail Trade	796.8	9.06
State and Local Government	745.1	8.48
Transportation and Utilities	727.9	8.28
Wholesale Trade	610.9	6.95
Construction	378.1	4.30
Federal Government	360.7	4.10
Agriculture	127.3	1.45
Mining	105.6	1.20
Statistical Discrepancy	-24.8	-0.28
TOTAL GDP	**$8,790.1**	**100%**

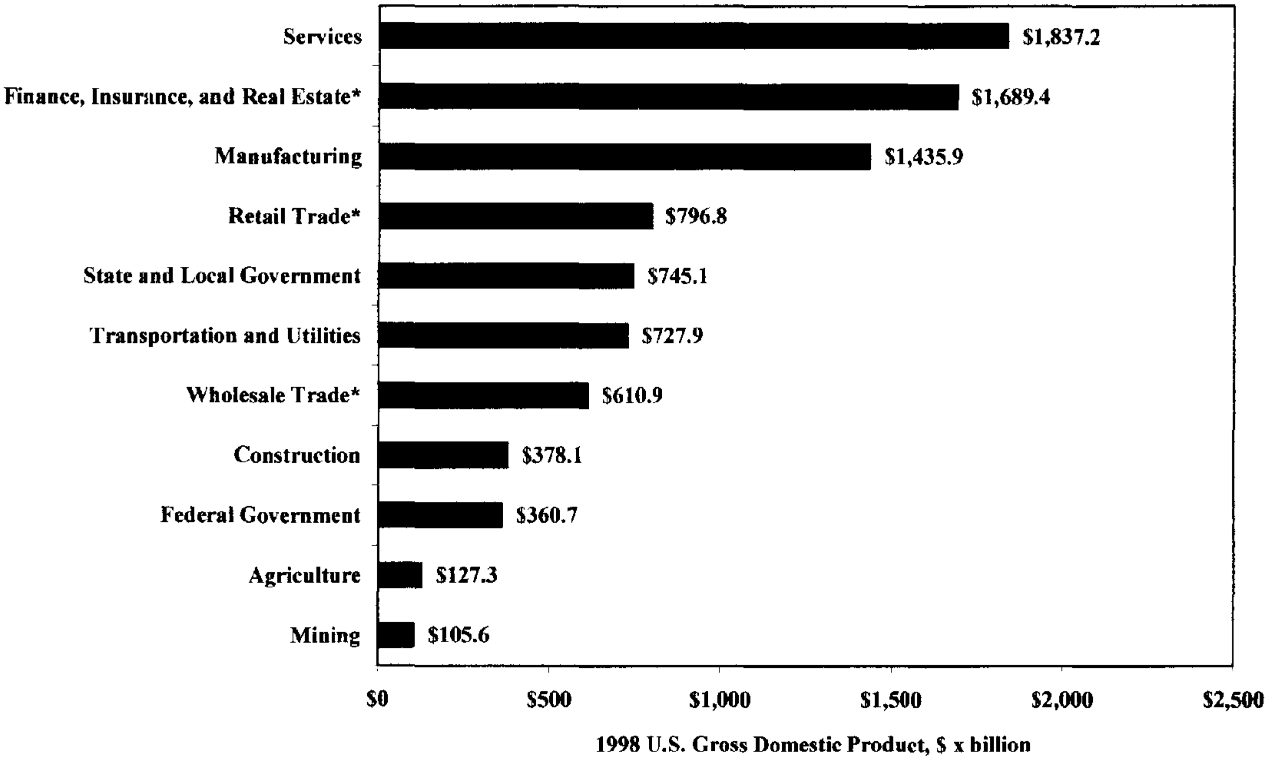


Figure 1. Distribution of 1998 U.S. gross domestic product for BEA industry categories.

Industry Sectors Selected for Current Study

The selection of industry sectors and analysis approach of the current study was based on the great impact of the transportation infrastructure in the U.S. economy. Therefore, it was decided to emphasize this part of the research on topics related to transportation infrastructure and types of conveyance utilizing the infrastructure for carrying goods and traffic.

It is further known that corrosion plays a major role in production and manufacturing. Machinery is used to its maximum potential by increasing parameters such as manufacturing speed, temperature, or stresses. In addition, producers continue to use existing equipment as long as possible, in many cases well beyond the original design life. The benefits of faster production and longer equipment life come at a cost to maintenance and repair due to corroding and deteriorating materials in aging equipment. To address these issues, several separate sectors were analyzed in the category of manufacturing and production.

The U.S. Government is responsible for special branches of the economy that are not covered in the private industries. The expected impact of corrosion in the maintenance of defense systems is very large, and in the packaging of nuclear waste for long-term storage the issue of corrosion must be addressed. Both defense and nuclear waste storage were addressed in separate sectors. In addition, federal and state governments build and maintain highways and bridges, which will be addressed in the Infrastructure category.

The criteria in the selection process included a variety of applications, diversity of economic parameters, magnitude of corrosion impact, and availability of data. Table 2 shows the list of 26 industry sectors that were analyzed in the current study, which were divided into 5 sector categories (not to be confused with the BEA categories).

In the sector category of *Infrastructure*, the following industry sectors were analyzed: highway bridges, gas and liquid transmission pipelines, waterways and ports, hazardous materials storage, airports, and railroads. In the sector category of *Utilities*, the analyzed industry sectors were: gas distribution, drinking water and sewer systems, electrical utilities, and telecommunications. For the sector category of *Transportation*, the analyzed industry sectors included: motor vehicles, ships, aircraft, railroad cars, and hazardous materials transportation. For the sector category of *Production and Manufacturing*, the analyzed industry sectors were: oil and gas exploration and production; mining; petroleum refining; chemical, petrochemical, and pharmaceutical industry; pulp and paper; agricultural; food processing; electronics; and home appliances. For the sector category of *Government*, the analyzed industry sectors were: defense and nuclear waste storage.

Table 2. Summary of the industry sectors analyzed in the current study.

SECTOR CATEGORY	26 ANALYZED INDUSTRY SECTORS
Infrastructure	Highway Bridges
	Gas and Liquid Transmission Pipelines
	Waterways and Ports
	Hazardous Materials Storage
	Airports
	Railroads
Utilities	Gas Distribution
	Drinking Water and Sewer Systems
	Electrical Utilities
	Telecommunications
Transportation	Motor Vehicles
	Ships
	Aircraft
	Railroad Cars
	Hazardous Materials Transport
Production and Manufacturing	Oil and Gas Exploration and Production
	Mining
	Petroleum Refining
	Chemical, Petrochemical, Pharmaceutical
	Pulp and Paper
	Agricultural
	Food Processing
	Electronics
	Home Appliances
Government	Defense
	Nuclear Waste Storage

The basis for selecting the industry sectors was, in part, to represent those areas of industry for which corrosion is known to exist. This was accomplished by examining the Specific Technology Groups (STGs) within NACE International (The Corrosion Society). Table 3 shows the listing of current STGs. Each STG has various Task Groups and Technology Exchange Groups. It can be expected that these groups are formed around those industrial areas that have the largest corrosion impact, because the membership of NACE represents industry corrosion concerns.

A comparison of the industry sectors (table 2) with the STGs (table 3) shows that the industry sectors selected for analysis in the current study cover most industries and technologies represented in NACE's STGs. One exception was noted: the absence of an industry sector that would represent the NACE STG of "Building Systems." Some of the NACE STGs do not have a direct sector related to them; however, those STGs are generally covered in the section on Corrosion Control Methods and Services (see Appendix C) in this report.

Table 3. Summary of specific technology groups in NACE International.

NACE SPECIFIC TECHNOLOGY GROUP NUMBER	SPECIFIC TECHNOLOGY GROUP NAME
01	Concrete and Rebar
02	Protective Coatings and Linings – Atmospheric
03	Protective Coatings and Linings – Immersion/Buried
05	Cathodic/Anodic Protection
06	Chemical and Mechanical Cleaning
09	Measurement and Monitoring Techniques
10	Nonmetallic Materials of Construction
11	Water Treatment
31	Oil and Gas Production – Corrosion and Scale Inhibition
32	Oil and Gas Production – Metallurgy
33	Oil and Gas Production – Nonmetallics and Wear Coatings (Metallic)
34	Petroleum Refining and Gas Processing
35	Pipelines, Tanks, and Well Casings
36	Process Industry – Chemicals
37	Process Industry – High Temperature
38	Process Industry – Pulp and Paper
39	Process Industry – Materials Applications
40	Aerospace/Military
41	Energy Generation
43	Land Transportation
44	Marine Corrosion and Transportation
45	Pollution Control, Waste Incineration, and Process Waste
46	Building Systems
60	Corrosion Mechanisms
61	Corrosion and Scaling Inhibition
80	Intersociety Joint Coatings Activities

Correlation Between BEA Categories and Industry Sectors

Table 4 shows BEA categories and corresponding industry sectors analyzed in the current study. Table 4 also shows the relative percentage of the GDP represented by each category or industry sector. Many of the current study's industry sectors fall into the two BEA categories of *Manufacturing* and *Transportation and Utilities.*

The table shows that 27.54 percent of the U.S. GDP was covered in the industry sectors analyzed in the current research. This is a significant portion of the economy. As mentioned earlier, the dollar values determined for each individual sector represent only the portion of corrosion cost that is considered to be a direct cost to the owner/operator of a structure, utility, or infrastructure. The indirect cost to users that may be affected by outages or the impact of unreliability of equipment is not included in these estimates.

Table 4. Correlation between BEA categories and the analyzed industry sectors.

BEA CATEGORY	**PERCENT OF GDP (as reported by BEA)**	**ANALYZED INDUSTRY SECTORS**	**PERCENT OF GDP (as reported by BEA)**
Services	20.90	Motor Vehicles – repair	0.92
Finance, Insurance, and Real Estate	19.22	-	-
Manufacturing	16.34	Motor Vehicles – new production	1.22
		Electronics*	-
		Home Appliances	0.29
		Food Processing	1.42
		Pulp and Paper	1.70
		Hazardous Materials Storage	2.55
		Chemical, Petrochemical, Pharmaceutical	
		Petroleum Refining	0.37
Retail Trade	9.06	-	-
State and Local Government	8.48	Highway Bridges**	7.74
Transportation and Utilities	8.28	Hazardous Materials Transport	1.24
		Railroad Cars	0.47
		Railroads	
		Ships	0.16
		Waterways and Ports	
		Aircraft	1.00
		Airports	
		Gas and Liquid Transmission Pipelines	2.41
		Gas Distribution	
		Drinking Water and Sewer Systems	
		Electrical Utilities	
		Telecommunications*	-
Wholesale Trade	6.95	-	-
Construction	4.30	-	-
Federal Government	4.10	Defense**	3.40
		Nuclear Waste Storage**	
Agricultural, Forestry, and Fishing	1.45	Agricultural	1.45
Mining	1.20	Mining	0.32
		Oil and Gas Exploration and Production	0.88
Statistical Discrepancy	-0.28		
GDP TOTAL:	**100%**	**COVERED GDP TOTAL:**	**27.54%**

* No cost of corrosion was estimated for these industry sectors, although corrosion impact was discussed.

**The percentages of GDP reported in these fields are for the entire state and local governments, while excluding state and local government enterprises, and for the entire federal government, while excluding federal government enterprises. The analyzed sectors Highway Bridges, Defense, and Nuclear Waste Storage account for only a fraction of the entire government percentages.

Table 5 shows a more detailed correlation between BEA categories and industry sectors analyzed in this study. This table shows all BEA subcategories, the value each contributes to the U.S. GDP, and the correlation between the analyzed industry sectors and the BEA subcategories.

Table 5. Schedule for correlating the cost of corrosion in analyzed industry sectors with the 1998 U.S. gross domestic product of BEA industry categories.

BEA Categories	Gross Domestic Product				BEA Subcategories	Appendix	Industry Sectors
	Total 1998	Covered GDP	Non-Covered GDP	Detailed GDP			
	$ x billion	$ x billion	$ x billion	$ x billion			
Agricultural, Forestry, and Fishing	127.3	127.3		127.3	Farms, agricultural services	X	Agricultural
Mining	105.6	105.6		28.2	Metal, coal, and nonmetallic minerals	T	Mining
				77.4	Oil and gas extraction	S	Oil and Gas Exploration and Production
Manufacturing	1,435.9	663.2		107.2	Motor vehicles and equipment	72% of N (*)	Motor Vehicles
				25.7	Miscellaneous manufacturing industries	AA	Home Appliances
				124.8	Food and kindred products	Y	Food Processing
				55.1	Paper and allied products	W	Pulp and Paper
				168.4	Chemicals and allied products	G	Hazardous Materials Storage
						87.5% of V (**)	Chemical, Petrochemical, Pharmaceutical
				55.1	Rubber and miscellaneous plastics products	12.5% of V (**)	Chemical, Petrochemical, Pharmaceutical
				32.9	Petroleum and coal products	U	Petroleum Refining
			772.7	172.8	Electronic and other electric equipment	Z (****)	Electronics
				41.4	Lumber wood products	-	-
				24.1	Furniture and fixtures	-	-
				38.2	Stone, clay, and glass products	-	-
				54.1	Primary metals industry	-	-
				102.2	Fabricated metals products	-	-
				150.8	Industrial machining and equipment	-	-
				59.2	Other transportation equipment	-	-
				57.7	Instruments and related products	-	-
				16.8	Tobacco products	-	-
				25.4	Textile mill products	-	-
				25.8	Apparel and other textile products	-	-
				94.0	Printing and publishing	-	-
				4.2	Leather and leather goods	-	-

Table 5. Schedule for correlating the cost of corrosion in analyzed industry sectors with the 1998 U.S. gross domestic product of BEA industry categories (continued).

BEA Categories	Gross Domestic Product				BEA Subcategories	Appendix	Industry Sectors
	Total 1998	Covered GDP	Non-Covered GDP	Detailed GDP			
	$ x billion	$ x billion	$ x billion	$ x billion			
Transportation and Utilities	727.9	465.3		109.3	Trucking and warehousing	R	Hazardous Materials Transport
				25.4	Railroad transportation	Q	Railroad Cars
						I	Railroads
				16.2	Local and interurban passenger transit	-	-
				14.1	Water transportation	O	Ships
						F	Waterways and Ports
				88.2	Transportation by air	P	Aircraft
						H	Airports
				6.1	Pipelines, except natural gas	68% of E (***)	Gas and Liquid Transmission Pipelines
				206.0	Electric, gas, and sanitary services	32% of E (***)	Gas and Liquid Transmission Pipelines
						J	Gas Distribution
						K	Drinking Water and Sewer Systems
						L	Electrical Utilities
			262.6	234.1	Communication, incl. telephone, radio, TV	M (****)	Telecommunications
				28.5	Transportation services	-	-
Services	1,837.2	80.9		80.9	Auto repair services and parking	28% of N (*)	Motor Vehicles
			1,756.3	76.0	Hotels and other lodging places	-	-
				55.4	Personal services	-	-
				447.1	Business services	-	-
				24.5	Miscellaneous repair services	-	-
				28.8	Motion pictures	-	-
				72.2	Amusement and recreation	-	-
				492.6	Health services	-	-
				116.4	Legal services	-	-
				66.7	Educational services	-	-
				57.1	Social services	-	-
				54.0	Membership organizations	-	-
				251.5	Other services	-	-
				14.0	Private households	-	-

Table 5. Schedule for correlating the cost of corrosion in analyzed industry sectors with the 1998 U.S. gross domestic product of BEA industry categories (continued).

BEA Categories	Gross Domestic Product Total 1998	 Covered GDP	 Non-Covered GDP	 Detailed GDP	BEA Subcategories	Appendix	Industry Sectors
	$ x billion	$ x billion	$ x billion	$ x billion			
Construction	378.1		378.1	378.1		-	-
Wholesale Trade	610.9		610.9	610.9		-	-
Retail Trade	796.8		796.8	796.8		-	-
Finance, Insurance, and Real Estate	1,689.4		1,689.4	1,689.4		-	-
Statistical Discrepancy	-24.8		-24.8	-24.8		-	-
Federal	360.7	298.6		298.6	General government	BB	Defense
						CC	Nuclear Waste Storage
			62.1	62.1	Government enterprises	-	-
State and Local	745.1	680.7		680.7	General government	DD	Highway Bridges
			64.4	64.4	Government enterprises	-	-
	TOTAL GDP	**Covered GDP**	**Non-Covered GDP**	**TOTAL GDP**			
	$8,790.1	**$2,421.6**	**$6,368.5**	**$8,790.1**			
	100%	**27.55%**	**72.45%**	**100%**			

*Based on the estimated cost of corrosion of motor vehicles found in the sector analysis, 72% is assigned to Manufacturing Motor Vehicles and Equipment, while 28% is assigned to Auto Repair Services and Parking.

**12.5% of the total value of shipments in the Chemical, Petrochemical, and Pharmaceutical industry is for Plastics Material and Resin Manufacturing (11.0%) and Synthetic Rubber Manufacturing (1.5%).

***Based on the mileage of transmission and gathering pipelines (328,000 km gas and 154,000 km oil), 32% of the corrosion costs of transmission pipelines is assigned to liquid lines, and 68% to gas lines.

****Placed in non-covered GDP, because the sector analysis for Electronics and for Telecommunications resulted in "no estimate made."

Estimating Total Cost of Corrosion

The method used for the extrapolation of corrosion cost per industry sector to total corrosion cost was based on the percentages of corrosion costs in the BEA categories. If a non-covered BEA category/subcategory was judged to have a significant corrosion impact, then an extrapolation was made for that non-covered BEA subcategory by multiplying its fraction of GDP by the percentage of corrosion costs for subcategories that were judged to have a similar corrosion impact. If a non-covered sector was judged to have no significant corrosion impact, then the direct corrosion cost for that non-covered sector was assumed to be zero.

RESULTS

Two different methods are used in the current study to determine the total cost of corrosion to the United States. Method 1 is based on the Uhlig method(10) where the costs of corrosion control materials, methods, and services are added up. Method 2 analyzes in detail the specific industry sectors that have a significant impact on the national economy. The percentage contribution to the nation's GDP is estimated, and the total cost of corrosion would then be expressed as a percentage of the GDP by extrapolation to the whole U.S. economy. It is noted that this extrapolation is non-linear because most of the analyzed sectors have more corrosion impact than the non-analyzed industrial sectors.

Method 1 – Corrosion Control Methods and Services (Appendix C)

The Uhlig method(10) estimates the total cost of corrosion control methods and services. The corrosion control methods that were considered include protective coatings, corrosion-resistant alloys, corrosion inhibitors, polymers, anodic and cathodic protection, and corrosion control and monitoring equipment. Other contributors to the total cost that were reviewed in this report include corrosion control services, corrosion research and development, and education and training. A detailed description of this approach is presented in Appendix C.

Protective Coatings

Both organic and metallic coatings are used to provide protection against corrosion of metallic substrates. These metallic substrates, mostly carbon steel, will corrode in the absence of the coating, resulting in the reduction of the service life of the steel part or component.

Organic Coatings

According to the U.S. Department of Commerce Census Bureau, the total amount of organic coating material sold in the United States in 1997 was 5.56 billion L (1.47 billion gal), at a value of $16.56 billion.(12) The total sales can be broken down into architectural coatings, product original equipment manufacturing (OEM) coatings, special-purpose coatings, and miscellaneous paint products. A portion of each of these can be classified as corrosion coatings.

The architectural coatings, at a value of $6.265 billion, are those applied on-site to new and existing residential, commercial, institutional, and industrial buildings. A small percentage of these are used as primers and undercoats, and may be classified as corrosion coatings. According to the 1997 Census Bureau data, the total cost for corrosion-related architectural coatings was estimated at $486 million. This value was approximately 8 percent of the $6.265 billion total spent on architectural coatings in 1997.

OEM coatings are factory-applied to manufactured goods as part of the manufacturing process. There is an element of decoration in OEM finishes; however, the primary function of OEM coatings applied to steel is corrosion control, either for weathering resistance or flash rust protection. The total market value of corrosion-related OEM coatings is estimated at $3.797 billion, which represents approximately 66 percent of the total OEM coatings market of $5.751 billion in 1997.

Special-purpose coatings include heavy industry corrosion coatings as well as marine and automotive refinishing coatings. The market value of corrosion-related special-purpose coatings is estimated at $2.298 billion, representing 79 percent of the $2.896 billion special-purpose coatings market in 1997. The greatest portion of special-purpose corrosion coatings is the automotive finishing industry at $1.302 billion.

The final category of miscellaneous allied paint products includes paint/varnish removers, thinners, pigment dispersions such as art supplies, and putties. The contribution to corrosion protection from this category includes only thinners used in non-architectural solvent-based coatings. Solvent-based corrosion coatings account for 75 percent of the solvent-based coating market. It is therefore estimated that the amount of thinner used in corrosion control applications is 75 percent of the thinner sold at $118 million. This value accounts for 7 percent of the $1.648 billion of allied paint products in the market.

Summarizing the corrosion coating portions from each of the above-described categories provides a total estimate of $6.7 billion for all corrosion markets in the paint industry, which is approximately 41 percent of the total $16.5 billion value of shipments of paint and allied products in 1997.

The raw material cost of any coating application, while significant, is only a portion of the cost of a coating application project. Different studies have shown that the material cost fraction of the coating material ranges from 4 to 20 percent of the total cost of application.(13-14) Using these figures, the total cost of application of the $6.7 billion in coatings is estimated to range from $33.5 billion to $167.5 billion for the entire coating industry in the United States. This cost figure does not include the costs of performance testing, personnel costs for time spent specifying coating products and application procedures, overhead for handling of bids and contracts, and other support services that are necessary for coating application. Moreover, the total cost does not include the costs of downtime, lost production, or reduced capacity during maintenance painting. The total annual direct cost (product cost plus application cost) of organic coatings for corrosion control ranges from $40.2 billion to $174.2 billion (average $107.2 billion).

Metallic Coatings

The most widely used metallic coating method for corrosion protection is galvanizing, which involves the application of metallic zinc to carbon steel for corrosion control purposes. Information released by the U.S. Department of Commerce in 1998 stated that approximately 8.6 million metric tons of hot-dip galvanized steel and 2.8 million metric tons of electrolytic galvanized steel were produced in 1997.(15) The total market for metallizing and galvanizing in the United States is estimated at $1.4 billion. This figure includes the total material cost of the metal coating and the cost of processing. It does not include the cost of the carbon steel member being galvanized/metallized.

Metallizing is defined as the application of very thin metallic coatings for either active corrosion protection (zinc or aluminum alloys) or as a protective layer (stainless steels and alloys). Common application techniques include flame-spraying, electroplating, and electrolyses plating. Other advanced processes such as plasma arc spraying can be used for exotic refractory metals for very demanding applications; however, most of the advanced processes are not used for corrosion control purposes. The metallizing anode market ranges from $5 million to $10 million annually.(16) The total cost of metallic coatings for corrosion control is therefore estimated at $1.41 billion.

Corrosion-Resistant Metals and Alloys

Corrosion-resistant alloys are used where corrosive conditions prohibit the use of carbon steels and protective coatings provide insufficient protection or are economically not feasible. These alloys include stainless steels, nickel-base alloys, and titanium alloys.

According to U.S. Census Bureau statistics, a total of 2.5 million metric tons of raw stainless steel was sold in the United States in 1997.(17) With an estimated cost of $2.20 per kg ($1 per lb) for raw stainless steel, a total annual production cost of $5.5 billion (1997) was estimated. It is assumed that all production is for U.S. domestic consumption.(18) The total consumption of stainless steel also includes imports, which account for more than 25 percent of the U.S. market. The total consumption of stainless steel can therefore be estimated at $7.3 billion.

Where environments become particularly severe, nickel-base alloys and titanium alloys are used. Nickel-base alloys are used extensively in the oil production and refinery and chemical process industries, where conditions are aggressive. Furthermore, there is an increased use of these alloys in other industries where high temperature and/or corrosive conditions exist. The annual average price of nickel has steadily increased from less than $2.20 per kg in the 1960s to about $4.40 per kg in 1998.(19) Chromium and molybdenum are also common alloying elements for both corrosion-resistant nickel-base alloys and stainless steels. The price of chromium has increased steadily from $2 per kg in the 1960s to nearly $8 per kg in 1998, while the price of molybdenum has remained relatively constant at $5 per kg.(20) With the average price for nickel-base alloys (greater than 24 percent nickel) at $13 per kg in 1998, the total sales value in the United States was estimated at $285 million.(21)

The primary use of titanium alloys is in the aerospace and military industries where the high strength-to-weight ratio and the resistance to high temperatures are properties of interest. Titanium and its alloys however, are also corrosion resistant to many environments, and have therefore found application in oil production and refinery, chemical processes, and pulp and paper industries. In 1998, it was estimated that 65 percent of the titanium alloy mill products were used for aerospace applications and 35 percent for non-aerospace applications.(22)

In 1998, the domestic operating capacity of titanium sponge, which is the most common form of titanium, was estimated at 21,600 metric tons per year. The total domestic consumption of titanium sponge was 39,100 metric tons which, at a price of approximately $10 per kg, sets the total price at $391 million. In addition, 28,600 metric tons of scrap was used for domestic consumption at a price of approximately $1 per kg, setting the total price at $420 million. As mentioned previously, only 35 percent of mill products were for non-aerospace applications, which leads to a titanium consumption price estimate of $150 million for titanium and titanium alloys with corrosion control applications.

The total consumption cost of the corrosion-resistant stainless steels, nickel-base alloys, and titanium alloys in 1998 is estimated at $7.7 billion ($7.3 billion + $0.285 billion + $0.150 billion).

Corrosion Inhibitors

A "corrosion inhibitor" may be defined, in general terms, as a substance that when added in a small concentration to an environment effectively reduces the corrosion rate of a metal exposed to that environment. Because there are a number of mechanistic and/or chemical considerations when classifying inhibitors, it is difficult to provide a more precise definition.

Inhibition is used internally with carbon steel pipes and vessels as an economic corrosion control alternative to stainless steels and alloys, coatings, or non-metallic composites. A particular advantage of corrosion inhibition is that it can be implemented or changed *in situ* without disrupting a process. The major industries using corrosion inhibitors are the oil and gas exploration and production industry, the petroleum refining industry, the chemical industry, heavy industrial manufacturing industry, water treatment facilities, and the product additive industries. The largest consumption of corrosion inhibitors is in the oil industry, particularly in the petroleum refining industry.(23) The use of corrosion inhibitors has increased significantly since the early 1980s. The total consumption of corrosion inhibitors in the United States has doubled from approximately $600 million in 1982 to nearly $1.1 billion in 1998.

Engineering Plastics and Polymers

In 1996, the plastics industry accounted for \$274.5 billion in shipments.(24) It is difficult to estimate the fraction of plastics used for corrosion control, because in many cases, plastics and composites are used for a combination of reasons, including corrosion control, light weight, economics, strength-to-weight ratio, and other unique properties.

While corrosion control is a major market for many polymers, certain polymers are used mostly, if not exclusively, for corrosion control purposes. The significant markets for corrosion control by polymers include composites (primarily glass-reinforced thermosetting resins), PVC pipe, polyethylene pipe, and fluoropolymers. The fraction of polymers used for corrosion control in 1997 is estimated at \$1.8 billion.

Cathodic and Anodic Protection

The cost of cathodic and anodic protection of metallic buried structures or structures immersed in seawater that are subject to corrosion can be divided into the cost of materials and the cost of installation, operation, and maintenance. Industry data have provided estimates for the 1998 sales of various hardware components, including rectifiers, impressed current cathodic protection (CP) anodes, sacrificial anodes, cables, and other accessories, totaling \$146 million.(25-26) The largest share of the CP market is taken up by sacrificial anodes at \$60 million, of which magnesium has the greatest market share. Major markets for sacrificial anodes are underground pipelines, the water heater market, and the underground storage tank market. The costs of installation of the various CP components for underground structures vary significantly depending on the location and the specific details of the construction. For 1998, the average total cost for installing CP systems was estimated at \$0.98 billion (range: \$0.73 billion to \$1.22 billion), including the cost of hardware components.(27) The total cost for replacing sacrificial anodes in water heaters and the cost for corrosion-related replacement of water heaters was \$1.24 billion per year; therefore, the total estimated cost for cathodic and anodic protection is \$2.22 billion per year.

Corrosion Control Services

In the context of this report, services are defined as companies, organizations, and individuals that are providing their services to control corrosion. By taking the NACE International membership as a basis for this section, a total number of engineers and scientists that provide corrosion control services may be estimated. In 1998, the number of NACE members was 16,000, 25 percent of whom are providing consulting and engineering services as outside consultants or contractors. Assuming that the average revenue of each is \$300,000 (including salary, overhead, benefits, and the cost to direct one or more non-NACE members in performing corrosion control activities), the total services cost can be calculated as \$1.2 billion. This number, however, is conservative since many engineers who follow a career in corrosion are not members of NACE International.

Research and Development

It has been observed that over the past few decades less funding has been made available for corrosion-related research and development, which is significant in light of the cost and inconvenience of dealing with leaking and exploding underground pipelines, bursting water mains, corroding storage tanks, aging aircraft, and deteriorating highway bridges. In fact, several government and corporate research laboratories have significantly reduced their corrosion research staff or even have closed down their research facilities.

Corrosion research can be divided into academic and corporate research. NACE International has listed 114 professors under the Corrosion heading. Assuming an average annual corrosion research budget of \$150,000, the total academic research budget is estimated at approximately \$20 million. No estimates were made for the cost of corporate or industry corrosion-related research, which is likely to be much greater than the annual academic budget.

Education and Training

Corrosion-related education and training in the United States includes degree programs, certification programs, company in-house training, and general education and training. A few national universities offer courses in corrosion and corrosion control as part of their engineering curriculum. Professional organizations such as NACE International (The Corrosion Society)(28) and SSPC (The Society for Protective Coatings)(29) offer courses and certification programs that range from basic corrosion to coating inspector to cathodic protection specialist. NACE International offers the broadest range of courses and manages an extensive certification program. In 1998, NACE held 172 courses with more than 3,000 students, conducted multiple seminars, and offered publications, at a total cost of $8 million.

Summary

A total annual direct cost of corrosion can be estimated by adding the individual cost estimates of corrosion control materials, methods, services, and education and training. Where possible, the cost estimates were based on averages for the years 1997, 1998, and 1999. Table 6 shows that the total cost was estimated at $121 billion, or 1.381 percent of the $8.79 trillion GDP in 1998. It should be noted that in some categories, such as organic coatings and cathodic protection, a wide range of costs was reported based on installation costs. When taking these ranges into account, the total cost sum ranges from $54.2 billion to $188.7 billion. The table shows that the highest cost is for organic coatings at $107.2 billion, which is approximately 88 percent of the total cost. This cost includes the cost of materials and the cost of preparation and application. Notably, the categories of Research and Development and Education and Training indicate unfavorably low numbers.

Table 6. Summary of annual costs of corrosion control methods and services.

MATERIAL AND SERVICES	RANGE	AVERAGE COST	
	($ x billion)	($ x billion)	(%)
Protective Coatings			
Organic Coatings	40.2 – 174.2	107.2	88.3
Metallic Coatings	1.4	1.4	1.2
Metals and Alloys	7.7	7.7	6.3
Corrosion Inhibitors	1.1	1.1	0.9
Polymers	1.8	1.8	1.5
Anodic and Cathodic Protection	0.73 – 1.22	0.98	0.8
Services	1.2	1.2	1.0
Research and Development	0.020	0.02	<0.1
Education and Training	0.01	0.01	<0.1
TOTAL	**$54.16 – $188.65**	**$121.41**	**100%**

Method 2 – Industry Sector Analysis

For the purpose of the Cost of Corrosion study, the U.S. economy was divided into 5 sector categories and 26 industrial sectors, selected according to the unique corrosion problems experienced within each of the groups. In this study, the sector categories were: (1) infrastructure, (2) utilities, (3) transportation, (4) production and manufacturing, and (5) government. The sum of the direct corrosion costs of the analyzed industrial sectors was estimated at $137.9 billion. Since these sectors only represent a fraction of the total economy, this cost does not represent the total cost of corrosion to the U.S. economy. In a later chapter, the total cost of corrosion will be calculated based on the sector totals and a non-linear extrapolation as a percentage of the U.S. GDP. Figure 2 shows the percentage contribution to the total cost of corrosion for the five sector categories analyzed in the current study.

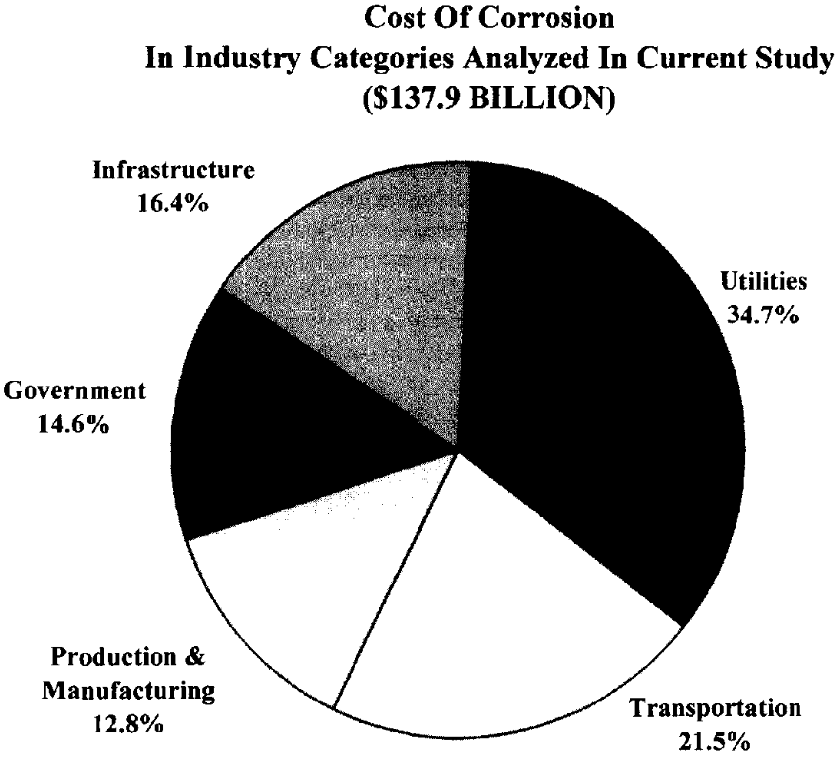


Figure 2. Percentage contribution to the total cost of corrosion for the five sector categories.

Infrastructure

The U.S. infrastructure and transportation system allows for a high level of mobility and freight activity for the nearly 270 million residents and 7 million business establishments.(30) In 1997, more than 230 million motor vehicles, transit vehicles, ships, airplanes, and railroad cars using more than 6.4 million km (4 million mi) of highways, railroads, and waterways connecting all parts of the United States were used. The transportation infrastructure also includes more than 800,000 km (approximately 500,000 mi) of oil and gas transmission pipelines, and 18,000 public and private airports. Figure 3 shows the annual cost of corrosion in the Infrastructure category to be $22.6 billion, which is 16.4 percent of the total cost of the sector categories examined in the study.

The Infrastructure category is divided into the following industry sectors: (1) highway bridges, (2) gas and liquid transmission pipelines, (3) waterways and ports, (3) hazardous materials storage, (5) airports, and (6) railroads.

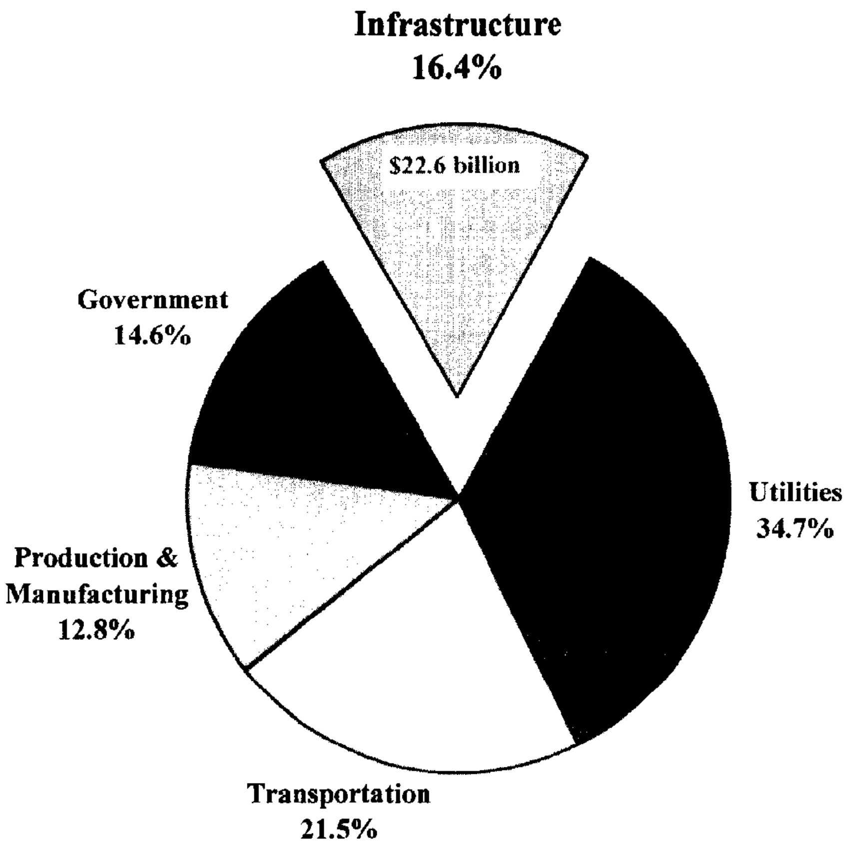
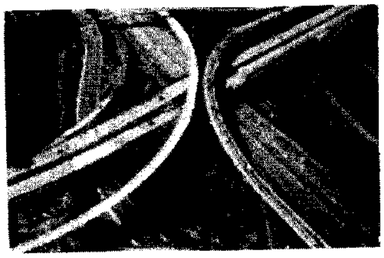


Figure 3. Annual cost of corrosion in the Infrastructure category.

Highway Bridges (Appendix D)



According to the National Bridge Inventory Database, the total number of highway bridges in the United States is approximately 600,000, of which half were built between 1950 and 1994. The materials of construction are concrete, steel, timber, masonry, timber/steel/concrete combinations, and aluminum. The vast majority of these structures built since 1950 are the reinforced-concrete and steel bridges, and many are subject to significant deterioration due to corrosion.

The elements of a typical bridge structure can be classified into two primary components, the substructure and the superstructure. The substructure refers to the elements of the bridge that transfer the loads from the bridge deck to the ground, such as abutments and piers. The superstructure refers to the elements of the bridge above the substructure, including the deck, floor system (beams or stringers), supporting members (beams, trusses, frames, girders, arches, or cables), and bracing. Other bridge elements that are subject to corrosion include guardrailing and culverts. Bridge construction materials that are subject to corrosion include conventional reinforced concrete, prestressed concrete, and steel. Of these three bridge types, steel has the highest percentage of structurally deficient structures, followed by conventionally reinforced concrete and prestressed concrete. Overall, approximately 15 percent of all bridges are structurally deficient, with the primary cause being deterioration due to corrosion. The mechanism is one of chloride-induced corrosion of the steel members, with the chlorides coming from deicing salts and marine exposure.

Significant advancement in corrosion prevention and control has been developed and put into practice over the past 25 years for bridge structures. Methods used for corrosion control on bridges are specific to the type of bridge construction and whether its intended use is for new construction or maintenance/rehabilitation of existing structures. For new construction, the preferred primary corrosion protection system is fusion-bonded epoxy-coated rebars in conjunction with a high-quality concrete. Solid stainless steel rebars and stainless steel-clad rebars are under development. Furthermore, the combined use of epoxy-coated rebar and a corrosion-inhibiting admixture, such as calcium nitrite, could serve as a reliable corrosion protection system. Research efforts are underway to identify new inhibitors that are more or equally effective than calcium nitrite.

For the protection of high-strength seven-wire strands encased in ducts in post-tensioned prestressed concrete members, mix designs for corrosion-resistant grout for filling the ducts have been developed. Prompted by the recent sudden collapse of two post-tensioned bridges in the United Kingdom and one in Belgium, the impact-echo nondestructive examination (NDE) inspection technique was developed to detect voids in post-tensioned ducts. This equipment is now commercially available. A complementary magnetic-based nondestructive technique for assessing section loss in the high-strength steel strands in the ducts also has been developed.

For the rehabilitation of bridge decks, overlays, such as latex modified concrete, low-slump concrete, high-density concrete, and polymer concrete, are most commonly used. Other methods that directly address the corrosion problem are cathodic protection (CP) and electrochemical removal of chlorides. CP is a method used to control the corrosion reactions, such that ongoing corrosion on the rebar is mitigated, thereby extending the life of the protected component. Electrochemical removal of chlorides extracts the chlorides from the concrete, reducing chloride levels to below the level that promotes corrosion, and thus extending component life.

Current CP technology for bridge decks has proven to be quite reliable and improved technology for substructures is still being developed and tested. When properly applied and maintained, CP mitigates corrosion of reinforcing steel and extends the performance life of a bridge. To date, more than 1.9 million m^2 (>20 million ft^2) of reinforced and prestressed concrete structures have been protected with CP worldwide. However, CP remains an underutilized technology for steel-reinforced concrete structures. Cooperative research with industry and states in the development of durable CP anodes, monitoring devices, and installation techniques has led to application of impressed-current CP systems on bridge decks as a routine rehabilitation technique. Titanium mesh anode, used in conjunction with a concrete overlay to distribute protective current, is filling the need for a durable anode for use in impressed-current CP of reinforced-concrete bridge decks. For CP of substructure members, especially those in a marine environment, several sacrificial anode systems have been developed, including thermal-sprayed zinc, thermal-sprayed aluminum-zinc-indium (Al-Zn-In), zinc hydrogel, and a zinc mesh pile jacket system.

Through extensive fundamental research and evaluation of CP system field trials, significant advances have been made in the technology of CP of prestressed concrete components. Concerns about (1) a loss of bond between the prestressing steel and concrete, and (2) the possibility of hydrogen embrittlement of the steel, have been alleviated by the establishment of criteria for qualification of prestressed concrete bridge components for CP. Generally, sacrificial anode CP systems are considered safe for prestressed steel because they operate below the threshold for hydrogen embrittlement. In addition, constant-current or constant-voltage rectifier impressed-current CP systems have been used.

While there is a downward trend in the percentage of structurally deficient bridges (a decrease from 18 percent to 15 percent between 1995 and 1999), the cost of replacing aging bridges increased by 12 percent during the same period. In addition, there has been a significant increase in the required maintenance of the aging bridges, since many of the 435,000 steel and conventional reinforced-concrete bridges date back to the 1920s and 1930s. Although the vast majority of the approximately 108,000 prestressed-concrete bridges have been built since 1960, many of these bridges will require maintenance in the next 10 to 30 years. Therefore, significant maintenance, repair, rehabilitation, and replacement activities for the nation's highway bridge infrastructure are foreseen over the next few decades before current construction practices begin to reverse the trend.

The dollar impact of corrosion on highway bridges is considerable. The annual direct cost of corrosion for highway bridges is estimated to be $8.29 billion, consisting of $3.79 billion for the annual cost to replace structurally deficient bridges over the next 10 years, $2.00 billion for maintenance and the cost of capital for concrete bridge deck, and $2.00 billion for maintenance and the cost of capital for substructures and superstructures (minus decks), and $0.50 billion for the maintenance painting cost for steel bridges. Figure 4 shows the cost of corrosion for highway bridges relative to the other industry sectors in the Infrastructure category.

Life-cycle analysis estimates indirect costs to the user due to traffic delays and lost productivity at 10 times the direct cost of corrosion. Although the user costs associated with bridge maintenance are greater than indirect costs in other sectors, it illustrates the significant indirect costs associated with corrosion.

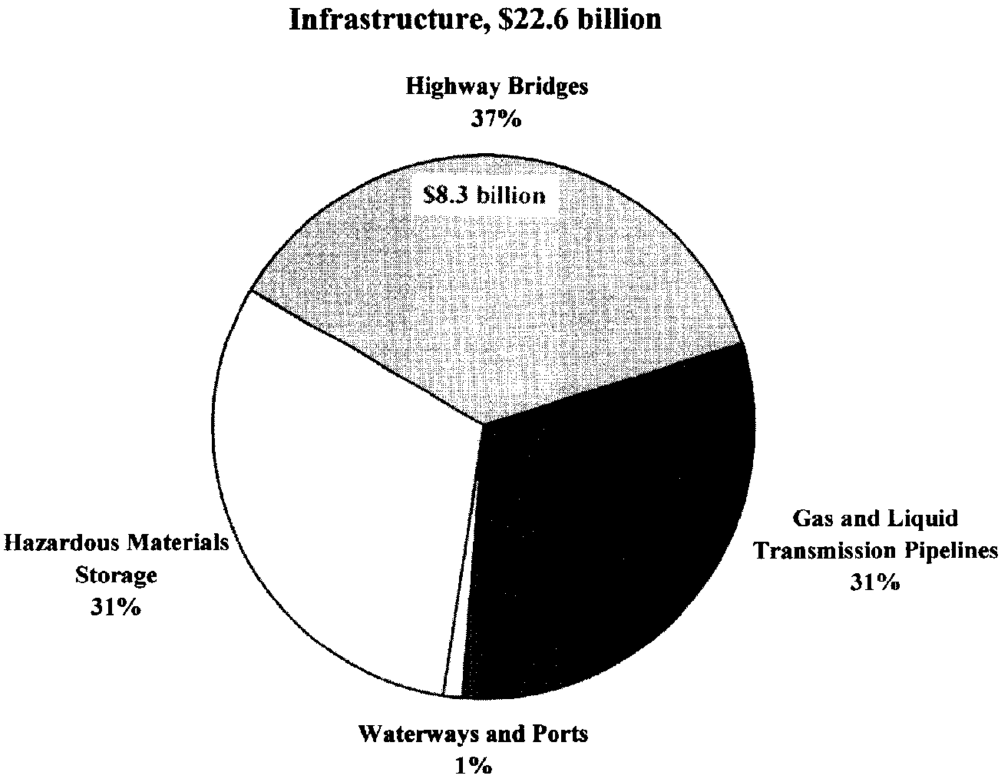
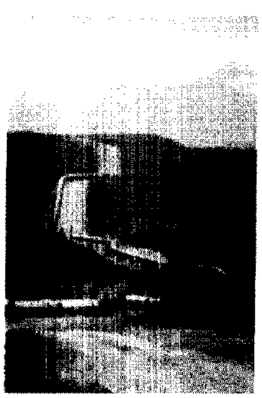


Figure 4. Annual cost of corrosion of highway bridges.

Gas and Liquid Transmission Pipelines (Appendix E)



This sector includes 528,000 km (328,000 mi) of natural gas transmission and gathering pipelines, 119,000 km (74,000 mi) of crude oil transmission and gathering pipelines, and 132,000 km (82,000 mi) of hazardous liquid transmission pipelines.(31-32) For all natural gas pipeline companies, the total gas-plant investment in 1998 was $63.1 billion, from which a total revenue of $13.6 billion was generated. For liquid pipeline companies, the investment was $30.2 billion, from which a revenue of $6.9 billion was generated. By the year 2010, it is anticipated that the growth in the natural gas market will require a $32.2 billion to $34.4 billion investment in a new pipeline and storage infrastructure.(33) At an estimated replacement cost of $643,800 per km ($1,117,000 per mi), the asset replacement value of the transmission pipeline system in the United States is $541 billion; therefore, a significant investment is at risk with corrosion being the primary factor in controlling the life of the asset.

The annual corrosion-related costs to the transmission pipeline industry are estimated at $5.4 billion to $8.6 billion. This can be divided into the cost of capital (38 percent), operation and maintenance (O&M) (52 percent), and failures (10 percent). The average annual cost of corrosion of $7.0 billion is approximately 31 percent of the Infrastructure category (see figure 5).

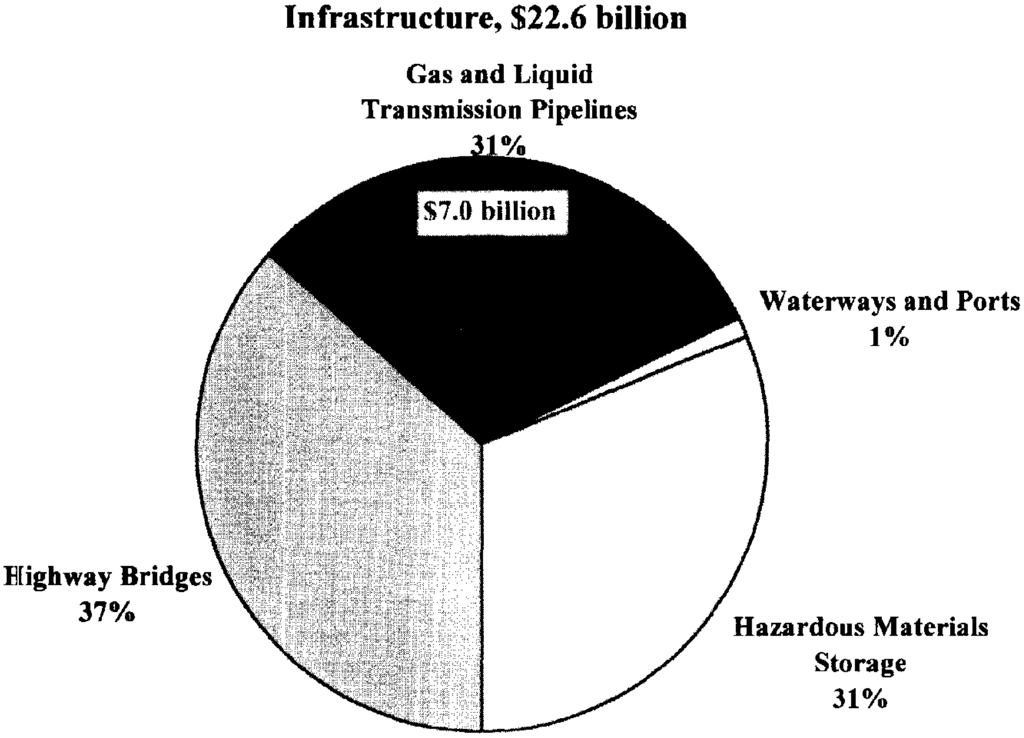


Figure 5. Annual cost of corrosion of gas and liquid transmission pipelines.

Significant maintenance costs for pipeline operation are associated with corrosion control and integrity management. The driving force for maintenance expenditures is to preserve the asset of the pipeline and to ensure safe operation without failures that may jeopardize public safety, result in product loss, or cause property and environmental damage. A recent survey of major pipeline companies indicated that the primary loss of cathodic protection was due to the following two reasons: (1) coating deterioration (30 percent), and (2) inadequate cathodic protection current (20 percent).(34) The majority of general maintenance is associated with monitoring and repairing problems, whereas integrity management focuses on condition assessment, corrosion mitigation, life assessment, and risk modeling. With a range of corrosion O&M cost of $3,100 to $6,200 per km ($5,000 to $10,000 per mi), the total corrosion O&M cost ranges from $2.42 billion to $4.84 billion.

If corrosion is allowed to progress unchecked, the integrity of the pipeline will eventually be compromised. Depending on the flaw size, the pipeline material properties, and the pressure, either a leak will form or a rupture will occur. Typically, a rupture of a high-pressure natural gas pipeline results in a sufficient release of stored energy to blow the pipeline out of the ground. An annual direct cost of corrosion-related accidents for both gas and liquid pipelines is estimated to range from $471 million to $875 million.

In the past few years, a number of well-publicized pipeline failures on both gas and liquid lines have focused major attention on pipeline safety. Public safety concerns are the primary driving force for new regulation to preserve the integrity of pipelines. One of the most significant requirements from a cost point of view is the requirement of regular pipeline inspections, such as hydrostatic testing, direct assessment, and in-line inspection (ILI). During ILI, an instrument or tool travels through the pipeline, measures the pipe wall thickness, and determines the presence of flaws. The ability of this technique to detect flaws larger than a certain size (10 percent of the pipe wall thickness) makes it valuable in finding flaws before they become critical; however, a major concern is that this is not a preventive approach and if pursued at the expense of corrosion prevention, the pipeline will continue to deteriorate and will eventually fail or be taken out of service. Both inspection and corrosion prevention are therefore needed to safely operate and preserve the useful life of both gas and liquid pipelines.

Furthermore, corrosion prediction models need to be developed in order to determine and prioritize the most effective corrosion preventive strategies. Development of new and improved inspection techniques are required to expand the capabilities of in-line inspection of flaws that cannot be currently detected and to improve resolution of existing tools.

Waterways and Ports (Appendix F)

In the United States, 40,000 km (25,000 mi) of commercial navigable waterways serve 41 states, including all states east of the Mississippi River.(35) Hundreds of locks facilitate travel along these waterways. In 1998, the U.S. Army Corps of Engineers owned or operated 276 lock chambers at 230 sites, with lifts ranging from 1.5 m to 15 m (5 to 49 ft) on the Mississippi River and up to 33 m (110 ft) at the John Daly Lock on the Columbia River.(36) In January 1999, 135 of the 276 chambers had exceeded their 50-year design lives. The oldest operating locks in the United States, Kentucky River Locks 1 and 2, were built in 1839.(37)

U.S. ports function as freight connections between ships and highway and railroad networks. In 1997, the nation's ports were nearly equally divided among deep-draft (ocean and Great Lake) and shallow-draft (inland waterway) facilities, with 1,914 located along the coasts and the Great Lakes and 1,812 located along inland waterways.(38)

Corrosion is typically found in piers and docks, bulkheads and retraining walls, mooring structures, and navigational aids. There is no formal tracking of corrosion-related costs. The U.S. Army Corps of Engineers estimated annual corrosion-related costs for locks and dams to be approximately $70 million at 5 percent of the O&M budget of $1.4 billion.(39) Because of the aging of the structures however, high replacement costs are anticipated due, in part, to corrosion. The annual corrosion cost of ports and waterways owned and/or operated by public port authorities is estimated at $182 million.(40)

The U.S. Coast Guard maintains navigational aids such as light structures, buoys, and other saltwater and freshwater exposed structures. In 1999, the corrosion-related cost for maintaining these structures was estimated at $41 million.(41)

The total annual cost of corrosion for waterways and ports is $293 million ($70 million + $182 million + $41 million). This must be a low estimate since the costs of harbor and other marine structures are not included. Figure 6 shows that the $293 million is approximately 1 percent of the total Infrastructure category corrosion cost.

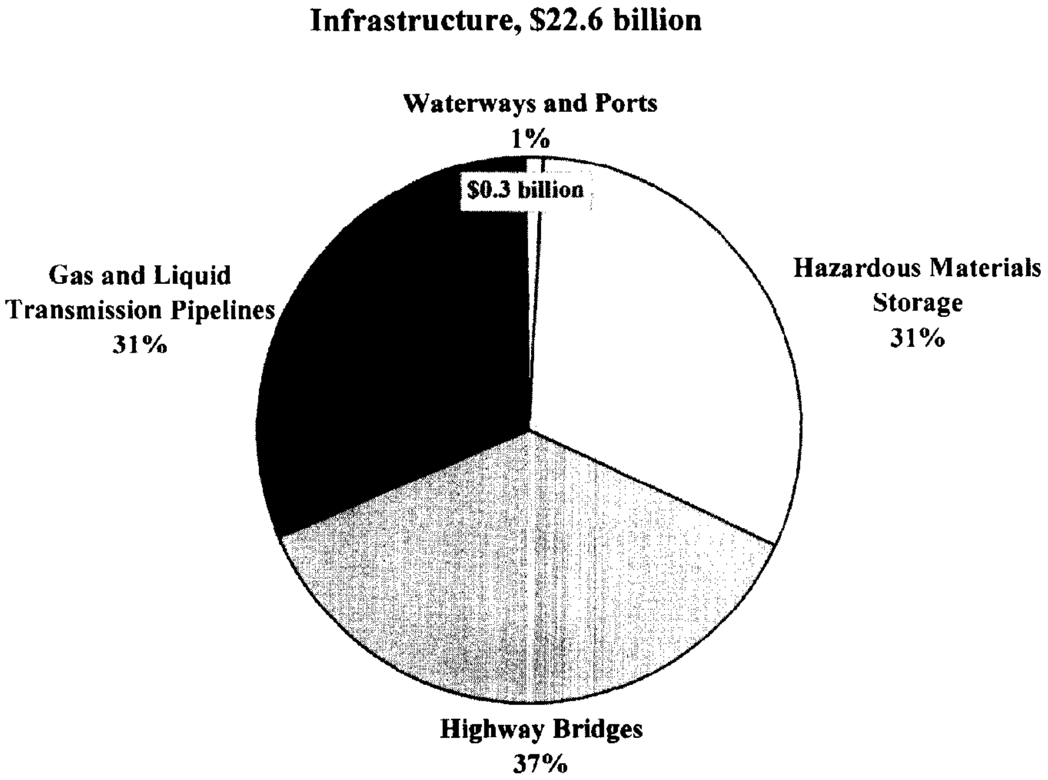
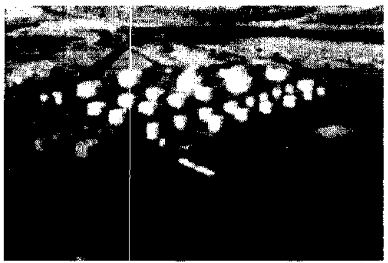


Figure 6. Annual cost of corrosion of waterways and ports.

Hazardous Materials Storage (Appendix G)



There are approximately 8.5 million regulated and non-regulated aboveground storage tanks (ASTs) and underground storage tanks (USTs) for hazardous materials (HAZMAT) in the United States. The regulated tanks can be divided into two groups: Spill Prevention Countermeasure and Control (SPCC)-regulated and Office of Underground Storage Tanks (OUST)-regulated. A total of 2.5 million tanks fall under SPCC regulations, 0.75 million tanks fall under OUST regulations, and 5.25 million are non-regulated tanks. HAZMAT tanks represent a large investment, and maintaining their structural integrity for a longer life is in the best interest of their owners. The U.S. Environmental Protection Agency (EPA) concerns itself with the environmental impact of spills from leaking tanks. In addition, the tank operators should be concerned about the potential economic impact of penalties and clean-up costs.

The total cost of corrosion for storage tanks is $7.0 billion per year (ASTs and USTs). The cost of corrosion for all ASTs was estimated at $4.5 billion per year. A vast majority of the ASTs are externally painted, which is a major cost factor for the total cost of corrosion. In addition, approximately one-third of ASTs have cathodic protection (CP) on the tank bottom, while approximately one-tenth of ASTs have internal linings. These last two corrosion protection methods are applied to ensure the long-term structural integrity of the ASTs.

The cost of corrosion for all USTs was estimated at $2.5 billion per year. The largest costs are incurred when leaking USTs must be replaced with new tanks. The soil remediation costs and oil spill clean-up costs are significant as well. In the last 10 years, the most common problem associated with USTs occurred at gasoline service stations that did not have corrosion protection on their USTs.

Figure 7 shows that the $7.0 billion corrosion cost for HAZMAT storage is approximately 31 percent of the total infrastructure cost of corrosion.

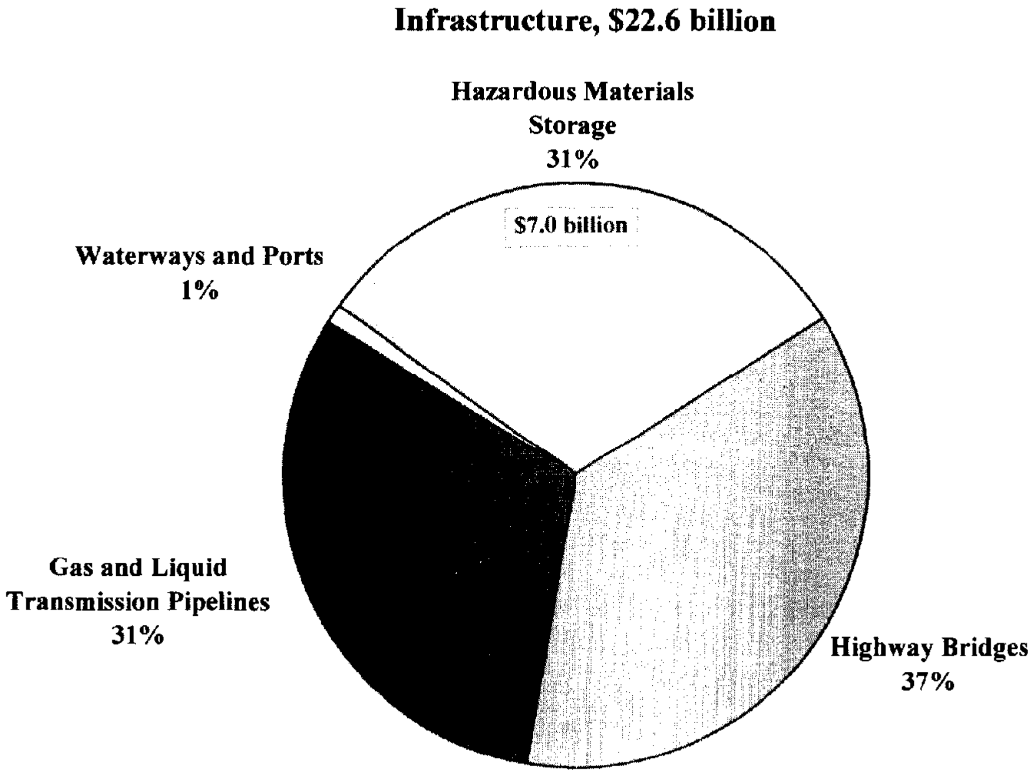
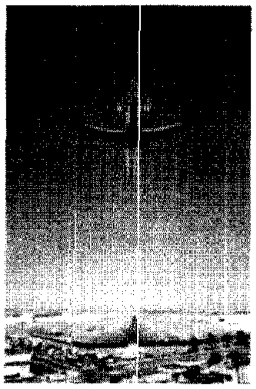


Figure 7. Annual cost of corrosion of hazardous materials storage.

In 1988, the EPA set a December 1998 deadline for UST owners to comply with the requirement to have corrosion control on all tanks, as well as overfill and spill protection. As a result, the number of USTs has decreased from approximately 1.3 million to 0.75 million in that 10-year period.[42] A trend existed toward replacing smaller tanks with larger ones. In addition, USTs were being closed, repaired, or replaced to achieve the necessary compliance with regulations, while the number of confirmed HAZMAT releases increased.

Approximately 30 percent of the total number of HAZMAT tanks (8.5 million) is SPCC-regulated. The SPCC program has increased the awareness that corrosion protection can work, that it prevents environmental problems, and that substantial savings can be achieved over the lifetime of the tanks. The majority of the remaining unregulated tanks are used for home heating oil, liquid propane gas, and kerosene. The level of corrosion awareness is low with the owners of these tanks, and a mentality of "bury it and forget it" is common. There is a significant potential for a large number of relatively small spills that affect many sites. It is therefore recommended to develop an approach to prevent and remediate corrosion with a similar approach as taken for the SPCC-regulated tanks.

Airports (Appendix H)



The United States has the world's most extensive airport system, which is essential to national transportation. Airports, which are among the most important and widely used facilities, play a major role in generating economic activity for the United States. According to 1999 Bureau of Transportation Statistics figures, there were 5,324 public-use airports and 13,774 private-use airports in the United States. The airports used by the scheduled air carriers are virtually all public facilities run by an agency of a state or local government, or a commission or port authority established by the state legislature. Since airports resemble small cities, they are organized accordingly, with departments for purchasing, engineering, finance, administration, etc.

A typical airport infrastructure is relatively complex, and components that might be subject to corrosion include the natural gas distribution system, jet fuel storage and distribution system, deicing storage and distribution system, water distribution system, vehicle fueling systems, natural gas feeders, dry fire lines, parking garages, and runway lighting. Generally, each of these facilities is owned or operated by different organizations and companies, and the impact of corrosion on an airport as a whole is not known or documented; however, the airports do not have any specific corrosion-related problems that have not been described in other sectors, such as corrosion in water distribution lines, gas distribution lines, corrosion of concrete structures, and aboveground and underground storage tanks.

Because of the diversity of airport facilities and different accountabilities, the costs due to corrosion are not apparent and, therefore, cannot be addressed in a systematic manner. In order for airports to reduce and control their corrosion costs, it is recommended that the airports establish databases that will allow engineers to track corrosion and corrosion costs and raise awareness.

Railroads (Appendix I)

In 1997, there were nine Class I freight railroads (railroads with operating revenues of $256.4 million or more).(43) These railroads accounted for 70 percent of the industry's 274,399 km (170,508 mi) operated. There were 35 regional railroads (those with operating revenues between $40 million and $256.4 million and/or operating at least 560 km (350 mi) of railroad). The regional railroads operated 34,546 km (21,466 mi). Finally, there were 515 local railroads (including switching and terminal railroads) operating more than 45,300 km (28,149 mi) of railroad.

The elements that are subject to corrosion include metal members, such as rail and steel spikes; however, corrosion damage to railroad components are either limited or go unreported. Therefore, a cost of corrosion could not be determined.

One area where corrosion has been identified is in electrified rail systems, such as those used for local transit authorities. Stray currents from the electrified systems can inflict significant and costly corrosion on non-railroad-related underground structures such as gas pipelines, waterlines, and underground storage tanks.

Utilities

Utilities form an essential part of the U.S. economy by supplying end users with gas, water, electricity, and telecommunications. All utility companies combined spent $42.3 billion on capital goods in 1998, an increase of 9.3 percent from 1997.(44) Of this total, $22.4 billion was used for structures and $19.9 billion was used for equipment. Figure 8 shows the annual cost of corrosion in the Utilities category to be $47.9 billion, which is

34.7 percent of the total cost of the sector categories examined in this study. The Utilities category is divided into the following industry sectors: (1) gas distribution, (2) drinking water and sewer systems, (3) electric utilities, and (4) telecommunications.

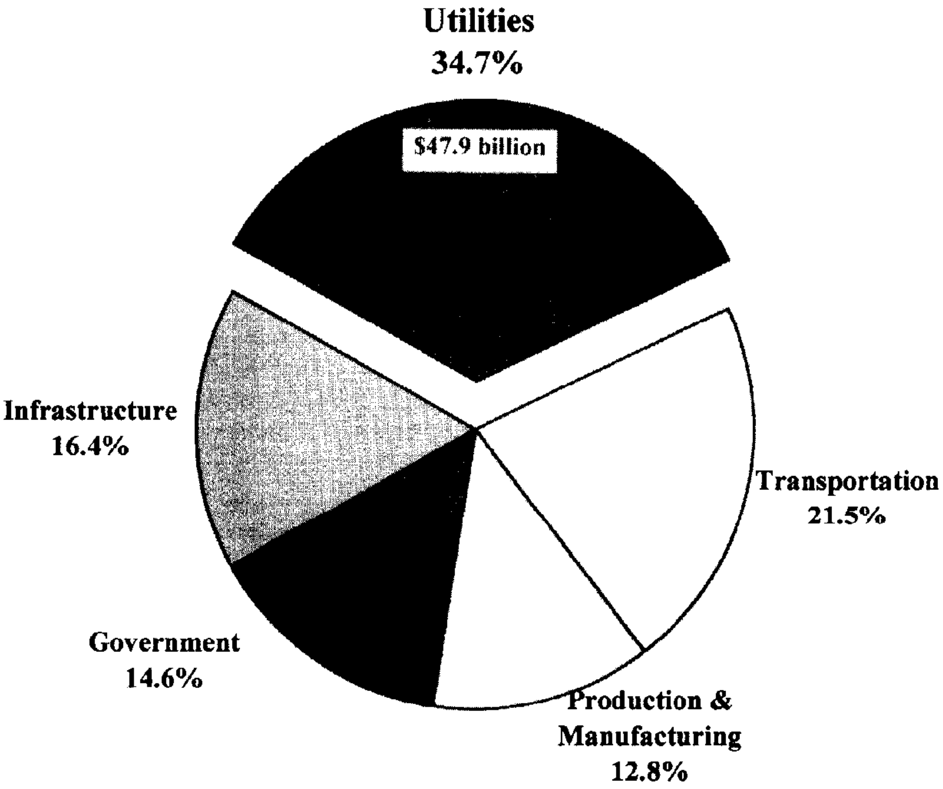
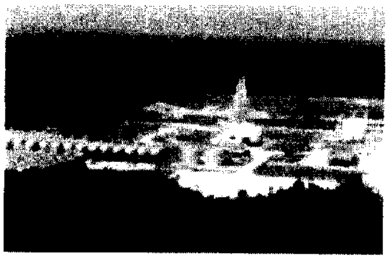


Figure 8. Annual cost of corrosion in the Utilities category.

Gas Distribution (Appendix J)



The natural gas distribution system includes 2,785,000 km (1,730,000 mi) of relatively small-diameter, low-pressure piping, which is divided into 1,739,000 km (1,080,000 mi) of distribution main and 1,046,000 km (650,000 mi) of services.[45-46] There are approximately 55 million services in the distribution system. The typical distribution of piping diameters is between 40 mm and 150 mm (1.5 in and 6 in) for main distribution piping and 13 mm to 20 mm (0.5 in to 0.75 in) for service piping. A small percentage of mains and services is larger diameter pipe, typically for commercial and industrial application.

Several different materials have been used for distribution piping. Historically, distribution mains were primarily made of carbon steel pipe; however, since the 1970s, a large portion of the gas distribution main lines have been made of plastic, mostly polyethylene (PE), but sometimes polyvinyl chloride (PVC). A large percentage of mains (57 percent) and services (46 percent) are made of metal (steel, cast iron, or copper). The methods for monitoring corrosion on the lines are the same as those used for transmission pipelines; however, leak detection is the most widely used technique.

The total cost of corrosion was estimated to be $5.0 billion, which is approximately 10 percent of the total Utilities category cost of corrosion (see figure 9).

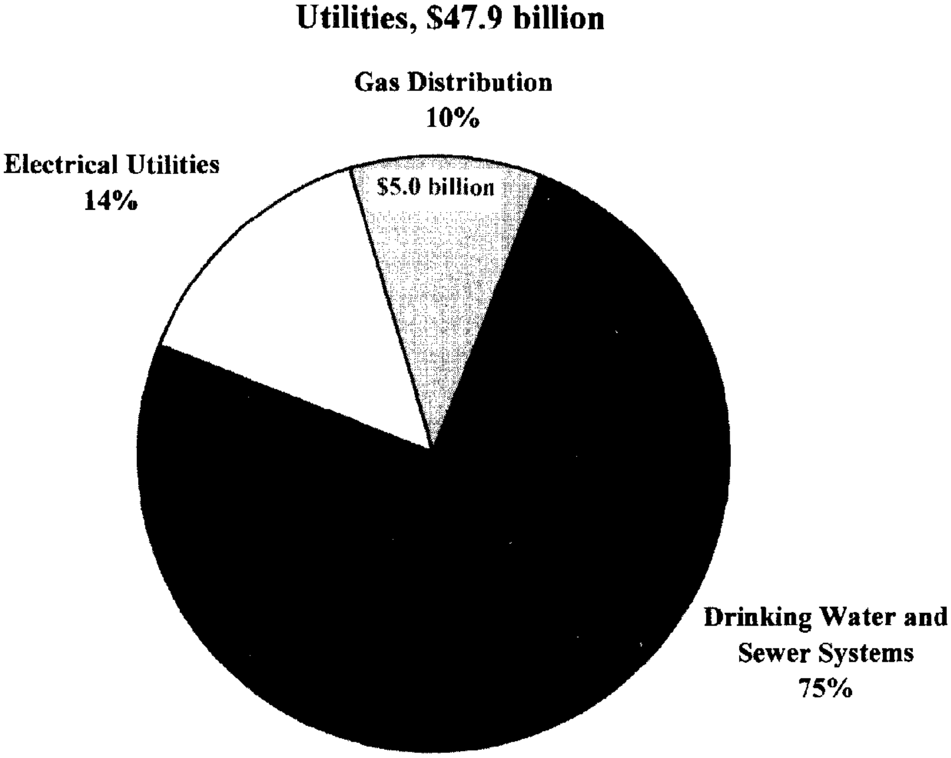
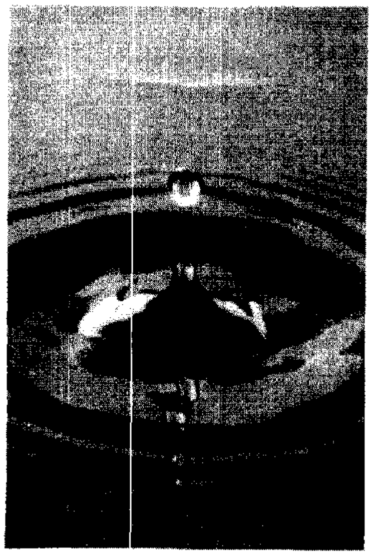


Figure 9. Annual cost of corrosion of gas distribution.

Drinking Water and Sewer Systems (Appendix K)



According to the American Water Works Association (AWWA) industry database, there is approximately 1.483 million km (876,000 mi) of municipal water piping in the United States.(47) This number is not exact, since it was found that most water utilities do not have complete records of their pipes. The total pipe length, pipe materials, and pipe diameters, as well as installation dates are often not known. The sewer system is similar in size to the drinking water system with approximately 16,400 publicly owned treatment facilities releasing some 155 million m^3 (41 billion gal) of wastewater per day during 1995.(48)

Americans consume and use approximately 550 L of drinking water per person per day, for a total annual quantity of approximately 56.7 billion m^3. The treated drinking water is transported through 1.4 million km of municipal water piping. The water piping is subject to internal and external corrosion, resulting in pipe leaks and water-main breaks.

The total cost of corrosion for the drinking water and sewer systems includes the cost of replacing aging infrastructure, the cost of unaccounted-for water, the cost of corrosion inhibitors, the cost of internal cement mortar linings, the cost of external coatings, and the cost of cathodic protection.

In March 2000, the Water Infrastructure Network (WIN)$^{(49)}$ estimated the current annual cost for new investments, maintenance, operation, and financing of the national drinking water system at $38.5 billion per year, and of the sewer system at $27.5 billion per year. The total cost of corrosion was estimated from these numbers by assuming that at least 50 percent of the maintenance and operation costs are for replacing aging (corrosion) infrastructure, while the other 50 percent would be for system expansions. This results in an estimated cost of corrosion for drinking water systems of $19.25 billion per year and for sewer systems of $13.75 billion per year.

WIN stated that the current spending levels are insufficient to prevent large failure rates in the next 20 years. The WIN report was presented in response to a 1998 study$^{(50)}$ by AWWA and a 1997 study by the EPA. Those studies had already identified the need for major investments to maintain the aging water infrastructure.

In addition to the costs for replacing aging infrastructure, there is the cost for unaccounted-for water. One city reported a constant percentage of unaccounted-for water of 20 percent in the last 25 years, with 89 percent of its main breaks directly related to corrosion. Nationally, it is estimated that approximately 15 percent of the treated water is lost. The treatment of water that never reaches the consumer results in inflated prices (national lost water is estimated at $3.0 billion per year) and extra capacity in treatment facilities to produce the lost water.

Adding these three major cost items results in a total annual cost of corrosion of $36.0 billion per year for drinking water and sewer systems combined. The corrosion cost for drinking water and sewer systems is approximately 75 percent of the total cost in the Utilities category (see figure 10).

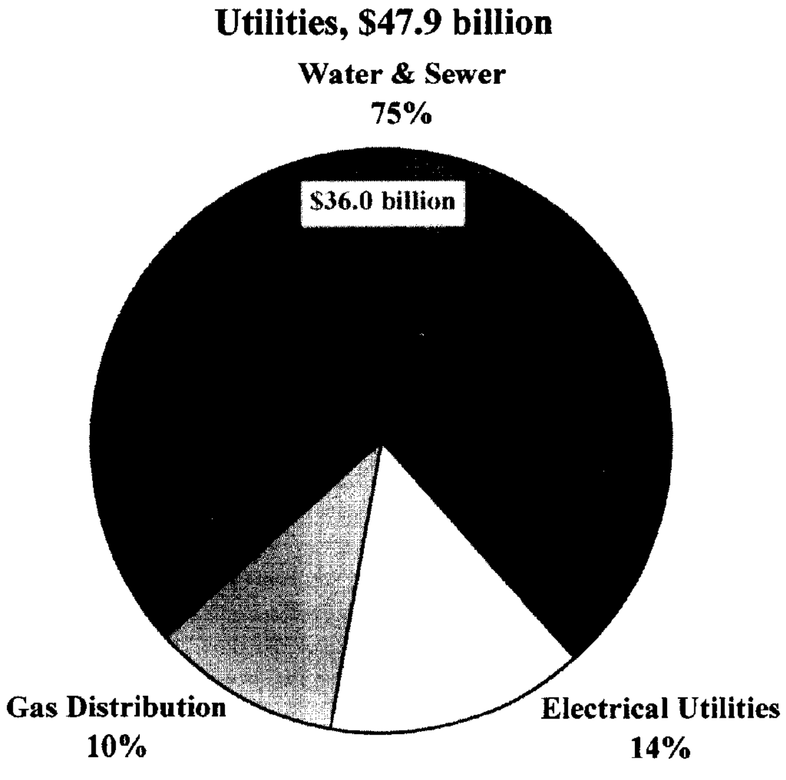
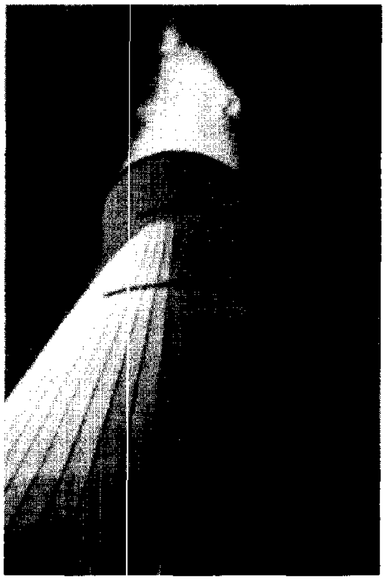


Figure 10. Annual cost of corrosion for drinking water and sewer systems.

A major barrier to progress in corrosion management of drinking water and sewer systems is the absence of complete and up-to-date information. Limited communication between water utilities limits the awareness of and the implementation of existing corrosion control technologies. The AWWA maintains partial records on the water systems of its members, and the EPA collects data from voluntary questionnaires. However, most water utilities do not maintain complete records of their entire buried pipeline system, and crucial information on pipe length and diameter, pipe material, and date of installation is often missing. The lack of information is often exacerbated by a lack of understanding and awareness of corrosion problems at the local level, and the limited time and funding dedicated to corrosion control. An attitude of "bury the pipe and forget about it" is common.

It is therefore recommended that a national resource expertise be created through, for example, the AWWA to establish a database where all water utilities submit records on their changes in their systems with the objective of better understanding system growth. Dissemination of information will enhance the understanding of corrosion-related issues and will enable the utilities to more accurately estimate pipe replacement rates and prioritize funding for corrosion maintenance and aging system rehabilitation.

Electrical Utilities (Appendix L)



The total amount of electricity sold in the United States in 1998 was 3,240 billion gigawatt hours (GWh) at a cost to consumers of $218 billion.(51) Electricity generation plants can be divided into seven generic types: fossil fuel, nuclear, hydroelectric, cogeneration, geothermal, solar, and wind. The majority of electric power in the United States is generated by fossil fuel and nuclear supply systems. The fossil fuel sector (including gas turbines and combined cycle plants) is the largest, with a generating capacity of approximately 488 GW, and a total generation of 2.2 million GWh in 1998.(52) In 1998, approximately 102 nuclear stations were operational, with a generating capacity of 97.1 GW, and a total generation of 0.67 million GWh.

Two different types of nuclear reactors are currently in use in the United States, namely the boiling water reactor (BWR) and the pressurized water reactor (PWR). The fuel for these types of reactors is similar, consisting of long bundles of 2 to 4 percent enriched uranium dioxide fuel pellets stacked in zirconium-alloy cladding tubes. The BWR design consists of a single loop in which the entering water is turned directly into steam for the production of energy. The PWR is a two-loop system that uses high pressure to maintain an all-liquid-water primary loop. Energy is transferred to the secondary steam loop through two to four steam generators. The PWR also uses a wet steam turbine. The electric power industry uses three different types of fossil fuel power plants. The most common and widely used is the pulverized coal-fired steam power plant. Fuel oil can be used instead of coal. Gas turbines are usually smaller units that are used for peak loads and operate only for a few hours per day. Combined cycle plants using both steam and gas turbines are generally used for baseload service, but also must be capable of addressing peak loads. Hydraulic power systems include both hydroelectric and pumped storage hydroelectric plants. In both processes, water is directed from a dam through a series of tapering pipes to rotate turbines that create electricity. In principle, the potential energy held in the dam converts into kinetic energy when it flows through the pipes. The concept behind the development of pumped storage plants is the conversion of relatively low-cost, off-peak energy generated in the thermal plant into high-value, on-peak power. Water is pumped from a lower to a higher reservoir when low-cost pumping is available from large, efficient thermal plant generation. It is released during periods of high power demand and displaces the use of inefficient, costly alternative sources of generation.

The total cost of electricity of $218.4 billion can be divided into operation and maintenance (O&M), depreciation, and forced outages. The corrosion-related cost of forced outages in the nuclear power industry was estimated at $670 million. The total cost of depreciation based on the 1998 Federal Energy Regulatory Committee (FERC) Form No. 1 data was $35.7 billion. Based on the evaluation of depreciation by facility type, a percentage due to corrosion was estimated. This cost percentage due to corrosion as part of the total utility depreciation in 1998 was 9.73 percent or $3.433 billion, with nuclear facilities at $1,546 million, fossil fuel facilities at $1,214 million, transmission and distribution at $607 million, and hydraulic and other power at $66 million. The corrosion portion of the annual O&M cost was estimated at $698 million for fossil fuel, $2,013 million for nuclear facilities, and $75 million for hydraulic power, for a total of $2,786 million. Thus, the total direct cost of corrosion in the electric utility industry in 1998 is estimated at $6.889 billion per year. In comparison, an Electric Power Research Institute (EPRI) study(11) estimated the cost of corrosion to the user/consumer to be $17.27 billion per year. The cost to consumers includes taxes, sales, administration, and profits. This analysis indicates that the indirect costs (to the user, $17.27 billion minus $6.889 billion = $10.381 billion) are 1.5 times the direct cost (to the owner/operator, $6.9 billion).

Because of the complex and often corrosive environments in which power plants operate, corrosion has been a serious problem, with a significant impact on the operation of the plants. In the 1970s and the 1980s, major efforts were spent on understanding and controlling corrosion in both nuclear and fossil fuel steam plants, and significant progress was made. However, with the aging of several plants, old problems persist and new ones appear. For example, corrosion continues to be a problem with electrical generators and with turbines. Specifically, stress corrosion cracking in steam generators in PWR plants and boiler tube failures in fossil fuel plants continue to be problems. There are further indications that aging of buried structures, such as service water piping, has started to result in leaks that cannot be tolerated.

Environmental requirements and deregulation of the power industry often result in less attention being paid to corrosion and deterioration of materials of construction. If not addressed in a timely manner, these materials will corrode to the point that major repair and rehabilitation are required. The cost of corrosion will then, in the near future, increase significantly.

Figure 11 shows that the annual cost of corrosion in the electrical utilities sector to be $6.9 billion, which is 14 percent of the total cost of the Utilities categories.

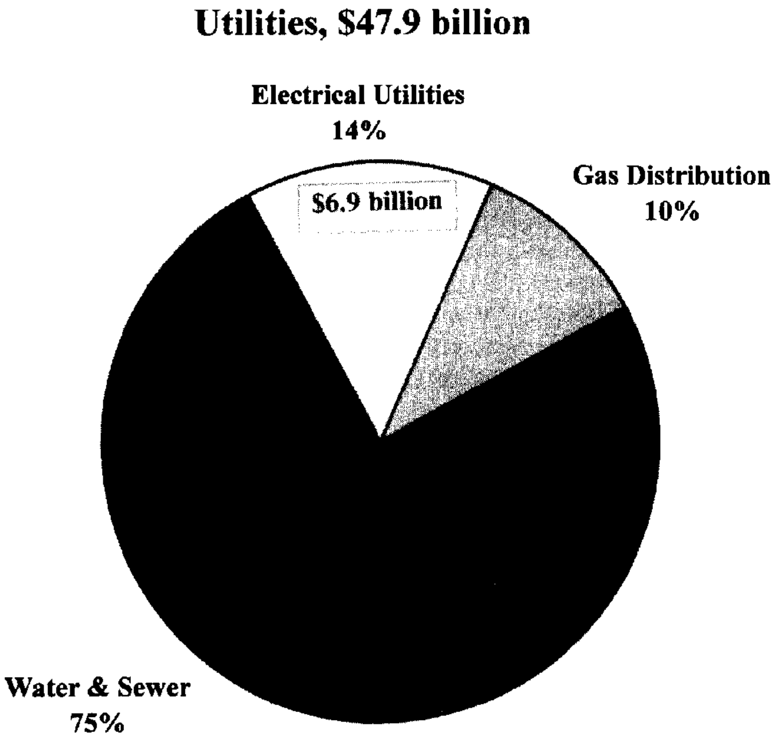


Figure 11. Annual cost of corrosion in the electrical utilities industry.

Telecommunications (Appendix M)

Telecommunications is an increasingly important part of modern society. The telecommunications infrastructure includes hardware such as electronics, computers, and data transmitters, as well as equipment shelters and the towers used to mount antennas, transmitters, and receivers. Wired communication systems include telephone and cable TV systems, while wireless communication systems include items such as personal computer systems and cellular telephones. According to the U.S. Census Bureau, the total value of shipments for communications equipment in 1999 was $84 billion.(53) An important factor to be considered for corrosion cost is the additional cost for corrosion protection of towers and shelters, such as painting and galvanizing. In addition, corrosion of buried copper grounding beds, as well as galvanic corrosion of the grounded steel structures, contributes to the cost of corrosion.

For this sector, no corrosion cost was determined because of the lack of information on this rapidly changing industry. Many components are being replaced before physically failing, because they become obsolete technology in a short period of time.

Transportation

The Transportation category includes vehicles and equipment used to transport people and products (i.e., automobiles, ships, aircraft, etc.). Figure 12 shows the annual cost of corrosion in the Transportation category to be $29.7 billion, which is 21.5 percent of the total cost of the sector categories examined in this study. The Transportation category is divided into the following industry sectors: (1) motor vehicles, (2) ships, (3) aircraft, (4) railroad cars, and (5) HAZMAT transport.

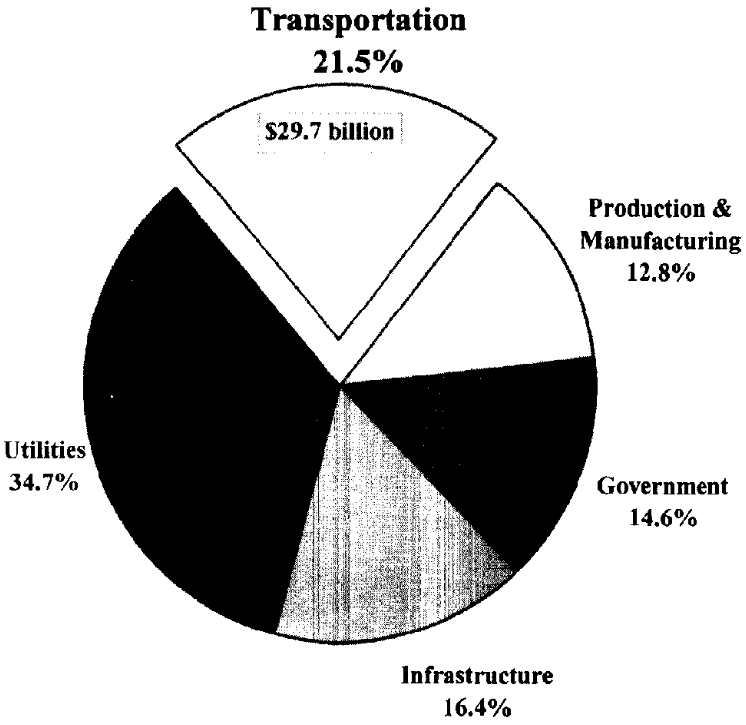
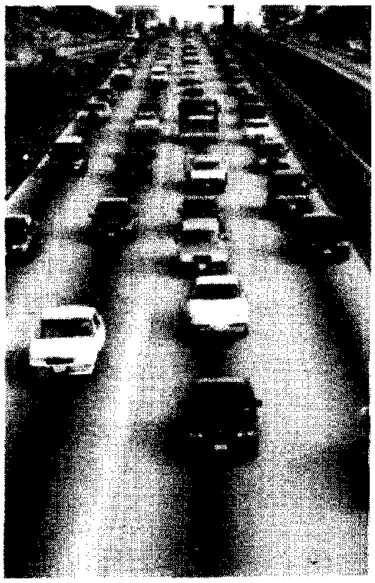


Figure 12. Annual cost of corrosion in the Transportation category.

Motor Vehicles (Appendix N)



U.S. consumers, businesses, and government organizations own more than 200 million registered vehicles.(54) Assuming an average value of $5,000, the total investment Americans have made in vehicles can be estimated at more than $1 trillion. Until the late 1950s, corrosion of motor vehicles was limited to marine environments; however, with the increased use of deicing salts, vehicles in the snowbelt regions began to corrode and literally fell apart within a few years after purchase. In fact, in the 1970s, the cost incurred due to corrosion was so high that in the Battelle-NBS study, the automotive industry sector was singled out as being the main driving force of corrosion costs in the U.S. economy.(1-2) In the late 1970s, automobile manufacturers started to increase the corrosion resistance of vehicles by using corrosion-resistant materials, employing better manufacturing processes, and by designing more corrosion-resistant vehicles through corrosion engineering knowledge. Because of the steps taken by the manufacturers, today's automobiles have very little visible corrosion and most vehicles survive structurally until the vehicle wears out mechanically. However, the total annual cost incurred is high and much can be done to further reduce the cost.

The total cost of corrosion to owners of motor vehicles is estimated at $23.4 billion per year or 79 percent of the Transportation category (see figure 13). This cost is divided into the following three components: (1) increased manufacturing costs due to corrosion engineering and the use of corrosion-resistant materials ($2.56 billion per year), (2) repairs and maintenance necessitated by corrosion ($6.45 billion per year), and (3) corrosion-related depreciation of vehicles ($14.46 billion per year).

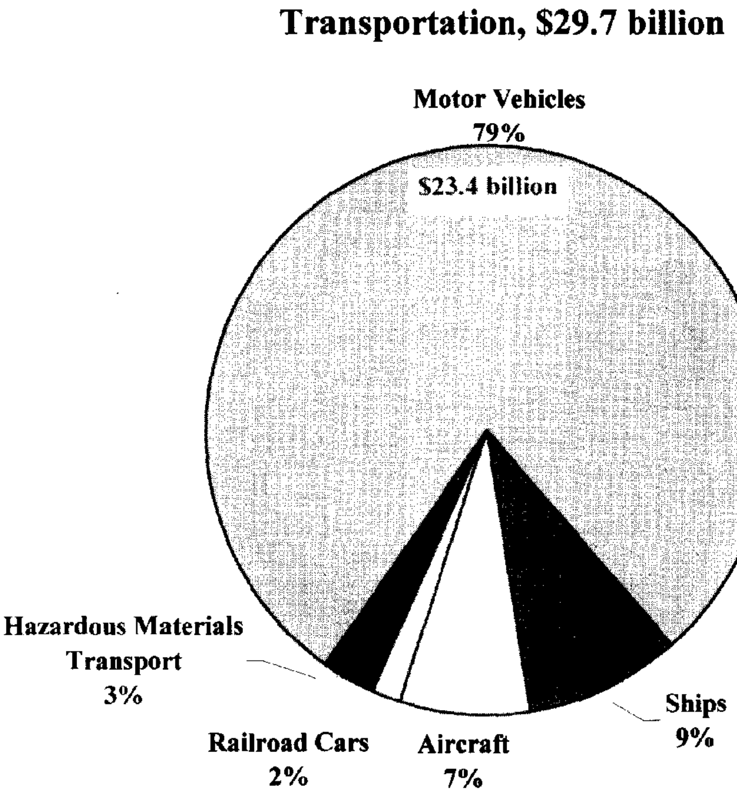


Figure 13. Annual cost of corrosion in the motor vehicle industry.

Twenty-five years ago, corrosion was of obvious concern to the general public because of visible rusting of car bodies and frames. Because there is generally no extensive car body corrosion being observed in less than 10 years, it is commonly believed that corrosion is not a consumer problem anymore. While there exist few opportunities to further improve the corrosion resistance of the body of motor vehicles, some areas for improvement in individual systems must be mentioned. These include fuel and brake systems, as well as electrical and electronic systems. Many failures of the latter components are due to corrosion, but because damage is not visible, there is very little public outcry and components are merely replaced. However, manufacturers are slowly upgrading and protecting electrical and electronic components from the environment to ensure a longer life.

Ships (Appendix O)

The size of the shipping industry over water can be measured by the number of miles that ships sail and the tons of cargo they haul (ton-miles). The U.S.-flag fleet can be divided into several categories as follows: the Great Lakes with 737 vessels at 100 billion ton-km (62 billion ton-mi), inland with 33,668 vessels at 473 billion ton-km (294 billion ton-mi), ocean with 7,014 vessels at 563 billion ton-km (350 billion ton-mi), recreational with 12.3 million boats, and cruise ships with 122 boats serving North American ports (5.4 million passengers).(55)

The annual corrosion-related costs of the U.S. marine shipping industry is estimated at $2.7 billion (see figure 14). This cost is divided into costs associated with new construction ($1.12 billion), maintenance and repairs ($810 million), and corrosion-related downtime ($785 million). Most ships that serve U.S. ports do not sail under the U.S. flag, but under that of nations with less restrictive laws and taxation; therefore, it is difficult to estimate the national cost of corrosion for this sector. Furthermore, the shipping industry is very diversified in terms of size, cost, and cargo. Finally, the shipping industry is primarily a commodity industry where short-term profits are often more important than long-term savings on assets.

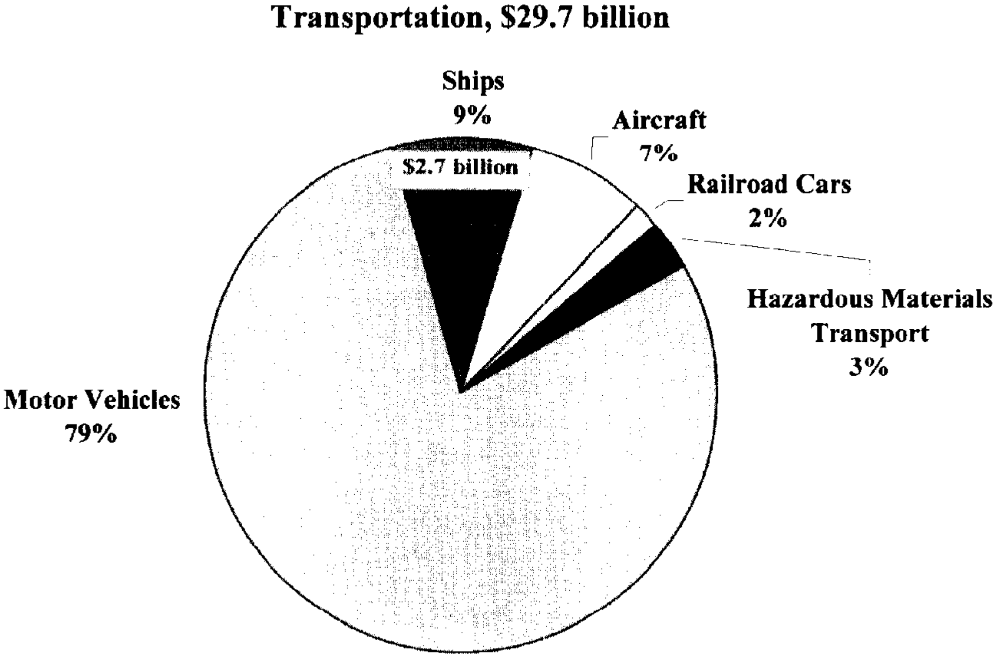
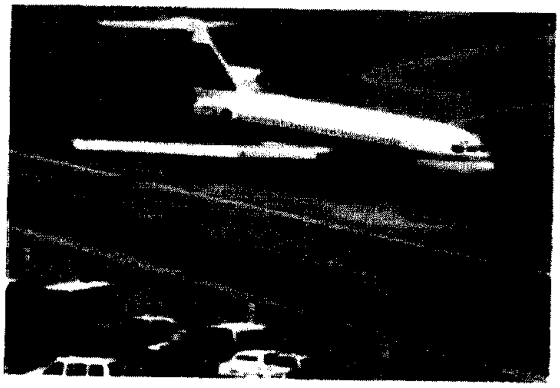


Figure 14. Annual cost of corrosion of ships.

One of the most significant developments in corrosion control in the shipping industry is the development of new long-lasting coatings that require less maintenance and repair than the traditional coatings. Further improvement in corrosion control exists in the manufacturing of double-hulled oil tankers. As a result of the Exxon Valdez oil spill in Prince William Sound, Alaska (March 24, 1989), oil tankers of a certain size must now be constructed with double-wall hulls. The first generation of these oil tankers experienced significant corrosion problems that were not anticipated in the design stage.

Aircraft (Appendix P)



In 1998, the combined aircraft fleet operated by U.S. airlines was more than 7,000, of which approximately 4,000 were turbojets.(56) At the start of the "jet age" (1950s to the 1960s), little or no attention was paid to corrosion and corrosion control. These aircraft, which include the Boeing 707, DC-9, Boeing 727, DC-10, and the earlier versions of the Boeing 737 and 747, are characterized by a design that primarily addresses strength and fail-safety. The second generation of jet aircraft built in the 1970s and the 1980s incorporated some corrosion control, but the emphasis was placed on the incorporation of damage tolerance standards into the design. This generation of aircraft include the B-737 (-300, -400, -500); B-747-400; B-757; B-767; MD-81, -82, and -83; MD-88; MD-11; and F-100. The third generation of jet transport aircraft includes the Boeing 777 and the new generation Boeing 737. In addition to key characteristics of the first- and second-generation aircraft, the third-generation aircraft are characterized by the incorporation of significant improvements in corrosion prevention and control in the design.

The annual (1996) corrosion cost to the U.S. aircraft industry is estimated at $2.225 billion, which includes the cost of design and manufacturing at $0.225 billion, corrosion maintenance at $1.7 billion, and downtime due to corrosion at $0.3 billion (see figure 15). With the availability of new corrosion-resistant materials and an increased awareness of the importance of corrosion to the integrity and operation of jet aircraft, the current design service life of 20 years has been extended to 40 years without jeopardizing structural integrity and significantly increasing the cost of operation.(57)

One of the major concerns of the aircraft and airline industry is the continued aging of several types of aircraft beyond the 20-year design service life. This aging of the fleet has been the subject of considerable attention by industry and government for many years, and has resulted in increased maintenance efforts for the aging aircraft. Due to the competitive nature of the airline industry however, corrosion maintenance is often not performed adequately. This also may have been due to the lack of understanding of the corrosion process and the inability to predict the nucleation and growth behavior of corrosion in airframe components. Hence, corrosion has not been incorporated into the damage tolerance assessments, where, instead, a "find and fix" approach has generally prevailed. This approach leads to extensive corrosion of both structural and non-structural components, significantly increasing the cost of maintenance. This may, in the near future, have a significant impact on the availability or downtime of the aging aircraft, further increasing the corrosion-related costs. Finally, as airframes continue to age and are kept in service, corrosion will increasingly affect the structural integrity of these airframes.

While it is upon the airframe manufacturers to mitigate corrosion, the operators must have a corrosion control program in place throughout the life of the airplane. The "find and fix" approach must be complemented by an approach based on an understanding of the corrosion process and the ability to predict and monitor its behavior. Corrosion prediction models must be developed so that a cost-effective corrosion integrity program can be developed. Moreover, there is a need for improved inspection and monitoring techniques to expand the capabilities to detect and monitor corrosion and cracks beginning at an early stage.

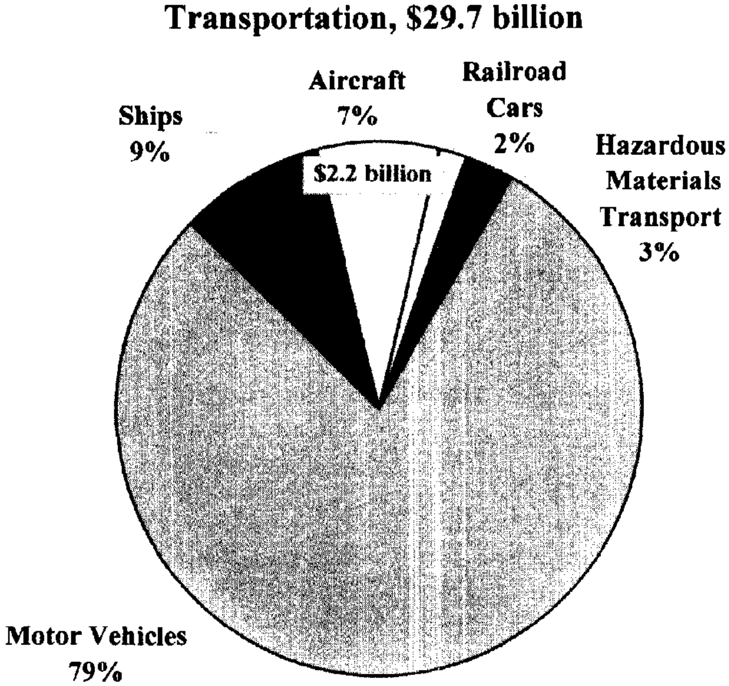
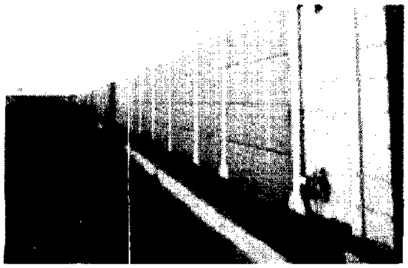


Figure 15. Annual cost of corrosion of aircraft.

Railroad Cars (Appendix Q)



In 1998, 1.47 million freight cars were reported to operate in the United States.(43) Covered hoppers at 28 percent make up the largest proportion of the freight car fleet, with tanker cars making up the second largest proportion at 18 percent. The type of commodities transported range from coal (largest volume) to chemicals, motor vehicles, farm products, food products, and metallic and non-metallic ores and minerals. It is estimated that the total annual corrosion-related maintenance cost for railroad cars is approximately $504 million ($258 million for external coatings and $246 million for internal coatings and liners) (see figure 16).

Railroad freight cars typically suffer from both external and internal corrosion. While external corrosion, primarily due to atmospheric exposure, is a concern, car appearance generally takes precedence. External corrosion is controlled by application of direct-to-metal coating systems (epoxies with or without urethane coating). Certain categories of cars, particularly tank cars, are leased by the shippers; therefore, the lessees often choose to apply an exterior paint to address the aesthetics. Internal corrosion is caused by corrosive cargo, such as coal, salt, or various acids.

The rate of corrosion has to be controlled in order to: (1) prolong the service life of the car, (2) prevent contamination of the transported product, such as food products or high-purity chemicals, and (3) prevent hazardous spills that could contaminate the environment and pose a public safety hazard. Protection from internal corrosion is achieved by using organic coating systems or rubber linings. As an alternative, cars for certain corrosive cargo services are manufactured from corrosion-resistant materials, such as aluminum or stainless steel, which raises the price of a car twofold.

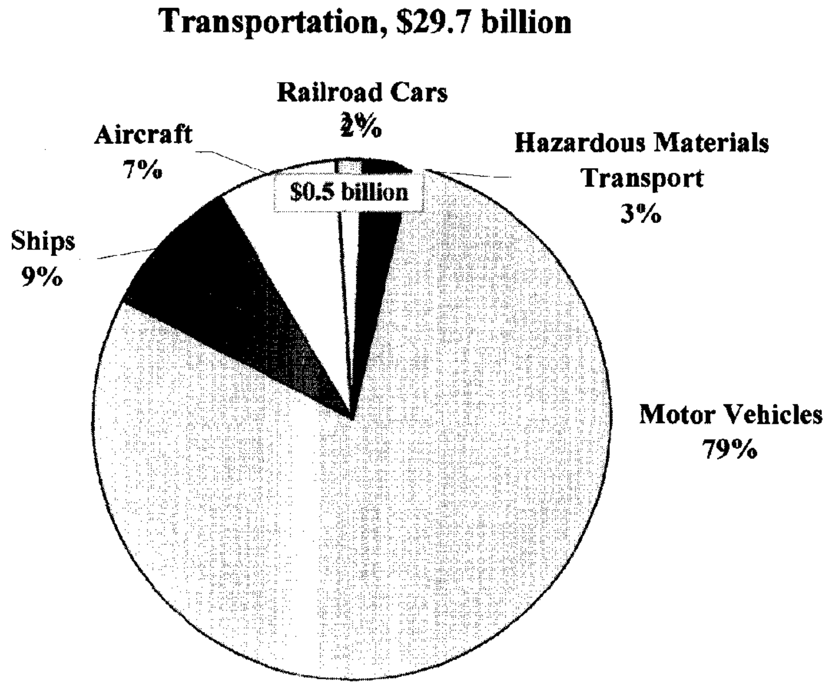


Figure 16. Annual cost of corrosion of railroad cars.

When it comes to corrosion, there are a limited number of regulations imposed on the industry.(58) Tank cars are required to be periodically inspected for corrosion damage to the shell and the heads. The frequency of inspection, the test techniques, and the acceptance criteria are left to the discretion of the owner/operator. The most common inspection interval for cars transporting benign commodities is 10 years. Cars that are used in an aggressive commodity service are typically inspected every 5 years.

Based on an industry survey, it was found that the railroad companies and shippers do not track corrosion-related costs. Considering that there are 1.47 million freight cars in service today, there is a considerable opportunity for the reduction of the corrosion-related costs in the railroad sector. However, in order to reduce these costs, the industry must first make an attempt to estimate the magnitude of the problem by documenting the costs for exterior and interior corrosion protection.

Hazardous Materials Transport (Appendix R)

Each year, nearly 2 billion metric tons of hazardous materials (HAZMAT) are produced in the United States.(59) The amount of HAZMAT shipments that are shipped each year is approximately 3 billion metric tons. Each shipment will be moved several times before reaching its destination. Bulk transportation of HAZMAT includes overland shipping by tanker truck and rail tank car, and by special containers that are loaded onto vehicles. Over water, ships loaded with specialized containers, tanks, and drums are used. In small quantities, HAZMAT requires specially designed packaging for truck and air shipment.

The total cost of corrosion for HAZMAT transportation is at least $0.887 billion per year (see figure 17). The elements of this cost include the corrosion-related cost of transport vehicles ($400 million per year), the cost of specialized packaging ($487 million per year), and the direct cost of $0.5 million per year of accidental releases and other corrosion-related transportation incidents. The indirect costs of releases are not known.

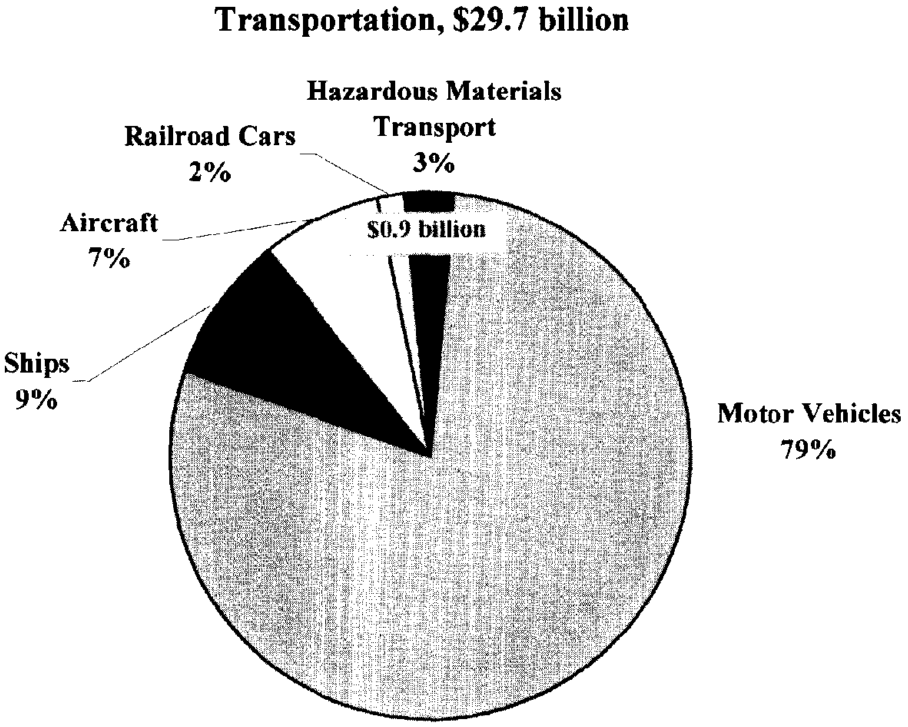


Figure 17. Annual cost of corrosion for hazardous materials transport.

Production and Manufacturing

This group includes industries that produce and manufacture products of crucial importance to the economy and the standard of living in the United States. These include gasoline products, mining, petroleum refining, various chemical and pharmaceutical products, paper, and agricultural and food products. Figure 18 shows the annual cost of corrosion in the Production and Manufacturing category to be $17.6 billion, which is 12.8 percent of the total cost of the sector categories examined in this study. The Production and Manufacturing category is divided into the following industry sectors: (1) oil and gas exploration and production, (2) mining, (3) petroleum refining, (4) chemical, petrochemical, and pharmaceutical, (5) pulp and paper, (6) agricultural production, (7) food processing, (8) electronics, and (9) home appliances.

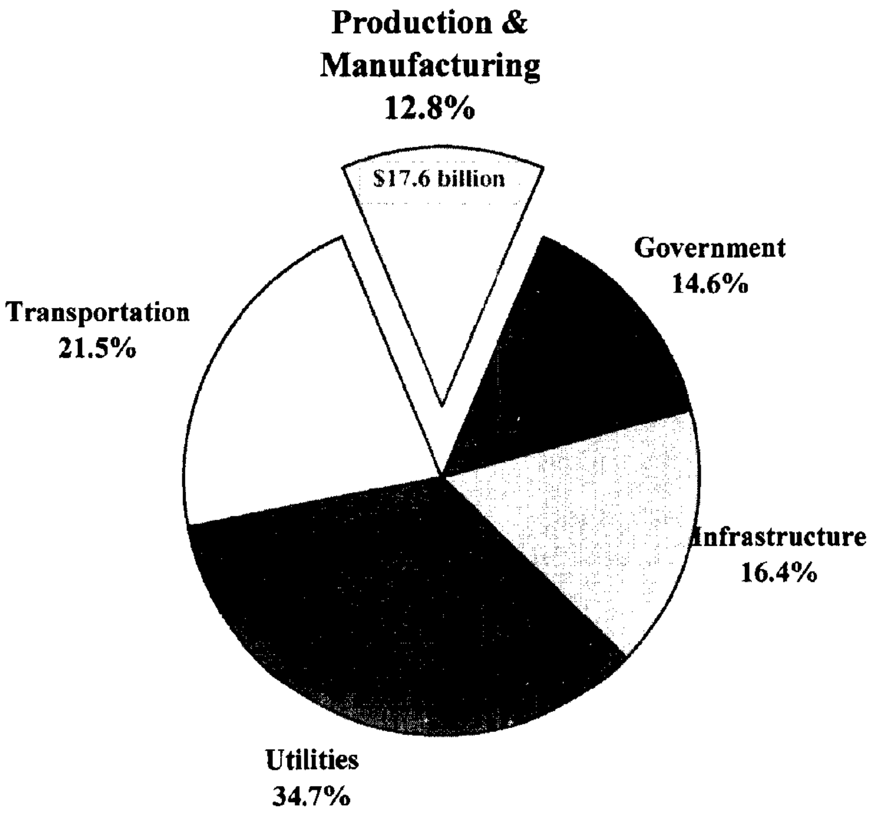
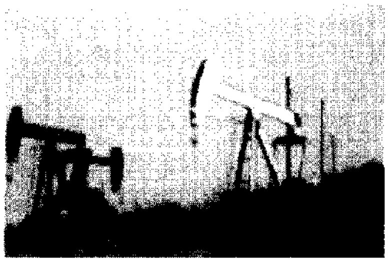


Figure 18. Annual cost of corrosion in the Production and Manufacturing category.

Oil and Gas Exploration and Production (Appendix S)



Domestic oil and gas production can be considered to be a stagnant industry, because most of the significant available onshore oil and gas reserves have been exploited. Oil production in the United States in 1998 consisted of 3.04 billion barrels.(60) The significant recoverable reserves left to be discovered and produced in the United States are probably limited to less convenient locations such as in deep water offshore, remote arctic locations, and difficult-to-manage reservoirs with unconsolidated sands. Materials and corrosion control technology used in the traditional onshore production facilities have not significantly changed since the 1970s. The material and corrosion control technology required for the more difficult production locations must be more reliable due to the excessive cost of replacement or failure in these locations. The commodity price of oil will continue to dictate whether or not these new developments will even be considered.

The majority of cost-savings for any oil production facility is in the prevention of failure in one of the production arteries, such as downhole tubing, surface pipelines, and production vessels.(61-62) Downhole tubing, surface pipelines, pressure vessels, and storage tanks in oil and gas production are subject to internal corrosion by water, which is enhanced by the presence of CO_2 and H_2S in the gas phase. Internal corrosion control is a major cost item consideration. The total cost of corrosion in the U.S. oil and gas production industry is estimated to be $1.372 billion annually, made up of $589 million for surface piping and facility costs, $463 million in downhole tubing expenses, and $320 million in capital expenditures related to corrosion. Figure 19 shows the annual corrosion cost for oil and gas production to be approximately 8 percent of the Production and Manufacturing category.

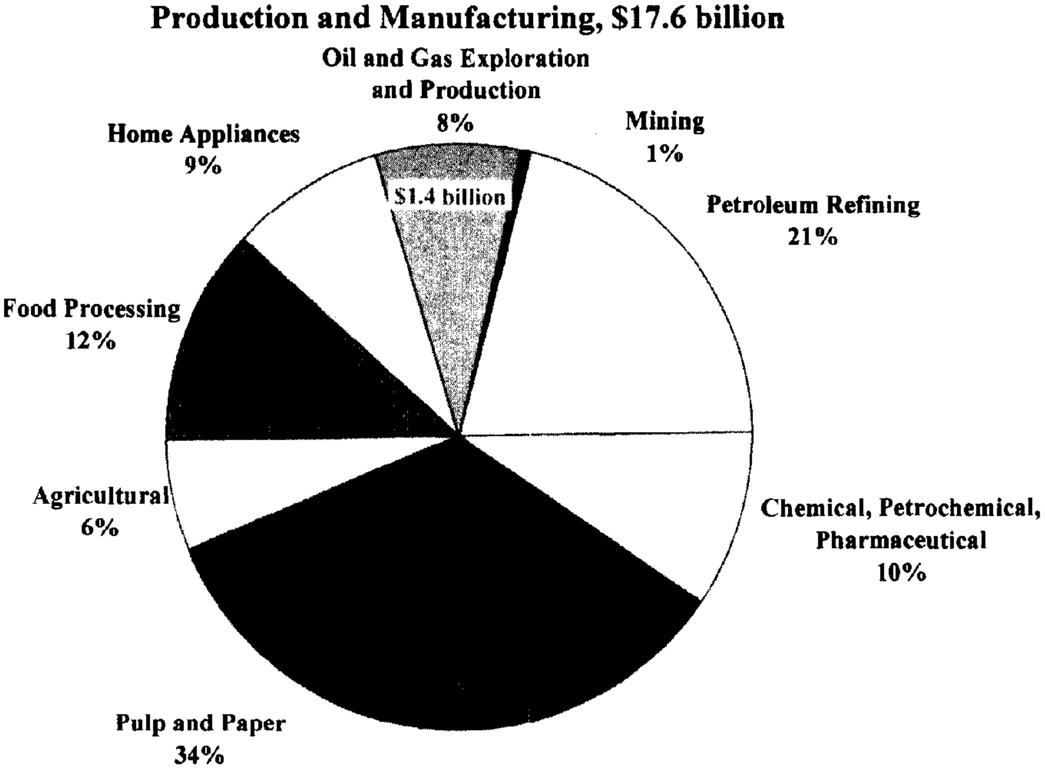
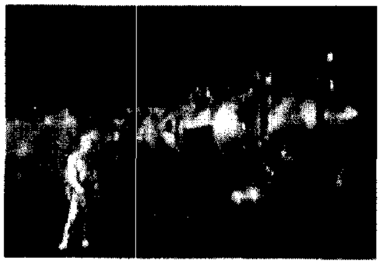


Figure 19. Annual cost of corrosion in the oil and gas exploration and production industry.

The relatively high costs associated with oil and gas production in the United States put the industry at a distinct disadvantage compared to the Middle East and the former Soviet Union, where the only barriers to increased production are investment capital and political complications. To remain competitive with the world market, maintenance costs must be kept to a minimum. In addition, the conservative culture in the oil industry seldom allows for new technology to be implemented. The use of corrosion-resistant alloys is currently limited by the high capital investment associated with these materials. Furthermore, a large portion of the cost to control internal corrosion lies in the use of corrosion inhibitors. Optimization of the inhibitor usage could be accomplished through the use of more advanced inhibitor treatment schemes, such as active monitoring systems connected to inhibitor pumps to adjust the dosage as corrosivity increases or decreases.

Mining (Appendix T)



Corrosion in the mining industry is not considered to be a significant problem. In the few instances where corrosion is a concern, the mining industry relies heavily on past experience and the knowledge of equipment suppliers to quickly resolve any problems in order to maintain production. There is a general consensus among mining engineers that the life-limiting factors for mining equipment are wear and mechanical damage before corrosion becomes an issue.(63) Maintenance painting, however, is heavily relied upon to prevent corrosion, with an average annual estimated expenditure for the coal mining industry of $93 million, which is a very small portion of the overall cost in the Production and Manufacturing category (see figure 20).

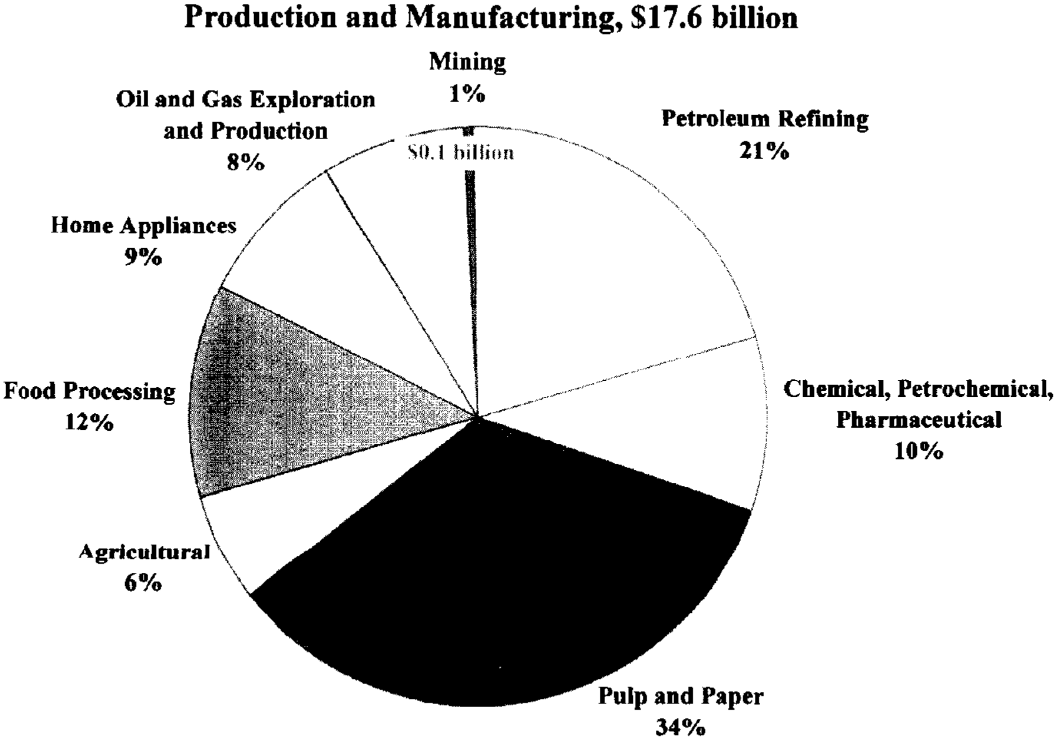


Figure 20. Annual cost of corrosion in the mining industry.

Petroleum Refining (Appendix U)

Petroleum is the single largest source of energy for the United States. The nation uses twice as much petroleum as either coal or natural gas. The U.S. refineries process approximately 23 percent of the world's petroleum production and represent the largest refining capacity in the world, with 163 refineries.(64) Most refineries are concentrated on the West and Gulf coasts, primarily because of access to major sea transportation and shipping routes. The majority of refineries are concentrated in large, integrated companies with multiple refining facilities. In 1996, U.S. refineries supplied more than 18 million barrels per day of refined petroleum products, which is an increase of more than 3 million barrels per day, compared with 1970. U.S. refineries rely on both domestic and foreign producers for crude oil. Future refining capacity in the United States is predicted to increase slightly and to level off in the next 20 years.

The total annual cost of corrosion for the petroleum refining industry is estimated at $3.692 billion, which is 21 percent of the Production and Manufacturing category (see figure 21). Of this total, maintenance-related expenses are estimated at $1.767 billion, vessel turnaround expenses at $1.425 billion, and fouling costs are approximately $0.500 billion annually. The costs associated with corrosion control in refineries include both the processing side and water handling. Corrosion-related issues regarding the processing side include the handling of organic acids, referred to as naphthenic corrosion, and sulfur species, particularly at high temperatures, as well as water carryover in processing vessels and pipelines. Water handling includes concerns with corrosives such as H_2S, CO_2, chlorides, and high levels of dissolved solids.

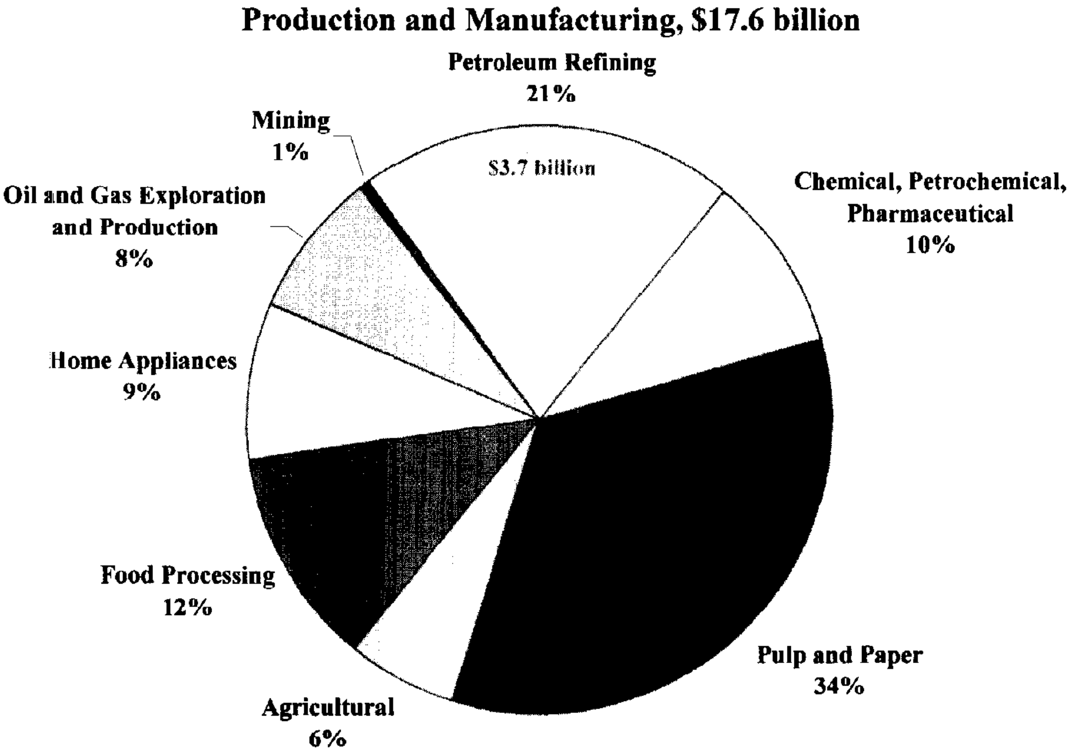
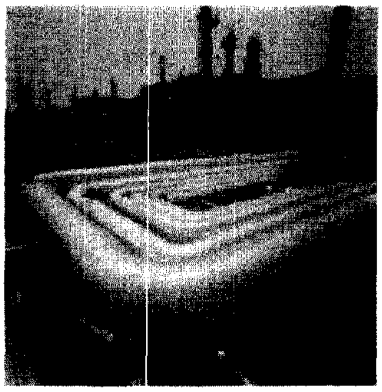


Figure 21. Annual cost of corrosion in the petroleum refining industry.

Increasing regulation and pressure from environmental groups have forced the refineries to implement defensive strategies where little attention is paid to improved corrosion control. This is compounded by overseas market forces, such as OPEC, which control the price of the feedstock oil. In a commodity-driven industry that is struggling to compete in the world market, investment in more effective corrosion control strategies often takes a backseat to across-the-board cost-cutting measures. The majority of pipelines and vessels in refineries are constructed of carbon steel, and opportunities for significant savings exist through the use of low-alloy steels and alloy-clad vessels, particularly as increasingly higher fractions of acidic crude oil are refined.

Chemical, Petrochemical, and Pharmaceutical (Appendix V)



For this sector, the cost of corrosion was estimated as a fraction of the annual capital expenditures in the industry. The total capital expenditures for the chemical industry are $15.06 billion, with $0.6 billion to $1.8 billion per year in corrosion costs. For the petrochemical industry, the total capital expenditures are $1.84 billion, with $0.07 billion to $0.22 billion per year in corrosion costs. For the pharmaceutical industry, the total capital expenditures are $4.0 billion, with $0.18 billion to $0.53 billion per year in corrosion costs. Therefore, the three industries combined have total capital expenditures of $21.30 billion in 1997, with $0.85 billion to $2.56 billion in annual corrosion costs. The estimated average direct corrosion cost are $1.7 billion per year (8 percent of the total capital expenditures).

No calculation was made for the indirect costs of production outages or indirect costs related to catastrophic failures. The costs of operation and maintenance related to corrosion were not readily available; estimating these costs would require detailed study of the data records of individual companies.

Figure 22 shows the annual corrosion cost for chemical, petrochemical, and pharmaceutical industry to be approximately 10 percent of the Production and Manufacturing category.

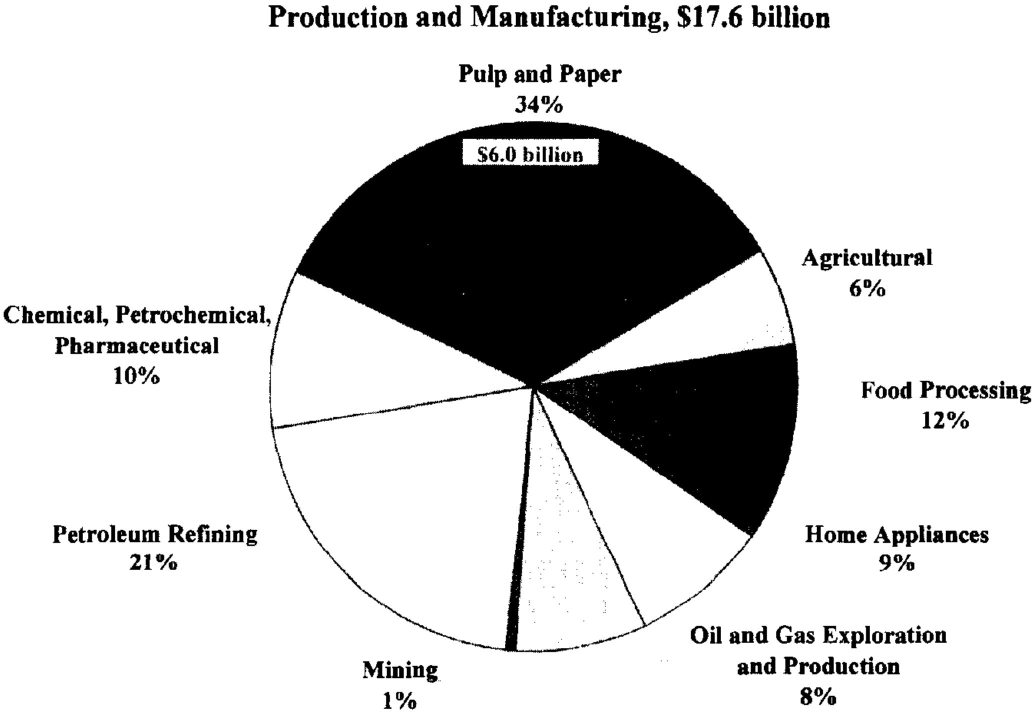


Figure 22. Annual cost of corrosion in the chemical, petrochemical, and pharmaceutical processing industry.

Over the past few years, the chemical, petrochemical, and pharmaceutical industries have placed increasing emphasis on minimizing corrosion failures by using corrosion-resistant alloys, corrosion monitoring, and implementing planned maintenance. Many chemical companies are now using risk-based inspection models to minimize the likelihood of failure in critical, often pressurized, equipment. Such models determine the risk level of high-risk equipment based on the consequences and propensity of failure. The safety of surrounding infrastructure in the proximity to the plant and public safety is taken into consideration.

Pulp and Paper (Appendix W)

The $165 billion in sales in the pulp, paper, and allied products industry supplies the United States with approximately 300 kg of paper per person per year.[(65)] More than 300 pulp mills and more than 550 paper mills support its production.

Paper production consists of a series of processes and can be roughly divided into five major manufacturing steps: pulp production, pulp processing and chemical recovery, pulp bleaching, stock preparation, and paper manufacturing. Each manufacturing step has its own unique corrosion problems related to the size and quality of the wood fibers, the amount of and the temperature of the processing water, the concentration of the treatment chemicals, and the materials used for machinery construction. Examples of corrosion affecting paper production are corrosion products polluting the paper and corrosion of the rolls scarring the sheets of paper. Corrosion of components may result in fractures or leaks in the machines, resulting in production losses and/or increased safety hazards.

The total annual corrosion costs for the pulp, paper, and paperboard industry, as determined as a fraction of the maintenance cost, is approximately $1.97 billion to $9.88 billion (average of $5.93 billion per year). These estimates are between 1.2 percent and 6.0 percent of the total sales for the entire U.S. pulp and paper industry. Figure 23 shows the annual corrosion costs for the pulp and paper industry to be approximately 34 percent of the Production and Manufacturing category.

Different paper mills take different approaches to corrosion management. In the majority of the mills, corrosion management is the responsibility of maintenance groups. The primary responsibility of these groups is to ensure that production runs continuously for 24 hours per day, 7 days per week. Only a few mills have dedicated corrosion engineers on staff. Particularly for those mills that have no dedicated corrosion engineers, it is recommended that corrosion awareness be increased through organizations such as NACE International or the Technical Association of the Pulp and Paper Industry (TAPPI).

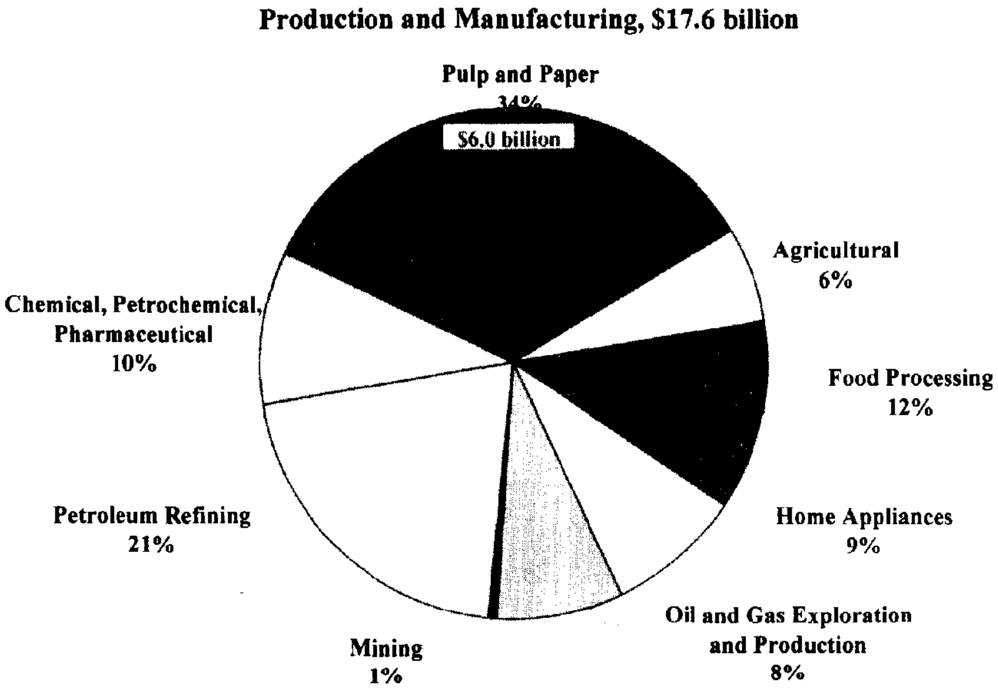
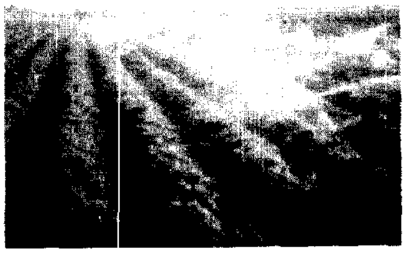


Figure 23. Annual cost of corrosion in the pulp and paper industry.

Agricultural Production (Appendix X)



Agricultural operations are producing livestock, poultry, or other animal specialties and their products, and producing crops, including fruits and greenhouse or nursery products.(66) According to the National Agricultural Statistics Service, there are approximately 1.9 million farms in the United States.(67) The eight major U.S. field crops are corn, sorghum, barley, oats, wheat, rice, cotton, and soybeans. The major livestock are poultry, cattle, hogs, and sheep.

Based on the 1997 Census, the total value of farm machinery and equipment is approximately $15 billion per year. The two main reasons for replacing machinery or equipment include: (1) upgrading old equipment and (2) substitution because of operational failure. Failure due to corrosion damage would be grouped into this category; however, national data on the types of failures occurring in farm equipment were not found. Discussions with people in this industrial sector resulted in an estimate of corrosion costs in the range of 5 percent to 10 percent of the value of all new equipment. This means that the total cost of corrosion in the agricultural production industry is in the range of $0.75 billion to $1.5 billion per year, with an average of $1.12 billion per year.

Corrosion control and prevention can be accomplished by keeping equipment clean and dry after each use, applying corrosion-resistant materials or materials with a corrosion allowance, applying external coatings (paints) or internal lining systems, or using cathodic protection. Strategies for maintaining and optimizing inspection programs for agricultural equipment (i.e., minimizing safety concerns for fertilizer tanks) with a high corrosion risk need to be developed. Development of new and improved inspection techniques is required to ensure the integrity of agricultural equipment.

Figure 24 shows the annual corrosion cost for the agricultural sector to be approximately 6 percent of the Production and Manufacturing category.

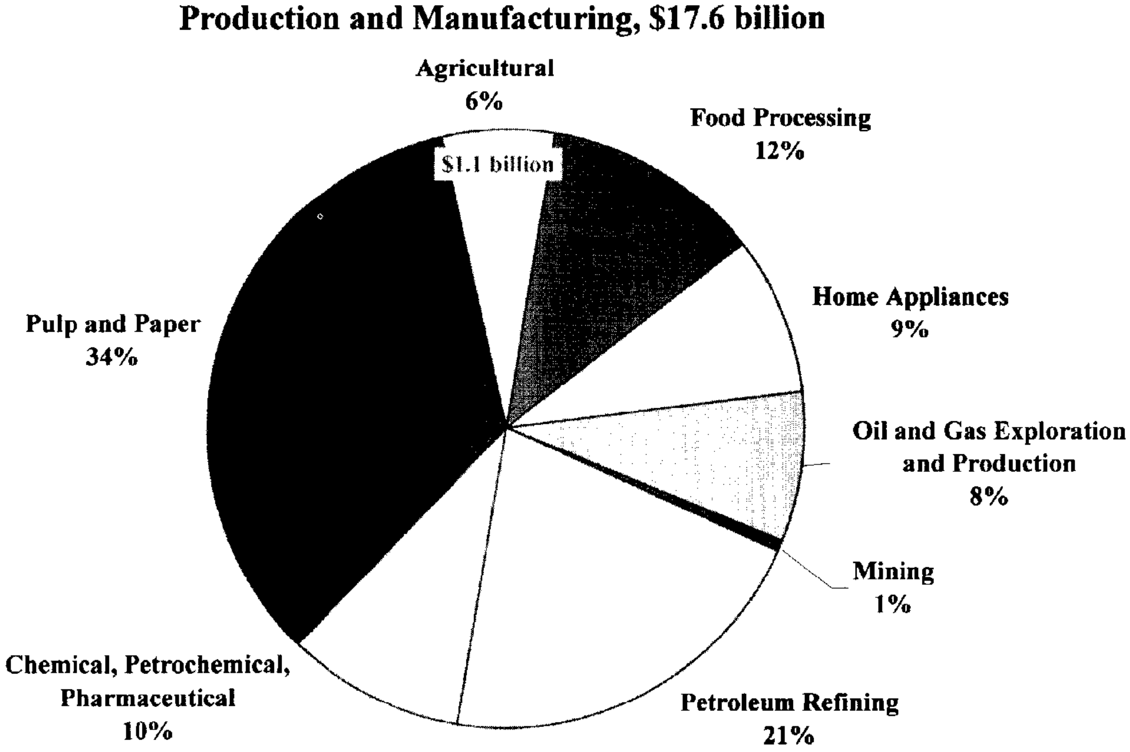


Figure 24. Annual cost of corrosion of the agricultural industry.

Food Processing (Appendix Y)

The food processing industry is one of the largest manufacturing sectors in the U.S. economy, accounting for approximately 14 percent of total U.S. manufacturing output.(68) According to composite statistics, sales for public food processing companies totaled $265.5 billion in 1999. Food processing equipment includes stoves, ranges, hoods, meat blocks, tables, counters, refrigerators, sinks, dishwashing machines, and steam tables.

Product quality, health, and sanitation issues are major concerns in the food processing industry. The industry cannot tolerate corrosion products (i.e., heavy metals) in the manufactured product. The industry, therefore, needs to account for corrosion control before production starts. The use of stainless steel in food processing is required for corrosion control and prevention. The total estimated cost of stainless steel for the food processing industry is $1.8 billion per year. This cost includes stainless steel used in beverage production, food machinery, cutlery and utensils, commercial and restaurant equipment, and appliances. The annual cost for aluminum cans is $250 million and the annual cost for corrosion inhibitors in the food processing industry is approximately $50 million. Therefore, the total estimated cost of corrosion in this sector is $2.1 billion per year. Figure 25 shows the annual corrosion cost for the food processing sector to be approximately 12 percent of the Production and Manufacturing category.

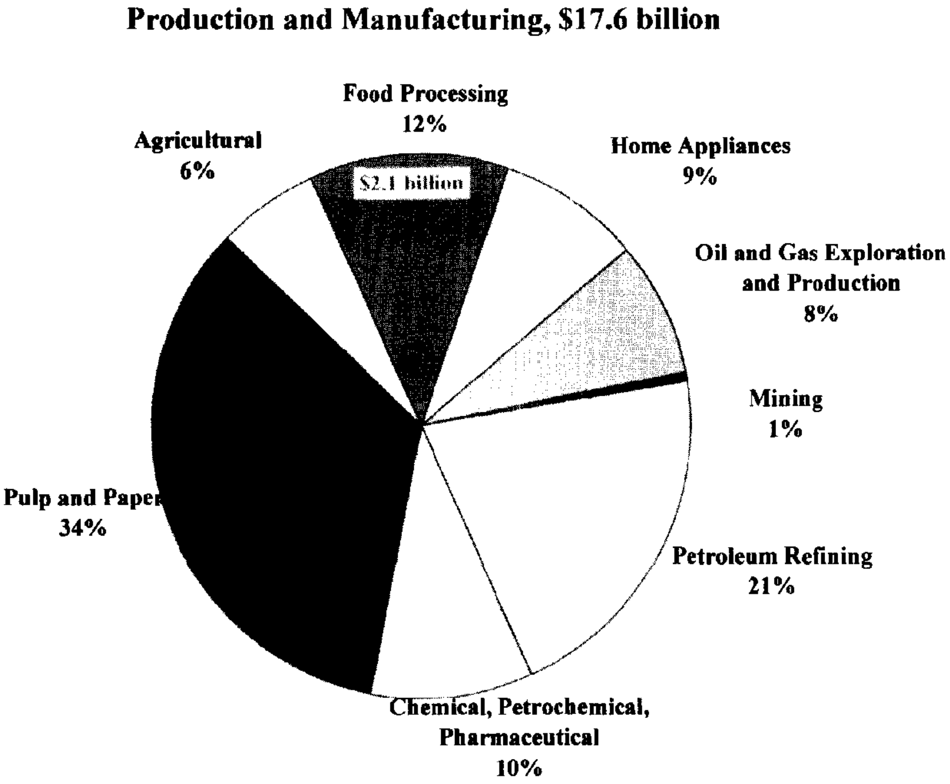
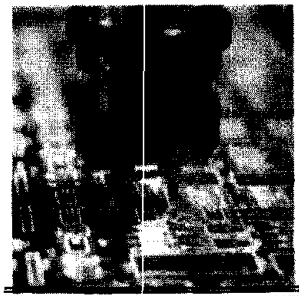


Figure 25. Annual cost of corrosion in the food processing industry.

Maintenance management systems are implemented in food processing plants to monitor machine production histories, downtime, and reliability to prioritize equipment and maintenance problems. Reliability-based maintenance (RBM) teams are used in conjunction with maintenance management systems to predict maintenance and root-cause analysis of food processing equipment failures. Strategic maintenance programs are part of the plant's overall vision of the future, which aims at boosting production efficiency.

Electronics (Appendix Z)



Corrosion in electronic components manifests itself in several ways. Computers, integrated circuits, and microchips are now an integral part of all technology-intensive industry products, ranging from aerospace and automotive to medical equipment and consumer products, and are therefore exposed to a variety of environmental conditions. Corrosion in electronic components are insidious and cannot be readily detected; therefore, when corrosion failure occurs, it is often dismissed as just a failure and the part or component is replaced.

Because of the difficulty of detecting and identifying corrosion failures, the cost of corrosion is difficult to determine. Arguably, in many instances, particularly in the case of consumer electronics, such devices would become technologically obsolete long before corrosion-induced failures. In addition, while corrosion-related user costs, due to irretrievable lost data, could be staggering, as the electronic information and data exchanges become more intensive, most sensitive information is frequently backed up. Capital-intensive industries with significant investments in durable equipment with a considerable number of electronic components, such as the defense industry and the airline industry, tend to keep the equipment for longer periods of time, and corrosion is likely to become an issue. Although the cost of corrosion in the electronics sector could not be estimated, it has been suggested that a significant part of all electric component failures are caused by corrosion.

Home Appliances (Appendix AA)

The appliance industry is one of the largest consumer product industries. For practical purposes, two categories of appliances are distinguished: Major Home Appliances and Comfort Conditioning Appliances. In 1999, a total of 70.7 million major home appliances and a total of 49.5 million comfort conditioning appliances were sold in the United States, for a total of 120.2 million appliances.

The average consumer buying an appliance is only marginally interested in corrosion issues; therefore, during the useful life of the appliance, no corrosion management is done by consumers. For example, very few people realize that there is an anode in every water heater, and that this sacrificial bar of metal should be checked and, if necessary, replaced with a new one, to prevent water heater failure due to internal corrosion. The life expectancy of appliances is determined from past experience and sales data. Improved corrosion design for appliances can increase their life expectancy. However, if improved corrosion protection would mean the use of more expensive components for the appliances, then consumers may not be interested.

A corrosion cost calculation was made for the sacrificial anodes in the 104 million water heaters in the United States. The benefits of anode maintenance are longer tank life, less rust buildup, and savings on costly changeovers. The increased life expectancy from anode maintenance can save money for consumers. However, a cost-benefit analysis may show that the cost of replacing anodes could exceed the benefits of increasing the life expectancy of water heaters. The annual cost of replacing water heaters was estimated at $460 million per year, the cost of anode replacement was estimated at $780 million per year, and a hypothetical design improvement that would increase the life expectancy of water heaters by 1 year was estimated to result in a savings of $778 million per year.

A corrosion cost calculation was also made for the annual coating costs of the 120.2 million newly purchased major appliances in the United States. Based on an estimated installed cost of coatings of $2 per appliance, the total cost is approximately $240 million per year. The cost of $2 is a marginal value in the average cost of appliances. Therefore, this cost is probably worth spending because of the more appealing appearance of non-corroding appliances. On the other hand, the internal components of appliances that are not directly visible to consumers should be protected from corrosion as well. For example, the above calculation does not consider the application of internal coatings, such as galvanizing steel, for a longer life.

The assumptions made in the anode calculations and the coating calculations are only approximations, and no adjustment is provided for the use of corrosion-resistant materials in most appliances. The calculations are probably not very accurate because of the great variety in appliances. Considering the great costs of appliances to consumers, and the fact that the potential savings from longer life expectancies can be considerable, it is recommended that a broad study, including a full analysis of statistical data, be performed to research the potential cost-savings related to increased life expectancies of appliances.

In summary, the cost of corrosion in home appliances is significant. The first cost is the purchase of replacement appliances because of premature failures due to corrosion. It is evident that water heater replacement is often attributed to corrosion. For water heaters alone, this cost was estimated at $460 million per year, using a low estimate of 5 percent of the replacements being corrosion-related. The cost of internal corrosion protection for all appliances includes the use of sacrificial anodes ($780 million per year), corrosion-resistant materials (no cost estimate), and internal coatings (no cost estimate). The cost of external corrosion protection using coatings was estimated at $260 million per year. Therefore, the estimated total annual cost of corrosion in home appliances is $1.5 billion per year ($460 million + $780 million + $260 million).

Figure 26 shows the annual corrosion cost for the home appliance sector to be approximately 9 percent of the Production and Manufacturing category.

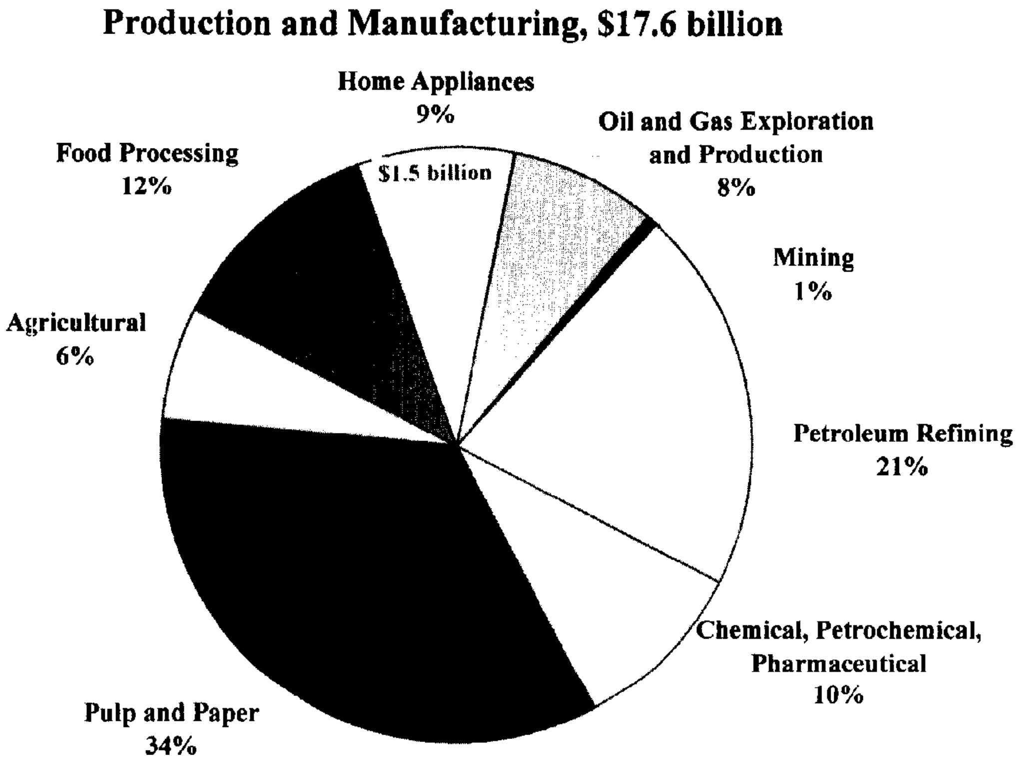


Figure 26. Annual cost of corrosion of the home appliance industry.

Government

Federal, state, and local governments play increasingly important roles in the U.S. economy, with a 1998 GDP of approximately $1.105 trillion. While the government owns and operates large assets under various departments, the U.S. Department of Defense (DOD) was selected because of its significant direct and indirect impact on the U.S. economy. A second government sector that was selected is nuclear waste storage under the U.S. Department of Energy (DOE). The cost of corrosion in these two sectors was used to estimate the cost of corrosion for the Government category. This cost was $20.1 billion per year, which is 14.6 percent of the corrosion costs for all sector categories (see figure 27).

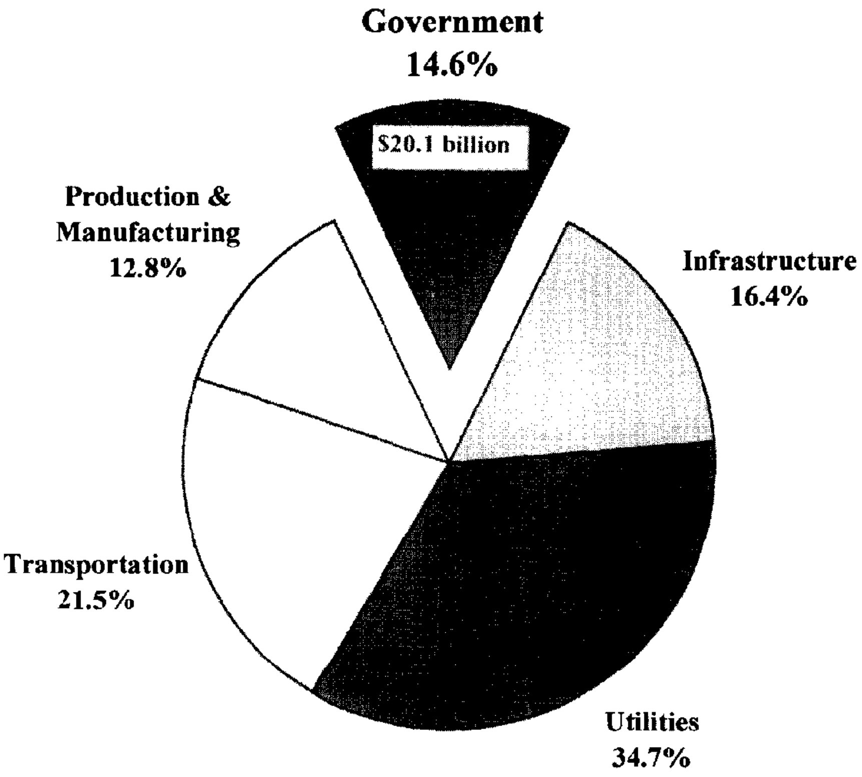
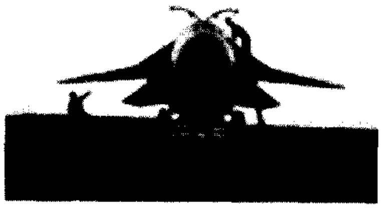


Figure 27. Annual cost of corrosion in the Government category.

Defense (Appendix BB)



The ability of the U.S. Department of Defense (DOD) to respond rapidly to national security and foreign commitments can be adversely affected by corrosion. Corrosion of military equipment and facilities has been, for many years, a significant and ongoing problem. The effects of corrosion are becoming more prominent as the acquisition of new equipment is slowing down and as the service of aging systems and equipment is becoming increasingly relied upon. The data provided by the military services (Army, Air Force, Navy, and Marine Corps) indicate that corrosion is the number one cost driver in life-cycle costs. The total annual cost of corrosion incurred by the military services for both systems and infrastructure was estimated at $20 billion.(69)

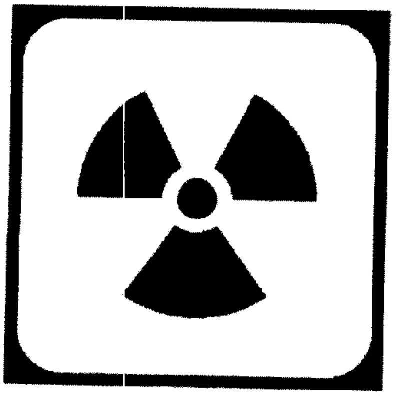
A considerable portion of the cost of corrosion to the Army is attributed to ground vehicles, including tank systems, fighting vehicle systems, fire support systems, high-mobility multipurpose wheeled vehicles (HMMWV), and light armored vehicles. Other systems that are affected by corrosion include firing platforms and helicopters. Many of the Army systems are well beyond their design service lives and because of generally aggressive operating environments, corrosion is becoming increasingly severe and costly. While often replacement of the aging systems is not budgeted, insufficient use is being made of existing technology to maintain these systems in a cost-effective manner. Even with the procurement of new equipment such as the HMMWV, the use of corrosion-resistant materials and design are often neglected in favor of quantity of procurement and system properties.

In recent years, the Air Force has experienced considerable corrosion problems. As with the commercial aircraft industry, corrosion on airframes in the past has not been considered to have a significant impact on structural integrity; therefore, a "find and fix" approach has long been the preferred way to deal with corrosion in aircraft. With no significant funding available for new system acquisition, the Air Force is forced to extend the operational life of many of the aircraft, such as the KC-135 tanker, far beyond their design service life.

Because of their missions, the Navy and the Marine Corps have always operated in corrosive marine environments. The Navy operates the fleet, as well as naval aircraft, and harbor and dock facilities. The fleet consists of various types of surface ships and submarines that are continuously exposed to marine environments. The primary defense against corrosion is the diligent use of protective coatings. In addition to protective coatings, cathodic protection systems are used for corrosion protection of the underwater hull. In recent years, cost-effective and durable paint systems have been introduced to replace what used to be very labor-intensive and inferior paint systems. Navy aircraft require constant maintenance due to operation in predominantly marine environments. As in the Air Force, many aircraft systems are operating beyond their design service life, which leads to an increase in the cost of corrosion maintenance.

The aging of military systems poses a unique challenge for maintenance and corrosion engineers in all four services. A most serious problem facing the military is aging equipment with no immediate promise of replacement. Therefore, there is a pressing need to develop corrosion maintenance programs that can carry the various aging systems well into the 21st century. Such a program requires cooperation between all the services and the commitment of system managers and maintenance personnel to succeed. In order to preserve the aging military assets, a DOD-wide corrosion control and maintenance plan must be developed and implemented. An important component of such a program is the gaining of awareness and recognition by all military personnel that corrosion is an important factor in the life, readiness, and integrity of all military systems. Courses and training will be needed to develop the knowledge to deal with corrosion. Funding needs to be made available to develop predictive corrosion models and new inspection and monitoring techniques that will enable system management to maintain their systems in a cost-effective manner.

Nuclear Waste Storage (Appendix CC)



Nuclear wastes are generated from spent nuclear fuel, dismantled nuclear weapons, and products such as radioactive pharmaceuticals. The most important design item for the safe storage of nuclear waste is the effective shielding of radiation and the prevention of leaking radioactive waste. In order to minimize the probability of nuclear exposure, special packaging is designed to meet the protection standards for temporary dry or wet storage, or for permanent underground storage. The most common materials of construction include steel and concrete. The wall thickness of the package is generally thick in comparison to the contained volume. Currently, nuclear waste is stored at temporary locations, including water basins in nuclear power plants and at dry locations above ground. Deep underground storage in Yucca Mountain, Nevada has been proposed as a permanent storage solution.

Corrosion is not considered a major issue in the transportation of nuclear wastes due to the stringent packaging requirements and the relatively short duration of the transport;(59) however, corrosion is an important issue in the design of the casks used for permanent storage, which have a design service life of several thousand years. In 1998, the Office of Civilian Radioactive Waste Management in DOE published an analysis of the total life-cycle cost for the permanent disposal of radioactive waste in Yucca Mountain, Nevada.(70) This analysis was based on the most current plans, strategies, and policies. The total estimated repository cost by the construction phase (2002) was estimated at $4.9 billion, with an average cost per year (from 1999 to year 2116) of $205 million. It is anticipated that about 20 percent of this annual cost, or $42 million, is corrosion-related.

Summary of Sector Studies

Table 7 shows the costs of corrosion for each industry sector analyzed in the current study. The dollar values are rounded to the nearest $0.1 billion because of the uncertainty in the applied methods. The total cost of corrosion in the analyzed sectors was $137.9 billion per year. Figure 28 shows the data in graphical form. The cost of $137.9 billion was believed to be a very conservative estimate. In each sector, only the "major" corrosion costs were considered. In addition, even major costs were left out when no basis for an estimate was found; most notable were: (1) no operation and maintenance costs were included for the Chemical, Petrochemical, and Pharmaceutical sector, (2) no capital costs were included for the Pulp and Paper sector, (3) no capital costs were included for the Gas and Distribution sector, and (4) replacement costs were considered only for water heaters in the Home Appliances sector. In most cases, conservative estimates were made when no basis was available; otherwise, most notable was that only 5 percent of water heaters are replaced due to corrosion. Therefore, the total cost of corrosion is a conservative value and is probably higher than that presented in this study.

Table 7. Summary of estimated direct cost of corrosion for industry sectors analyzed in this study.

CATEGORY	INDUSTRY SECTORS	APPENDIX	ESTIMATED DIRECT COST OF CORROSION PER SECTOR	
			$ x billion	**percent***
Infrastructure (16.4% of total)	Highway Bridges	D	8.3	37
	Gas and Liquid Transmission Pipelines	E	7.0	31
	Waterways and Ports	F	0.3	1
	Hazardous Materials Storage	G	7.0	31
	Airports	H	**	**
	Railroads	I	**	**
		SUBTOTAL	**$22.6**	**100%**
Utilities (34.7% of total)	Gas Distribution	J	5.0	10
	Drinking Water and Sewer Systems	K	36.0	75
	Electrical Utilities	L	6.9	14
	Telecommunications	M	**	**
		SUBTOTAL	**$47.9**	**100%**
Transportation (21.5% of total)	Motor Vehicles	N	23.4	79
	Ships	O	2.7	9
	Aircraft	P	2.2	7
	Railroad Cars	Q	0.5	2
	Hazardous Materials Transport	R	0.9	3
		SUBTOTAL	**$29.7**	**100%**
Production and Manufacturing (12.8% of total)	Oil and Gas Exploration and Production	S	1.4	8
	Mining	T	0.1	1
	Petroleum Refining	U	3.7	21
	Chemical, Petrochemical, Pharmaceutical	V	1.7	10
	Pulp and Paper	W	6.0	34
	Agricultural	X	1.1	6
	Food Processing	Y	2.1	12
	Electronics	Z	**	**
	Home Appliances	AA	1.5	9
		SUBTOTAL	**$17.6**	**100%**

Table 7. Summary of estimated direct cost of corrosion for industry sectors analyzed to this study (continued).

CATEGORY	INDUSTRY SECTORS	APPENDIX	ESTIMATED DIRECT COST OF CORROSION PER SECTOR	
			$ x billion	percent*
Government (14.6% of total)	Defense	BB	20.0	99.5
	Nuclear Waste Storage	CC	0.1	0.5
		SUBTOTAL	**$20.1**	**100%**
		TOTAL	**$137.9**	

*Individual values do not add up to 100% because of rounding.

**Corrosion costs not determined.

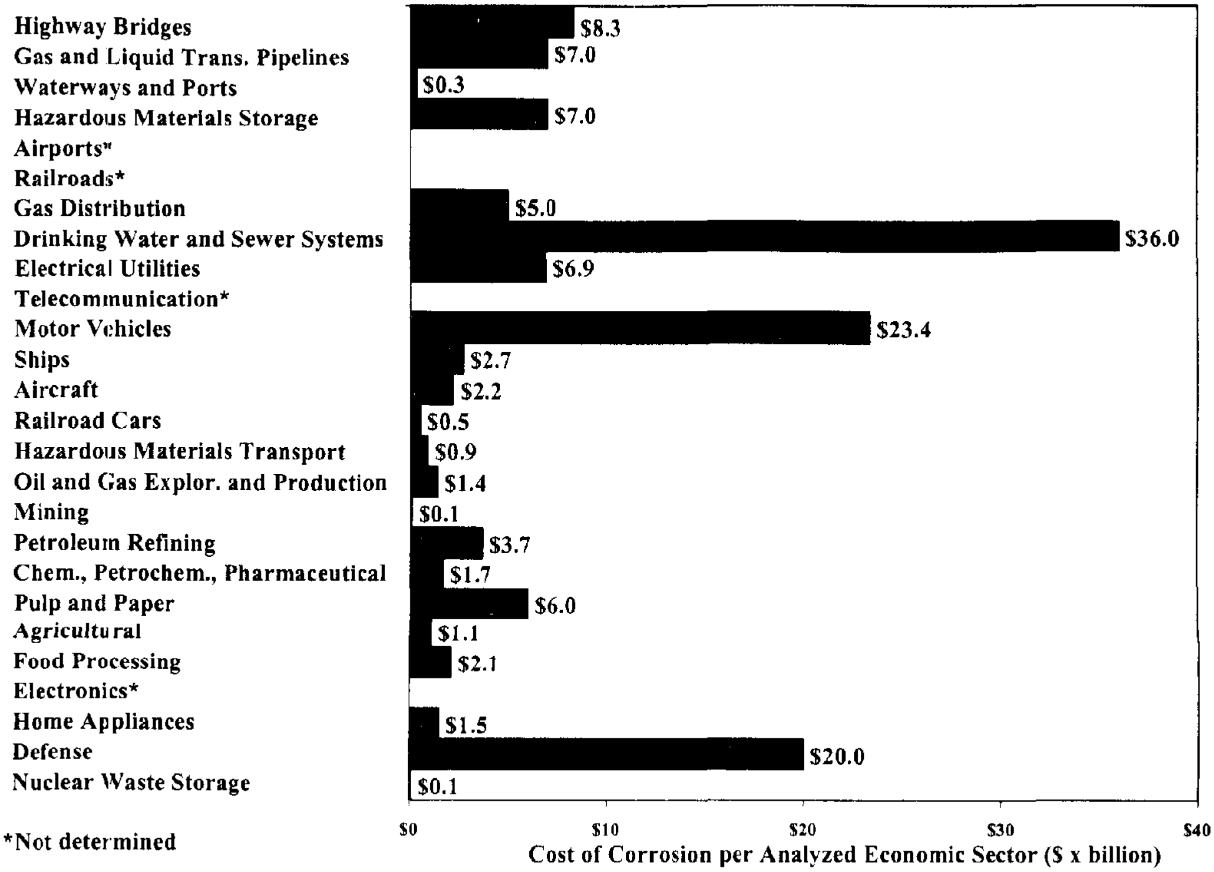


Figure 28. Summary of estimated direct cost of corrosion for industry sectors analyzed in this study.

These data show that the highest corrosion costs are incurred by drinking water and sewer systems. The largest value of $36.0 billion per year for both types of systems together is due to the extent of the water transmission and distribution network in the United States. For the U.S. population of 265 million people, an average of 550 L (145 gal) per person per day is used for personal use and for use in production and manufacturing. The metal piping systems are aging and will require increased maintenance in the future. For the drinking water sector, large indirect costs are expected as well, but are not quantified in the current study.

The second largest corrosion cost ($23.4 billion per year) was found in the motor vehicles sector. With more than 200 million registered vehicles, the corrosion impact consists of corrosion-related depreciation costs (62 percent), corrosion-resistant materials of construction (10 percent), and the cost of increased maintenance because of corrosion (28 percent). The indirect cost in this sector is expected to be large, especially because of the time users of motor vehicles lose when having to deal with car maintenance and repair.

The third largest corrosion cost ($20 billion per year) was observed in defense systems. Reliability and readiness are of crucial importance, and thus, military vehicles, aircraft, ships, weapons, and facilities must be continuously maintained. A determining factor in the defense sector is the readiness for operation under any circumstance and in corrosive environments such as seawater, swamps or wetlands, and in rain and mud.

Large corrosion costs were also found in the sectors for highway bridges ($8.3 billion per year), gas and liquid transmission pipelines ($7.0 billion per year), electrical utilities ($6.9 billion per year), pulp and paper ($6.0 billion per year), and gas distribution ($5.0 billion per year). There were two factors that were important for these sectors: (1) large number of units, and (2) severely corrosive environments. The following lists specific concerns regarding corrosion for some of the sectors that have large corrosion costs:

- The national system of highways requires many bridges to be maintained. With the commonly used approach that bridges are constructed to have a design life, rather than "being there forever," the burden to maintain and repair this infrastructure will continue to grow because of aging components.
- The network of transmission pipelines is quite large [779,000 km (484,000 mi)] and transports potentially corrosive liquids and gas, which makes their operation sensitive to public opinion related to environmental spills and highly publicized ruptures. Although pipelines have proven to be the safest way to transport large quantities of product over long distances, preventing corrosion costs is a significant cost.
- The same argument for potential spills (oil) holds for the hazardous materials storage sector. Corrosion protection is a significant cost per tank for both underground and aboveground tanks, and the total number of HAZMAT storage tanks is estimated at 8.5 million.
- Electrical utilities have large corrosion costs due to the effected operation and maintenance costs, depreciation costs, and the cost of forced outages. The greatest cost is found for nuclear power-generated plants, because of the higher inspection frequency in nuclear plants as opposed to fossil fuel plants.
- The pulp and paper industry uses corrosive media to make pulp from wood. Changes in processing conditions over the last decades have had a significant impact on the materials used for construction. Paper quality and processing reliability are driving spending in this sector.

In the following discussion, the individual sector analyses will be extrapolated to calculate total corrosion costs in the United States.

DISCUSSION

Extrapolation to Total Cost of Corrosion

Since not all BEA industry categories were examined, the sum of the estimated direct corrosion costs of the analyzed industry sectors does not represent the total cost of corrosion in the entire U.S. economy. Table 8 shows how the corrosion costs of the analyzed sectors are distributed over the BEA categories and how the extrapolation was executed to calculate the total cost of corrosion in the United States.

The impact of corrosion (total direct cost) showed large differences between the BEA industry categories (see figure 29a). The largest impact is for the Transportation and Utilities, and Manufacturing. Construction is large as well because it is extrapolated assuming the same corrosion impact as Transportation and Utilities. If the direct corrosion costs are expressed as a percentage of the GDP of the BEA industry category, the relative impact can be shown (see figure 29b). The largest relative impact (in percent) is seen for the Transportation and Utilities, Construction, Federal Government, and Manufacturing BEA categories.

Table 8. Extrapolation of the direct cost of corrosion from analyzed industry sectors to the 1998 U.S. GDP for BEA industry categories.

BEA Categories	BEA Subcategories	Appendix	Sector Name	Detailed GDP	Covered GDP	Non-Covered GDP	Cost of Corrosion per Sector	Cost of Corrosion for Covered Sectors	Corrosion Fraction of GDP	Extrapolated Cost of Corrosion
				$ x billion	$ x billion	$ x billion	$ x billion	$ x billion	%	$ x billion
Agricultural, Forestry, and Fishing	Farms, agricultural services	X	Agricultural	127.3	127.3		1.1	1.1	0.86%	1.1
Mining	Metal, coal, and non-metallic minerals	T	Mining	28.2	105.6		0.1	1.5	1.42%	1.5
	Oil and gas extraction	S	Oil and Gas Exploration and Production	77.4			1.4			
Manufacturing	Motor vehicles and equipment	72% of N (*)	Motor Vehicles	107.2	663.2		16.9	38.9	5.87%	38.9
	Miscellaneous manufacturing industries	AA	Home Appliances	25.7			1.5			
	Food and kindred products	Y	Food Processing	124.8			2.1			
	Paper and allied products	W	Pulp and Paper	55.1			6.0			
	Printing and publishing			94.0						
	Chemicals and allied products	G	Hazardous Materials Storage	168.4			7.0			
		87.5% of V (**)	Chemical, Petrochemical, Pharmaceutical				1.5			
	Rubber and miscellaneous plastics products	12.5% of V (**)	Chemical, Petrochemical, Pharmaceutical	55.1			0.2			
	Petroleum and coal products	U	Petroleum Refining	32.9			3.7			
	Electronics and other electric equipment	Z (****)	Electronics	172.8		772.7	No estimate made	-	Same as in analyzed sectors: 5.87%	45.3
	Lumber wood products	-	-	41.4			-			
	Furniture and fixtures	-	-	24.1						
	Stone, clay, and glass products	-	-	38.2						
	Primary metals industry	-	-	54.1						
	Fabricated metals products	-	-	102.2						
	Industrial machining and equipment	-	-	150.8						
	Other transportation equipment	-	-	59.2						
	Instruments and related products	-	-	57.7						
	Tobacco products	-	-	16.8						
	Textile mill products	-	-	25.4						
	Apparel and other textile products	-	-	25.8						
	Leather and leather goods	-	-	4.2						

Table 8. Extrapolation of the direct cost of corrosion from analyzed industry sectors to the 1998 U.S. GDP for BEA industry categories (continued).

BEA Categories	BEA Subcategories	Appendix	Sector Name	Detailed GDP	Covered GDP	Non-Covered GDP	Cost of Corrosion per Sector	Cost of Corrosion for Covered Sectors	Corrosion Fraction of GDP	Extrapolated Cost of Corrosion
				$ x billion	$ x billion	$ x billion	$ x billion	$ x billion	%	$ x billion
Transportation and Utilities	Trucking and warehousing	R	Hazardous Materials Transport	109.3	465.3		0.9	61.5	13.22%	61.5
	Railroad transportation	Q	Railroad Cars	41.6			0.5			
		I	Railroads				No estimate made			
	Local and interurban passenger transit									
	Water transportation	O	Ships	14.1			2.7			
		F	Waterways and Ports				0.3			
	Transportation by air	P	Aircraft	88.2			2.2			
		H	Airports				No estimate made			
	Pipelines, except natural gas	68% of E (***)	Gas and Liquid Transmission Pipelines	6.1			4.8			
	Electric, Gas, and Sanitary Services	32% of E (***)	Gas and Liquid Transmission Pipelines	206.0			2.2			
		J	Gas Distribution				5.0			
		K	Drinking Water and Sewer Systems				36.0			
		L	Electrical Utilities				6.9			
	Communications, inc. telephone, radio, TV	M (****)	Telecommunications	234.1		262.6	No estimate made	-	Same as in analyzed sectors: 13.22%	34.7
	Transportation services	-	-	28.5			-			
Services	Auto repair services and parking	28% of N (*)	Motor Vehicles	80.9	80.9		6.5	6.5	8.03%	6.5
	Miscellaneous repair services	-	-	24.5		24.5	-	-	Same as in analyzed sector: 8.03%	2.0
	Amusement and recreation	-	-	72.2		72.2	-	-		5.8
	Hotels and other lodging places	-	-	76.0		1,659.6	-	-	0.0%	0
	Personal services	-	-	55.4						
	Business services	-	-	447.1						
	Motion pictures	-	-	28.8						
	Health services	-	-	492.6						
	Legal services	-	-	116.4						
	Educational services	-	-	66.7						
	Social services	-	-	57.1						
	Membership organizations	-	-	54.0						
	Other services	-	-	251.5						
	Private households	-	-	14.0						

Table 8. Extrapolation of the direct cost of corrosion from analyzed industry sectors to the 1998 U.S. GDP for BEA industry categories (continued).

BEA Categories	BEA Subcategories	Appendix	Sector Name	Detailed GDP	Covered GDP	Non-Covered GDP	Cost of Corrosion per Sector	Cost of Corrosion for Covered Sectors	Corrosion Fraction of GDP	Extrapolated Cost of Corrosion
				$ x billion	$ x billion	$ x billion	$ x billion	$ x billion	%	$ x billion
Construction	Construction	-	-	378.1		378.1	-	-	Same as in Utilities Category: 13.22%	50.0
Wholesale Trade	Wholesale trade	-	-	610.9		610.9	-	-	0.0%	0
Retail Trade	Retail trade	-	-	796.8		796.8	-	-	0.0%	0
Finance, Insurance, and Real Estate	Finance, insurance, and real estate	-	-	1,689.4		1,689.4	-	-	0.0%	0
Statistical Discrepancy	Statistical discrepancy	-	-	-24.8		-24.8	-	-	0.0%	0
Federal	Federal general government	BB	Defense	298.6	298.6	-	20.0	20.0	6.70%	20.1
		CC	Nuclear Waste Storage				0.1	0.1		
	Federal government enterprises	-	-	62.1		62.1	-	-	0.0%	0
State and Local	State and local general government	DD	Highway Bridges	680.7	680.7		8.3	8.3	1.22%	8.3
	State and local government enterprises	-	-	64.4		64.4	-	-	0.0%	0
				TOTAL GDP	**Covered GDP**	**Non-Covered GDP**	**TOTAL**	**TOTAL in Sectors That Were Analyzed**		**TOTAL in U.S. Economy**
				$8,790.1	**$2,421.6**	**$6,368.5**	**$137.9**	**$137.9**		**$275.57**
					27.55%	**72.45%**				**3.1% of GDP**

*Based on the estimated cost of corrosion of motor vehicles found in the sector analysis, 72% is assigned to Manufacturing Motor Vehicles and Equipment, while 28% is assigned to Auto Repair Services and Parking.

**12.5% of the total value of shipments in the Chemical, Petrochemical, and Pharmaceutical industry is for Plastics Material and Resin Manufacturing (11.0%) and Synthetic Rubber Manufacturing (1.5%).

***Based on the mileage of transmission and gathering pipelines (328,000 km for gas and 154,000 km for oil), 32% of the corrosion costs of transmission pipelines is assigned to liquid lines, and 68% to gas lines.

****Placed in non-covered GDP, because the sector analysis for Electronics and for Telecommunications resulted in "no estimate made."

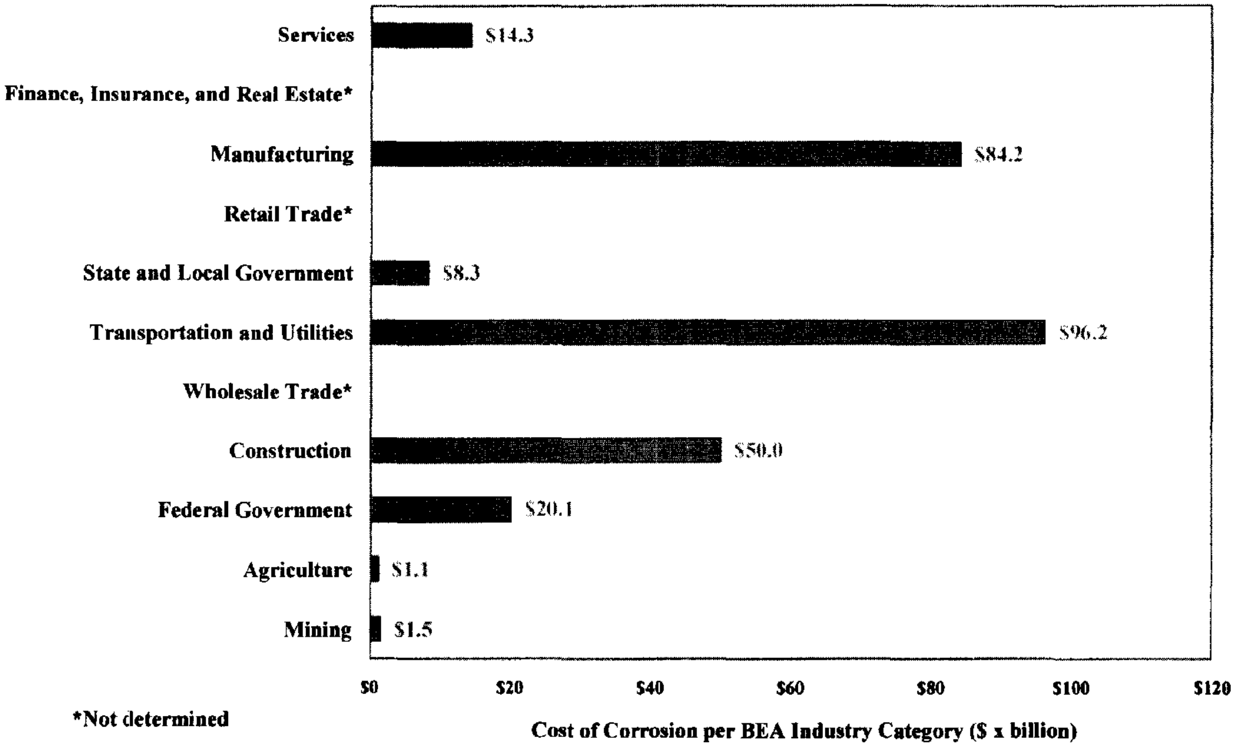


Figure 29a. Direct corrosion costs per BEA industry category.

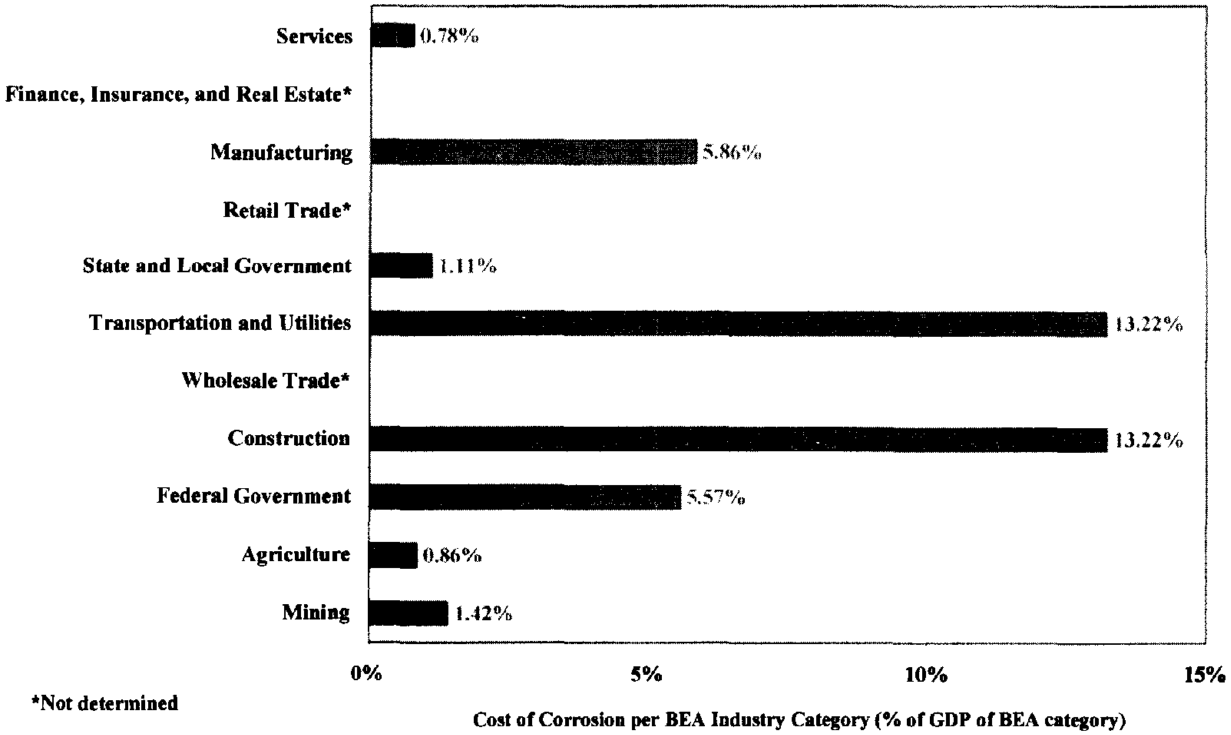


Figure 29b. Corrosion costs as a percentage of GDP per BEA industry category.

The total cost of corrosion in the analyzed sectors was $137.9 billion per year. This estimate was based on detailed analysis of industrial sectors that are known to have a significant corrosion impact. The sum of these sectors represented 27.55 percent of the GDP. Based on the procedure for extrapolation, which used the percentage of cost of corrosion for BEA subcategories, an estimated total direct cost of corrosion of $275.7 billion per year was calculated. This is 3.1 percent of the 1998 U.S. GDP.

Figure 30 illustrates the impact of corrosion on the nation's economy. The purpose of this figure is to show the relative corrosion impact (3.1 percent) with respect to the total GDP. In fact, corrosion costs are as great as or greater than some of the individual categories, such as agriculture and mining.

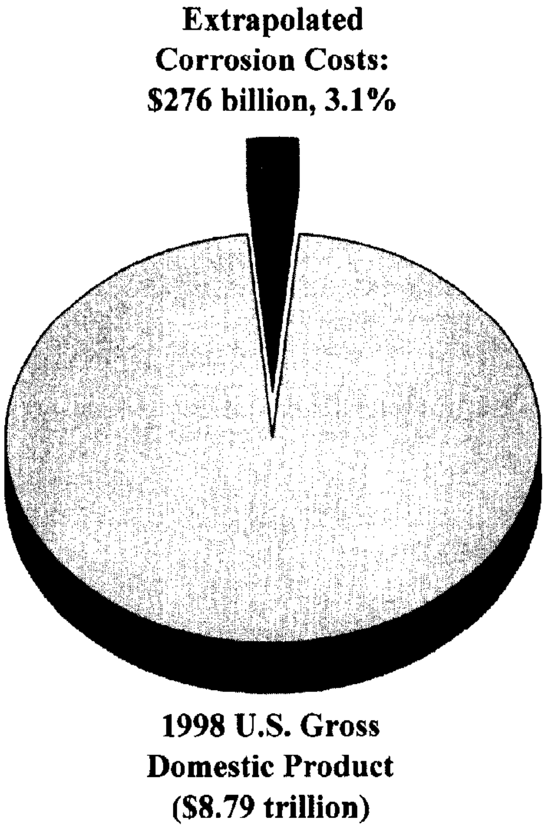


Figure 30. Diagram illustrating the impact of corrosion on the U.S. economy.

It must be noted that a straight, linear extrapolation is not recommended because of the expected lower overall corrosion impact in some of the non-analyzed sectors (i.e., Wholesale Trade, Retail Trade, and Finance, Insurance, and Real Estate). If one would proceed with the linear extrapolation, the $137.9 billion for 27.55 percent of GDP would result in an estimate of total annual direct corrosion cost of $500.5 billion per year (5.8 percent of GDP) (see figure 31). However, a doubling of the extrapolated direct costs may be justified if indirect costs would be taken into account.

In comparison, the non-linear extrapolation shows a stepwise, cumulative calculation for total corrosion cost. Table 9 shows a summary of the partial and cumulative fractions of the GDP for different industry categories, and the corrosion cost that was analyzed and/or extrapolated for each. Figure 32 shows the non-linear extrapolation graphically, and figure 33 shows the corrosion cost per BEA category.

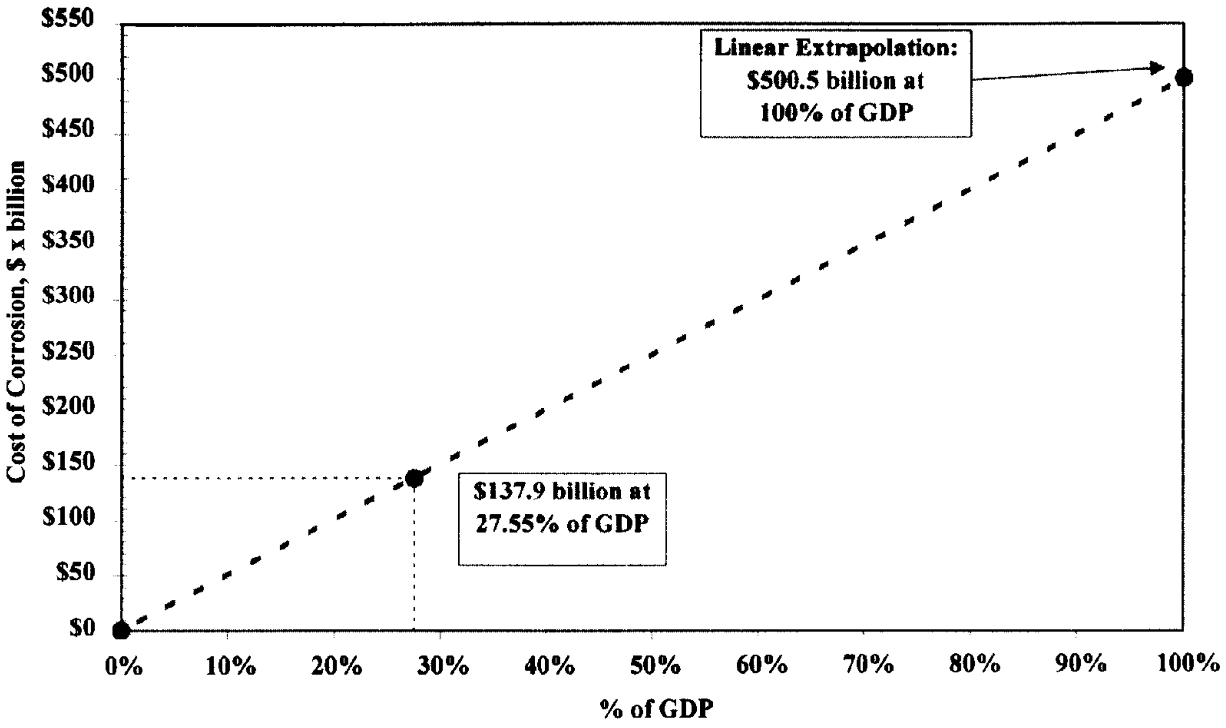


Figure 31. Illustration of linear extrapolation of cost of corrosion based on the assumption that non-analyzed sectors have a corrosion impact that is identical to the analyzed sectors.

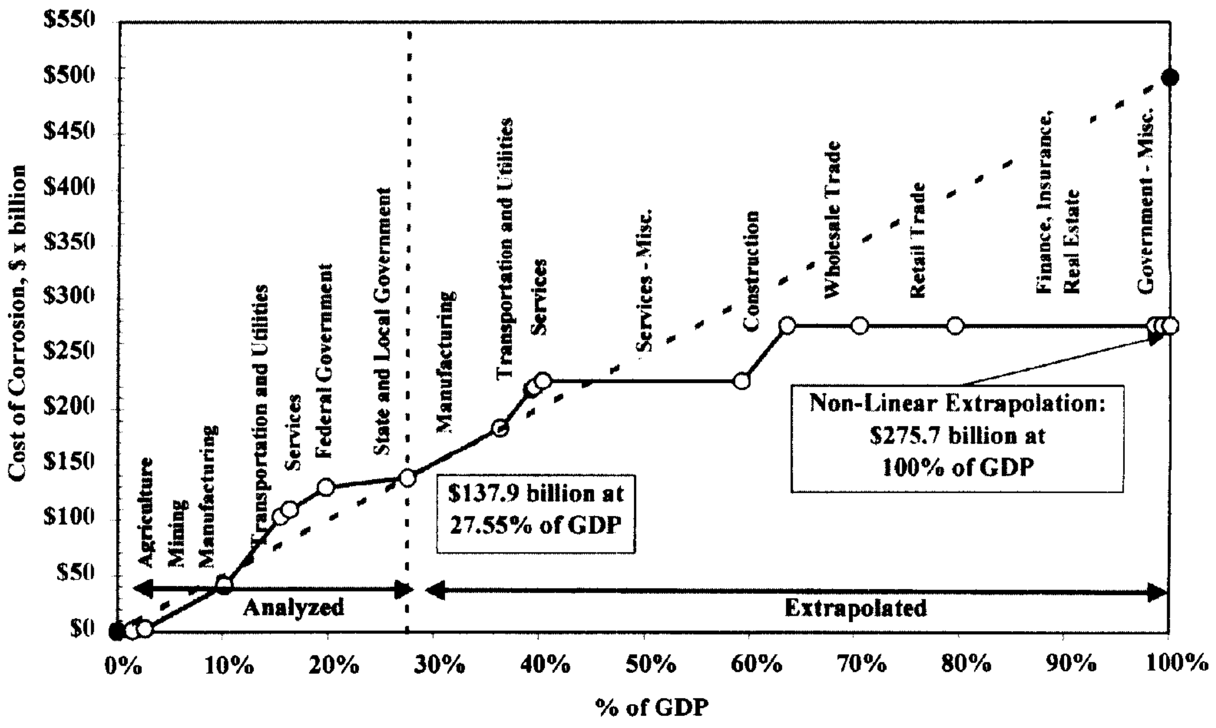


Figure 32. Illustration of non-linear extrapolation of cost of corrosion based on assumption that non-analyzed sectors have a different corrosion impact, depending on industry category.

Table 9. Schematic for non-linear extrapolation graph.

		GDP	**GDP**	**Corrosion Cost**	**Cumulative GDP**	**Cumulative Corrosion Cost**
		$ x billion	**%**	**$ x billion**	**%**	**$ x billion**
ANALYZED	Agricultural, Forestry, and Fishing	127.3	1.448	1.1	1.45	1.1
	Mining	105.6	1.201	1.5	2.65	2.6
	Manufacturing	663.2	7.545	38.9	10.19	41.5
	Transportation and Utilities	465.3	5.293	61.5	15.49	103.0
	Services	80.9	0.920	6.5	16.41	109.5
	Federal Government	298.6	3.397	20.1	19.81	129.6
	State and Local Government	680.7	7.744	8.3	27.55	137.9
EXTRAPOLATED	Manufacturing	772.7	8.791	45.3	36.34	183.2
	Transportation and Utilities	262.6	2.987	34.7	39.33	217.9
	Services - Misc. Repair	24.5	0.279	2.0	39.61	219.9
	Services - Amusement and Recreation	72.2	0.821	5.8	40.43	225.7
	Services - Other	1,659.6	18.880	-	59.31	225.7
	Construction	378.1	4.301	50.0	63.61	275.7
	Wholesale Trade	610.9	6.950	-	70.56	275.7
	Retail Trade	796.8	9.065	-	79.62	275.7
	Finance, Insurance, and Real Estate	1,689.4	19.219	-	98.84	275.7
	Statistical Discrepancy	- 24.8	- 0.282	-	98.56	275.7
	Federal Government	62.1	0.706	-	99.27	275.7
	State and Local Government	64.4	0.733	-	100.00	275.7
	TOTAL	**$8,790.1**	**TOTAL**	**$275.7**		

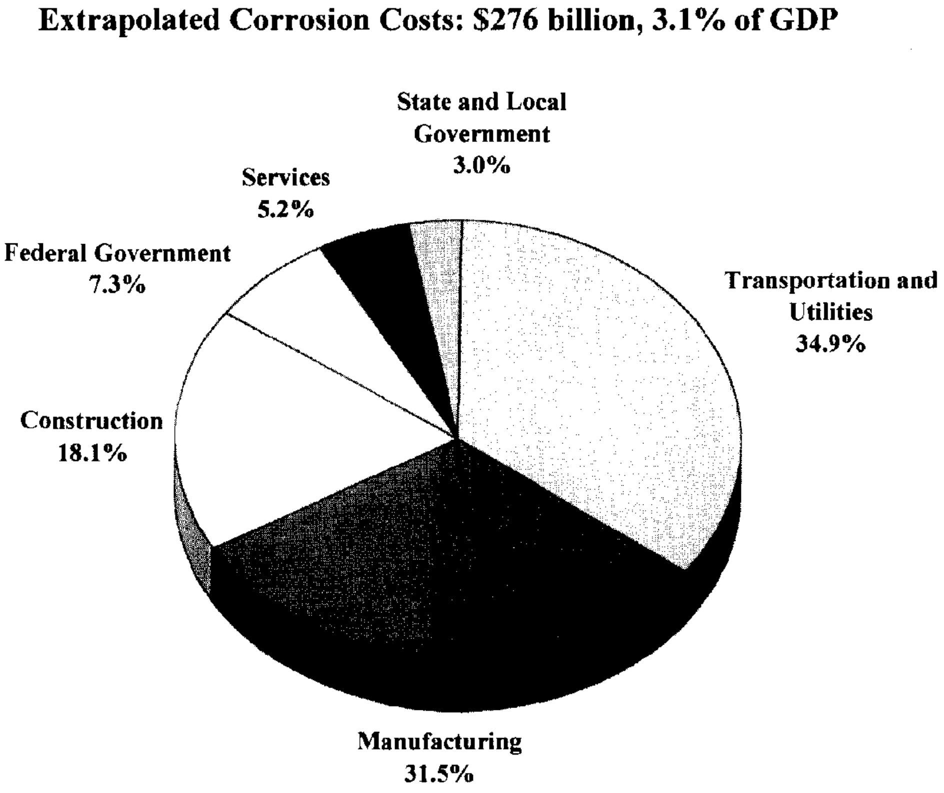


Figure 33. Total direct corrosion costs for BEA categories.

The direct corrosion costs were estimated based on direct costs to the owners or operators. The indirect costs incurred by other than owners or operators were not included in the cost estimates. Definitions of direct and indirect costs are given in "Economic Analysis" (Appendix C). For one particular economic sector, i.e. Highway Bridges (Appendix D), an attempt was made to estimate the indirect costs to users of bridges. An analysis of the indirect cost for bridges indicated that the indirect cost due to traffic congestion during repairs, resulting in lost productivity, can be 10 times or more greater than the direct bridge cost of corrosion. Analysis of electrical utilities indicated that the indirect costs (taxes and overhead costs to the user) were 1.7 times the direct cost to the utility owner/operator.

At 3.1 percent of the GDP, the cost of corrosion to the U.S. economy is already significant if only based on the direct cost of corrosion. However, the impact of corrosion can be significantly greater when indirect costs are included. The assumption can be made that the indirect costs over the entire industry can be equal to, if not greater than, the direct costs. This would result in a total direct and indirect impact of corrosion of approximately $551.4 billion annually, or 6.3 percent of the GDP (see figure 34).

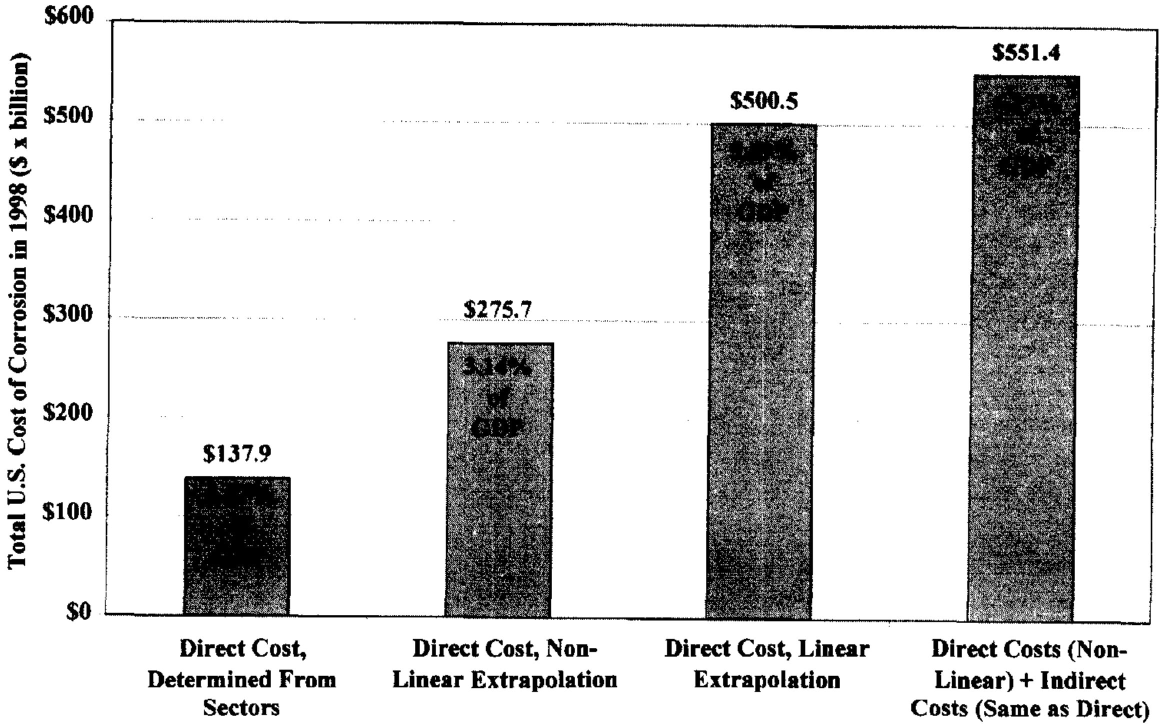


Figure 34. Comparison of methods to determine total U.S. cost of corrosion.

Comparing the total impact of corrosion (direct costs + indirect costs), based on the extrapolated values from the industry sector costs ($551.4 billion per year) to the cost of products and services used for corrosion control methods ($121 billion), shows a considerable difference in cost. This difference can be explained by the fact that in the latter estimation, only materials and outside services are included. As demonstrated, a large portion of the cost of corrosion is owner/operator corrosion management (not included in "outside services") and indirect costs.

In the above analysis, a best effort was made to extrapolate without bias, so that neither a high nor a low cost number would be achieved. However, it was decided to err on the conservative (low) side of the cost of corrosion when estimating sector costs. The following provides specifics on the justification for the extrapolations made in this study:

- The sectors for Electronics and Telecommunications were arranged under the non-covered portion of the GDP, because the sector analyses resulted in "no estimate made." The average percentage for Manufacturing was applied to extrapolate for Electronics and the average percentage for Transportation and Utilities was applied to extrapolate for Telecommunications.
- The data from the analyzed sectors showed that it is justified to assign more weight (larger percentage) to the economic categories of Transportation and Utilities (13.22 percent), Manufacturing (5.87 percent), and Repair Services (8.03 percent) than to other categories. For Manufacturing, sectors totaling $663.2 billion were analyzed in detail and extrapolated to the non-analyzed $772.7 billion in this category. For Services, no other data were available than the coarse estimate of 28 percent of the motor vehicles cost under Auto Repair Services and Parking. It was judged that Miscellaneous Repair Services and Amusement and Recreation may have the same impact (8.03 percent); therefore, those two categories were extrapolated, while the corrosion impact in the other Services was assumed to be zero.

- Identifying corroding components in sectors related to Wholesale Trade, Retail Trade, and Finance, Insurance, and Real Estate is difficult. In these categories with low corrosion impact (no large capital investments in equipment and buildings that could be susceptible to corrosion), the cost of corrosion was estimated to be zero. The same reasoning was used for the category of Government (non-defense).
- The BEA industry category Construction was extrapolated using the average percentage determined for Transportation and Utilities. This category did not have an analyzed industry sector. However, it was judged that the methods used to protect buildings from corrosion are also used to protect buildings in power plants, airports, railroads, pipelines, drinking water, sewage, and natural gas.
- It was considered that categories such as Real Estate (for example, buildings in marine environments, corrosion of parking garages, and corrosion of metallic siding) could possibly be underestimated. After evaluating this issue, it was found that this would not be significant, because Real Estate was listed in the BEA category under Finance, Insurance and Real Estate. This can be interpreted to address the economical process of buying and selling real estate. The extrapolation of Construction, using the average percentage for Transportation and Utilities, is intended to include corrosion concerns in buildings and structures, for both new construction and existing structures.
- In the category Government no other corrosion impact was identified other than Defense and Nuclear Waste Storage. One could suggest that a significant corrosion impact would have been overlooked for the large number of government installations and buildings, and for government vehicles (for example, postal service and police cars). However, all of these items are considered to be covered sufficiently under Construction (extrapolated to be $50.0 billion in table 8) and Motor Vehicles.
- In the current research, no extrapolation was made for Wholesale Trade and Retail Trade. Only if it would be assumed that large additional inventory would be kept to replace corroded items, then a cost of corrosion could be assigned. However, in today's business environment, companies keep minimum inventory and work with the shortest possible lead-time for ordering parts. It is known that the quantities of replacement equipment that are held in inventory have decreased during the last decades. Therefore, no large corrosion cost is expected for inventory. It is possible that the cost of lost time during the procurement of replacements is significant, but that cost was not quantified in the current study. Because of the absence of detailed data and the expected low corrosion cost, it was judged that assigning zero corrosion cost would be reasonable.

Summary of Total Cost of Corrosion Calculation

The research presented in this report showed that the direct cost of corrosion in the United States was approximately $275.7 billion per year, which is 3.1 percent of the GDP. The industrial areas with major corrosion impact are the transportation and utilities industry; the manufacturing industry; and federal, state and local governments. This percentage lies in the range that previous studies for various countries showed in the past. However, the current study was more detailed and specified corrosion costs using two methods: (1) cost of corrosion control methods and services, and (2) corrosion costs in individual industrial sectors. It is estimated that the indirect cost to the end user can double the economic impact, making the cost of corrosion, including indirect costs, $551.4 billion or more.

Of the corrosion control methods, paints and corrosion-control coatings make up the largest portion. Other commonly used methods include the use of corrosion-resistant metals and alloys, the application of cathodic and anodic protection, the use of corrosion inhibitors, and the use of polymers. The cost of corrosion-related services was estimated to be small.

The aging infrastructure of drinking water and sewer systems is critical, a large cost is incurred in the corrosion-related depreciation of motor vehicles, and large costs are incurred for corrosion prevention maintenance of critical defense equipment and vehicles. Highway bridges have large and increasing costs because of the aging and expanding highway network. Gas and liquid transmission pipelines and natural gas distribution pipelines have large corrosion costs because of environmental and safety considerations. A large corrosion cost is related to aboveground and underground storage tanks for hazardous materials. Exterior and interior coatings, and cathodic and anodic protection systems make up a significant portion of tank costs, and maintenance and repair of the large number of tanks are expensive as well. The electrical utilities incur corrosion-related costs in operation and maintenance, depreciation, and forced outages. The pulp and paper industry has significant corrosion costs because of the environments used in the pulping processes and the restrictions on the use of chemicals and water.

Other industrial sectors were found to have significant corrosion cost as well. Ships and aircraft require regular corrosion-related maintenance. The oil and gas industry has significant costs for exploration and production, and the petroleum refining portions of their businesses, and for the previously mentioned pipelines. Various manufacturing industries have corrosion costs, which are mostly related to the reliability and quality of the production process. Forced outages must be prevented by the application of corrosion protection systems and the use of preventive inspection and maintenance.

CONCLUSIONS

Preventive Strategies, Barriers, and Recommendations (Appendix DD)

The nation's infrastructure is essential to the quality of life, industrial productivity, international competitiveness, and security. Everything depends upon a functional, reliable, and safe infrastructure system, including food, water, and energy needs; transportation for work; education and recreation; the production and delivery of goods and services; communications; and the treatment and disposal of wastes. Each component of the nation's infrastructure, such as highways, airports, water supply, waste treatment, energy supply, and power generation, represents a complex system and significant investments.

Corrosion is damage that results from the interaction of structures and materials with their environment. In some cases, corrosion damage is tolerable and perhaps only leads to somewhat higher maintenance costs and minimal losses; however, corrosion can result in catastrophic failures with loss of life and disruption of essential services. In fact, corrosion is a primary cause of degradation and a principal threat to the nation's infrastructure. As documented in this report, the direct costs of corrosion represent 3.2 percent of the U.S. GDP, and the total costs to society can be twice that or greater. The infrastructure replacement cost is a major driver in the economic impact of corrosion and can be greater still if corrosion prevention strategies are not properly employed. The opportunities for savings through improved corrosion control are presented in every industrial sector and can be significant.

The principal challenges in realizing the significant savings that result from improved corrosion control include an unfortunate lack of awareness of corrosion costs by the public and policy-makers, and a widely held misconception that nothing can be done about corrosion. The opportunities and the challenges for better corrosion control fall into two categories: First, there are technical issues for the realization of technological advances and the implementation of those advances. Second, there are non-technical issues of perception regarding the policies and the practices used for improved corrosion control. Strategies are presented for progress in both categories.

There is an increasing recognition and a growing shift in emphasis from the building of a new infrastructure to the preservation and extended use of existing infrastructure. In *Connecting America – 1999 Report to the Nation*,(71) the Federal Highway Administrator noted that FHWA has shifted focus from constructing new highways to preserving and operating existing highways. Increased capacity, greater safety, and a longer life are desired from the existing infrastructure. The critical need for progress in preservation and extended use is also pertinent to the "invisible" infrastructure (i.e., those components of the infrastructure that are not recognized by the public and whose performance is taken for granted until a failure or loss of service occurs). This "invisible" infrastructure includes items such as water mains, gas and oil pipelines, power plants, and telecommunications systems.

The preservation and the extension of the useful life of existing infrastructure is a great challenge because of the long lives that are desired. The operating life of critical components of the infrastructure is often extended well beyond the original design service life. For instance, the Brooklyn Bridge was constructed in 1883. Furthermore, there are cast-iron water mains that were constructed in the early 1900s and remain in service today. These water mains continue to be a critical component for the municipal water supplies even after nearly 100 years of use.

While the focus may recently have shifted from building a new infrastructure to the preservation and extended use of the existing infrastructure, the necessary changes in public attitudes; adjustments to the allocation of resources; changes to the industrial, government, and academic institutions; and revisions to policies, practices, and procedures have only just begun. The adjustments made to date do not adequately address the needs and opportunities. There are great opportunities for increased integrity, durability, and savings; however, both systemic and programmatic corrections are required so that these benefits can be realized.

In the remainder of this section, the opportunities for improved corrosion prevention and control for increased integrity, durability, and savings are presented. Barriers to progress and the effective implementation of improved corrosion control and prevention are identified, and implementation strategies are recommended.

Preventive Strategies

Prior studies, as well as the current study of the costs of corrosion, have found that there are significant opportunities for major savings across the entire economy and within a wide range of industrial sectors. Opportunities for the U.S. infrastructure were emphasized in this study.

It is widely recognized that there is a significant annual shortfall between investment requirements and available revenues for improvement of our public works infrastructure. The issue is addressed in *Infrastructure for the 21st Century*, a report of the Committee on Infrastructure Innovation, National Research Council, 1987.(72) A framework for a research agenda for the technological improvement of the nation's infrastructure is presented. This study provides a solid underpinning for the current work on the impact of corrosion.

Improved corrosion control and management practices address the critical issue of our nation's aging infrastructure and the crucial shortfall between investment requirements and available revenues. There are cost-effective corrosion management procedures that significantly extend the service life of existing systems and reduce new construction and replacement requirements. Unfortunately, these preventive strategies often have not been recognized and applied. Examples are presented in the sector studies for cast-iron water mains in municipal water systems, underground storage tanks, and gas transmission pipelines. In addition, advanced design practices for better corrosion management can extend the service life and reduce total life-cycle costs. Examples are presented in the sector studies for highway bridges and for a major procurement of military (HMMWV) vehicles.

The large corrosion costs and the potential for savings provide opportunities for government, industry, and academia. Government and industry can reduce their costs from the direct impact of corrosion. This study has estimated that the indirect costs of corrosion are equal to or greater than the direct costs (up to 10 times greater for the life-cycle cost of bridges when loss of productivity due to traffic delays is considered) affecting government, industry, and the public. Advanced technology comes from the research and development efforts of the government, industry, and university laboratories. There are opportunities for focused studies and cross-disciplinary, collaborative work.

Preventive Strategies in Non-Technical Areas

Changes in non-technical areas are crucial to many corrosion cost-savings opportunities. Policy and management practices set the framework for the decision-making and the resource allocations that ultimately favor or restrict the effective implementation of sound corrosion management. Progress is required in the following areas:

1. Increase awareness of the significant corrosion costs and potential savings.
2. Change the misconception that nothing can be done about corrosion.
3. Change policies, regulations, standards, and management practices to increase corrosion cost-savings through sound corrosion management.
4. Improve education and training of staff in the recognition and control of corrosion.

Preventive Strategies in Technical Areas

Opportunities for increased integrity, durability, and savings have both technical and non-technical aspects. The latter include the policy and management practices that determine the form and the substance of corrosion control. Technological advances hold the answers to many of the corrosion cost-savings opportunities. Systemic and programmatic changes are required for both the research and the development phases, as well as the technology transfer and implementation phases. Progress is required in the following areas:

1. Advance design practices for better corrosion management.
2. Advance life prediction and performance assessment methods.
3. Advance corrosion technology through research, development, and implementation.

In the individual sector studies, numerous challenges and missed opportunities are presented. "Preventive Strategies" (Appendix DD) addresses the issues, benefits, approach, and recommendations concerning these opportunities.

Barriers

Barriers to Progress and Effective Implementation

While corrosion management has improved over the past several decades, the United States is still far from implementing optimal corrosion control practices. There are significant barriers to both the development of advanced technologies for corrosion control and the implementation of those technological advances. In order to realize the savings from the reduced costs of corrosion, changes are required in three areas: the policy and management framework for effective corrosion control, the science and technology of corrosion control, and the technology transfer and implementation of effective corrosion control. The policy and management framework is crucial because it governs the identification of priorities, the allocation of resources for technology development, and the operation of the system for implementation.

Barriers to Improved Policy and Management

The following are barriers to more effective policy and management practices for improved corrosion prevention and control:

- Lack of awareness of significant corrosion costs and potential savings.
- Fragmentation of funding and policy responsibilities.
- Short-range and near-term mentality.
- Negative impact of deregulation.

Lack of Awareness of Significant Corrosion Costs and Potential Savings

The greatest barrier to progress in the policy and management areas regarding the high costs of corrosion and the potential savings is a lack of awareness by the management and policy-makers. Corrosion costs are often not recognized, and the impact of these costs on profitability and productivity are not considered. Moreover, too often where major corrosion problems become apparent, cost-effective remedial methods and corrosion control technologies are not fully utilized.

Fragmentation of Funding and Policy Responsibilities

The policy and management decisions that concern the assessment of corrosion costs are scattered throughout and across multiple organizations. There is no systematic approach to the consideration of corrosion costs and potential savings. Changes to "business as usual" are impeded by organizational inertia. Because of this inertia, existing specifications, regulations, and standards are not readily or quickly changed to incorporate cost-saving technology.

Short-Range and Near-Term Mentality

The increasing attention and pressures on short-range performance and the next quarterly report do not favor sound corrosion control practices. Well-conceived and irrefutable life-cycle cost-saving practices may not show benefits in the short-term analysis. Favorable economic analysis of effective increased capital costs and preventive maintenance for corrosion control require the consideration of life-cycle costs. Corrosion damage may be inevitable, but it is seldom instantaneous. Today's decisions, such as deferred maintenance, will result in definite and irreversible damage.

Negative Impact of Deregulation

The deregulation of major industrial sectors has a great potential for a negative impact on cost-effective corrosion control. Few of the barriers to the realization of corrosion cost-savings are lowered or removed by deregulation. For example, deregulation typically results in fragmentation and increases the pressures on short-term profit-making.

Barriers to Technological Advances for Corrosion Cost-Savings

The following are barriers to technological advances to reduce corrosion costs:

- Fragmentation of organizations, responsibilities, and resources.
- Corrosion problems are complex and multidisciplinary.
- Erosion of corrosion research capabilities in the United States.
- Negative image and perception.

Fragmentation of Organizations, Responsibilities, and Resources

Corrosion science and technology efforts are scattered throughout industrial and government organizations. The advantage of this is that corrosion control can be integrated within a system's approach to performance, reliability, and durability. Unfortunately, these integrated efforts are rare, minimal, and scattered.

Corrosion Problems Are Complex and Multidisciplinary

Materials science, electrochemistry, surface science, mechanics, and electrical expertise are all often required to address corrosion issues. It is often difficult to assemble an effective team with expertise in these varied disciplines. Problems arise when this varied expertise is not available and when there is inadequate funding to support the effort. "Quick fixes" are therefore used in solving corrosion problems and in making advances.

Erosion of Corrosion Research Capabilities in the United States

The laboratories and the institutions for corrosion research have been reduced and weakened. In many cases, there are not enough laboratories and institutions left to effectively undertake a major single or collaborative effort. Manufacturers call upon their suppliers for technological advances; however, suppliers have insufficient resources and commitment. For example, all metal producers have severely reduced or eliminated their research and development efforts. There have been major reductions and complete elimination of technical groups because of downsizing and consolidation. Institutions such as the Electric Power Research Institute (EPRI) and the Gas Research Institute (GRI), now the Gas Technology Institute (GTI), are under severe pressure to sustain funding or to reduce their budgets. The programs of these industry-focused institutions are endangered. Few government agencies have focused efforts in corrosion control commensurate with the magnitude of corrosion problems and opportunities. Furthermore, there is no national agenda for improved corrosion control.

Negative Image and Perception

Corrosion is a negative, deterioration-inducing, and life-threatening phenomenon. Success with damage prevention and life extension is not deemed as worthy of news releases or awards as are new designs and construction. No awards are known to exist for successfully maintaining and preserving the life of a structure; however, there are numerous awards for new designs and practices in architecture and civil engineering.

Barriers to the Implementation of Effective Corrosion Control

The following are barriers to the implementation of effective corrosion control to reduce corrosion costs:

- Absence of a strong market incentive.
- Lack of presentation of corrosion technology in a usable form.
- Uncertainty in the calculation of savings.

Absence of a Strong Market Incentive

There is often a disparity between those who control corrosion costs and those who incur the costs. This can lead to a mentality of "build it cheaper and fix it later" and a disregard for life-cycle costs. The situation is exacerbated when the builder is not made responsible for the repair costs (for example, federal funds are used to build bridges, yet state funds are used to maintain the bridges). This can lead to conflicts in the trade-off between lower construction costs and higher maintenance costs. In addition, the indirect costs of corrosion, often borne by the public, may not be allocated to the owner/operator. Conversely, the owner/operator cannot take credit for or receive additional compensation for long-term savings.

Lack of Presentation of Corrosion Technology in a Usable Form

Progress is required in the presentation of corrosion science and technology to designers, engineers, and operators in terms and formats that can be understood and effectively applied. Presently, information is not readily available and usable by the decision-makers in the design, manufacture, and operation phases.

Uncertainty in the Calculation of Savings

Greater uncertainty reduces confidence and increases the reluctance to incur additional initial costs with the promise of increased savings later. The science and procedures of life prediction and performance assessment are areas of active research that continue to evolve. Incorporation of corrosion damage into these models is a particularly difficult challenge. While cost-benefit procedures are well established, there are no long-term performance data (except for accelerated laboratory testing data) for new technologies for input into the calculations; rather, estimates of performance under different operating scenarios are used (the uncertainty in these estimates can be great).

Recommendations

An implementation strategy is needed for progress in three important categories:

- Policy and management framework to realize corrosion cost-savings.
- Technological advances for corrosion cost-savings.
- Implementation of more effective corrosion control.

The goal should be to develop and carry out a national agenda to reduce the economic impact of corrosion. No simple solution or single strategy will accomplish this goal; rather, progress can be made on several fronts, any of which will have significant benefits.

Advances in management and public policy, as well as advances in science and technology, are required. It is necessary to engage a larger constituency comprised of the primary stakeholders, government and industry leaders, the general public, and consumers. A major challenge involves disseminating corrosion awareness and expertise that are currently scattered throughout government and industry organizations. In fact, there is no focal point for the effective development, articulation, and delivery of corrosion cost-savings programs.

Two major recommendations are made below, followed by sets of recommendations in the areas of policy, science, and implementation.

Recommendation to Form a Committee on Corrosion Control and Prevention of the National Research Council

Several of the opportunities identified in this project are systemic and pertain to national interests above and beyond particular economic sectors. While significant corrosion cost-savings programs in specific economic sectors or particular technologies can be realized, a national-level effort is recommended to address these issues for the government, the public, and the scientific and engineering communities. Innovative means and programmatic changes are required in order to make progress toward these goals on a national level. A National Research Council (NRC) Committee is recommended in order to elicit the input and the participation of a wide range of stakeholders, such as federal agencies, the industry and professional community, and the public.

The focus of a Committee on Corrosion Control and Prevention would be on the preservation and the extended use of existing infrastructure and equipment. Representative major items include highway systems, drinking water systems, gas and oil pipelines, electric power plants, airplanes, and automobiles. There are three facets of the problem identified throughout this report that need to be addressed:

1. Policy and management framework, with special consideration of the effects of regulations, funding and procurement methods, and tax policy.

2. Science and technological advances in the development of a national agenda of research needs, assessment of facilities and expertise for conduct of research, and the recommendation of budget and funding alternatives.
3. Technology transfer and implementation for more effective movement of research to practice; cross-fertilization among industries; and education and training of managers, designers, and operators.

Recommendation to Develop a National Focus on Corrosion Control and Prevention

A useful and appropriate organizational template for the national focus on corrosion prevention and control is the National Cancer Institute (NCI). Corrosion is the cancer of our automobiles, airplanes, highway systems, and other crucial infrastructure. The NCI Director identified the following functions for NCI. Corrosion terminology was added in italics by the authors of this report.

- Conduct, coordinate, and support cutting-edge research and its application.
- Build upon past discoveries and promote creativity and innovation.
- Support development of, access to, and the use of new technologies.
- Disseminate cancer *(corrosion)* information.
- Support training and career development for cancer researchers *(corrosion managers, technicians, engineers, and scientists).*
- Facilitate the movement of research findings into clinical *(industrial)* practice.
- Maintain support mechanisms and collaborative environments to link scientists *(designers/engineers/operators)* with their colleagues and with critical technological and information resources.
- Develop strategies to define, improve, measure, and monitor the quality of cancer *(corrosion)* prevention and care (*corrosion control*) and reduce disparities in outcomes.

NCI deals with all of the scientific, technological, policy, and educational issues to reduce losses due to cancer. An analogous treatment of corrosion through the formation of a National Corrosion Center is required to reduce the staggering cost of corrosion.

Recommendations for Improved Policy and Management

The following recommendations are made in the area of policy and management that will result in corrosion cost-savings:

- Establish a committee on corrosion control and prevention.
- Raise the awareness of the general public and policy-makers.
- Avoid a "*build it cheap and repair it later*" mentality.
- Treat preventive maintenance and life-extension costs on the same basis as new construction and capital costs.
- Raise awareness of "*remedial treatment vs. replacement.*"
- Overcome the barriers of fragmentation.
- Consider the consequences of corrosion.
- Change resource allocations to develop effective corrosion cost-savings technology.

Establish a Committee on Corrosion Control and Prevention

This committee of the National Research Council will identify and promote innovative means and programmatic changes for the preservation and the extended use of the existing infrastructure and equipment.

Raise the Awareness of the General Public and Policy-Makers

In order to raise the awareness of the general public and policy-makers, innovative means are required to identify the large potential savings in corrosion costs and to change the misconception that nothing can be done about corrosion. Efforts are required at the federal, state, and local levels to educate policy-makers and the financial entities responsible for investment and resource allocation decisions.

Avoid a "Build It Cheap and Repair It Later" Mentality

Changes are required in policy management and financial procedures for corrosion control and maintenance to avoid a "build it cheap and repair it later" mentality. Poor corrosion control practices result from mistaken and short-term economics that further result in excessive costs later. Tax laws, budget allocations, and accounting practices can bias decisions away from sound corrosion control.

Treat Preventive Maintenance and Life-Extension Costs on the Same Basis as New Construction and Capital Costs

Sound corrosion control extends service life and reduces the demand for new construction and replacement. Preventive maintenance and life-extension projects should not be overlooked by budget allocation where they are combined with routine maintenance costs and regular maintenance budgets. Equivalent treatment regarding budget allocation, accounting practices, and taxation would put these viable and useful alternatives on more equal footing and remove the present bias against life-extension projects.

Raise the Awareness of "Remedial Treatment vs. Replacement"

When corrosion problems are recognized, there is a common perception that all is lost and must be replaced. However, sound technical, remedial treatments are often better economic practice than replacement and new construction and should be considered. Policy and procurement procedures may not recognize the remedial option, thereby removing a viable alternative from consideration. For example, cathodic protection extends the life of bridges, parking garages, pipelines, storage tanks, and water mains. This technology has been applied to existing structures after corrosion damage was discovered and has successfully mitigated further corrosion.

Overcome the Barriers of Fragmentation

Practices and procedures should be established to overcome fragmentation where the policy and management decisions that determine corrosion control and costs are scattered throughout and across multiple organizations. Government agencies, industry consortia, and technical associations can be effective communication conduits to fragmented industries.

Consider the Consequences of Corrosion

Because corrosion can have a major effect on the useful life and the operating costs of a structure, the impact of corrosion should be on the checklist of items to be considered for all major procurement and construction projects. The goal is to use policies and management practices to enhance the implementation of corrosion cost-savings, improve tax and financial practices to promote effective corrosion management, and increase regulations and standards that effectively promote sound corrosion management.

Change Resource Allocations to Develop Effective Corrosion Cost-Savings Technology

There needs to be a commensurate increase in resources (funds and staff) to balance the increased emphasis on the preservation and extension of the use of existing structures. This includes resources for research; implementation of research in practices, and education, training, and public awareness.

Recommendations for Technological Advances for Corrosion Cost-Savings

The following recommendations are made for technological advances that will result in corrosion cost-savings:

- Develop a national agenda for corrosion research.
- Reverse the loss of research capabilities for corrosion control in the United States.
- Further research on performance assessment and life prediction.
- Further research on preservation and life extension.
- Further research on corrosion performance and the status of existing structures.
- Promote collaboration through centers, networks, and consortia.

Develop a National Agenda for Corrosion Research

Topics that need to be considered in a national agenda for corrosion research include design practices for better corrosion management; life prediction and performance assessment methods; improved understanding of corrosion processes; detection and evaluation methods for corrosion damage; and advances in corrosion control technologies, such as protective coatings, corrosion-resistant materials, inhibitors/water treatment, and cathodic protection.

Reverse the Loss of Research Capabilities for Corrosion Control in the United States

Changes in the allocation of existing resources and an increase in allocations are required for further corrosion research in the United States. A critical review and subsequent modifications to the policies that are incentives/disincentives for the conduct of industrial research are required. Industrial laboratories have been ravaged by corporate consolidation and downsizing. Few government agencies have corrosion research efforts commensurate with the magnitude of corrosion problems. Industry-focused institutions such as the Electric Power Research Institute (EPRI) and the Gas Technology Institute (GTI) are under severe pressure and corrosion research programs are endangered.

Further Research on Performance Assessment and Life Prediction

The effective determination of the remaining life of a structure and the effects of alternative operation and repair options is the major challenge of corrosion science and engineering. The current models and methodologies for life prediction and performance are rudimentary and lack sufficient accuracy and reliability for a number of crucial applications. Progress is required in the fundamental understanding of corrosion processes, detection and inspection techniques, material property and performance databases, and modeling of complex systems.

Further Research on Preservation and Life Extension

Research topics that should be further developed include life extension, remedial methods to control corrosion, preventive maintenance, new designs and materials for existing structures, and alternative designs and materials for existing structures and systems.

Further Research on Corrosion Performance and the Status of Existing Structures

The scientific analysis of corrosion problems and the evaluation of alternative remedial actions are hampered by non-existent or inadequate data on real structures. Information is desired on service conditions, corrosive environments, and performance over the life of the structure. Progress is required in both the methods and the instruments to determine the current status of existing structures. Progress is additionally required in the information systems to gather, analyze, and disseminate the data.

Promote Collaboration Through Centers, Networks, and Consortia

Progress on complex and interrelated corrosion problems can benefit from the efforts of scientists and engineers from diverse disciplines working together in teams.

Recommendations for Implementation of Effective Corrosion Control

In addition to the recommended actions in policy and science matters, it is imperative to improve implementation of existing and new technologies. The following are recommendations for the implementation of effective corrosion control:

- Change the contemporary design paradigm.
- Implement the current knowledge.
- Support national demonstrations of advanced corrosion control.
- Identify emerging trends in corrosion control.
- Translate, disseminate, and promote advances in corrosion control.
- Promote widespread use of effective corrosion control.
- Build information systems to collect and share corrosion technology.
- Provide education and training in the recognition and control of corrosion.
- Provide training, education, and career development.

Change the Contemporary Design Paradigm

There is a crucial need for a change in the design paradigm to include consideration of corrosion control as an integral part of the design process. Designers routinely deal with the effects of structural loads (mechanical stresses) and high-temperature effects (thermal stresses) on the strength and the performance of structures. The treatment of corrosion (*chemical stresses)* in the design process is often inadequate. While technological advances for life prediction and performance assessment will no doubt facilitate the treatment of corrosion through design in the future, the availability of adequate tools is not the primary problem.

The primary problem is that corrosion is often not considered in the design phase of a structure. Consideration needs to be given to the impact of corrosion on service life, the effects of corrosion on maintenance costs during the life of a structure, the benefits of alternate materials of construction, and the effects of alternative methods of corrosion control built into the structure and applied to the structure throughout its service life. Furthermore, a cost-benefit analysis or life-cycle cost analysis provides a quantitative basis for the selection of design alternatives.

Implement the Current Knowledge

The state of knowledge for corrosion control is generally beyond current practices, primarily because the decision-makers are not aware of either the magnitude of corrosion costs or the existence of effective corrosion control options. To align practices more closely with the state of knowledge, communication needs to be improved between policy-makers and technical staff familiar with corrosion control. In addition, policies and practices that encourage and reward the use of sound corrosion control need to be developed and implemented.

More effective transfer and implementation of corrosion control technology can be realized through the encouragement of technology transfer among peers, support for innovation champions, through demonstrations and experiments, by the dissemination of information on costs and benefits, and cooperative research and development efforts. Successful technology development and implementation can be encouraged and realized with either a centralized or a decentralized organization. FHWA programs for highway systems and the U.S. Department of Agriculture's Cooperative Extension Service are examples of centralized and decentralized organizations, respectively, that have had major success in fostering the implementation of current technology.

Support National Demonstrations of Advanced Corrosion Control

National demonstration projects of advanced corrosion control should be supported as an effective means to rapidly move advances in corrosion control into use on a broad basis. New systems are put into service under controlled and well-monitored conditions. Results are subsequently disseminated to the affected community.

Identify Emerging Trends in Corrosion Control

Accurate and reliable information regarding incidents of corrosion failure, detection of corrosion damage, and the efficacy of corrosion control methods can greatly benefit decision-making. Some industries have reasonable information systems in place; however, many do not. Even where the information systems exist, great improvements could be made to add more useful information relevant to corrosion control.

Translate, Disseminate, and Promote Advances in Corrosion Control

An effort should be made to translate, disseminate, and promote advances in corrosion control to decrease the gap between scientific advances and implementation. The scientific advances in preventing, detecting, and treating corrosion should be translated into procedures and methods applicable in service to preserve and extend the life of existing structures.

Promote Widespread Use of Effective Corrosion Control

There is clearly a disparity in the application of effective corrosion control among industrial sectors and among entities within an industrial sector. The overall goal is to identify the barriers that impede the application of effective corrosion control and to take action to stimulate more widespread use of effective corrosion control.

Build Information Systems to Collect and Share Corrosion Technology

Emerging information technologies show great promise for the compilation and delivery of corrosion technology in flexible and effective formats. Technical associations, such as NACE International, have been particularly effective and efficient in the gathering, documentation, and dissemination of corrosion control technology. Government-sponsored projects are recommended for the further development of these information systems. Material property databases, performance/service experience, and literature compilations are extremely beneficial in the development of information technology regarding corrosion control and management.

Provide Education and Training in the Recognition and Control of Corrosion

A particular problem in dealing with corrosion-related issues is that decision-makers simply do not have information regarding corrosion control. Effective education and training tools are required to address this problem at multiple levels, including-policy makers; production and finance managers; designers and engineers; and operation, construction, and manufacturing staff. Partnerships between government and industry with technical associations are a recommended approach in the development and the delivery of these tools. Input from the management and business communities, as well as from the technical communities, is required.

Provide Training, Education, and Career Development

The challenges of corrosion control continue to evolve as materials are used in more demanding applications and in more hostile environments, as performance demands increase, and as service lives are extended to longer periods. A well-trained and effective workforce is required to meet these challenges.

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REVIEW OF PREVIOUS STUDIES

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SUMMARY

In the past, cost of corrosion studies have been undertaken by several countries. The earliest study was reported in 1949 by H.H. Uhlig, who estimated the total cost of corrosion by summing materials and method costs related to corrosion control. The 1949 report was followed in the 1970s by a number of national studies in Japan, the United States, and the United Kingdom. The study by Japan conducted in 1977 followed the Uhlig method. In the United States, the Battelle-NBS study conducted in 1978 estimated the total direct cost of corrosion using an economic input/output model. This model was later adapted by studies in two other nations, namely Australia in 1983 and Kuwait in 1995. In the United Kingdom, a study was conducted in 1970 using a method similar to the one used by Uhlig; however, in the U.K. study, the total cost was estimated by collecting data through interviews and surveys of targeted sectors. The table below summarized the total corrosion costs and percentage of gross national product (GNP) of the respective economies. The table shows that the national costs of corrosion vary between 1.5 and 5.2 percent.

COUNTRY	TOTAL ANNUAL CORROSION COST	PERCENT OF GNP	YEAR
USA	$5.5 billion	2.1	1949
UK	£1.365 billion*	3.5	1970
Japan	$9.2 billion	1.8	1974
USA	$70 billion	4.2	1975
Australia	$2 billion	1.5	1982
Kuwait	$1 billion	5.2	1987
W. Germany	$6 billion	3.0	1967
Finland	$54 million	-	1965
India	$320 million	-	1960

*not reported in U.S. dollars

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INTRODUCTION

Cost of corrosion studies have been undertaken by several countries including, the United States, the United Kingdom, Japan, Australia, Kuwait, Germany, Finland, Sweden, India, and China. The studies have ranged from formal and extensive efforts to informal and modest efforts. The common finding of these studies was that the annual corrosion costs ranged from approximately 1 to 5 percent of the Gross National Product (GNP) of each nation. Several studies separated the total corrosion costs into two parts: (1) the portion of the total corrosion cost that could be avoided if better corrosion control practices were used and (2) those where savings require new and advanced technology (currently unavoidable costs). Estimates of avoidable corrosion costs varied widely with a range from 10 to 40 percent of the total cost. Most of the studies allocated corrosion costs to industrial sectors or to categories of corrosion control products and services. All studies addressed direct costs. A common conclusion was that the indirect costs, due to corrosion damage, often are significantly greater than the direct costs. The indirect costs were more difficult to estimate.

Potential savings and recommendations in terms of ways to realize the savings were included in most of the reports as formal results or as informal directions and discussion. Two of the most important and common findings were:

1. better dissemination of the existing information through education and training, technical advisory and consulting services, and research and development activities, and
2. the opportunity for large savings through more cost-effective use of currently available means to reduce corrosion. Studies addressed only the magnitude of possible savings, but did not identify the means of realizing such savings.

The review of prior studies on the costs of corrosion has provided useful background and direction for the current study. Both technical content and methods were reviewed. Some specific areas where the prior studies were useful include:

- development of a comprehensive list of corrosion cost elements to be used in the analysis of total costs and costs to individual sectors,
- identification of categories in which to divide the total economy (this led to two sets of subcategories to estimate the total cost of corrosion, namely, a set of industrial sectors and a list of corrosion control methods),
- gathering of background and reference information on the costs of corrosion and corrosion control methods, and
- identification of preventive strategies and recommendations for potential savings.

In the following section, previous studies on the cost of corrosion were reviewed. The review addresses the methods used for data collection and economic analysis in each report. The findings of these studies are presented to review the total costs of corrosion, as well as preventive strategies to reduce the costs of corrosion. The major studies are reviewed in chronological order.

UNITED STATES (1949): THE UHLIG REPORT

The 1949 study, "The Cost of Corrosion in the United States" led by H.H. Uhlig,(1) was the earliest effort to estimate the costs of corrosion. The annual cost of corrosion to the United States was estimated to be $5.5 billion or 2.1 percent of the 1949 GNP. This study attempted to measure the total costs by summing up the cost for both the owner / operator (direct cost) and for the users (indirect cost) of corroding components. The cost for the owners / operators was estimated by summing up cost estimates for corrosion prevention products and services used in the entire U.S. economy. The study estimated the total amount of corrosion prevention products and services through the whole economy (for example, coatings, inhibitors, corrosion-resistant metals and cathodic protection) and multiplied it by their prices. The cost for private consumers / users were evaluated as costs due to domestic water heater replacement, automobile internal combustion engine repairs, and replacement of automobile mufflers. An advantage of the method is that the cost data are more readily available for well-defined products and services.

A breakdown of the direct costs by dollar amount and percentage of the total corrosion costs for corrosion control is illustrated in table 1:

Table 1. Direct and indirect costs of corrosion.

	ITEM	COST ($ x million)	PERCENT OF TOTAL CORROSION COSTS
DIRECT COSTS	Paint	2,000	36
	Metallic coatings & electroplate	472	9
	Corrosion-resistant metals	852	15
	Boiler and other water treatment	66	1
	Underground pipe maintenance and replacement	600	11
INDIRECT COSTS	Domestic water heater replacement	225	4
	Automobile internal combustion engine repairs	1,030	19
	Automobile muffler replacement	66	1

UNITED KINGDOM (1970): THE HOAR REPORT

In March 1966, the U.K. Committee on Corrosion Protection was established by the U.K. Minister of Technology under the chairmanship of T.P. Hoar. In 1970, the committee issued its report entitled *Report of the Committee on Corrosion and Protection.*(2)

The committee summarized its findings as follows: "We conservatively estimate the cost of corrosion as £1,365 million per annum, which represents 3.5 percent of the gross national product of 1970. We believe that a saving of approximately £310 million per annum could be achieved with better use of current knowledge and techniques." This represents savings of approximately 20 to 25 percent of the total national corrosion costs. The reference year of the U.K. study was 1970.

The three most important findings of the Hoar report were:

1. the need for better dissemination of information on corrosion protection,
2. the need for more education in corrosion and protection, and
3. the need for an increased awareness of the hazards of corrosion.

It was further stated that to achieve a substantial savings, a number of improvements would have to be made on a national scale, particularly in the field of education and information dissemination. Several firm recommendations were outlined in the report.

Method to Estimate Costs of Corrosion

The Hoar report (United Kingdom, 1970)(2) determined the cost of corrosion for industry sectors of the economy. The cost of corrosion for each industry sector was subsequently added together to arrive at an estimate of total cost of corrosion for the whole U.K. economy. The report identified the sources for the cost of corrosion by sectors of the economy. It evaluated and summarized the direct expenditures (costs to owner / operator) in each economic sector. Indirect costs (cost for user) were not included in the study.

Information was gathered by interviewing corrosion experts who worked in companies and agencies, and by surveys on expenditures for corrosion protection practices. Corrosion experts estimated corrosion costs and the potential savings based on their experiences with major economic sectors. Technical judgments and estimates of industry experts were used extensively.

Information on education and research in the corrosion field was obtained by a questionnaire distributed to universities and technical colleges. The inquiry into research and information dissemination was extended to research associations, development associations, and government departments. Trade associations and professional bodies assisted in the information gathering. Information gathered for a specific industry was used to estimate costs in other similar industry sectors.

Corrosion Costs of Industry Sectors

The U.K. national costs of corrosion by major areas of industry are presented in table 2. These costs include direct costs of the industry and, in certain cases, those costs sustained by the users of the product due to maintenance or replacement. Costs from interactions among sectors were not included.

The study noted that the U.K. corrosion costs were substantial; however, these costs were not higher than should have been expected based on the consideration of annual expenditures for corrosion protection technologies. The annual expenditures in the United Kingdom on protective coatings, including the cost of application, were estimated to be £772 million. In addition, approximately £620 million were estimated for annual expenditures on corrosion-resistant materials such as austenitic stainless steels and non-ferrous alloys. It was noted that these costs were not incurred solely for the purpose of corrosion resistance.

Table 2. U.K. national costs of corrosion by major area of industry.

INDUSTRIAL SECTOR	**ESTIMATED NATIONAL CORROSION COSTS**	
	(£ x million)	**(%)**
Building and Construction	250	18
Food	40	3
General Engineering	110	8
Government Departments and Agencies	55	4
Marine	280	21
Metal Refining and Semi-Fabrication	15	1
Oil and Chemical	180	13
Power	60	4
Transport	350	26
Water	25	2
TOTAL	**£ 1,365**	**100%**

Potential Savings

The Hoar report estimated that approximately 20 to 25 percent of the total corrosion costs could be saved by better use of current knowledge of corrosion control. For each industry, the percentage savings ranged from approximately 10 to 40 percent of the industry's corrosion costs. The estimated potential savings by industry are presented in table 3.

Table 3. Estimated potential savings of U.K. national costs by industry.

SECTOR NAMES	ESTIMATED POTENTIAL SAVINGS (£ x million)	ESTIMATED CORROSION COSTS (£ x million)	SAVINGS AS % OF INDUSTRY CORROSION COSTS	CHANGES REQUIRED TO ACHIEVE SAVINGS
Building and Construction	50	250	20	More awareness in selection, specification control of corrosion protection
Food	4	40	10	More awareness in selection of equipment and protection methods
General Engineering	35	110	32	Greater awareness of corrosion hazards in design stage and throughout manufacture
Government Departments and Agencies	20	55	36	Mainly on defense items by better design and procedures
Marine	55	280	20	Improved design, awareness, and application
Metal Refining and Semi-Fabrication	2	15	13	Improved awareness in plant and product protection
Oil and Chemical	15	180	8	Improved effectiveness in selection of materials and protection
Power	25	60	42	Greater use of protection and improved awareness in design stage
Transport	100	350	29	Change of exhaust system material and improved awareness in design stage
Water	4	25	16	Improved awareness of corrosion protection
TOTAL	£310	£1,365		

The potential savings were estimated with the assistance of the more "corrosion conscious" organizations, (i.e., those companies and organizations that have substantial awareness of corrosion and practice conscientious corrosion control). The estimates were judged to be conservative.

Factors Bearing on Costs

The U.K. committee and industrial organizations listed 16 factors that could lower the cost of corrosion. The factors, in order of priority assigned by the combined judgment of experts, are presented below:

1. Better dissemination of existing corrosion control information.
2. Improved protective treatments.
3. Closer control over the application of existing protective measures.
4. Improved design with existing materials.
5. Greater awareness of corrosion hazards by the users.
6. Use of new materials.
7. Cost-effectiveness analysis of materials and protective treatments leading to procurement based on total life-cycle costs.
8. Previous feedback on service performance.
9. Improved specifications for protective treatments.
10. More basic research on corrosion mechanisms.
11. Improved communication between government departments.
12. Improved storage facilities.
13. Information on corrosion sensitivity of equipment.
14. Better nondestructive testing techniques.
15. Standardization of components.
16. More frequent or longer duration maintenance periods.

The single most important factor considered necessary to reduce the costs of corrosion in the United Kingdom was better dissemination of existing information on corrosion control.

The effect of taxation in the United Kingdom on the costs of corrosion was also considered. It was noted that the taxation system encouraged a low capital investment and a high maintenance approach within some industries. Maintenance costs effectively qualified for tax relief because these costs could be expensed in the year in which they were incurred. Therefore, a company fully conscious of the consequences of corrosion may deliberately have selected inferior materials for plant construction, resulting in a reduced capital outlay, but increased maintenance costs. The Hoar report concluded that such a tax system, in fact, increased the cost of corrosion.

Preventive Strategies to Reduce Costs

The U.K. report discussed some preventive strategies in detail to reduce corrosion costs, including:

- information dissemination and corrosion awareness,
- education and training, and
- research and development.

Information Dissemination and Corrosion Awareness

The Hoar report found that a great amount of corrosion control information was available in the United Kingdom, where its exchange between corrosion technologists was good. However, it was also concluded that only certain industries, notably the oil and chemical industries and the aircraft and nuclear power industries, paid attention to corrosion in the design stage. These industries either needed to control corrosion to enable a process to work or were vitally concerned with the avoidance of accidents arising from corrosion damage. Other industries exhibited a wide range of corrosion awareness, ranging from excellent to deplorable. The less corrosion conscious companies had little or no idea where to obtain information, even when corrosion became a pressing problem.

Four principal reasons for corrosion problems were identified: (1) lack of foresight by management, (2) lack of information dissemination, (3) minimization of initial capital outlay, and (4) lack of basic knowledge. The study found that the dissemination of information on corrosion and protection was fragmented in many organizations throughout the different industries. While several hundred sources of corrosion information were available, companies that operated outside the chemical and metallurgical fields often did not know where to obtain advice on corrosion and corrosion control. Moreover, the lack of awareness of corrosion resulted in the fact that assistance was usually sought only after severe problems had been encountered.

The study concluded that the alleged "lack of foresight by management" was the result of information on the economic aspects of corrosion and on the methods of corrosion prevention not being readily available to management.

The study found that large companies in the chemical industry that formed a "materials of construction group" led to a 30 percent reduction in corrosion costs. This was probably the result of the easy availability of full-time corrosion specialists and consultants.

Education and Training in Corrosion Protection

The study concluded that the education and training of scientists, technologists, and technicians in the principles and practices of corrosion and protection were clearly of the utmost importance. The committee extensively surveyed teaching and research programs at universities and polytechnic and technical colleges and presented its findings in the report.

Research and Development

The study documented that research and development in corrosion and protection were carried out in academic institutions, national laboratories, research associations, development associations, and industrial laboratories. However, the study further found that there was too little cooperation and interchange of information between these institutions. Such lack of cooperation and coordination could lead to excessive concentration on some aspects and neglect of other important issues of corrosion.

Recommendations

In its recommendations, the U.K. report focused on dissemination of information and education regarding corrosion and corrosion control. Four specific recommendations were made:

1. establish a national corrosion and protection center,
2. receive education and training,
3. provide better research opportunities and channels, and
4. develop closer links between technical and trade organizations.

National Corrosion and Protection Center

The Hoar report concluded that there was a need for a focal point of all corrosion and protection interests in the United Kingdom. The establishment of a National Corrosion and Protection Center could best meet this need. Such a center should reinforce, rather than replace, existing organizations. Its function would be to encourage interaction between institutions and coordinate existing knowledge and new research. The center could be organized so that interaction between industry, education, and research can be stimulated, while maintaining independence from any particular section of industry. The proposed center would greatly assist in the implementation of the Hoar report's other recommendations from education, research, and technical and trade organizations.

Education

The Hoar report recommended that engineers, designers, and architects receive education in corrosion and corrosion control during their undergraduate and professional training. In addition, short specialized courses and ongoing training could be made available to those already employed in the industry.

Research

The Hoar report further recommended that more emphasis be placed on fundamental work on the methods of corrosion protection. Cooperation and exchange of information must be encouraged between the research departments of industry, research associations, development associations, national laboratories, and academic institutions.

Technical and Trade Organizations

The report emphasized and encouraged further cooperation and closer links between technical societies and trade associations dealing with corrosion control.

JAPAN (1977)

Japan conducted a survey of the cost of corrosion to its economy in 1977 through the Committee on Corrosion and Protection.(3) The committee was chaired by G. Okamoto and was organized by the Japan Society of Corrosion Engineering and the Japan Association of Corrosion Control. Support for the study came from the Ministry of International Trade and Industry.

Total Costs

The survey determined that the annual cost of corrosion to Japan was approximately 2.5 trillion yen (US$9.2 billion) in 1974. Estimating Japan's GNP at 136 trillion yen for the year 1974, the cost of corrosion was the equivalent of 1 to 2 percent of Japan's GNP for 1974. The study included direct cost only. It was estimated that the total costs would be much higher if indirect costs were included.

Method to Estimate Costs of Corrosion

Japan's committee estimated the cost of corrosion: (1) by corrosion protection products and services, and (2) by corrosion cost by industry sector. Questionnaires and interviews were used to gather data and information from industry experts.

The Uhlig method determined the costs based primarily on the cost of corrosion protection products and services, (e.g., coatings, inhibitors, corrosion-resistant materials, and cathodic protection). These results are summarized in table 3. Total costs by this method were approximately 2.5 trillion yen (US$9.2 billion). Paints and protective coatings accounted for nearly two-thirds of the corrosion costs. Surface treatments and corrosion-resistant materials accounted for approximately one-quarter and one-tenth of the costs, respectively. All other corrosion control methods considered accounted for less than 5 percent of the costs.

Table 4. Costs to prevent corrosion by protection method.(3)

CORROSION PROTECTION METHOD	**COST (yen x billion)**	**TOTAL CORROSION COSTS (%)**
Paints and protective coatings	1,595	63
Surface treatment	648	25
Corrosion-resistant materials	239	9
Rust-prevention oils	16	1
Inhibitors	16	1
Cathodic protection	16	1
Research	22	1
TOTAL	**2,551 yen**	**100%**

The Hoar method was applied to determine the cost of corrosion by specific industry sector. The results are summarized in table 5. Total costs by this method were approximately 1 trillion yen. Machinery and manufacturing had the highest cost of corrosion, with more than 40 percent of the total costs. The study found corrosion costs to be substantial for all of the sectors it considered.

Table 5. Costs to prevent corrosion by industry sector.(3)

INDUSTRY SECTOR	**CORROSION COST (yen x billion)**	**TOTAL CORROSION COST (%)**
Energy	60	6
Transportation	195	19
Building	175	17
Chemical industry	154	15
Metal production	27	3
Machinery and manufacturing	433	42
TOTAL	**1,043 yen**	**100%**

The difference between the total cost estimates of the two methods is quite large. The Uhlig method's estimate is 1.5 trillion yen higher then that of the Hoar method. This difference was partially due to omissions of some costs by the second method. It is typically expected that the "industry sector analysis" (Hoar method) provides a higher cost than the "materials and services" (Uhlig method).

For example, the cost to prevent corrosion in the food industry had not been calculated. The Uhlig method estimated the cost of surface treatment for tin-coated steel (used for production of cans) at 79 billion yen. In addition, the cost to prevent corrosion by using tin-free steel (TFS) (used for soft drink cans) was also not included in the Hoar method. Therefore, more than 100 billion yen were omitted in the food industry alone in the Hoar method.

Another significant difference between the two estimation methods involved the treatment of painting costs in the transportation industry (ship, railroad, and motor vehicle). The cost of painting to prevent corrosion was estimated at more than 800 billion yen by the Uhlig method. By the second method, this cost was less than

200 billion yen. Therefore, a difference of approximately 600 billion yen between the two methods resulted from the treatment of the transportation industry. Furthermore, there was another significant difference (150 billion yen) involving the building industry. Again, the estimates made by the Hoar method were lower.

However, even after accounting for such differences, the difference between the two methods was still on the order of 400 billion yen. This difference was ascribed to the difficulties and uncertainties in the investigation of the costs of corrosion.

Potential Savings

The study did not investigate, and therefore did not make any estimate of, the potential savings.

Recommendations

The study's main conclusion was that corrosion costs to Japan were high. The study expressed hope that, based on its findings, awareness of corrosion and its effects will increase in the factories, in transportation equipment and facilities, and in daily life. Reducing the cost of corrosion could contribute not only to energy and resources savings, but also to improved safety.

In order to increase the effectiveness of the cost of corrosion study, two areas of supplementary investigation were recommended:

1. determine the indirect costs when a factory operation is stopped by a corrosion accident, and
2. determine the decrease in the cost of corrosion by full use of the known corrosion control techniques and knowledge.

The report made recommendations in three areas to reduce the losses due to corrosion:

1. In terms of information dissemination, the following recommendations were made:
    - establish a corrosion prevention service center of technical experts,
    - increase communication among academic institutions and the industry, and
    - enhance the training of engineers.
2. In terms of education, the study recommended building awareness for the saving of material resources and conservation of the environment from elementary school to the university level.
3. In terms of research and development, the study expressed the need for monitoring and inspection methods of equipment and machines for corrosion prevention control.

UNITED STATES (1978): THE BATTELLE-NBS REPORT

In response to a Congressional Directive, the National Bureau of Standards [NBS, now the National Institute of Standards and Technology (NIST)] studied the cost of metallic corrosion in the United States. The analysis required in the study was placed under contract to Battelle Columbus Laboratories (Battelle). The results of this work were presented in two reports and a series of publications in Materials Performance.(4-6)

The Battelle-NBS study was the first to combine the expertise of corrosion and economics experts to determine the economic impact of corrosion on the U.S. economy. The study used a version of the Battelle National Input/Output Model to estimate the total corrosion cost. This model quantitatively identified corrosion-related changes in the resources (i.e., materials, labor, and energy), changes in capital equipment and facilities, and changes in the replacement lives of capital items for entire sectors of the economy. The input/output model is able to account for both the direct effects of corrosion on individual sectors and the interactions among various sectors.

Total Costs

The final results of the Battelle-NBS study, after adjustments by NBS to the Battelle report, for the base year of 1975 were:

- the total U.S. cost of metallic corrosion per year was estimated to be $70 billion, which comprised 4.2 percent of the GNP in 1975, and
- 15 percent or $10 billion was estimated to be avoidable by the use of the most economically effective, presently available corrosion technology.

An uncertainty of ± 30 percent for the total corrosion cost figure was estimated, while greater uncertainty was estimated for the avoidable costs.

These final results were based on the NBS analysis of uncertainty in the Battelle input/output model estimates and adjustments to the Battelle results based on the uncertainty analysis. For reference, Battelle estimated the total costs of metallic corrosion to be $82 billion, 4.9 percent of the $1.677 trillion GNP of the United States in 1975. Approximately 40 percent of this ($33 billion, 2 percent of GNP) was estimated to be avoidable.

Method to Estimate Costs of Corrosion

The Battelle-NBS study (United States, 1978)(4-6) used an input/output framework to estimate the cost of corrosion for the U.S. economy. The U.S. economy was divided into 130 industrial sectors in the input/output model. For each industry sector, the investigators asked experts to estimate the costs of corrosion prevention (use of coatings, etc.) and the cost of repair and replacement due to corrosion.

The input-output (IO) analysis was invented by Wassily Leontief, for which he received a Nobel Prize in 1973. IO is a general equilibrium model of an economy showing the extent to which each sector uses inputs from the other sectors to produce its output – and thus showing how much each sector sells to each other sector. The IO model shows the increase in economic activity in every other sector that would be required to increase net production of a sector by, for example, $1 million. If $1 million worth of paint were required for corrosion prevention, the IO model would show the total activity through all the sectors in order to produce this amount of paint. Since the U.S. IO matrix was constructed by the U.S. Department of Commerce based on the census of manufacturers in 1973, it represents the actual structure of the U.S. economy at that time. The IO framework has been invaluable for planning. For example, the IO framework has been utilized to estimate the total economic activity that will flow from additional net purchases from a sector and the total economic loss due to closing an industrial facility.

Economic IO analysis explicitly accounts for all the direct[3] (within the sector) and indirect[3] (within the rest of the economy) inputs to produce a product or service by using the IO matrices of a national economy. Each sector of the economy is a row (or corresponding column) of the IO matrix. The rows and columns are normalized to add up to one. When selecting a column (industrial sector P), the coefficients in each row would tell how much input from each sector is needed to produce $1 worth of output in industry P. For example, the column of the steel industry

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[3] The IO literature has different definitions for the terms "direct" and "indirect". Direct inputs are those that are from within the sector, while indirect inputs are those that are from other sectors. Only in describing the IO method in this paragraph do we use direct input and indirect input as the IO literature defines them. For this document, direct costs refer to those costs incurred by the owner / operator of the structure. Indirect corrosion costs are not incurred by the owner / operator but by other people, companies, or organizations.

specifies the quantities of each input purchased by the steel industry to make a ton of steel. For example, an IO matrix might indicate that producing $1 worth of steel requires $0.15 worth of coal, $0.10 of iron ore, etc. (The numbers 0.15, 0.10, etc. are called coefficients.) A row of the matrix specifies to which sectors the steel industry sells its product. For example, steel might sell $0.13 to the automobile industry, $0.06 to the truck industry, etc. of every dollar of revenue.

Elements were identified within the various sectors that represented corrosion expenditures, e.g., coatings for steel pipelines. The coefficient of coatings for the steel pipelines was modified so that, for example, pipelines spend nothing on coatings, where the only purpose of coatings is to prevent corrosion. Once particular coefficients in the steel pipelines column were modified, the column was renormalized to add to one. This new matrix represented the world without corrosion. With the new matrix, the level of resources used to produce GNP in a world of corrosion would produce a higher GNP in a world without corrosion.

The Battelle-NBS study collected data on corrosion-related changes in:

- resources (material, labor, energy, value added required to produce a product or service),
- capital equipment and facilities,
- replacement rates for capital stock of the capital items, and
- final demand for a product.

Based on these data, coefficients in the IO model were adjusted. Data were gathered through interviews with knowledgeable individuals associated with a specific industry, review of the literature, and consultation of technical experts. Technical judgment was used extensively.

In the study, the total cost of corrosion was defined as "...that increment of total cost incurred because corrosion exists." The study asked, "What cost would not be incurred if corrosion did not exist?" It developed three "worlds" for its analysis as follows:

- World I: real world *of corrosion* (year 1975 was modified to full employment level of economic activity);
- World II: hypothetical world *without corrosion* (to establish a baseline); and
- World III: hypothetical world in which the *economically most effective corrosion prevention* method was practiced by everyone.

The IO model was constructed to describe these three "worlds".

The study then determined the total national cost of corrosion as the difference between the GNP of World I and the GNP of World II.

The Battelle-NBS study further divided the total cost into avoidable and unavoidable costs, with the following definitions for these two terms:

1. Avoidable costs of corrosion is the difference between the GNP of World I and the GNP of World III or "cost which are amenable to reduction by the most economically efficient use of recently available corrosion control technology."

2. Unavoidable costs of corrosion is the difference between the GNP of World II and the GNP of World III or "those which are not amenable to reduction by presently available technology."

The following direct costs (cost to owner / operator of the structure) were included in the study:

- replacement of equipment or buildings
- loss of product
- maintenance and repair
- excess capacity
- redundant equipment
- corrosion control (such as inhibitors, organic and metallic coatings)
- engineering research and development testing
- design
  - material of corrosion not for structural integrity
  - material of corrosion for product purity
  - corrosion allowance
  - special processing for corrosion resistance
- insurance
- parts and equipment inventory

However, indirect costs (cost to others) of the structures were not included in the study.[4]

Corrosion Cost of Sectors

The Battelle-NBS study primarily used the IO model to estimate the cost of corrosion to sectors. In addition to the IO model, the report included limited-scope studies that focused on four areas: the federal government, personally owned automobiles, the electric power industry, and loss of energy and materials. In the following, the use of the IO model for determining the cost of corrosion for individual sectors is discussed.

Sector Costs Based on the Input-Output Model

Based on the experts' judgments, "industry indicators" (coefficients in the IO matrix) were calculated to indicate the cost of corrosion for specific industrial sectors. These indicators reflected expert judgment as to how much specific purchases could be reduced if there were no corrosion. The effects of corrosion were reflected in:

- changes to the materials inputs to produce products, e.g., coatings, corrosion inhibitors, and corrosion-resistant materials,
- changes in the capital equipment and facilities of the industry due to corrosion effects on replacement lives of equipment, and
- changes in other areas such as technical services.

The breakdown of industry indicators into its components is shown in figure 1 for two randomly selected sectors. The areas of the circles are proportional to the magnitude of total costs and avoidable costs, respectively. The contributions of four components to the corrosion costs are as follows:

Inputs: There are corrosion effects on inputs required to make a product. These effects include the costs of coatings and plating for corrosion control, corrosion inhibitors, maintenance and repair, corrosion-resistant metals, and cathodic protection.

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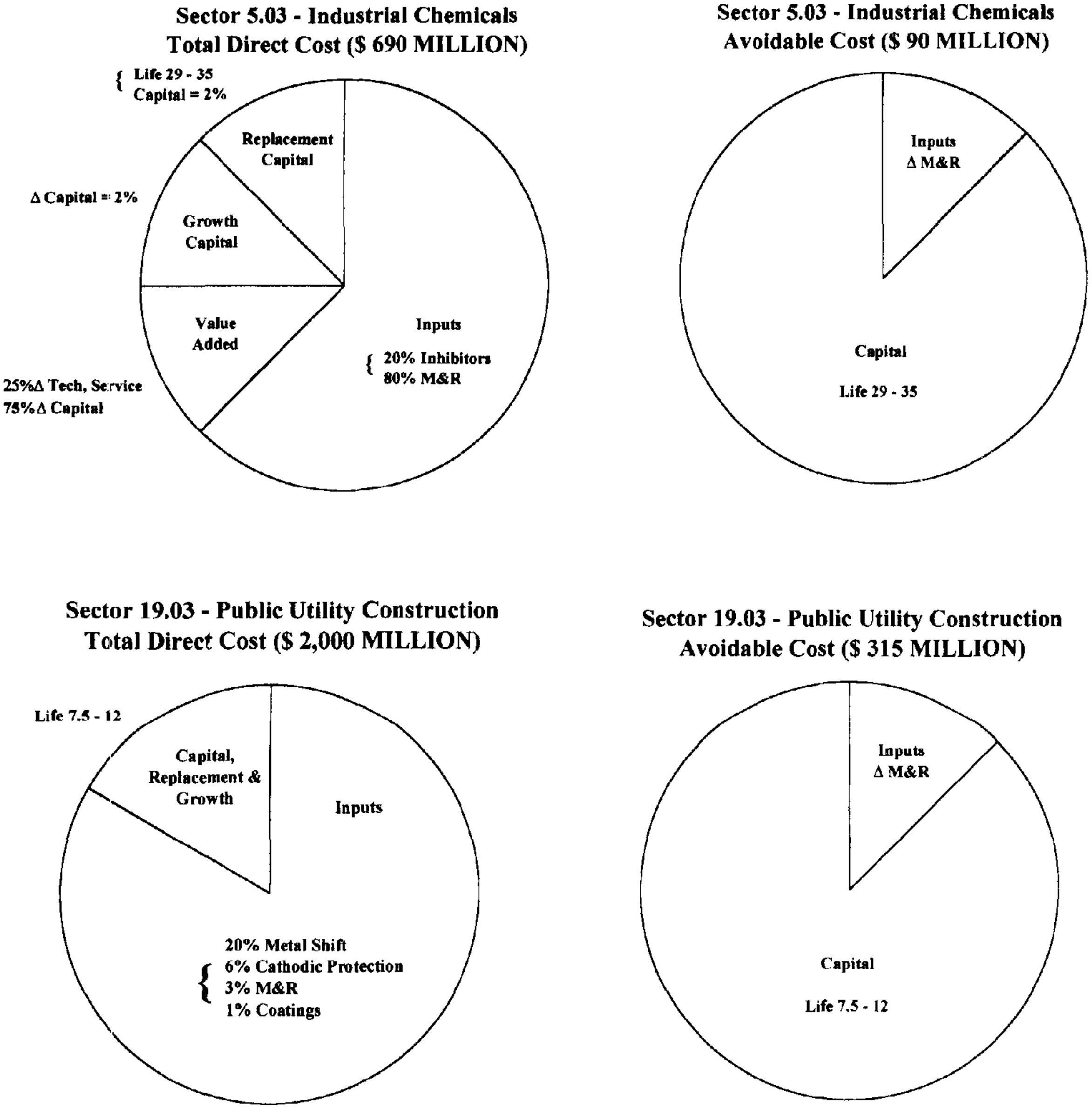
[4] Note that the Battelle report used different definitions for direct cost and indirect cost. We do not use the Battelle study's definition in this report. Even in describing the Battelle report, we use our definitions for these terms.

Capital Replacement: Replacement of capital equipment and facilities in the industry is affected by corrosion through changes in the replacement lives for the capital items, excess capacity, and redundant equipment.

Growth Capital: The costs of capital equipment and facilities for growth are affected by corrosion through changes in the replacement lives for the capital items.

Value Added: Activity of the industry is affected by corrosion through changes of inputs, including costs of research and development and technical services.



Sector 5.03 - Industrial Chemicals Total Direct Cost ($ 690 MILLION)

Sector 5.03 - Industrial Chemicals Avoidable Cost ($ 90 MILLION)

Sector 19.03 - Public Utility Construction Total Direct Cost ($ 2,000 MILLION)

Sector 19.03 - Public Utility Construction Avoidable Cost ($ 315 MILLION)

Figure 1. Breakdown of industry indicators into its components, according to Battelle-NBS study.[(4)]

In addition, the adjustments were made to account for changes in the use of corrosion control, maintenance and repair, replacement lives of capital equipment, etc. The relative contributions of cost elements and the proportions of the cost elements that can be avoided vary from sector to sector.

Once the coefficients (industry indicators) in the IO matrix are modified to reflect the absence of corrosion, the IO matrix can now be used to indicate the inputs needed to produce the same bundle of goods and services that consumers purchased in the world with corrosion. The IO matrix will indicate a cost-savings, due to corrosion being absent. In other words, we would need less input to produce the same output if there were no corrosion in the world. Since the IO matrix is in dollars, the savings (or the difference between the real world and the world without corrosion) are immediately indicated.

The impact of corrosion is that, in comparison to the world without corrosion, the real world needs to spend more on input to produce the same output. This additional input is the cost of corrosion. In the Battelle-NBS report, this cost was determined on two different bases: as a percentage of sales and on a dollar basis. The highest total costs of corrosion based on percent sales were attributed to mining, manufacturing, public utilities, and construction. For the highest total cost on a dollar basis, the industry sectors with the largest corrosion costs were wholesale and retail trade, automobile manufacturers, livestock, and petroleum refining.

The list of industries with the highest avoidable corrosion costs was considerably different from the list for total costs. The highest avoidable corrosion costs based on percentage of sales were in industries such as livestock and agriculture, mining, transportation, construction, and trade and business services. The list of industries with the highest avoidable costs based on dollars included livestock and agriculture, transportation, construction, trade and business services, food industry, and pulp and paper industry.

The analysis identifies sources of corrosion costs attributed to an industrial sector and the relative importance of adjustments to the costs. It is apparent that the source of the corrosion costs varies significantly from industry to industry. For example, the effect of the replacement lives of capital equipment and facilities account for nearly all of the corrosion costs in the livestock, wholesale, and retail trade industries. For industrial chemicals, the largest segment of total corrosion costs comes from inputs such as inhibitors/water treatment, and maintenance and repair, while the largest segment for avoidable costs is due to the effect of the replacement lives of equipment. For public utility construction, the largest segment of the total costs is from inputs such as corrosion-resistant materials, and cathodic protection and coatings, while the effect of the replacement lives of equipment is the largest contributor to avoidable costs.

Corrosion Costs Analysis of Four Special Areas

Separate from the IO model, the Battelle-NBS study examined four specific areas of the economy, including the federal government, personally owned automobiles, the electric power industry, and loss of energy and materials. The findings for these four areas are summarized below.

Federal Government

The study focused on agencies that owned the greatest amount of capital equipment. Subsequently, a government-wide estimate was obtained by scaling the data. The initial data were obtained from the U.S. Department of Defense (DOD), the National Aeronautics and Space Administration (NASA), the U.S. Coast Guard, the U.S. Government Services Administration (GSA), the Legislative Branch, and the National Bureau of Standards [NBS, now National Institute of Standards and Technology (NIST)].

A total cost of corrosion to the federal government was estimated to be $8 billion, which was comprised of capital costs of $6 billion and maintenance costs of $2 billion. These total corrosion costs represented approximately 2 percent of the total federal budget ($400 billion). Of the total $8 billion cost, approximately 20 percent was estimated to be avoidable.

The capital costs of corrosion to the federal government resulted from redundant equipment due to corrosion and the effects of corrosion on the replacement lives of equipment and structures. The total federal capital in aircraft was estimated to be $195 billion, while the annual corrosion maintenance costs of aircraft was estimated at $990 million. Lifetime in service was judged to be unaffected by corrosion; however, an increase of 5 to 8 percent in aircraft downtime was judged to be the result of corrosion. Corrosion-related expenditures for the Coast Guard and Navy were estimated to be $400 million for ships. This is 0.7 percent of the estimated federal capital in ships of $56 billion. Buildings and structures comprise 36 percent of the total federal capital. An estimate of the corrosion fraction of maintenance at DOD installations was used to calculate the DOD corrosion maintenance costs at $280 million. The total federal real estate property corrosion maintenance costs were estimated to be $375 million annually. Table 6 summarizes the total capital and corrosion maintenance costs for aircraft, ships, and buildings and real estate.

Table 6. Total capital and maintenance costs for government assets.

	TOTAL CAPITAL ($ x billion)	**MAINTENANCE COST ($ x billion)**
Aircraft	195	0.99
Ships	56	0.4
Buildings and Real Estate	144	0.655
TOTAL	**$395**	**$2.045**

Personally Owned Automobiles

The total annual cost of corrosion for personally owned automobiles was determined to range from $6 billion to $14 billion. Avoidable costs were estimated between $2 billion and $8 billion.

At the time of the study, the principal areas of corrosion in cars were associated with the degradation of iron and steel components, which comprised approximately 80 percent of the weight of the automobile. The elements of the automobile costs were: (a) the cost of built-in corrosion protection included in the purchase price, (b) the portion of maintenance and operating costs attributable to corrosion, and (c) the cost of premature replacement of automobiles due to corrosion.

The built-in costs of corrosion for automobiles were identified primarily as corrosion protection for steel body panels such as metallic zinc coatings, paint, adhesives and sealants, non-ferrous metals, corrosion-resistant materials, and non-metals. The major operating and maintenance expenses for the owner of a car were body corrosion, after-market rust-proofing, heat exchanger components, mufflers, and tail pipe corrosion. The greatest impact on the cost of corrosion for automobiles was the adverse effect of corrosion on the cost of replacement of the automobile. Sensitivity analysis showed that in both the IO model and in the focused sector study, the cost of replacement of automobiles dominated the total cost and avoidable cost-estimation. Since the automobile sector had a significantly higher cost than any other sector, the cost of this sector was the single most significant driving factor in estimating the total corrosion cost for the entire United States.

Electric Power Industry

The total corrosion costs to the electric power industry in the generation and distribution of power were estimated to be about $4 billion. Of these costs, the annual corrosion-related maintenance expenditures were estimated at $1.1 billion.

Many power plants have planned outages of several hundred hours per year to maintain turbines and boilers. In addition, excess capacity (more power generation plants and equipment) has been built in to account for these outages and to produce the desired amount of electricity. A significant portion of the excess capacity of power plants was ascribed to be due to corrosion, where corrosion-related excess capacity was assumed to be approximately 10 percent of the total capital investment.

Two main segments of the electric power industry were considered: generation and transmission/distribution of electricity. Five types of electric power generating plants were identified: fossil fuel, hydroelectric, nuclear, geothermal, and solar. Corrosion costs varied considerably depending on the type of generation plant. The study found that corrosion greatly increased the frequency and duration of outages, resulting in significant costs. For the transmission and distribution of electricity, atmospheric corrosion and underground corrosion of buried structures were found to be the primary contributors to corrosion costs.

Energy and Materials Losses

The output of the Battelle-NBS analysis was used to estimate the additional energy and materials consumed because of metallic corrosion. Approximately 3.4 percent of the country's energy consumption ($1.4 billion) was related to corrosion. Within the energy sectors, the impact of corrosion was greater on coal usage than on petroleum or natural gas usage. Approximately one-sixth (0.6 percent of energy consumption or $0.23 billion) was estimated to be avoidable.

Approximately 17 percent of the nation's demand for metallic ores ($1.4 billion) resulted from corrosion, and about one-eighth of that (2.1 percent of metallic ore demand or $180 million) was judged to be avoidable. Within the materials sectors, the effects of corrosion were concentrated mainly on the metallic ores.

Potential Savings

The Battelle-NBS study found two sources of potential savings in terms of corrosion (technology advancements and technology transfers). Approximately 15 percent of the total $70 billion ($10 billion) was estimated to be avoidable by more cost-effective use of currently available technology. The research found that additional savings could be realized in the presently (1970) unavoidable costs by technology advancements in corrosion control.

The amount of total costs and avoidable costs were found to vary greatly from sector to sector. Furthermore, it was found that the distribution of cost elements was also sector-dependent (portion of costs due to changes in (a) inputs to the production process, (b) replacement capital, (c) growth capital, and (d) value added).

Preventive Strategies

The scope of the Battelle-NBS study did not include the identification and analysis of preventive strategies to mitigate the impact of corrosion on the U.S. economy.

Recommendations

The study did not make any specific recommendations, although it noted that the corrosion costs could be reduced significantly through broader application of existing corrosion control technology.

Summary

The Battelle-NBS study was undertaken to provide a reference to allow the economic impact of corrosion to be compared with other factors affecting the U.S. economy. In summary, the following items were cited as accomplishments of the Battelle-NBS study:

- measure of the severity of corrosion costs,
- indication of where and how the impacts of corrosion are felt,
- useful method for the analysis of corrosion costs,
- bibliography and database on corrosion economics,
- reference point for the impact of corrosion against which the relative effect of other factors affecting the economy can be measured,
- basis for technological assessments to assess the economic effect of proposed means to reduce corrosion costs, and
- identification of specific sectors where high affordable and presently unavoidable corrosion costs are encountered.

It was further noted that new corrosion problems would arise in the areas of energy, environment, materials conservation, and food production. As an example, new energy technologies that would utilize materials under higher temperatures and pressures in highly corrosive environments were cited in which future costs of corrosion were projected to rise substantially in some sectors.

AUSTRALIA (1983)

In 1982, the Commonwealth Department of Science and Technology commissioned a study to determine the feasibility of the establishment in Australia of a National Center for Corrosion Prevention and Control. The feasibility study included a determination of the annual cost of corrosion to Australia, a market survey of the need for a National Center for Corrosion Prevention and Control, and a review of national corrosion centers in European countries. The study considered the organizational structure, technical functions, and the financial structure for the proposed center. The results were presented in a 1983 report entitled *Corrosion in Australia The Report of the Australian National Centre for Corrosion Prevention and Control Feasibility Study.*(7)

Total Costs

The study concluded that the annual cost of corrosion to the Australian economy could amount to AUS$2 billion at 1982 prices, approximately 1.5 percent of Australia's GNP in 1982. The report indicated that improved technology transfer and implementation could potentially recover a large portion of the corrosion costs, and that there was a clear need in Australia for the establishment of a national corrosion control center. Furthermore, it was noted that the value of the savings to the Australian community from improved corrosion control would make a worthwhile contribution to the nation's economy.

Method to Estimate Costs of Corrosion

The Australian study was patterned after the Battelle-NBS study. An IO model of the Australian national economy was constructed to first represent the real world and secondly to represent the world of optimum corrosion mitigation technology. Differences between the two scenarios were used as estimates of the avoidable costs of corrosion and to indicate areas of potential savings.

The study used statistical data from the Australian Bureau of Statistics and therefore did not perform any major data collection. Preparation of a model of the complexity of the Battelle method was clearly beyond the scope of the study.

It was noted that while these cost estimates were large, they did not include the cost to users and the cost of disruption. For example, if a bridge corrodes, a disruption cost would accrue to the users of that bridge because of its reduced capacity. Similarly, a high-pressure gas pipeline that fails due to corrosion would result in a disruption cost to third parties dependent upon the delivery of gas. While that study did not quantify these costs, it noted that corrosion could cause widespread problems within industries and the community. The results, both socially and economically, could be alarming. For example, corrosion processes could cause gas pipelines to rupture, industrial plants to fail, buildings to deteriorate, and aircraft to crash. Although the study did not quantify them, secondary costs resulting from corrosion failures could also be large and, in many cases, affect third parties not associated with the corrosion engineering system.

Potential Savings

The potential savings (avoidable costs) were estimated to be equal to the total corrosion costs at 1.5 percent of Australia's GNP in 1982. The study estimated that 35 percent of the total savings was due to personal consumption expenditures; 55 percent was due to private fixed-capital formation; and 5 percent was due to federal, state, and local government expenditures.

Insufficient use of corrosion mitigation technology was one source of corrosion costs. The study concluded that possible potential savings provided a valid economic argument for improving technology transfer and for the creation of facilities for corrosion mitigation practices. Various industry sectors expressed that the creation of a National Center for Corrosion Prevention and Control could lower the costs of corrosion. They expressed the need for a review of national corrosion centers in European countries.

Preventive Strategies

The survey of Australian industry and government departments found considerable expertise in the corrosion mitigation field within the various sectors. However, the study identified a need for a centralized organization, which could coordinate the resources, technology transfer, and coordinate research facilities in the field of corrosion.

Recommendations

The primary conclusion of the study was that there is a clear need in Australia for the establishment of a National Corrosion Control Center. The study identified three roles for such a center: consulting, research, and education. The consulting role would entail quick advisory services and provide a technological information resource center for both industry and government agencies. The research role would provide for long-term applied research for corrosion-related problems. Finally, the educational role would support technology transfer and training in corrosion control technologies.

KUWAIT (1995)

In 1992, Kuwait conducted an economic assessment of the total cost of corrosion to its economy using a modified version of the Battelle-NBS IO model. The results of this assessment were presented in a 1995 report.(8)

Total Costs

The total cost of corrosion was estimated at about $1 billion (1987 dollars), representing 5.2 percent of Kuwait's 1987 Gross Domestic Product (GDP). Avoidable corrosion costs were estimated at $180 million or 18 percent of the total cost.

Method to Estimate Costs of Corrosion

The Kuwait study was patterned after the Battelle-NBS IO method. Data gathering and information required for the model's adjustments came from three sources:

1. data compiled from a survey specifically designed for industries in Kuwait,
2. judgment of experts in the field of corrosion in Kuwait, and
3. experience of other countries and previous studies.

The questionnaire or survey was the first choice for data compilation. The following elements of corrosion were considered: replacement of equipment and buildings, excess capacity and redundant equipment, loss of product, maintenance and repair, and corrosion control.

Two years were analyzed, 1987 and 1992. The costs of corrosion in 1992 were determined to be less than those estimated for 1987, which was explained by the following factors:

- the economy in 1992 was smaller than in 1987,
- the 1992 model assumed a more efficient economy with respect to corrosion and therefore, less cost of corrosion for each unit of output in the IO model,
- the study assumed that the economy in 1992 was operating below capacity, and
- the study assumed that only the more efficient equipment was used in the production process.

On the sector level, the estimates for total cost of corrosion in the oil sectors (crude petroleum and petroleum refining) were $65 million in 1987. The avoidable cost in these sectors was estimated to be $10 million in 1987. The commercial services sector, the government, and the social and household services sectors were responsible for the largest share (70 percent) of the total cost of corrosion.

Potential Savings

In this study, the potential savings were expressed as avoidable costs. The study suggested that the corrosion control efforts could be more cost-effective in those sectors that had the highest cost per dollar of value added, (i.e., non-metallic products, basic metal products, construction, and other manufacturing sectors).

Preventive Strategies

The scope of the study did not include the identification and analysis of preventive strategies.

Recommendations

The study emphasized that the estimates reported in the study should be considered as the best available indicator for the economic effect of corrosion. The estimates provided a benchmark against which the relative impact of other factors affecting the economy could be compared and assessed. This could help in the development of a program for corrosion control to prioritize: (a) actions to be taken and (b) the resource allocations to support these actions.

OTHER COSTS OF CORROSION REPORTS

Other cost of corrosion studies have been cited as background to prior studies. These range from fairly informal estimates with little or no supporting information to fairly extensive data-gathering and interpretation efforts toward estimating the cost of corrosion. Some of these studies are briefly acknowledged below.

West Germany (1969)

West Germany conducted a study of corrosion at the end of the 1960s. The total cost of corrosion was estimated to be 19 billion Deutschmarks (DM) (US$6 billion) for the period of 1968 to 1969. Of this cost, 4.3 billion DM (US$1.5 billion) was estimated to be avoidable. This gave a total cost of corrosion equivalent to approximately 3 percent of the West German GNP for 1969 and avoidable costs were roughly 25 percent of total corrosion costs.(9) There was no information presented as to what these figures included or how they were computed.

Finland and Sweden (1965)

Finland conducted a study of the cost of corrosion in 1965. The cost of corrosion to Finland's economy was estimated to be between 150 and 200 million markaa (US$47 million and US$62 million) for the year 1965. Linderborg referred to these losses in his article describing factors that must be taken into account in assessing corrosion costs to the Finnish nation.(10)

Linderborg quotes a partial study of corrosion costs done in Sweden, in which painting expenditures to combat corrosion were analyzed for the year 1964. These costs were found to be 300 to 400 million crowns (US$58 million to US$75 million) of which between 25 and 35 percent were found to be avoidable.

India (1961)

India conducted a study of corrosion in 1961. The cost of corrosion to India was estimated at 1.54 billion rupees (US$320 million)(11) for the period 1960 to 1961. This was based on calculations of expenditures for certain measures to prevent or control corrosion, including direct material and labor expenses for protection, additional costs for increased corrosion resistance and redundancy, cost of information transfer, and funds spent on research and development.

The breakdown of corrosion control costs was:

- 25 percent for paints, varnishes, and lacquers,
- 20 percent for metallic coatings and electroplatings, and
- 55 percent for corrosion-resistant metals.

Other corrosion control methods and materials were not cited.

China (1986)

In 1986, it was reported that a preliminary cost of corrosion study was conducted in 1980, although China had not yet carried out a nationwide investigation of corrosion losses.(12) In that study, 148 enterprises in the chemical industry were surveyed. The comprehensive results of 10 such enterprises showed that the average corrosion cost was 4 percent of their annual income. The results of another survey of an iron and steel complex indicated that corrosion costs were 1.6 percent of their annual income.

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ECONOMIC ANALYSIS METHODS

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COST OF CORROSION

The goal of this project is to estimate the current cost of corrosion for the U.S. economy. The first step of the project involved a selection of representative sectors of the economy. Then, a definition for the "cost of corrosion" and the method to estimate the cost of corrosion for the sectors were established. Finally, these estimates were extrapolated to the cost to the whole economy.

The current cost of corrosion measures the cost of corrosion management to improve the function of, and to extend the life of a structure or facility. The first step is to estimate how much companies and government agencies are spending on corrosion prevention and protection (direct costs). The second step is to determine the benefits of corrosion management in terms of extending the service life and functionality of the protected structure or facility. The third step is to estimate the annualized value of indirect (user) costs and the cost of mishaps throughout the service life of the structure. Since these costs occur at different times during the service life of the structure, they are annualized in order to make them comparable. In addition, an important question to ask is whether and how the current cost can be lowered.

Documenting the changes in corrosion control over the past few decades places the current cost of corrosion into perspective. Specifically, by documenting the role and significance of unexpected accidents, regulations, and research in bringing about changes in the treatment of corrosion, significant milestones can be identified. Savings made by changing from current corrosion management practices to more cost-effective practices point out the possible benefits of optimized corrosion management. Determination of the most cost-effective practices was based on the evaluation of the current practices. Thus, savings are possible if the annualized cost of the most cost-effective corrosion management strategy is lower then that of the current practice.

DEFINITIONS

The current cost of corrosion was estimated using the concepts that are discussed in the following sections.

Corrosion Management

Engineered structures are built to serve particular functions. Service requirements are defined by the level of quality of service and by the length of service. Corrosion management includes all activities throughout the service life of the structure that are performed to mitigate corrosion, to repair corrosion-induced damage, and to replace the structure, which has become unusable as a result of corrosion. In general, maintenance is defined as an activity that maintains the level of service of a structure or facility. Repair activities restore the damaged structure to its original or required service levels, but do not eliminate the causes of corrosion. Rehabilitation activities restore the damaged structure to its original or required service level and correct the deficiency that resulted in corrosion deterioration. The repair and rehabilitation activities are performed at different times throughout the service life of the structure. Maintenance is considered a regular activity, characterized by an annual cost. Inspections are scheduled periodic activities, and repair is performed on an as-needed basis. Repair can involve the replacement of parts, but not the replacement of the basic structure. Rehabilitation of structures such as bridges is usually done only once or twice during the service life of the structure, generally at a high cost.

Direct and Indirect Costs

The total cost of corrosion is divided into the two main categories of direct and indirect costs. Direct costs are defined as the costs that are directly incurred by the owner or operator of the facility, plant, or structure. Indirect costs are defined as those costs that are incurred by others, such as the public, and are not directly felt by the owner or operator.

In order to determine accurate corrosion costs, it is important to include indirect costs in the analysis of alternatives. The cash flow must include all expenditures by the owner and all expenditures to others, such as the cost of delays, service interruption, or environmental damage. The design with the lowest annualized cost is then the design with the lowest cost of providing the service to the entire society. If, on the other hand, only direct costs are included, the design with the lowest cost to the owner may not be the one with the lowest cost to society. An example is the case of a leak forming in a pipeline, where the cost of replacing the corroded pipe section (direct cost) is negligible compared to the cost of the environmental damage (indirect cost). If the pipeline operator compensates its customers for disruptions in service and pays for environmental damage resulting from the leak, the lowest corrosion management cost to the operator will also be the lowest cost to society. If, however, either of these costs is omitted, the operator will not have the proper incentive to select a design or corrosion maintenance program that has the lowest cost for society.

Life-Cycle Costing

When optimizing both the direct and indirect costs of corrosion, it is important that all benefits and costs of all the options are accounted for. This benefit-cost analysis (BCA) determines the net present value of options and the highest net benefit to society. In addition, BCA helps to determine the cost per unit of service, which is, in fact, the highest aggregation of costs and benefits.

LCC analysis is used in this project to assess corrosion management alternatives. It determines the Annualized Value (AV) of each option, which is used to compare the alternatives. Since in the analysis it is assumed that all options meet the same service requirement, the lowest cost option is therefore the most cost-effective option to achieve the service requirement. While LCC is an appropriate method to compare the costs of different options, it simplifies the benefit side by only considering the benefits of the specified service level. For example, if the required service level is a four-lane bridge designed to last for 60 years, the benefit of the bridge will be very different for one serving 5,000 cars per day than for one serving 50,000 cars per day. An analysis of the former case would probably conclude that a two-lane bridge was sufficient, while an analysis of the latter case would conclude that a six-lane bridge was required.

It is important to emphasize that the costing of project alternatives cannot be based on their initial costs. For example, it costs less to build an uncoated carbon steel pipe (first option) than a coated carbon steel pipe (second option); however, the coated pipe would last longer. Therefore, for the correct comparison, the construction cost must be annualized over the entire service life of the pipeline. It holds true if one factors in rehabilitation and repair costs for each pipeline. A comparison of the two options is therefore based on the annualized value of each.

CURRENT COST OF CORROSION

The current cost of corrosion is defined as the sum of the corrosion-related costs of design and construction/manufacturing; the cost of corrosion-related maintenance, repair, and rehabilitation (corrosion management); and the cost of depreciation or replacement of structures that have become unusable as a result of corrosion. Theoretically speaking, the current cost of corrosion is the difference between the approach where no consideration is given to corrosion and corrosion control and the current approach. It is calculated by LCC analysis and characterized by the annualized value.

Measurement of the current cost of corrosion is carried out in the following steps:

1. Determine the cash flow of corrosion-related activities: describe corrosion management practices (materials, actions, and schedule), determine the elements of corrosion cost, and assign cost to all materials and activities that are corrosion-related.
2. Calculate present discounted value (PDV) of the cash flow.
3. Calculate Annualized Value for the PDV.

These steps are discussed in more detail in the following sections.

Cash Flow

After the corrosion management practices are analyzed, the direct and indirect elements of the corrosion costs are identified. The corrosion-related cash flow of a structure/facility includes all costs, direct and indirect, that are incurred due to corrosion throughout the entire life-cycle of the structure.

The current practices to control corrosion vary greatly between the different industry and government sectors that are described in this report. Even within a sector, there are different approaches to design and maintenance of similar facilities or structures. One approach to determine the total corrosion cost is to extrapolate from a typical corrosion cost to the entire sector.

As discussed previously, the cost of corrosion is divided into **direct and indirect costs**. Examples of some of the direct costs are:

- Amount of additional or more expensive material used to prevent corrosion damage, multiplied by the (additional) unit price of the material.
- Number of labor hours attributed to corrosion management activities, multiplied by the hourly wage.
- Cost of the equipment required as a result of corrosion-related activities.
- Loss of revenue due to lower supply of goods. For example, consider the case of a leaking pipeline. When, as a result of the leak, the pipe is shut down for repair, the revenue loss due to this service interruption should be accounted for as a cost of corrosion. If the market is such that other companies in the industry can meet the demand for the same cost, then the revenue loss of one company is the revenue gain for another and, therefore, would not be counted as a corrosion cost.

As previously defined, indirect costs are incurred by others than the owner or operator. Once a dollar value is assigned to these items, they are included in the cash flow of the corrosion management and treated the same way as all other costs. Some examples of indirect costs are:

- Increased costs for consumers of the product (lower product supply on the market results in a higher cost to consumers) or lost time due to the search for the alternative goods/service.
- Effect on local economy (loss of jobs).
- Effect on the natural environment by pollution.

Present Discounted Value of the Cash Flow

Structures are designed to serve their function for a required period of time, which is referred to as the service life. More than one option can be utilized to satisfy the service level for the required service life. Once the cash flow for the service life is determined, the value of each option for the entire life-cycle can be determined. One cash-flow cycle (a complete life-cycle) of a structure is as follows:

Year Zero: Direct cost is the total initial investment of constructing a new structure or facility. If there is an old structure, its removal cost is not included. There is a user cost associated with the construction of a new structure. If there is an old structure, the user cost associated with its removal is not included.

During Service: Direct cost includes all costs associated with maintenance, repair, and rehabilitation. The user cost can be generated by the worsening conditions of the structure that reduces the level of service of the structure during any maintenance, repair, or rehabilitation.

Last Year: Direct cost includes all costs of structure removal. If the old structure is replaced with a new one, the cost of the new structure is not included. There is a user cost associated with the removal of the structure. After the removal of the old structure, a new life-cycle begins.

All materials and activities incurring corrosion-related costs during the service life of the structure must be identified, quantified, and valuated. Direct costs of the corrosion management activities, or the cost to the owner or operator, include material, labor, and equipment costs. (The price of labor, material, and equipment are assumed to be the same for all design and all corrosion management alternatives.) As stated earlier, all indirect costs should be accounted for as well. For example, if a corrosion-related maintenance activity on a bridge deck requires traffic maintenance, its cost needs to be included.

The corrosion management schedule of the structure determines the direct-cost cash flow. Calculation of the present value of the cash flow entries is presented in the following sections.

The initial investment occurs in the "present"; therefore, no discounting is necessary.

Annual maintenance is assumed to be constant throughout the life-cycle of the structure. Thus, the present discounted annual value PDV{AM} is calculated back to the present as follows:

$$\mathrm{PDV}\{\mathrm{AM}\} = \mathrm{AM} \times [1 - (1 + i)^{-N}] / i$$

where AM = cost of annual maintenance ($ per year)
N = length of service life in years
i = interest rate

For the calculation of the present value of activities that grow annually at a constant rate (**g**), a modified interest rate needs to be calculated using the following formula:

$$i_0 = (i - g) / (1 + g) \text{ and } i > g$$

where i_0 = modified interest rate
i = interest rate
g = constant annual growth rate

If the first payment (P_1) occurs in year one, the present value of a cash flow that grows annually at a constant rate over **n** years is calculated using the following formula:

$$\mathrm{PV}\{P\} = [P_1 / (1 + g)] \times [1 - (1 + i_0)^{-n}] / i_0$$

PV{P}, the present value of a cash flow series that starts at P1 in year 1 and grows at a constant rate **g** for **n** years when interest rate is **i**, is equivalent to the present value of an annuity of [P1/ (1 + g)] for **n** years when interest rates are $\mathbf{i_0}$, where $\mathbf{i_0}$ is given by the equation above.

The first payment for repair activities, however, usually does not occur in year one, but, rather in year **t**; therefore, the above formula calculates the value at year **(t-1)** discounted back to year zero of the life-cycle to determine the present discounted value of the repair:

$$PDV\{P\} = PV\{P\} \times (1 + i)^{-(t-1)}$$

The PDV of one-time costs, such as one-time repairs (R), rehabilitation (RH), or removal of an old structure (ROS) is calculated as follows:

$$PDV\{R\} = R \times (1 + i)^{-tR}$$
$$PDV\{RH\} = RH \times (1 + i)^{-tRH}$$
$$PDV\{ROS\} = ROS \times (1 + i)^{-tROS}$$

where R = cost of the repair
RH = cost of the rehabilitation
ROS = cost of removing the old structure
t = year in which the cost is incurred

The present value (PV) of alternatives is calculated as the sum of the PV of its cash flow added to the initial capital investment (I):

$$PDV = I + PDV\{AM, P, R, RH, ROS\}$$

Annualized Value of the Cash Flow

In calculating the service life cost of alternative corrosion management approaches, the irregular cash flow of the entire service life is transformed into an annuity (a constant annual value paid every year) for the same service life. The annualized value (AV) of the alternative approach is calculated from the PV by use of the following formula:

$$AV = PDV \times i / [1 - (1 + i)^{-N}]$$

The annuity of the initial investment (I) made in year zero is determined such that its present discounted value is equal to the present discounted value of its annuity:

$$PDV\{I\} = PDV[A\{I\}] = \Sigma_{n=1}^{N} [A\{I\} / (1+r)^{N}]$$

where A{I} = annualized value of the capital investment
A{CM} = annualized value of all corrosion management costs
r = annual discount rate
n = service year, n = 1… N,
N = entire service life
PDV{I} = present discounted value of the initial investment
PDV[A{I}] = present discounted value of annuity of the initial investment

The actual corrosion management costs throughout the "n" years of the structure's service life will fluctuate. The fluctuating cash flow is replaced with an equivalent uniform cash flow of its annuity. The annuity of the corrosion management yearly cash flow is determined such that the present discounted value of the original cash flow is equal to the present discounted value of the annuity:

$$PDV[A\{CM\}] = PDV\{CM\} = \Sigma_{n=1}^{N} [A\{CM\} / (1+r)^{N}]$$

where PDV{CM} = present discounted value of the original cash flow of corrosion management
PDV[A{CM}] = present discounted value of the uniform cash flow or annuity

The annuity of the original cash flow is then:

$$A = A\{I\} + A\{CM\}$$

This annuity or "annualized cost" is a constant annual value paid every year; present discounted value is equal to the present discounted value of the irregular cash flow for the entire service life of the structure.

In summary, the current cost of corrosion is the sum of the amount spent preventing corrosion at the design and construction phase; the amount spent on maintenance, repair, and rehabilitation to control and correct corrosion (cost of corrosion management); the amount spent on removing and replacing structures that become unusable due to corrosion (depreciation or cost of replacement); and the indirect (user) cost generated by or during these activities.

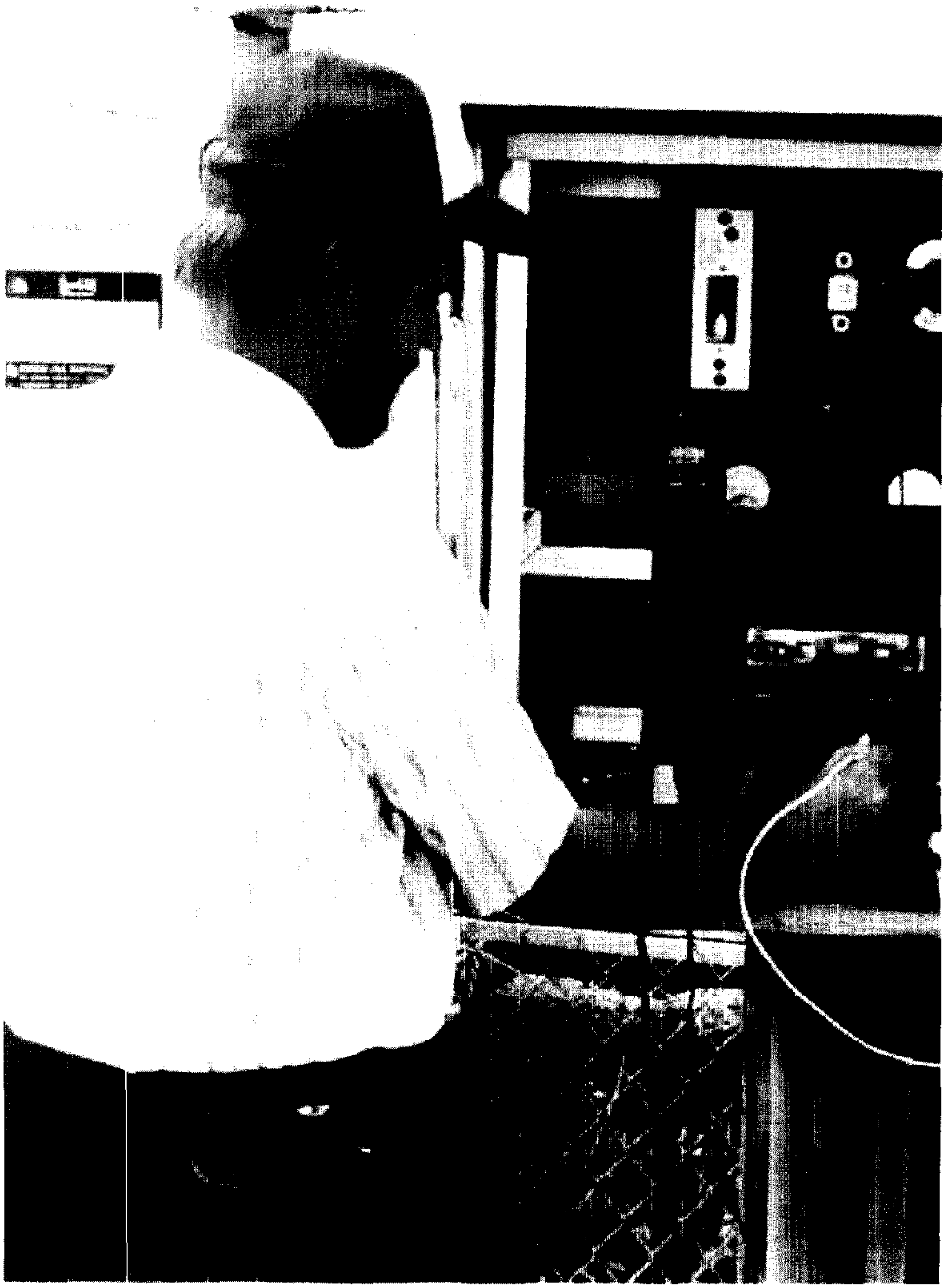
POSSIBILITY OF COST-SAVINGS THROUGH IMPROVEMENT OF CORROSION MANAGEMENT

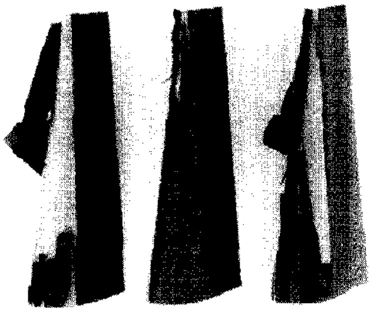
Within any industrial sector, there is a range of current practices of dealing with corrosion, from the old technology to the current state-of-the-art. While one of the practices achieves the most for its cost, i.e., is the most cost-effective, others could be improved to be more cost-effective. Hence, an important question is whether improvement of the currently used practices could lower the current cost of corrosion. While this project did not attempt to answer this question, efforts were made to identify sources of possible savings. For example, in the case of reinforced-concrete bridge decks (low cost, "basic" design), an attempt was made to estimate the magnitude of the savings by employing the most cost-effective corrosion management practice.

The goal of corrosion management is to achieve the desired level of service at the least cost (which, in order to estimate the total economic cost, should include user costs). Finding the corrosion management program that has the greatest net benefits to society requires a careful analysis of all the direct and indirect costs involved. This analysis requires specific corrosion-related cost information. Unfortunately, because of the complexity of corrosion control and management issues or the reluctance of the experts to share the data, for many industrial sectors, insufficient information was available to identify the design-maintenance option that had the lowest annual cost. However, in nearly all the sectors, a wide range of current corrosion management practices was observed, suggesting that one of these practices is likely to be more cost-effective than the others.

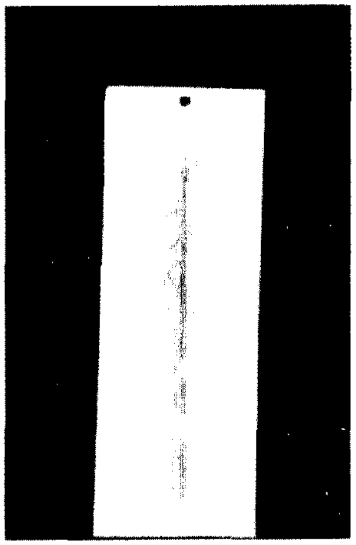
APPENDIX C

CORROSION CONTROL METHODS AND SERVICES

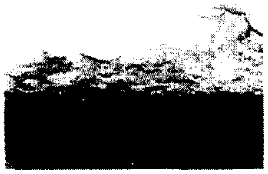




Coating bend tests

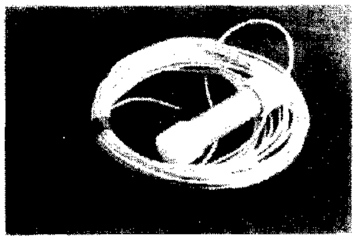


Coated test panel after
salt fog exposure

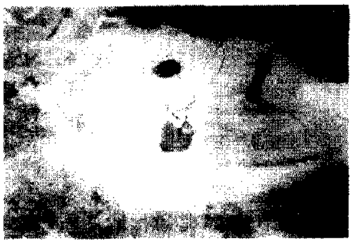


General corrosion

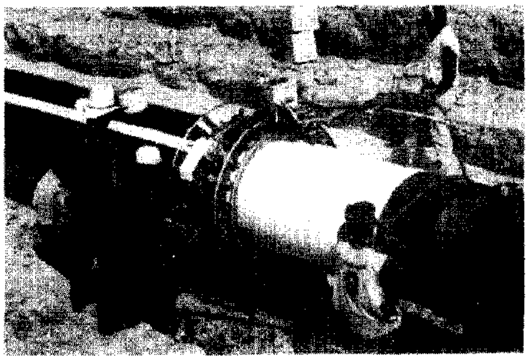
Flaking paint



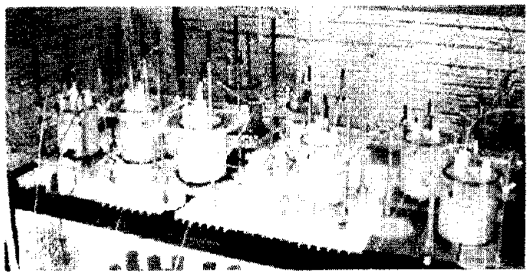
Copper/copper sulfate
reference half-cell



Reference cell on
concrete floor

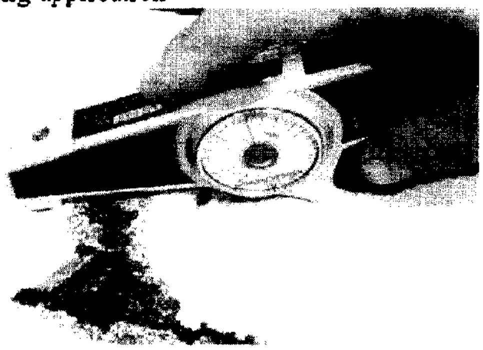


Tape coating application



Testing

On-site measurements



Coating thickness measurement

APPENDIX C

CORROSION CONTROL METHODS AND SERVICES

GERHARDUS H. KOCH, PH.D.[1] AND GREGORY R. RUSCHAU, PH.D.[1]

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[1] CC Technologies Laboratories, Inc., Dublin, Ohio.

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COST OF CORROSION CONTROL METHODS

One of the two methods described in this report to estimate the total cost of corrosion is based on a method where the total cost of corrosion control methods and services is estimated. This method was used by Uhlig(1) in one of the first studies that examined the cost of corrosion in the United States, and was later adapted to estimate the cost of corrosion to the Japanese economy.(2-3) These studies are described in more detail in the section titled "Review of Previous National Cost of Corrosion Studies."

The corrosion control methods that were considered include protective coatings, corrosion-resistant metals and alloys, corrosion inhibitors, polymers, anodic and cathodic protection, corrosion control services, corrosion research and development, and education and training. The total annual cost of corrosion estimated with this method for the average year of 1998 was $121.41 billion or 1.381 percent of the $8.79 trillion Gross Domestic Product (GDP). Table 1 shows the distribution of the corrosion control methods and services costs.

Table 1. Costs of corrosion control methods and services.

MATERIAL AND SERVICES	RANGE	AVERAGE COST	
	($ x billion)	**($ x billion)**	**(%)**
Protective Coatings			
Organic Coatings	40.2 – 174.2	107.2	88.3
Metallic Coatings	1.4	1.4	1.2
Metals and Alloys	7.7	7.7	6.3
Corrosion Inhibitors	1.1	1.1	0.9
Polymers	1.8	1.8	1.5
Anodic and Cathodic Protection	0.73 – 1.22	0.98	0.8
Services	1.2	1.2	1.0
Research and Development	0.020	0.02	<0.1
Education and Training	0.01	0.01	<0.1
TOTAL	**$54.16 – $188.65**	**$121.41**	**100%**

Protective Coatings

Both organic and metallic coatings are used to provide protection against corrosion of metallic substrates. These metallic substrates, particularly carbon steel, will corrode in the absence of the coating, resulting in a reduction of the service life of the steel part or component. Both types of coating are reviewed in the following sections.

Organic Coatings

The major organic coatings are often classified by a curing mechanism, with the two basic types of cured coatings being nonconvertible and convertible.(4) The nonconvertible coatings cure solely by evaporation of the solvent with no chemical change in the resin matrix. They can be re-dissolved in the solvent originally used to dissolve the resin. Convertible coatings, on the other hand, cure primarily by a polymerization process in which the resins undergo an irreversible chemical change.

The common types of nonconvertible coatings include the following:

Chlorinated rubbers – elastomers formed when natural rubber or a polyolefin is reacted with chlorine. These materials are usually modified by other resins to obtain high solid contents and to decrease brittleness.

Vinyls – made by dissolving polyvinyl chloride (PVC) polymers in a suitable solvent. They are generally low solid coatings applied in very thin coats. Vinyl coatings are used for their weathering ability.

Acrylics – made by dissolving polymers made from acrylic acid and methacrylic acid or acrylonitrile. Water-based acrylics are widely used due to their weathering properties and ease of application.

Bitumen – generally based on residues from petroleum or coal mining processes. Bitumen coatings can also come from naturally occurring sources such as gilsonite. The presence of aromatic hydrocarbons (such as benzene) in some of these coatings has limited their acceptability in recent years due to health and environmental concerns.

Flame-spray polymers – these are not evaporative cure coatings; rather, they cure by cooling from a molten state. The most common flame-spray polymer is polyethylene, which is ground into a powder state and flocced through a flame, which converts the polyethylene into a molten state. The molten polymer hits the substrate and cools, solidifying into a protective film. This type of coating can be re-melted or dissolved by an appropriate solvent, although there are very few solvents for polyethylene.

Coalescence coatings – in this type of coating, tiny particles of resin are encapsulated in a soap-like material and then dispersed in water, which acts as a dilutent rather than a true solvent. This type of blend is known as an emulsion. When the water evaporates, the resin particles fuse (coalesce) to form a stable, cured coating film. These coatings, once cured, cannot be re-dissolved in water, although stronger solvents may dissolve them. Examples of these include acrylic latex suspensions and epoxy emulsions.

Most convertible coatings cure by polymerization. Polymerization occurs when two or more resin molecules combine to form a single, more complex molecule. The resin molecules may be monomers (single units) or they may be shorter chain polymers, which react to form longer chain polymers. There are four main types of polymerization used in coating technology (oxygen-induced, chemically-induced, heat-induced, and hydrolysis). Other types of polymerization, such as radiation-induced polymerization, are possible; however, the vast majority of convertible coatings use one of the following four mechanisms.

Oxygen-induced polymerized coatings:

Alkyds – referred to as oil-based primers and topcoats, alkyds are based on vegetable or fish oils blended with pigments and catalysts in a solvent. The film forms when the oil reacts with oxygen assisted by the catalyst, and the solvent evaporates. Most paints that are sold in spray cans are alkyds.

Drying oils – penetrating oils and lacquers that form a thin protective film.

Chemically-induced polymerized coatings:

Epoxies – the preferred corrosion control coating for severe environments. Epoxies are a generic class of materials based on the presence of an epoxide polymer side group. They exhibit superior adhesion and chemical resistance properties, yet are susceptible to weathering degradation (by chalking) and are often topcoated to shield them from ultraviolet (UV) light.

Polyurethanes – these set the standard for color retention and weathering, and are widely used over steel for long-term decorative corrosion protection. Polyurethanes also vary widely in chemistry and can be formulated to be very flexible elastomers, rigid foams, or dense brittle films.

Heat-induced polymerized coatings:

Polyesters and vinyl esters – these materials are based on styrene monomers with a very reactive catalyst. They could be classified as chemically-induced curing polymers; however, the actual reaction is heat-induced. The catalytic reaction generates a great deal of heat, which polymerizes the styrene monomer and the ester groups. They are used as tank linings and form the basis for many freestanding fiberglass structures.

Phenolics – these are thin films, which form by evaporation of solvent followed by baking at high temperatures [204 °C (400 °F) or greater]. Phenolics form a very strong, hard chemical- and temperature-resistant film used for storage of strong acids and solvents.

Silicones – chemically, silicones vary greatly; however, the corrosion-resistant coatings based on silicone are baked to create an inorganic silicone backbone that withstands very high temperatures. In applications such as furnaces and boilers, silicone-based coatings are often the only option.

Fusion-bonded epoxies – powder-based epoxies that are applied to hot substrates. When the powder hits the hot substrate, it melts and the chemical reaction occurs. Upon cooling, the film solidifies. Fusion bonded epoxies are widely used for pipelines and concrete rebar applications.

Hydrolysis-induced polymerized coatings:

Inorganic zinc – usually zinc metal powder is dispersed in a zinc silicate binder, and the zinc silicate uses moisture from the air to form a cured matrix. The zinc particles behave as individual anodes to sacrificially protect the steel from corrosion. Many steel bridges and freestanding structural steel members are coated with inorganic zinc, which has a characteristic gray-green color. For other applications, the zinc is topcoated with an epoxy and/or polyurethane to provide an excellent system for corrosion control. There are also water-based inorganic zinc coatings, which react with CO_2 to cure.

Moisture-cured polyurethanes – some polyurethane coatings form their protective cured film by reaction with moisture from the air. Their properties are usually quite different from two-component polyurethanes, but contain a basic urethane side group, which classifies them as polyurethanes.

The selection of coating chemistry for the different industrial applications is based on intended service, application, intended service life, and cost. According to the U.S. Department of Commerce, Census Bureau, the total amount of organic coating material sold in the United States in 1997 was 5.56 billion L (1.47 billion gal), at a value of $16.56 billion.(5) Table 2 summarizes the total volume and value of paint sold in the United States for the years 1990 to 1999. The total sales can be broken down into four categories: architectural coatings, Original Equipment Manufacturers (OEM) coatings, special-purpose coatings, and miscellaneous allied paint products.

Table 2. Summary of estimated U.S. total quantity and value of shipments of paint and allied products: 1990 to 1999 "As Revised," as reported by the U.S. Census Bureau.(5)

	TOTAL		ARCHITECTURAL COATINGS		OEM COATINGS		SPECIAL-PURPOSE COATINGS		MISCELLANEOUS ALLIED PRODUCT COATINGS	
	Quantity	Value	Quantity	Value	Quantity	Value	Quantity	Value	Quantity	Value
	gal x million	$ x million	gal x million	$ x million	gal x million	$ x million	gal x million	$ x million	gal x million	$ x million
1999	1,486.3	18,012.3	677.1	6,816.2	446.0	6,208.2	170.4	3,496.2	192.8	1,491.7
1998	1,443.7	17,298.2	631.6	6,115.2	428.3	6,098.2	173.3	3,472.0	210.5	1,612.8
1997	1,472.8	16,559.5	655.6	6,264.9	425.4	5,750.7	181.8	2,896.0	210.0	1,647.9
1996	1,468.2	16,554.7	640.3	6,246.3	398.7	5,474.1	208.9	3,263.8	220.3	1,570.5
1995	1,407.2	15,923.7	622.5	6,057.1	385.3	5,279.9	196.0	3,076.7	203.4	1,510.0
1994	1,431.1	15,645.2	644.8	5,888.3	372.9	5,069.9	193.8	3,197.3	219.6	1,489.7
1993	1,336.5	14,630.1	608.1	5,615.3	356.6	4,788.3	179.0	2,937.7	192.8	1,288.8
1992	1,236.0	13,595.1	575.6	5,294.3	311.7	4,213.5	172.7	2,933.8	176.0	1,153.5
1991	1,226.8	13,009.4	537.9	4,900.7	320.4	4,005.4	179.5	2,910.8	189.0	1,192.5
1990	1,281.9	12,898.4	558.4	4,913.6	338.6	4,032.6	195.6	2,781.5	189.3	1,170.7

Architectural coatings are applied on-site to new and existing residential, commercial, institutional, and industrial buildings. Small percentages of these are used as primers and undercoats, and may be classified as corrosion control coatings. Water-based and water-thinned coatings dominate the architectural market. In fact, more than 75 percent of all architectural coatings are now water-based.(6) Table 3 shows the markets for corrosion-related architectural coatings according to the 1997 Census Bureau data.

Table 3. Value of corrosion-related architectural coatings sold in 1997.(5)

TYPES OF UNDERCOATS AND PRIMERS	VALUE ($ x million)
Exterior Solvent-Based	91
Exterior Water-Thinned	100
Interior Solvent-Based	101
Interior Water-Thinned	194
TOTAL	**$486**

This value of $486 million for corrosion-related architectural coatings is approximately 8 percent of the $6.2649 billion total spent on architectural coatings in 1997.

OEM coatings are factory-applied to manufactured goods as part of the manufacturing process. There is an element of decoration in OEM finishes, but for those applied to steel, their primary function is corrosion control, either for weathering resistance or flash rust protection. Their market breakdown is given in table 4.

The value of the total OEM corrosion control coatings indicated in table 4 represents approximately 66 percent of the total OEM market of $5.7507 billion in 1997. Other OEM coatings include wood furniture and flatboard finishes, container/closure finishes, and electrical insulation coatings.

Table 4. Value of OEM corrosion control coatings sold in 1997.(5)

OEM CORROSION CONTROL COATINGS	VALUE ($ x million)
Automotive Finishes	1,128
Automotive Part Finishes	78
Heavy-Duty Truck/Bus/RV Finishes	369
Aircraft/Railroad Finishes	166
Heating/AC/Appliance Finishes	84
Metal Building Product Finishes	662
Machinery and Equipment Finishes	241
Non-Wood Furniture and Fixture Finishes	384
Automotive Powder Coatings	110
General Metal Finishing Powder Coatings	311
Other OEM Powder Coatings	130
Product Finishes for OEM Equipment	134
TOTAL	**$3,797**

Special-purpose coatings include heavy industry corrosion control coatings as well as marine and automotive refinishing. The distribution of corrosion-related special-purpose coatings is shown in table 5.

Table 5. Value of special-purpose corrosion control coatings sold in 1997.(5)

SPECIAL PURPOSE CORROSION CONTROL COATINGS	VALUE ($ x million)
Industrial Maintenance Coatings-Interior	139
Industrial Maintenance Coatings-Exterior	609
Automotive Refinishing	1,302
Marine Paints for Shipping/Offshore	248
TOTAL	**$2,298**

The value of special-purpose corrosion control coatings represents 79 percent of the $2.896 billion special-purpose coatings market in 1997. Also included in this category by the Census Bureau, which are not corrosion control coatings, were traffic marking paints (both for signs and road markings) and aerosol can labeling finishes.

The final category of total sales is miscellaneous allied paint products, which includes paint/varnish removers, thinners, pigment dispersions such as art supplies, and putties. The contribution to corrosion protection from this category includes only thinners used in non-architectural solvent-based coatings. Solvent-based corrosion control coatings account for 75 percent of the solvent-based coating market; therefore, it can be estimated that the amount of thinner used in corrosion control applications is 75 percent of the thinner sold at a cost of $118 million. This $118 million value accounts for 7 percent of the $1.6479 billion allied paint products market in 1997.

Extracting the corrosion coating portions from each of these as described above provides a total estimate of all corrosion markets in the paint industry (see table 6).

Table 6. Summary for corrosion control coatings sold in 1997.[5]

CORROSION CONTROL COATINGS	**VALUE ($ x million)**
Total Architectural Corrosion Control Coatings	486
Total OEM Corrosion Control Coatings	3,797
Total Special-Purpose Corrosion Control Coatings	2,298
Total Miscellaneous Allied Corrosion Control Paint Products	118
TOTAL	**$6,699**

A survey by the Steel Structures Painting Council (SSPC) of industrial coatings performed in 1998 separated the coating sales by end-use industry.[7] Table 7 shows the breakdown of the high-performance coatings by industry.

Architectural coatings, some of which may be considered corrosion control coatings, but are applied to non-metallic surfaces such as wood and concrete, were not considered in this study. Furthermore, it should be noted that the automotive industry, which is one of the largest users of organic coatings, was not included in the SSPC study.

Table 7. Distribution of 1998 coating sales by end-use industry, as reported by SSPC.[7]

END-USE INDUSTRY	**% OF SALES**
Petroleum refining and chemical production	14
Bridges and highways	8
Railroads	8
Water and waste treatment	7
Offshore oil & gas production	7
Marine	7
Defense/space	7
Electric utilities/gas	5
Pulp & paper	4
Land-based oil & gas production	4
Food & beverages	3
Primary metals and mining	3
Airlines/aircraft	1
Other (not specified)	22
TOTAL	**100%**

The average cost per gallon of paint is estimated at $23, which is derived from a wide range of costs for high-performance coatings such as epoxies [$7.9 to $13.2 per L ($30 to $50 per gal)] and polyurethanes [$21.1 per L ($80 per gal)] to industrial waterborne acrylics [$3.17 to $3.46 per L ($12 to $15 per gal)].[7]

The raw material cost of any coating application, while significant, is only a portion of the cost of a coating application project. The SSPC survey(7) indicated that, for example, for a typical aboveground crude oil storage tank, the total cost of coating is distributed as shown in figure 1. The figure clearly demonstrates that surface preparation (40 percent) and coating application (15 percent) require a significant portion of the total coating budget, whereas the actual coating material cost is only 9 percent.

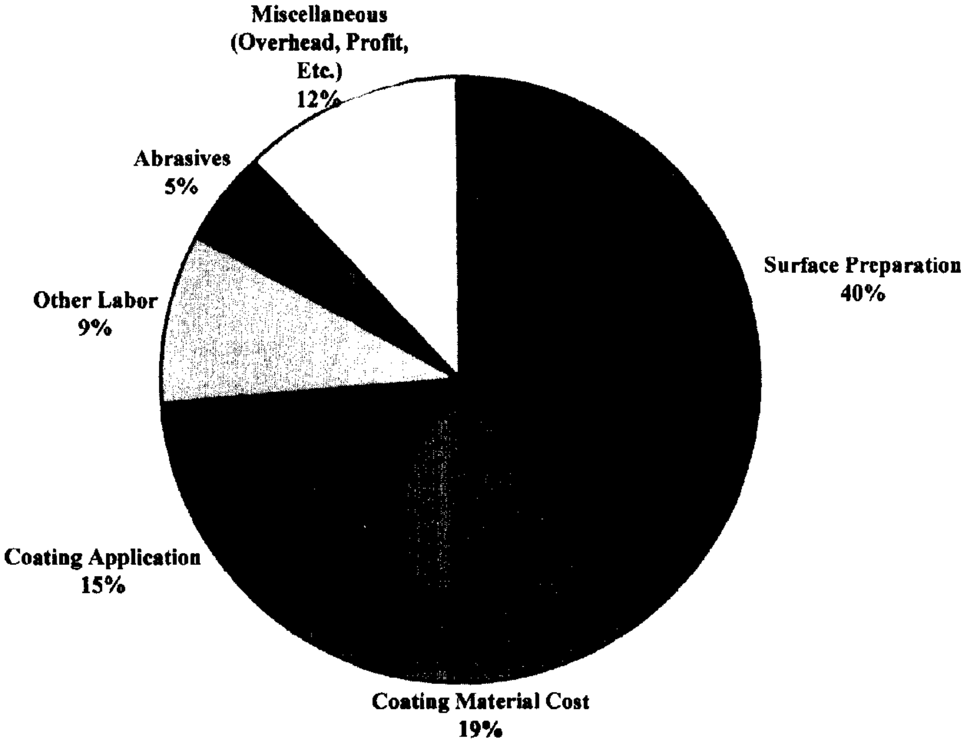

Figure 1. Cost distribution of coating application on an aboveground storage tank.(7)

A report by the Federal Highway Administration(8) indicated that, for a typical heavy-duty maintenance job on a steel bridge structure, the cost of coating material is even a smaller fraction (4 percent) of the total cost (see figure 2). Large portions of the total cost are taken by access cost (20 percent), containment (19 percent), and workers' health (15 percent).

Using these figures, the total cost of application of the $6.699 billion in coatings is estimated to range from $35.3 billion to $167.5 billion for the entire coating industry in the United States. These cost figures do not include the costs of hard-to-define cost items, such as the costs of performance testing, personnel costs for time spent specifying coating products and application procedures, overhead for handling of bids and contracts, and other support services that would be unnecessary if coating application had not been needed. Moreover, the total cost does not include the costs of downtime, lost production, or reduced capacity during maintenance painting.

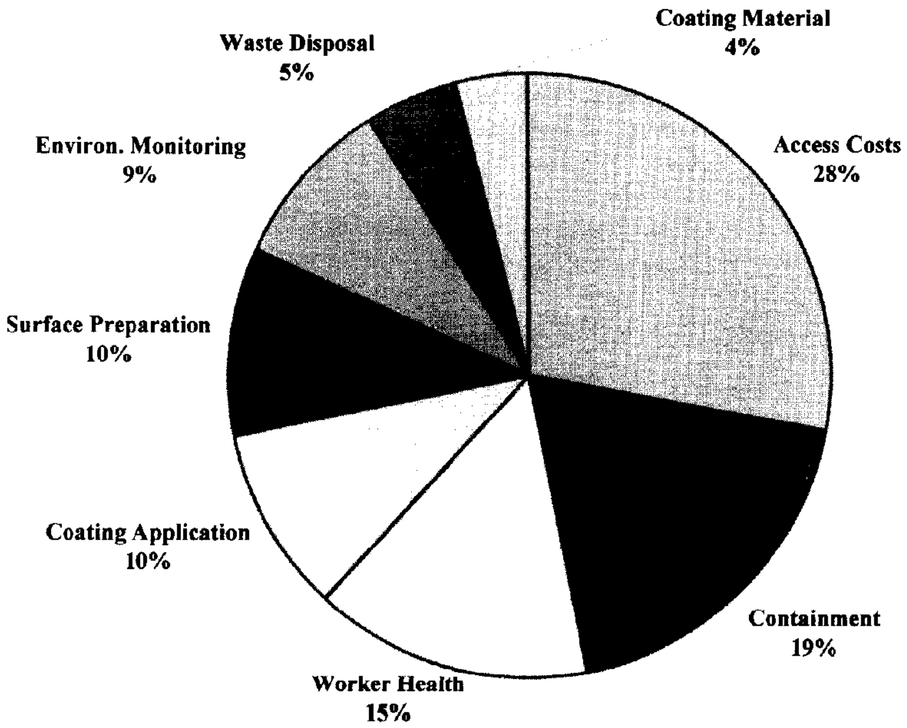

Figure 2. Cost distribution of coating application on steel highway bridge structure.(8)

Several major changes have affected the coating industry over the past 15 to 20 years. The first major change was brought on by the environmental restrictions on volatile organic compounds (VOCs). Paint manufacturers in the United States are being forced by regulations to develop either high-solid coatings with minimal solvents, or waterborne equivalents of the existing solvent-borne coatings. More than 10 percent of the high-performance industrial coatings in the United States are now of the waterborne variety. The second major change is the use of lead-free paint. Concern over existing lead-based paints has spawned an entire industry of lead abatement and remediation. Currently, a total of 4 percent of all coating sales are for the purpose of replacing lead-containing coatings.(7) A third major change is the banning of chromates, which have been incorporated into corrosion-inhibiting primers, particularly for aluminum alloys. Chromates, which are very effective corrosion inhibitors, have been designated as carcinogens and are therefore being phased out. Although extensive research is being conducted to replace this powerful corrosion inhibitor, no comparable replacements have yet been found or developed.

Metallic Coatings

The most widely used metallic coating process for corrosion protection is galvanizing, which involves the application of metallic zinc to carbon steel for corrosion control purposes. Information released by the U.S. Department of Commerce in 1998 stated that approximately 8.6 million metric tons of hot-dip galvanized steel and 2.8 million metric tons of electrolytic galvanized steel were produced in 1997.(9) The total market for metallizing and galvanizing in the United States, which is considered a corrosion control cost is estimated at $1.4 billion. This figure is the total material cost of the metal coating and the cost of processing. It does not include the cost of the carbon steel member being galvanized/metallized.

Galvanizing

Hot-dip galvanizing differs from other zinc coatings and the metallizing process in that the zinc is alloyed to the metal during galvanizing. By contrast, organic or inorganic zinc coatings (and electroplated metallic coatings) are non-alloyed coatings, although their protection mechanism is essentially the same. Both alloyed and non-alloyed zinc coatings act as barriers to the corrosive environment and as sacrificial anodes when the barrier is breached.

The degree of protection offered by galvanizing depends entirely on the thickness of the galvanized layer. Galvanizing is unique in that empirical data accumulated over the years provide guides for estimating the service life of galvanized coating under a wide range of specific exposure conditions. Figure 3 shows this service life prediction for several "standard" environments.(10) Hot-dip galvanizing is the most common process, and as the name implies, it consists of dipping the steel member into a bath of molten zinc.

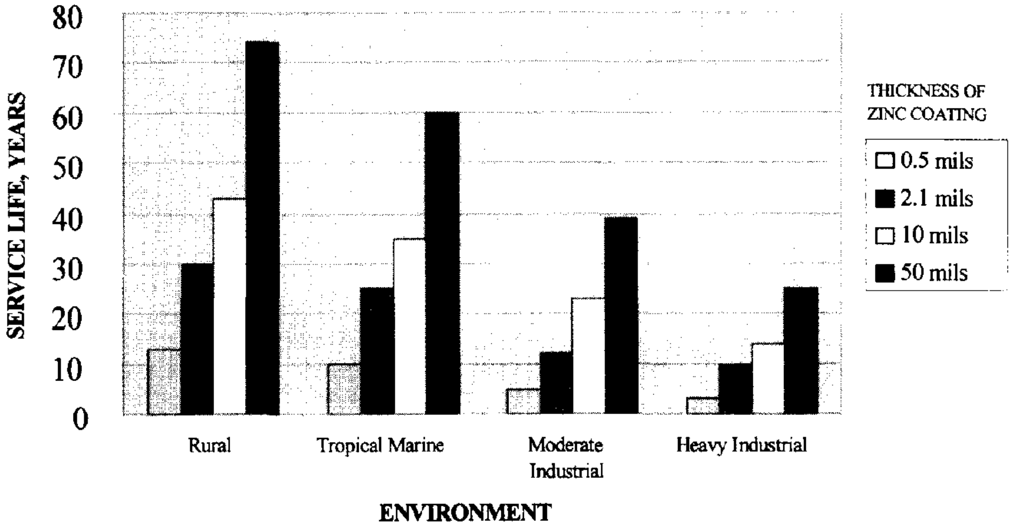

Figure 3. Expected service life of galvanized steel under different atmospheric conditions.(10)

The galvanizing industry in the United States is divided into two classes, namely fabrication and sheet galvanizing. Figure 4 shows the relative size of these markets (along with metallizing) on a monetary basis.(11) The fabrication business deals with structural components such as piping, I-beams, poles, handrails, and other heavy-duty steel products. The sheet business deals with galvanized sheet metal for equipment, roofing, panels, and other non-structural steel applications.

In 1998, fabrication industry sales were approximately $750 million.(11) This industry has grown in volume by an average of 8.4 percent over the past 4 to 5 years; however, the profitability of the galvanizing industry is directly tied to the commodity price of zinc, which has remained fairly steady at $1.06 to $1.15 per kg ($0.48 to $0.52 per lb) over the past 10 years. As in most industries, the production costs have gone up, but efficiencies have improved to offset the rising materials/labor costs.

According to the American Zinc Association, in 1999, sheet and strip galvanizing accounted for 540,000 metric tons of zinc.(11) The commodity price of zinc was $1,076 per metric ton, with an additional average premium of $60 per metric ton paid by manufacturers.

The cost for processing sheet steel into galvanized parts is dependent upon the facility; however, the cost ranges from $50 to $100 per metric ton of zinc.(12) Using a mid-range of $75 per metric ton for processing costs, in 1999, the total sheet galvanizing industry sales were $654 million.

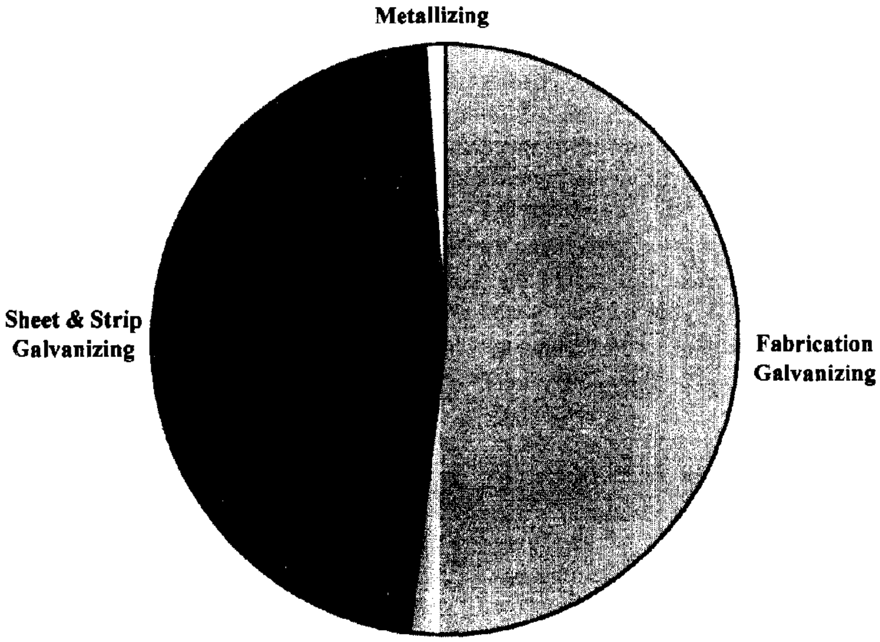

Figure 4. Relative market size for metallic coatings.(13)

While the profitability of galvanizing is linked to the zinc commodity price, the size of the market is controlled by the construction climate. Two growth markets have been identified by the American Galvanizers Association for the next several years. One is in the transition of utility poles from treated wood to galvanized steel. A joint effort of the steel manufacturers, the zinc suppliers, and the galvanizing industry is promoting this effort due to the environmental concerns over both the toxicity of the leachant from telephone poles and deforestation issues. The elimination of wooden poles in favor of galvanized steel poles would add another $200 million to $300 million for the galvanizing industry.

Another growth market, which is becoming increasingly popular, is the use of galvanized metal studs for home construction. This market is, of course, also tied to the home-building industry, which is closely related to the general economy of the United States.

Metallizing

Metallizing is defined as the application of very thin metallic coatings for either active corrosion protection (zinc or aluminum anodes) or as a protective layer (stainless steels and alloys). Application can be by flame spraying or electroplating. Other advanced processes, such as plasma arc spraying, can be used for exotic refractory metals for very demanding applications; however, most of the advanced processes are not utilized for corrosion control mechanisms.

The metallizing anode market ranges from $5 million to $10 million annually, and continues to grow due to the recognition by government agencies that life-cycle costs are important.(13)

Metals and Alloys

Corrosion-resistant alloys are used where corrosive conditions prohibit the use of carbon steels and where protective coatings provide insufficient protection or are economically not feasible. These alloys include stainless steels, nickel-based alloys, and titanium alloys. The total cost for these alloys used in corrosion control applications is $8.3 billion, with $7.9 billion for stainless steels, $0.28 billion for nickel-based alloys, and $0.15 billion for titanium alloys.

According to U.S. Census Bureau statistics, a total of 2.5 million metric tons of raw stainless steel was sold in the United States in 1997.(14) With an estimated cost of the raw stainless steel of $2.20 per kg ($1 per lb), the total annual production cost of $5.5 billion (1997 numbers) was calculated. It can be assumed that all production is for U.S. domestic consumption.(15) The total consumption of stainless steel also includes imports, which account for more than 25 percent of the U.S. market; therefore, the total consumption of stainless steel can be estimated at $7.5 billion. The 1998-end market consumption for stainless steel products is presented in table 8.(15) The table reviews the stainless steel products (sheet and strip, plate, bar, and pipe and tube) that are used by the various industrial consumers. The total volume for each product and industry sector is presented in metric tons, as well as percentages. The table shows the end-market consumption for various major industry sectors. The volume and percentage is given for both the total of the products and the individual product. The table indicates that the transportation sector is the highest user of stainless steel products at 23.8 percent of the total, with the food equipment and construction sectors at 15.3 and 14.2 percent, respectively. Notably, the oil and gas sector and chemical sector only had 1.4 percent users.

Table 8. End-market consumption of stainless steel in the United States for 1998 (in metric tons), as reported by Publications Resource Group.(15)

DESCRIPTION	SHEET & STRIP		PLATE		BAR		PIPE & TUBE		TOTAL	
	Metric Tons	%	Metric Tons	%	Metric Tons	%	Metric Tons	%	Metric Tons	%
CONSTRUCTION										
General	24,874	1.4	8,197	2.9	2,319	0.9	3,158	3.3	38,548	1.6
Roofing/Panels/Flooring/Etc.	115,472	6.4	21,273	7.6	7,254	3.0	12,365	12.8	156,364	6.5
Heating/AC	82,822	4.6	1,286	0.5	2,088	0.9	3,146	3.3	89,342	3.7
Window & Doors	16,177	0.9	205	0.1	190	0.1	180	0.2	16,752	0.7
Elevators/Moving Stairs	10,903	0.6	184	0.1	564	0.2	34	0.0	11,685	0.5
Plumbing	19,629	1.1	16	0.0	265	0.1	265	0.3	20,175	0.8
Arch/Ornamental/Hardware	5,988	0.3	1,228	0.4	449	0.2	2,644	2.7	10,309	0.4
Bridges/Highways	1,369	0.1	491	0.2	0	0.0	0	0.0	1,860	< 0.1
TOTAL	**277,234**	**15.4**	**32,880**	**11.7**	**13,129**	**5.4**	**21,792**	**22.6**	**343,175**	**14.2**
FOOD EQUIPMENT										
General	8,854	0.5	2,528	0.9	3,198	1.3	4,490	4.7	19,070	0.8
Beverage	6,566	0.4	64	0.0	10.	0.0	0	0.0	6,640	0.3
Food Machinery	139,618	7.7	25,157	9.0	21,974	9.0	18,490	19.2	205,239	8.5
Food Service Machinery	43,614	2.4	5,940	2.1	3,215	1.3	4,093	4.2	56,862	2.3
Cutlery/Utensil	38,102	2.1	0	0.0	6,867	2.8	0	0.0	44,968	1.9
Comm/Restaurant Equipment	15,269	0.8	60	0.0	0	0.0	0	0.0	15,329	0.6
Appliances	21,974	1.2	37	0.0	0	0.0	0	0.0	22,011	0.9
TOTAL	**273,997**	**15.2**	**33,786**	**12.1**	**35,264**	**14.4**	**27,073**	**28.1**	**370,119**	**15.3**
OIL/GAS - CHEMICAL										
General Chemical	2,135	0.1	2,354	0.8	2,412	1.0	749	0.8	7,650	0.3
General Petroleum	501	0.0	448	0.2	1,085	0.4	153	0.2	2,187	0.1
Oil & Gas Machinery	312	0.0	1,837	0.7	8,630	3.5	1,286	1.3	12,065	0.5
Oil & Gas Process Vessels	4,797	0.3	966	0.3	40	0.0	0	0.0	5,803	0.2
Other	4,542	0.3	920	0.3	26	0.0	139	0.1	5,627	0.2
TOTAL	**12,287**	**0.7**	**6,525**	**2.3**	**12,193**	**5.0**	**2,327**	**2.4**	**33,332**	**1.4**

Table 8. End market consumption of stainless steel in the United States for 1998 (in metric tons), as reported by Publications Resource Group[15] (continued).

DESCRIPTION	SHEET & STRIP		PLATE		BAR		PIPE & TUBE		TOTAL	
	Metric Tons	%	Metric Tons	%	Metric Tons	%	Metric Tons	%	Metric Tons	%
FABRICATED METAL PRODUCTS										
Containers	2,382	0.1	307	0.1	0	0.0	0	0.0	2,689	0.1
Plate Fabrication	50,787	2.8	72,885	26.0	5,415	2.2	6,882	7.1	135,969	5.6
Screw Machine Products	1,129	0.1	102	0.0	29,215	11.9	315	0.3	30,761	1.3
Fasteners	11,731	0.7	205	0.1	8,467	3.5	45	0.0	20,448	0.8
Stampings	94,803	5.3	6,142	2.2	2,204	0.9	270	0.3	103,419	4.3
Forgings	3,386	0.2	409	0.1	5,436	2.2	90	0.1	9,321	0.4
TOTAL	**164,218**	**9.1**	**80,050**	**28.6**	**50,737**	**20.7**	**7,602**	**7.9**	**302,607**	**12.5**
INDUSTRIAL/COMMERCIAL MACHINERY										
General Bearings	485	0.0	0	0.0	195	0.1	0	0.0	680	0.0
Const./Matl. Handling	6,638	0.4	3,062	1.1	2.592	1.1	375	0.4	12,667	0.5
Metal Working Equipment	917	0.1	43	0.0	395	0.2	1,030	1.1	2,385	0.1
Farm/Agriculture Machinery	26,271	1.5	6,123	2.2	2,273	0.9	2,233	2.3	36,900	1.5
Tools	1,678	0.1	0	0.0	704	0.3	0	0.0	2,382	0.1
Surgical/Hospital	1,434	0.1	0	0.0	247	0.1	0	0.0	1,681	0.1
Pumps/Values	60	0.0	0	0.0	1,356	0.6	0	0.0	1,416	0.1
Textile	5,607	0.3	5,205	1.9	4,287	1.8	3,654	3.8	18,753	0.8
Industrial Equipment	9,800	0.5	3,754	1.3	1,462	0.6	610	0.6	15,626	0.6
Comm./Ind. Equipment	551	0.0	0	0.0	18	0.0	136	0.1	705	0.0
Misc.	2,009	0.1	0	0.0	93	0.0	0	0.0	2,102	0.1
TOTAL	**55,450**	**3.1**	**18,187**	**6.5**	**13,622**	**5.6**	**8,038**	**8.3**	**95,297**	**3.9**
TRANSPORTATION										
Automotive – Mills	486,028	26.9	141	0.1	1,109	0.5	22	0.0	487,300	20.1
Automotive – Secs	62,154	3.4	13,864	5.0	7,175	2.9	3,436	3.6	86,629	3.6
Rail	478	0.0	0	0.0	0	0.0	0	0.0	478	0.0
Ship/Marine	94	0.0	0	0.0	0	0.0	3	0.0	97	0.0
Aircraft	1,412	0.1	0	0.0	436	0.2	231	0.2	2,079	0.1
TOTAL	**550,166**	**30.5**	**14,005**	**5.0**	**8,720**	**3.6**	**3,692**	**3.8**	**576,583**	**23.8**
ELECTRIC										
TOTAL	**80,125**	**4.4**	**2,882**	**1.0**	**5,238**	**2.1**	**995**	**1.0**	**89,240**	**3.7**
FURNITURE & FIXTURES										
TOTAL	**9,803**	**0.5**	**50**	**0.0**	**150**	**0.1**	**324**	**0.3**	**10,327**	**0.4**
PULP & PAPER										
TOTAL	**2,951**	**0.2**	**14,096**	**5.0**	**7,531**	**3.1**	**1,273**	**1.3**	**25,851**	**1.1**
MEASURE/ANALYZE										
TOTAL	**14,526**	**0.8**	**1,159**	**0.4**	**9,052**	**3.7**	**1,905**	**2.0**	**26,642**	**1.1**
ELECT./GAS/SANITARY										
TOTAL	**962**	**0.1**	**1,894**	**0.7**	**1,244**	**0.5**	**143**	**0.1**	**4,243**	**0.2**
ALL OTHERS/NOT CLASSIFIED										
TOTAL	**208,636**	**11.6**	**44,956**	**16.1**	**85,686**	**35.0**	**20,472**	**21.2**	**359,750**	**14.8**
CONVERSION (PIPE & TUBE)										
TOTAL	**153,844**	**8.5**	**29,379**	**10.5**	**1,993**	**0.8**	**862**	**0.9**	**186,078**	**7.7**
OVERALL TOTAL	**1,804,199**	**100.0**	**279,849**	**100.0**	**244,559**	**100.0**	**96,498**	**100.0**	**2,425,105**	**100.0**

The total volume of products used in 1998 was 2,423,245 metric tons. A survey of stainless steel product suppliers indicated that the average price for the products listed in the table is $3.25 per kg ($1.45 per lb); therefore, the total cost of stainless steel products in 1998 was estimated at $7.9 billion, which closely approximates the estimate for the U.S. Census Bureau.

Where environments become particularly severe nickel-based and titanium alloys are used. Nickel-based alloys are used extensively in the oil production and refinery, and the chemical process industries, where conditions are aggressive. Furthermore, there is an increased use of these alloys in other industries where high-temperature and/or corrosive conditions exist. The annual average price of nickel has steadily increased from less than $2.20 per kg ($1 per lb) in the 1960s to about $4.40 per kg ($2 per lb) in 1998 (see figure 5).(16) The price of nickel, shown in figure 5, depends very much on global, political, and economic conditions. For example, in 1990, during the Persian Gulf War, there was a sharp increase in price, followed by a sharp decrease in price. In addition, following the dissolution of the Soviet Union in 1991, there was a sharp increase in exports of Russian nickel. In the late 1990s, stainless steel production accounted for more than 60 percent of the world nickel consumption and was the primary factor in nickel pricing. Chromium and molybdenum are also common alloying elements for both corrosion-resistant nickel-based alloys and stainless steels. The price of chromium has steadily increased from $2 per kg ($2,000 per metric ton) in the 1960s to nearly $8 per kg ($3.6 per lb) in 1998 (see figure 6), while the price of molybdenum has remained relatively constant at approximately $5 per kg (see figure 7).(17) Again, the prices of these metals are sensitive to major global events.

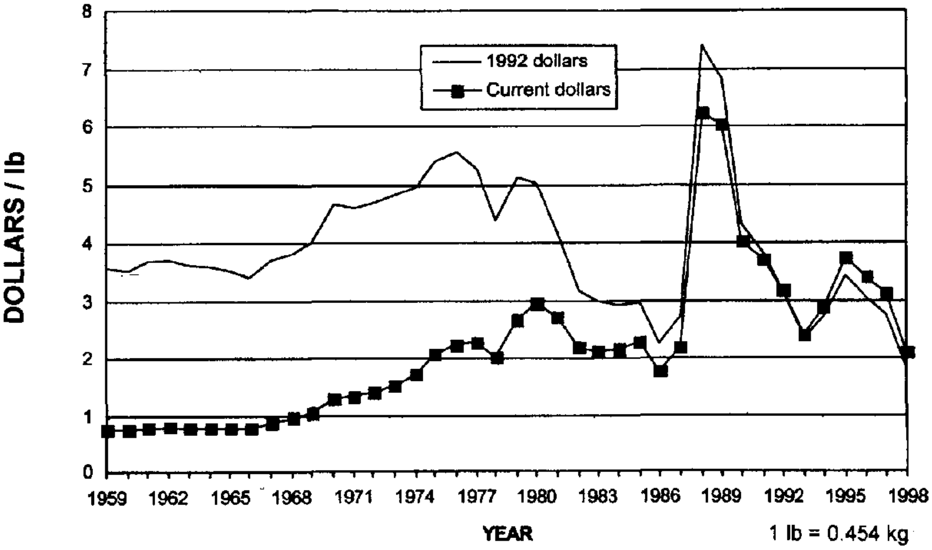

Figure 5. Annual average nickel price (dollars per lb).(16)

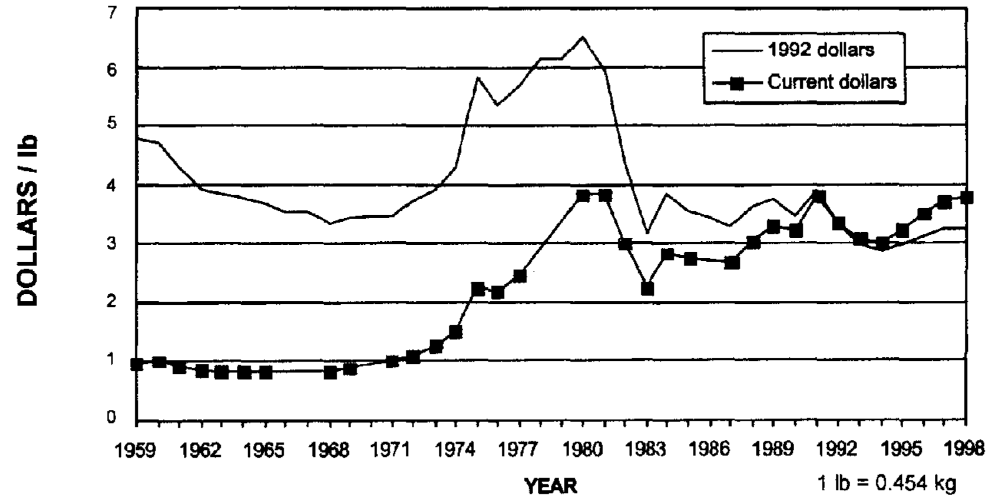

Figure 6. Annual average chromium price (dollars per lb).[7]

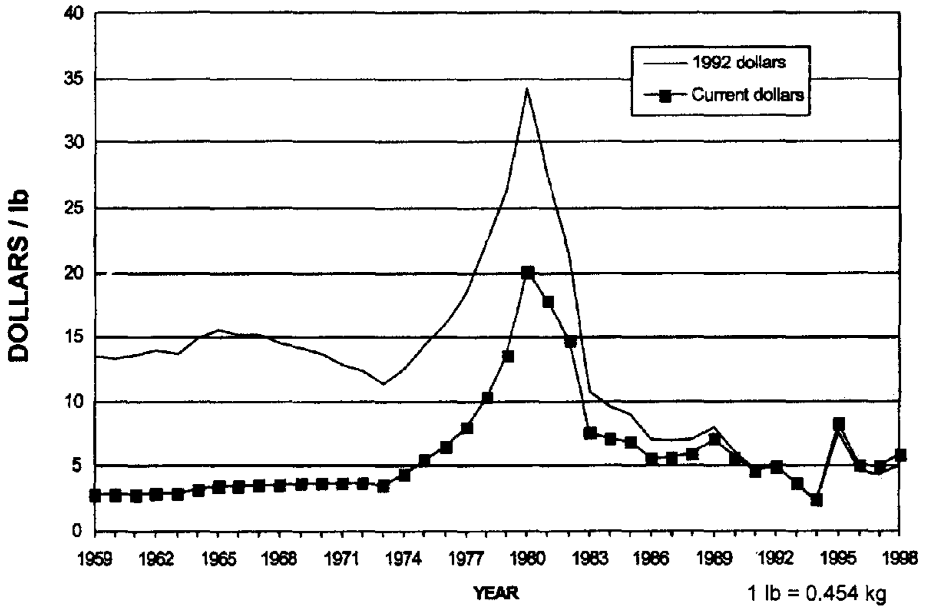

Figure 7. Average molybdenum concentrate price (dollars per lb).[7]

The 1998 average price for nickel-based alloys was $13 per kg ($6 per lb).[18] Nickel-based alloys are limited to those containing 24 percent or more nickel, and include low-nickel alloys such as alloys 825, 25-6 Mo, and AL 6XN and high-nickel alloys such as alloys C-2000, C-22, 625, 686, and 59. The total value of 1999 sales in the United States was estimated at $285 million. This number has remained relatively steady from 1995 through 1999.

The primary use of titanium alloys is in the aerospace and military industry where the high strength-to-weight ratio and the resistance to high temperatures are properties of interest; however, titanium and its alloys are also corrosion-resistant to many environments and have, therefore, found application in the oil production and refinery, chemical process, and pulp and paper industries. In 1998, it was estimated that 65 percent of mill products were used for aerospace applications and 35 percent were used for non-aerospace applications.(19) The most common metal form of titanium is titanium sponge, which is produced in the United States, China, Japan, Russia, and Kazakhstan. The price of titanium sponge has increased from less than $4.40 per kg ($2 per lb) during the 1960s to more than twice that amount during the 1980s and the 1990s (see figure 8).(19) The price of titanium is particularly sensitive to the aerospace industry. As a result of a military aircraft production peak and a rapid increase in commercial aircraft orders in the late 1970s, the price of titanium went up sharply, but fell following a collapse of the commercial aircraft market in the early 1980s.

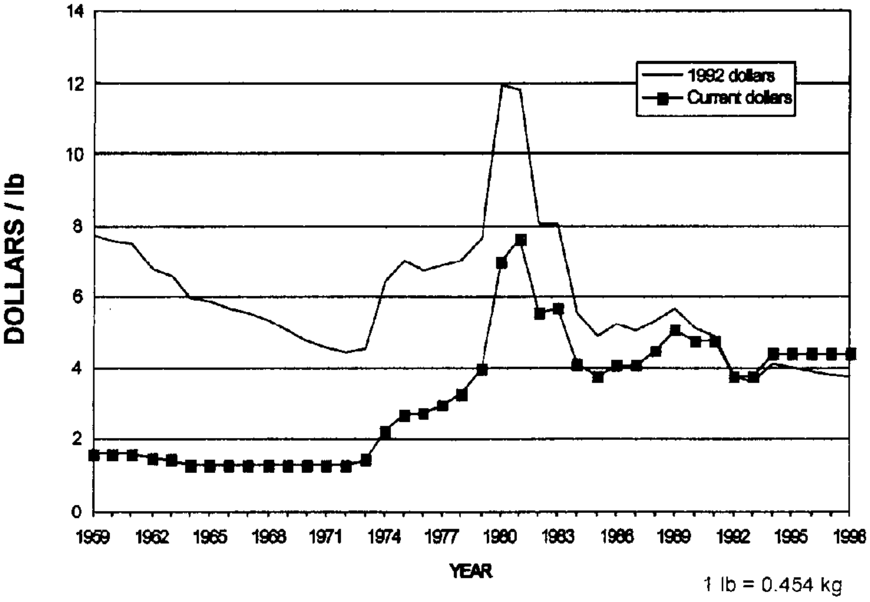

Figure 8. Average titanium sponge price (dollars per lb).

In 1998, the domestic operating capacity of titanium sponge was estimated at 21,600 metric tons per year. The total domestic consumption of titanium sponge was 39,100 metric tons, which at a price of approximately $10 per kg, set the total price at $391 million. In addition, 28,600 metric tons of scrap were used for domestic consumption at a price of approximately $1 per kg, setting the total price at $420 million. As mentioned previously, only 35 percent of mill products were used for non-aerospace applications, which leads to a consumption price estimate of $150 million for titanium and titanium alloys for corrosion control applications.

Corrosion Inhibitors

General Description

A corrosion inhibitor may be defined, in general terms, as a substance which, when added in a small concentration to an environment, effectively reduces the corrosion rate of a metal exposed to that environment. Because there are a number of mechanistic and/or chemical considerations when classifying inhibitors, it is difficult to provide a more precise definition.

In most cases, inhibition is achieved through interaction or reaction between the corrosion inhibitor and the metal surface, resulting in the formation of an inhibitive surface film. In other cases, the chemistry of the environment may be modified to make it less corrosive, whether by adjusting the pH to promote passivation, scavenging dissolved oxygen, or neutralizing acidic species. Anodic inhibitors such as chromates, phosphates, and nitrites are designed to interfere with the corrosion reaction at the anodic site. Cathodic inhibitors such as carbonates and arsenates are designed to reduce net current flow by inhibiting the cathodic reaction. The film-forming organic inhibitors (amines, imidazolines) may be anodic or cathodic or both.

Inhibition is used internally with carbon steel pipes and vessels as an economic corrosion control alternative to stainless steels and alloys, coatings, or non-metallic composites. A particular advantage of corrosion inhibition is that it can be implemented or changed *in situ* without disrupting a process. For example, in processes that produce environments of increasing corrosivity with time, such as "souring" oil fields, corrosion can be effectively controlled with the proper inhibitor.

The major industries that use corrosion inhibitors are petroleum production and refining, chemical and heavy industrial manufacturing, and the product additive industry. The usage summary of 1998 consumption among the major markets is shown in table 9.(20)

Table 9. 1998 U.S. consumption of corrosion inhibitors in various industries, as reported by the Society of Plastics Industry.(20)

END-USE INDUSTRY	**1998 CONSUMPTION**		
	(kg x million)	**(lb x million)**	**($ x million)**
Petroleum Refining	248.1	547	246
Petroleum Production and Drilling	63.0	139	153
Petroleum Storage and Transport	15.4	34	31
Pulp and Paper	182.8	403	198
Chemical Manufacturing	272.2	600	180
Iron and Steel	57.2	126	50
Miscellaneous material handling (includes food processing, utilities, and institutions)	132.9	293	88
Additives to petroleum products	54.4	120	108
Automotive and fuel additives, others	4.5	10	12
TOTAL	**1,030.5**	**2,272**	**$1,066**

The table indicates that the largest consumption of corrosion inhibitors is in the oil industry, with the single highest number for the petroleum refining industry. The use of corrosion inhibitors has increased significantly since the early 1980s. Figure 9 shows that in 1998, the total consumption of corrosion inhibitors in the United States was nearly $1.1 billion.

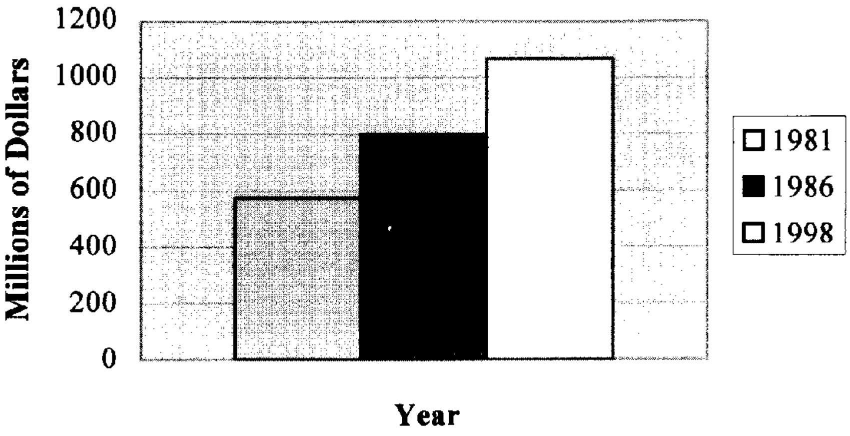

Figure 9. Total U.S. consumption of corrosion inhibitors in 1981, 1986, and 1998.(20)

Figure 10 shows the change in inhibitor usage in the past 20 years for three of the largest industrial sectors, namely, the oil production, chemical, and refining industries. Notice that the increase in inhibitor usage for petroleum production in 1986 occurred during the time that the U.S. oil industry suffered a downfall due to the increase in oil prices to above $30 per barrel. This was followed by a significant drop in prices during the second half of the 1980s. With the 1998 oil prices lowering to values below $10 per barrel by year's end, domestic production dropped. Consequently, this coincided with the drop in inhibitor usage for drilling and production.

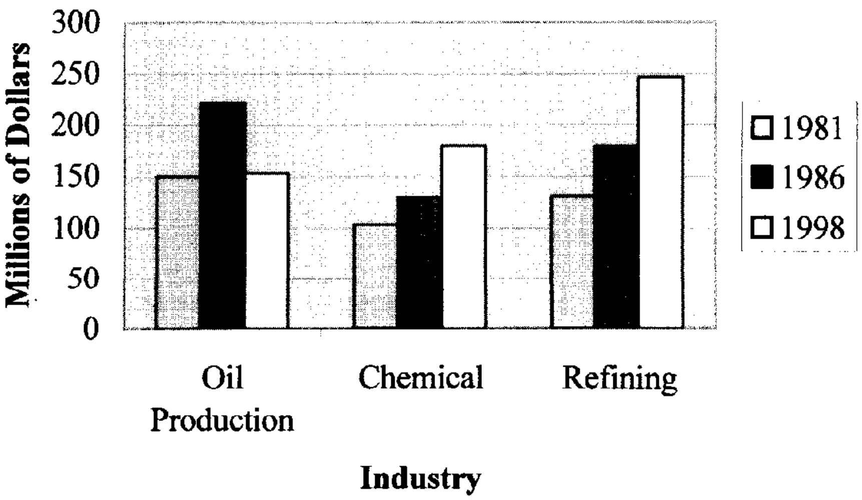

Figure 10. Consumption of corrosion inhibitors by industry in 1981, 1986, and 1998.(20)

In the following section, the use of corrosion inhibitors for various key industries is discussed, including petroleum production, transportation and refining, pulp and paper, iron and steel production, and additives.

Industry Applications

Petroleum Production, Transportation, and Refining

The consumption of inhibitors in the petroleum industry is directly tied to the size of the petroleum-based products market. This, in turn, is tied to the price of crude oil. Overall consumption of gasoline in the United States has increased only slightly since 1980. While there are more cars on the road, the average consumption per car has declined. Increasing quantities of crude oil on a relative basis are being imported from foreign sources, particularly the Middle East.

The increased import of foreign oil results in a reduction in the amount of inhibitor used by the U.S. oil companies in the production sector, but not in the refining sector. Quite often, the petroleum production and refining industries run in opposite economic cycles. When the crude oil price is high, domestic production is profitable; however, the profit margin on refining is lowered. Conversely, when oil prices are low, refinery feedstock is cheap and the production of refined products and specialty chemicals results in a higher profit, since consumption of the products is only slightly tied to oil prices.

Upstream oil production uses inhibition for drilling operations (as an ingredient in drilling fluids to preserve the equipment) as well as in permanent production tubulars and pipelines, where two- and three-phase production streams are treated with film-forming inhibitors. The amount used ($153 million) in production is dependent upon the amount of water produced with the oil. The economics of such a system are calculated as cost per barrel of oil or water produced. This has been estimated, in the lower 48 states, to range from $0.02 per barrel of oil produced to $0.23 per barrel of oil produced, depending on factors such as temperature, corrosive gases present, and operating procedures.

Refinery operations utilize the highest amount of inhibitors ($246 million), primarily due to the higher temperature processes encountered in refining operations. Not only do process and boiler water streams require inhibition, but also process environments create acids such as HCl, which must be neutralized with pH-modifying inhibitors. Imported oils from Middle East sources tend to be sour (containing sulfur) and are more corrosive; therefore, in terms of per barrel of oil refined, costs for inhibition for production crudes are expected to increase. An annual rate of increase in the refining sector has been predicted to be approximately 2.5 percent.

The cost of inhibitors for petroleum storage and transportation is approximately $31 million, which is tied to the price of oil since new pipelines are only built when oil prices are high enough to justify the costs of construction and operation. As domestic oil exploration and production moves farther offshore and to more remote areas without an existing pipeline infrastructure, the need for new pipelines will continue, but only if the oil prices remain at a high enough level to sustain the increased operating costs far offshore.

Pulp and Paper

The majority of the corrosion in the pulp and paper industry is in the papermaking process, which uses large quantities of process water. Pulp and paper consumption of corrosion inhibitors from 1996 to 1998 increased an average of 2 percent per year. In 1998, the total spent on corrosion inhibitors was $198 million.

Over the past 25 years, the pulp and paper industry has moved from open-water systems to closed-loop systems, thereby increasing the severity of the environment. These "white liquors" are acidic and corrosive, and crevice corrosion problems can be severe whenever the process flow is halted.

The paper industry in the United States is a mature industry, but is expected to maintain steady growth in the coming years. The demand for paper products is closely related to the growth of the economy and disposable income. Most paper is consumed by packaging, printing, publishing, and business communications, which are tied directly to business expansions. Likewise, consumption of cardboard and paper shipping containers is tied to the demand for industrial production.

Competitive materials and technologies (i.e., plastics for packaging and electronic publications / communications) are encroaching on traditional markets for paper products. While these are not realistically expected to replace paper (although the term "paperless system" is currently popular), they will curtail growth in the paper market.

Iron and Steel

The U.S. production of raw steel in the 1990s is plotted in figure 11. Inhibitor usage in 1998 was $50 million. Inhibitors used in the production of steel are expected to increase only slightly (1 to 1.5 percent) in the near future. Like most systems requiring inhibition, the water treatment piping and vessels in both cooling and boiler water systems are the most affected.

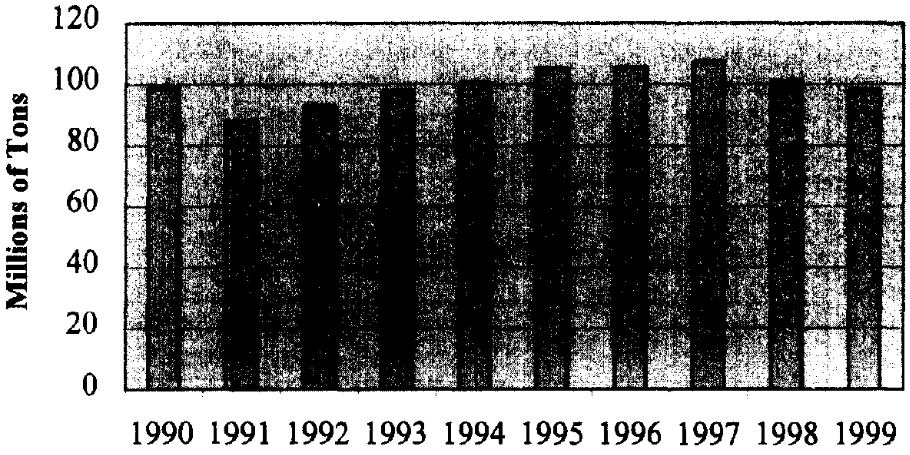

Figure 11. Production of raw steel in the United States in the 1990s.(20)

Additives

The applications of corrosion inhibitor additives are primarily for petroleum products such as gasoline, motor oil, and grease. Other inhibiting additives include antifreeze and coolants, brake fluids, fuel additives, and plant cleaning and metalworking fluids.

Of the $120 million market for corrosion-inhibiting additives, $90 million is spent on an additive that is used for 568 billion L (150 billion gals) of motor fuel (gasoline and diesel). Consumption of gasoline, as previously mentioned, is growing at a slow rate due to a steady increase in the fuel-efficiency of automobiles since the early 1980s.

A potentially lucrative market for corrosion inhibitors exists in deicers used on streets and bridges in many northern states. These deicers, which consist of rock salt with calcium carbonate, cause corrosion damage not only to automobiles, but also to steel and steel reinforcements in bridges, light stanchions, and underground pipes and cables. The technical challenge is to formulate an inhibitor, which is not only non-toxic to the environment, but is also economical enough to be attractive for city budgets.

Engineering Composites and Plastics

In 1996, the plastics industry accounted for $274.5 billion in shipments.(21) It is difficult to estimate the use of plastics for corrosion control, since in many cases, plastics and composites are used for a combination of reasons, including corrosion control, light weight, economics, strength-to-weight ratio, and other unique properties.

Certain polymers are used largely, if not exclusively, for corrosion control purposes. The significant markets for corrosion control by polymers include composites (primarily glass-reinforced thermosetting resins), PVC pipe, polyethylene pipe, and fluoropolymers.

Composites

Composites, in terms of corrosion control, generally refer to glass- or other fiber- or flake-reinforced thermosetting resins. Composite products utilized for their anti-corrosion properties include fiberglass-reinforced pipe and storage tanks, fiber-reinforced plastic grating, handrails, I-beams, and other shapes equal to these that are made of steel.

The Composites Institute, a division of the Society of Plastics Industry, Inc., estimates that composite shipments in 1998 were 1.63 billion kg (3.59 billion lb), an increase of 53 percent since 1991.(22) Table 10 shows the distribution of composite shipments according to industry sectors and indicates that the largest percentage of these shipments is to the transportation and construction sectors. Corrosion-resistant applications account for only 11.8 percent.

Table 10. Distribution of composite shipments.(22)

INDUSTRY SECTORS	PERCENTAGE OF SHIPMENTS
Transportation	31.6
Construction	20.8
Marine	10.1
Electrical/Electronic	10.0
Appliances and Business Equipment	5.5
Consumer Goods	6.3
Aircraft	0.6
Corrosion-Resistant Applications	11.8
Other	3.3
TOTAL	**100%**

The cost of composites was estimated by one major manufacturer of fiber-reinforced plastics (FRP) for corrosion-resistant applications to be $9.70 per kg ($4.41 per lb).(23) This correlates to a total dollar value of $1.864 billion (0.118 x 3.59 billion lb x $4.41 per lb) spent on composites in the United States for industrial corrosion-resistant applications.

One product, which is representative of composites used for corrosion control reasons, is fiberglass pipe. The fiberglass pipe market in the United States is estimated to be $350 million.(24) Approximately a third of this market is in oil and gas production, 25 percent is in gasoline transportation and storage, and 15 percent is in the petrochemical industry. Offshore, the light weight of fiberglass pipe provides another advantage aside from corrosion protection; however, the offshore market is very small in comparison.

Because the composites are a replacement for steel, the total dollar amount spent on composites cannot entirely be considered a cost of corrosion. Only the difference in installed cost between steel and FRP can be used to estimate the cost of corrosion.

For a pipe less than 20-cm (8-in) in diameter, the installed cost of FRP pipe is 50 percent higher compared to steel pipe, while for 20-cm to 40-cm (8-in to 16-in) pipe, the installed cost of FRP is about the same as that of steel pipe. For a pipe larger than 40 cm (16 in) in diameter, the installed cost works out to be less than that of steel pipe. Overall, the installed cost of an FRP pipe is approximately 30 percent higher than the installed cost of steel.(24) Because the pipe is used in place of steel, the 30 percent extra cost is the actual cost of corrosion; therefore, the annual contribution to the total cost of corrosion by composites is $1.864 billion x 30 percent = $559 million annually.

Plastics

Polyvinyl Chloride

Polyvinyl chloride (PVC) pipe was first developed in World War II by German scientists to replace civilian water pipes destroyed by allied bombings in German cities. Since this time, the PVC piping industry has grown into a major market force. A total of 6.6 billion kg (14.5 billion lb) of PVC resin was produced in the United States in 1998, of which 907 million kg (2 billion lb) are used for the manufacture of PVC pipe. For buried pipes 10.2 cm (4 in) in diameter and larger, which includes water, sanitary, and storm sewers, 137,500 km (86,000 mi) of PVC were produced in 1997 worth a total of $1 billion.(25)

PVC pipes have numerous advantages over steel pipes, including corrosion resistance. Other advantages include light weight, ease of fabrication (no welding required), and ease of installation (no torch cutting required); therefore, the figures on the total dollar amount of PVC pipes are not a direct cost of corrosion. The industry, however, has become a significant player, largely because of its resistance to corrosion. The cost attributable to corrosion is approximately $500 million.

Polyethylene

Polyethylene is the most used polymeric material in the United States. More than 12.2 billion kg (27 billion lb) of polyethylene resin was produced in the United States in 1998, 30 percent of the total of all plastics produced domestically. While chemical inertness is a major attraction of polyethylene, most is not used in corrosion control applications.(26) Only polyethylene pipe can be considered a significant corrosion-resistant market for this material (see table 11).

Table 11. The use of polyethylene pipe by industry in the United States in 1998, as reported by the Tube and Conduit Plastic Pipe Institute.(26)

APPLICATION	QUANTITY	
	(kg x million)	(lb x million)
Potable Water	30.4	67
Irrigation/Agriculture	15.4	34
Gas Distribution	94.3	208
Oil/Gas Production	51.7	114
Industrial/Sewers	94.8	209
Other	62.1	137
TOTAL	**348.7**	**769**

On a dollar basis, the commodity price of polyethylene pipe is $1.32 per kg ($0.60 per lb). This translates into a total cost of $461.4 million of polyethylene pipe sold in the United States. This is considered a corrosion-related cost.

Fluoropolymers

Fluoropolymers include all polymers that contain fluorine side groups in their molecular structure. The high electronegativity of fluorine offers both excellent high-temperature stability and chemical resistance.

Polytetrafluoroethylene, known by the trade name Teflon, is the best known of all of the fluoropolymers. Other fluoropolymers have found a niche in the petrochemical and specialty chemical market due to improved physical and mechanical properties. Cost is a major concern with any of the fluoropolymers. On a weight basis, their cost is 50 to 65 times that of polyethylene. The fraction of fluoropolymers most used for corrosion in 1997 was estimated at $560 million.(27)

In summary, the fraction of polymers used for corrosion control in 1997 was as follows:

Composites	$559 million
PVC (pipe)	$500 million
Polyethylene (pipe)	$461 million
Fluoropolymers	$560 million
TOTAL	$2,080 million

Cathodic and Anodic Protection

The cost of cathodic protection (CP) and anodic protection of metallic structures subject to corrosion can be divided into the cost of materials and the cost of installation and operation. Industry data have provided estimates for the 1998 sales of various hardware components totaling $146 million (see table 12).(28-29)

Table 12. Total cost of components for cathodic and anodic protection (includes materials only).(28-29)

COMPONENTS	COST ($ x million)
Rectifiers	15
Impressed-Current CP Anodes	25
Sacrificial Anodes	60
Cable	6
Accessories	40
TOTAL COST	**$146**

The largest share of the CP market is taken up by sacrificial anodes at $60 million, of which magnesium has the greatest market share. The costs of installation of the various components vary significantly depending on location and the specific details of the construction. Table 13 shows the range of cost for labor plus materials and the number of installations for the various systems in 1998. The table shows that the cost for CP installation in 1998 ranged from $0.73 billion to $1.22 billion per year (average $0.98 billion).

A major market for sacrificial anodes, which is not included in table 13, is the domestic water heater market. Currently, there are approximately 104 million water heaters in use. If it is assumed that 5 percent of all water heaters get their anodes replaced each year and that the cost to install a magnesium anode in a typical water heater is $150, then an annual expenditure of $780 million can be estimated. Annually, approximately 9.2 million water heaters are replaced.(30) Assuming that 5 percent of the water heater replacements are due to corrosion and an average replacement cost of $1,000, an annual expenditure of $460 million can be estimated. Adding the average for CP costs ($0.98 billion) and the cost of domestic water heater anodes ($1.24 billion) results in a total cost of $2.22 billion per year.

Table 13. Cost of installation of cathodic protection systems (includes labor and materials).(29,31)

INSTALLATION	COST RANGE PER INSTALLATION ($ x thousand)	ESTIMATED ANNUAL NUMBER OF INSTALLATIONS (for 1998)	TOTAL COST RANGE ($ x billion)
Rectifier (replacement)	1.5 – 2.5	800 rectifiers	0.0012 – 0.002
Impressed-Current CP (ICCP) groundbed, including rectifier and 10 anodes per bed	8 – 12	6,000 ICCP groundbeds	0.048 – 0.072
Galvanic groundbed with magnesium anodes (10 anodes per bed)	0.35 – 0.6**	1,000,000 anodes	0.35 – 0.6
CP on underground storage tank (3 USTs with 1 ICCP system)	6 – 10	50,000* UST-CP systems	0.3 – 0.5
CP on aboveground storage tank (37-m-diameter AST)	15 – 25	2,000 AST-CP systems	0.03 – 0.05
		TOTAL	**$0.73 – $1.22**
			Average: $0.98 billion / year

*1998 was a "big" year for CP on USTs due to the compliance deadline by the Environmental Protection Agency (EPA) (see Appendix G, "Hazardous Materials Storage"). Every year since, the number of installations has been approximately 2,000.

**Cost range was estimated from anode bed with 10 anodes, at a total cost of $3,500 to $6,000 per bed.

A detailed analysis of the cost of CP on underground and aboveground storage tanks is given in Appendix G, "Hazardous Materials Storage" in this report.

Services

In the context of this report, services are defined as companies, organizations, and individuals that are providing their services to control corrosion. When taking the National Association of Corrosion Engineers (NACE) International membership as a basis for this section, a total number of engineers and scientists that provide corrosion control services may be extrapolated. In 1998, the number of NACE members was approximately 16,000, 25 percent of whom are providing consulting and engineering service both externally and internally. Assume that the average revenue generated by each is $300,000. This number includes salary, overhead, and benefits for the NACE member, as well as the cost to persons who are non-members in performing corrosion control activities. The total services cost can be estimated as $1.2 billion. This number, however, is conservative since many engineers who follow a career in corrosion are not members of NACE.

Research and Development

It has been observed that over the past few decades, less funding has been made available for corrosion-related research and development. This is significant in light of the cost and inconvenience of dealing with leaking and exploding underground pipelines, bursting water mains, corroding storage tanks, and aging aircraft. In fact, several government and corporate research laboratories have significantly reduced their corrosion research capabilities or even have closed down. Moreover, less research and development funding has been available from both government and private sources.

Corrosion research can be divided into academic and corporate research. NACE International has listed 114 professors under the heading of corrosion research. Assuming an average annual corrosion research budget of $150,000, the total academic research budget is less than $20 million.

As discussed elsewhere in more detail, corporate research in the area of corrosion has decreased dramatically to the point where only a few companies support a corporate group dedicated to corrosion research. More companies conduct product and materials testing.

Education and Training

Corrosion-related education and training in the United States includes degree programs, certification programs, company in-house training, and general education and training. A few national universities offer courses in corrosion and corrosion control as part of their engineering curriculum. Professional organizations such as NACE International (The Corrosion Society)(32) and SSPC (The Society for Protective Coatings)(33) offer courses and certification programs that range from basic corrosion to coating inspector to cathodic protection specialist. NACE International offers the broadest range of courses and manages an extensive certification program. In 1998, NACE held 172 courses with more than 3,000 students, conducted multiple seminars, and offered publications, at a total cost of $8 million.(34)

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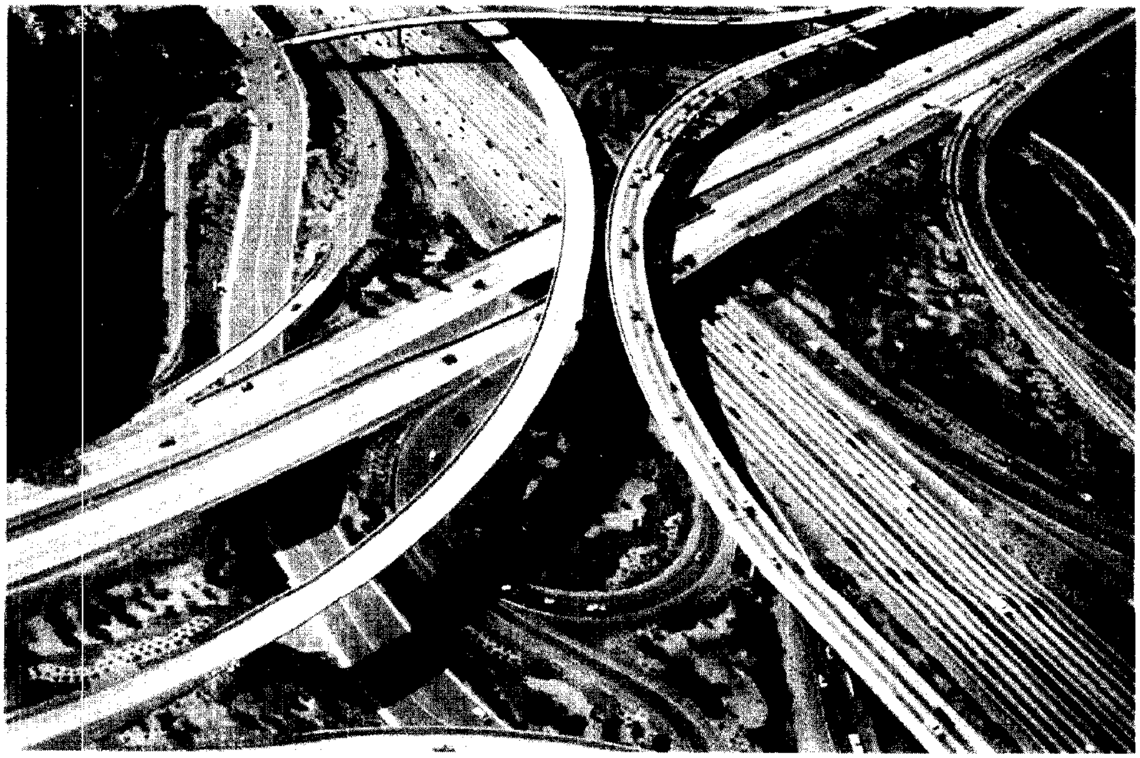
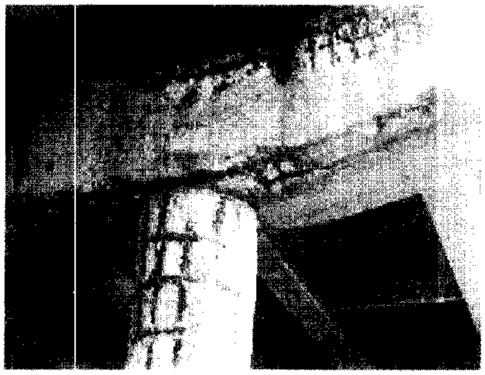
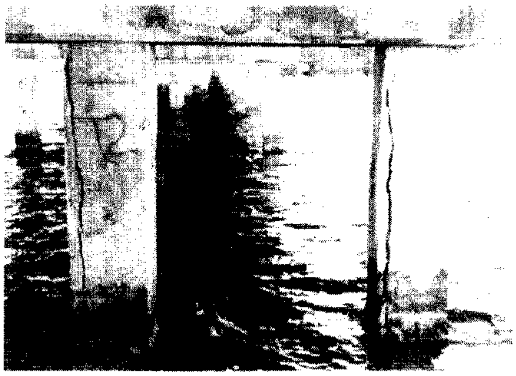
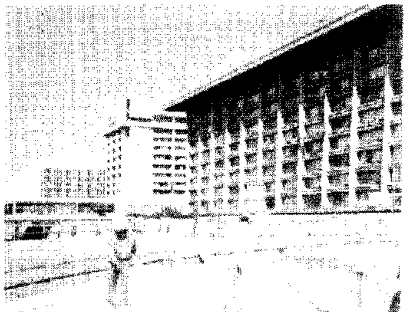
APPENDIX D

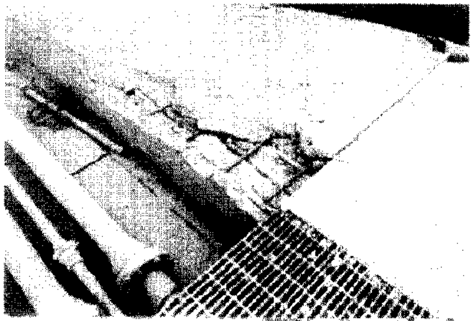
HIGHWAY BRIDGES




Corroded bridge column


Cracking and spalling of piers in marine environment

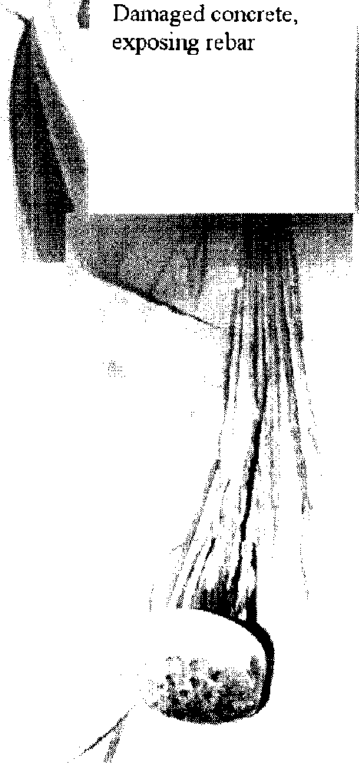



Damaged concrete, exposing rebar

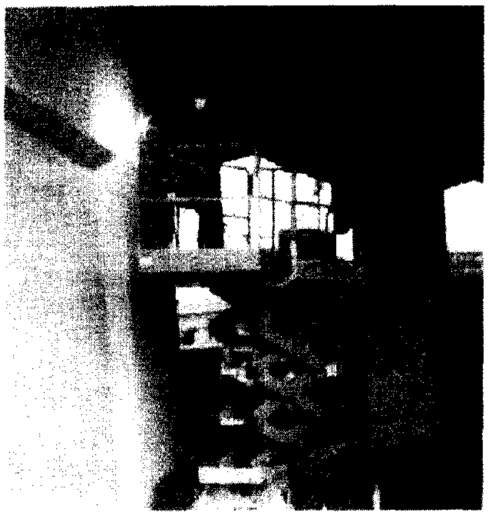
Condition assessment

Corroded rebar

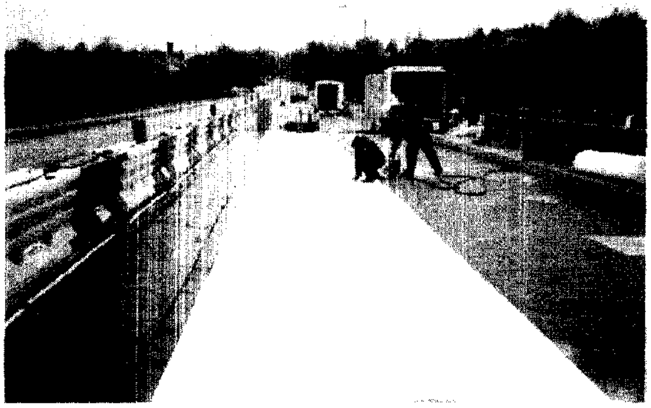

Corroded concrete column


Failed strands

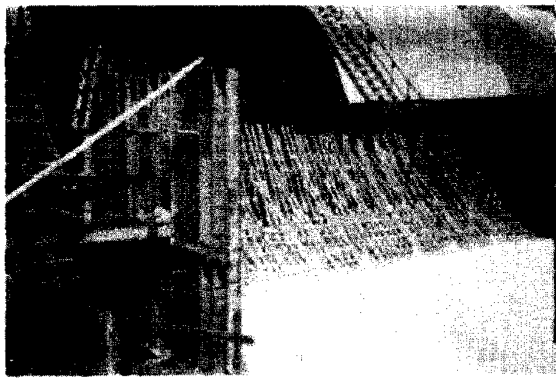

Corrosion in the free length of tendon



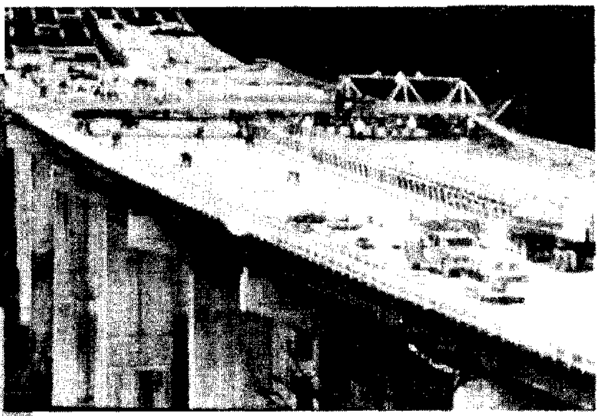
Application of thermal spray metal coating as sacrificial anode system on bridge pier



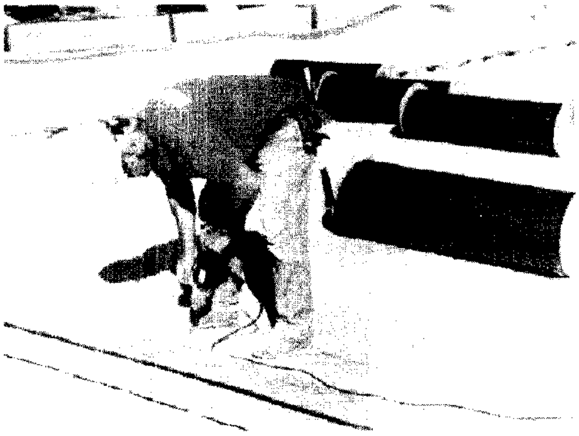
Deck installation of titanium mesh and synthetic felt anode system on bridge deck.



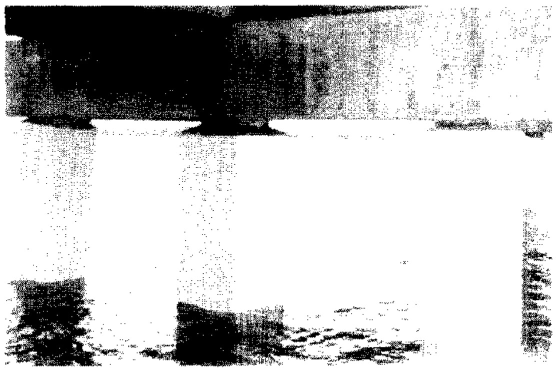
ALSEA bridge, Oregon, with epoxy-coated rebar substructure



Epoxy-coated rebar construction on deck



Installation of titanium mesh impressed-current anode system on bridge deck



Sacrificial CP applied to pier columns in marine environment

APPENDIX D

HIGHWAY BRIDGES

MARK YUNOVICH,[1] NEIL G. THOMPSON, PH.D.,[1] TUNDE BALVANYOS, PH.D.,[2] AND LESTER LAVE, PH.D.,[2]

SUMMARY AND ANALYSIS OF RESULTS

Corrosion Control and Prevention

Cost of Corrosion

The dollar impact of corrosion on highway bridges is considerable. The annual direct cost of corrosion for highway bridges is estimated to be $6.43 billion to $10.15 billion, consisting of $3.79 billion to replace structurally deficient bridges over the next 10 years, $1.07 billion to $2.93 billion for maintenance and cost of capital for concrete bridge decks, $1.07 billion to $2.93 billion for maintenance and cost of capital for concrete substructures and superstructures (minus decks), and $0.50 billion for the maintenance painting cost for steel bridges. This gives an average annual cost of corrosion of $8.29 billion. Life-cycle analysis estimates indirect costs to the user due to traffic delays and lost productivity at more than 10 times the direct cost of corrosion. In addition, it was estimated that employing "best maintenance practices" versus "average practices" can save 46 percent of the annual corrosion cost of a black steel rebar bridge deck, or $2,000 per bridge per year.

While there is a downward trend in the percentage of structurally deficient bridges (a decrease from 18 percent to 15 percent between 1995 to 1999), the costs to replace aging bridges increased by 12 percent during the same period. In addition, there has been a significant increase in the required maintenance of the aging bridges. Although the vast majority of the approximately 108,000 prestressed concrete bridges have been built since 1960, many of these bridges will require maintenance in the next 10 to 30 years. Therefore, significant maintenance, repair, rehabilitation, and replacement activities for the nation's highway bridge infrastructure are foreseen over the next few decades before current construction practices begin to reverse the trend.

Conventional Reinforced-Concrete Bridges

The primary cause of reinforced-concrete bridge deterioration is chloride-induced corrosion of the black steel reinforcement, resulting in expansion forces in the concrete that produce cracking and spalling of the concrete. The chloride comes from either marine exposure or the use of deicing salts for snow and ice removal. Because the use of deicing salts is likely to continue, if not increase, little can be done to prevent bridge structures from being exposed to corrosive chloride salts. Therefore, bridge designs and concrete mixes must be resistant to chloride-induced corrosion. This can be accomplished by: (1) preventing chlorides from getting to the steel surface (physical barriers at the concrete surface, coating the rebar, or low chloride-permeable concrete), (2) making the concrete less corrosive at specific chloride levels (inhibitors or admixtures), or (3) making the rebar resistant to corrosion (corrosion-resistant alloys, composites, or clad materials).

Over the past 20 years, there has been a trend in new construction toward utilizing higher quality concrete and more corrosion-resistant rebars. Longer bridge service life is currently achieved by using epoxy-coated rebars

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[2] Carnegie Mellon University, Pittsburgh, Pennsylvania.

in the majority of new bridge construction, with the limited use of stainless steel-clad or solid rebars in more severe environments. The expected service life of a newly constructed bridge is typically 75 years and up to 120 years for stainless steel rebar construction. Admixtures to the concrete for the purpose of increased corrosion resistance have included corrosion-inhibiting admixtures and mineral admixtures such as silica fume. High-range water reducers permit the use of low water-cement ratio concretes that have lower permeability to corrosive agents and, thus, result in longer times to corrosion initiation of the rebar. Many of these methods are used in combination with each other to obtain a longer service life.

Many rehabilitation methodologies designed to extend the service life of bridges that have deteriorated due to corrosion of the reinforcing steel have been developed and put into practice within the past 25 years. These include cathodic protection, electrochemical chloride removal, overlays, and sealers. Although each of these methods have been shown to be successful, continuing developments are necessary to improve effectiveness and increase the life extension provided by these methods.

Prestressed Concrete Bridges

Whereas some of the methods discussed for conventional reinforced-concrete bridges are applicable to prestressed concrete components (e.g., high-performance concrete and corrosion inhibiting admixtures), special consideration for corrosion prevention of prestressed reinforced-concrete bridges is required.

Most of these bridges are relatively new and their numbers are relatively low; therefore, the overall economic impact is not as significant as for conventional reinforced-concrete bridges. However, failure of the high-strength prestressing steel can compromise the integrity of the prestressed concrete bridge (corrosion-related deterioration compromising the structural integrity of a conventional concrete structure is highly unlikely). This makes close attention to construction details and subsequent monitoring and inspection of the prestressed concrete bridges critical.

Corrosion prevention of pretensioned structures is primarily accomplished through the use of high-performance concretes or the addition of corrosion-inhibiting admixtures. Remedial measures such as cathodic protection are possible as long as care is taken to prevent overprotection that can lead to hydrogen-induced cracking of the high-strength steel. Other measures such as electrochemical chloride removal cannot be used for prestressed concrete structures because of the relatively large amounts of hydrogen produced at the steel surface during the removal process.

Recent failures of post-tensioned structures have underscored the importance of maintaining void-free grouting of the tendons, especially near the anchorage. Maintaining the integrity of the post-tensioned tendon starts with ensuring the integrity of the duct (typically polyethylene), followed by the application of a good-quality grout that is continuous around the strands. Placement of the grout is often more difficult when low water-cement ratio mixes and/or mineral admixtures are employed. Improved grouting practices are continuing to be developed. In addition, the use of corrosion-inhibiting admixtures can provide added protection against corrosion of the prestressing steel strands. Note that in August 2001, the American Segmental Bridge Institute conducted a 3-day training school for certifying grouting specialists. This training school will be held in the future once or twice a year.

Steel Bridges

The primary cause of corrosion of steel bridges is the exposure of the steel to atmospheric conditions. This corrosion is greatly enhanced due to marine (salt spray) exposures and industrial environments. The only corrosion prevention method for these structures is to provide a barrier coating (paint).

Changes in environmental protection regulations have brought about transformation of the approach to corrosion protection for steel bridges. Until the mid- to late-1970s, virtually all steel bridges were protected from corrosion by multiple thin coats of lead- and chromate-containing alkyd paints applied directly over mill scale on the formed steel. Maintenance painting for prevention of corrosion was rare and primarily was practiced on larger bridge structures. Since the majority of the steel bridges in the interstate highway system were constructed between 1950 and 1980, most of these structures were originally painted in this manner; therefore, a large percentage of the steel bridges in the interstate system are protected from corrosion by a coating system that is now beyond its useful service life.

Moreover, the paint system commonly used for steel bridge members contains chromium and lead and can no longer be used because of the effects it has on humans and the environment. The bridge engineers have a choice of either replacing the lead-based paints with a different coating or painting over the deteriorating areas. Removal of lead-based paint incurs high costs associated with the requirements to contain all the hazardous waste and debris.

Developments include: (1) improved and environmentally safe coating systems and (2) methodologies to optimize the use of these systems, such as "zone" painting (adjusting coating types and maintenance schedules based on the aggressiveness of the environment within different zones on the bridge). Overpainting techniques to eliminate the cost of expensive paint removal also have been developed.

Opportunities for Improvement and Barriers to Progress

A typical dilemma of bridge management is how to allocate the often insufficient funds for construction, rehabilitation, and maintenance. Compounding the problem is that funding typically comes from city, state, and federal sources with spending restrictions based on the funding source. This makes allocating the funds in order to optimize construction, rehabilitation, and maintenance decisions difficult. The cooperation of these different funding agencies is required to permit allocation of resources to achieve the best cost benefit.

An increased need for bridge inspection has placed additional drains on maintenance funds. In the case of prestressed concrete bridges, the issue of careful inspection becomes particularly acute because an individual failure of a tendon may have a significant impact on the structural integrity of the bridge. The importance of inspection was recently illustrated when tendon failures in two Florida bridges were identified through routine inspections before the safety of the bridges was compromised. The economic analysis performed in this study showed that monitoring of bridge condition and subsequent maintenance based on that information (information-based maintenance) was the most cost-effective maintenance strategy.

The economic analysis further indicated that capital funding for the higher quality materials of construction (e.g., epoxy-coated rebars) results in lower annualized costs due to postponement of repair/rehabilitation expenses incurred by the owner agency. The analysis further indicated that user costs (traffic delays during maintenance) are significant and can be 10 times greater than the direct costs to the owner/operator. This places a premium on the selection of materials of construction that minimize maintenance over the bridge service life. It also highlights the importance of careful planning for traffic control and alternative routes during bridge maintenance and rehabilitation activities.

The significant rise in costs for maintenance of steel bridges (environmental issues dealing with lead paint removal and handling of volatile organic compounds) has placed a significant strain on maintenance budgets. In fact, over the past few years, environmental regulations have become the single most influential force in the bridge painting industry. The focus for expenditures must shift to long-term effectiveness of dollars spent. This is a significant change in philosophy for a majority of the bridge painting industry. To date, bridge maintenance painting has been accomplished based on incremental budgets, rather than life-cycle considerations.

Additionally, the use of technological advances among bridge owners has not been uniform. This can, in part, be explained by the difference in funding and technical staffing between the agencies. Because of the perceived high costs of certain corrosion control methods, these methods go unused. With the general tendency to reduce the maintenance departments' size and budget, corrosion control becomes one of the many responsibilities of personnel without the experience to understand the problems and without the knowledge of available solutions. There remains a significant need for life-cycle cost analysis to aid in the selection of repair-rehabilitation-replacement decisions.

Recommendations and Implementation Strategy

The technological advances, both in concrete (conventional and prestressed) and steel bridge corrosion control methodologies and construction materials, provide the opportunity that the newly constructed bridges will last considerably longer than the bridges that were constructed 20 to 30 years ago. However, newly developed materials of construction and corrosion control methodologies must be implemented properly over the entire bridge project (both design and construction phases).

These improvements, however, do not signify that the problems with corrosion on highway bridges will disappear soon. The percentage of deficient bridges, while declining, still remains high. At the same time, the costs of bridge repair and rehabilitation are steadily increasing, thereby offsetting any potential savings. Some of the bridges owned by state and city agencies simply cannot be replaced due to their historic value and/or the enormous strain on the traffic resulting from a bridge closure (e.g., the New York City East River bridges and the Oregon coastal U.S. Highway 101 bridges). These bridges are maintained and rehabilitated even at high costs.

There is an urgent need for allocation of greater monetary resources, so that the bridge engineers can properly maintain the structures based on timely inspections, thereby optimizing maintenance practices. At present, maintenance personnel are forced to make the choices based on inadequate funds, which will ultimately lead to a less-than-optimal cost benefit.

Despite appreciation of the corrosion-related issues in the bridge community, there is still a need for raising awareness and the transfer of the advanced methodologies for efficient corrosion protection to the end-users. The Federal Highway Administration (FHWA), which has amassed considerable research and field application data on corrosion protection methods for concrete and steel bridges, has served as an effective conduit for dissemination of such information through periodic demonstration programs and educational seminars. These demonstration programs have been successful and should be continued with increased staffing and funding levels.

There remains a considerable need for additional research in innovative construction materials such as corrosion-resistant alloy/clad rebars (metallic and non-metallic) and more durable concretes with inherent corrosion-resistant properties. In addition, research and development is needed in rehabilitation technologies that can mitigate corrosion with minimal maintenance requirements, such as sacrificial cathodic protection systems.

Summary of Issues

Increase consciousness of corrosion control costs and potential savings.	The bridge owners are typically aware of the severity of corrosion problems and the need to prevent corrosion through better construction and regular maintenance; however, the best intentions are often hampered by the shortage of funds and insufficient staffing. The agencies often face the necessity of spreading the funds over the large population of bridges, favoring the use of cheaper conventional materials of construction and methods of rehabilitation, despite higher life-cycle costs. The maintenance burden will probably increase and become more costly with time. There is a need for greater funding levels and better allocation of resources to encourage optimum life-cycle costing decisions. When the cost of a particular project is calculated, the indirect costs to society typically are not taken into consideration, although these can be considerably higher than the capital expenditures. At present, the decision-making process is controlled by the owner agency, which is primarily concerned with direct budget costs.
Change perception that nothing can be done about corrosion.	There is insufficient awareness of corrosion control in some of the agencies. Knowledge of advanced corrosion control methods is unevenly distributed among the bridge operators. Research, education seminars, and demonstration programs administered through FHWA should be given higher priority in the agency budget.

Advance design practices for better corrosion management.	The modern methods of corrosion protection are well documented in FHWA, NACE, and other industry publications. Limited use of some of the approaches to corrosion-resistant bridge construction is largely predicated on balancing the available capital funds with new construction and rehabilitation needs.
Change technical practices to realize corrosion cost-savings.	While lack of capital funding for higher cost, corrosion-resistant materials is certainly a concern, these higher costs may result in a lower annualized cost for the bridge. An example of this is the use of epoxy-coated rebars for concrete structures in non-marine applications. There is only a marginal increase in the overall construction costs (typically 1 percent); however, the extension of the bridge service life can be significant when compared to conventional black steel rebars. The use of epoxy-coated rebar is an example where practices have changed; the majority of new construction uses the new technology.
Change policies and management practices to realize corrosion cost-savings.	Diligent maintenance of steel and concrete bridges is imperative because it saves money in the long term. Some structures, such as post-tensioned bridges, require particular attention because they can suffer sudden catastrophic failures if not properly maintained, leading to significant losses (both direct and indirect). Often, optimum bridge management is hampered by funding mechanisms (there is an imbalance in maintenance, rehabilitation, and new construction funds); more flexible cooperation among funding agencies is required.
Advance life-prediction and performance assessment methods.	Many attempts have been made to develop life-prediction models for concrete bridge decks based on the materials of construction, repair materials, and exposure conditions. Although these models have become progressively more complex and require multiple data parameter inputs, they still fall short of the desired accuracy in predicting the remaining life of the structure. This failure is primarily because corrosion is dependent on a wide range of factors that are difficult to account for in the model. Further research is required in this direction, with an additional focus on making the models software-based and user-friendly to ensure the wider usage.
Advance technology (research, development, and implementation).	It is important to continue research efforts to further understanding of the impact of different corrosion control methodologies on bridge performance. There may be a potential benefit from establishing an industry-wide coordinating body to ensure that the efforts are not duplicated, and the findings become available to the community at large. Presently, research programs are sponsored by a variety of bodies, such as FHWA, state highway departments, National Cooperative Highway Research Program, the American Concrete Institute, the Precast/Prestressed Concrete Institute, or private institutions.
Improve education and training for corrosion control.	Despite the generally high level of awareness about the issue of corrosion in this sector, there is a disparity between the degree of awareness and the application of knowledge of modern corrosion control methodologies. Given the often insufficient staffing of the maintenance departments of the bridge owner agencies, education of the responsible personnel in corrosion control and monitoring methodology becomes particularly important. The use of the life-cycle cost analysis has been limited and should be aggressively promoted.

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SECTOR DESCRIPTION

Background

According to the National Bridge Inventory Database, the total number of bridges in the United States is approximately 600,000, of which half were built between 1950 and 1994.(1) The materials of construction for these bridges are concrete, steel, timber, masonry, timber/steel/concrete combinations, and aluminum. This sector is focused on reinforced-concrete and steel bridges, which make up the vast majority of these structures built since 1950 and which can undergo significant deterioration due to corrosion.

The elements of a typical bridge structure can be classified into two primary components, the substructure and the superstructure. The substructure refers to the elements of the bridge that transfer the loads from the bridge deck to the ground, such as abutments and piers. The superstructure refers to the elements of the bridge above the substructure, including the deck, floor system (beams or stringers), supporting members (beams, trusses, frames, girders, arches, or cables), and bracing. Other bridge elements, which are subject to corrosion, include guardrailings and culverts.

The maintenance burden of aging bridges has become significant. In a 1998 report by the American Society of Civil Engineers (ASCE), the condition of bridge structures was rated as "poor" and was recognized as being among the largest contributors to the U.S. infrastructure cost of corrosion.(2) The important issues related to corrosion causes and corrosion control with respect to steel reinforced-concrete bridges and steel bridges are discussed in detail below. The types of bridges refer to the superstructure from which the bridge is constructed.

Steel Reinforced-Concrete Bridges

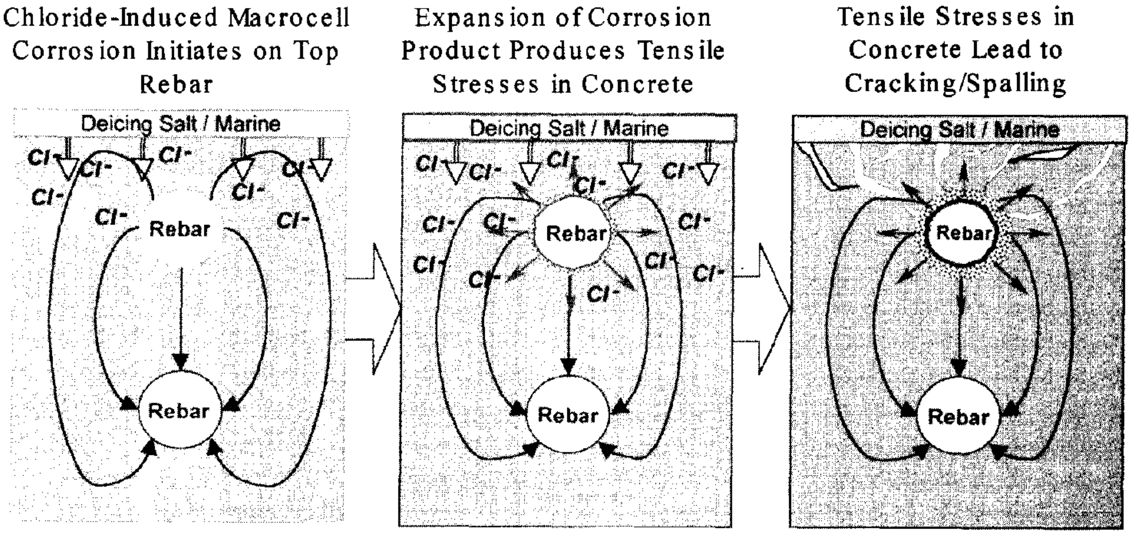
Due to the specific concrete property of weak tensile strength as compared to its compressive strength, steel reinforcing is placed in the tension regions in concrete members, such as decks and pilings. The two primary forms of steel reinforcing in concrete bridges are "conventional" reinforcing bar (rebar) and prestressed tendons. The difference between conventional reinforcement and prestressed tendon reinforcement is that prestressed tendons are loaded in tension (prestressed) either prior to placing the concrete (pretensioned) or after placing and curing of the concrete (post-tensioned). In addition, prestressed-tendon steel typically has a higher tensile strength than conventional rebar steel.

The majority of the concrete deterioration leading to reduced service life and/or replacement is associated with conventional reinforced-steel bridge structures. This is, in part, due to these structures making up the majority of reinforced-concrete bridges and the longer in-service times experienced by these structures. Although conventional rebar and prestressed tendon bridge structures have specific design and construction corrosion-related concerns and consequences, the basic mechanism of corrosion is similar and many corrosion control methods are applicable to both (see below).

Conventional Reinforced Concrete

Reinforced-concrete bridges suffer from corrosion of the reinforcement and, consequently, concrete degradation due to the high tensile forces exerted by the corroding steel (corrosion products have a three to six times greater volume than the original steel). These high tensile forces cause cracking and spalling of the concrete at the reinforcement (see figures 1 and 2). Steel in high-pH concrete in the absence of chloride ions is normally passive and corrosion is negligible, which in theory should give reinforced-concrete structures an extremely long operating life. However, in practice, corrosion in concrete can be accelerated through two primary mechanisms:
(1) breakdown of the passive layer on the steel by chloride ions and, to a lesser degree, (2) carbonation due to carbon dioxide reactions with the cement phase of the concrete. For highway bridge structures with a relatively thick concrete layer over the reinforcing steel, the vast majority of problems are caused by chloride ion migration into the

concrete due to deicing salt application and marine exposure. Once the chloride ions reach the steel surface, the passive film becomes locally disrupted, creating conditions conducive to accelerated corrosion attack on the reinforcing steel.



Chloride-Induced Macrocell Corrosion Initiates on Top Rebar

Expansion of Corrosion Product Produces Tensile Stresses in Concrete

Tensile Stresses in Concrete Lead to Cracking/Spalling

Figure 1. Schematic of corrosion damage to rebar.

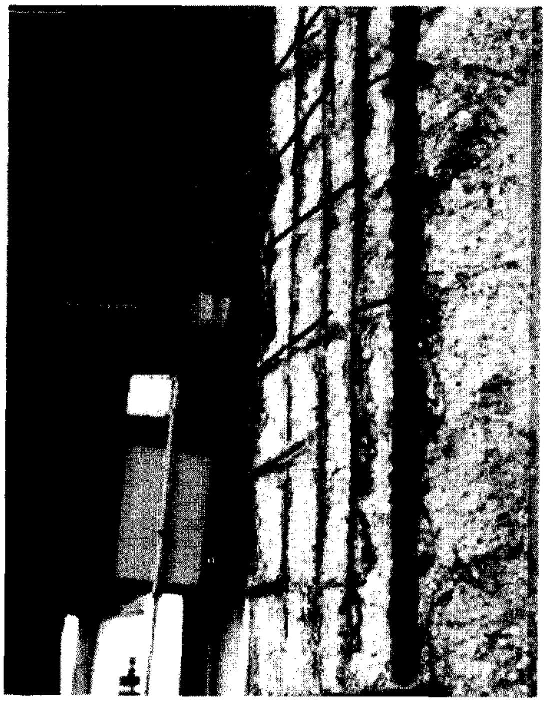


Figure 2. Example of deteriorating bridge element.

In addition to the chloride ions necessary to disrupt the passive layer created by the high-pH concrete environment, oxygen is required for accelerated corrosion. Chemical, physical, and mechanical properties of concrete can have a significant effect on concrete deterioration by controlling: (1) the chloride and oxygen permeation in the concrete, (2) the sensitivity of the passive layer to chloride attack, (3) the rate of corrosion reactions at the steel surface following corrosion initiation, and (4) the rate of cracking and spalling of the concrete when exposed to the expansion forces of the corrosion products. Thompson et al. examined in detail the effect of concrete properties on the corrosion and concrete deterioration processes of bridge structures.(3-4) It was shown that concrete mix design has a significant effect on the corrosion of rebar.

The uneven distribution of chloride ions in the concrete and at the steel surface (high chloride concentration at the outside concrete surface and decreasing at distances into the concrete) also greatly affects corrosion. For example, the greater chloride concentration around the top layer of the reinforcing steel makes it anodic (accelerates corrosion) to the bottom (inside) reinforcement, which becomes the cathode (no or decreased corrosion). This type of accelerated corrosion due to chloride concentration difference is termed "macro-cell" corrosion.

Corrosion of steel in concrete is a very complex phenomenon. Although significant research on modeling the corrosion processes of steel in concrete has been performed, accurate life prediction for concrete structures is difficult.

Non-marine, corrosion-related reinforced-concrete bridge failures became a growing problem beginning in the 1960s in the "snowbelt" regions following the increased usage of deicing salts. In the worst cases, bridges began to require maintenance after a service life of as little as 5 to 10 years, with the average maintenance interval being around 15 years. In the 1970s and the 1980s, the quality of the concrete used for bridge construction generally improved. This, coupled with increased cover thickness and the use of epoxy-coated rebar, has lead to increased service lives. New bridge structures built and maintained with the use of the contemporary corrosion control methods (high-performance concrete, greater cover thickness, corrosion-resistant rebar, corrosion-inhibiting admixtures, overlays, sealants, and improved cathodic protection practices) are expected to have service lives between 75 and 120 years. However, in designing for a long-lived bridge structure, consideration must be given to the fact that changing load and capacity requirements may render such a structure functionally obsolete before it becomes structurally deficient. Therefore, emphasis should be placed on forecasting traffic loads and patterns and on designs to accommodate anticipated changes in the traffic volume.

Prestressed Concrete

Prestressed concrete bridges also face major corrosion-related issues. However, because most of these bridges are relatively recent and because their numbers are relatively low (18 percent of the bridges), the total economic impact of corrosion is not as great as that for conventional reinforced-concrete bridges (40 percent of the bridges). However, on an individual basis, failure of a prestressed concrete component may have a significant impact on the structural integrity of a bridge. Because prestressed concrete members rely on the tensile strength of the tendons to sustain load, the loss of even a few tendons may lead to the catastrophic failure of a bridge component.

The first prestressed concrete bridge in the United States was opened to traffic in 1950 and the majority of the 107,700 prestressed concrete bridges were built after 1960.(5) Corrosion problems associated with prestressed concrete structures have been recognized beginning in the 1990s. The FHWA report *Corrosion Protection: Concrete Bridges* summarized corrosion of prestressed concrete bridges, in addition to conventionally reinforced-concrete bridges.(6)

In the fall of 1992, the U.K. Ministry of Transportation imposed a temporary ban on the commissioning of grouted, bonded post-tensioned bridges. This ban resulted from the collapse of two footbridges in 1960, the collapse of a single-span, segmental post-tensioned bridge in Wales in 1985, and an examination of nine other segmental bridges. The United Kingdom is not the only place with the problem of voids in the grouted ducts resulting in insufficient coverage over prestressing steel strands. For example, in 1992, the post-tensioned Melle Bridge across the Scheldt River in Belgium, which was constructed in 1956, collapsed. This failure was traced to corrosion of the post-tensioned strands even though the bridge had been inspected, load tested, and rated satisfactorily. The U.K. moratorium was lifted in 1996 with the publication of the advisory report *Post-Tensioned Concrete Bridges: Planning Organization and Methods for Carrying Out Special Inspections* by the construction industry and owners of this type of bridge.

The underlying difficulty is that there are no reliable, cost-effective, and rapid nondestructive methods for providing assurance to the owners that the built structures have met construction specifications. One of the major inspection concerns is to determine whether the ducts in the post-tensioned bridge members have been completely filled with the grouts and whether there is uniform coverage over the prestressing steel. In many instances, it has been determined that there exists large void areas in the grouted ducts (i.e., partially filled ducts). In addition, it is very difficult to assess the condition of anchorage areas.

Voids in the grout can be a result of: (1) poor grouting application not completely filling the duct or (2) bleeding of the grout during curing in which a volume of the duct is filled with bleed water (typically at high points in the duct). In the case of bleed water formation, it has been proposed that the bleed water is sufficiently corrosive to initiate corrosion of the exposed strands. In other cases, chloride-bearing water can find its way through the anchorage area into the ducts and eventually initiate corrosion of the prestressing steel inside the duct. Water can also access the ducts through faulty and leaky joints. Over time, chloride ions can penetrate through the concrete cover and accelerate the corrosion of the prestressing steel in the ducts (either after the corrosion of the metallic ducts or through defective plastic ducts). In addition to causing pitting of the prestressed strands, corrosion reactions lead to the evolution of atomic hydrogen, which is subsequently absorbed into the steel, leading to hydrogen embrittlement of the steel strands and causing the strands to fail at lower than designed bridge loads. Since prestressed concrete bridge members rely on the tensile strength of the strands to resist loads, loss of even a few tendons can prove to be catastrophic. In addition, due to the high stresses to which the strands are subjected, corrosion can be accelerated.

Corrosion protection methods adopted at present in the construction of prestressed concrete members included: (1) the application of highly impermeable concrete by using silica fume or fly ash additions and controlled curing of the concrete at the fabrication site, and (2) the use of corrosion-inhibiting admixtures. The use of epoxy-coated strands is not yet common in prestressed concrete members and additional research is needed.

Steel Bridges

Atmospheric corrosion of exposed steel is inevitable and can be seen everywhere, from steel buildings to automobiles to steel bridges. Painting of steel structures is the universal solution to corrosion due to exposure to environmental conditions. Paints themselves deteriorate due to moisture uptake, ultraviolet exposure, wear or mechanical damage, and exposure to chemicals. For example, the performance of the same coatings will vary significantly depending on exposure to industrial, urban, rural, or marine environments. Once a coating is compromised, corrosion can initiate and, often, is accelerated beneath a deteriorated coating more than in the absence of the coating. Therefore, selection of the proper coating for the right application is critical for a long service life. In addition, proper and timely maintenance of the structure can extend the overall life of the coating significantly.

There are approximately 200,000 steel bridge structures in the United States (see figure 3). Until the mid- to late-1970s, virtually all steel bridges were protected from corrosion by three to five thin coats of lead- and chromate-containing alkyd paints applied directly over mill scale on the formed steel. Maintenance painting for prevention of corrosion of the majority of these bridges has been rare and has been limited to larger bridge structures and toll bridges. Since the majority of the steel bridges in the interstate system were constructed between 1950 and 1980, most of these structures were originally painted in this manner. Therefore, a large percentage of the interstate steel bridges are protected from corrosion by an old coating system that is now beyond its useful life. Moreover, this coating system is considered to be hazardous to humans and the environment.

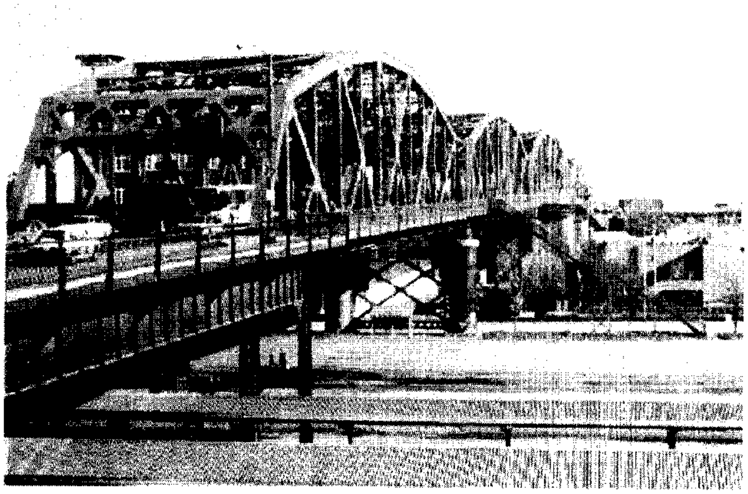


Figure 3. Steel bridge structure.

The current maintenance burden for corrosion protection of steel bridges presents a major challenge to bridge owners. The past decade has had significant increases in the costs associated with steel bridge maintenance painting. As recently as 10 years ago, bridge painting was a relatively simple operation with little emphasis on regulatory compliance, quality, or life-cycle performance of materials. Bridges were either painted over repeatedly in a low-tech, low-cost attempt to combat corrosion and deteriorating aesthetics, or they were cleaned by open abrasive blasting and were repainted. These approaches could be accomplished for \$11 to \$22 per m^2 of steel or less.(7) The increasing age of steel bridges has lead to the need for increased maintenance, resulting in higher maintenance costs. These costs have increased almost tenfold, largely facilitated by environmental regulations covering all aspects of bridge painting from construction to rehabilitation to routine maintenance. Over the past few years, environmental regulations have become the single most influential force in the bridge painting industry. Specifically, regulations having a significant impact are those regarding: (1) the volatile organic compound (VOC) content of protective coatings and (2) environmental and worker health and safety associated with the removal of lead-containing paint. Table 1 lists the most pertinent regulations and summarizes their effect on bridge painting operations.

Table 1. Effect of regulations on coating operations.

IMPACTING REGULATION	EFFECT ON COATING OPERATIONS
OSHA; CFR 29 1926.62, Lead in Construction, 1993	Establishes guidelines for protection and monitoring of workers removing lead paint from bridges. Requires lead training and monitoring for workers.
EPA; Resource Conservation and Recovery Act (RCRA), 1976	Regulates the handling, storage, and disposal of lead- (and other heavy metal) containing waste. Can increase the cost of disposal of waste from bridge paint removal by a factor of 10.
EPA; Title X, Residential Lead-Based Paint Reduction Act of 1992	Mandates training and supervision requirements for workers associated with lead-containing paint removal.
EPA; Comprehensive Environmental Response Compensation and Liability Act (CERCLA 1980 and Superfund 1986)	Assigns ownership of and responsibility for hazardous waste to the generator "into perpetuity."
EPA; Clean Water Act, 1972	Regulates discharge of materials into waterways.
EPA; Clean Air Act Amendments, 1970	Mandates restrictions on allowable VOC content of paints and coatings. Regulates discharge of dust into air from bridge painting operations.

As maintenance budgets continue to shrink or remain static and the cost of bridge maintenance continues to rise, the focus for expenditures must shift to long-term effectiveness of dollars spent. This is a significant change in philosophy for a majority of the bridge painting industry. To date, bridge maintenance painting has been accomplished based on incremental budgets rather than life-cycle cost considerations.

Cable and Suspension Bridges

Although cable bridges comprise only a small percentage of the nation's bridges, they are typically highly visible. There are approximately 150 cable bridges, several of which are old (100 to 130 years). Stahl and Gagnon have reviewed cable bridge construction and corrosion control practices.(8) Concern over a few well-publicized cable failures and condition reports for other bridges has focused on the importance of thorough inspections and scheduled maintenance. Corrosion problems associated with these structures tend to be specific to the individual design, making general rules-of-thumb difficult to utilize. The corrosion problems are highly dependent on specific structural configurations, maintenance and operational practices, and local environmental conditions.

Corrosion concerns on cable-supported structures and corrosion control practices have been present from the early designs. For example, galvanized (zinc) coating of the wires was first used on the Brooklyn Bridge, which was completed in 1883. At that time, it was already standard practice to coat the wire with linseed oil, circumferentially wrap the assembled cable with soft galvanized wire laid into red lead paste, and to paint the finished cable. These corrosion control practices have been refined since then, but the basic principle of keeping the moist environment away from the steel surface remains unchanged.

Some of the oldest and best known bridges in the United States, such as the Golden Gate and Brooklyn bridges, are suspension bridges (see figures 4 and 5, respectively). Significant costs are incurred in maintaining these bridges, but because of historic reasons or strategic location, these bridges cannot be replaced or taken out of service for any length of time. Of specific concern with these bridges is the condition of the strands. The strands are susceptible to corrosion, stress-corrosion cracking, and hydrogen embrittlement, which can lead to premature failure of the strands.

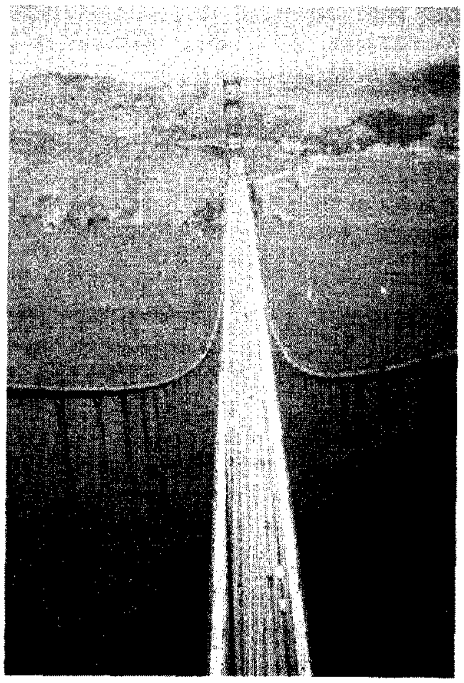


Figure 4. Golden Gate Bridge (suspension).

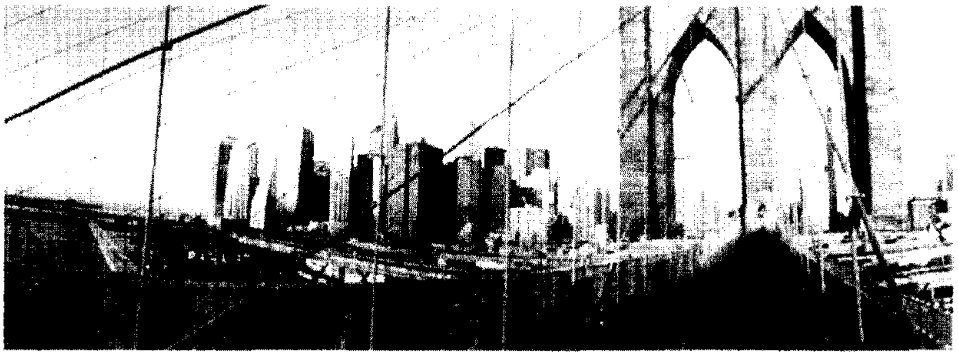


Figure 5. Brooklyn Bridge (suspension).

A more recent design of cable bridges is the so-called cable-stayed bridge (see figure 6). Presently, there are only 30 cable-stayed bridges in the United States. However, because the integrity of the cables is critical to the structural integrity of the entire bridge structure, and inspection of the cables is very difficult, the cable-stayed bridges are built with special considerations for corrosion protection.(9)

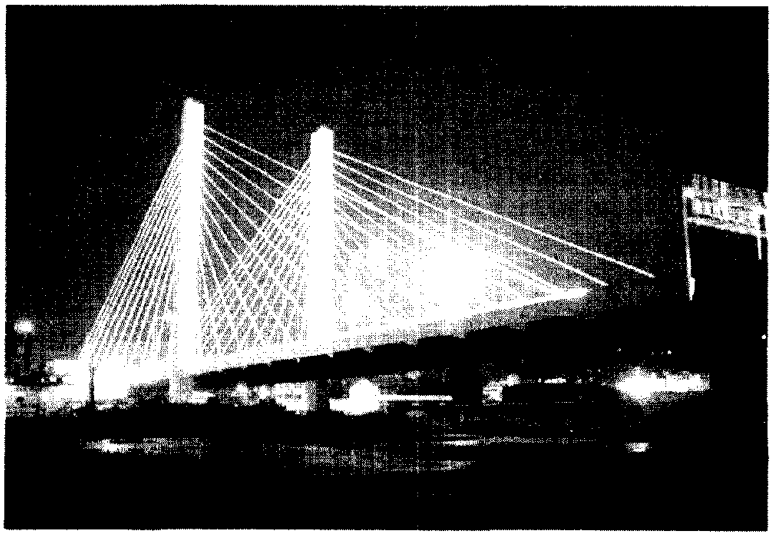


Figure 6. SR509 bridge in Tacoma, WA (cable-stayed).

Although different levels of protection are used depending on the design and the environmental conditions, the following represents an example of current practice. The individual wires comprising the strand are epoxy coated or galvanized. In the monostrand construction, the interstices of the individual strands are filled with a corrosion-inhibiting grease and then each strand is sheathed with a high-density polyethylene (HDPE) sleeve. The stays consisting of multiple strands are encased in an HDPE tube and then injected with cement grout.

Despite precautions, failures of cables have occurred, but no catastrophic failures have been reported. To maintain this record, improved inspection procedures and maintenance programs need to be developed. Nondestructive techniques such as magnetic flux leakage (MFL) have been developed for the identification of corrosion in the free length of the cable, but it cannot be used in the anchorage areas, which are of significant concern. Refinement of the MFL method and development of new technologies need to be continued in order to provide more accurate and reliable methods for identifying cable problems at the earliest possible time.

AREAS OF MAJOR CORROSION IMPACT

The condition of the bridge inventory in the United States can be characterized by the significant portion of bridges that are listed as "structurally deficient" (bridge that can no longer sustain the loads for which it was designed). The nation's structurally deficient bridges as of the end of fiscal year 1999 and the preceding 7-year period are summarized in table 2.(5,10) The data include all materials of construction, including concrete, steel, wood, aluminum, and other material. The trend shows that, as older bridges are being replaced or rehabilitated, there is a decrease in both the number (118,757 to 88,184) and the percentage (20.7 to 15.0) of structurally deficient bridges. During the same period, the number of bridges in the inventory rose from 572,633 to 585,947.

Table 2. National Bridge Inventory data – structurally deficient bridges.(5,10)

	1992	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**
Bridges in Inventory	572,633	574,191	576,472	577,919	582,043	583,207	583,414	585,947
Number Deficient	118,757	111,543	107,512	103,686	101,544	98,521	93,119	88,184
Percent Deficient	20.7	19.4	18.6	17.9	17.4	16.9	16.0	15.0

The 1998 data are presented in more detail in table 3. This table focuses on those bridges constructed of materials that are subject to corrosion (conventional reinforced concrete, prestressed concrete, and steel). Of these three bridge types, steel has the highest percentage of structurally deficient structures, followed by conventionally reinforced concrete and prestressed concrete. Listings for each state (FHWA bridge inventory(5)) suggest that the states with colder and damper weather have a high percentage of reinforced-concrete deficient bridges. These states include New York, Alaska, Rhode Island, Pennsylvania, and Vermont. The most structurally deficient bridges for a single state are in New York, which also has a larger total bridge area for conventional reinforced-concrete and steel bridges than any other state.

Table 3. Structurally deficient bridges based on material of construction in 1998.(11)

	CONVENTIONAL REINFORCED CONCRETE	**PRESTRESSED CONCRETE**	**STEEL**	**OTHER**	**TOTAL**
Bridges in Inventory	235,151	107,666	200,202	40,395	583,414
Structurally Deficient	21,164	3,230	54,054	14,671	93,119
Percent Deficient	9	3	27	36	16

The estimated service life expectancy for each of the above bridge types is shown in table 4. Many of the steel and reinforced concrete bridges have reached or are approaching the end of their design service life, making bridge maintenance, rehabilitation, and replacement decisions a priority.

Table 4. Estimated service life for bridges with different materials of construction.(1)

MATERIAL OF CONSTRUCTION	AVERAGE ESTIMATE (Years)
Conventional Reinforced Concrete	72
Prestressed Concrete	73
Steel	58

The impact of corrosion on the highway bridge infrastructure has been estimated by several different sources using different approaches. Reconstruction of the nation's bridges was estimated to cost between $20 billion and $200 billion dollars.(6,11) An FHWA report on corrosion protection of concrete bridges estimates that the total cost to eliminate the backlog of deficient bridges (both structural and functional) is between $78 billion and $112 billion, depending on the time required to carry out the task.(12) In addition, the average annual cost through the year 2011 for just maintaining the overall bridge conditions (maintaining the total number and distribution of deficient bridges) is estimated to be $5.2 billion. While corrosion is not the sole cause of bridge deficiency, it is a major contributor to the costs given above.

An additional estimate of the total corrosion costs related to the replacement of structurally deficient bridges is possible using the National Bridge Inventory data for December 1999.(5) Unit costs for bridge replacement, calculated by taking the mean for all states, are given in table 5. The overall area of structurally deficient bridges (conventional reinforced concrete, prestressed concrete, and steel) is 34.2 million m^2 (368.5 million ft^2). Assuming that these structural deficiencies are largely attributable to corrosion (obsolete bridges were not included), and using the average unit cost data [$858 per m^2 ($80 per ft^2)], the total cost of replacing the structurally deficient bridges is estimated to be $29.3 billion (34.2 million m^2 x $858 per m^2).

Table 5. Highway Bridge Replacement and Rehabilitation Program unit costs.(5)

	1995	1996	1997	1998	1999
Unit costs,* $/$m^2$	768	771	836	855	858

*Average between federal aid and non-federal aid projects.

The overall magnitude of the corrosion-induced deterioration of concrete bridges has increased considerably in the last three decades due primarily to the increased use of deicing salts. Although the cost of bridge deck maintenance is high, the use of deicing salts is not likely to be discontinued. In fact, it has been reported that its use has actually increased in the first half of the 1990s after leveling off in the 1980s. Although some alternative means of deicing have been studied (namely, calcium magnesium and potassium magnesium acetates), the high price of the chemicals and lower efficiencies for melting ice prevents their widespread use.(13) Since the discontinued use of deicing salts is unlikely, understanding and utilizing other methods of corrosion control is important.

CORROSION CONTROL METHODS

Methods utilized for corrosion control on bridges are specific to the type of bridge construction and whether its intended use is for new construction or maintenance/rehabilitation of existing structures. In this section of the report, corrosion control practices are reviewed for the three types of bridge structures focused on in this sector (conventional reinforced concrete, prestressed concrete, and steel). For the purposes of discussion, conventional reinforced concrete and prestressed concrete corrosion control methods are combined. Although prestressed concrete bridges have very special concerns (e.g., anchorage in both post-tensioned and pretensioned structures and ducts for post-tensioned structures), the general corrosion control methods are applicable to both prestressed and conventional reinforced bridges.

Reinforced-Concrete Bridges

Conventional reinforced-concrete bridges refer to those with superstructure constructed with conventional reinforced concrete. Often, prestressed concrete and steel bridges will have conventional reinforced-concrete decks or substructures. Therefore, corrosion control practices for conventional reinforced concrete are applicable to components of many other bridge structures. Therefore, a significant amount of detail is provided for conventional reinforced-concrete corrosion control practices.

New Construction

Corrosion protection can be incorporated into new bridge structures by proper design and construction practices, including the use of high-performance concrete (e.g., silica fume additions), low-slump concrete, and an increase in concrete cover thickness. Each of these attempt to impede migration of chlorides and oxygen (or other corrosive agents) through the concrete to the steel rebar surface. However, eventually, these corrosive agents will penetrate through the concrete cover and cracks, making other corrosion control practices necessary. A widely used method of corrosion prevention is the use of coated carbon steel rebar and, to some degree, corrosion-resistant alloy/clad rebars. The typical organic rebar coating is fusion-bonded epoxy, while the metallic rebar coating is galvanizing (very limited use in bridge structures). Rebar cladding with a corrosion-resistant alloy (e.g., stainless steel) is relatively new. Solid rebars constructed of stainless steel alloys have been used on a limited basis. In addition, non-metallic composite materials have been used. Another corrosion control practice available to new construction is the addition of corrosion-inhibiting admixtures to the concrete.

Epoxy-Coated Rebars

A Technical Note prepared by the FHWA and summarized here reviews the use of epoxy-coated rebar in bridge decks.(14) Epoxy coatings (often referred to as powders or fusion-bonded coatings) are 100 percent solid, dry powders. These dry epoxy powders are electrostatically sprayed over cleaned, preheated rebar to provide a tough impermeable coating. The coatings achieve their toughness and adhesion to the substrate as a result of a chemical reaction initiated by heat. Since these epoxy powders are thermosetting materials, their physical properties, performance, and appearance do not change readily with changes in temperature. The epoxy coating becomes a physical barrier between aggressive chloride ions (permeating the concrete cover) and the steel rebar.

For many years, bridge deck deterioration, stemming from corrosion of reinforcing bars, has been the number one problem for bridges. Prior to 1970, it was thought that portland cement itself provided sufficient protection to the reinforcing steel against corrosion. In the early 1970s, it became evident that corrosion of the reinforcing steel was related to the increasing application of deicing salts. Unfortunately, this was not learned until after thousands of bridge decks containing black reinforcing steel showed signs of spalling about 7 to 10 years after construction. It was also observed that substructure members were also deteriorating because of the leakage of the deicing salts through joints or exposure to seawater. Although the deterioration of substructure components is less obvious than the deterioration of bridge decks, it is much more serious and costly to repair or rehabilitate substructures.

Epoxy-coated rebar was introduced in the mid-1970s as a means of extending the useful life of reinforced-concrete bridge components by minimizing concrete deterioration caused by corrosion of the reinforcing steel. The epoxy coatings are intended to prevent moisture and chlorides from reaching the surface of the reinforcing steel and reacting with the steel. Since the late 1970s, the highway industry has widely used epoxy coatings as the preferred protective system for bridge decks due to its excellent performance in resisting corrosion and significantly delaying subsequent deterioration of the concrete. As for all coating systems, the coating will degrade over time and corrosion of the rebar will proceed in the presence of sufficient chlorides in the concrete.

When used in substructures and exposed to a severely corrosive marine environment, the epoxy-coated rebars did not perform as well as in bridge deck applications. Such was the case with a number of concrete bridges located in the Florida Keys. Significant premature corrosion of the epoxy-coated rebar was observed in substructure members of these bridges after only 6 to 9 years. These members are subjected to salt spray in the splash zone where the usual wetting/drying cycles, and high water and air temperatures produce a very corrosive environment. The deterioration observed on the Florida Keys bridges and on some other bridges located in harsh environments raised questions concerning epoxy-coated rebar as a durable corrosion protection system.

After an evaluation of the performance of epoxy-coated rebar decks by several state departments of transportation agencies, the overall condition of the bridge decks was considered to be good. Deck cracking did not appear to be corrosion-related. Very few of the decks had any delamination or spalling associated with the epoxy-coated rebar. Any delamination or spalling associated with corrosion of epoxy-coated rebar was small and generally isolated. The epoxy-coated rebar did not appear to perform as well in cracked concrete as it did in uncracked concrete. Corrosion was observed on epoxy-coated rebar segments extracted from locations having heavy cracking, shallow concrete cover, high concrete permeability, and high chloride concentrations. Reduced adhesion and softening of the coating also occurred as a result of prolonged exposure to a moist environment. The number of defects in the epoxy coating had a strong influence on the adhesion and performance of epoxy-coated rebar. There was no evidence of significant premature concrete deterioration that could be attributed to corrosion of the epoxy-coated rebar. It was concluded that the use of sufficient good-quality concrete cover, adequate inspection, finishing, and curing of the concrete, and the use of epoxy-coated rebar has provided effective corrosion protection for bridge decks since 1975.

At present, epoxy-coated rebar is the most common corrosion protection system and is used by 48 state highway agencies. To date, there are approximately 20,000 bridge decks using fusion-bonded epoxy-coated rebar as the preferred protection system. This represents roughly 95 percent of new deck construction since the early 1980s.

The data from the Concrete Reinforcing Steel Institute (CRSI) shows that more than 3.6 billion kg (4 million tons) of epoxy-coated rebar (approximately 158 million m^2 of reinforced concrete) were used worldwide as of 1998, with 79 percent installed in the last 10 years.(15) A significant portion of this epoxy-coated rebar was used in bridge decks. Over the past 20 years, the formulation of the epoxy has been modified to achieve increased performance of the epoxy coating.(15)

To estimate the cost of different construction options, the cost of the baseline case for black steel rebar is first calculated. The following cost analysis is provided to compare epoxy-coated rebar to black steel rebar. The amount of rebar contained in a bridge deck depends on the design. A typical "traditional" bridge deck (e.g., with two mats – each mat contains one longitudinal and one transverse rebar at 15-cm (6-in) centers – one mat of No. 5 rebar and one mat of No. 4 rebar) contains 33.2 kg of steel per square meter of deck (6.8 lb per ft^2). Other designs (e.g., two mats – each mat contains one longitudinal and one transverse rebar at 20-cm (8-in) centers – both mats of No. 4 rebar) contain 19.6 kg of steel per square meter of deck (4 lb per ft^2). An average of these two scenarios gives 26.4 kg of steel per square meter of deck (5.4 lb per ft^2). The cost of black steel rebar is estimated at $0.44 per kg ($0.20 per lb).(16) Using 26.4 kg per m^2 (5.4 lb per ft^2) as the weight of rebar in a square meter of deck, the cost of rebar in a black steel deck is $11.60 per m^2 ($1.08 per ft^2). The cost of a deck installed using black steel rebar is assumed to be $484 per m^2 ($45 per ft^2).(6,16) It is estimated that black steel rebar provides an expected life of 10 years prior to required maintenance resulting from concrete deterioration due to corrosion of the rebar.(14)

Typically, the cost of epoxy-coated rebar adds $0.22 per kg ($0.10 per lb) to the cost of rebar, which is an increase in the cost of rebar of 50 percent.(16-17) This gives a cost of rebar for an epoxy-coated rebar deck of $17.40 per m^2 ($1.62 per ft^2) of deck or an increase in the cost of epoxy-coated rebar as compared to black steel of $5.80 per m^2 ($0.54 per ft^2) of deck. However, the rebar is a relatively small portion of the total deck construction costs. The added cost of epoxy-coated rebar depends on whether both mats of rebar are coated (many bridges have been constructed with only the top mat of rebar epoxy coated, although current practice typically uses both mats epoxy coated) and on the overall construction costs. Assuming the cost of new construction for a bridge deck is \$484 per m^2 (\$45 per ft^2) and both mats are epoxy coated, the increase to the total deck cost is 1.2 percent (\$5.80 / \$484 x 100). This value is consistent with other references discussed below. It is estimated that epoxy-coated rebar provides an expected bridge deck life of 20 to 40 years.(14,18) The service life depends, in part, on whether a single top mat of epoxy-coated rebar is used in conjunction with a bottom mat of black steel rebar versus both mats constructed of epoxy-coated rebar. With the current practice of coating both rebar mats and current coating formulations, a 40-year life is typically assumed. The costs for using only a single mat of epoxy-coated rebar would be estimated at 50 percent of that for both mats coated.

The Concrete Reinforcing Steel Institute (CRSI) estimates that the increase in the total cost of the structure due to coating both mats of rebar is typically between 1 and 3 percent.(17) An FHWA study provided data for three Illinois bridge decks (1994 construction data) and showed that the increase in the cost of the deck due to using epoxy-coated rebar on both mats was between 0.5 and 2.2 percent, with an average increase of 1.4 percent.(16)

The New York State Department of Transportation (DOT)(19) has been using epoxy-coated rebars in the top mat reinforcements for the past 20 years. A summary of the data is presented in table 6. For deck replacement, the increase in the cost of coating the top mat was approximately 0.1 percent and, for rehabilitation, the cost increase was approximately 0.25 percent. The New York State DOT estimates that this small increase in costs for epoxy-coated rebars gives at least a 10-year life extension for the bridge structures. One factor that explains the lower percent increase in the structure cost due to using epoxy-coated rebar is that, in New York, only the top mat of rebar was coated. In addition, the bridge construction costs are higher in New York, making the average percent increase due to using epoxy-coated rebar lower.

Table 6. New York State DOT data on epoxy-coated rebar costs for bridge deck replacement and rehabilitation.(19)

		1/1/90-1/1/97	**1/1/97-1/1/98**	**1/1/98-1/1/99**
Replace	Average area of deck, m^2	580	495	393
	Average cost per project, \$ (in millions)	0.93	1.11	1.04
	Cost increase due to use of epoxy-coated rebars, %	0.11	0.08	0.06
Rehabilitate	Average area of deck, m^2	3,645	573	1107
	Average cost per project, \$ (in millions)	1.66	0.32	0.89
	Cost increase due to use of epoxy-coated rebars, %	0.37	0.3	0.21

Metal-Coated/Clad Rebars and Solid Corrosion-Resistant Alloy Rebars

To provide a more corrosion-resistant rebar, a number of metallic coatings, metallic claddings, and rebar alloys have been tested. The most promising are galvanized (zinc-coated) rebars, stainless steel-clad rebars, and solid stainless steel rebars.(6) Titanium has also been discussed as a clad or solid rebar material, but its cost is significantly greater than that of stainless steel, and the increased corrosion resistance (relative to stainless steel) may not be required.

Galvanized Rebars

Hot-dipped galvanized coatings for reinforcing steel in concrete have been used since the 1940s. ASTM A767, "Standard Specification for Zinc-Coated (Galvanized) Steel Bars for Concrete Reinforcement," specifies the requirements for the galvanized coating. A Class I coating has a zinc coating weight of approximately 1,070 g per m^2 (3.5 oz per ft^2) and a Class II zinc coating has a coating weight of approximately 610 g per m^2 (2.0 oz per ft^2).

The effectiveness of galvanized rebars in extending the life of reinforced-concrete structures is questionable. In other applications, galvanized steel has been shown to extend the life of structures exposed to atmospheric conditions and low-chloride underground environments, but not high-chloride environments. An FHWA study by McDonald et al. reviewed the performance of galvanized rebar and is summarized here.(16) Several studies conducted in the 1980s and 1990s provided conflicting evaluations for the performance of galvanized steel in concrete. In general, the findings are in agreement with those for other exposure conditions, i.e., (1) zinc corrodes as fast (or faster) than steel in high-chloride environments and (2) zinc corrosion can be accelerated by macro-cell action when a large cathodic area is present. Accelerated macro-cell corrosion can occur when a galvanized upper mat of reinforcement is connected to a bare steel lower mat (in which the concrete surrounding the lower rebar mat has a lower chloride concentration than the concrete of the upper mat). Therefore, both mats of reinforcement should be galvanized. The general consensus is that galvanizing extends the life of the concrete structure due to a higher threshold for chloride-induced corrosion of the zinc-galvanized coating as compared to black steel.

Although galvanized rebar may provide a benefit in certain chloride-containing environments, the majority of the problems are associated with deicing salts and marine exposures where the chloride content of the concrete continuously increases to a point where any benefit of galvanization becomes marginal.

Stainless Steel Rebars

Research in stainless steel rebars has taken two directions, clad stainless steel over a carbon steel substrate and solid stainless steel rebar. If a stainless steel alloy is selected that possesses sufficient corrosion resistance for the service conditions, the primary concerns of cladding are: (1) adherence to rebar substrate, (2) defects formed after bending, (3) uniform cladding thickness [a typical cladding for stainless steel is 0.5 mm (0.020-in) thick], and (4) metallurgical changes due to the cladding process that may affect the corrosion resistance. It should be realized that the chloride threshold for pitting in a non-aqueous (non-homogeneous) environment such as concrete can be significantly less than for the same aqueous environment. Therefore, any research must utilize realistic concrete environments. For instance, the use of stainless steel piping in underground service, generally, has been discontinued due to pitting and subsequent perforation of the pipe in the non-homogeneous unsaturated soil environment with relatively low chloride contents. Pitting in conventional reinforced-concrete bridge components may not be as significant a concern as decreasing the average corrosion rate (overall metal weight loss).

Several studies that examined the performance of solid stainless steel rebars were summarized by McDonald et al.(16) These studies showed that the austenitic stainless steel (Types 304 and 316) performed well, while the ferritic stainless steels (Types 405 and 430) developed pitting. In all cases, the stainless steel performance was greatly superior to carbon steel; with the stainless steel rebar generally performing with no (or negligible) corrosion. In a study summarized by Virmani and Clemena, Type 316 stainless steel-clad rebar greatly extended the estimated time to cracking of the concrete beyond that of conventional steel rebar (to 50 years), but not as much as solid Types 304 and 316 stainless steel (100 years).(6) In addition, McDonald et al. reported on two highway structures constructed with stainless steel rebar. Following a 10-year exposure, no corrosion was observed for solid Type 304 stainless steel rebar in a bridge deck in Michigan and for Type 304 stainless steel-clad rebar in a bridge deck in New Jersey.(16) However, at that time, the chloride levels in both bridge decks were below or at the threshold chloride level for corrosion initiation in black steel rebars.

The cost of solid stainless steel rebars is estimated to be $3.85 per kg ($1.75 per lb). Assuming similar weights of solid stainless steel rebar as used above for black steel rebar, the cost of solid stainless steel rebar is estimated at

\$101.64 per m^2 (9.44 per ft^2) (\$3.85 per kg x 26.4 kg per m^2 = \$101.64 per m^2). This is an increase in the cost of rebar of \$90 per m^2 (\$8.40 per ft^2) when comparing the cost of solid stainless steel to black steel (\$11.60 per m^2). Assuming that the cost of new construction for a black steel rebar bridge deck is \$484 per m^2 (\$45 per ft^2), the cost increase to construct the deck using solid stainless steel rebar is 18.6 percent (\$90 / \$484 x 100). This value is consistent with other references discussed below. It is estimated that the use of solid stainless steel rebar provides an expected life of 75 to 120 years.(6,16)

McDonald et al. estimated the costs, at three installation sites, of the use of rebar made from solid stainless steel.(20) The authors estimated that, compared to the cost of black steel rebar, the overall construction cost would have increased by 6 percent to 16 percent if solid stainless steel rebars were used.

Stainless steel rebars have been reported to be used in several projects in the United States, including Michigan and Oregon.(21) The Oregon DOT estimates that the cost of stainless steel rebar (Type 316LN, Nitronic 50) is approximately \$4 per kg (installed), with an overall cost increase of 10 to 15 percent when used in the deck and superstructure, and another 5 percent if used in the substructure. Although the cost of \$4 per kg is greater than that used in the analysis above, the percent increase in the cost of the structure is similar. The expected service life of the structure using stainless steel rebar was stated to be 120 years.

Fluctuation in the cost of raw materials used in the production of stainless steel has a significant effect on the economic viability of the use of stainless steel rebar in concrete decks. The rebar cost also is dependent on the grade of stainless steel used.

One means of minimizing the cost of the stainless steel rebar is to utilize stainless steel-clad rebar. It has been estimated that the cost of stainless steel-clad rebar is \$1.54 per kg (\$0.70 per lb), which gives a cost of \$40.66 per m^2 of deck (\$3.78 per ft^2) or an increase of \$29 per m^2 (\$2.70 per ft^2) over that of a black steel deck. Assuming the cost of new construction for a black steel rebar bridge deck is \$484 per m^2 (\$45 per ft^2), the cost increase to construct the deck using stainless steel-clad rebar is 6 percent (\$29 / \$484 x 100). It is estimated that the use of stainless steel-clad rebar provides an expected life of 50 years.(6)

The cost of stainless steel cladding can vary depending on the raw material market prices, just like solid stainless steel, but it is also dependent on the cladding manufacturer, the cladding thickness, and the chosen grade of stainless steel. The purity of the stainless steel is a consideration as well, since many cladding operations use recycled material to reduce costs. However, with proper quality control, stainless steel-clad rebar promises to be an effective means of control for bridge deterioration due to corrosion of the reinforcing steel.

Alternative Means of Protection

In addition to the use of coated or alloy rebar, other approaches to mitigate corrosion of the reinforcing steel in bridge structures include high-performance concrete, corrosion-inhibiting admixtures, or a combinations of these.

High-Performance Concrete

High-performance concretes were developed as a means of impeding ingress of chlorides to the rebar (by reducing concrete permeability). This is accomplished by using lower water-to-cement ratio concrete and adding mineral admixtures to the concrete mix. The most common admixtures are silica fume and fly ash (pozzolanic materials). Low water-to-cement ratios are achieved using high-range water reducers.

Although low chloride permeability is one of the main features of mineral admixtures, they impart other properties to the concrete (depending on the admixture selected), such as: (1) corrosion resistance (higher chloride threshold for corrosion and low corrosion rate following initiation), (2) greater cumulative corrosion prior to cracking, and (3) higher resistivity to minimize macro-cell corrosion. An FHWA study by Thompson and Lankard reviewed the effect on the corrosion of steel in concrete of several variables, including cement types, mineral admixtures, water-to-cement ratio, and aggregate type.(3-4) This study showed that silica fume was by far the most effective mineral admixture in mitigating corrosion of steel rebar. It also suggested that careful selection of the concrete mix components could greatly extend the life of a concrete bridge member.

The cost of a high-performance concrete depends on the admixtures used. Berke et al. estimated the addition of silica fume would increase the bridge cost by \$4.30 per m^2 (\$0.40 per ft^2).(22) Assuming that the cost of new construction for a black steel rebar bridge deck is \$484 per m^2 (\$45 per ft^2), the cost increase associated with the use of a high-performance concrete containing silica fume is 0.9 percent (\$4.30 / \$484 x 100). It is estimated that the use of silica fume admixture provides an increase in expected life of 10 years beyond that provided by black steel rebar in conventional concrete.(23)

Corrosion-Inhibiting Admixtures

In the past decade, the use of corrosion-inhibiting concrete admixtures has emerged as a promising method for delaying the onset of corrosion of prestressing and conventional reinforcing steel.(24) Inhibitors are usually employed with permeability-reducing pozzolanic additives such as fly ash or silica fume. As such, the concrete has low permeability and the corrosion inhibitor essentially increases the chloride concentration required for corrosion initiation. Inhibitor action may also reduce the rate of corrosion after initiation, resulting in less corrosion-induced concrete deterioration.

Inhibitors are compounds that are able to reduce corrosion rates when present at relatively small concentrations at or near the steel surface. Corrosion inhibitors are generally classified as organic or inorganic. Organic corrosion inhibitors generally work either by forming a protective film on the steel and/or by preventing the corrosive agents from reaching the steel. Inorganic corrosion inhibitors work by reducing either the oxidation or the reduction reactions at the steel surface.

Extensive technical literature exists on the inorganic calcium nitrite products. This product has been shown to provide passivity at relatively high chloride concentrations. Commercially available organic-based inhibitors are also available. The organic inhibitors are believed to be comprised of amides and esters. A recent National Cooperative Highway Research Program (NCHRP) project by Thompson et al. reviewed the performance of corrosion inhibitors used in concrete and performed a range of laboratory tests to assess the performance of the commercially available inhibitors.(25)

The cost of calcium nitrite (one of the most commonly used corrosion-inhibiting admixtures) with and without the addition of silica fume was discussed by Berke et al.(22) The cost of a calcium nitrite protection system was estimated to be \$5.40 per m^2 (\$0.50 per ft^2). Assuming that the cost of new construction for a black steel rebar bridge deck is \$484 per m^2 (\$45 per ft^2), the cost increase to construct the deck using calcium nitrite inhibitor is 1.1 percent (\$5.40 / \$484 x 100). It is estimated that the use of inhibitors may provide an increase in expected life of 20 to 25 years beyond that provided by black steel rebar and conventional concrete.(23)

Multiple Protection Systems

Corrosion inhibitors are increasingly used as a part of multiple corrosion protection systems in conjunction with epoxy-coated rebars and low-permeability concrete, especially for marine application. As yet, epoxy-coated seven-wire strands are not commonly used for prestressed concrete bridge members. In lieu of coated seven-wire strands, corrosion inhibitors have found their niche in the prestressed highway construction industry.(24)

Summary of Current Practice for New Construction

The following items summarize the current practice based on research, field performance, and emerging technologies.(6)

The preferred primary corrosion-protection system is fusion-bonded epoxy-coated rebars, which have been used in approximately 20,000 reinforced-concrete bridge decks and approximately 100,000 total structures. Epoxy-coated rebar has performed very well in alleviating the problem of corrosion-induced deterioration of concrete bridge decks. The only caution is its use in severe marine applications.

With continued updates in the American Association of State Highway and Transportation Officials (AASHTO) and American Society for Testing and Materials (ASTM) specifications for epoxy-coated rebar, this corrosion protection system will continue to improve. The specifications involve all aspects of the fabrication of epoxy-coated rebar, including the following: certification of coating plants; proper storage of coating powder at the plants; restrictions on surface imperfections on the bars; removal of dust and salt from the surface of the bars prior to coating; and better quality control of thickness, continuity, flexibility, adhesion, etc. In addition, requirements related to job-site storage and handling of the coated bars have also been established. All of these will result in improved performance of epoxy-coated rebar and more durable new concrete structures.

To provide even longer service life to the concrete decks (75 to 120 years) without any need to repair corrosion-induced concrete damage, a number of solid and clad corrosion-resistant alloy rebars are under development. Most notable are solid Type 304 or 316 stainless steel rebars and stainless steel-clad rebars, which have performed well in accelerated corrosion screening tests. Both of these two new alternative reinforcing bars have the potential to provide an excellent corrosion protection system, albeit at a higher initial cost. Although Type 316 stainless steel is a proven corrosion-resistant alloy, more research is needed for clad rebar and other alloys.

The combined use of epoxy-coated rebar and a corrosion-inhibiting admixture, such as calcium nitrite, could serve as a reliable corrosion protection system, especially for marine applications such as piles, etc. However, the long-term stability of this inhibitor is still under study. In addition, research efforts are underway to identify new inhibitors.

The combination of high temperature (38 °C) and an intermediate level of humidity or moisture (75 percent) have been identified as environmental conditions that lead to high corrosion rates for steel in concrete. Use of a low water-to-cement ratio concrete, incorporation of mineral admixture, and proper selection of cement type and aggregates contribute to production of a high-performance concrete with significant corrosion resistance.(4)

For the protection of high-strength, seven-wire strands encased in ducts, mix designs for corrosion-resistant grout for filling the ducts have been developed. In addition, an accelerated corrosion test method has been developed for evaluating new grout mixes.(26) These developments became the basis for a new grout specification recently published by the Post-Tensioning Institute (PTI) in 2001.

Prompted by the recent sudden collapse of two post-tensioned bridges in the United Kingdom and one in Belgium, the impact-echo nondestructive evaluation (NDE) technique was developed to detect voids in post-tensioned ducts. This equipment is now commercially available. A complementary magnetic-based nondestructive technique for assessing section loss in the high-strength steel strands in the ducts also has been developed. In combination, the impact-echo and the magnetic-based techniques allow inspection of post-tensioned systems, reducing the likelihood of any sudden collapse of post-tensioned bridges in the United States. Continued development of these techniques is required to increase reliability, accessibility around trumpet locations, resolution, and user confidence.

Summary of New Construction Cost Alternatives

Table 7 gives the costs of new construction alternatives for bridge structures. Also provided is the expected service life for each alternative. There are many choices for corrosion prevention, and careful life-cycle cost analysis and risk assessment are required to select the most appropriate one for any given application. In addition, the alternatives are not mutually exclusive (i.e., combinations of (1) corrosion-inhibiting admixture and silica fume or (2) epoxy-coated rebar and corrosion-inhibiting admixture have been used).

Table 7. Summary of costs and life expectancy for new construction alternative.

CORROSION CONTROL PRACTICE	COST OF BAR	BAR WEIGHT PER DECK AREA	COST PER DECK AREA	INCREASE IN COMPARISON TO BASELINE	PERCENT INCREASE	ESTIMATED SERVICE LIFE
	\$/kg	kg/m^2	\$/m^2	\$/m^2	%	Year
Black steel (baseline)	\$0.44	26.4	\$11.60	NA	-	10
2-layer epoxy-coated rebar	\$0.66	26.4	\$17.40	\$5.80	1.2%	40
2-layer solid SS rebar	\$3.85	26.4	\$101.64	\$90.04	18.6%	75 - 120
2-layer SS-clad rebar	\$1.54	26.4	\$40.66	\$29.00	6.0%	50
Calcium Nitrite CIA	-	-	-	\$5.40	1.1%	30
Silica Fume	-	-	-	\$4.30	0.9%	20

Rehabilitation

Salt-induced reinforcing steel corrosion in concrete bridges has become a considerable economic burden to many state and local transportation agencies that are generally tasked with maintenance and repair activities. Although the positive effect of adoption of corrosion protection measures can already be seen on individual structures, there are thousands of existing bridges constructed without the latest corrosion control methods. In addition, even the latest corrosion control methods are not likely to prevent all corrosion for the life of the bridge structure. Therefore, repair/rehabilitation of bridge structures and the mitigation of existing corrosion will be a major activity for bridge engineers for years to come.

There are several remedial methods available for rehabilitation of concrete structures that have deteriorated due to chloride-induced corrosion of the reinforcing steel. Because problems on concrete structures are typically found after significant deterioration has resulted in cracking and spalling of the concrete, the vast majority of the remedial methods are applied following removal and patching of the damaged concrete. The available methods are based on one of the following principles and have been summarized by Virmani and Clemena.(6)

- Provide a barrier on the surface of the concrete to prevent future ingress of chloride (overlays, membranes, etc.).
- Control the electrochemical reactions at the steel surface to mitigate the corrosion reactions by imposing the proper voltage field on the rebar (cathodic protection).
- Modify the concrete environment to make it less corrosive. One way of accomplishing this is to extract the chlorides from the concrete (electrochemical chloride removal).

Each state DOT has specifications and criteria for rehabilitation of deteriorated concrete bridge components. One example of a decision process for rehabilitation or deck replacement is as follows (Caltrans):(27)

- If spalling of the concrete is observed, the surface is checked for delamination by chain drag and core samples are taken to determine the chloride concentration.
- If the chloride concentration is greater than 1.8 kg per m^3 (3 lb per yd^3), the concrete is removed to depths where the concentration is less than 1.2 kg per m^3 (2 lb per yd^3).
- If less than 75 mm (3 in) is removed to reach an acceptable chloride level, the removed concrete is replaced by an overlay.
- If more than 75 mm (3 in) is removed, the entire deck must be replaced.

- Cathodic protection is applied only in the case of partial disbondment of the concrete and when there is no extensive spalling.

Surface Barriers

The application of an overlay of low-slump concrete, latex-modified concrete (LMC), high-density concrete, polymer concrete, or bituminous concrete with membrane on the existing concrete provides a barrier that impedes continued intrusion of chloride ions, moisture, and oxygen that are necessary for corrosion to continue. However, past experience indicates that when such barrier systems are employed without first decontaminating the existing concrete of the active corrosive agents, these corrosive agents become entrapped in the existing concrete and the effectiveness of the barrier may be neutralized. Traditionally, greater than 90 percent of the rehabilitation jobs used low water-to-cement ratio concrete or LMC overlay as the preferred method. FHWA Report FHWA-RD-98-088 indicated that state highway agencies estimate the life of these rehabilitation methods to be around 15 years.(6)

Various studies have reported performance and cost data for different overlay and patching systems. (See references 12, 28, 29, 30, and 31.) Table 8 summarizes the costs presented by Sprinkel et al.(29) These costs are based on both literature review and questionnaires sent to state DOTs. The cost data are for 1988. The numbers were discounted by 5 percent annual percentage rate (APR) to estimate 1998 costs. There is a wide range of cost and life expectancies provided, which probably corresponds to the range of application methods and detailed specifications used for these classifications.

Table 8. Cost (1998 adjusted) and life expectancy for overlay and patching options for concrete bridges.(29)

TYPE OF MAINTENANCE	AVERAGE COST	RANGE OF COSTS	AVERAGE EXPECTED LIFE	RANGE OF EXPECTED LIFE
	($/m^2)	($/m^2)	(years)	(years)
Portland Cement Concrete Overlay*	170	151 – 187	18.5	14 – 23
Bituminous Concrete with Membrane	58	30 – 86	10	4.5 – 15
Polymer Overlay/Sealer	98	14 – 182	10	6 – 25
Bituminous Concrete Patch	90	39 – 141	1	1 – 3
Portland Cement Concrete Patch	395	322 – 469	7	4 – 10

*Includes latex-modified concrete (LMC).

Cathodic Protection

Cathodic protection (CP) is a corrosion control method that imposes an external voltage on the steel surface in a manner that forces the steel to become cathodic (reduction reactions are favored and anodic reactions, which result in metal loss, are decreased), thereby mitigating corrosion. In simple terms, CP transfers the oxidation (anodic) reactions, which result in metal loss (and thereby corrosion) of the rebar, over to the anode of the CP system. Therefore, selection of the proper anode material for the application is critical, since anode failure results in CP system failure.

The primary strength of CP is that it can mitigate corrosion after it has been initiated. Although CP is often placed on pipelines, underground storage tanks, and other structures during construction, it is generally installed on bridge members only after corrosion has initiated and some amount of deterioration has occurred. The primary reason for not installing CP systems on bridge components during construction is that corrosion often does not initiate for 10 to 20 years following construction; therefore, the CP system maintenance and a large portion of the CP system design life would be used on a structure that is not corroding. Furthermore, the use of CP on newly constructed bridge components is limited since materials such as epoxy-coated rebar provide economic, long-term corrosion prevention for these structures. The exception to this is that CP is installed on newly constructed bridge pilings exposed to marine and brackish waters where corrosion is known to be a severe problem.

Although problems with early CP systems have cast a negative image with certain bridge engineers, current technology for bridge decks has proven to be quite reliable and improved technology for substructures is still being developed and tested. When properly applied and maintained, CP mitigates corrosion of the reinforcing steel and extends the performance life of a bridge. However, CP remains an under-utilized technology for steel-reinforced concrete structures.

CP systems are characterized by the source of the driving voltage that forces the rebar to become cathodic with respect to the anode. The two principal methods for applying CP are impressed-current CP and sacrificial (galvanic) anode CP. In an impressed-current CP system, an external power source is used to apply the proper driving voltage between the rebar and the anode. For impressed-current systems, the anode can be a wide range of materials since the driving voltage can be adjusted to suit the application and anode material selected. For a sacrificial anode CP system, the driving voltage is created by the electrochemical potential difference between the anode and the rebar. Therefore, selection of the anode material is more limited.

Impressed-Current CP

The basic characteristics of an impressed-current CP system are: (1) an external power source is required, (2) the driving voltage can be varied (variable power source), (3) the applied current can be varied, (4) the CP system can be designed for almost any current requirement, and (5) the CP system can be used in almost any level of resistivity. To date, more than 1.9 million m^2 (>20 million ft^2) of reinforced and prestressed concrete structures have been cathodically protected worldwide.

Anode selection and application have proven to be among the most difficult problems in designing CP systems for concrete structures with adequate life. The anode for a concrete bridge deck must have the following characteristics: (1) capability to withstand traffic loads, (2) resistance to environmental influences (moisture, temperature fluctuations, etc.), (3) sufficient durability to have a design life equal to or greater than that of the wearing surfaces, (4) sufficient conductive surface area to minimize or completely prevent premature deterioration of the surrounding concrete, and (5) it must be economical.

Over the past 30 years, several anode configurations have been utilized for concrete bridge decks and substructures, including those listed below.(6) A Strategic Highway Research Program (SHRP) study published in 1993 reviewed CP systems used for bridge structures, including performance, costs, and service life.(32) The cost data are for 1991; a discount rate of 5 percent was used to estimate the costs in 1998 dollars. The estimated costs and service lives are given, but it should be realized that specific problems have developed that have limited the actual service life achieved in some cases.

- Coke-asphalt anode system used high silicon iron anode material and required a wear surface. The application costs are estimated at $92 per m^2 with a service life of 20 years.(32)
- Non-overlay slotted anode system used platinized-niobium-copper wire anode laid in regularly spaced slots designed to distribute CP current evenly to the rebar mat and was filled with a conductive polymer concrete. The application costs are estimated at $92 per m^2 with a service life of 15 years.(32)
- Conductive polymer mound anode system used the platinized-niobium-copper wire anode with the conductive polymer mounded on the wire anode and a rigid concrete overlay on top. The application costs are estimated at $137 per m^2 with a service life of 20 years.(32)

- Activated titanium mesh anode is secured to the concrete and covered with either a conventional concrete or a latex-modified concrete overlay. The application costs are estimated at \$137 per m^2 with a service life of 35 years.(32)
- Activated titanium mesh anode is also applicable to substructures when overlaid with shotcrete. The application costs are estimated at \$211 per m^2 with a service life of 35 years.(32)
- Other anode designs have been specially developed for use in impressed-current CP systems for substructures. These include sprayable conductive polymer coatings, metallized zinc coating, and conductive paints. Typical primary anode for the conductive polymer or paints is platinized-niobium wire attached to the concrete prior to application. The application costs are estimated at \$76 per m^2 with a service life of 5 years.(32)
- The metallized zinc used either small stainless steel or copper plates epoxied to the concrete surface to make a connection back to the power source. The application costs are estimated at \$137 per m^2 with a service life of 15 years.(32)

Problems with the CP systems have included: (1) debonding of the conductive coating that arises when the materials are used in environments where the concrete is constantly wet or when the materials are applied before the concrete is sufficiently dry; (2) degradation of conductive coating after extended current passage; and (3) increase in the electrical resistance between the anode and the steel due to insufficient moisture or accumulation of insulating byproducts at the anode/concrete interface.

Of the systems identified above, only the titanium mesh anode and metallized zinc are still actively used today. Furthermore, the use of titanium mesh on bridge decks is widely accepted in terms of providing long-term durability. The thermal-sprayed zinc is free of the debonding problem, but suffers from an increase in anode resistance over time. However, the Oregon DOT has had significant success with the thermal-sprayed zinc anode on substructure components (see Case Study 3). Recently, the use of thermal-sprayed titanium metal as a new anode has shown some promise when used on a trial basis on a bridge in Oregon.

Some DOTs, such as the Florida DOT, have undertaken experimental programs that investigate alternative energy sources for applied CP systems, such as solar power and long-life batteries.(33) The systems are intended for use on the substructure elements exposed to brackish waters.

In certain cases, CP offers the only acceptable service life extension as an alternative to replacement of a critical bridge component. For example, Oregon DOT has successfully implemented thermal-sprayed zinc CP systems on historic bridges (built in the 1930s) along Highway 101 (see Case Study 3).

Missouri DOT leads North America in the use of CP to extend the life of salt-contaminated and corroding concrete bridges. In Missouri, CP is primarily used for corrosion control of voided slab structures, although CP is also used on steel frame and stringer type structures. Conventional repair methods proved to be unsuccessful for limiting corrosion on bridges, many of which were built in the late 1950s and early 1960s. Since 1975, Missouri has installed CP systems on more than 140 bridges.

Many CP systems have been evaluated and used in Missouri. First introduced in 1986, the activated titanium mesh anode system with concrete overlay has become the exclusive CP system installed on Missouri DOT bridges. To date, this system has provided a high level of corrosion control to more than 30 bridge decks in the Kansas City and St. Louis areas.

Sacrificial Anode CP

The basic characteristics of a sacrificial anode CP system are: (1) no external power source is required, (2) the driving voltage is fixed, (3) the applied current is dependent on the driving voltage and the resistance between the rebar and the anode, (4) the CP system is limited to relatively low current requirements, and (5) the CP system is limited to relatively low-resistivity concrete environments.

Sacrificial anode CP systems have been used about as long as impressed-current anode systems for corrosion control of bridge decks. Two of the earliest field trials (1977) for sacrificial anode CP systems were: (1) perforated zinc sheets fastened on the deck with a bed of mortar, then covered with an concrete overlay, and (2) conventional zinc ribbons embedded in grooves cut into the concrete.(6) Both systems performed satisfactorily for 14 years prior to removal due to failure of the asphalt overlay and the necessity of widening the structure. Although the above field tests showed that sacrificial anode systems can be successfully applied to bridge decks, the majority of the CP systems on bridge decks are impressed-current systems.

Because of the relatively high resistivity of atmospherically exposed concrete substructures, most anodes utilize impressed current to achieve the necessary driving voltages to supply the current required for corrosion control. An exception to this is the use of sacrificial zinc anodes for CP of coastal bridges in Florida, which have a relatively low concrete resistance. However, studies continue to examine the use of sacrificial anodes primarily due to the benefit of very low maintenance compared to impressed-current CP systems. Two of these studies include the zinc-hydrogel anode system and the thermal-sprayed alloy anode system. The zinc-hydrogel anode system uses zinc sheet anodes (10-20 mm thick) attached to the concrete with ionically conductive hydrogel adhesive. Field trials have shown that this system is capable of supplying sufficient current for effective corrosion control. The thermal-sprayed alloy anode system utilizes a conventional metallization (flame- or arc-spraying) process to form metallized coating on the concrete surface. The two most promising anode materials were Al-Zn-In alloy and zinc.(6)

The cost of CP systems varies depending on the type of system used. Virginia DOT has issued a report entitled *Evaluation of Anodes for Galvanic Cathodic Prevention of Steel Corrosion in Prestressed Concrete Piles in Marine Environments in Virginia.*(34) This data and data published by Virmani(6) suggest that the sprayed Al-Zn-In alloy or the zinc-hydrogel alloy systems cost between \$108 and \$129 per m^2 (\$10 and \$12 per ft^2). The life of these systems is estimated to be 10 to 20 years.

Cathodic Protection for Prestressed Concrete Bridge Members

The primary concern for CP of prestressed concrete members is the possibility of hydrogen-induced cracking failure (hydrogen embrittlement) of the tendons at operating loads. Hydrogen production at the steel surface is a product of CP at potentials more negative than –0.90 V saturated calomel electrode. For this reason, CP for prestressed concrete has focused on the use of sacrificial anode systems and constant current or constant voltage rectifier impressed current systems. An additional concern is the application on bridge members that have an uneven electrical resistivity across the concrete surface. This will lead to the uneven distribution of the CP current and the possibility of overprotection in the low-resistivity regions. It is generally agreed that CP of prestressed concrete members can be accomplished safely and reliably if proper care is given to maintain minimum CP requirements and to prevent overprotection.

Electrochemical Chloride Extraction

Virmani and Clemena recently reviewed the use of electrochemical chloride removal.(6) When a direct current is conducted through concrete, the relatively mobile ions (such as chloride, hydroxide, sodium, potassium, calcium, etc.) in the concrete will migrate, with each ion moving toward the electrode with the charge opposite to it. The feasibility of removing the undesirable chloride ions from a contaminated concrete by such electrochemical means, instead of excavation of the contaminated concrete from a structure, was studied in the mid-1970s by Kansas DOT.

It was shown that chloride ions can be expelled from concrete by passing a direct current between the steel bars and anode, as in CP except at considerably greater current densities. However, unnecessarily high levels of direct current used in early investigations had some adverse effects on the concrete (e.g., decreased concrete-to-steel bond, increased porosity, and increased cracking in the concrete). The concern about these adverse effects on treated concrete delayed the use of electrochemical chloride extraction as a remedial method for the permanent rehabilitation of concrete bridges. Subsequent studies found that if the level of current applied is kept below 5 A per m^2 (0.5 A per ft^2), these adverse effects were not observed.

Because of the relatively high current densities (even at 5 A per m^2) and concerns about hydrogen-induced cracking, electrochemical extraction of chloride would not be used on prestressed concrete structures.

Full-scale pilot treatments have demonstrated that it is feasible and simple to conduct the treatment on full-sized reinforced-concrete bridge members, although it is comparatively more difficult to conduct the treatment on concrete piers. One difficulty encountered was predicting the necessary length of treatment required to reduce the chloride concentration at the steel rebar level to below the corrosion threshold or to some equilibrium concentration of chloride. Preliminary studies suggested that a total charge of 600 to 1,500 A-h per m^2 is sufficient in most cases, which means a total treatment time of 10 to 50 days is required.

While it is impossible to remove all the chlorides from the concrete by electrochemical means, chloride extraction depletes the amount of chloride immediately in contact with the steel and replenishes the passive layer (between 40 and 95 percent of the chloride ions are generally removed). Field data, so far, show that this is effective in stopping corrosion for at least 8 years. FHWA predicts that electrochemical removal technology will extend the life of bridges by as much as 20 years.(35) To date, there has been approximately 372,000 m^2 (4,000,000 ft^2) of concrete worldwide that has been treated.

The cost of electrochemical removal varies depending on the type and size of the structure. Treatment of bridge decks typically cost between $53 and $129 per m^2 ($5 and 12 per ft^2), depending on the size and contract requirements. The cost of electrochemical removal on substructures (vertical and overhead applications) is between $107 and $215 per m^2 ($10 and $20 per ft^2). Very small substructures (i.e., one or two columns) may cost up to $269 per m^2 ($25 per ft^2) if done on a stand-alone basis.(36)

Summary of Current Practices for Rehabilitation

The following items summarize the current practices based on research, field performance, and emerging technologies.(6)

Overlays, such as latex-modified concrete, low-slump concrete, high-density concrete, and polymer concrete, are the most common method used for the rehabilitation of bridge decks. This procedure extends the life of the bridge deck by approximately 15 years.

Cooperative research with industry and states in the development of durable anodes, monitoring devices, installation techniques, etc. has led to application of impressed-current CP systems on bridge decks as a routine rehabilitation technique. Titanium mesh anode, used in conjunction with a concrete overlay to distribute protective current, is filling the need for a durable anode for use in impressed-current CP of reinforced-concrete bridge decks and is, in fact, now widely accepted by state and local transportation agencies.

For CP of substructure members, especially those in a marine environment, several promising sacrificial anode systems have been developed (i.e., thermal-sprayed zinc, thermal-sprayed aluminum-zinc-indium (Al-Zn-In) alloys, zinc hydrogel, and zinc mesh pile jacket systems). Initiatives in the industry and in some states, in cooperation with FHWA, have led to further developments and identification of anodes suitable for impressed-current CP of inland concrete substructures.

Through extensive fundamental research and evaluation of CP systems that have been installed, significant advances have been made in the technology for CP of prestressed concrete components. Concerns about a loss of bond between the prestressing steel and concrete and possible hydrogen embrittlement (from overprotection of the prestressing steel) have been alleviated by the establishment of criteria for qualification of prestressed concrete bridge components for CP.

Summary of Rehabilitation Cost Alternatives

Table 9 gives the costs of electrochemical rehabilitation alternatives for bridge structures. Also provided is the expected life for each alternative. Often, electrochemical methods are in competition with rehabilitation utilizing an overlay such as low-slump, high-performance, or latex-modified concrete (see table 8 for costs). The deck condition is often the controlling factor in the rehabilitation method selected. In some cases, a combination of these methods is selected, e.g., electrochemical removal followed by an overlay or an overlay in conjunction with CP to mitigate any further corrosion.

Table 9. Summary of costs and life expectancy for rehabilitation alternatives.

TYPE OF MAINTENANCE	AVERAGE COST ($/m²)	RANGE OF COSTS ($/m²)	AVERAGE EXPECTED LIFE (years)	RANGE OF EXPECTED LIFE (years)
Impressed-Current CP (Deck)	114	92 - 137	35*	15 - 35
Impressed-Current CP (Substructure)	143	76 - 211	20	5 - 35
Sacrificial Anode CP (Substructure)	118	108 - 129	15	10 - 20
Electrochemical Removal (Deck)	91	53 - 129	15	10 - 20
Electrochemical Removal (Substructure)	161	107 - 215	15	10 - 20

*Current technology.

Deicing Alternatives

Calcium magnesium acetate (CMA) and potassium acetate (PA) have been identified as the most promising deicing alternatives. These compounds contain 76 percent and 61 percent of acetic acid, respectively, which represents approximately half of the formulations' costs. The annual usage of rock salt (sodium chloride) in the United States for deicing purposes is approximately 15.4 billion kg (17 million tons). A 1987 study showed that 910 kg (1 ton) of road salt, while costing $50, causes more than $1,450 in damages to vehicles, bridges, and the environment.(37) CMA's current price is approximately $1.10 per kg ($1,000 per ton) versus $0.04 per kg ($35 per ton) for rock salt.(38) This cost differential means that CMA usage will be limited to critical structures sensitive to corrosion unless some means of sharing costs based on the overall damage caused by the use of salt is devised.

In addition to the high price, CMA use is hampered by other limitations, e.g., CMA is slower acting than rock salt, if applied as a solid, and CMA exhibits marginal performance in light traffic, freezing rain, and dry and cold storm conditions. However, recent studies have shown that if the compound is applied as a concentrated solution or a pre-wetted solid, the rate of action is similar to that of a rock salt.(38) New York City DOT has implemented, on an experimental basis, a spray-on delivery of a liquid agent for anti-icing of certain sections of the Brooklyn Bridge deck (see Case Study 2).

Steel Bridges

In this section, various steel bridge coating installation and maintenance options are discussed, along with their costs and expected life. (7)

Coating Options

In addition to the traditional coating methodologies used on steel bridges, research to date has identified several technologies and maintenance methodologies that promise to provide cost-saving alternatives for bridge maintenance painting. Among these are: (1) the zone painting approach, (2) the use of overcoating or maintenance repair painting techniques, and (3) the selected use of metal spray coatings.

Traditional Coating System

A two- to three-coat system is traditionally applied over a clean, blasted surface. These coating systems include:(39)

- organic zinc primer, epoxy or polyurethane intermediate coat, and aliphatic polyurethane topcoat,
- inorganic zinc silicate primer, chemically curing epoxy or polyurethane intermediate coat, and aliphatic polyurethane topcoat,
- high-build, high solids, good-wetting epoxy primer with aliphatic polyurethane topcoat,
- three-coat waterborne acrylic, and
- three-coat, lead-free alkyd.

Zone Painting

Due to the increasing cost of the repainting of existing bridge structures, it has become economically advantageous to consider the use of zone painting approaches in lieu of wholesale removal and repainting of entire bridge structures. This concept is especially attractive for larger structures and, in fact, has been employed on structures such as the Golden Gate and Bay bridges in California and several of the bridges in the New York City area. These larger bridges have distinctly different exposure environments within the same structure simply because of their size and their location near saltwater. In addition, these bridges are maintained by bridge authorities, who collect tolls and generally have greater resources to focus on intermittent or periodic maintenance activities.

The vast majority of the bridges in this country are neither large nor maintained by toll authorities. Hence, the zone painting approach has not been applied on a widespread basis. This may change as the costs for full removal and repainting of even smaller structures have dramatically risen. The fact is that even on smaller structures, coating breakdown and corrosion is limited to areas where there are measurable levels of salt contamination and significant times of wetness. For bridges in marine or semi-marine environments, this is the entire structure; however, for bridges in non-marine environments (a majority of the bridges), these corrosive areas are generally limited to expansion joints, drainage, traffic splash, and tidal areas. If these areas can be isolated and maintained using a better corrosion protection system, large expenditures can be avoided on the remaining surface area of the bridge. This change in philosophy will require more informed engineering input during specification development and more oversight during repainting operations. In addition, improved inspection procedures and standards will be an essential input into the decision-making process.

Overcoating

Similarly, overcoating has become a more attractive option for state agencies as the cost of full removal and repainting has increased. This approach limits the amount of surface preparation to those areas that have failed paint and corrosion. These areas are spot primed and one or two full coats are applied over the entire structure for uniformity of color. This approach can be effective in less corrosive environments where the condition of the existing coating is relatively good. However, since this method of preservation will usually have a significantly lower initial cost than full repainting, the effect on life-cycle cost of this approach must be examined very carefully.

Metal Spray Coatings

Non-traditional bridge coating systems have been investigated for potential long-term performance benefits. While some of the candidates tested have not shown immediate usefulness (e.g., powder coatings), others, such as metallized coatings, appear to have the benefit of excellent long-term corrosion resistance. Although these systems are applied at a somewhat higher initial cost, the changing overall economics of bridge repainting operations has made their use more competitive in terms of life-cycle cost.

Coating Installation - Maintenance Costs

The coating system installation cost is not easy to define. Over the past several years, there have been significant changes in the methodology of bridge maintenance painting operations. The most significant changes have been in response to dramatic increases in environmental and worker protection regulations that impact these operations. The use of containment structures to capture hazardous waste and pollutants generated during removal of old coatings and the gradual institutionalization of worker health and safety practices associated with the removal of hazardous materials, have introduced significant cost impacts to bridge maintenance painting. This has caused a large diversity in operational practices and in the resultant cost of these operations.

The issue of applying protective coatings to the steel bridges to prevent corrosion is further complicated by the requirement to contain or remove the previously applied lead-based paint, as regulated by the Environmental Protection Agency. Congressional regulations (the Resource Conservation and Recovery Act and the Hazardous and Solid Waste Amendment) now require that all wastes be treated.

According to 1992 National Cooperative Highway Research Program (NCHRP) data,(40) approximately 80 percent of the steel highway bridges have been coated with lead-containing paints. The report estimated that $100 million to $130 million is spent annually on bridge painting. A total of 10 to 20 percent of the costs of bridge painting are incurred because of the requirement to contain paint, abrasive, and dust fallout. In addition, the costs of treatment can range from $0.33 to $0.55 per kg ($300 to $500 per ton) where lead paint removal activities generate an estimated 181 million kg (200,000 tons) of lead-contaminated abrasives.

The overall cost is comprised of the costs for surface preparation, the material itself, and application activities. The estimates for some of the above coating systems are given in table 10.(7) The service life of the coating systems is significantly affected by the service conditions. For example, a two-coat alkyd primer with the topcoat exposed to mild conditions (rural or residential area with no industrial fumes/fallout) would last only 3 years until the next maintenance. On the other end of the spectrum is the triple system consisting of a moist-cured urethane zinc-rich coat, a high-build acrylic urethane coat, and an acrylic urethane topcoat. The expected service life of this coating system in severe conditions (heavy industrial and chemical plant area with high levels of fumes and fallout) is 15 years.

Table 10. Cost for alkyd, epoxy, and epoxy/urethane systems in moderate industrial environment in the southeast United States.(7)

System	SSPC Surface preparation	DFT****	Cleaning Cost	Material Cost	Application Cost	Total Installed Cost	System Life (5-10% breakdown)	Cost/year
		(mm)	(\$/m^2)	(\$/m^2)	(\$/m^2)	(\$/m^2)	(years)	(\$/m^2)
Two-coat alkyd	2*	0.10	\$5.92	\$1.08	\$5.38	\$12.38	3	\$4.09
	6**		\$9.15			\$15.61	6	\$2.58
Two-coat epoxy	2	0.15	\$5.92	\$1.72	\$6.46	\$14.10	7.5	\$1.83
	6		\$9.15			\$17.33	10.5	\$1.61
	10***		\$10.76			\$18.94	12	\$1.61
Two-coat epoxy/ urethane	6	0.15	\$9.15	\$2.26	\$7.00	\$18.41	9	\$2.05
	10		\$10.76			\$20.02	10.5	\$1.94

*Hand-cleaned surface.
**Commercial blast.
***Near-white blast.
****Dried-film thickness.

Presently, the costs of total paint removal and repainting jobs can range from \$43.00 per m^2 (\$4.00 per ft^2) to as much as \$215.25 per m^2 (\$20.00 per ft^2).(41) This range can be partially explained by factors that make each bridge maintenance job unique, such as access for high structures or structures over water, the condition of bridge deterioration, and unusual traffic control. However, a significant portion of the cost range is attributable to uneven application of regulatory compliance measures for environmental and worker safety issues.

An alternative to paint removal is overcoating, which includes cleaning of the structure, priming rusty areas, and applying intermediate coats and topcoats either over repaired areas or over the full structure. The cost of overcoating for bridges was estimated to range from \$11 to \$54 per m^2 (\$1 to \$ 5 per ft^2), with some evidence that the tighter OSHA standards(42) push the cost up to \$86 per m^2 (\$8 per ft^2).

The present effort to implement bridge corrosion control maintenance practices, which achieve regulatory requirements and cost-efficiency, cannot be successful without the development of reliable task-based cost data for bridge painting jobs. These data are dependent on a variety of factors, which vary from local cost differences (e.g., labor) to structural differences (e.g., accessibility) to contractor costing rules (e.g., limits on certain items such as mobilization). Development of reliable data and an understanding of regional influences on these data will help to improve analysis of the cost data.

It is estimated that roughly 50 percent of the cost of an average maintenance painting job is now attributable to environmental protection and worker health measures. This increase in "other" job costs has raised the total cost of coating removal jobs from an average of \$54.36 per m^2 (\$5.05 per ft^2) in 1992 to an average of \$114.10 per m^2 (\$10.60 per ft^2) in 1995, while the cost for the actual work (surface preparation and coating materials) has stayed relatively constant. Note that the savings incurred by paying slightly less for a less durable coating material are minor as a percentage of the overall cost. This highlights the need for life-cycle cost analysis.

Estimated time to failure for several coating systems is presented in table 11. Table 12 presents the estimated costs for painting options used in the sample analysis. The costs presented in the table are composite figures based on information from several different sources (41,43) and are expected to vary across the United States. Table 11 data show that depending on the surface preparation (i.e., blasting versus overcoating) and the type of coating, the assumed service life (life to 10 percent of degradation) can vary considerably, from as few as 3 years to 30 years. Similarly, table 12 suggests that the longevity of a coating is closely related to the costs of surface preparation and coating application. For example, overcoating, lasting only a short time, is inexpensive at \$3.22 per m^2

($0.30 per ft^2), whereas, near-white metal blasting followed by metallizing, which is expected to serve for 30 years, costs 10 times as much.

Table 11. Coating system time-to-failure estimates in a marine environment.[41,43]

COATING SYSTEMS	ESTIMATED COATING SYSTEM LIFE*
Ethyl Silicate Inorganic Zinc/Epoxy Polyamide/Aliphatic Urethane over SP-10 Near-White Metal Blast	15 years
Epoxymastic/Aliphatic Urethane over SP-10 Near-White Metal Blast	10 years
Epoxymastic/Aliphatic Urethane Overcoat over Existing Paint and SP-3	4 years**
85% Zinc/15% Aluminum Metallizing over SP-10 Near-White Metal Blast	30 years***
Low-VOC Alkyd Three-Coat System Overcoat over Existing Paint and SP-3	3 years**

*Lifetime was defined as 10 percent degradation of the coatings.

**Estimates based on data from FHWA programs.

***Estimates based on the performance of metallized coatings in this program.

Table 12. Estimated costs for painting options.[41,43]

CATEGORY	TYPE	ESTIMATED COST, ($/m^2)
Surface Preparation (labor + material)	SP-10 Near-White Metal Blast	$13.45
	SP-3 Power-Tool Cleaning	$ 6.46
Coating Application	Three-Coat Full Painting	$13.45
	Overcoating	$ 3.23
	Metallizing	$26.91
Coating Material	IOZ/Epoxy/Urethane	$ 5.27
	Epoxymastic/Urethane	$ 4.52
	Metallizing	$16.15
	Moisture-Cured Urethane	$ 2.69
	Three-Coat Alkyd	$ 2.05
Other Job Costs	Containment and Air Filtration Systems, SP-3 only	$ 5.38
	Containment and Air Filtration Systems, SP-10 only	$21.53
	Inspection, SP-3 only	$ 5.38
	Inspection, SP-10 only	$10.76
	Rigging	$ 5.38
	Mobilization	$ 5.38
	Hazardous Waste Storage and Disposal, SP-3 only	$10.76
	Hazardous Waste Storage and Disposal, SP-10 only	$26.91
	Worker Health and Safety, SP-3	$10.76
	Worker Health and Safety, SP-10	$21.53

Table 12 also contains information on extra costs such as containment and waste disposal-related costs, and worker health and safety costs. The numbers show that these types of costs are equal to or exceed the costs of surface preparation, coating material, and coating application.

A sample cost distribution, shown in figure 7 for a typical heavy-duty maintenance job on a steel bridge structure, indicates that only a small portion of the total job cost is attributed to paint and paint application.(41) More than half of the cost is taken by access, containment, and workers health costs. Not included are the lead abatement and waste treatment costs, which can result in as much as a sevenfold increase in cost.

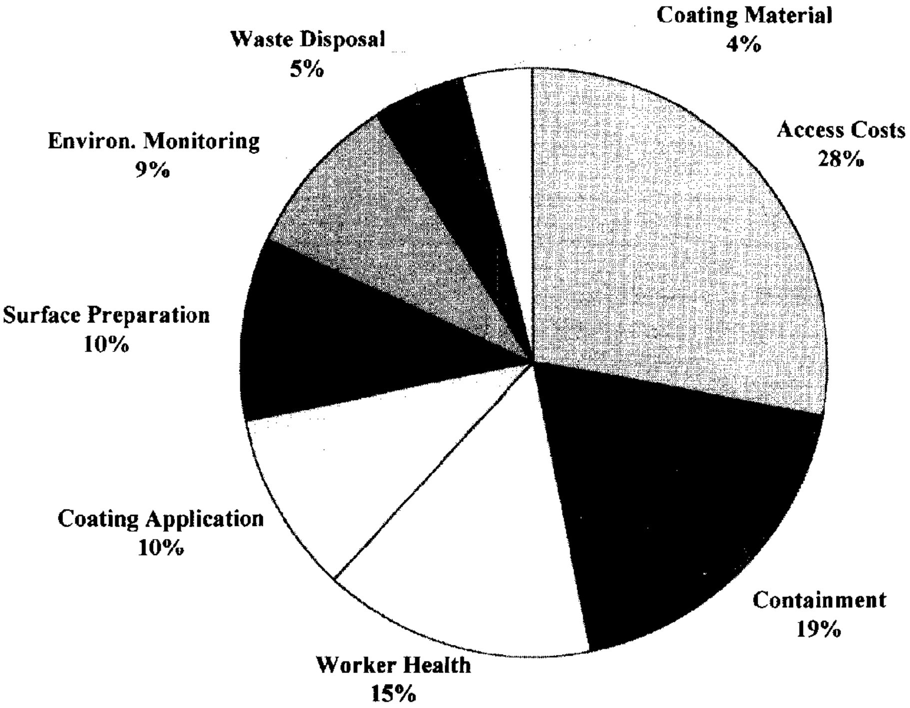


Figure 7. Cost distribution of coating application on steel highway bridge structure.(41)

Sample Cost Analysis for Coating Options

Sample life-cycle cost analysis data for different coating options, assuming a 60-year life span of a bridge, are presented in table 13.(7) The overcoating options offer the lowest initial cost; however, these are not always the lowest annual cost. In fact, the coating removal options show the lowest annual costs in a severe environment, but the choice was less clear as the environment was made less severe.

Table 13. Summary of sample analyses.

Approach	Coating System	Coating Life	Surface Prep.	No. of Maint. Cycles	Cost Per Maint. Cycle	Total Cost in Present Day Dollars	Total Present Value	Annual Costs
		(years)			($/m^2)	($/m^2)	($/m^2)	($/m^2/year)
Existing lead-based paint; repair and overcoat with three-coat alkyd	3-coat alkyd	3	SP-3	20	$56.94	$1,138.80	$477.92	$34.01
	Epoxymastic/ polyurethane	4	SP-3	15	$59.42	$891.30	$458.22	$32.61
Existing lead-based paint; full removal by blasting	85% Zn / 15% Al metallizing at 6 to 8 mils	30	SP-10	2	$158.77	$317.54	$227.44	$16.15
	IOZ/epoxy/ Polyurethane	15	SP-10	4	$123.68	$494.72	$300.64	$21.42
Existing lead-based paint; full removal and maintenance over approximately 20% of the surface area every 5 years after the initial 15-year service life.	IOZ/epoxy/ Polyurethane	15	SP-10	1	$123.68	$690.41	$351.01	$24.97 $0.00
	Maintenance	5	SP-3	9	$62.97			
Existing lead-based paint; remove and replace	Epoxymastic/ Polyurethane	10	SP-10	6	$120.23	$721.38	$413.33	$29.49
Existing lead-based paint; repair and overcoat	3-coat alkyd	10	SP-3	6	$56.94	$341.64	$156.72	$11.19
Existing lead-based paint; full removal	85% Zn / 15% Al metallizing at 6 to 8 mils	60	SP-10	1	$158.77	$158.77	$158.77	$11.30

Cost of Corrosion for Bridges

The following analysis was used to provide an estimate of the annual direct cost of corrosion for highway bridges. The analysis is divided into: (1) cost to replace structurally deficient bridges, and (2) corrosion associated life-cycle cost for remaining (non-deficient) bridges, including the cost of construction, routine maintenance, patching, and rehabilitation.

The annual cost of structurally deficient bridges (see figure 8) is estimated as the cost to replace these bridges over a 10-year period; it is calculated using a $29.3 billion as a present value of the cost (see "Areas of Major Corrosion Impact" for calculation) at a 5 percent annual percentage rate (APR). Assuming annual payments for the replacement cost, the annual cost to replace structurally deficient bridges (both reinforced concrete and steel) over the next 10 years is $3.79 billion per year. Recall that this value is for the current number of deficient bridges and does not account for the additional ones added to this number each year. Therefore, this cost is potentially greater than that given here.

Figure 8. Examples of severe corrosion resulting in deficient bridges.

There are 543,019 concrete and steel bridges, of which 78,448 are structurally deficient (see table 3), leaving 464,571 bridges to be maintained. For the purposes of this estimate, it is assumed that all of these bridges have a conventionally reinforced concrete deck. The annualized life-cycle direct cost (no user cost) of original construction, routine maintenance, patching, and rehabilitation for a black steel rebar deck ranges in cost from $22,000 (experienced-based maintenance) to $18,000 (information-based maintenance with crack repair) for an "average" size bridge deck (see figure 19 at 5 percent interest). This annual life-cycle cost of $22,000 to $18,000 per bridge includes those costs associated with corrosion (see figure 9), as well as non-corrosion-related costs. To establish the corrosion-related costs requires the calculation of the life-cycle cost associated with a theoretical "corrosion-free" bridge deck (i.e., what if corrosion did not exist). The "corrosion-free" scenario used the same cost basis as the above bridge deck with corrosion, with the following assumptions for the life cycle: (1) cost of construction is the same as for the deck with corrosion, (2) annual routine maintenance is the same as for the deck with corrosion, (3) no patching is required, (4) an overlay is required for improved skid resistance at 50 and 85 years (an overlay life of 35 years), giving a bridge life of 120 years, and (5) deck is removed at 120 years. This scenario gave an annual cost for a "corrosion-free" bridge deck of $15,700 (see "Theoretical Corrosion-Free Bridge - Direct Cost Only"). Therefore, the cost of corrosion for an "average" bridge deck is estimated by the difference in the annual cost of a "deck with corrosion" and a "corrosion-free deck," or $6,300 ($22,000 - $15,700) to $2,300 ($18,000 - $15,700). The total estimated cost of corrosion for bridge decks is $2.93 billion ($6,300 per deck x 464,571 bridges) to $1.07 billion ($2,300 per deck x 464,571 bridges).

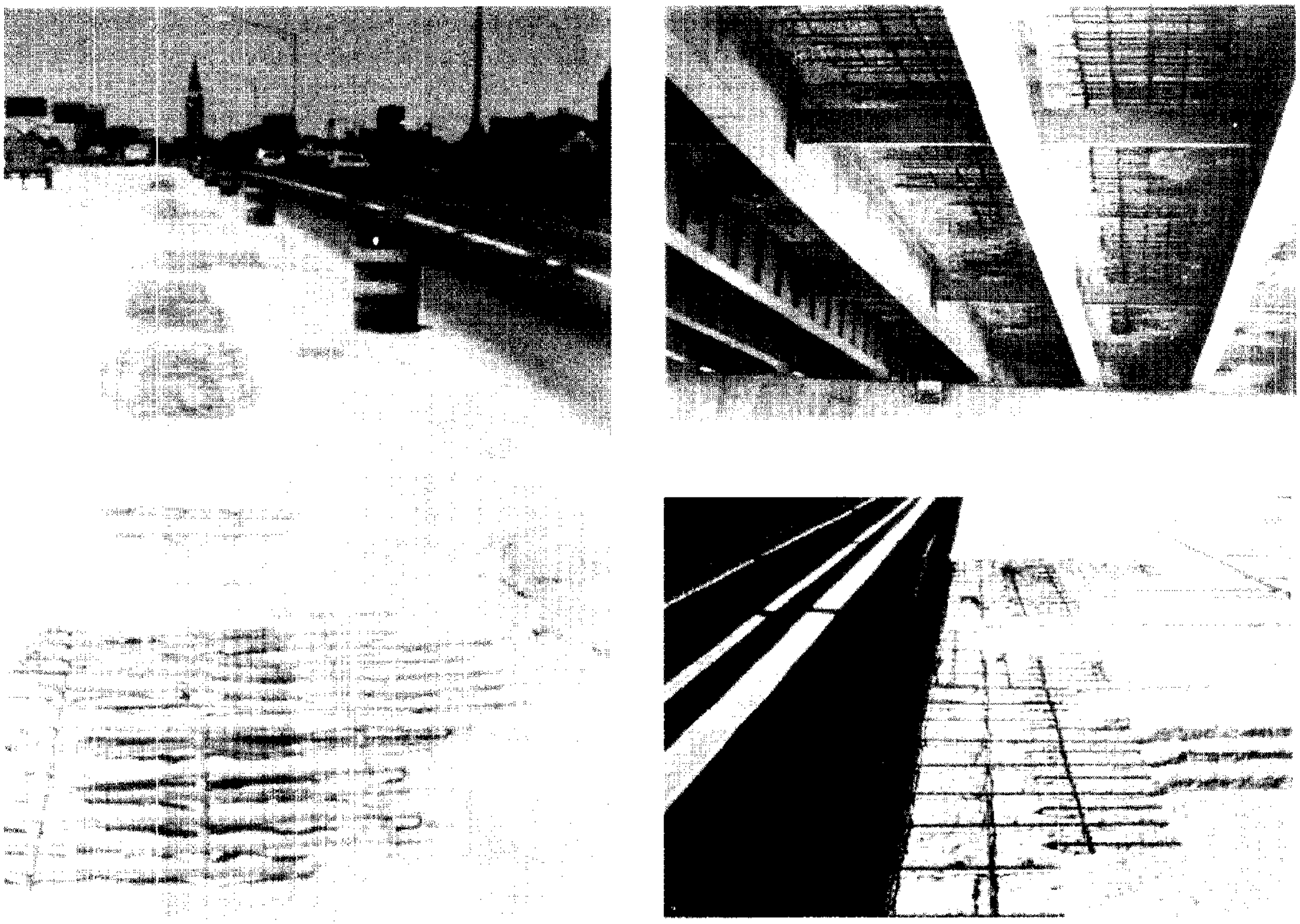


Figure 9. Examples of bridge deck corrosion.

The differences in the two maintenance scenarios that resulted in this range of corrosion-related costs were the "experience-based maintenance" and "information-based maintenance with crack repair" (see "Life-Cycle Cost Analysis for Bridge Decks" for details). This difference represents the range of maintenance from minimal practice to best practice. The cost analysis estimated the cost of corrosion from $6,300 (minimal practice) to $2,300 per deck per year (best practice). These values show that a savings of 63 percent [($6,300 – $2,300) / $6,300] of the cost of corrosion is possible by improving the maintenance from minimal to best practice. However, the actual bridge maintenance practice is somewhere between the minimal and the best practice. If it is assumed that today's maintenance practice represents the "average" in the above range [($6,300 - $2,300) / 2 = $4,300], 46 percent savings [($4,300 – $2,300) / $4,300] or $2,000 per bridge per year can be achieved by improving maintenance practice.

These savings were calculated for black steel rebar decks for which improved maintenance can still provide savings. However, corrosion of many black steel rebar decks has progressed to the extent that improved maintenance will not make a significant difference. For those decks, other rehabilitation options must be considered (e.g., cathodic protection, overlays, or electrochemical chloride removal). If the savings of $2,000 per bridge per year is applied to the total number of bridges, the total savings would be $0.93 billion per year. As previously mentioned, this savings is not available today for all bridges, but the significance of "best engineering practice" for maintenance cannot go unnoticed.

The area of the substructure and superstructure (minus deck) was estimated to be similar to the deck surface area for an "average" bridge. The following was taken into consideration for estimating the cost of substructures and superstructures (minus deck): (1) repair and maintenance for the substructure/superstructure cost significantly more per surface area than the deck; (2) in non-marine applications, the percent of surface area deteriorated due to corrosion of the reinforcing steel is much less and often is limited to areas beneath expansion joints and drains, which are exposed to deicing salt runoff; and (3) conversely, corrosion problems are more prevalent on substructures than decks in severe marine environments. With these considerations, it was estimated that the cost of corrosion for substructures and superstructures (minus deck) is similar to the cost for bridge decks, i.e., $2.93 billion to $1.07 billion (see figure 10).

The cost for steel bridges has an additional cost for maintenance painting. The expenditure for painting steel bridges is estimated at $0.50 billion per year.(7)

The total annual direct cost of corrosion for bridges is estimated to be $10.15 billion to $6.43 billion, which is the sum of all costs itemized above ($3.79 billion to replace structurally deficient bridges over the next 10 years plus $2.93 billion to $1.07 billion for maintenance and cost of capital for concrete bridge decks plus $2.93 billion to $1.07 billion for maintenance and cost of capital for concrete substructures and superstructures (minus decks) plus $0.50 billion for the maintenance painting cost for steel bridges). This gives an average annual cost for corrosion of bridges of $8.29 billion. As seen in the case studies presented later, the cost of corrosion can be significantly greater than the above for individual bridges, especially those of historical significance or those that are critical to traffic flow. In addition, problems in post-tensioned bridges or cable and suspension bridges can be very costly to repair. Although the direct costs presented above are estimated by making broad assumptions, the calculated cost represents the relative cost of corrosion for the highway bridge industry sector. Life-cycle analysis estimates indirect costs to the user due to traffic delays and lost productivity at more than 10 times the direct cost of corrosion (see "Life-Cycle Cost Analysis for Bridge Decks").

Figure 10. Examples of substructure corrosion.

CASE STUDIES

Case Study 1. Corrosion of Florida Post-Tensioned Bridges(44-45)

Recent inspections of two Florida post-tensioned bridges (Niles Channel and Mid-Bay bridges) have identified corrosion-induced strand and tendon failures. These recent failures highlight the need for better inspection techniques and tools to identify problems before bridge integrity is compromised.

Niles Channel Bridge

The Niles Channel Bridge is a 1,389-m- (4,557-ft-) long structure built in 1983 located in the Florida Keys. The superstructure is comprised of segmental, precast concrete post-tensioned box girders with a deck width of 11.7 m (38.5 ft). All of the conventional reinforcing bars are coated with epoxy. The box girders are post-tensioned by means of 19 strand tendon bundles situated along the interior web walls and anchored into the bulkheads at the ends of each 29.1-m (95.5-ft) span. The tendon bundles are encased in polyethylene ducts, which attach to the metal anchorage assemblies cast into the bulkheads. The polyethylene ducts join the anchorage externally with a banded rubber sleeve. Both the ducts and the anchorages are grouted with a portland cement-based material. The tensioning ends of the anchorage assemblies are protected by means of cast-in-place blocks (pour-backs) either 152 or 304 mm (6 or 12 in) thick, depending on the location.

During a 1999 routine inspection, it was noted that the pour-back concrete had spalled, exposing the wedge plate at the NW anchorage (middle tendon) at Expansion Joint No. 2 (Pier 9). Subsequent investigation revealed that each of the 19 strands making up that tendon had failed due to corrosion, thus rendering the tendon nonfunctional. The appearance of the failed strand is shown in figure 11. Following removal of the wedge plate and strands, the examination of the trumpet showed heavy corrosion on the upper-half of the trumpet with moderate pitting. The appearance indicated that the upper-half of the trumpet had never been in contact with grout, but instead that space had been occupied by bleed water. Although the heaviest corrosion on the strands was in the trumpet region, corrosion extended up approximately 1.5 m (5 ft) from the bulkhead. The likely cause of corrosion was determined to be due to bleed water being present at the time of construction, recharging of the environment within the void, and possibly aggravation by chlorides.


(a) (b)

Figure 11. (a) corrosion in the free length of tendon, (b) failed strands.

Further investigation revealed heavy corrosion on two strands of another tendon where the polyethylene duct attaches to the trumpet at the middle tendon, NE anchorage, at Expansion Joint No. 2 (Pier 9, but on the opposite web wall from the failed tendon). Both strands were broken at some point inside the trumpet and evidence of voids in the grout along with bleed-water staining was present. Although minor corrosion was observed on other tendons, no other significant corrosion was detected.

During further investigations, Florida DOT employed several nondestructive evaluation methods to determine the extent of the strand corrosion. These included the vibration method (frequency analysis of induced tendon vibration), electrical method (measurements of electrical resistance between the strands and the anchorage), and the magnetic flux method (detection of variations in the strength of the magnetic field applied to strands). The effectiveness of these methodologies in detecting corrosion or voids in the grout resulting from bleed water has not been fully established.

Mid-Bay Bridge

The Mid-Bay Bridge is 5,872 m (19,265 ft) in length and made up of 141 spans crossing Choctawhatchee Bay in Okaloosa County, Florida. The superstructure is comprised of segmental, precast post-tensioned box girders. During a routine inspection, a post-tensioning tendon in Span 28 was observed to be significantly distressed. The polyethylene duct was cracked, exposing the strands, of which several had failed. An immediate walk-through indicated complete failure of a post-tensioned tendon in Span 57, as evidenced by pull-out of the tendon from the expansion joint diaphragm.

The discovery of the failed strands and tendon led to a rigorous inspection and testing regimen consisting of the following:

- sounding post-tensioned tendons for voids,
- bore scope inspections of post-tensioned anchors,
- vibration testing,
- visual void inspections,
- magnetic flux testing, and
- grouting mock-up tests.

No single inspection or testing method is able to provide complete evaluation of the corrosion of external post-tensioned tendons. Techniques that provide information in the free length of the tendon do not give results in the anchorage zones. The approach taken for the Mid-Bay Bridge was to conduct a battery of tests chosen to develop an understanding of the tendon conditions. Based on these tests, corrosion was found at several locations, but no other tendon failures were discovered. The primary cause of corrosion was the presence of water in the tendons, probably due to bleeding of the grout, although other possible sources were not completely ruled out.

Based on the above inspections, 11 post-tensioned tendons were identified as needing replacement. In addition, significant repair was required at anchorages, including: (1) replacement of all pour-backs located at expansion joint piers – 89 required, (2) grouting of anchorage voids with strands visible – 274 required, (3) grouting of anchorage voids without strands visible – 316 required, (4) replacement of pour-back at interior piers – 307 required, and (5) coating of undamaged pour-backs with coal-tar epoxy – 408 required. Because of voids and cracks in the polyethylene duct, which serves as a protective barrier against the ingress of corrosive agents, wrapping of up to 35,000 linear m (115,000 linear ft) of duct was undertaken.

Summary of Case Study 1

Corrosion identified on post-tensioned tendons is a major concern to bridge engineers. Part of the concern is that it is extremely difficult to inspect for problems in post-tensioned designed structures. Therefore, only isolated problems are observed, and then only by visual observation during routine inspection. The concern is whether deterioration due to corrosion that affects the structural integrity of the bridge structure can be found during routine inspections prior to major failure.

The cause of the corrosion in both the Niles Channel and Mid-Bay bridges appears to be bleeding of the grout, resulting in water-filled voids in the tendon and subsequent recharging of the voids with external water/moisture. The bleed water is often sufficiently corrosive to permit corrosion of the high-strength steel strands. In both bridges, problems were identified during routine inspections, underscoring the importance of such inspections for all post-tensioned bridges. Several deficiencies in post-tensioned bridge construction and inspection practices are apparent from these two case studies:

- Bleeding of grouts remains a significant problem, even following much research and acknowledgment of the problem for many years. Improved grout placement methodology is necessary to minimize grout bleeding and void formation. Improved grout mix designs should be used (the Post-Tensioning Institute has recently issued new specifications for grouting of post-tensioned structures). Recently, pre-packaged grout mixtures have been made available, which minimizes problems associated with bleed water and formation of voids in the ducts.
- Overall post-tensioned bridge designs should be reviewed to permit improved inspection capability of the tendons and anchorages.
- Better methods are needed to evaluate construction practices to ensure void-free grout placement.
- Inspection technologies specifically designed or adapted to post-tensioned bridge designs need to be fully developed with respect to their effectiveness in detecting a certain type of flaw or performance criterion, resolution of detection, and reliability. One possible outcome would be that a nondestructive inspection report forms the basis for acceptance by the owner of a completed bridge.

Case Study 2. East River Bridges in New York City(46-48)

Introduction

The four East River bridges, the Brooklyn, the Williamsburg, the Manhattan, and the Queensboro, have permitted New York City to claim its place among the greatest centers of urban activity worldwide by connecting the boroughs of Manhattan, Brooklyn, and Queens. At their peak, the four bridges carried nearly 2 million passengers a day; today, they carry more than a million passengers and remain a vital link for the city and metropolitan area.

Their historical significance is as important as their practical significance. In 1883, the Brooklyn Bridge became the worlds longest suspension bridge, with a main span of 487 m and side spans of 284 m each. In 1903, the Williamsburg Bridge pushed the main span record to 488 m. The Manhattan Bridge opened in 1908 and was the first fully suspended bridge to be designed by large deflection theory (main span of 449 m and side spans of 222 m). The Queensboro Bridge is a five-span cantilever truss structure, built in 1912, with a longest span of 361 m and a total length of 1,136 m. The Brooklyn Bridge has become one of the most recognizable landmarks for New York City.

At nearly 100 years old or older, these bridges have undergone numerous repairs and are undergoing rehabilitation. The rehabilitation strategies for these bridges have evolved over the past two decades and will continue to evolve. Numerous innovative repair and rehabilitation designs are being tried or have been implemented on these bridges in an attempt to find new cost-effective and life-extending solutions to the bridge's aging problems.

Inspection Strategies

Bridge inspection and maintenance strategies, which have led to the current bridge condition, were ones of minimizing initial and current expenditures. Historically, the federal programs for investment and new construction led to the bridge management decisions to obtain maximum service at a minimum cost and then replace the structure at the end of the service life. Actions by FHWA and New York State DOT (NYSDOT) have gone a long way toward changing these policies. In 1971, the National Bridge Inspection Standards (NBIS) were established to promote a national bridge inspection and inventory program. NBIS set national policy regarding bridge inspection frequency, personnel qualifications, and reporting procedures. NYSDOT established a Uniform Code of Bridge Inspection, which prescribed bridge inspection standards and evaluation of all publicly owned bridges in the state. In 1988, NYSDOT was given the responsibility of inspecting all publicly owned bridges in the state.

The NYSDOT bridge inspection program identifies 30 to 40 items per span that are inspected and rated using a 1 to 7 numeric rating system: 1 indicates that the item is totally deteriorated or failed and 7 indicates that the item is in new condition or has no deterioration. The Brooklyn Bridge had a rating of 2.79 in 1989 and 2.88 in 1998 (a 3 rating is serious deterioration or not functioning as originally designed). The Manhattan Bridge had a rating of 3.23 (lower roadway) and 1.81 (upper roadway) in 1989 and 3.42 and 3.64, respectively, in 1998 (only slightly better than a 3 rating). Williamsburg Bridge had a rating of 1.88 in 1989 and 2.37 in 1998. The Queensboro Bridge had a rating of 2.65 (lower roadway) and 1.62 (upper roadway) in 1989 and 4.86 and 4.39, respectively, in 1998 (a 5 rating is minor deterioration and functioning as originally planned). Although, the ratings for the bridges have improved from 1989 to 1998, significant problems persist.

Rehabilitation

The East River bridges rehabilitation project began in 1980 and is currently scheduled to continue through 2008. Upon completion, the rehabilitation program costs are expected to be more than $2.5 billion. This program has been a cooperative effort between NYSDOT and the federal aid programs, which have funded a large part of these costs. Tables 14 through 17 present a summary of the major rehabilitation projects and their respective costs for each bridge.

A major focus of the Brooklyn Bridge rehabilitation program was an early 1980's inspection that revealed that the entire stay and suspension system was corroded and required replacement. The main suspension cables were found to be in good condition.

Table 14. Major rehabilitation projects for the Brooklyn Bridge.

REHABILITATION ACTIVITY	COST ($ x million)
Rehabilitate cables in anchorage and replace suspenders; rehabilitate balance of promenade and construct bikeway and new pedestrian ramp. (1988)	22.68
Rehabilitate and paint York, Main, William, and Prospect Streets structures and main bridge roadway deck overlay. (1988)	6.21
Replace suspenders, cable posts, stay cables, hand-rope necklace lights, main cable wrapping; paint suspended spans. (1991)	53.57

Table 14. Major rehabilitation projects for the Brooklyn Bridge (continued).

REHABILITATION ACTIVITY	COST ($ x million)
Rehabilitate ramps D and H in Manhattan, permanent improvement of promenade at Manhattan approach. (1993)	17.92
Rehabilitate floor systems, stiffening trusses, roadways of suspended spans and Franklin Square trusses. (1994)	66.30
Rehabilitate ramp D and widen along FDR Drive. (1996)	11.39
Arch supports for Franklin Square truss structure.	7.50
Replacement of suspended span deck. (in progress)	33.80
Resurfacing of the main spans. (1998)	6.67
Rehabilitate and paint Brooklyn approach and ramps; rehabilitate and paint Manhattan approaches and ramps. (in progress)	115.00
TOTAL (All contracts, not summation of table)	**$351.26**

The Williamsburg Bridge was temporarily closed to all traffic (eight automobile lanes and two subway tracks) in 1988 following an inspection until an estimate of the structural safety could be completed. Although an original recommendation for replacement was made, an expert task force appointed by the mayor determined that rehabilitation was the best course of action. The technical decision for rehabilitation was predicated upon the determination that the four suspension cables could be saved with a complete re-wrapping, preceded by wedging, cleaning, oiling, re-splicing of broken wires, and re-anchoring of broken strands.

Table 15. Major rehabilitation projects for the Williamsburg Bridge.

REHABILITATION ACTIVITY	COST ($ x million)
Replace main-span outer roadway. (1983)	11.20
Replace one-third of suspenders. (1984)	3.20
Component repairs of flag conditions on the north outer roadway and north inner roadway. (1994)	4.12
Rehabilitate main cables and new suspender system. (1996)	74.00
Demolish DOS and DOH buildings, replace entire south outer roadway approach structures, rehabilitate south outer roadway deck and south inner roadway deck of the main bridge, and replace south inner roadway substructure of the approaches. (1998)	155.00
Portion of Contract #6 BMT track structure work transferred to ongoing Contract #5 south approach roadway reconstruction work. (1998)	65.00
Paint main and intermediate towers. (in progress)	7.40
Reconstruct BMT subway structure; install new signals, tracks, and communications system. (in progress)	130.00
Miscellaneous rehabilitation work: tower rehabilitation, replace bearings travelers, architectural work, painting, suspender adjustment, tower jacking, construction of colonnades.	73.50
Replace north approach structures (Manhattan/Brooklyn), rehabilitate north half of bridge and paint the main bridge. (in progress)	202.80
TOTAL (All contracts, not summation of table)	**$748.51**

The Manhattan Bridge has had extensive and innovative work performed on the bridge anchorages in order to rehabilitate the cable eyebars, and dehumidification is planned for the anchorage chambers to reduce the risk of reoccurring corrosion problems.

Table 16. Major rehabilitation projects for the Manhattan Bridge.

REHABILITATION ACTIVITY	**COST** **($ x million)**
Repair floor beams. (1982)	0.70
Replace inspection platforms, subway stringers on approach spans. (1992)	6.30
Install anti-torsional fix (side spans) and rehabilitate upper roadway decks on approach spans on east side. (1989)	40.30
Eyebar rehabilitation – Manhattan anchorage chamber "C". (1992)	12.20
Replacement of maintenance platform in the suspended span. (1996)	4.27
Reconstruct maintenance inspection platforms, repairs to structural steel support system of lower roadway for future functioning of roadway as a detour during later construction contracts. (1997)	23.50
Install anti-torsional fix on west side (main and side spans); west upper roadway decks; walkway rehabilitation; rehabilitate cables in both anchorage chambers; dehumidify Brooklyn and Manhattan anchorages. (1993)	96.90
Removal of existing suspender ropes and sockets in the suspended spans; removal of existing main cable wrapping; cleaning of main cables; application of new protective paste on main cables; replacement of new main cable wrapping; reinforcement of truss verticals and gusset plates. (1987)	70.00
Interim steel rehabilitation and painting cable and saddle repairs on lower roadway; cable and suspender repairs, removal of parking deck, paint entire west side, all four cables. (1997)	124.10
Stiffening of main span; reconstruction of north subway framing; reconstruction of north upper roadway deck at suspended spans; rehabilitation of north approach spans; installation of Intelligent Vehicle Highway System for north and south upper roadways as well as for lower roadway. (in progress)	201.00
Rehabilitation of lower roadway. (in progress)	17.00
TOTAL (All contracts, not summation of table)	**$702.20**

Corrosion has severely reduced the floorbeam sections of the Queensboro Bridge. Although no longer functioning as designed, the bridge is still adequate for current loads. The roadways have been replaced with concrete-filled steel gratings and repainting with full lead removal has been completed in certain areas, while others are pending.

Table 17. Major rehabilitation projects for the Queensboro Bridge.

REHABILITATION ACTIVITY	**COST** **($ x million)**
Repair lower outer roadways reconstruct two ramps in lower Queens. (1984)	18.80
Reconstruct south upper roadway, replace inspection platforms, lighting. (1986)	31.50
Interim rehabilitation contracts A, B, & C (repairs to lower deck and main bridge approaches). (1985)	2.80
Interim rehabilitation, contract D (repairs to lower deck, main bridge, and new median barrier). (1988)	3.00
Reconstruct north upper roadway and Queens approaches A & B, rehabilitate bearings at Queens approach. (1989)	50.00
Reconstruct ramps C & D (Queensboro only, not Thompson Ave.). (1988)	10.40
Rehabilitate bridge bearings, pier tops, and truss lower chords. (1989)	18.00
Rehabilitate Queens approach trusses, lower inner roadways on the main span and approaches. (1996)	172.00
Rehabilitate lower outer roadways main span and approaches, (bikeway) cleaning and painting. (in progress)	161.40
Cleaning and painting main bridge upper trusses. (in progress)	48.50
TOTAL (All contracts, not summation of table)	**$516.40**

Preventive Maintenance

The East River bridges are part of the Preventive Maintenance Management System implemented by the New York City Department of Transportation in the early 1990s. The preventive maintenance system includes such action items as: (1) debris removal; (2) sweeping; (3) cleaning of drain system, pier and abutment tops, open gratings, and expansion joints; (4) washing of salt splash zones; (5) painting of the steel; (6) spot painting of the steel; (7) painting of salt splash zones; (8) patching of sidewalk; (9) sealing of cracks; (10) electrical maintenance; (11) oiling of mechanical parts; and (12) replacing of wearing surfaces. Painting and spot painting of the steel represents almost half of the overall cost of the program.

The elements directly related to corrosion control are washing of the deck and salt splash zones to remove deicing salts (once a year), painting of the steel (once every 8 years), spot painting of the steel, and painting of salt splash zones (once every 4 years). The painting cycle is shown in figure 12.

In addition to the rehabilitation costs described above, the preventive maintenance program expenditures for the Brooklyn Bridge for the 10-year period from 1999 to 2008 are estimated at approximately $6.2 million. The painting contracts for the 12-year period starting in 2000 are estimated at $48 million. The Brooklyn Bridge is also the site for an experimental anti-icing system, which uses calcium magnesium acetate (CMA) spray to prevent ice formation on the bridge deck. There are presently two manually operated systems. One system is designed to cover the three-lane width of the Brooklyn-bound roadway by two nozzle lines running on either side. The other system sprays the CMA from one side of the Manhattan-bound roadway. The costs of operating the two systems are estimated at approximately $300,000 per year for the 2000 to 2003 period.

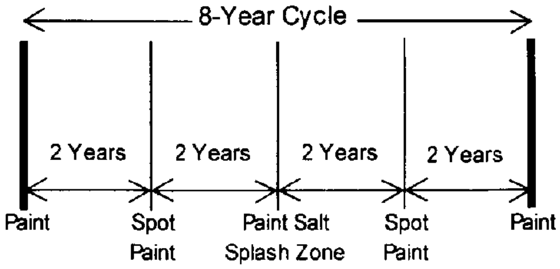


Figure 12. Preventive maintenance painting cycle.

Although some of the costs are contained in the rehabilitation contracts discussed above, it is estimated that $12 million is being spent each year for preventive maintenance programs on the four East River bridges.

Management

The magnitude of the rehabilitation and preventive maintenance investment continues to draw attention to the operation and management of bridges in the future. The management of the East River bridges has been alternatively under New York city, state, and, since 1989, once again, city management. Rehabilitation has been funded from federal, state, and city sources and contracts managed by both city and state, with federal participation. Maintenance has been traditionally funded from local taxes. The lack of dedicated funding is considered the primary cause for the decline of the bridge condition.

The question of obtaining optimal bridge service for the funds spent has gained worldwide attention over the past two decades. During this period, the federal government has introduced bridge management programs and life-cycle cost analysis. A number of FHWA and Transportation Research Board (TRB) publications contain guidelines on bridge management in the United States.

One of the continuing management concerns is in maintenance and inspection staffing to accomplish the necessary work load. This has been a recommendation in various reports on the condition of the East River bridges. To that end, FHWA has made funding available to increase staff levels for maintenance personnel.

Summary of Case Study 2

The rehabilitation of the East River bridges is an important example of the bridge management challenges that face major metropolitan centers. It is a prime example of the cooperation required by federal, state, and city government agencies in addressing funding requirements and managing of critical infrastructure components. The result of the learned experiences for the East River bridges should be to eliminate the past error of designating maintenance as an "expense" item to be deferred until the "capital" funded replacement becomes inevitable. In addition, the East River bridges highlight the need for proper inspection prior to critical stage rehabilitation (resulting in temporary closure) or replacement as the only alternatives.

Case Study 3. Cathodic Protection of Historic Oregon Bridges(49-50)

Introduction

Oregon's coastal highway includes more than 120 bridges, of which 12 are historic structures. The majority of these bridges are reinforced-concrete design and continued salt ingress from wind, fog, and spray have caused significant chloride-induced corrosion deterioration of the reinforced-concrete components. The major bridges were designed by Conde B. McCullough and built in the late 1920s and 1930s. The 1987 replacement of the Alsea Bay Bridge resulted in public protest at the loss of a landmark bridge.

The major issues of public funding and safety are similar to those faced by other DOTs. The issue of preservation of historic structures further complicates the decision-making process. Oregon DOT has selected CP to mitigate corrosion in an attempt to prevent further deterioration of the bridges.

Cathodic Protection Options

In 1985, Oregon DOT installed conductive carbon paint over platinum-niobium wire anodes on the north approach spans of the Yaquina Bay Bridge. This is the oldest carbon paint anode system still in service.

Since 1988, Oregon DOT has installed impressed-current thermal-sprayed zinc anode CP systems on five bridges: Cape Creek, Yaquina Bay, Depoe Bay, Big Creek, and Cape Perpetua. The total installed systems exceed 40,000 m^2 (430,000 ft^2), with an average cost of $151 per m^2 ($14 per ft^2) (in 1997 dollars). Approximately half of the cost is for the thermal-sprayed zinc and half for preparation of the concrete surface (including concrete repair). There are plans to install the thermal-sprayed zinc system on three additional bridges.

In addition to the thermal-sprayed zinc CP systems, demonstration projects are ongoing using non-consumable thermal-sprayed catalyzed titanium anodes on the Depoe Bay Bridge and thermal-sprayed Al-Zn-In and zinc hydrogel anodes on the Cape Perpetua Bridge. Although the thermal-sprayed zinc anode was originally designed as a sacrificial anode, Oregon DOT also utilizes this anode in conjunction with impressed-current CP systems. In many applications where the moisture content in the concrete is low, the concrete resistivity is too great for the application of sacrificial anode CP.

The zinc hydrogel anode is a 0.25-mm- (0.01-in-) thick zinc foil, backed with a conductive, pressure-sensitive adhesive. The adhesive is a 0.75-mm- (0.03-in-) thick hygroscopic acrylate polymer containing sulfonic acid. Application of the hydrogel is relatively simple and the concrete preparation is similar to that required for thermal spraying. The zinc hydrogel foil comes in rolls 250 mm (10 in) wide. The backing is removed, exposing the adhesive, and the foil is pressed on the concrete. The edges of the foil are sealed with silicon rubber. Painting of the foil backing is optional.

The Al-Zn-In and the titanium materials are thermal sprayed onto the concrete surface in the same way as the zinc thermal-sprayed anode. The Al-Zn-In anode is an aluminum alloy anode and has demonstrated in both field and laboratory testing its ability to provide effective levels of CP. The titanium is catalyzed following thermal spraying using a brush- or spray-applied cobalt nitrate amine complex in a pH 3.47 aqueous solution. A cost premium for installing the catalyzed titanium anode was 18 percent more than that for the thermal-sprayed zinc.

Moisture substantially reduces the anode resistance of the thermal-sprayed anodes by increasing conductivity of the electrolyte. The application of humectants, salts that attract water, is one way of increasing moisture content at the anode/concrete interface. Lithium bromide and lithium nitrate are two promising humectants that were tested in trials at the Yaquina Bay Bridge.

Cathodic Protection System Performance

CP system performance is based primarily on the current output of the anodes, circuit resistance of the anode rebar, and bond strength of the anode to the concrete. Based on the examination of current output for sacrificial anodes on the Cape Perpetua Half-Viaduct, the thermal-sprayed zinc performed best, followed by the zinc hydrogel and the thermal-sprayed Al-Zn-In alloy, with the Al-Zn-In alloy at or slightly below the desired current density for corrosion protection. It should be noted that development of the Al-Zn-In anode has continued with promising results. Humectant-treated anodes on the Yaquina Bay Bridge significantly decreased circuit resistance over the 90-day trial.

The early conductive carbon paint over platinum-niobium wire anode system continues to function well after 15 years of service, although it shows signs of aging. The thermal-sprayed zinc anodes have been in operation for 12 years. An estimated service life of 25 years is predicted for the thermal-sprayed zinc anodes at the operating current densities for these bridges.

Summary of Case Study 3

Several of the trial CP options appear promising, including the use of humectants to reduce anode resistance for the thermal-sprayed anode systems. In addition, the catalyzed titanium thermal-sprayed anode may be effective in maintaining a low circuit resistance and extending the life of the CP system.

Since 1985, the use of CP to mitigate corrosion and extend the life of critical bridge structures has been shown to be successful. Most of the structures have been protected utilizing thermally sprayed zinc anodes in conjunction with impressed-current CP. Without the use of CP to stop ongoing corrosion, many of these historical structures would have been (or would soon be) lost. With properly maintained CP systems, the service lives of these bridges can be significantly extended.

LIFE-CYCLE COST ANALYSIS FOR BRIDGE DECKS

When it comes to designing a reinforced-concrete bridge, bridge engineers have a variety of options to achieve the service requirements. There is a general understanding that comparing the options on the "initial cost" basis is not a good predictor of life-cycle costs, i.e., corrosion maintenance costs are also important. Past economic analyses have treated life-cycle costing in different ways, with only a few estimating indirect costs, such as user costs associated with disruption caused by deteriorating deck surfaces and maintenance, repair, and replacement. (See references 12, 18, 51, and 52.) For a bridge that carries a high volume of traffic, indirect (user) costs can be substantially larger than materials and labor costs for bridge repair/rehabilitation. This means that to capture the total economic impact of the project, the analysis must include these indirect costs. The best way to compare bridges with different rebar materials and different corrosion maintenance practices is on the basis of annualized value (AV), which represents discounted cash outflows related to both the construction/maintenance costs and user costs associated with these activities (see Appendix B, "Economic Analysis Methods").

The following sections demonstrate this approach using direct and indirect cost calculations for several bridge deck designs [different rebar materials: black steel rebar, epoxy-coated rebar (see figure 13), and stainless steel rebar (see figure 14)]. The analysis focuses on decks rather than other bridge elements because the corrosion-related problems are most obvious on the deck, the most visible part of the bridge. In addition, only new construction alternatives are examined. Even for new construction, several alternatives such as inhibitors or high-performance silica fume concrete were not examined. Also not examined were several rehabilitation options, such as CP and electrochemical chloride removal. This does not mean that these options are not viable, certainly CP has proven to be success in mitigating ongoing corrosion on bridge decks and is an effective long-term rehabilitation alternative to replacement. The life-cycle costs given here are an example of how life-cycle costing can be accomplished.

The values used in this example, while being realistic estimates and originating from referenced sources, are meant to illustrate the relative magnitude of the components of the total economic impact of bridge construction and maintenance. The readers are encouraged to view this data as an example and are encouraged to input their own data based on their experience to evaluate life-cycle costs.

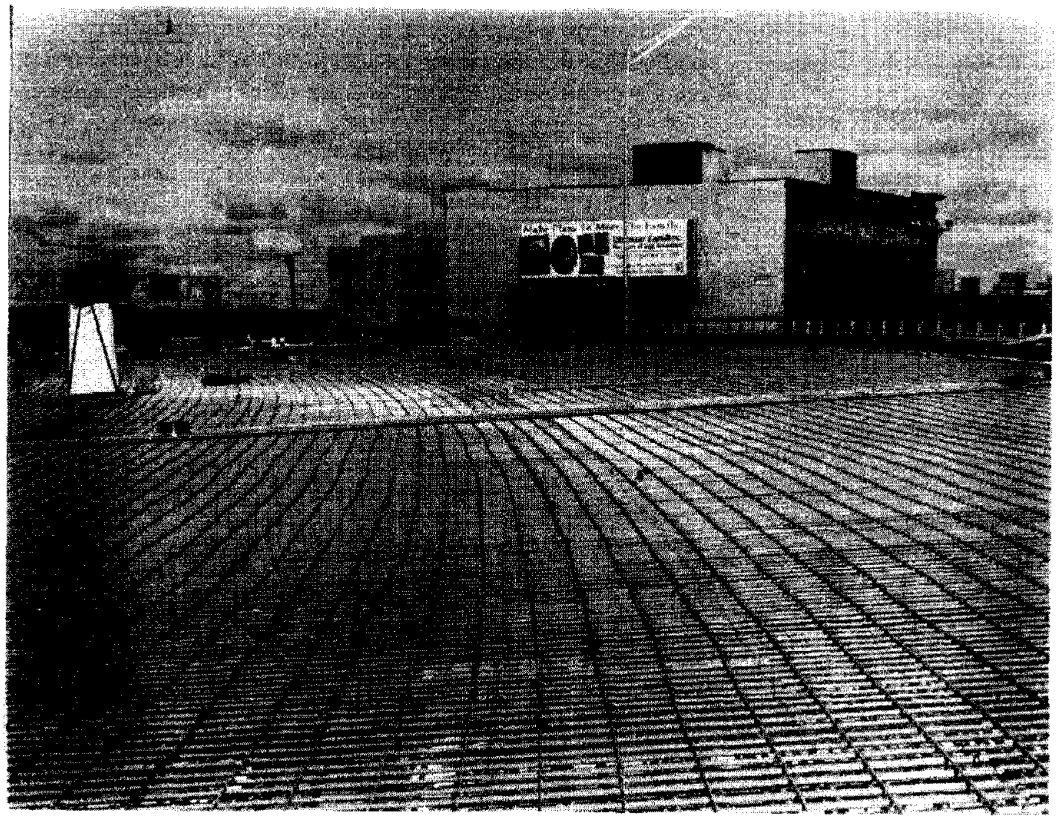


Figure 13. Epoxy-coated rebar deck construction.

Figure 14. Stainless steel-clad rebar deck construction.

Approach for Life-Cycle Cost Analysis

"Average" Bridge Scenario

This analysis uses an "average" reinforced-concrete bridge, based on the National Bridge Inventory (NBI) data (see table 18). The "average" bridge deck has a surface area of 583 m^2 (6,280 ft^2), two lanes in each direction, a length of 36.9 m (121 ft) and a width of 15.8 m (52 ft), and average daily traffic (ADT) of 24,000 vehicles.

Table 18. "Average" bridge deck parameters used in the analysis.

ITEM	VALUE	SOURCE
Average number of lanes	2.1	NBI
Average daily traffic (ADT)	24,000 vehicles	NBI
Average deck area	583 m^2 (6283 ft^2)	NBI
Average operating load rating	41.5 metric tons	NBI
Average bridge deck thickness	190.5 mm (7.5 in)	Estimated
Average concrete cover over top reinforcing bar mat	51 to 64 mm (2 to 2.5 in)	Estimated
Average bottom cover	25.4 mm (1 in)	Estimated

Design Options

The bridge is located in a moderate environment. The analysis focuses on three rebar design configurations:

1. Both rebar mats are black steel rebar.
2. Top rebar mat is epoxy-coated rebar – bottom rebar mat is black steel rebar.
3. Both rebar mats are solid stainless steel rebar.

The purpose of selecting these rebar configurations was to provide a range of possible conditions for the economic analysis. It is not proposed that these selections represent the most common or the only configurations worthy of consideration. The top-mat epoxy-coated rebar design was selected because there were deterioration models available for it from the literature. For all scenarios, the structural concrete quality is assumed to be the same. Also, it is assumed that, for all scenarios, the labor hours, the cost of labor, the cost of material, and the cost of equipment are the same.

Construction/Repair/Rehabilitation Options

For this analysis, four construction-repair-rehabilitation options were selected. For all the scenarios, the same type of maintenance sequence was applied.

Routine Maintenance

Annual routine maintenance costs are estimated at $1,000 per year. No user cost is associated with annual maintenance activities. These costs include any maintenance required on the bridge, including miscellaneous repair patching as the deck ages, but do not include scheduled maintenance for significant patching of deteriorating concrete deck.

Repair/Patch

Repair/patch is scheduled maintenance when the deck surface can no longer be maintained by "routine maintenance." Patching costs are estimated at $90 per m^2 ($8 per ft^2).

It is assumed that patching can be done on weekends, thus avoiding user costs. However, the worsening deck surface condition affects driving speed, which generates user cost and is accounted for in the analysis.

Rehabilitation

Latex-modified concrete (LMC) overlay is used for rehabilitation. The cost of this overlay is estimated to be $170 per m^2 ($16 per ft^2) with a service life of 18 years (see table 8). For the average bridge used in this study (583 m^2), the total cost of the overlay is $99,100.

It is assumed that the rehabilitation takes 63 days, of which 45 days have user cost due to queuing.

Original Construction-Replacement

The original black steel rebar deck cost is assumed to be $484 per m^2, which gives a total cost of $282,200 for the 583-m^2 deck (table 21 gives the cost for each construction option). It was assumed that construction takes 135 days, of which 96 days have peak periods. User cost due to queuing for the 96 days of the construction is included.

After one rehabilitation cycle, the deck is replaced. User cost is estimated for the time period needed to remove the deck (90 days, 64 of which have user cost), but not for building another new deck.

Concrete Deterioration Model

The rate of deterioration with time is required to perform a life-cycle cost using the "information-based" maintenance practice described below. McDonald et al. published estimated times as a function of delamination for a black steel rebar deck and the top-mat epoxy-coated rebar deck (based on laboratory experiments), which is used as a foundation for the deterioration models (see figure 15).(18) The deterioration models also consider the impact of repairing cracks in the concrete. Repairs to the cracks tend to significantly extend the time to delamination in the early life of the deck, but after 10 percent delamination, the effect becomes much less.

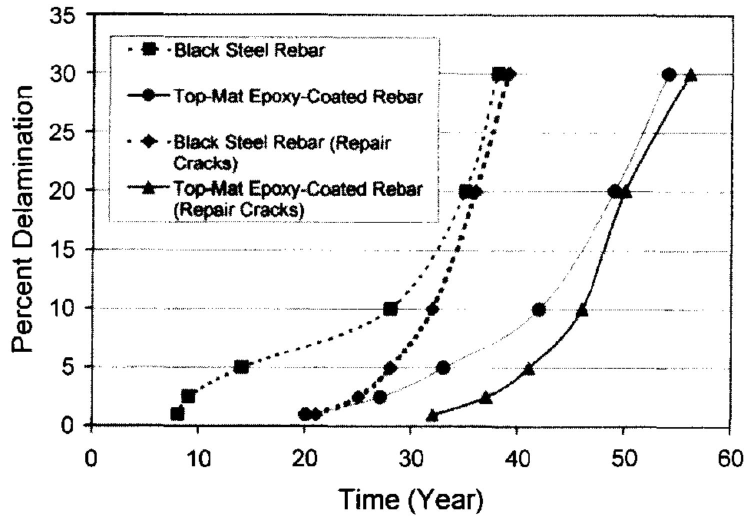


Figure 15. Deterioration models for the black steel rebar and top-mat epoxy-coated rebar deck.

Corrosion Management Alternatives

The approach employs two corrosion management scenarios:

1. Information-based practice.
2. Experience-based practice.

Corrosion management activities and their schedule determine the service life for each scenario (service life ends when the deck is replaced). In order to reduce the number of variables, it was assumed that for both scenarios, the same actions incurred the same costs (both agency and user costs).

Information-Based Practice

In this scenario, corrosion management decisions are based on the condition of the deck estimated through regular inspections. Because decisions are made based on known deck condition, maintenance is performed on a timely basis, thus ensuring optimum maintenance scheduling and maximum service life to the deck. In this scenario, the deterioration rate dictates the corrosion management activities, which are performed on the following schedule:

1. Repair/patching maintenance of the deck becomes a significant activity when 2.5 percent of the deck surface area exhibits delamination and spalling, which is assumed to affect the traffic flow. It is assumed that annual maintenance consisting of repair/patching of the deck continues until 10 percent of the deck surface has been affected. For the information-based maintenance, two maintenance scenarios are examined: (1) cracks in the deck are repaired as they appear and (2) no cracks in the concrete deck are repaired. Whether cracks are repaired or not defines the choice of the deterioration model (see figure 15).
2. It is assumed that when 10 percent of the deck surface area is delaminated, the deck is rehabilitated with a latex-modified concrete (LMC) overlay.
3. The life of this deck ends at the end of the service life of the rehabilitation overlay. For the purposes of this analysis, the service life is estimated at 18 years (table 8). At this time, the deck is replaced.

It is obvious that other milestones (percent delamination) could have been selected for determining repair/rehabilitation options. The selections made are provided as an example only and are not meant to apply to any specific bridge.

Experience-Based Practice

In this scenario, corrosion management is based on engineering experience and deck maintenance is scheduled based on the experience from similar bridges. This is often the case when there are several similarly designed bridges in a bridge inventory. For experience-based maintenance, activities are scheduled based on a specific time (deck life), not on the measured condition of the bridge deck, because regular monitoring of the bridge deck is not performed. As experience dictates different maintenance for black steel rebar decks versus epoxy-coated rebar decks, the maintenance follows the schedule(s) described below (recall that in the scenario used in this analysis only the top mat of rebar is epoxy-coated). It should also be noted that, other than for a few substructures of bridges in the Florida Keys exposed to severe marine environments, significant deterioration of a bridge deck made with epoxy-coated rebars has not been observed; therefore, the "experience-based" maintenance schedule for epoxy-coated rebar is "estimated" and not based on actual experience.

1. Repair/patching maintenance becomes a significant activity after 10 years for black steel rebar deck and 40 years for a top-mat epoxy-coated rebar deck.
2. Repair/patching continues on an annual basis until year 20 for black steel rebar deck and year 50 for a top-mat epoxy-coated rebar deck, at which time the deck is rehabilitated with an LMC overlay.
3. At the end of the 18-year service life of the rehabilitation overlay, the deck is replaced (year 38 for black steel rebar deck and year 68 for top-mat epoxy-coated rebar deck). For the purposes of this analysis, the rehabilitation overlay life is assumed to be the same as for the information-based scenario.

The schedule selected above is based on information discussed in the literature and by the industry experts; it is meant to be representative of "reasonable" values and users are encouraged to input their own experience and data.

Scheduling of Maintenance

Tables 19 and 20 summarize the maintenance scheduling for the scenarios involving black steel and epoxy-coated rebar. For the information-based maintenance, the year in which action is taken is governed by the deterioration model selected (see figure 15). The action is based on monitoring the deck, determining the extent of the damaged area, and acting after a specific area of the deck is affected by delamination/spalling. The year in which action is taken for the experience-based maintenance is based on the operator's historic operating experience and follows a preset schedule.

For the stainless steel rebar scenario, it is assumed that the deck does not show any corrosion damage. It is understood that the concrete surface wears down due to traffic abrasion, and worsened surface traction conditions require some treatment of the deck surface at around 50 years of age. An LMC overlay is applied at year 50 and 85 and is assumed to have a 35-year life (no corrosion of the rebar). This gives a service life of 120 years.

Table 19. Scenarios of corrosion management for decks with black steel rebar.

ACTIONS	INFORMATION-BASED (NO REPAIR OF CRACKS)		INFORMATION-BASED (REPAIR CRACKS)		EXPERIENCE-BASED
	% of deck damaged	Year for action	% of deck damaged	Year for action	Year for action
Patching starts	2.5	9	2.5	25	10
Rehabilitation overlay	10	28	10	32	20
Deck replacement	NA	46	NA	50	38

NA = not applicable

Table 20. Scenarios of corrosion management for decks with epoxy-coated rebar.

ACTIONS	INFORMATION-BASED (NO CRACK REPAIR)		INFORMATION-BASED (CRACK REPAIR)		EXPERIENCE-BASED
	% of deck damaged	Year for action	% of deck damaged	Year for action	Year for action
Patching starts	2.5	27	2.5	37	40
Rehabilitation overlay	10	42	10	46	50
Deck replacement	NA	60	NA	64	68

NA = not applicable

Cost Summary

Cost details are based on the previous discussion of corrosion control methods (tables 7 and 8). The initial cost of the black steel rebar deck is estimated to be \$484 per m^2 (\$45 per ft^2) or \$282,000 for the "average" deck. Cost for the top-mat epoxy-coated rebar deck and two-mat solid stainless steel rebar deck are assumed to be 0.6 percent and 18.6 percent greater, respectively, than the costs for a black steel rebar deck. (The 0.6 percent increase for the top-mat epoxy-coated rebar deck is assumed to be 50 percent of the increase given in table 7 for a two-mat epoxy-coated rebar deck.) Table 21 summarizes these costs and life expectancies for this analysis.

Table 21. Summary of costs used in the economic analysis.

COST OPTION	COST PER DECK AREA	TOTAL COST	LIFE EXPECTANCY (EXPERIENCE)
	$/m^2$	$	Years
New Construction - Black steel (baseline)	484	282,200	10*
New Construction - Top layer epoxy-coated rebar	487	283,900	40*
New Construction – 2-layer solid SS rebar	574	334,600	120
Patching (Bituminous)	90	-	1
LMC Overlay	170	99,100	18**
Old Deck Removal***	240	139,900	NA****

*Time to scheduled patching.

**35-year life is projected for stainless steel rebar system with no corrosion (18-year life is for decks with ongoing corrosion).

***Assumed to be approximately 50% of new construction.

****NA = not applicable

Annualized Cost Analysis

General Procedure for Cost Analysis

The analysis consists of the following steps:

1. The variables in each scenario include the rebar material used in construction, the series of corrosion maintenance actions, and the schedule of each action.
2. The direct and user costs of each item are calculated, establishing the cash flow for each deck design/maintenance scenario combination. The cash flow for each scenario includes the direct cost of materials and labor, as well as the user costs associated with any corrosion management activities that interrupt traffic flow.
3. Using these cash flows, the present value (PV) is calculated. From the PV, the annualized value (AV) is calculated for the service life of the scenario.

Critical stages in the life cycle of a deck are summarized in table 22. The life-cycle costs are characterized by their AV, which serves as the basis for comparison. It is assumed that there is an existing bridge that is having its deck replaced

Table 22. Life cycle of scenarios.

ONE LIFE CYCLE FOR A SCENARIO		
YEAR	**DIRECT COST**	**USER COST**
Year 0	Total initial investment for constructing a new deck. The removal cost for the old deck is not included.	User cost associated with the construction of a new deck. User cost associated with the removal of an old deck is not included.
Service years	Maintenance, repair, rehabilitation.	User cost generated by worsening deck conditions and by lane closure required by any maintenance, repair, or rehabilitation action.
Last year	Cost of deck removal. Cost of new deck is not included.	User cost associated with removal of the deck. User cost generated by construction of new deck is not included.

Direct Costs

Direct costs of the corrosion management activities include material, labor, and equipment cost. The cost of traffic maintenance, if necessary, is added separately, unless otherwise noted. It was assumed that the costs for the same actions are the same for all studied scenarios.

In general, direct cost of one-time expenditures, such as the new construction, routine maintenance, rehabilitation overlays, and removal of old deck, were calculated the same way:

Direct cost = {unit cost of action} * {area where applied}

The cost of the annual maintenance was treated as a series of uniform annual payments:

Annual maintenance cost = {annual maintenance cost per area} * {deck surface area}

The corrosion management schedule determines the direct cost cash flow. The calculations of the present value (PV) of the cash outflows are presented in the following sections. (Initial investment happens in the "present," therefore no discounting is necessary.)

Annual maintenance (AM) is constant throughout the life cycle of the scenarios. This annual value is calculated back to the present by the following formula:

$$PDV\{AM\} = AM * [1 - (1 + i)^{-N}] / i$$

where

PDV = present discounted value, \$
AM = cost of annual maintenance, \$/year
N = length of the deck's service life, years
i = interest rate, %

The cost of patching grows annually at a constant rate (g); for the calculation of the PV of patching, a modified interest rate needs to be calculated by the following formula:

$$i_0 = (i - g) / (1 + g) \qquad \text{and} \qquad i > g$$

where

i_0 = is the modified interest rate, %
i = interest rate, %
g = constant annual growth rate, %

If the first payment (P_1) occurs in year 1, the present value of a cash flow that grows annually at a constant rate over n years can be calculated by the following formula:

$$PV\{P\} = [P_1 / (1 + g)] * [1 - (1 + i_0)^{-n}] / i_0$$

PV{P}, the present value of a cash flow series that starts at P1 in year 1 and grows at a constant rate g for n years when interest rate is i, is equivalent to the present value of an annuity of [P1 / (1 + g)] for n years when interest rates are i_0, where i_0 is given by the equation above.

However, the first payment for patching does not occur in year 1, but in year t. Therefore, the above formula calculated a value at year (t-1) that is equivalent to the cash flow series of patching through n years. This value needs to be discounted back to year 0 of the life cycle to determine the present discounted value of the patching:

$$PDV\{P\} = PV\{P\} * (1 + i)^{-(t-1)}$$

The PDV of one-time costs, such as the rehabilitation overlay (RH) and old deck removal (ODR), are calculated as follows:

$$PDV\{RH\} = RH * (1 + i)^{-tRH}$$
$$PDV\{ODR\} = ODR * (1 + i)^{-tODR}$$

where

RH = cost of rehabilitation overlay, \$
ODR = cost of removing the old deck, \$
t = year in which the cost is incurred

The PDV of the scenario is calculated as the sum of the PDVs of its cash flow:

$$PDV = I + PDV\{AM, P, RH, ODR\}$$

The annualized value (AV) of the scenarios is calculated from the PV using the following formula:

$$AV = PDV * I / [1 - (1 + i)^{-N}]$$

where

N = service life of the deck, years

Indirect (User) Cost

The only calculated social cost is that to the users. User cost is estimated as the value of time lost due to two causes: (1) the additional time it takes for drivers to reach their destination due to worsened driving conditions caused by corrosion of the bridge deck and (2) time lost due to the corrosion maintenance activities (repair, rehabilitation, and deck replacement) taking place on the deck and requiring closure of lane(s).

User cost is estimated as the product of additional travel time and the value of time. The value of time was assumed to be 50 percent of the average wage for 1998 ($8.50 per hour) for all scenarios. Traffic is characterized by the following parameters (see table 23):

Table 23. Traffic parameters.

PARAMETERS	VALUE RANGES
Average daily traffic (ADT)	20,000 – 32,000
Percent of daily traffic in peak, %	30 – 50%
Number of peak periods per direction per day	1
Length of peak period, minute	90 – 140
Discharge rate, throughput, cars / hr	Max: 2,400
Maximum waiting time before diversion, minutes	30

User Cost Due to Worsening Deck Conditions

Before the deck is repaired or rehabilitated, the condition of the deck can affect traffic flow, causing speed reduction and congestion, thus resulting in increased travel time and user cost. It was assumed that a worsening deck condition only slows the traffic flow, but does not cause congestion, which makes the user cost estimate very conservative. Other costs such as wear-and-tear on automobiles were not included in this analysis.

User Cost During Corrosion Management Activities

User cost can be incurred during corrosion maintenance activities, requiring the closure of a lane. This closure reduces the throughput (number of cars that can cross per unit time) of the bridge, causing slower traffic flow or congestion. The analysis of the user cost due to lane closure is based on a paper by Boardman and Lave,(53) which establishes the traffic speed-flow relationships for a four-lane (2 x 2) highway, and a general first come, first served queuing theory, which approximates total delay due to congestion. Two basic transportation system cases were assumed:

1. No Diversion, i.e., no alternative route is available for the drivers; thus, they must suffer the effect of the closure.

2. Diversion Available, i.e., alternative routes are available and thus drivers choose their route to minimize their travel time. It is assumed that the range of maximum tolerable delay by individual drivers is between 10 and 30 minutes.

User cost estimation for congested cases involves the following general steps:

- Estimation of the throughput of the bridge with and without lane closures to determine the maximum arrival and discharge rates for peak and off-peak periods.
- Selection of a value for the number of vehicles using the bridge at peak periods, the length of the peak period, and the discharge rate for the given average daily traffic.
- Approximation of a total delay time for cases with and without diversion using the general queuing theory.
- Estimation of the user cost per peak period as a product of total delay time and the value of time.

Lacking specific bridge data, the calculation makes some simplifying assumptions. It is assumed that the additional travel time due to congestion can be reasonably approximated by the total delay time due to queuing for the same number of vehicles. A general first come, first served queuing theory is used to estimate the total delay time for the number of cars affected by the lane closure. Discharge rate, arrival rate, and the peak traffic volume determine the total delay due to queuing per peak period.

For simplicity, in the analysis, the number of peak periods per day is fixed at two. The duration of each corrosion management activity determines how many peak periods are affected by the closure. (It was assumed that there were no peak periods during weekends.)

Then the cost of congestion to users (both with and without diversion) is estimated by multiplying the total time delay due to queuing per peak period by the number of peak periods in a day, the number of days of lane closure, and by the value of time (VoT). The PV and AV of the user costs were calculated by using the same formulas as presented for direct cost.

Results of Life-Cycle Cost Analysis

The majority of cost-benefit analyses are performed without considering the impact on the user (indirect costs). Typically, this is because the owner-operator is not willing to accept user costs as a part of the decision process (the owner-operator does not have to incur these costs). However, in examining the total impact of corrosion on the national economy, user costs often make up a portion greater than the costs incurred by the owner-operators. Therefore, the following analysis is divided into two parts, without and with user costs (direct and indirect costs, respectively). Example cost calculations are provided at the end of this section ("Sample Life-Cycle Cost Calculations").

In order to isolate the effect of rebar type and maintenance schedule, it was assumed that the same maintenance actions (annual maintenance, inspection, repair, and rehabilitation) were applied to all scenarios, except that the timing of the maintenance actions differed for the different maintenance scenarios. For example, repairing potholes on the decks takes the same amount of work-hours and the same level of traffic disruption regardless of the types of rebar and the scheduling of the activity.

The authors would again like to caution the reader that the results of the analysis presented here are meant to be an example of the economic impact of design parameters, maintenance scenarios, traffic options, and user costs. It is important to realize that the specific values were selected to be reasonable and are not typical of a particular bridge structure. The readers are encouraged to input their specific experience and data to evaluate life-cycle costs.

No User Costs

In the following analysis, no indirect (user) costs are included. This is typical of the majority of life-cycle costing performed. This analysis focuses on the effect of the rebar design and maintenance scenario.

Effect of Rebar Design (No User Cost)

Since it was assumed that the only design variable is the type of reinforcing bar used, the cost of rebar determines the initial price of the deck. Based on the initial construction cost ("sticker price"), black steel rebar design would always be the cheapest. However, black steel rebar has the shortest expected life and the highest cost of corrosion maintenance. Life-cycle cost analysis gives a more useful representation of the expenditures than does the initial cost. No user costs were included in the following analysis.

Cash flow associated with a bridge structure is characterized by high initial capital investment, the expected service life, annual maintenance costs, and repair and rehabilitation costs. Since the cash flow occurring in the future has to be discounted to the present time, a low interest rate used to discount the future cash outflows to their present value favors scenarios with low maintenance costs (e.g., stainless steel rebar deck design). A high interest rate heavily discounts future maintenance costs and tends to favor low initial cost (e.g., black steel rebar deck design). The comparisons of the deck designs/corrosion maintenance scenarios are based on the estimated annualized value (AV).

Figure 16 shows the "information-based with crack repair" maintenance scenario applied to the three rebar design cases. The first observation is that annualized costs increase with increasing interest rates. At low interest rates (below 3 percent), the stainless steel rebar design (high initial capital cost) has the lowest annualized cost; while at higher interest rates, epoxy-coated rebar has the lowest costs. Although the epoxy-coated rebar design has a lower cost than black steel rebar design at all interest rates, as the interest rate increases, black steel rebar design costs approach those for the top-mat epoxy-coated rebar design. It is interesting to note that black steel rebar and its increased maintenance has a lower annualized cost than stainless steel rebar design at interest rates greater than 5 percent.

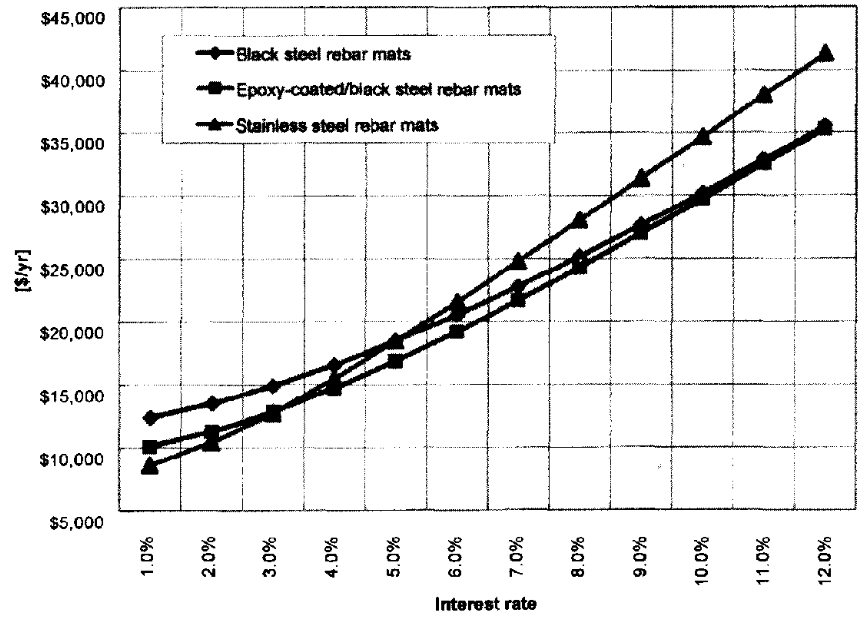


Figure 16. Effect of the interest rate on the annualized values for the "information-based with crack repair" scenario for the three bridge deck designs (no user cost).

Effect of Maintenance Approach (No User Cost)

Figures 16, 17, and 18 show the annualized costs for the three maintenance scenarios: (1) information-based with crack repair, (2) information-based with no crack repair, and (3) experienced-based, respectively. [Readers should note that the stainless steel rebar deck has only one maintenance scenario, therefore, its graph does not change in figures 16 through 18.] Figures 19 and 20 compare the three maintenance scenarios for the carbon steel and top-mat epoxy-coated rebar designs, respectively.

As maintenance is neglected (going from figure 16 to 17 to 18), more corrosion-resistant designs are preferred (the difference in the annualized cost for the black steel rebar design relative to the epoxy-coated rebar design increases). The cause of this effect can be seen by comparing figures 19 and 20. Figure 20 shows that the annualized cost for the corrosion-resistant epoxy-coated rebar design shows little sensitivity to the maintenance scenario used. In fact, table 20 shows minimal difference in the information-based (crack repair) and experienced-based scenarios.

Figure 19 shows that the more maintenance-intensive black steel rebar design was more sensitive to the maintenance scenario selected. The annualized cost decreased with the more aggressive maintenance schedule (the lowest annualized cost was achieved by the "information-based with crack repair" scenario and the "experience-based" scenario had the highest annualized cost). This observation suggests that regular inspection of the black steel rebar deck can lower cost through timely scheduling of the repairs.

In comparing the black steel rebar design to the stainless steel rebar design, the interest rate below which the stainless steel rebar design has a lower annualized cost increases with the less intensive maintenance schedule (5 percent for information-based with crack repair, 6 percent for information-based with no crack repair, and 8 percent for experience-based). Because the maintenance scenario had little effect on the epoxy-coated rebar design and only one maintenance scenario is used for the stainless steel rebar (no corrosion), the interest rate below which stainless steel has a lower annualized cost than the epoxy-coated rebar design remained constant at approximately 3 to 4 percent for the scenarios used. The annualized cost for epoxy-coated rebar design was lower than the black steel rebar design at all interest rates for each maintenance scenario.

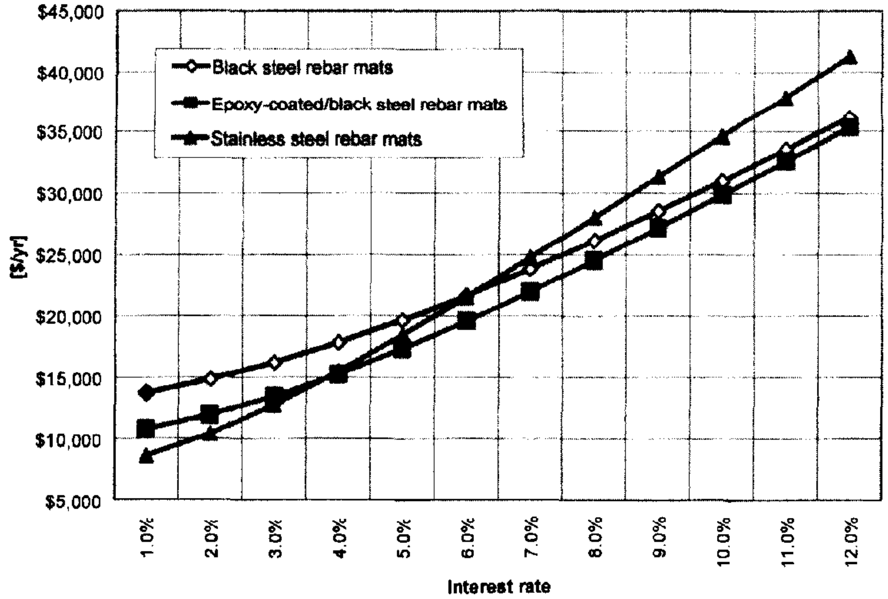


Figure 17. Effect of the interest rate on the annualized values for the "information-based, no crack repair" scenario for the three bridge deck designs (no user cost).

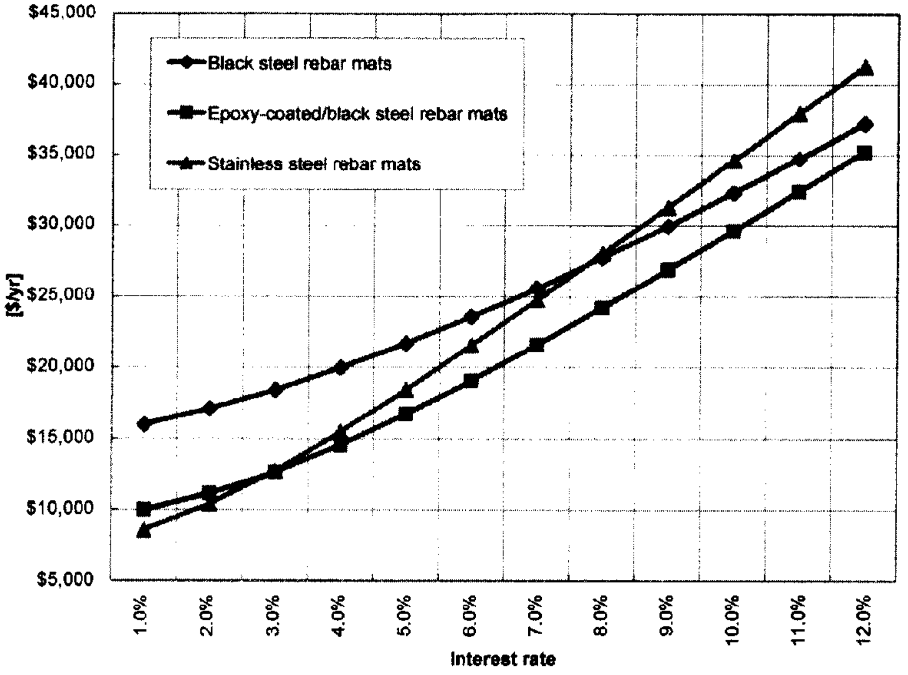


Figure 18. Effect of the interest rate on the annualized values for "experience-based" scenarios for the three bridge deck designs (no user cost).

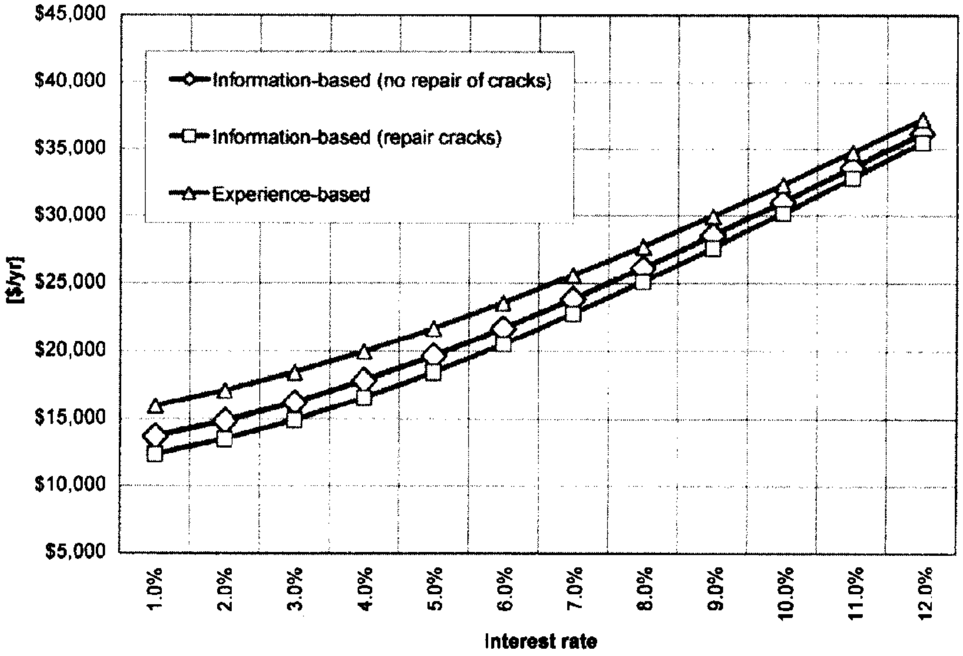


Figure 19. Effect of the interest rate on the annualized values for three corrosion maintenance scenarios and based on the black steel rebar design (no user cost).

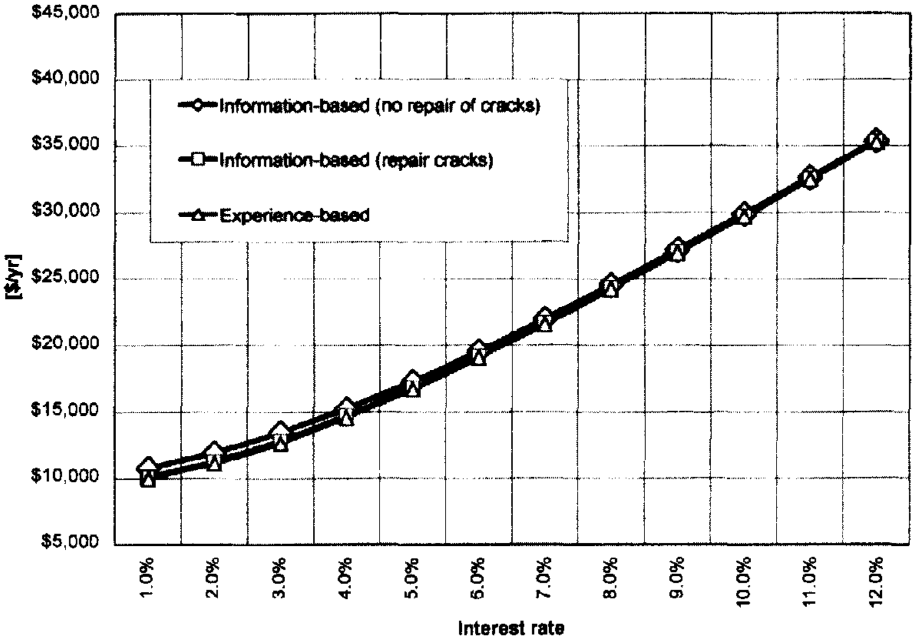


Figure 20. Effect of the interest rate on the annualized values for three corrosion maintenance scenarios and based on the top-mat epoxy-coated rebar design (no user cost).

User Costs Included

The effect of including user cost is to significantly increase the cost of both initial investment and later maintenance. The annual value of the scenarios is different for every level of user cost. The initial analyses are based on the traffic scenario that is characterized by the values given in table 24.

Table 24. Traffic scenario for user cost calculations.

Average daily traffic	24,000
% of ADT in peaks	40%
Length of peak, minutes	120
Discharge rate, cars / hr	1,700
User cost per day, $/day – no diversion	**$35,936**
Maximum waiting time, minutes	30
User cost per day, $/day – with diversion	**$29,291**

Effect of Rebar Design (User Cost Included)

Figure 21 shows that including the user cost in the analysis does not change the basic conclusions that lower interest rates favor high initial costs, while high interest rates favor high maintenance cost scenarios. For comparison, the cost for the black steel rebar design "with no user costs" is included in each figure. Including user costs increased the annualized cost of the bridge by a factor of 10 to 15.

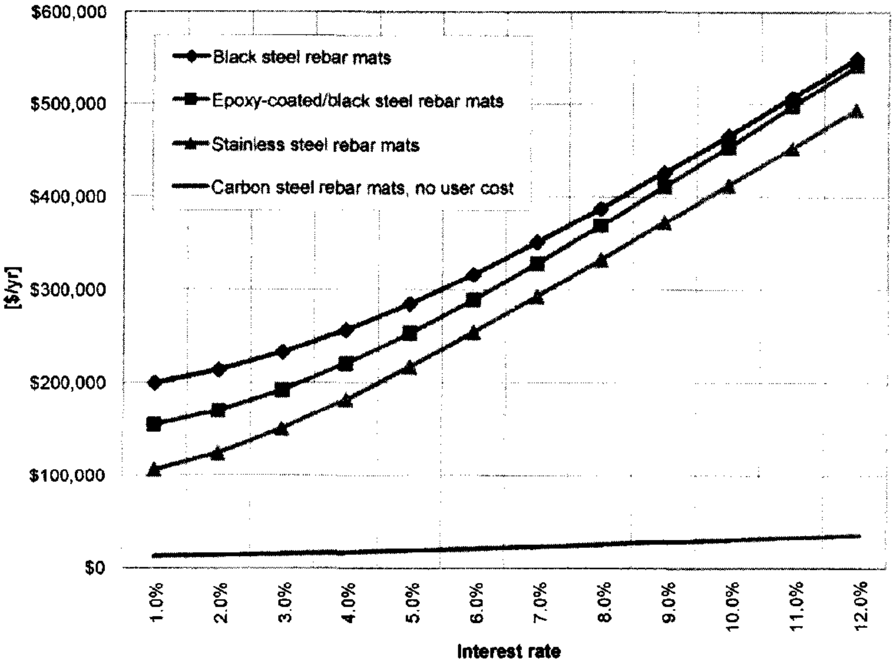


Figure 21. Effect of the interest rate on the annual values for "information-based with crack repair" maintenance scenario for the three deck designs (user cost included, no diversion).

The general relationship between the epoxy-coated rebar design and the black steel rebar design did not change from that discussed for "no user costs." The epoxy-coated rebar design had a lower annualized cost than the black steel rebar design at all interest rates. Including the user costs made the lower maintenance stainless steel rebar design also a lower cost design at all interest rates. This is because the lower maintenance stainless steel rebar design produced a significantly lower disruption of traffic than either the epoxy-coated rebar design or the black steel rebar design. Therefore, when comparing the stainless steel rebar design to the top-mat epoxy-coated rebar design, the life-cycle analysis including the user cost yields a different result (as to the most cost-effective approach) than the life-cycle analysis without the user cost.

As previously noted, bridge owner-operators do not incur user costs. Therefore, there is little incentive for the owner-operator to make decisions that include user costs in the life-cycle analysis. In addition, the capital budget of the owner-operator is a factor in deciding on the higher capital option of the stainless steel design. Both considerations influence the decision of the owner-operator in the selection of the bridge deck design.

It should be noted that in the epoxy-coated rebar design, only the top mat of reinforcing steel was coated, the bottom mat was black steel. It is generally accepted that epoxy coating on both rebar mats will extend the service life of the deck into the future and delay the time to the first required maintenance. Therefore, the two-mat epoxy-coated rebar design would become more favorable than the top-mat epoxy-coated design used in this analysis.

Effect of Maintenance Approach (User Cost Included)

Figures 21, 22, and 23 show the annualized costs, including the user cost, for the three maintenance scenarios: (1) information-based crack repair, (2) information-based no crack repair, and (3) experienced-based. The effect of the maintenance approach was similar to that described for the no user cost analysis, i.e., only the black steel rebar design was sensitive to the choice of maintenance scenario. The relationship between top-mat epoxy-coated rebar design and stainless steel rebar design remained the same for each maintenance scenario, i.e., the stainless steel rebar design is favored for all interest rates.

Including the user cost does not change the observation that the "information-based with crack repair" maintenance scenario has the lowest annualized cost (as compared to the other approaches to corrosion maintenance) for the black steel rebar design. This suggests that regular repairs to the black steel rebar deck can lower costs.

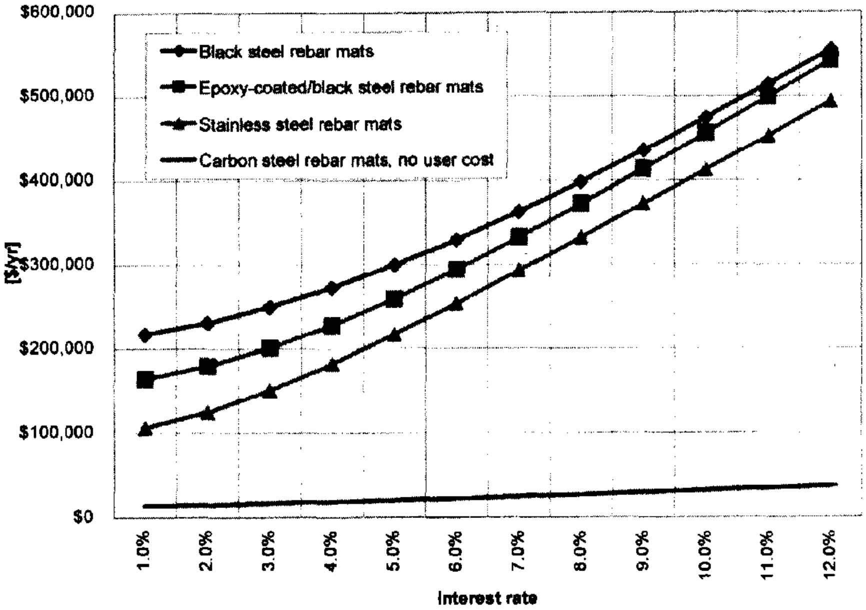


Figure 22. Effect of the interest rate on the annual values for "information-based with no crack repair" maintenance scenario for the three deck designs (user cost included, no diversion).

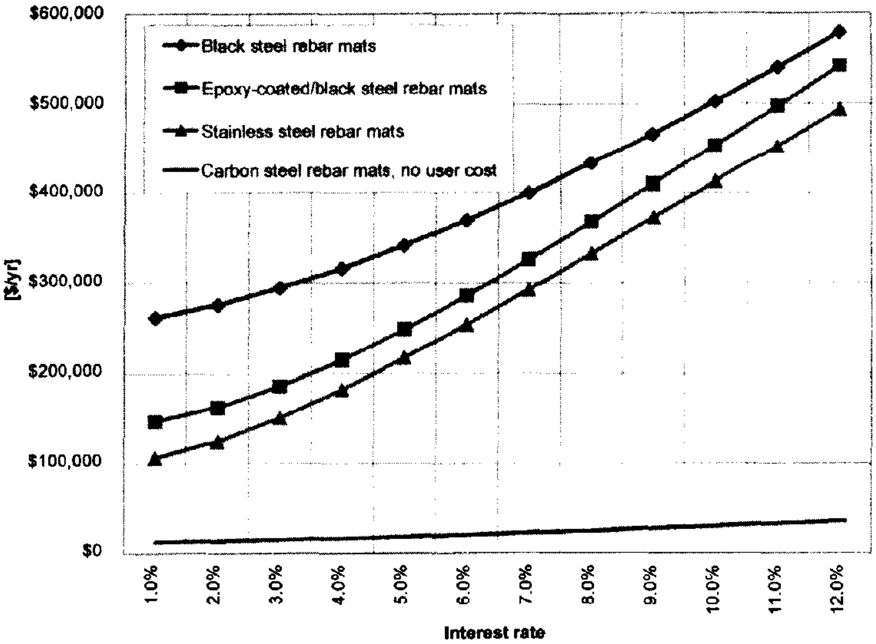


Figure 23. Effect of the interest rate on the annual values for "experience-based" maintenance scenario for the three deck designs (user cost included, no diversion).

Effect of Traffic Options

Two basic traffic options were analyzed: (1) no diversion of traffic and (2) traffic diversion available. "No diversion" means that no alternative route is available for the drivers; thus, they must suffer the effects of the closure. "Diversion available" means that alternative routes are available and, thus, drivers choose their route to minimize their travel time. It was assumed that the range of maximum tolerable delay by individual drivers is between 10 and 30 minutes. The user cost data presented above was for the "no diversion" case. No diversion is the worst case and results in the higher user cost.

Figure 24 shows the case for the "information-based with crack repair" maintenance scenario for the "diversion available" traffic option. Figure 24 also includes the no user costs for each of the rebar designs. Comparison of figures 21 and 24 provide a measure of the difference in costs between the "no diversion" and "diversion available after 30-minute delay" traffic options. The annualized costs are less when diversion is possible, but none of the trends change.

Table 25 gives the annualized costs for the "information-based with crack repair" maintenance scenario at 5 percent interest. This provides a relative comparison of the costs for: (1) no user costs, (2) user costs with no diversion, and (3) user costs with diversion available. The largest magnitude increase in cost occurs when user costs are included. However, the traffic options also have a significant effect. An annualized cost decrease of approximately $35,000 occurred when going from a "no diversion" scenario to a "diversion available" (30-minute delay) scenario. Table 25 is an example in which stainless steel rebar design went from the least desirable to the most desirable upon including user cost.

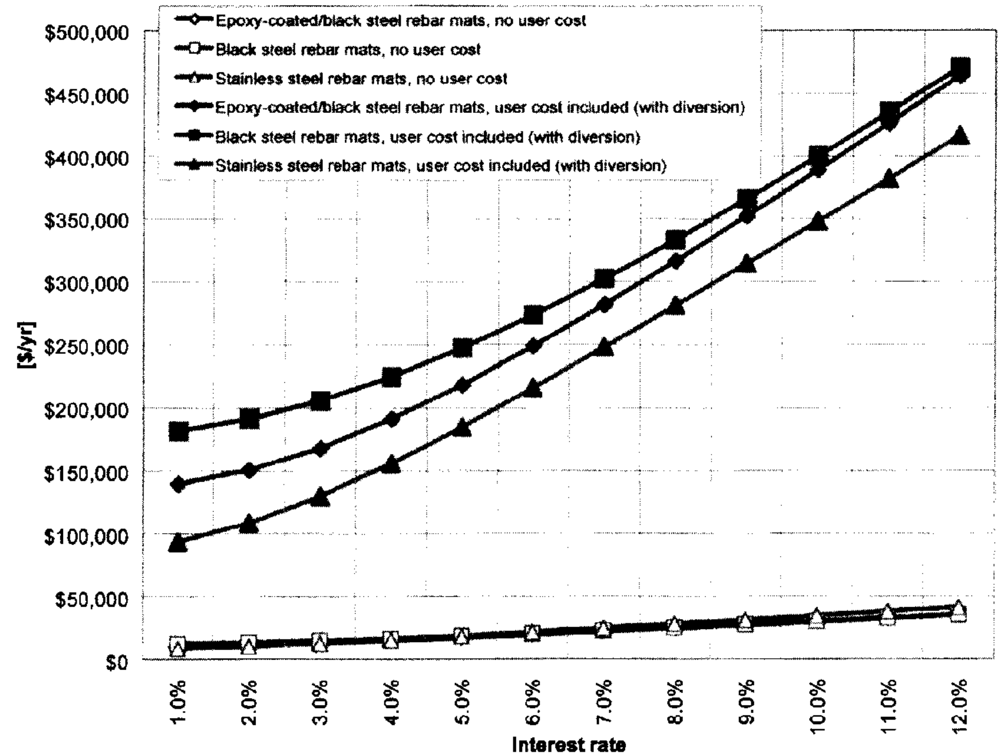


Figure 24. Comparison of the effect of the interest rate on the annual values for the "information-based with crack repair" maintenance scenario for the three deck designs with and without user costs (with diversion after 30 minutes).

Table 25. Annualized cost comparison for "information-based with crack repair" at 5 percent interest rate.

REBAR DESIGN	ANNUALIZED COST WITH NO USER COST	ANNUALIZED COST WITH USER COST, NO DIVERSION	ANNUALIZED COST WITH USER COST, DIVERSION AVAILABLE
Black Steel	$18,000	$284,500	$247,300
Top-Mat Epoxy-Coated	$16,800	$253,000	$218,300
Stainless Steel	$18,400	$216,800	$185.000

Effect of Traffic Flow

The sensitivity of user cost to traffic flow patterns is analyzed below. The traffic variables were chosen by trial to give the three desired levels of user cost (low, medium, and high). Table 26 shows the traffic variables and the user cost per day for these three levels. The daily user cost can vary significantly depending on the traffic flow assumed. The traffic flow assumed in the above analysis (see table 24) is most similar to the "low" level presented below (see table 26).

Table 26. Traffic scenarios corresponding to the user cost levels.

	"LOW" LEVEL OF USER COST	"MEDIUM" LEVEL OF USER COST	"HIGH" LEVEL OF USER COST
Average daily traffic	24,000	28,000	32,000
% of ADT in peaks	40%	40%	50%
Length of peak, minutes	140	120	140
Discharge rate, [cars/h]	1600	1700	2000
User cost per day, $/day – no diversion	**$28,784**	**$68,609**	**$124,025**
Maximum waiting time, minutes	30	30	30
User cost per day, $/day – with diversion	**$26,400**	**$39,502**	**$58,830**

Figure 25 shows the top-mat epoxy-coated rebar design annualized cost for the "information-based with crack repair" maintenance scenario with three different levels of user costs (with diversion) compared to that without user cost. A significant increase in annualized bridge cost occurs when the user costs increase. For example, at a 5 percent interest rate, the range of user cost presented in table 26 results in an increase in annualized cost of the bridge deck from $16,800 with no user cost to $205,000 at low user cost to $400,000 at high user cost.

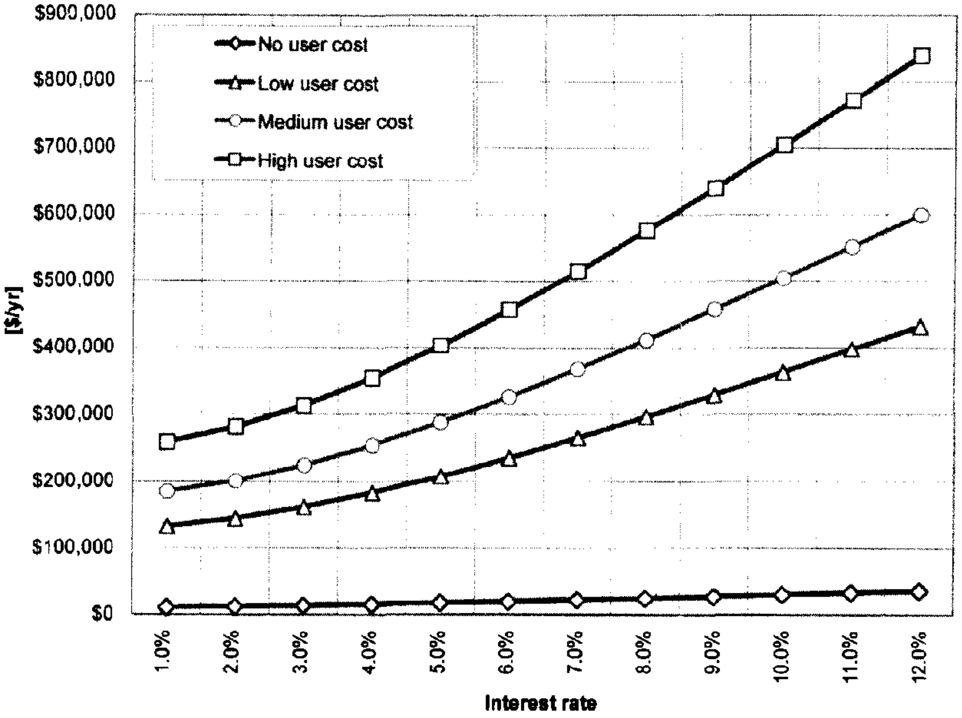


Figure 25. Effect of the interest rate on the annual values for the "information-based with crack repair" maintenance scenario for the epoxy-coated rebar mat design with three levels of user costs (with diversion).

Conclusions of the Life-Cycle Cost Analysis for Bridge Decks

1. Although direct costs are the primary driver for owner-operator cost option decisions, indirect (user) costs can be significantly more than the direct costs. Indirect costs were greater than the direct costs by a factor of 10 or more.

2. The discount rate had a significant effect on the deck design options considered. Therefore, incorporating the rate-of-return (discount rate) is strongly recommended for evaluating construction/maintenance options. For example, when considering direct costs only, the top-mat epoxy-coated rebar design was a lower cost option than the stainless steel rebar design at interest rates above 3 to 4 percent; below 3 to 4 percent, stainless steel rebar was the lowest cost option.

3. Including user costs in the life-cycle analysis favors corrosion-resistant rebar designs that eliminate corrosion-related deterioration repair and maintenance. For example, stainless steel rebar design provided a significantly smaller annualized cost option than top-mat epoxy-coated rebar design when user costs were included.

4. The maintenance approach can have a considerable effect on the annualized cost for black steel rebar design, but it is much less significant for more corrosion-resistant rebar designs. Early repair of cracks and selection of information-based maintenance to optimize repair scheduling resulted in a longer life for the black steel rebar deck and significantly reduced annualized costs.

5. Given the impact of the user costs on the life-cycle bridge deck costs, a significant emphasis should be placed on traffic planning options and on developing construction/repair/rehabilitation strategies that reduce lane/bridge closures and traffic interruptions.

Sample Life-Cycle Cost Calculations

Black Steel Rebar Bridge With Corrosion – Direct Cost Only

The example given is for the black steel rebar deck with the "information-based no crack repair" maintenance scenario at an interest rate of 5 percent. The following values apply:

Bridge deck surface area:	583 m^2
Unit construction cost:	\$484 per m^2
Total construction cost:	\$282,200
Annual routine maintenance cost:	\$1,000
Patching cost:	\$90 per m^2
Rehabilitation cost:	\$99,100
Old deck removal cost:	\$139,900
Patching starts in year:	9 (2.5% of deck damaged)
Patching ends in year:	28 (10% of deck damaged)
Rehabilitation in year:	28
Deck life ends in year:	46

Annual Maintenance

Annual maintenance (AM) is constant throughout the life cycle of the scenarios. This annual value is calculated back to the present by the following formula:

$$PDV\{AM\} = AM * [1-(1+i)^{-N}] / i$$

where

PDV = present discounted value, \$
AM = cost of annual maintenance, \$/year : 1000
N = length of the deck's service life, years: 46
i = interest rate: 0.05

$$\begin{aligned} PDV\{AM\} &= \$1000 * [1-(1+0.05)^{-46}] / 0.05 \\ &= \$17,900 \end{aligned}$$

Patching

The cost of patching grows annually at a constant rate (g); for the calculation of the PV of patching, a modified interest rate needs to be calculated by the following formula:

$$i_0 = (i-g) / (1+g) \qquad \text{and} \qquad i > g$$

where

i_0 = is the modified interest rate
i = interest rate: 0.05
g = constant annual growth rate: (increase in percent patching) / (years of patching to be performed)

$$g = (0.10\text{-}0.025) / (28\text{-}9) = 0.00395$$
$$i_0 = (0.05-0.00395) / (1+0.00395) = 0.0459$$

If the first payment (P_1) occurs in year 1, the present value of a cash flow that grows annually at a constant rate over n years can be calculated by the following formula:

$$PV\{P\} = [P_1 \;/\; (1 + g)] \;*\; [1 - (1 + i_0)^{-n}] \;/\; i_0$$

where

P_1 = cost of patching (\$90 per m^2) times the amount of deck patched (2.5% of surface area)

$$PV\{P\} = [\$90 * 583 * 0.025 \;/\; (1 + 0.00395)] \;*\; [1 - (1 + 0.0459)^{-(28-9)}] \;/\; 0.0459$$
$$= \$16,300$$

PV{P}, the present value of a cash flow series that starts at P1 in year 1 and grows at a constant rate g for n years when the interest rate is i, is equivalent to the present value of an annuity of [P1 / (1 + g)] for n years when interest rates are i_0, where i_0 is given by the equation above.

However, the first payment for patching does not occur in year 1, but in year t. Therefore, the above formula calculated a value at year (t-1) that is the equivalent of the cash flow series of patching through n years. This value needs to be discounted back to year 0 of the life cycle to determine the present discounted value of the patching:

$$PDV\{P\} = PV\{P\} \;*\; (1 + i)^{-(t-1)}$$

$$PDV\{P\} = \$16,300 \;*\; (1 + 0.05)^{-(9-1)}$$
$$= \$11,000$$

Rehabilitation

The PDV of one-time costs, such as the rehabilitation overlay (RH) is calculated as follows:

$$PDV\{RH\} = RH \;*\; (1 + i)^{-tRH}$$

where

RH = cost of rehabilitation overlay, \$
t = year in which the cost is incurred: 28

$$PDV\{RH\} = \$99,100 \;*\; (1 + 0.05)^{-28}$$
$$= \$25,300$$

Old Deck Removal

The PDV of one-time costs, such as the old deck removal (ODR) is calculated as follows:

$$PDV\{ODR\} = ODR \;*\; (1 + i)^{-tODR}$$

where

ODR = cost of removing the old deck, \$
t = year in which the cost is incurred: 46

$$PDV\{ODR\} = \$139,900 \;*\; (1 + 0.05)^{-46}$$
$$= \$14,800$$

Present Discounted Value

The PDV of the scenario is calculated as the sum of the PDVs of its cash flow:

$$PDV = I + PDV\{AM, P, RH, ODR\}$$

where

I = initial cost of the deck.

$$\begin{aligned} PDV &= \$282{,}200 + \$17{,}900 + \$11{,}000 + \$25{,}300 + \$14{,}800 \\ &= \$351{,}200 \end{aligned}$$

Annualized Value

The annualized value (AV) of the scenarios is calculated from the PDV using the following formula:

$$AV = PDV * i / [1 - (1 + i)^{-N}]$$

where

N = service life of the deck, years: 46

$$\begin{aligned} AV &= \$351{,}200 * 0.05 / [1 - (1 + 0.05)^{-46}] \\ &= \$19{,}600 \end{aligned}$$

The annualized value for this sample calculation is $19,600 and corresponds to the value for black steel rebar at 5 percent interest given in figure 12.

Indirect Cost (User Cost)

The example given above without user costs is repeated below, but now includes user costs associated with deck construction/removal and maintenance activities. The illustrated traffic scenario is "no diversion." The user costs included in the calculation include those due to the reduced throughput during the lane closure and those due to congestion. (See table 22 for assumptions concerning bridge construction.) In addition to the parametric values listed above, additional values apply:

Time to cross the bridge	0.03 h
Increase in travel time	150%
Days to build new deck	135
Days with user cost	96
Days to rehabilitate deck	62
Days with user cost	44
Days to remove the deck	90
Days with user cost	64
Value of time	$8.50/h
Traffic affected (only one lane closed)	12,000 cars
User costs due to traffic congestion (no diversion)*	$35,936

*All traffic congestion costs are calculated by a model developed by Boardman and Lave; the values of which are presented in table 22 and table 26 for the conditions discussed in this section.

Present discounted values and annualized values are calculated similarly to the direct cost example. (Recall that it was assumed there was no user cost associated with the patching activities.)

Bridge Construction

User cost due to lane closure during original bridge deck construction $P_{uc}\{BC\}$ is calculated as:

$P_{uc}\{BC\}$ = Time to cross * Increase in travel time * Days with user cost * Value of time * Traffic affected
$P_{uc}\{BC\} = 0.03 * (1+1.50) * 96 * \$8.50 * 12{,}000$
$= \$737{,}700$

Present value of this user cost $PDV_{uc}\{BC\}$ is equal to $P_{uc}\{BC\}$ as the costs occur at present time (year 0), i.e., $PDV_{uc}\{BC\} = \$737{,}700$

User cost due to traffic congestion during original bridge deck construction $P_{uc}\{BC\text{-}TC\}$ (and present discounted value $PDV_{uc}\{BC\text{-}TC\}$) is calculated using the appropriate cost from table 24.

$P_{uc}\{BC\text{-}TC\}$ = Days with user cost * User cost due to traffic congestion
$P_{uc}\{BC\text{-}TC\} = PDV_{uc}\{BC\text{-}TC\} = 96 * \$35{,}936$
$= \$3{,}449{,}900$

Rehabilitation

User cost due to lane closure during bridge rehabilitation $P_{uc}\{RH\}$ is calculated as:

$P_{uc}\{RH\}$ = Time to cross * Increase in travel time * Days with user cost * Value of time * Traffic affected
$P_{uc}\{RH\} = 0.03 * (1+1.50) * 44 * \$8.50 * 12{,}000$
$= \$343{,}300$

Present discounted value of user costs due to lane closure because of the rehabilitation activities ($PDV_{uc}\{RH\}$) is calculated as:

$PDV_{uc}\{RH\} = P_{uc}\{RH\} * (1+i)^{-tRH}$
$PDV_{uc}\{RH\} = \$343{,}300 * (1+0.05)^{-28}$
$= \$87{,}600$

User cost due to traffic congestion during rehabilitation $P_{uc}\{RH\text{-}TC\}$ is calculated using the cost provided in table 24.

$P_{uc}\{RH\text{-}TC\}$ = Days with user cost * User cost due to traffic congestion
$P_{uc}\{RH\text{-}TC\} = 44 * \$35{,}936$
$= \$1{,}581{,}200$

Present discounted value ($PDV_{uc}\{RH\text{-}TC\}$) is calculated by discounting the $P_{uc}\{RH\text{-}TC\}$ value back to present time:

$PDV_{uc}\{RH\text{-}TC\} = P_{uc}\{RH\text{-}TC\} * (1+i)^{-tRH}$
$PDV_{uc}\{RH\text{-}TC\} = 1{,}581{,}200 * (1+0.05)^{-28}$
$= \$403{,}400$

Old Deck Removal

User cost associated with the lane closures due to old deck removal $P_{uc}\{ODR\}$ is calculated as:

$$P_{uc}\{ODR\} = \text{Time to cross} * \text{Increase in travel time} * \text{Days with user cost} * \text{Value of time} * \text{Traffic affected}$$
$$P_{uc}\{ODR\} = 0.03 * (1+1.50) * 64 * \$8.50 * 12{,}000 = \$491{,}800$$

Present discounted value for old deck removal ($PDV_{uc}\{ODR\}$) is calculated by discounting the $P_{uc}\{ODR\}$ value back to present time:

$$PDV_{uc}\{ODR\} = P_{uc}\{ODR\} * (1+i)^{-tODR}$$
$$PDV_{uc}\{ODR\} = \$491{,}800 * (1+0.05)^{-46} = \$52{,}100$$

User cost due to traffic congestion for old deck removal $P_{uc}\{ODR\text{-}TC\}$ is calculated using the costs provided in table 24.

$$P_{uc}\{ODR\text{-}TC\} = \text{Days with user cost} * \text{User cost due to traffic congestion}$$
$$P_{uc}\{ODR\text{-}TC\} = 64 * \$35{,}936 = \$2{,}300{,}000$$

Present discounted value ($PDV_{uc}\{ODR\text{-}TC\}$) is calculated by discounting the $P_{uc}\{ODR\text{-}TC\}$ value back to present time:

$$PDV_{uc}\{ODR\text{-}TC\} = P_{uc}\{ODR\text{-}TC\} * (1+i)^{-tODR}$$
$$PDV_{uc}\{ODR\text{-}TC\} = \$2{,}300{,}000 * (1+0.05)^{-46} - \$243{,}800$$

Deteriorating Quality of Riding Surface Condition

The user cost calculations also include the costs due to the deteriorating quality of the riding surface (during the period covered by the patching activities). This cost is calculated on the basis of the data developed by Boardman and Lave(56) and presented in table 27.

Table 27. User cost data (costs due to deteriorating riding surface condition).

PERCENT DECK AREA AFFECTED BY PATCHING	YEAR IN WHICH PATCHING OCCURS	USER COST	PRESENT DISCOUNTED VALUE OF USER COST
2.50%	9	$5.08	$3.27
2.89%	10	$9.13	$5.60
3.29%	11	$15.22	$8.90
3.68%	12	$23.96	$13.34
4.08%	13	$35.99	$19.09
4.47%	14	$52.08	$26.30
4.87%	15	$73.04	$35.13
5.26%	16	$99.77	$45.71
5.66%	17	$133.24	$58.13

Table 27. User cost data (costs due to deteriorating riding surface condition) (continued).

PERCENT DECK AREA AFFECTED BY PATCHING	YEAR IN WHICH PATCHING OCCURS	USER COST	PRESENT DISCOUNTED VALUE OF USER COST
6.05%	18	$174.50	$72.51
6.45%	19	$224.67	$88.91
6.84%	20	$284.96	$107.40
7.24%	21	$356.63	$128.01
7.63%	22	$441.04	$150.77
8.03%	23	$539.62	$175.69
8.42%	24	$653.87	$202.74
8.82%	25	$785.36	$231.92
9.21%	26	$935.76	$263.17
9.61%	27	$1,106.78	$296.45
10.00%	28	$1,300.24	$331.68
	TOTAL	**$7,250**	**$2,300**

Total present discounted value user cost due to lower quality of the riding surface condition ($PDV_{uc}\{RSC\}$) is fairly minor:

$$PDV_{uc}\{RSC\} = \$2,300$$

Present Discounted Value of User Costs

The PDV_{uc} of the user costs is calculated as the sum of the individual PDV_{uc}'s due to lane closure and traffic congestion:

$$PDV_{uc} = PDV_{uc}\{BC, RH, ODR, RSC\} + PDV_{uc}\{BC\text{-}TC, RH\text{-}TC, ODR\text{-}TC\}$$
$$PDV_{uc} = \$737,700 + 87,600 + 52,100 + 2,300 + 3,449,900 + 403,400 + 243,800$$
$$= \$4,976,800$$

Annualized Value of User Costs

The annualized value (AV_{uc}) of the user costs is calculated from the PDV_{uc} using the following formula:

$$AV_{uc} = PDV_{uc} * i / [1 - (1 + i)^{-N}]$$

where

N = service life of the deck, years: 46

$$AV_{uc} = \$4,976,800 * 0.05 / [1 - (1 + 0.05)^{-46}]$$
$$\$278,300$$

Total Costs (Annualized Value of Total Costs)

Combining the direct and user costs, we arrive at:

$$AV_{total} = \$19,600 + \$278,300 = \$297,900$$

The annualized value for this sample calculation is $297,900 and corresponds to the value for black steel rebar deck design at 5 percent interest given in figure 22.

Theoretical "Corrosion-Free" Bridge – Direct Cost Only

The life-cycle calculation given here is for the non-existent "corrosion-free" bridge (i.e., what if corrosion did not exist). A cost estimate for a "corrosion-free" bridge is necessary to compare to the cost of a bridge with corrosion; the difference is the "cost of corrosion." The example given below estimates the life-cycle direct cost for a black steel rebar deck that is "corrosion-free" and at an interest rate of 5 percent (same as given above for the corrosion example). The following values apply:

Bridge deck surface area:	583 m^2
Unit construction cost:	$484/$m^2$
Total construction cost:	$282,200
Annual routine maintenance cost:	$1,000
Patching cost:	no cost (no corrosion-induced deterioration)
Rehabilitation (wear only) cost:	$99,100
Old deck removal cost:	$139,900
Patching starts in year:	never starts
Rehabilitation in year:	50 (for wear only, lasts 35 years)
Second rehabilitation in year:	85 (for wear only, lasts 35 years)
Deck life ends in year:	120

Annual Maintenance

Annual maintenance (AM) is constant throughout the life cycle of the scenarios. This annual value is calculated back to the present by the following formula:

$$PDV\{AM\} = AM * [1 - (1 + i)^{-N}] / i$$

where

PDV = present discounted value, $

AM = cost of annual maintenance, $/year: $1000

N = length of the deck's service life, years: 120

i = interest rate: 0.05

$$PDV\{AM\} = \$1000 * [1 - (1 + 0.05)^{-120}] / 0.05$$
$$PDV\{AM\} = \$19,900$$

Patching

There is no corrosion, therefore no patching is required.

$$PDV\{P\} = 0$$

Rehabilitation at Year 50

The PDV of one-time costs, such as the rehabilitation overlay (RH), is calculated as follows:

$$\text{PDV}\{\text{RH}\} = \text{RH} * (1 + i)^{-t\text{RH}}$$

where

RH = cost of rehabilitation overlay: \$99,100
t = year in which the cost is incurred: 50

$$\begin{aligned}\text{PDV}\{\text{RH}\} &= \$99{,}100 * (1 + 0.05)^{-50} \\ &- \$8{,}600\end{aligned}$$

Rehabilitation at Year 85

The PDV of one-time costs, such as the rehabilitation overlay (RH), is calculated as follows:

$$\text{PDV}\{\text{RH}\} = \text{RH} * (1 + i)^{-t\text{RH}}$$

where

RH = cost of rehabilitation overlay, \$99,100
t = year in which the cost is incurred: 85

$$\begin{aligned}\text{PDV}\{\text{RH}\} &= \$99{,}100 * (1 + 0.05)^{-85} \\ &= \$1{,}600\end{aligned}$$

Old Deck Removal

The PDV of one-time costs, such as the old deck removal (ODR), is calculated as follows:

$$\text{PDV}\{\text{ODR}\} = \text{ODR} * (1 + i)^{-t\text{ODR}}$$

where

ODR = cost of removing the old deck, \$139,900
t = year in which the cost is incurred: 120

$$\begin{aligned}\text{PDV}\{\text{ODR}\} &= \$139{,}900 * (1 + 0.05)^{-120} \\ &= \$400\end{aligned}$$

Present Discounted Value

The PDV of the scenario is calculated as the sum of the PDVs of its cash flow:

$$\text{PDV} = \text{I} + \text{PDV}\{\text{AM, P, RH[50], RH[85], ODR}\}$$

where

I = initial cost of the deck

$$\begin{aligned}\text{PDV} &= \$282{,}200 + 19{,}900 + 0 + 8{,}600 + 1{,}600 + 400 \\ &= \$312{,}700\end{aligned}$$

Annualized Value

The annualized value (AV) of the scenarios is calculated from the PDV using the following formula:

$$AV = PDV * i / [1 - (1 + i)^{-N}]$$

where

N = service life of the deck, years: 120

$$AV = \$312{,}700 * 0.05 / [1 - (1 + 0.05)^{-120}]$$
$$= \$15{,}700$$

The annualized life-cycle cost for this "corrosion-free" scenario is $15,700.

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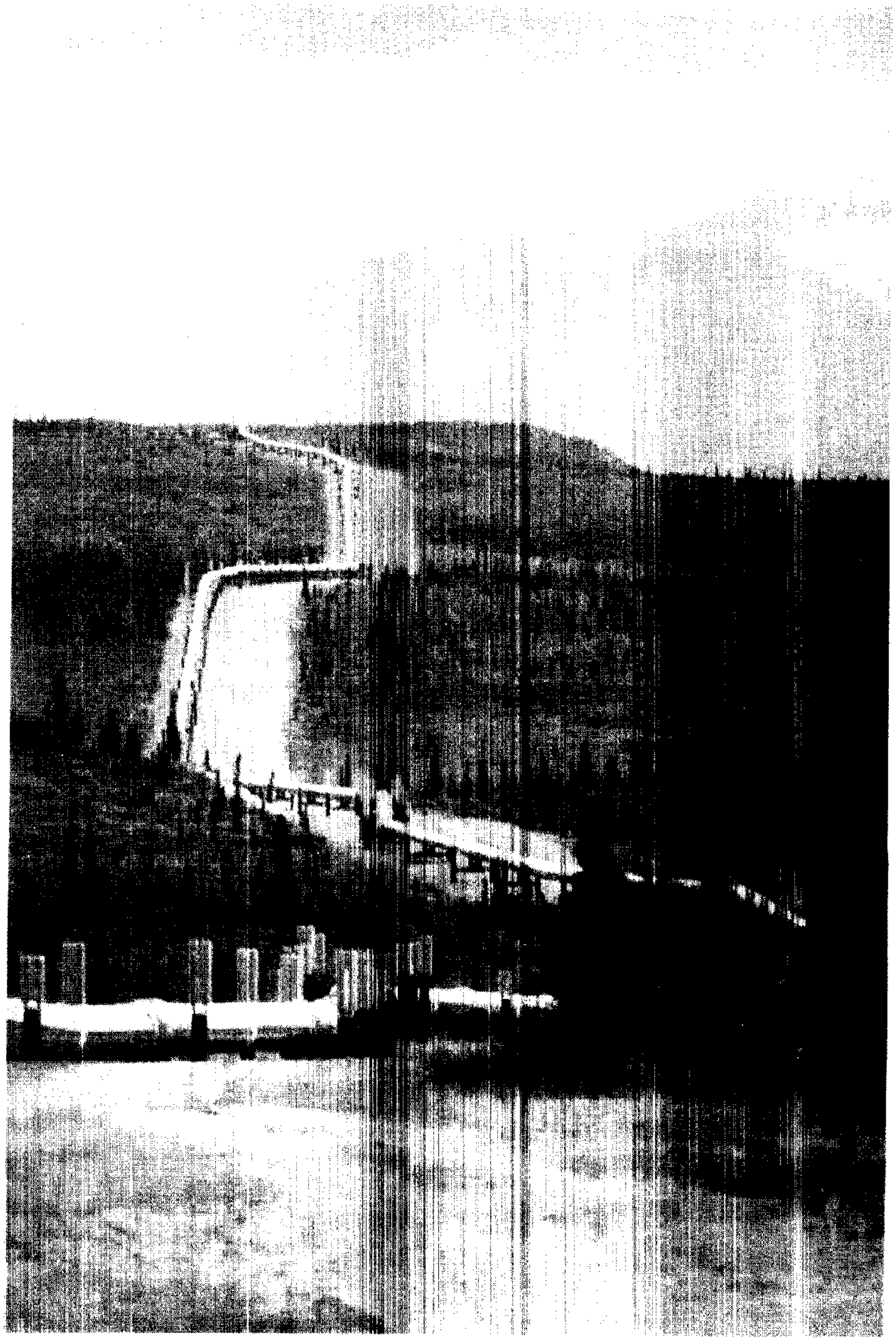
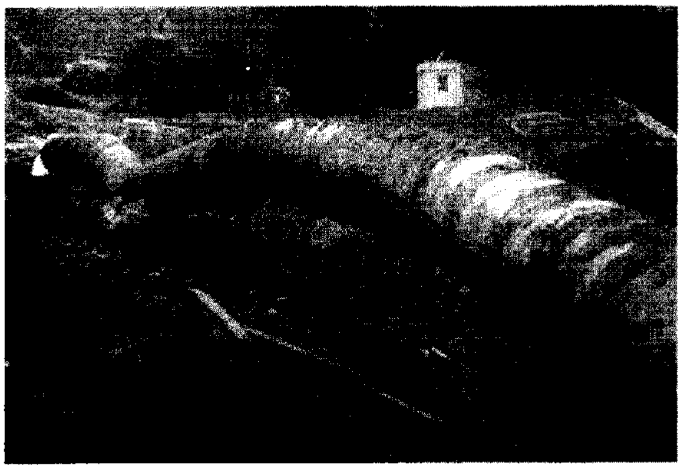
APPENDIX E

GAS AND LIQUID TRANSMISSION PIPELINES



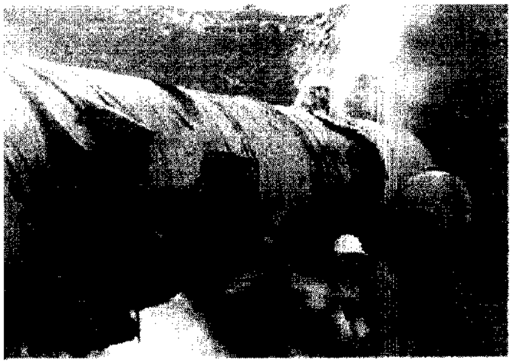


Pipeline failure

Disbonded coating

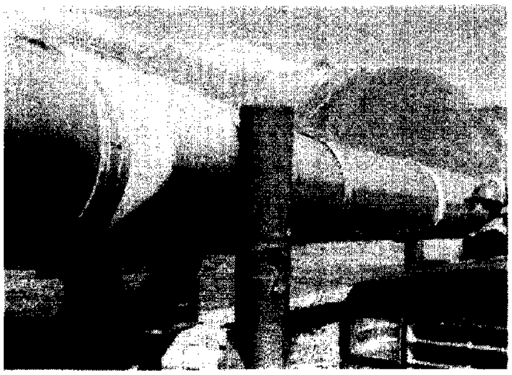
Transgranular stress-corrosion cracking

Pipeline excavation

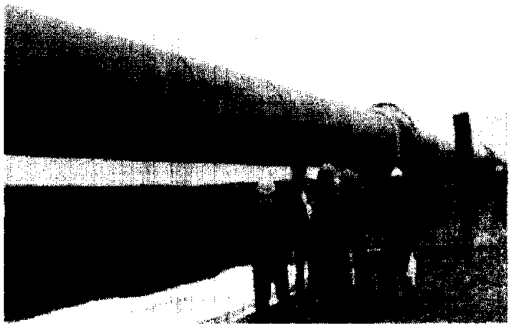


Coating repair

Intergranular stress-corrosion cracking



Alaskan Pipeline



APPENDIX E

GAS AND LIQUID TRANSMISSION PIPELINES

NEIL G. THOMPSON, PH.D.[1]

SUMMARY AND ANALYSIS OF RESULTS

Corrosion Control and Prevention

The corrosion-related cost to the transmission pipeline industry is approximately $5.4 to $8.6 billion annually. This can be divided into the cost of failures, capital, and operations and maintenance (O&M) at 10, 38, and 52 percent, respectively. Although data management, system quantification through the use of global positioning surveys, remote monitoring, and electronic equipment developments have provided significant improvement in several areas of pipeline corrosion maintenance, there have been few basic changes in the approach to the management of corrosion on pipelines until recently. These changes have been in the development of risk assessment strategies and pipeline integrity management programs.

In the past few years, a number of high-profile pipeline failures (both liquid and natural gas) have refocused concern on pipeline safety. Public safety concerns have provided the driving force for new regulations governing pipeline operations. The most significant of these, from a cost point of view, is the requirement for pipeline inspections. In-line inspection (i.e., "smart pigging") is the one most often discussed. The ability of this technique to find corrosion flaws larger than a certain size (10 percent of pipe wall thickness) makes it extremely valuable for locating flaws before they become critical and cause pipeline failure (either leaks or rupture). The major concern is that a "find it and fix it" mentality is pursued at the expense of corrosion prevention strategies. Both approaches are required to optimize the cost benefit of corrosion management programs. Operators may be tempted to adopt a "find it and fix it" attitude due to the significant cost of pipeline inspection, which is estimated to be as high as $35 billion over the next 5 to 7 years. If operators cut conventional corrosion O&M costs while pursuing pipeline inspection, corrosion prevention will suffer. Without a best practices corrosion prevention strategy, corrosion will continue and the cost of repairing a deteriorating pipeline will continue to escalate. Thus, a "find it and fix it" strategy utilizing in-line inspection at the expense of corrosion prevention may save money in the short term, but will greatly increase capital expenditures for pipeline replacement and major rehabilitation in the long-term.

Opportunities for Improvement and Barriers to Progress

Developing an optimum approach that includes both inspection and corrosion prevention strategies is critical to the future safety and the cost-effective operation of transmission pipelines. The overall goal of the pipeline industry must be to preserve the pipeline as an asset ($541 billion replacement cost). Corrosion consumes the asset, which cannot be recovered; this makes corrosion prevention a critical part of any strategy. Realizing that corrosion prevention will never be 100 percent effective, an inspection strategy ("find it and fix it"), in addition to the corrosion prevention strategy, is required for those pipelines that have a higher probability of corrosion. Significant savings are possible by optimizing the inspection and corrosion prevention strategies. In order to achieve such optimization, improved prediction models for both internal corrosion and external corrosion need to be developed. Inspection strategies should include all three currently available methodologies (in-line inspection, hydrostatic testing, and direct assessment), depending on the pipeline conditions.

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[1] CC Technologies Laboratories, Inc., Dublin, Ohio.

Regulatory pressures can both be an effective driving force and a barrier to cost-effective engineering practices. The regulations should permit operators to implement integrity management programs that permit incorporation of developments, while allowing the use of any and all strategies available to the operator. Another barrier to the development of cost-effective programs is the increased costs associated with inspection strategies. There will be significant pressure to downplay existing corrosion prevention strategies in order to fund the new federally mandated inspection regulations. The current corrosion prevention strategies must be maintained while the inspection strategies are implemented. The corrosion prevention and inspection approaches must eventually be combined into a comprehensive cost-effective integrity management program.

Recommendations and Implementation Strategy

Corrosion prediction models need to be developed in order to more accurately determine inspection intervals and to prioritize the most effective corrosion prevention strategies. Development of new and improved inspection techniques is required to expand the capabilities of in-line inspection of flaws that cannot be currently detected and to improve resolution for existing tools.

Summary of Issues

Increase consciousness of corrosion costs and potential savings.	Impact of regulations can be to increase corrosion control costs by 50 percent to 100 percent over the next 5 to 7 years. Strategies utilizing best engineering practices can produce significant savings.
Change perception that nothing can be done about corrosion.	Corrosion prevention practices are well defined and generally known in the pipeline sector.
Advance design practices for better corrosion management.	Corrosion prevention design practices for pipelines are generally well understood. Computer models for cathodic protection design of complex systems are recently becoming available.
Change technical practices to realize corrosion cost-savings.	Technical practices will have to change based on new regulations involving increased pipeline inspection. Incorporating these inspection methods into the current corrosion prevention practices in a cost-effective manner will be critical to operators.
Change policies and management practices to realize corrosion cost-savings.	The key for management will be to incorporate inspection strategies into current corrosion prevention strategies while continuing to improve corrosion prevention.
Advance life prediction and performance assessment methods.	Life-prediction modeling for internal and external corrosion is critical to cost-effective pipeline integrity management. These models are not always available and are, in general, specific to individual pipeline conditions. Corrosion growth and life-prediction models are required for establishing inspection frequency and prioritizing corrosion prevention maintenance.
Advance technology (research, development, and implementation).	Technology advancements needed include improved inspection techniques (better reliability, resolution, crack detection).
Improve education and training for corrosion control.	New federal regulations require training of corrosion technicians. NACE International (National Association of Corrosion Engineers) has recently updated and is now providing courses and certification especially for cathodic protection technicians.

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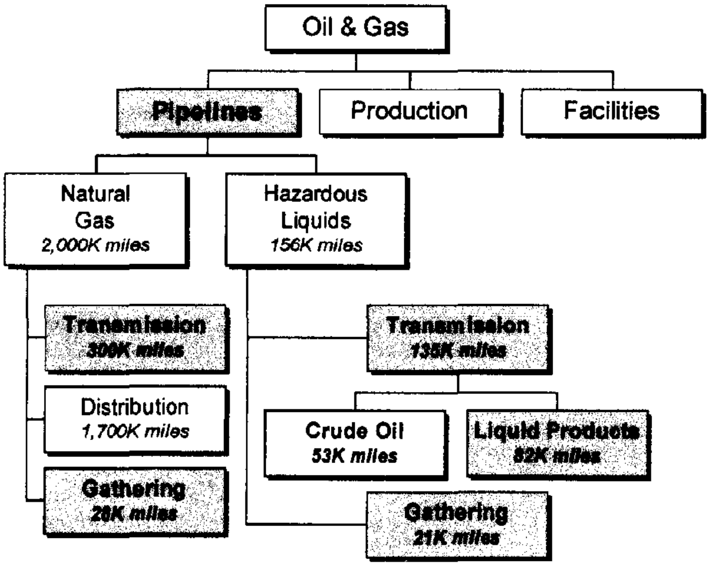
SECTOR DESCRIPTION

The "Gas and Liquid Transmission Pipelines" sector is a part of the oil and gas industry. This sector includes 217,000 km (135,000 mi) of hazardous liquid transmission pipelines, 34,000 km (21,000 mi) of crude oil gathering pipelines, 483,000 km (300,000 mi) of natural gas transmission pipelines, and 45,000 km (28,000 mi) of natural gas gathering pipelines.(1-3) Figure 1 summarizes the transmission pipeline sector. The boxes in gray indicate the type of pipelines addressed in this sector. Included in this sector are the above-described pipelines and the associated equipment and facilities (valve and metering stations and compressor/pump stations). In the United States, there are approximately 60 major natural gas transmission pipeline operators and 150 major hazardous liquid pipeline operators (1998 data).(4)



1 mi = 1.61 km

Figure 1. Chart describing transmission pipeline sector.

Figure 2 illustrates the different components of a natural gas production, transmission, storage, and distribution system. The components include production wells, gathering lines within the production fields, processing plants, transmission pipelines, compressor stations (periodically along the transmission pipelines), storage wells and associated gathering pipelines, metering stations and city gate at distribution centers, distribution piping, and meters at distribution sites (residential or industrial). Hazardous liquid systems include production wells and gathering lines for crude oil production, processing plants, transmission pipelines, pump stations, valve and metering stations, and aboveground storage facilities.

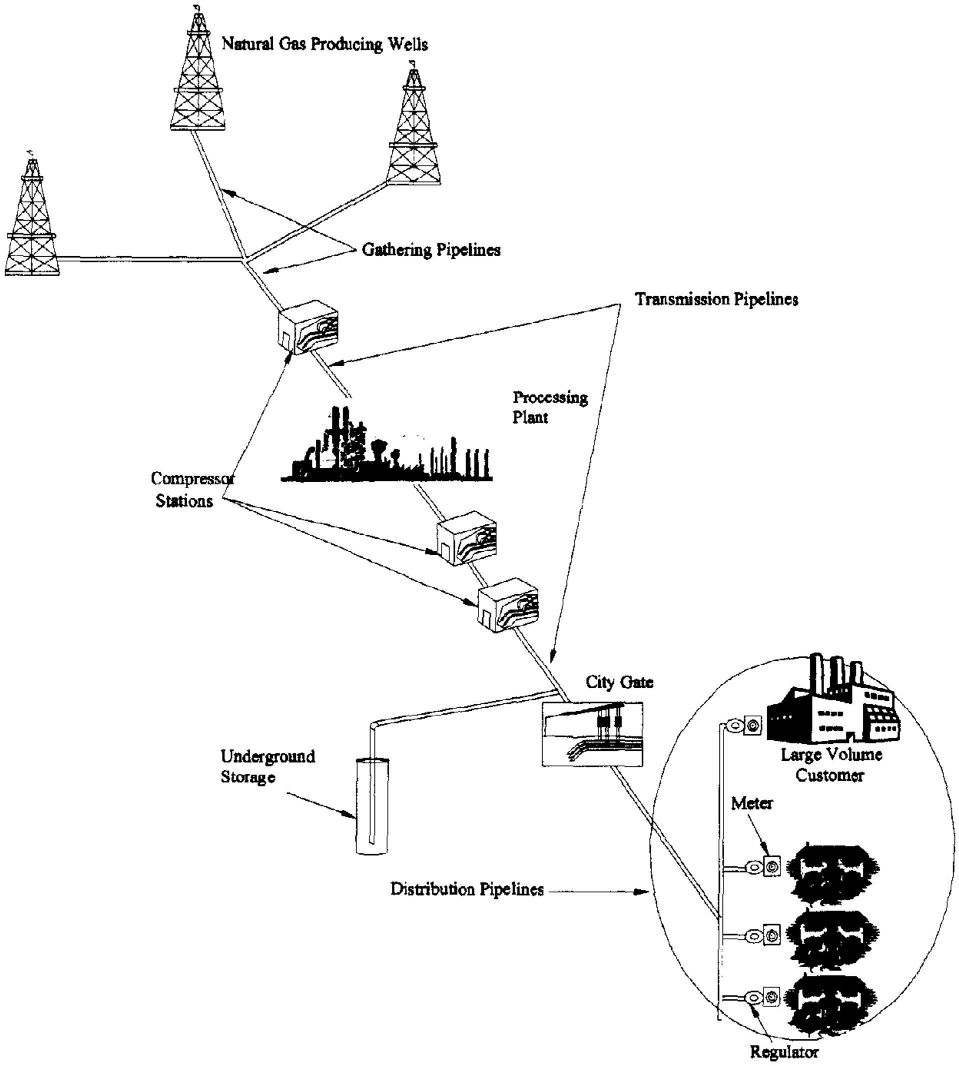


Figure 2. Components of a natural gas production, transmission, and distribution system.

Background

Underground pipelines transport large quantities of a product from the source to the marketplace. The first oil pipeline, which measured at 175 km (109 mi) in length and 152 mm (6 in) in diameter, was laid from Bradford to Allentown, Pennsylvania in 1879. Since the late 1920s, virtually all oil and gas pipelines have been made of welded steel. Although the first cross-country pipeline was laid in 1930 that connected some major cities, it was not until World War II that large-scale pipelines were laid connecting different regions of the country. In the 1960s, larger diameter pipelines ranging from 813 to 914 mm (32 to 36 in) were built. Even a 1,016-mm- (40-in-) diameter pipeline was constructed connecting Louisiana to Illinois. Discovery of oil on Alaska's North Slope resulted in the construction of the country's largest pipeline, the Trans-Alaska Pipeline System (TAPS), with a 1,219-mm- (48-in-) diameter and 1,287-km- (800-mi-) length.

Throughout this section, distinctions are made between natural gas and hazardous liquid pipelines. Although the basic design and purpose of the natural gas and liquid transmission pipeline systems are similar, there are differences in the conveyance systems and in the maintenance systems. The following brief discussion highlights some of the specific conditions for these systems.

Liquid Pipelines

Crude oil must undergo refining before it can be used as product. Once oil is pumped from the ground, it travels through pipelines to tank batteries. A typical tank battery contains a separator to separate oil, gas, and water. After the crude oil is separated, the crude oil is kept in storage tanks, where the oil is then moved through large-diameter, long-distance trunk lines to refineries, other storage tanks, tanker ships, or railcar. The pressure in the trunk lines is initiated and maintained by pumps to overcome friction, changes in elevation, or other pressure-decreasing factors. Drag reducing agents (DRAs) are also used to improve throughput by decreasing the effects of friction. Pump stations are located at the beginning of the line and are spaced along the pipeline at regular intervals to adequately propel the oil along. In 1998, there were 80 companies operating crude oil pipelines in the United States.(4)

Once oil is refined, product pipelines transport the product to a storage and distribution terminal. The products include gasoline, jet fuel, diesel fuel, ammonia, and other liquids. Other product pipelines transport liquified petroleum gases (LPG) and liquified natural gas (LNG) and highly volatile liquids (HVL) such as butane and propane.

Breakout tanks are aboveground tanks used to relieve surges in a liquid pipeline system, or to receive and store liquid transported by a pipeline prior to continued transportation by the pipeline.

Natural Gas Pipelines

The purpose of natural gas gathering and transmission pipelines is similar to that of crude oil gathering and crude oil trunk lines; however, the operating conditions and equipment are quite different. For example, gas transmission pipelines use compressors instead of pumps to force the gas through the pipe. The transmission lines connect to the distribution systems through the "city gate" valve and the metering station, which delivers the natural gas to the consumers via small-diameter, low-pressure lines. Natural gas is often treated in scrubbers or filters to ensure that it is dry prior to distribution.

In addition to the vast mileage of underground piping spanning the United States, a multitude of other facilities were required for the interstate transport of liquids and gases. The major facilities of interest in this study are pump and compressor stations, valve stations, and metering devices. For instance, gathering lines connect individual gas wells to field gas treatment facilities and processing facilities, or to branches of a larger gathering system. The natural gas is processed at the treatment facility to remove water; sulfur; and acid gases, hydrogen sulfide, and carbon dioxide. From the field processing facilities, the dried and cleaned gas enters the transmission pipeline. Each of these components has corrosion-related costs associated with them. The majority of the discussion in this section is directed toward the pipeline system.

CORROSION OF UNDERGROUND PIPELINES

Types of Corrosion

General Corrosion

Corrosion of the pipe wall can occur either internally or externally. Internal corrosion occurs when corrosive liquids or condensates are transported through the pipelines. Depending on the nature of the corrosive liquid and the transport velocity, different forms of corrosion may occur, including uniform corrosion, pitting/crevice corrosion, and erosion-corrosion. Figure 3 shows an example of internal corrosion that occurred in a crude oil pipeline due to high levels of saltwater and carbon dioxide (CO_2).

Figure 3. Internal corrosion of a crude oil pipeline.

There are several different modes of external corrosion identified on buried pipelines. The primary mode of corrosion is a macro-cell form of localized corrosion due to the heterogeneous nature of soils, local damage of the external coatings (holidays), and/or the disbondment of external coatings. Figure 4 shows typical external corrosion on a buried pipeline. The 25-mm- (1-in-) grid pattern was placed on the pipe surface to permit sizing of the corrosion and nondestructive evaluation (NDE) wall thickness measurements.

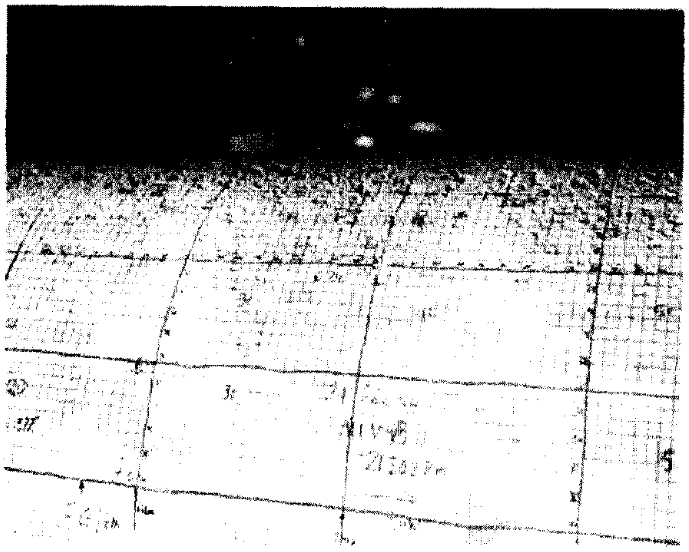


Figure 4. External corrosion on a buried pipeline.

Stray Current Corrosion

Corrosion can be accelerated through ground currents from dc sources. Electrified railroads, mining operations, and other similar industries that utilize large amounts of dc current sometimes allow a significant portion of current to use a ground path return to their power sources. These currents often utilize metallic structures (pipelines) in close proximity as a part of the return path. This "stray" current can be picked up by the pipeline and discharged back into the soil at some distance down the pipeline close to the current return. Current pick-up on the pipe is the same process as cathodic protection, which tends to mitigate corrosion. The process of current discharge off the pipe and through the soil of a dc current accelerates corrosion of the pipe wall at the discharge point. This type of corrosion is called stray current corrosion (see figure 5).

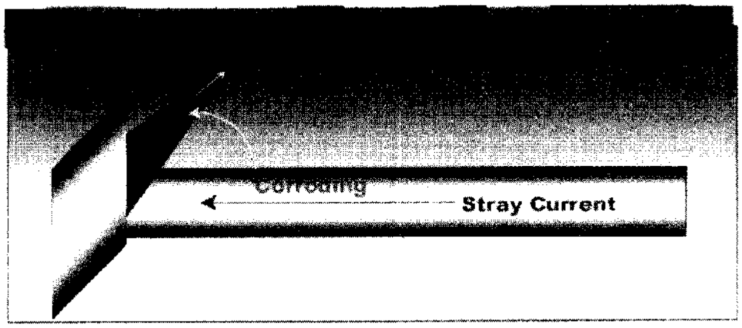


Figure 5. Schematic of stray current corrosion.

Microbiologically Influenced Corrosion (MIC)

Microbiologically influenced corrosion (MIC) is defined as corrosion that is influenced by the presence and activities of microorganisms, including bacteria and fungi. It has been estimated that 20 to 30 percent of all corrosion on pipelines is MIC-related. MIC can affect either the external or the internal surfaces of a pipeline. Microorganisms located at the metal surface do not directly attack the metal or cause a unique form of corrosion. The byproducts from the organisms promote several forms of corrosion, including pitting, crevice corrosion, and under-deposit corrosion. Typically, the products of a growing microbiological colony accelerate the corrosion process by either: (1) interacting with the corrosion products to prevent natural film-forming characteristics of the corrosion products that would inhibit further corrosion, or (2) providing an additional reduction reaction that accelerates the corrosion process.

A variety of bacteria have been implicated in exacerbating corrosion of underground pipelines and these fall into the broad classifications of aerobic and anaerobic bacteria. Obligate aerobic bacteria can only survive in the presence of oxygen, while obligate anaerobic bacteria can only survive in its absence. A third classification is facultative aerobic bacteria that prefer aerobic conditions, but can live under anaerobic conditions. Common obligate anaerobic bacteria implicated in corrosion include sulfate reducing bacteria (SRB) and metal-reducing bacteria. Common obligate aerobic bacteria include metal-oxidizing bacteria, while acid-producing bacteria are facultative aerobes. The most aggressive attacks generally take place in the presence of microbial communities that contain a variety of types of bacteria. In these communities, the bacteria act cooperatively to produce conditions favorable to the growth of each species. For example, obligate anaerobic bacteria can thrive in aerobic environments when they are present beneath biofilms/deposits in which aerobic bacteria consume the oxygen. In the case of underground pipelines, the most aggressive attack has been associated with acid-producing bacteria in such bacterial communities (see figure 6).

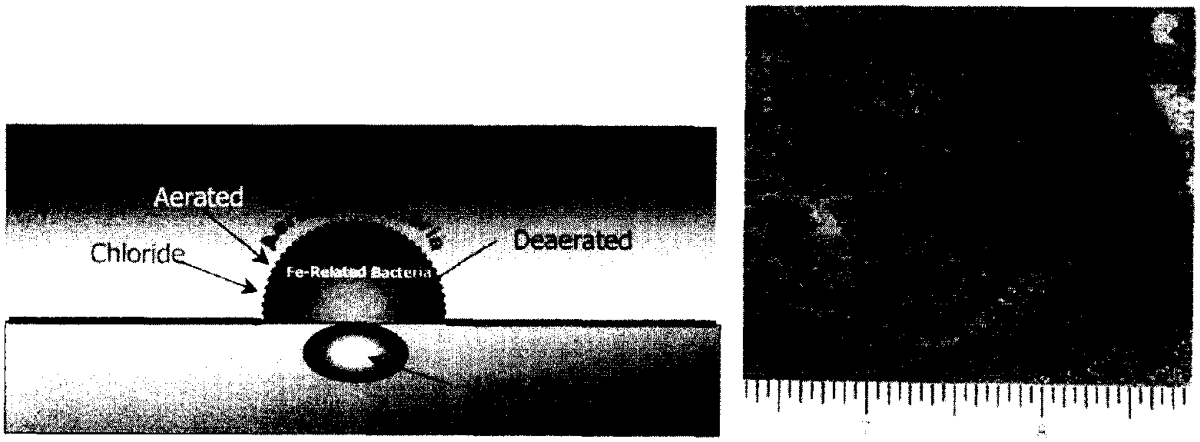


Figure 6. Iron-related bacteria reacting with chloride ions to create locally acidic environment.

Stress Corrosion Cracking

A particularly detrimental form of pipeline corrosion is known as stress corrosion cracking (SCC). SCC is defined as the brittle fracture of a normally ductile metal by the conjoint action of a specific corrosive environment and a tensile stress. On underground pipelines, SCC affects only the external surface of the pipe, which is exposed to soil/groundwater at locations where the coating is disbonded. The primary component of the tensile stress on an underground pipeline is in the hoop direction and results from the operating pressure. Residual stresses from fabrication, installation, and damage in service contribute to the total stress. Individual cracks initiate in the longitudinal direction on the outside surface of the pipe. The cracks typically occur in colonies that may contain hundreds or thousands of individual cracks. Over time, the cracks in the colonies interlink and may cause leaks or ruptures once a critical-size flaw is achieved. Figure 7 shows an SCC hydrostatic test failure on a high-pressure gas pipeline (see later section on hydrostatic testing).

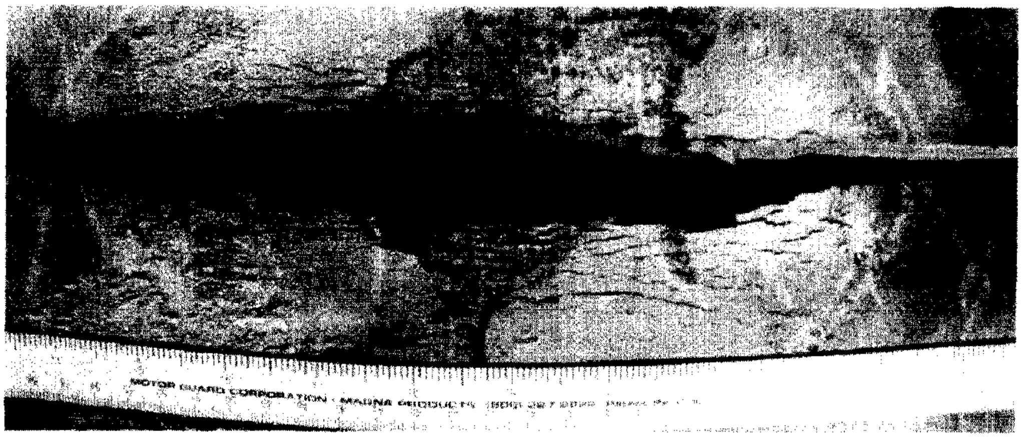


Figure 7. SCC colony found on a large-diameter, high-pressure transmission gas pipeline.

The two basic types of SCC on underground pipelines that have been identified are classical or "high pH" cracking (pH 9 to 10), which propagates intergranularly, and "near-neutral pH" cracking, which propagates transgranularly. Each form of SCC initiates and propagates under unique environmental conditions. Near-neutral pH SCC (< pH 8) is most commonly found on pipelines with polyethylene tape coatings that shield the cathodic protection current.(5) The environment that develops beneath the tape coating and causes this form of cracking is dilute carbonic acid. Carbon dioxide from the decay of organic material in the soil dissolves in the electrolyte beneath the disbonded coating to form the carbonic acid solution. High-pH SCC is most commonly found on pipelines with asphalt or coal tar coatings. The high-pH environment is a concentrated carbonate bicarbonate solution that develops as a result of the presence of carbon dioxide in the groundwater and the cathodic protection system.

Mitigation of Corrosion

External Corrosion

Corrosion is an electrochemical phenomenon and, therefore, can be controlled by altering the electrochemical condition of the corroding interface. For external wall surfaces, altering the electrochemical nature of the corroding surface is relatively simple and is done by altering the voltage field around the pipe. By applying a negative potential and making the pipe a cathode, the rate of corrosion (oxidation) is reduced (corrosion is mitigated) and the reduction process is accelerated. This means of mitigating corrosion is known as cathodic protection (CP).

CP is achieved in practice by one of two primary types of CP systems, including sacrificial anode (galvanic anode) CP and impressed-current CP. Sacrificial anode CP utilizes an anode material that is electronegative to the pipe steel. When connected to the pipe, the pipe becomes the cathode in the circuit and corrosion is mitigated. Typical sacrificial anode materials for underground pipelines are zinc and magnesium.

Impressed-current CP utilizes an outside power supply (rectifier) to control the voltage between the pipe and an anode (cast iron, graphite, platinum clad, mixed metal oxide, etc.) in such a manner that the pipe becomes the cathode in the circuit and corrosion is mitigated.

CP is most often used in conjunction with a coating. There are always flaws in the coating due to application inconsistencies, construction damage, or the combination of natural aging and soil stresses. If left unprotected, corrosion will occur at these coating flaws (holidays). Often the rate of attack through the wall is much higher at the holiday than the general attack of a bare steel surface. The use of a coating greatly reduces the total amount of current required to achieve protection of the pipeline system; therefore, CP and external coatings are utilized together wherever possible.

CP can be used to mitigate all types of corrosion previously discussed (general, stray current, MIC, and SCC). Sometimes it is difficult to determine the level of CP necessary to mitigate the different corrosion mechanisms and to identify which type of corrosion is present. Stress corrosion cracking presents additional problems. First, the high-pH form of SCC is only found on pipelines protected with CP. The products that result from cathodic reactions occurring on the pipe surface during CP in conjunction with soil chemistry produce the environment necessary for high-pH SCC. Since high-pH SCC only propagates in a very limited potential range, maintaining the potential of the pipe surface outside of this range by proper CP control will prevent growth of the high-pH SCC cracks. In addition, it has been established that proper CP control can inhibit the growth of near-neutral SCC cracks.

Internal Corrosion

Internal corrosion is also an electrochemical process; however, CP is not a viable option for mitigating internal corrosion in a pipeline. One of the first defense systems against corrosion for transmission pipelines is to ensure that the product being transported is free of moisture. Dry, deaerated natural gas and moisture-free oil and petroleum products are not corrosive. For corrosion to occur, there must be moisture, CO_2, oxygen, or some other reduction reactant, such as one produced by microbes. Operators typically control moisture, oxygen, and CO_2 contents of the transported product, but these constituents can enter the pipeline through compressor or pump stations, metering stations, storage facilities, or other means. Gathering lines in production fields have a much more significant problem with internal corrosion than the typical transmission pipeline.

One option available for mitigating internal corrosion is chemical treatment of the product being transported. Chemical inhibitors for mitigating corrosion and biocides to prevent microbiological activity are used. Both of these methods can be effective in either natural gas or liquid pipelines. The cost of either the inhibitor or biocide the treatment is significant. Recall that large volumes of products are continuously flowing through the pipeline. To mitigate corrosion through chemical treatment requires continuous injection or regular batching of the inhibitor or biocide.

Inspection of Pipelines

Electrical Surveys

Electrical surveys have been performed to evaluate the level of CP ever since the application of CP to pipelines in the 1940s. These surveys consist of measuring the potential (pipe-to-soil potential) of the pipe surface with respect to a reference electrode [typically copper/copper sulfate electrode (CSE)]. These measurements can be performed at permanent test station locations (test point surveys) or they can be performed continuously with a 1- to 2-m (3- to 6-ft) spacing along the entire length of the pipeline (close interval surveys). Pipe-to-soil potential surveys can be performed with the CP system energized (on-potentials) or with the CP system interrupted (off-potentials). There has been much discussion over the past 10 to 20 years as to the most appropriate survey methodology. While each method has its benefits, it is commonly accepted that the IR-voltage (voltage drop due to current, I, through a resistance, R) correction made by the off-potential measurement is most closely related to the corrosion condition of the pipeline. Figure 8 shows a schematic of a pipe-to-soil potential measurement.

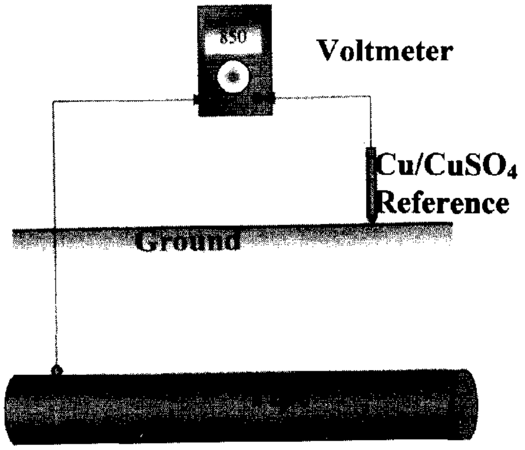


Figure 8. Schematic of pipe-to-soil potential measurement.

The basic pipe-to-soil potential measurement techniques are applied to establish whether one or more of the recommended CP criteria are met. Criteria for establishing the effectiveness of a CP system to mitigate corrosion are outlined in the NACE International Recommended Practice RP0169-96, "Control of External Corrosion on Underground or Submerged Metallic Piping Systems" and have been adopted, in part, in U.S. Department of Transportation (DOT) regulations CFR 49, Parts 192 and 195. In general, if one or more of the recommended criteria are met, the CP system is assumed to be applying a sufficient cathodic current to mitigate corrosion.

There are many survey techniques directed at detecting coating damage or establishing overall coating quality. Other surveys characterize stray current conditions, locate shorts, monitor current flow in the pipe, and establish proper rectifier operation. Over the years, the aforementioned electrical surveys have been the primary means for establishing the proper operation of a CP system, troubleshooting problem areas, establishing the necessary level of CP, and identifying areas for remedial measures.

Certain pipeline conditions make conventional electrical survey techniques difficult to interpret. These include areas of stray or telluric currents, congested areas where multiple pipelines and other utilities share rights-of-way, and pipelines with non-interruptible sacrificial CP systems. In these areas, either significant care must be taken to interpret conventional surveys or other methods of monitoring must be utilized. One such technology is the use of coupon test stations. The coupon test stations permit accurate potential measurements for a test specimen (coupon) that simulates a holiday on the pipe surface.

Direct Inspection (Digs)

Inspection digs (bell-hole inspections) are a means of verifying the condition of the coating and the pipe. The process of inspection digs includes uncovering and visually inspecting a section of the pipe (see figure 9). Nondestructive evaluation (NDE) techniques can be used to determine wall loss. Visual findings can be correlated to various electrical survey findings. Often, a dig program is used to verify the effectiveness of other techniques in establishing the condition of the pipe (i.e., electrical inspection and in-line inspection).

Figure 9. Inspection dig and pipeline repair.

In-Line Inspection (Smart Pigs)

In-line inspection (ILI) tools, also referred to as smart or intelligent pigs, are devices that are propelled by the product in the pipeline and are used to detect and characterize metal loss caused by corrosion. There are two primary types of ILI tools: magnetic flux leakage (MFL) tools and ultrasonic tools (UT). The more advanced ILI tools (high-resolution tools) are capable of discriminating between internal and external corrosion.

MFL tools measure the change in magnetic flux lines produced by the defect and produces a signal that can be correlated to the length and depth of a defect. In recent years, the magnetics, data storage, and signal interpretation have improved, resulting in improved mapping of the flaw and a decrease in the number of unnecessary excavations. The high-resolution MFL tool is typically capable of readily detecting corrosion pits with a diameter greater than three times the wall thickness. Once detected, these tools can typically size the depth of the corrosion within ±10 percent of the wall thickness with an 80 percent level of confidence. The MFL tool can be used to inspect either liquid products pipelines or natural gas pipelines.

UT tools utilize large arrays of ultrasonic transducers to send and receive soundwaves that travel through the wall thickness, permitting a detailed mapping of the pipe wall. UT tools can indicate whether the wall loss is internal or external. The typical resolution of a UT tool is ±10 percent of the pipe wall thickness with an 80 percent level of confidence. UT tools are typically used in products pipelines (e.g., crude oil, gasoline, etc.) since the product in the pipeline is used as the required couplant for the ultrasonic sensors. This tool can be used to inspect natural gas pipelines, but requires introducing a liquid (i.e., water) into the pipeline for transporting the ILI tool through the line.

Figure 10 shows a typical MFL tool. The wire brushes in the front of the tool are used to transfer the magnetic field from the tool to the pipe wall. The ring of sensors between the wire brushes are used to measure the flux leakage produced by defects in the pipe. The drive cups are the mechanism that is used to propel the tool by the product in the pipeline. The odometer wheels monitor the distance traveled in the line and are used to determine the location of the defects identified. The trailing set of inside diameter/outside diameter sensors (ID/OD sensors) is used to discriminate between internal and external wall loss.

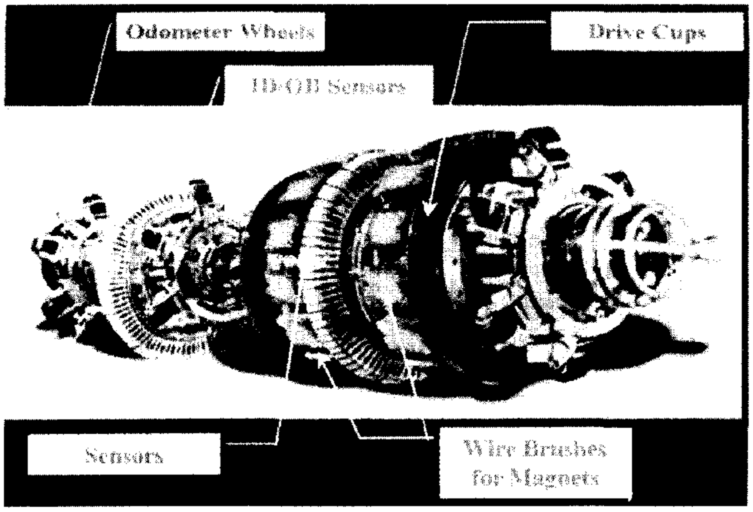


Figure 10. MFL tool for pigging a pipeline.

ILI tools are 3.0 to 5.5 m (10 to 18 ft) in length. The ILI tools must be capable of readily passing through the pipeline and the sensors must be able to produce good contact (MFL tool) or stand-off from the pipe wall (UT tool). For these reasons, pipelines with large buckles, large dents, tight-radius bends, or valves that do not open fully can provide difficulty in conducting an inspection and, in some cases, will cause limitations that make the lines not "piggable". The tool will simply not fit through the pipeline. In addition, pipelines to be inspected by ILI tools must be fitted with launchers and retrievers.

Hydrostatic Testing

The purpose of hydrostatic testing is to cause failure at existing "near critical" flaws during controlled hydrostatic testing as opposed to the flaw growing to critical size and failing during operation. Hydrostatic testing involves pressurizing the pipeline with water to a pressure that exceeds the maximum allowable operating pressure

(MAOP) for the pipeline. The concept is relatively simple. If there is a flaw that is near critical size at or below MAOP, that flaw will cause a pipeline failure when pressurized above the MAOP. In most cases, the pipeline must be tested to at least 125 percent MAOP to provide an adequate margin between the test pressure and the operating pressure.

An essential factor is to establish a proper hydrostatic test frequency. If hydrostatic testing is used as the primary defense against pipeline failure, the frequency must be equal to the time required for a flaw to grow from a size that just passes the hydrostatic test (125 percent MAOP) to a size that is critical at operating pressure. Hydrostatic testing is also used to commission a pipeline for initial service and as a criterion for qualifying a pipeline for return to service.

AREAS OF MAJOR CORROSION IMPACT

Areas of major economic impact associated with the corrosion of pipeline systems include capital cost related to corrosion control, general maintenance for corrosion control, replacement/repair costs, and costs associated with corrosion-related failures. The costs of each of these areas are discussed below. Corrosion plays a major role in decision-making concerning pipeline systems in both direct and indirect ways. Although the direct costs (costs to the owner or operator) regarding the impact of corrosion on pipelines are difficult to determine with accuracy, they are relatively easy to understand. On the other hand, indirect costs (costs to third parties) associated with corrosion of pipelines are more difficult to understand and are even more difficult to assign a value. The following are examples of indirect costs:

- Costs associated with damages to the environment or disruption to the public due to release of products (costs not directly paid by the operator as part of clean-up).
- Public relations costs for dealing directly with the public are increasing. Public opinion runs high against new pipelines in "their backyard." The public is becoming concerned about aging pipelines, primarily due to a lack of information and a few recent high-visibility failures. This public attitude makes it difficult to obtain new rights-of-way and these are at a much higher cost than in the past. In addition, the negative public attitude will probably force decisions on the pipeline operators that are not necessarily the most optimal and cost-effective.
- Legal costs associated with a failure have become staggering when the failure has resulted in injury or death ($280 million in a case involving one fatality). These costs include defending against negligence on the part of the operator, criminal defense for officers in the company, and punitive damages awarded to the estate of the deceased or injured. Indirect costs would be the lost productivity of staff and public costs associated with the judicial process.
- Lost revenue for the producers arising from not being able to ship their product while the section of pipeline is out of service due to rupture.
- Lost revenue or increased costs to the end users for disruption of service or higher costs for alternative sources of fuels.

Capital Cost

Current Investment in Capital

For all natural gas pipeline companies, the total gas plant investment as of 1998 was $63.1 billion. "Gas plant" refers to the physical facilities used to move natural gas, such as compressors, metering stations, and pipelines. From this investment, a total revenue of $13.6 billion was generated. For liquid pipeline companies, the investment in carrier property was $30.2 billion. The total revenue for liquid pipeline companies was $6.9 billion. Therefore, the total capital investment for the transmission pipeline industry was $93.3 billion as of 1998.

Growth Requirements for Capital

It is anticipated that by the year 2010, the growth in the natural gas market will require a $32.2 billion to $34.4 billion investment in new pipelines and storage infrastructures.(6) This is in addition to the current annual capital investment for the pipeline industry. A significant portion of this growth comes from power generation and industrial sectors. This growth will be required because of federal Environmental Protection Agency (EPA) regulations to reduce atmospheric pollutants. The reduction in pollution will be achieved primarily by using natural gas, which is a significantly cleaner fuel for power utilities and plants than that currently used.

In addition to $93.3 billion invested in hazardous liquid and natural gas pipeline companies as of 1998, transmission pipeline companies spent $6.4 billion in capital improvements in 1998, of which approximately 75 percent was associated with the pipeline system ($4.8 billion).(4,7) Adding this $4.8 billion to the expected increase in capital due to an increase in the natural gas market of $3.3 billion ($32.2 billion to $34.4 billion divided by 10 years) gives an annual capital requirement of $8.1 billion.

Cost of Corrosion in Pipeline Construction

The average cost of new construction (onshore pipelines) for North American gas pipeline projects in 1998 and 1999 was $746,000 per km ($1.2 million per mi).(4,7) For 1998, there were approximately 2,576 km (1,600 mi) of pipeline constructed in the United States. These costs are broken down into the following categories: materials (line pipe, pipe coating, and cathodic protection), labor, miscellaneous (surveying, engineering, supervision, contingencies, telecommunications equipment, allowances for funds used during construction, overheads, and regulatory filling fees), and ROW (costs for obtaining right-of-way and allowing for damages). Table 1 shows costs for each category for 1998 and 1999 construction for natural gas onshore pipeline projects.

Table 1. Summary of construction costs for 1998 and 1999 onshore pipeline projects (natural gas pipelines).

	COST PER MILE		
	1998 Construction*	**1999 Construction**	**Average 1998 & 1999**
	($ x thousand)	**($ x thousand)**	**($ x thousand)**
Material	488	276	382
Labor	500	468	484
Miscellaneous	219	283	251
ROW and Damages	35	76	56
TOTAL	**$1,242**	**$1,103**	**$1,173**

*Estimated materials and labor cost for land projects based on total projects.

Cost of Pipeline Coating and CP

The cost of corrosion, in terms of materials, is incorporated in the $237,400 per km ($382,000 per mi) materials cost, i.e., pipeline coating, cathodic protection (CP), etc. The cost of coating is estimated at 7 percent to 10 percent of the material cost of the pipe, or $17,000 to $24,000 per km ($27,000 to $38,000 per mi).(8) The cost of an average CP system for new construction is approximately $12,000 for 24 km (15 mi) of pipeline, or $500 per km

($800 per mi).[9] The coating and CP costs discussed above are inclusive of the cost of materials and cost of labor associated with application/installation.

Cost of Corrosion Allowance

Although, a safety factor is built into the design calculations, corrosion allowance has not been specifically made a part of the design calculations. In addition, pipe wall thickness in high-risk areas is increased still further to provide an overall increased level of safety from integrity threats. Although corrosion is accounted for in the typical design safety factor for pipe wall thickness, without that safety factor, a corrosion allowance would be required. Therefore, in this study, it is estimated that the cost of the corrosion allowance for the pipe wall thickness accounts for 5 percent to 10 percent of the material cost, or $12,000 to $24,000 per km ($19,000 to $38,000 per mi).[10]

Cost of Specifications/Designs

It is estimated that the CP and coating specifications, design, and associated purchasing accounts for 2 percent to 5 percent of the miscellaneous costs or $3,000 to $7,760 per km ($5,000 to $12,500 per mi).

Total Cost of Corrosion for Construction

A total cost of corrosion can be estimated for new pipeline construction of $32,500 to $55,500 per km ($51,800 to $89,300 per mi) of pipeline, or 4.4 percent to 7.6 percent (average of 6 percent) of the total cost of pipeline construction. This breaks down into:

- $17,000 to $24,000 per km for pipeline coating.
- $500 per km for CP system.
- $12,000 to $24,000 per km for corrosion allowance.
- $3,000 to $7,000 per km for specifications/designs.

Replacement Cost of Pipeline Infrastructure

With the cost of new pipeline construction at $694,100 per km ($1,117,000 per mi) [total cost minus right of way (ROW) cost] and 778,900 km (484,000 mi) of the needed transmission pipelines, the cost of replacement of the transmission pipeline infrastructure is $541 billion. This is compared to the total book asset value of $93.1 billion for pipeline operations.

Portion of Capital Cost Due to Corrosion

Annual Cost of Capital for Pipeline Replacement

It is assumed that 25 percent of the new capital costs of $8.1 billion is for replacement of aging pipeline. Furthermore, it is assumed that all of the replacement is related to corrosion. Therefore, the annual capital cost due to corrosion for replacement of pipeline infrastructure is $2.02 billion.

Annual Cost of "Non-Replacement" New Capital

The "non-replacement" new capital expenditure is $6.08 billion ($8.1 billion minus $2.02 billion). Assuming that the average percentage of construction costs attributed to corrosion (4.4 to 7.6 percent) can be applied to capital costs, the capital expenditure related to the cost of corrosion is $268 million to $462 million (4.4 to 7.6 percent of $6.08 billion).

Depreciation of Existing Capital

Assuming that the capital cost of corrosion for total pipeline system assets ($93.3 billion) is the same as the cost of corrosion for construction, there is $4.1 billion to $7.1 billion (4.4 to 7.6 percent of $93.3 billion) in corrosion-associated existing capital. Amortizing these costs at an annual rate of 5 percent gives an annual cost of corrosion for existing capital of $205 million to $355 million.

Total Capital Costs

The total cost of corrosion for capital items is estimated at $2.50 billion to $2.84 billion ($2.02 billion for replacement capital, $0.27 billion to $0.46 billion for new capital, and $0.21 billion to $0.36 billion for depreciation of existing capital.

Operations and Maintenance (Corrosion Control)

Significant maintenance costs for pipeline operation are associated with corrosion control and integrity management. The driving forces for the expenditure of maintenance dollars are to preserve the asset of the pipeline, which is equal to $93.3 billion in book value and $541 billion in replacement value, and to ensure safe operation without failures that jeopardize public safety, result in loss product and throughput, and cause property and environmental damage, which is estimated at $470 million to $875 million per year (see "Corrosion-Related Failures").

External Corrosion

A recent survey of major pipeline companies indicated that the primary cause of loss of corrosion protection was due to coating deterioration (30 percent) and inadequate CP current (20 percent).(11) Other contributing causes included shorts or contacts (12 percent) and stray current (7 percent). The majority of general maintenance is associated with monitoring and repairing these problems. Integrity management concerns are focused on condition assessment, mitigation of corrosion, life assessment, and risk modeling.

External Corrosion Coatings

The use of protective coatings (in conjunction with CP) is the most widely used form of corrosion protection in the pipeline sector. Since the 1950s, several coating systems have been utilized, including fusion-bonded epoxy, extruded polyethylene, coal tar enamel, liquid epoxy, tape, polyurethane, mastic, and wax. Pipelines with each of these coating systems remain in service today. The most widely specified coating used on new pipelines is fusion-bonded epoxy. New multi-layered coatings are now on the market.

Coatings have been specified for all new pipeline construction since the 1960s. As previously stated, the average cost of coating pipe for new construction is estimated at $24,000 per km ($38,000 per mi). If this cost is applied to the total length of existing transmission pipe [778,900 km (484,000 mi)], the total coating corrosion prevention investment in the pipeline industry can be estimated at $18.4 billion in replacement costs.

With nearly 30 percent of the operational pipeline corrosion problems being attributed to coating deterioration, a large portion of the corrosion control budget is expended on monitoring, identifying, and repairing coating anomalies. In addition, extreme coating deterioration can significantly impact the ability to cathodically protect the pipeline from corrosion in terms of cost-effectiveness. To extend the operating life of a pipeline, an emerging method of pipeline corrosion control is pipeline coating rehabilitation (re-coating the pipeline).

Cathodic Protection

Cathodic protection is the required method of corrosion control on buried pipelines (CFR 49, Parts 192 and 195). The two forms of CP utilized are impressed-current and sacrificial anode systems. Both forms of protection represent technologies that have been used by the industry for many years and operating personnel are familiar with their installation and operation (NACE Recommended Standard RP0169-96).

Impressed-current CP systems represent the vast majority of CP systems for transmission pipelines. Impressed-current systems can be readily adjusted to compensate for changes in the amount of current required to adequately protect the structure; however, they may also contribute to the interference of other structures in the vicinity. Depending upon soil, pipe coating properties, and pipe size, impressed-current CP systems can be used to protect long lengths of pipe. However, impressed-current CP systems require more expensive installation and equipment, increased monthly monitoring, and greater power consumption charges than that of sacrificial anode systems. It is estimated that there are between 48,000 and 97,000 CP rectifiers in operation today [778,900 km (484,000 mi) of pipe with rectifiers every 8 to 16 km (5 to 10 mi)].(12) With an average installation cost of $12,000 per rectifier/groundbed, the total pipeline investment in impressed-current CP systems is between $0.6 billion and $1.2 billion. It is estimated that the annual investment by pipeline companies in impressed-current CP systems is $40 million (new installations and replacement of existing systems).

Sacrificial anode CP systems are used extensively to protect gas distribution pipelines, but are applied more as a remedial measure for problem areas on transmission pipelines. Sacrificial anodes are relatively inexpensive, do not require an external power supply, and require no regular monitoring of the anode (rectifiers for impressed-current systems require bimonthly monitoring to ensure proper operation). Due to their low driving voltages, however, sacrificial anodes are not applicable in all environments and do not have the power to protect long lengths of pipeline. Sacrificial anodes are often used to compliment impressed-current CP systems by providing protection to local areas where additional protection is required due to inadequate coating quality. It is estimated that $30 million of sacrificial anode material (zinc and magnesium) are purchased by the pipeline industry each year.(13) If it is assumed that 30 percent of the sales are for transmission pipelines, the annual cost is $9 million. The majority of the remaining $21 million goes to distribution pipelines.

Internal Corrosion

Internal pipeline corrosion is mitigated through various measures, including dewatering, inhibition, cleaning (pigging), and internal pipeline coatings. Dewatering consists of removal of the corrosive fluids prior to their introduction into the pipeline. Dewatering components are typically located at pipeline compressor and pump stations. In other cases, specific low points are selected along the pipeline right-of-way for the installation of "drips" that allow the corrosive fluids to be collected and periodically removed from the line to prevent corrosion of the pipe downstream from the site.

Inhibition consists of the addition of corrosion-inhibiting chemicals to the gas or product stream. These chemicals act in a variety of ways to mitigate the corrosion to an acceptable rate. Costs associated with corrosion-inhibition programs vary widely and are dependent upon the corrosiveness of the environment. In addition to the costs associated with introducing the chemicals to the system, most corrosion-inhibitor programs have general maintenance costs associated with the monitoring of the inhibitor additions and the determination of inhibitor effectiveness.

Another means of mitigating internal corrosion of pipelines is the periodic cleaning of the line. This is accomplished through a process called "pigging" (cleaning and scraping pigs). Pigging involves inserting one of a variety of different "pigs" into the line and propelling it through the line with gas or another product. As the pig passes through the line, it pushes and/or scrapes fluids, waxes, and debris from the line. These cleaning operations can also make use of various cleaning media, including solvents, biocides, acids, and detergents to aid in cleaning effectiveness. Corrosion is reduced by the elimination of the corrosive environment from the line. Costs associated with the pipe pigging process include the cost of preparing the line for pigging (installation of pig launchers and receivers, removal of appurtenances that could cause the pig to become lodged, etc.), possible reduced throughputs during the pigging operations, cost of pigs, solvents, etc., and the cost of the disposal of the material removed from the pipe.

Rehabilitation of internally corroded pipelines is somewhat more difficult to manage than external corrosion issues. Internal corrosion often requires cutting out and replacing the affected sections of the pipeline. Other methods of internal rehabilitation include pulled liners and epoxy flood coating. Cost estimates for these options can vary greatly and are predominantly dependent upon the extent of cleaning required to prepare the internal surface for coating.

Cost of Operations and Maintenance (Corrosion Control)

The most effective way to account for all of the related operating and maintenance costs associated with corrosion is to examine the total operating and maintenance budgets for representative companies. Table 2 shows the annual estimated cost for operations and maintenance associated with corrosion and corrosion control of three pipeline transmission companies. These costs typically include the costs associated with annual test point CP surveys, close interval surveys, monthly rectifier readings, CP maintenance and upgrades (including materials), pipe inspection at excavations, casing and insulator inspection, record-keeping, training, and aboveground maintenance coating operations. If the average corrosion operation and maintenance cost of $4,400 per km ($7,100 per mi) of pipe is representative of most operating pipeline companies, the total transmission pipeline industry cost can be estimated at $3.4 billion ($4,400 x 778,900 km of pipe). With a range of costs equal to $3,000 to $6,200 per km ($5,000 to $10,000 per mi), the range of annual operation and maintenance costs associated with corrosion is $2.42 billion to $4.84 billion.

Table 2. Estimated costs for operations and maintenance associated with corrosion and corrosion control.

COMPANY IDENTIFICATION	MILES OF PIPE	TOTAL O&M COSTS	O&M PER MILE	O&M COSTS DUE TO CORROSION	CORROSION COSTS PER MILE
	(mi x thousand)	($ x million)			
A	11,000	$358.9	$32,627	15%	$4,894
B	10,000	$707	$70,700	15%	$10,605
C	5,000	$192	$38,400	15%	$5,760
				AVERAGE COST PER MILE	$7,086

1 mi = 1.61 km

Replacement/Rehabilitation

Introduction

Decisions for pipeline replacement versus pipeline rehabilitation are often difficult, with several important considerations. Rehabilitation includes repairing existing flaws in the pipeline and recoating the pipeline. In order to make the most effective decisions on replacement versus rehabilitation of a pipeline or segment of pipe, it is important to understand the extent of the corrosion existing on the line and the coating condition of the pipeline. For example, excessive cutouts and replacements rapidly increase the cost of coating rehabilitation. In addition, hidden costs must be taken into account, including such items as shorter coating service lives of *in situ* coatings. The following three specific conditions make replacement/rehabilitation necessary: (1) severe corrosion damage of a pipeline not properly cathodically protected, (2) severe coating deterioration leading to increased CP requirements, and (3) stress corrosion cracking along a large area of pipeline.

Corrosion

Pipeline integrity management programs are used by pipeline operators to determine the locations in which corrosion defects pose a threat to safe operation. Repairs at these locations can vary from the installation of a reinforcing sleeve to the implementation of a large-scale pipe rehabilitation or replacement program. For localized corrosion flaws, the repair process can include composite sleeves, full-encirclement steel sleeves, or replacement of a pipe segment. For local flaws, decisions regarding the repair process can typically be handled by company procedures and criteria. For large-scale corrosion and/or coating deterioration issues, the replacement/rehabilitation decision must consider both operational and economic factors.

In-line inspections (ILI) are widely used to generate a profile of defects found in a pipeline. The high-resolution UT and MFL ILI tools available today can determine the geometry and the orientation of corrosion defects. These inspections can be used to determine the number and the location of near-critical flaws that should be immediately examined (dig program to verify flaw and to repair). With appropriate corrosion growth models, predictions can be made on future dig/repair and/or reinspection requirements for the ILI inspected line. If the density of the corrosion defects is high or the potential exists for continued increase in dig/repair frequency, the affected pipe section may be a candidate for repair or replacement.

Aging Coating

Another concern related to corrosion assessment is the cost of maintaining the required level of CP. The effectiveness of the CP system can be verified using corrosion surveys. An increased number of coating defects require an increased amount of CP current. This is accomplished by increasing the current output of the impressed-current rectifiers, installing impressed-current rectifiers at more locations along the pipeline, or installing additional sacrificial anodes. Coating defects can be identified by conventional potential surveys or by specific coating defect surveys and verified by direct visual inspection (dig program). Under certain circumstances, coatings fail in a manner that makes assessment of the corrosion condition of the pipe through conventional surveying methods difficult. Aging coating and the associated increase in coating defects can make the continuous need for CP upgrading uneconomical.

Stress Corrosion Cracking

The presence of extensive stress corrosion cracking (SCC) may qualify a pipeline for replacement or rehabilitation. Because SCC is dependent on unique environmental conditions, a large-scale recoating program may protect against these environmental conditions and permit continued operation of the line. Based on the severity and density of the stress corrosion cracks, however, pipe replacement may be the most economical option.

Considerations

Replacement/rehabilitation decisions involve several considerations. These considerations include terrain conditions, expected or required life, excess capacity and throughput requirements, internal versus external corrosion, etc. A comprehensive list of considerations for pipeline rehabilitation is given in table 3.(14) Only a few of these are discussed in detail below.

Table 3. Considerations for pipeline rehabilitation.

PIPE	ANOMALIES	BURIAL	OPERATING	LABOR	MATERIAL	EQUIPMENT
Size	Position	Depth	Interruptability	Contractor versus Internal	Pipe	Digging Equipment
Span	Size	Location	Ability to Lower Pressure	Bidding versus Time & Materials	Coating(s)	Non-Digging Equipment
Grade	Quantity	Soil Conditions	Cathodic Protection	Employee Skill Level	Sleeves	Specialty Items
Wall Thickness	Profile	Drainage Conditions	Welding Issues	Job Limitations	Fittings	Transportation
Operating Pressure	Concentration	Season	Regulations	Availability	Cathodic Protection	
Availability	Wall Loss	Other Facilities	Company Standards	Location	Specialty Repair Items	
Company Specifications	Cause	Environmental Issues		Union Requirements	Site Restoration	
		Legal Issues		Benefits	Availability	

The location of the pipeline is critical to repair considerations. For example, a pipe in swampy clay would exclude recoating as a repair option. Alternatively, the prairies are conducive to recoating, with firm footing for the equipment and good accessibility.

If the expected life of a section of pipeline is relatively short, the operator must decide whether recoating and repair would extend the life of the pipe section to match the rest of the pipeline. If not, recoating is not an economically sound solution. Replacing the pipe may then be the best solution.

Several alternatives may be considered beyond replacement or rehabilitation, including abandonment of the pipe section with a bypass loop, increasing the frequency of ILI, increasing the CP level, and de-rating the pipe. Increasing the frequency of ILI enables greater accuracy in determining the point of failure for existing defects. De-rating the pipe may extend the life of the pipe, provided that throughput requirements are met. The throughput issue is strictly a function of an operator's contracts to ship products and to ensure that they are able to continue to provide service in some capacity. For either the replacement or repair option, it is generally necessary to have a looped system and allow for pressure restrictions or interruptible service to facilitate repairs.

Internal corrosion problems are not as easily addressed as external corrosion problems. The application of an internal coating or lining to ensure mitigation of active corrosion sites inside a pipe is possible. For internal coating repair, the pipeline will have to be completely out of service. This is not always required for external recoating.

Replacement/Rehabilitation Case Studies

TransCanada Transmission Pipeline (TCPL) 1996 Trial Program

A trial program was launched by TCPL in 1996 to investigate the feasibility of large-scale mainline recoating. The program was initiated after field measurements indicated substantial deterioration of the coating on TCPL's older pipelines. The project involved the rehabilitation of 1.6 km (1 mi) of an 864-mm- (34-in-) diameter pipeline. The cost of rehabilitation was $804,000. This cost was estimated to be approximately 60 percent of the cost of replacing the pipe.(15)

TCPL 1998 Mainline Recoating Program

With the success of the 1996 trial project, an annual mainline recoating program was established.(16) Table 4 presents a summary of the costs for the TCPL mainline rehabilitation program. Each project used liquid epoxy that was applied by spraying onto the pipe. As a cost example, the cost of rehabilitation in 1998 was $10.6 million for 26.2 km (16.3 mi) of 864-mm- (34-in-) diameter pipe [$404,000 per km ($650,000 per mi)]. Replacing this section with new pipe would have cost approximately $17.2 million [$656,000 per km ($1.06 million per mi)]. Recoating saved 38 percent over the cost of new pipe.

In 1998, the mainline recoating program eliminated the need for an estimated 28 digs. With an average estimated dig and repair cost of $50,000, the program produced a cost-savings of $1.4 million. In addition, rehabilitation was credited for reducing the overall maintenance cost of future pigging, hydrostatic testing, corrosion monitoring, and SCC investigations (not included in the cost calculations).

Table 4. Economic summary of TCPL's mainline recoating program.

YEAR	LENGTH RECOATED	PIPE DIAMETER	TOTAL COST*	COST
	(mi)	(in)	($ x thousand)	(per mi)
1996	1	34	804	$804,000
1997	9	34	5,829	$647,667
1998	16.3	34	10,586	$649,448
1999	19.3	42	16,415	$850,518

*The amounts in this table are in U.S. dollars; the conversion rate used was: U.S. $ = 0.67 x CAN$

1 in = 25.4 mm, 1 mi = 1.61 km

1994 - 1997 Replacement/Rehabilitation Studies in the United Arab Emirates (UAE)

Abu Dhabi National Oil Company of U.A.E. conducted a detailed comparison of the cost of rehabilitating an existing 610-mm- (24-in-) diameter oil pipeline and converting it to condensate service versus replacing it with a new 457-mm- (18-in-) diameter condensate line.(17) The analysis quantified the hidden costs of using older pipelines, primarily due to higher leakage risk, extra inspections, and higher maintenance costs. These costs were somewhat offset by lower pump costs for the larger diameter rehabilitated pipeline. Taking this into account, the rehabilitated pipeline was only 59 percent of the cost of the new pipeline. If the savings in pump costs were not counted, the cost of the rehabilitated pipeline was estimated to be 81 percent of the new pipeline costs; therefore, operational cost adjustments are critical to the analysis.

In a second project, the costs associated with installing a new 914-mm- (36-in-) diameter pipeline versus rehabilitation of two existing main oil lines were compared. It is important to note that operational costs over a 30-year service life were included. The cost of rehabilitation of the two existing pipelines was 76 percent of the cost of replacement with one large-diameter pipeline; however, it was decided to construct a new pipeline for the following reasons:

- The risks of rehabilitating in-service pipelines require either complete shutdown of the pipeline or the use of hot taps and stopples. This measure creates numerous dead-leg branches with higher leakage risks.
- More than 700 clamps and sleeves could not be reliably inspected by ILI tools. There is a high risk of leaks from these old clamps and sleeves.

- Rehabilitation of the old pipelines would have taken a long time due to terrain.
- Environmental conditions (wind, dust, humidity) would have compromised coating application.
- Installation of a new, larger diameter main oil line yielded greater operational flexibility.

East Coast (U.S.) Oil Pipeline

A major pipeline company estimated that rehabilitation costs generally are 40 percent to 80 percent of the cost of a new pipeline, depending on terrain, location, old/new coating type, length of pipe to be rehabilitated, and pipe diameter. The cost for rehabilitation was given as $577,000 to $1,650,000 per km ($924,000 to $2,640,000 per mi).(18) These rehabilitation costs do not account for repair of pipeline defects.

Transcontinental Gas Pipe Line Corp. (Transco USA)

Transco USA has had a recoating program since the early 1970s. For a 610-mm- (24-in-) diameter pipeline, a field-applied double-wrap polyethylene tape coating system was utilized. Although the cost-savings of rehabilitation were not available, the cost of recoating was estimated to be 15 percent of the rehabilitation project.(19) The recoating costs were $98,000 per km ($158,000 per mi), giving a total rehabilitation cost of $0.652 million per km ($1.05 million per mi).

Cost of Replacement Versus Rehabilitation

As discussed previously, several considerations can affect the economics of replacement versus rehabilitation. As pointed out by multiple sources, the number of repairs made to the pipeline can make the difference between the cost-effectiveness of rehabilitation versus the cost-effectiveness of replacement. In addition, operational costs, projected life, throughput requirements, and projected leak risks all play a role in the final decision. It is clear that the unique conditions of each pipeline must be considered individually. Rehabilitation of existing pipelines can be 60 percent of replacement costs, resulting in a significant cost-savings for rehabilitation versus replacement.

Corrosion-Related Failures

Introduction

If corrosion is permitted to continue unabated, the integrity of a pipeline will eventually be compromised. In other words, the pipeline will fail. Depending on the flaw size, the pipeline material properties, and the pipeline pressure, failure refers to either a leak or a rupture.

Typically, rupture of a high-pressure natural gas pipeline results in the sufficient release of stored energy (compressed gas) that the pipeline is blown out of the ground. A leak results when a flaw penetrates the pipe wall, but is not of sufficient size to cause a rupture. Typically, leaks on natural gas pipelines are detected by either periodic inspections or third party reporting and are repaired without significant incident; however, leaks can result in problems that are more substantial if they are not detected promptly. Natural gas leaks, for instance, can fill enclosed or confined spaces and, if an ignition source is present, explosions and/or fires can result, causing substantial property damage and possible injuries or deaths. For natural gas leaks or ruptures, the immediate environmental impact is minimal.

A liquid (non-compressible) pipeline has less stored energy than a natural gas pipeline; therefore, a rupture does not immediately result in a major explosion. However, once leaked out into the environment, a major explosion can occur upon ignition of an explosive liquid product. For a hazardous liquid product pipeline, the environmental impact can be as significant as the risk of an explosion. The risk of an oil leak from the TransAlaskan pipeline, for example, has continued to be the primary driver for the aggressive corrosion prevention and inspection program maintained by the operator. Of major concern is the risk of product leakage into surface waters, thereby, contaminating water supplies.

The costs associated with corrosion-induced pipeline failures can be divided into the following seven categories: (1) loss of product, (2) property damage, (3) personal injury or death, (4) clean-up of product (hazardous liquid pipelines), (5) pipeline repair and back-to-service program, (6) legal, and (7) loss in throughput. To prevent failures, an aggressive maintenance and integrity program is necessary.

Pipeline Safety

In a recent report by the U.S. General Accounting Office entitled *Pipeline Safety*, the history of pipeline safety is reviewed.(2) Compared to other forms of transportation, pipelines are inherently safer; however, pipeline accidents can have serious consequences. For example, in June 1999, a pipeline rupture in Bellingham, WA, spilled approximately 946,000 L (250,000 gal) of gasoline into a creek. When the gasoline ignited, three people were killed, eight more were injured, several buildings were damaged, and the banks of the creek were destroyed along a 2.4-km (1.5-mi) section. In July 2000, a natural gas pipeline ruptured in Carlsbad, NM. When the gas ignited, 12 people were killed.

Figures 11 through 15 give statistics on major pipeline accidents and injuries between 1989 and 1998.(2) A "major" accident (the term "incident" is typically used for natural gas pipelines and the term "accident" is typically used for hazardous liquid pipelines; "accident" will be used in this discussion) is defined as one that results in a fatality, injury, or $50,000 or more in property damage. Accidents are reported to the Office of Pipeline Safety (OPS). Property damage includes all costs of the failure (i.e., lost product, repair costs, and third party damage). Other accidents that are required to be reported to OPS, but are not defined here as "major," include events that require emergency shutdown of a liquefied natural gas facility and any event concerning a hazardous liquid pipeline that results in an explosion or fire, or the release of 50 or more barrels of hazardous liquid (or carbon dioxide), or the escape into the atmosphere of more than five barrels per day of highly volatile liquids. Over the past 10 years, a larger number of accidents have occurred on distribution natural gas pipelines than for either natural gas transmission pipelines or hazardous liquid pipelines (see figure 11). Distribution piping, however, has the lowest average number of accidents per 16,000 km (10,000 mi) of pipe, and hazardous liquid pipelines have the highest average number of accidents (see figure 12).

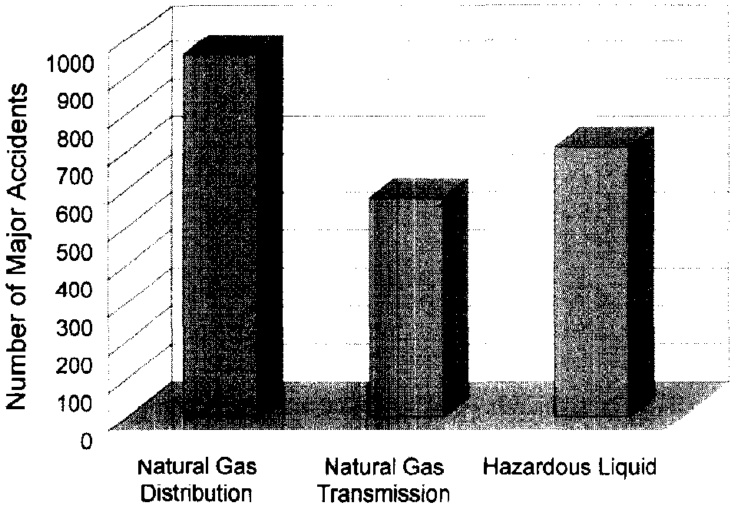


Figure 11. Number of major accidents between 1989 and 1998 for each major pipeline category.

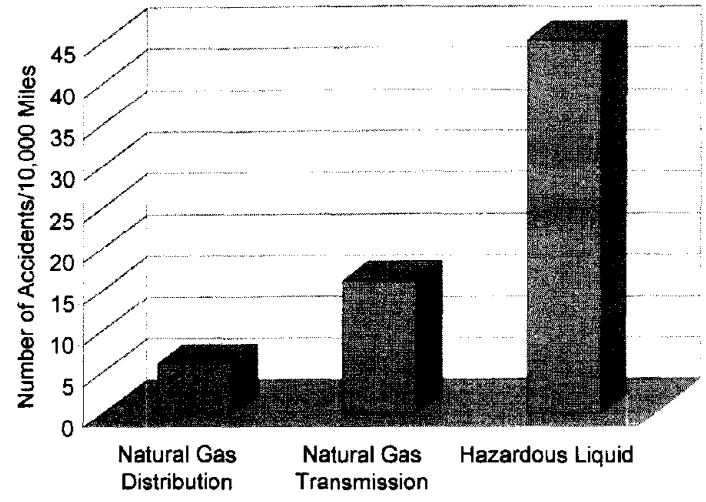


Figure 12. Average number of major accidents per 16,000 km (10,000 mi) of pipeline between 1989 and 1998 for each major pipeline category.

Natural gas distribution pipelines accounted for 77 percent and 72 percent of all of the fatalities and injuries, respectively, between 1989 and 1998 (see figures 13 and 14). Figure 15 shows the amount in dollars associated with property damage from these accidents between 1989 and 1998. Approximately 50 percent of the property damage was caused by accidents on hazardous liquid pipelines. For the accidents reported to OPS, 1.53 million barrels of hazardous liquids were spilled into the environment. In addition to the accidents reported to OPS, the Environmental Protection Agency (EPA) estimated that 16,000 spills of fewer than 50 barrels occurred between 1989 and 1998 (1,600 annually) for oil pipelines in which the spill could cause pollution of navigable waters.

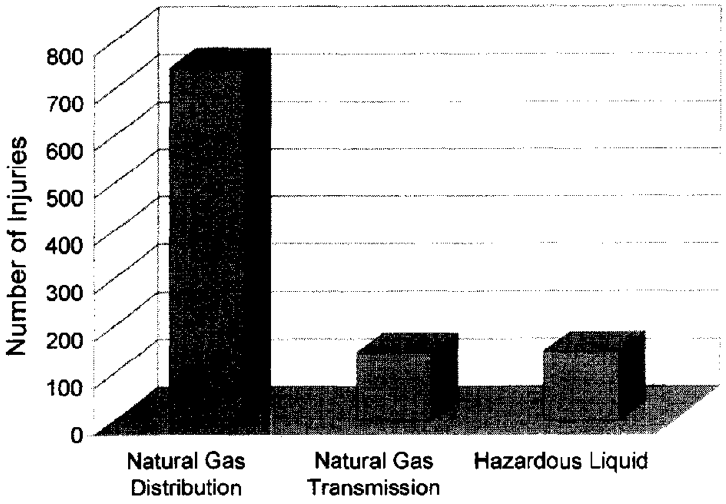


Figure 13. Number of injuries between 1989 and 1998 due to major accidents for each major pipeline category.

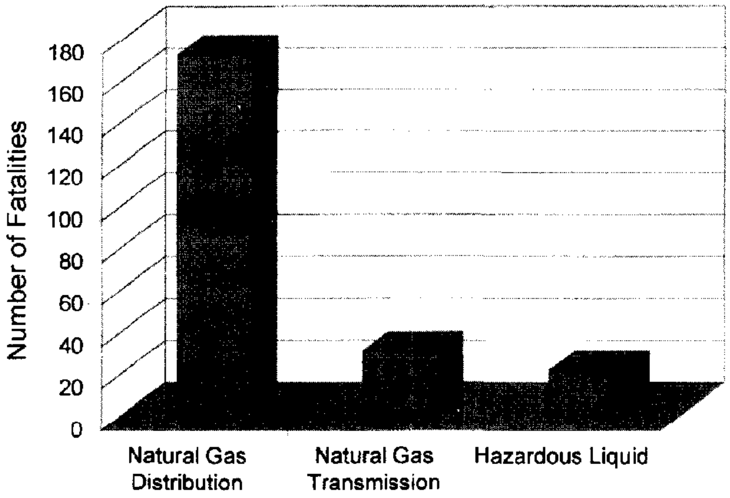


Figure 14. Number of fatalities between 1989 and 1998 due to major accidents for each major pipeline category.

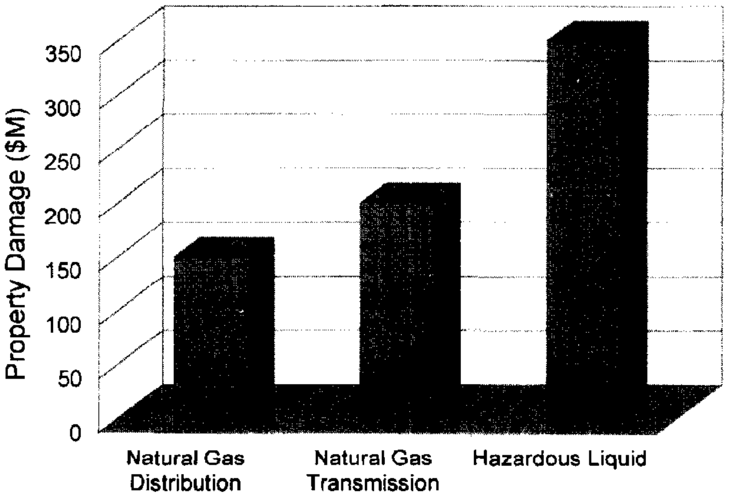


Figure 15. Property damage between 1989 and 1998 due to major accidents for each major pipeline category.

Cost of Corrosion Failures

For this study, it is important to examine the accidents caused by corrosion. For reporting purposes, a distinction is typically made between external and internal corrosion. In addition, it is likely that corrosion contributed to some of the accidents listed as "other." In fact, a review of the detailed reports indicates that corrosion is described in the report for only a small percentage of the accidents reported as "other" cause. For this review, only those accidents listed as caused by corrosion are included below.

Corrosion-Related Failures

Table 5 provides a summary of the major accidents reported to the U.S. Department of Transportation by the operators for the 6-year period between 1994 and 1999.$^{(20)}$ The data show that for transmission pipeline systems (both hazardous liquid and natural gas), approximately 25 percent of all reported accidents were due to corrosion (see table 5). Of the hazardous liquid pipeline accidents caused by corrosion, 65 percent were due to external corrosion and 34 percent were due to internal corrosion. For natural gas transmission pipeline accidents, conversely, 36 percent were caused by external corrosion and 63 percent were caused by internal corrosion. For natural gas distribution pipeline accidents (see Appendix J of this report), only approximately 4 percent of the total accidents were caused by corrosion, and the majority of those were caused by external corrosion.

Table 5. Summary of corrosion-related accident reports on hazardous liquid, natural gas transmission, and natural gas distribution pipelines from 1994 to 1999.

	HAZARDOUS LIQUID TRANSMISSION	NATURAL GAS TRANSMISSION	NATURAL GAS DISTRIBUTION
Total Accidents Due to Corrosion Accidents (1994–1999)	271	114	26
Total Accidents (1994–1999)	1,116	448	708
Percent of Total Accidents Due to Corrosion	24.3%	25.4%	3.7%
Percent of Corrosion Accidents Due to External Corrosion	64.9%	36.0%	84.6%
Percent of Corrosion Accidents Due to Internal Corrosion	33.6%	63.2%	3.8%
Percent of Corrosion Accidents Cause Not Specified	1.5%	0.9%	11.5%

In a summary report for incidents between 1985 and 1994, corrosion accounted for 28.5 percent of pipeline incidents on natural gas transmission and gathering pipelines.(21) In a summary report for incidents between 1986 and 1996, corrosion accounted for 25.1 percent of pipeline incidents on hazardous liquid pipelines.(22) These values correspond very well to the statistics for 1994 to 1999 presented in table 5.

Recall that the accidents reported in table 5 are for major accidents that resulted in injury, fatality, or more than $50,000 in property damage. In addition to the reportable accidents, an average of 8,000 corrosion leaks per year are repaired on natural gas transmission pipelines(23) and 1,600 spills per year are repaired and cleaned up for liquid product pipelines.

Property Damage

Table 6 summarizes the property damage due to the reported accidents for the three pipeline categories. The reported property damage includes all direct costs of the accident (lost gas, repair, etc.). For hazardous liquid and natural gas transmission pipelines, the percentage of the total damages due to corrosion were 19 percent and 15 percent, respectively. Combining table 5 and table 6 gives an average property damage due to corrosion for hazardous liquid pipelines of $192,300 per accident and for natural gas transmission of $169,500 per accident (incident).

Table 6. Summary of property damage due to corrosion-related accidents on hazardous liquid, natural gas transmission, and natural gas distribution pipelines from 1994 to 1999.

	HAZARDOUS LIQUID TRANSMISSION	NATURAL GAS TRANSMISSION	NATURAL GAS DISTRIBUTION
Total Property Damage Due to Corrosion Accidents (1994–1999) ($ x thousand)	$52,115	$19,326	$4,923
Total Property Damage Due to All Accidents (1994-1999) ($ x thousand)	$279,270	$127,727	$137,925
Percent of Total Property Damage Due to Corrosion Accidents	18.7%	15.1%	3.6%
Percent of Property Damage From Corrosion Accidents Due to External Corrosion	56.0%	42.2%	84.8%
Percent of Property Damage From Corrosion Accidents Due to Internal Corrosion	40.1%	57.8%	1.4%
Percent of Property Damage From Corrosion Accidents Cause Not Specified	3.9%	0.0%	13.8%

Loss of Throughput

The cost to the pipeline operator, producer, and refinery/user of loss of throughput is not included in the property damage. Making the following assumptions permits a cost for loss of throughput to be estimated:

- 5,520 kPag (800 psig) for either liquid or natural gas.
- Liquid pipeline:
  406-mm- (16-in-) diameter pipeline.
  128,000 barrels per day throughput.(24)
- Natural gas pipeline:
  610-mm- (24-in-) diameter pipeline.
  8 million m^3 [287 million ft^3 (Mcf)] per day throughput.(24)

Furthermore, it is assumed that for the major accidents reported, the average time to return to service is 1 to 2 days. For those accidents involving injuries, fatalities, or major environmental damage, the loss of throughput could be weeks or months and could require major integrity inspection of the entire pipeline; for other pipelines, which have parallel or looped lines, the loss of throughput may be minimal. For liquid lines, the estimated loss of throughput is 128,000 to 256,000 barrels. The cost of loss of throughput to the pipeline operator, producer, and refinery/user is assumed to be 50 percent of the cost of the product or $9 per barrel [it is estimated that the average cost of the product (oil and refined product) in 1998 was $18 per barrel of product];(25) therefore, the average cost of loss of throughput for a hazardous liquid transmission pipeline accident is between $1.15 million and $2.30 million.

A similar analysis for natural gas pipelines gives a loss of product of between 8 million and 16 million m^3 (287 Mcf and 574 Mcf). At a cost of $71.50 per thousand m^3 ($2 per thousand ft^3)(26) and the assumption that the cost of loss of throughput is 50 percent of the product cost, the average cost of loss of throughput for a natural gas transmission pipeline incident is between $287,000 and $574,000.

Fatalities and Injuries

Tables 7 and 8 summarize the fatalities and the injuries caused by pipeline accidents, respectively. In the 6 years between 1994 and 1999, two fatalities from hazardous liquid transmission pipelines occurred. The four fatalities caused by corrosion-related accidents occurred on natural gas distribution pipelines. Only five injuries occurred on transmission pipelines (liquid and natural gas) as compared to 16 injuries on natural gas distribution pipelines.

Table 7. Summary of fatalities due to corrosion-related accidents on hazardous liquid, natural gas transmission, and natural gas distribution pipelines from 1994 to 1999.

	HAZARDOUS LIQUID TRANSMISSION	NATURAL GAS TRANSMISSION	NATURAL GAS DISTRIBUTION
Total Fatalities Due to Corrosion Accidents (1994-1999)	2*	0	4
Total Fatalities (1994-1999)	15	7	130

*Two fatalities from a 1996 liquid pipeline failure not reported in reference.

Table 8. Summary of injuries due to corrosion-related accidents on hazardous liquid, natural gas transmission, and natural gas distribution pipelines from 1994 to 1999.

	HAZARDOUS LIQUID TRANSMISSION	NATURAL GAS TRANSMISSION	NATURAL GAS DISTRIBUTION
Total Injuries Due to Corrosion Accidents (1994-1999)	2	3	16
Total Injuries (1994-1999)	62	61	460

During the period from 1985 to 1994, the corrosion-related accidents on natural gas transmission pipelines resulted in 5 fatalities and 10 injuries.(21) All five fatalities occurred in one accident in 1985. From 1986 through 1999, there were no fatalities from corrosion-related accidents on natural gas transmission pipelines; however, in 2000, a single accident, caused by internal corrosion, resulted in 12 fatalities. From 1986 to 1996, corrosion-related accidents on hazardous liquid pipelines resulted in three fatalities and three injuries.(22) Therefore, on average, it is estimated that there is approximately one fatality and one injury per year on transmission pipelines.

Summary of Costs Due to Corrosion Failures

A summary of the average annual cost for natural gas (NG) and hazardous liquid (HL) transmission pipeline accidents is given in table 9. The fatality, injury, and "added legal" costs are all estimates based on discussions with industry experts. For these costs, high and low estimates are provided. The cost of hazardous liquid spills or natural gas leaks varies depending on the severity of the leak and the repair method selected.(14) Table 10 provides a range of costs for repair options. For estimating the cost of non-reportable leaks and spills, the pipe replacement costs are not utilized since this would place the accident in a reportable category (greater than $50,000). In addition, there is a clean-up cost associated with the hazardous liquid spills. Because of the range for these estimates, the total annual cost of corrosion-related accidents (including non-reportable leaks and spills) ranges from $471 million to $875 million.

Table 9. Summary of annual cost for corrosion-related transmission pipeline failures.

	DESCRIPTION	LOW ESTIMATE ($ x thousand)	HIGH ESTIMATE ($ x thousand)
Fatalities	One fatality per year (NG and HL combined) @ $1,000,000 to $4,000,000 per occurrence	1,000	4,000
Injuries	One injury per year (NG and HL combined) @ $500,000 to $1,000,000 per occurrence	500	1,000
Added Legal	Legal issues and liability (civil and punitive) @ $100,000,000 to $200,000,000 per fatality and injury (2)	200,000	400,000
Property Damage – HL	45 HL accidents/year @ $192,300 per occurrence	8,654	8,654
Property Damage – NG	19 NG accidents/year @ $169,500 per occurrence	3,220	3,220
Loss of Throughput – HL	45 HL accidents/year @ $1.15 million to $2.3 million per occurrence	51,750	103,500
Loss of Throughput – NG	19 NG accidents/year @ $287,000 to $574,000 per occurrence	5,453	10,906
Non-Reportable HL Spills	1,600 oil spills/year (HL) of less than 50 barrels @ $25,000 to $40,000 per occurrence	40,000	64,000
Non-Reportable NG Leaks	8,000 leaks/year (NG) @ $20,000 to $35,000 per occurrence	160,000	280,000
TOTAL ANNUAL COST OF CORROSION-RELATED PIPELINE FAILURES		**$470,577**	**$875,280**

NG – Natural Gas; HL – Hazardous Liquid.

Table 10. Cost comparison of composite sleeve, full-encirclement steel sleeve, and pipe replacement repair techniques.

	COMPOSITE SLEEVE	STEEL SLEEVE	10-FT PIPE REPLACEMENT
Material Cost	$1,000	$1,600	$500
Labor Cost	$11,000	$16,500	$30,000
Gas Loss*	$0	$0	$19,000
Other Expenses**	$7,000	$7,000	$20,000
TOTAL REPAIR COST	**$19,000**	**$25,100**	**$69,500**

*Gas loss calculated from 16-km section at 5,520 kPag (10-mi section at 800 psig).

**Surveys, permits, inspection services, ROW-related expenses, etc.

Total Cost of Corrosion

The total cost of corrosion is determined by the cost of capital, operations and maintenance (O&M), and the cost of failures (non-related O&M costs). The pipeline rehabilitation and replacement costs are included in the capital costs. The costs presented in table 11 summarize these costs for typical pipeline operations in the 1990s. The total costs are estimated to be $5.40 billion to $8.56 billion annually. Figure 16 gives the percentage breakdown of the total cost of corrosion for the transmission pipeline sector. Operation and maintenance costs are 52 percent of the total costs associated with corrosion.

Table 11. Summary of the total cost of corrosion in the transmission pipeline sector.

	LOW ESTIMATE	HIGH ESTIMATE	AVERAGE	
	($ x million)	($ x million)	($ x million)	(percent)
Cost of Capital	2,500	2,840	2,670	38
Operations and Maintenance (O&M)	2,420	4,840	3,630	52
Cost of Failures (Non-Related O&M)*	471	875	673	10
TOTAL COST DUE TO CORROSION	**$5,391**	**$8,555**	**$6,973**	**100%**

*Non-Related O&M costs include indirect costs associated with fatalities, injuries, loss of throughput, and legal expenses (see table 9).

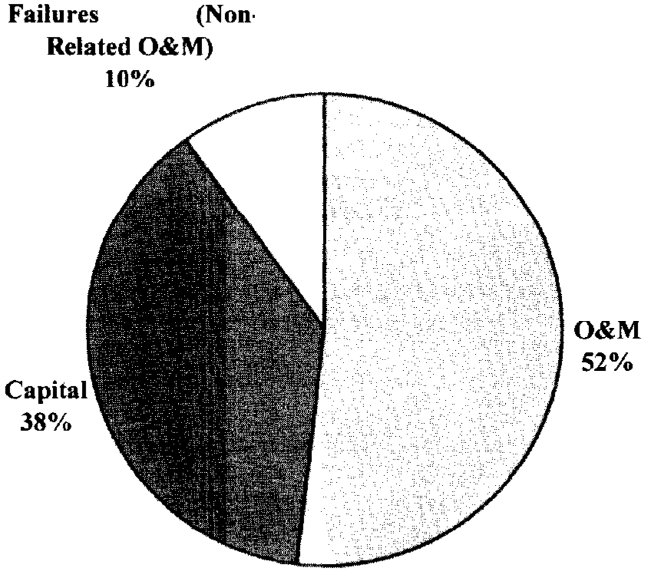


Figure 16. Percentage breakdown of the total cost of corrosion for the transmission pipeline sector.

CORROSION MANAGEMENT

Impact of Federal Regulations

In the future, pipeline operators may be faced with tough challenges due to the aging pipeline infrastructure and the new federal regulations that promote pipeline safety. The key to corrosion management will be to optimize the operational and maintenance costs in the face of a growing demand for pipeline safety. Two areas that will affect pipeline operational costs are pipeline personnel qualification programs and enhanced pipeline inspection programs. In the following paragraphs, the economic impact of these regulations is discussed. The costs associated with these programs are, for the most part, added to the existing programs that the pipeline operator has in place prior to 2000. The costs of these programs can be significant and optimization of the corrosion control program will be critical.

Personnel Qualifications

Table 11 above shows corrosion-related operation and maintenance costs. These costs are expected to change in the upcoming years as new federal regulations are enacted. One such regulation requires specific qualifications for pipeline personnel. While all pipeline operators utilize some form of a corrosion control program, a recent survey indicated that only 30 percent of those surveyed have personnel completely dedicated to corrosion control activities, and only slightly more than half require their corrosion technicians to be certified.(11)

The new regulations require pipeline operators to develop and maintain a written qualification program for individuals performing corrosion-related tasks. The intent of the regulation is to ensure a qualified work force and to reduce the probability and consequences of corrosion-related incidents. It is estimated that the qualification program set-up will cost $210 million, transitional evaluations and qualification assessments will cost $140 million, subsequent evaluations and qualification assessments will cost $87.5 million, and there will be annual costs of $32.4 million. Assuming that there are approximately 175,000 covered pipeline employees, it can be estimated that the initial cost of a qualification program will be $437 million or approximately $2,500 per employee and a very conservative annual cost of only $185 per employee.(27)

Integrity Management

With the aging of North America's pipeline systems and with changing regulations, many operators have implemented integrity management programs involving a combination of monitoring, assessment, mitigation, and life extension, coupled with a risk assessment model. A pipeline integrity management program specifies some or all of the following: an overall CP monitoring and inspection program, intervals and locations for in-line inspection, intervals and locations for hydrostatic testing, intervals and locations for a direct assessment program, safe operating conditions, repair criteria, and prioritization for inspection, re-coating, or repair. Future regulations will probably provide specific requirements for integrity inspections, including required time intervals and permitted methodologies. These integrity inspection programs will be coupled with overall risk management programs to maintain safe operation of the pipeline, provide for public safety, and protect the environment.

The integrity inspection methods that will probably be permitted include in-line inspection (ILI), hydrostatic testing, and direct assessment (see previous discussion in "Inspection of Pipelines"). The primary strengths and weaknesses of the assessment methods are summarized in table 12.

Table 12. Assessment methods summarized.

METHOD	STRENGTH	WEAKNESS
In-Line Inspection	Measures and maps remaining wall thickness.	Single run does not identify active corrosion and the accuracy of multiple run predictions is uncertain. Resolution of tools varies.
Hydrostatic Testing	Causes a controlled hydrostatic rupture of near-critical flaws.	Does not identify the presence or severity of flaws other than critical axial flaws that fail at the pressure tested.
Direct Assessment	Identifies areas of high probability of active corrosion.	Verifies accuracy through dig program, does not provide 100% direct assessment of pipeline.

In the following sections, the costs associated with each inspection methodology are examined. For comparison purposes, it will be assumed that 100 percent of the transmission pipeline system will be inspected by each method. In this manner, a direct comparison of the costs for each method and the overall impact of inspecting all pipelines can be made.

In-Line Inspection Economics and Reliability

The ILI method is the most widely accepted method of inspection of pipelines due to its ability to measure wall thickness with near 100 percent coverage of the pipe inspected. If gathering lines are omitted for the purposes of this discussion, there are approximately 217,000 km (135,000 mi) of liquid pipelines and approximately 483,000 km (300,000 mi) of natural gas pipelines [total of 700,000 km (435,000 mi) of high-pressure transmission pipelines]. Industry discussion has focused on the possibility of ILI for all high-pressure transmission pipelines in the United States. Present regulations are focused on pipelines in "high-consequence areas" (HCAs). The definition of high-consequence pipelines has not yet been agreed upon; however, in general, they would include areas where the consequences of failures are significant because of a high-population density or a great environmental impact. This could include as much as 60 percent of the pipeline system or 420,000 km (261,000 mi) of pipeline.(28)

It has been estimated that 85 percent of the liquid transmission pipelines can be readily inspected using ILI techniques. For natural gas transmission pipelines, only 30 percent can be readily inspected by ILI; another 25 percent can be converted for ILI; 43 percent would be difficult to convert for ILI, and 2 percent cannot be inspected by ILI. It is estimated that so far only 30 percent of the pipelines in the United States have been inspected by ILI.(29)

Pipeline Preparation for ILI

The cost to prepare a pipeline for inspection can vary greatly depending on the condition, the age, the location, etc. of the pipeline. Modifications and preparations for existing pipelines to permit ILI include the following:

- ILI tool launchers and receivers must be added to the pipeline. The costs of modifying a pipeline for a launcher/receiver combination can range from \$80,000 to \$100,000.(30)
- Caliper tools are run to identify restrictions and bend the radius of the pipe prior to the ILI tool to ensure that the pipeline is free from defects that could cause the ILI tool to be stuck or damaged. The cost of running the caliper tool is \$620 to \$810 per km (\$1,000 to \$1,300 per mi).(31)
- Clearing bends or other restrictions (i.e., reduced opening in valves) requires digging out the pipeline and replacing the problem valve or pipe section. It is estimated that replacement of an obstruction, including the cost of loss of throughput, can range from \$50,000 to \$250,000 (with the high cost being the replacement of a valve).(32)
- Cleaning the pipeline is required prior to ILI with either magnetic flux leakage (MFL) or ultrasonic testing (UT); however, the UT tool requires a cleaner pipe. The cost of mechanical cleaning (scraper tools) was estimated at \$270 per km (\$430 per mi). Chemical cleaning is significantly more expensive at \$2,220 per km (\$3,570 per mi) for the same line.(33) On average, it is assumed that the cost for cleaning natural gas pipelines is \$310 per km (\$500 per mi) (very little chemical cleaning is required). For liquid pipelines, it is assumed that 35 percent are chemically cleaned and 65 percent are mechanically cleaned (approximate split between crude oil and refined product pipelines), giving an average cleaning cost of \$1,550 per km (\$2,500 per mi).

The following provides a minimum cost of preparing a pipeline for ILI. The cost of the caliper tool is \$620 to \$810 per km (\$1,000 to \$1,300 per mi). Typically, launchers and receivers are required for every 160 km (100 mi) of pipeline, giving an average cost of \$500 to \$620 per km (\$800 to \$1,000 per mi). Clearing of restrictions will vary greatly; however, assuming a minimum of one obstruction per 16 km (10 mi) of pipeline gives a cost of \$3,100 to \$15,500 per km (\$5,000 to \$25,000 per mi). The overall estimated minimum cost for preparing a pipeline for ILI ranges from \$4,200 to \$16,900 per km (\$6,800 to \$27,300 per mi) of pipeline.

A natural gas company estimated the cost of converting their system to ILI to be $300 million for 16,100 km (10,000 mi) of pipeline, or $18,600 per km ($30,000 per mi).(29) This value is reasonable based on the costs provided above for preparing launchers and receivers, clearing bends, etc. In fact, the cost per km for preparing a pipeline with multiple bends and obstructions per mile of pipeline can potentially be much greater than the $18,600 per km ($30,000 per mi).

Cost of ILI

The cost of performing ILI includes the cost of cleaning (see above) plus the cost of the ILI. The cost for ILI ranges from $1,250 to $1,850 per km ($2,000 to $3,000 per mi) for the MFL and $1,250 to $2,500 per km ($2,000 to $4,000 per mi) for UT.(34) Taking an average for the two methods gives a cost for ILI between $1,250 and $2,150 ($2,000 and $3,500 per mi).

This does not include the inter-company cost of manpower and labor for planning, bid and selection of contractor, overseeing, and reporting. It is estimated that 20 person-days are required for this, giving an overall cost of $10,000 for a typical ILI run of 160 km (100 mi) or $62 per km ($100 per mi).(35)

For ILI, the pipeline typically has minimal downtime such that the loss of throughput is negligible for liquid lines, i.e., the velocity of liquid flow [2.5 to 3.1 km per hour (4 to 5 mi per hour)] is the same as the ILI tool. For natural gas pipelines, the estimated flow though a 610-mm- (24-in-) diameter pipeline at 5,520 kPag (800 psig) is 8.75 km per hour (14 mi per hour). The lower velocities during the ILI operation [3.1 km per hour (5 mi per hour)] decreases the throughput by the difference in the velocities. If the velocity is decreased by 64 percent, then the throughput is decreased by 64 percent. In our "typical" pipeline, the normal throughput is 340,000 m^3 per hour (12 million ft^3 per hour).(24) A 64 percent loss corresponds to a loss of 217,500 m^3 (7.68 Mcf) per hour. At a speed of 3.1 km per hour (5 mi per hour) and a loss of throughput of 217,500 m^3 (7.68 Mcf) per hour, the loss of throughput corresponds to an average of 43,000 m^3 (1.54 Mcf) per mile of pipe inspected. Due to prior planning, the indirect cost of loss of throughput (pipeline operator, producer, and user) is estimated to be 20 percent to 40 percent of the cost of the product. At $71.50 per thousand m^3 ($2 per thousand ft^3) the loss of throughput is estimated to be $375 to $750 per km ($600 to $1,200 per mi) of natural gas transmission pipeline inspected.

Table 13 summarizes the ILI cost for inspection of all transmission pipelines. The cost of ILI for natural gas versus hazardous liquid pipelines is different primarily due to the different costs for cleaning and loss of throughput. The range of costs for ILI of natural gas pipelines is $2,000 to $3,300 per km ($3,200 to $5,300 per mi). The range of costs for ILI of hazardous liquid pipelines is $2,850 to $3,800 per km ($4,600 to $6,100 per mi).

Table 13. Summary of ILI costs for inspection of transmission pipelines.

PIPELINE	**COST OF ILI FOR NATURAL GAS PIPELINES**		**COST OF ILI FOR LIQUID PIPELINES**		**TOTAL COST FOR ALL PIPELINES**	
	Low Estimate ($ per mi)	**High Estimate ($ per mi)**	**Low Estimate ($ per mi)**	**High Estimate ($ per mi)**	**Low Estimate ($ x million)**	**High Estimate ($ x million)**
Cleaning	500	500	2,500	2,500	488	488
Inspection	2,000	3,500	2,000	3,500	870	1,522
Operator Oversight	100	100	100	100	44	44
Loss of Throughput	600	1,200	0	0	180	360
TOTALS	**$3,200**	**$5,300**	**$4,600**	**$6,100**	**$1,582**	**$2,414**

1 mi – 1.61 km

Note: Assumes 483,000 km (300,000 mi) and 217,000 km (135,000 mi) of natural gas and hazardous liquid transmission pipelines, respectively.

Cost of ILI for All Pipelines

The analysis assumes the following:

- ILI cost for natural gas pipelines is \$2,000 to \$3,300 per km (\$3,200 to \$5,300 per mi).
- ILI cost for hazardous liquid pipelines is \$2,850 to \$3,800 per km (\$4,600 to \$6,100 per mi).
- Preparation of "readily inspected" pipelines is \$4,200 to \$16,900 per km (\$6,800 to \$27,300 per mi).
- Preparation for "possible to convert" pipelines is \$15,500 to \$46,600 per km (\$25,000 to \$75,000 per mi).
- Preparation for "difficult to convert" pipelines is \$46,600 to \$155,000 per km (\$75,000 to \$250,000 per mi).(36)
- 30 percent of both natural gas and liquid pipelines have been inspected by ILI.

Table 14 gives the estimate for the cost of preparing all pipelines for ILI. It was assumed that 30 percent of each natural gas and liquid pipeline system has been previously inspected and that the remaining pipes fall into the categories given above (and in table 14). For example, 30 percent of the total miles of liquid pipelines were previously inspected, of the remaining 70 percent, 85 percent is "readily inspected," 7 percent is "possible to convert," 7 percent is "difficult to convert," and 1 percent "cannot be inspected" by ILI. Summing the natural gas and liquid pipelines gives a total cost for preparing all pipelines for ILI of \$9.72 billion to \$32.58 billion.

Table 14. Summary of ILI costs for preparation.

PIPELINE	**Cost of Preparation For ILI**		**Natural Gas Pipelines**	**Liquid Pipelines**	**Cost of Preparation for ILI for Natural Gas Pipelines**		**Cost of Preparation for ILI for Liquid Pipelines**	
	Low Estimate	**High Estimate**			**Low Estimate**	**High Estimate**	**Low Estimate**	**High Estimate**
	(\$ per mi)	**(\$ per mi)**	**(mi)**	**(mi)**	**(\$ x million)**	**(\$ x million)**	**(\$ x million)**	**(\$ x million)**
Previously Inspected	0	0	90,000	40,500	0	0	0	0
Readily Inspected	6,800	27,300	63,000	80,325	428	1,720	546	2,193
Possible to Convert	25,000	75,000	52,500	6,615	1,312	3,938	165	496
Difficult to Convert	75,000	250,000	90,300	6,615	6,772	22,575	496	1,654
Cannot Be Inspected	0	0	4,200	945	0	0	0	0
Totals			**300,000**	**135,000**	**\$8,512**	**\$28,233**	**\$1,207**	**\$4,343**

1 mi = 1.61 km

The total cost for performing the inspection for all transmission pipelines by ILI is estimated in table 13 to be \$1.58 billion to \$2.41 billion. Therefore, the first-time cost of ILI for all pipelines is \$11.3 billion to \$35.0 billion (cost of preparation plus the cost of inspection). Afterwards, the cost for subsequent ILI is \$1.58 billion to \$2.4 billion. Typical inspection times are 5 to 7 years. Therefore, the annual cost for the first 5 to 7 years is \$1.61 billion (\$11.3 billion divided by 7 years) to \$7.00 billion (\$35.0 billion divided by 5 years); subsequent years would be \$226 million (\$1.58 billion divided by 7 years) to \$482 million (\$2.41 billion divided by 5 years).

Reliability of ILI

The reliability of ILI tools can be evaluated through three performance characteristics: detection, discrimination, and sizing. The first measure is the ability of the tool to detect an anomaly. In the case of MFL tools, it is the ability to detect a magnetic anomaly in the pipe. Once an anomaly is detected, the ability to discriminate between different types of defects is critical. For example, UT tools are capable of detecting mid-wall laminations, which are not typically a concern. However, it is important to be able to discriminate between mid-wall laminations and corrosion-caused metal loss that could pose a potential integrity concern. Lastly, once an area of corrosion has been detected and classified, the data are used to determine the severity of the corrosion, namely, the depth of the wall loss and the axial and circumferential extent.

The high-resolution ILI tools are readily capable of detecting and discriminating corrosion. Typically, the ability to detect corrosion anomalies with a diameter less than three times the wall thickness is more difficult. Once the corrosion exceeds these dimensions, the ILI tools are more capable of detecting and sizing corrosion anomalies. Typically, ILI tools (both MFL and UT) are capable of sizing corrosion within ±10 percent of the pipe wall thickness with an 80 percent level of confidence.

Hydrostatic Testing Economics and Reliability

A strength of hydrostatic testing is that if a near critical axial flaw exists in the pipeline, it will fail during hydrostatic testing; however, hydrostatic testing provides no information on the condition of the pipeline other than for those flaws that fail during the test and it provides minimal levels of increased safety for most circumferentially oriented flaws. If corrosion rates or stress corrosion cracking (SCC) propagation rates are known, minimum times between hydrostatic tests can be calculated to have a high confidence that no service failures will occur prior to the next retest. Certain types of cracks cannot be detected with confidence by present ILI technology, leaving hydrostatic testing as the only reliable inspection method to ensure integrity when such cracks are known to exist. In addition, upon initial start-up or as part of a return-to-service program, hydrostatic testing may be required. In the following analysis, and as a comparison to ILI and direct assessment, it is assumed that all transmission pipelines will be hydrostatically tested.

Pipeline Preparation for Hydrostatic Testing

There is some preparation required to hydrostatically test a pipeline. This typically involves isolating a section of the pipeline to be tested. A typical hydrostatic test segment is 32 to 64 km (20 to 40 mi). It is assumed that the cost to prepare a pipeline is $50,000 to $100,000 per segment. This gives a preparation cost range of $775 to $3,100 per km ($1,250 to $5,000 per mi).(37)

Cost of Hydrostatic Testing

The cost of hydrostatic testing is divided into two categories: (1) the actual cost of testing and (2) the loss of throughput. It is estimated that the cost of hydrostatic testing is $1,240 per km ($2,000 per mi).(38) These costs include water handling and all testing costs.

The loss of throughput for hydrostatic testing is much more than that for ILI. A typical hydrostatic test takes 6 to 10 days to retest a 160-km (100-mi) section from the time the line is taken out of service until it isplaced back into service. This assumes multiple crews to keep downtime to a minimum. Making the following assumptions permits a cost of loss of throughput to be estimated (these are the same assumptions made for the analyses of pipeline failures and ILI costs):

- 5,520 kPag (800 psig) for either liquid or natural gas.

- Liquid pipeline:
  406-mm- (16-in-) diameter pipeline.
  128,000 barrels per day of throughput.(24)
- Natural gas pipeline:
  610-mm- (24-in-) diameter pipeline.
  8 million m^3 (287 Mcf) per day of throughput.(24)

Six to ten days of loss of throughput are equivalent to 48 million to 80 million m^3 (1,722 to 2,870 Mcf) for the natural gas pipeline and 768,000 to 1,280,000 barrels for the hazardous liquid pipeline. Making the assumption that the indirect cost in loss of throughput to the pipeline operator, producer, and refinery/user is 20 percent to 40 percent of the cost of the product $71.50 per thousand m^3 ($2 per thousand ft^3) for natural gas and $18 per barrel for the liquid product, the range of cost for loss of throughput is $689,000 to $2,296,000 for 160 km (100 mi) of natural gas pipeline and $2,765,000 to $9,216,000 for 160 km (100 mi) of hazardous liquid pipeline. This is $4,300 to $14,300 per km ($6,890 to $22,960 per mi) for natural gas pipelines and $17,200 to $57,300 per km ($27,650 to $92,160 per mi) for hazardous liquid pipelines.

Table 15 summarizes the costs for hydrostatic testing. The cost of the loss of throughput is by far the largest cost associated with hydrostatic testing. The total cost for hydrostatic testing of all pipelines would be between $7.21 billion and $22.37 billion for the first time. Because the preparation costs are relatively small, the cost of subsequent testing is only marginally less at $6.67 billion to $20.20 billion. It is obvious that operators that utilize hydrostatic testing on a regular basis must have other parallel pipelines or the pipelines are looped to reduce the cost of loss of throughput.

Table 15. Summary of hydrostatic testing costs.

ACTIVITY	**COST OF HYDROSTATIC TESTING FOR NATURAL GAS PIPELINES**		**COST OF HYDROSTATIC TESTING FOR LIQUID PIPELINES**		**TOTAL COST FOR ALL PIPELINES**	
	Low Estimate	**High Estimate**	**Low Estimate**	**High Estimate**	**Low Estimate**	**High Estimate**
	($ per mi)	**($ per mi)**	**($ per mi)**	**($ per mi)**	**($ x million)**	**($ x million)**
Preparation	1,250	5,000	1,250	5,000	544	2,175
Inspection	2,000	2,000	2,000	2,000	870	870
Loss of Throughput	6,890	22,960	27,650	92,160	5,800	19,330
TOTALS					**$7,214**	**$22,375**

Note: Assumes 483,000 km (300,000 mi) and 217,000 km (135,000 mi) of natural gas and hazardous liquid transmission pipelines, respectively. 1 mi = 1.61 km

Reliability of Hydrostatic Testing

Hydrostatic testing is 100 percent reliable at removing all axially orientated flaws that are critical at or below a stress level corresponding to the pre-selected hydrostatic re-test pressure. Hydrostatic re-testing, however, has limited capabilities for removing circumferentially orientated flaws and short deep axial flaws that would be expected to leak rather than rupture in service.

Direct Assessment Economics and Reliability

"Direct assessment" is a systematic combination of existing proven monitoring methods with risk modeling to ensure pipeline integrity. A company that does minimum preventive monitoring may require an extensive exploratory dig program to assess whether or not the pipeline meets integrity standards, while a company with a regular monitoring program (close interval surveys, etc.) may require a smaller exploratory dig program to ensure integrity. Direct assessment is applicable to both external and internal corrosion and mechanical damage.

Pipeline Preparation for Direct Assessment

There is no pipeline preparation required for direct assessment. The methods employed are, for the most part, conventional methods employed by pipeline operators.

Cost of Direct Assessment

There is typically no product interruption; however, a lowering of pressure is typical during the exploratory dig. Therefore, there is loss of product depending on the pressures specified by company procedures.

The cost of direct assessment is dependent on the standard in-house practices of the individual operator. The following assumptions are made:

- $620 per km ($1,000 per mi) for detailed monitoring and diagnostic testing.
- Exploratory digs every 3.2 to 8 km (2 to 5 mi) at $5,000 to $10,000 per dig.

It is estimated that the cost of direct assessment is $1,250 to $3,100 per km ($2,000 to $6,000 per mi) of pipeline. This gives a total cost for direct assessment of all transmission pipelines of $0.87 billion to $2.61 billion.(39)

The cost of loss of throughput is due to the lowering of pressure during a direct assessment dig. It is assumed that the pressure is lowered to 50 percent of normal operating pressure. This lowering is for 12 hours in the day during the dig. It is further assumed that on any given line, two dig crews would be working and four digs per day could be accomplished (eight digs per day total). Assuming one dig per 3.2 to 8 km (2 to 5 mi), a 12-hour day would allow the inspection of 26 to 64 km (16 to 40 mi) of pipeline. For the natural gas pipeline scenario used throughout this analysis, reducing the pressure by 50 percent would reduce the throughput by 50 percent, giving a reduction in throughput of 168,000 m^3 (6 Mcf) per hour. A 12-hour workday would give a total reduction in throughput of 2 million m^3 (72 Mcf) of natural gas. Assuming the cost of loss of throughput is 20 percent to 40 percent of the $71.50 per thousand m^3 ($2 per thousand f^3) cost of the product and assessment of 26 to 64 km (16 to 40 mi) in a 12-hour day gives a range of cost for loss of throughput of $450 to $2,250 per km ($720 to $3,600 per mi) of pipeline for direct assessment. Multiplying by the 483,000 km (300,000 mi) of natural gas transmission pipelines gives a cost of loss of throughput of $216 million to $1.08 billion to assess all natural gas pipelines using direct assessment.

For hazardous liquid pipelines, the throughput is not as significant a function of operating pressure as for natural gas pipelines. In addition, the risks are not as great to the personnel performing the dig; therefore, although a pressure reduction may be required, the loss of throughput is assumed to be minimal.

Table 16 summarizes the costs for direct assessment of pipelines. The largest portion of the costs is the inspection, with a significant cost of loss of throughput for natural gas pipelines. The total cost for direct assessment of all pipelines is between $1.09 billion and $3.69 billion.

Table 16. Summary of direct assessment costs.

ACTIVITY	COST OF DIRECT ASSESSMENT FOR NATURAL GAS PIPELINES		COST OF DIRECT ASSESSMENT FOR LIQUID PIPELINES		TOTAL COST FOR ALL PIPELINES	
	Low Estimate	**High Estimate**	**Low Estimate**	**High Estimate**	**Low Estimate**	**High Estimate**
	($ per mi)	**($ per mi)**	**($ per mi)**	**($ per mi)**	**($ x million)**	**($ x million)**
Preparation	0	0	0	0	0	0
Inspection	2,000	6,000	2,000	6,000	870	2,610
Loss of Throughput	720	3,600	0	0	216	1,080
TOTALS					**$1,086**	**$3,690**

1 mi = 1.61 km

Reliability of Direct Assessment

Variations of direct assessment technologies have been applied and tested through validation digs and have produced reliable results with a 70 to 80 percent positive predictive capability.

Comparison of Inspection Costs

Table 17 shows a comparison of inspection costs. The costs are compared by showing the total cost for inspecting all pipelines by each inspection method. By this comparison, the impact of the different inspection methods is readily apparent. The costs vary greatly depending on several factors. The costs of preparing the pipelines are extremely large for ILI, while the costs of performing hydrostatic testing are much greater than the other inspection methods because of the significant cost of loss of throughput. Direct assessment has no preparation costs; however, in general, the costs of inspection are comparable to the cost of ILI. The larger range of direct assessment costs is due primarily to the range in the number of digs required for direct assessment. The most cost-effective program, however, probably includes a combination of ILI, hydrostatic testing, and direct assessment.

Table 17. Comparison of costs for inspection methodologies.

INSPECTION METHOD	TOTAL COST OF PREPARING ALL PIPELINES		TOTAL COST OF INSPECTING ALL PIPELINES	
	Low Estimate	**High Estimate**	**Low Estimate**	**High Estimate**
	($ x billion)	**($ x billion)**	**($ x billion)**	**($ x billion)**
ILI	9.72	32.57	1.58	2.41
Hydrostatic Testing	0.54	2.17	6.67	20.20
Direct Assessment	0	0	1.09	3.69

The number of miles of pipeline inspected by ILI, hydrostatic testing, or direct assessment on a regular basis is small, probably less than 20 percent of all pipelines.(40) In the future, the cost of inspection will significantly add to the present cost of operation and maintenance for pipeline operators. It is expected that little cost reduction in their current operating practices will result. In fact, identifying problem areas that are currently not known would initially be expected to increase the costs of repair; however, eventual savings will result from fewer leaks and fewer spills, the cost of which would continue to increase if not prevented by proper corrosion mitigation. In the long-term, preservation of an asset that has an estimated replacement cost of $541 billion is a major benefit.

CHANGES FROM 1975 TO 2000

Changes from 1975 to 2000 are minor in comparison with the changes that are anticipated for the future, as described above. Although there were many technical advances that took place in the last quarter of the 20th century, the basic corrosion control programs remained unchanged. The implementation of risk assessment programs and integrity management programs coupled with the continued aging of the pipeline infrastructure make the next 25 years very different from the previous 25 years. In addition, the deregulation of pipeline companies over the past 5 years significantly affected the free-market competitive nature of a company's operation. All of these factors will have a strong effect on pipeline operation in the future.

CASE STUDIES

Case Study 1. Integrity Maintenance on TAPS

Introduction

The Trans-Alaskan Pipeline System (TAPS) is one of the most critical pipelines in North America. It delivers approximately 1.35 million barrels per day (1998) of hot [50 °C (120 °F)] crude oil 1,290 km (800 mi) across Alaska, from the Prudhoe Bay production fields to the oil terminal at Valdez. In addition, environmental issues are of paramount concern. For both of these reasons, a single leak in this pipeline is considered to be unacceptable.

Background

The 1,219 mm- (48-in-) diameter pipeline was constructed between 1974 and 1977.(41) Of the 1,290 km (800 mi) that the pipeline stretches across Alaska, 680 km (420 mi) is above ground and 610 km (380 mi) is buried. The aboveground portion is coated and thermally insulated with only minor corrosion concerns. The buried portion is coated and cathodic protection (CP) is applied. The original sacrificial CP system consisted of continuous zinc ribbon buried in the bottom of the pipe ditch on both sides of the pipe. The pipe was originally coated with a fusion-bonded epoxy (FBE). Coating adhesion problems were encountered early in the construction phase and the FBE was overwrapped with polyethylene tape and elastomeric heat shrink tape.

At peak production in 1988, TAPS delivered 2.1 million barrels per day (bbl/day), nearly 25 percent of the U.S. domestic oil supply. Currently, an essential factor in integrity planning is that production at Prudhoe Bay is declining, which impacts the cost benefit of corrosion mitigation upgrades. An additional aspect of the TAPS system is that 75 percent of the pipeline crosses regions of permafrost, making engineering solutions more difficult and making costs significantly higher than for typical pipeline systems.

Historically, an in-line inspection program has been performed in conjunction with potential survey techniques to monitor the effectiveness of the CP system. In-line inspection utilizing the most sophisticated tools available has been performed almost every year since start-up. The in-line inspection identifies areas of probable corrosion by measuring loss in pipe wall thickness. Electrochemical potential measurement techniques (pipe-to-soil potential test station measurements and long-line surveys) typically provide an accurate measurement of the effectiveness of the CP system in mitigating corrosion.

In the early 1990s, Alaska became concerned with whether the existing CP system was mitigating corrosion and whether conventional over-the-line pipe-to-soil potential survey methods were adequately assessing the effectiveness of the CP system. The consequence was that it was concluded that the CP system may not be effective in mitigating corrosion; therefore, the operator is left with the in-line inspection program to identify areas of significant wall loss and to repair the identified areas prior to failure. The long-term problem with this approach is that if corrosion continues, the effort of repairing the pipe would become economically overwhelming as the number of critical corrosion sites increased. With this, a cooperative program was established that included Alyeska (the TAPS operator), the state of Alaska representatives, and the Federal Bureau of Land Management. The task was to identify technical and cost-effective means of improving the corrosion mitigation system of TAPS.

Overall System Integrity Program

There are five strategic elements to the system integrity approach for TAPS: (1) pipeline system design, (2) CP monitoring and maintenance, (3) integrity monitoring and repair, (4) supplemental CP, and (5) corrosion data management.

Pipeline System Design

Pipeline system design consists of a wall thickness design and a CP system design. The pipeline wall thickness was designed in accordance with ASME B31.4 standards and U.S. DOT regulation 49 CFR 195. The pipeline wall thickness design provides at least 10 percent nominal wall thickness (nwt) corrosion allowance. Operation at pressures below maximum allowable operating pressure (MAOP) can create additional corrosion tolerance. Furthermore, engineering calculations and experience show that a corrosion failure is unlikely if the corrosion depth is less than 50 percent nwt.

The CP system design consisted of the FBE primary coating overwrapped with polyethylene tape and twin zinc galvanic anode ribbons placed in the bottom of the ditch to provide protection to holidays (damaged areas) in the coating. This CP system design is critical because it establishes limitations on alternative remedial methods for enhancing the effectiveness of cathodic protection.

CP Monitoring and Maintenance

CP monitoring consists of: (1) monitoring 1,100 permanent test stations on the TAPS, (2) close interval pipe-to-soil surveys used to monitor between the test stations, and (3) 400 coupon test stations used for monitoring interference and IR-drop free pipe-to-soil potentials.

General CP system maintenance consists of placing remedial magnesium anodes in areas of low protection in accordance with NACE RP0169 and 49 CFR 195. Approximately 50 percent of the buried pipeline has remedial anodes [more than 450,000 kg (1 million lb)], and 3.2 to 8.0 km (2.0 to 5.0 mi) of remedial anodes are placed each year.

Integrity Monitoring and Repair

In-line inspections (monitoring pigs) are run annually compared to many other pipelines that run in-line inspections every 5 to 7 years. First-generation ILI tools were used prior to 1989 and were only capable of locating relatively severe corrosion (i.e., wall loss greater than 30 to 50 percent of the pipe wall thickness). More advanced, high-resolution ILI tools were used beginning in 1989 and have provided a more realistic representation of the status of corrosion on the pipeline. Curvature and deformation pigs are also used to indicate high stress areas where possible settlement has occurred.

Field inspection requires digging up the pipe for visual and ultrasonic inspection of the surface. Repair methodologies following inspections include the following: cleaning and recoating, sleeving, large-scale refurbishment, and pipe replacement.

Supplemental CP

Supplemental cathodic protection to be added to the TAPS system was mandated through the cooperative program based on a Tariff Settlement between the State of Alaska and the TAPS owners. The supplemental CP program provided protection beyond the original CP design. The original CP maintenance program was completely driven by meeting regulatory requirements. The trend of increasing the number of inspection digs required, based on pig reports, indicated that the practice of installing magnesium anodes at "low potential" areas was not effective in mitigating corrosion on the TAPS.

The primary concept of the supplemental CP program was that by supplying properly designed CP systems based on impressed-current CP, corrosion would be effectively mitigated and the number of inspection digs required would decrease over time. The supplemental CP project selection was based on economic advantages. Each supplemental CP project had to provide a net economic advantage based on the cost of the supplemental CP, the maintenance of the system, and the savings incurred by eliminating inspection digs.

Corrosion Data Management

The corrosion data management (CDM) system contains information relevant to corrosion and corrosion control, including the pipeline design and hydraulic data, in-line inspection monitoring data, CP monitoring data, and field investigation data. The CDM system also has built-in engineering calculations to support the decision process.

Life Cycle of the TAPS

The supplemental CP program is designed to minimize the life-cycle cost of corrosion on the TAPS. The life cycle for TAPS can be defined by the intersection of the revenue curve and the cost of the maintenance curve (see figure 13). One particular issue regarding TAPS is that its throughput is declining; therefore, the revenue generated by TAPS is declining. Figure 17 shows two scenarios, one for a "high" projected maintenance cost and one for a "low" projected maintenance cost. At present, approximately 10 percent of the maintenance cost is spent on corrosion-related items. The primary differences between the two scenarios is in the cost due to corrosion (dig programs, repairs, etc.) and in the projections of the life cycle for TAPS, which differs by 10 years. This indicates that optimizing corrosion-related practices can have a major impact on the life cycle of the TAPS.

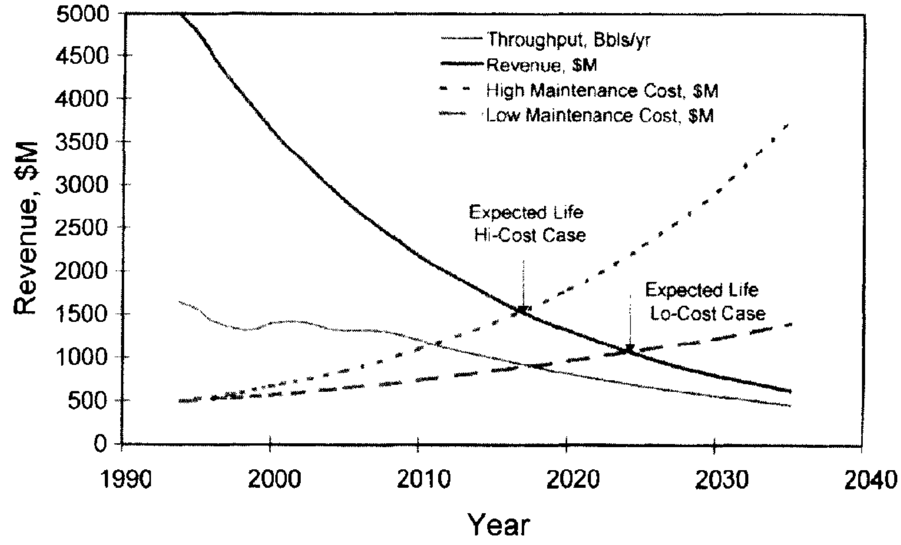


Figure 17. Hypothetical revenue versus cost for two maintenance scenarios on the TAPS.

Case Study 2. Integrity Management Program Development

Background

A gas transmission company experienced numerous corrosion-related pipeline failures.(42) From 1961 to 1997, 24 service failures were experienced (0.67 per year). An extensive pipeline integrity management program was developed in 1986. The program, which has been evolving ever since its inception, incorporates the following practices:

1. In-line inspection and excavation program (intelligent pigging).
2. Hydrostatic re-testing program.
3. Discrete investigative dig program (bell-hole inspection).
4. Soils modeling to predict likelihood for corrosion-related failures.
5. Remaining life assessments.
6. Cathodic protection monitoring, upgrading, and effectiveness testing.
7. Large-scale coating reconditioning program.

In 1998, a review was undertaken to assess the cost-effectiveness of the 13-year old pipeline integrity management program. This case study presents the results of that review.

Failures Prevented by an Integrity Management Program

Data were compiled to total the hydrostatic test failures, service failures, and in-line inspection indications ("pig indications" or "pig calls") during the 1986-1998 preventive maintenance program. The key indicator to be examined was the number of service failures prevented by the pipeline integrity management program. Each flaw associated with either a hydrostatic test failure or a direct inspection dig program that had a predicted burst pressure less than or equal to 100 percent of the specified minimum yield stress (SMYS) was analyzed to predict the expected life had that feature not been removed from the pipeline. Each of these flaws became a failure prevented by the integrity management program at a projected time based on the predicted life.

The life prediction was based on the flaw growing from its current size, as determined by an in-line inspection tool or a hydrostatic test, to a size that would have a burst pressure equal to 100 percent of the maximum allowable operating pressure (MAOP). The burst pressures were calculated using CorLAS™. Flaw growth rates, based on research by CC Technologies Laboratories, Inc. and field data, indicated an upper-bound growth rate of 0.3 mm per year for a corrosion flaw and 0.6 mm per year for an SCC flaw. By adding the remaining life as calculated above to the date of the last in-line inspection or hydrostatic re-test, the projected failure date, assuming no action had been taken, was established for each flaw.

Based on these data, the number of prevented failures can be plotted for each year, starting at the beginning of the program (1986). Figure 18 shows the prevented failures by year for three program sessions using data for 1986-1996, 1986-1997, and 1986-1998. In general, it is shown that the integrity management program implemented by the gas transmission company prevented a significant number of in-service failures. In addition, each additional year's data from 1996 to 1998 indicates an increasing number of failures prevented.

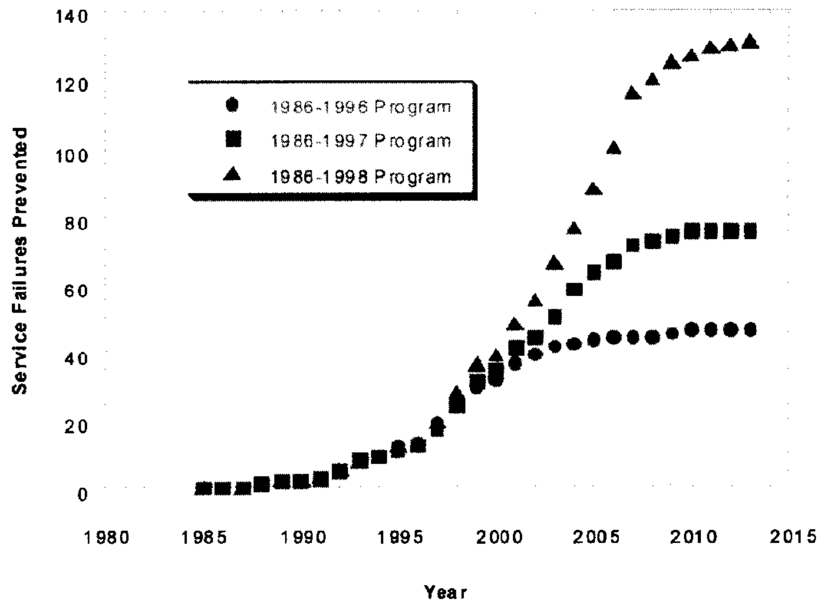


Figure 18. Number of failures prevented by the integrity management program (IMP).

Cost of Integrity Management Program

Figure 19 shows the cumulative failures and the cumulative costs of the integrity management program. The actual failures are plotted assuming zero future in-service failures, which is the technical objective of the integrity management program. The number of failures with no integrity management program is shown for comparison (based on figure 18 and actual in-service failures). Also plotted in figure 19 is the cumulative cost of the integrity management program since its initiation in 1986.

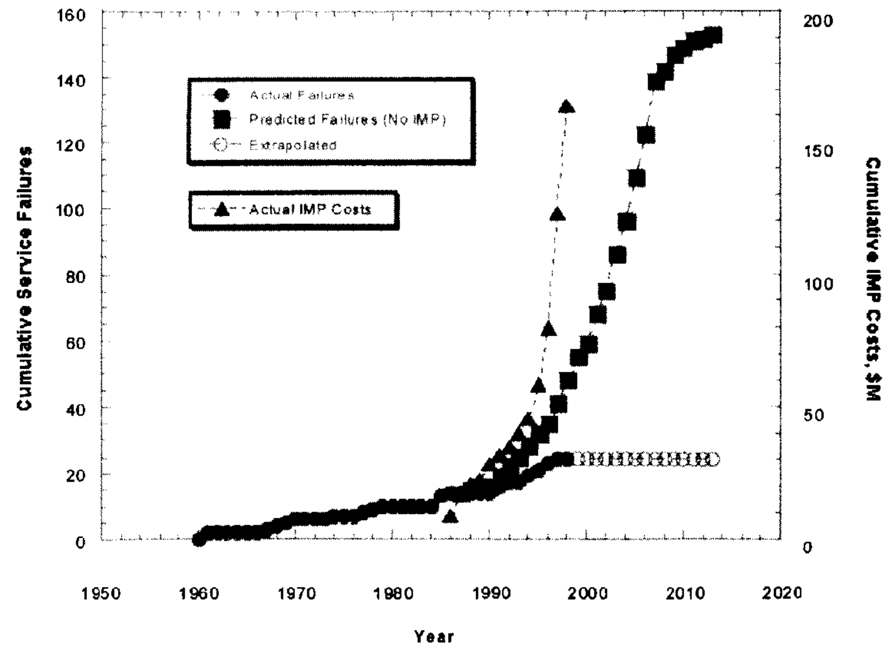


Figure 19. Cumulative in-service failures compared to cumulative costs of the integrity management program (IMP).

There are several benefits of an integrity management program, including prevented failures, continued operation at desired pressure (pressure reduction is a threat if integrity is not maintained), preservation of the pipeline asset, etc. Since inception, it is estimated that the integrity management program has prevented 125 failures (see figure 19). This alone is significant enough to justify the program.

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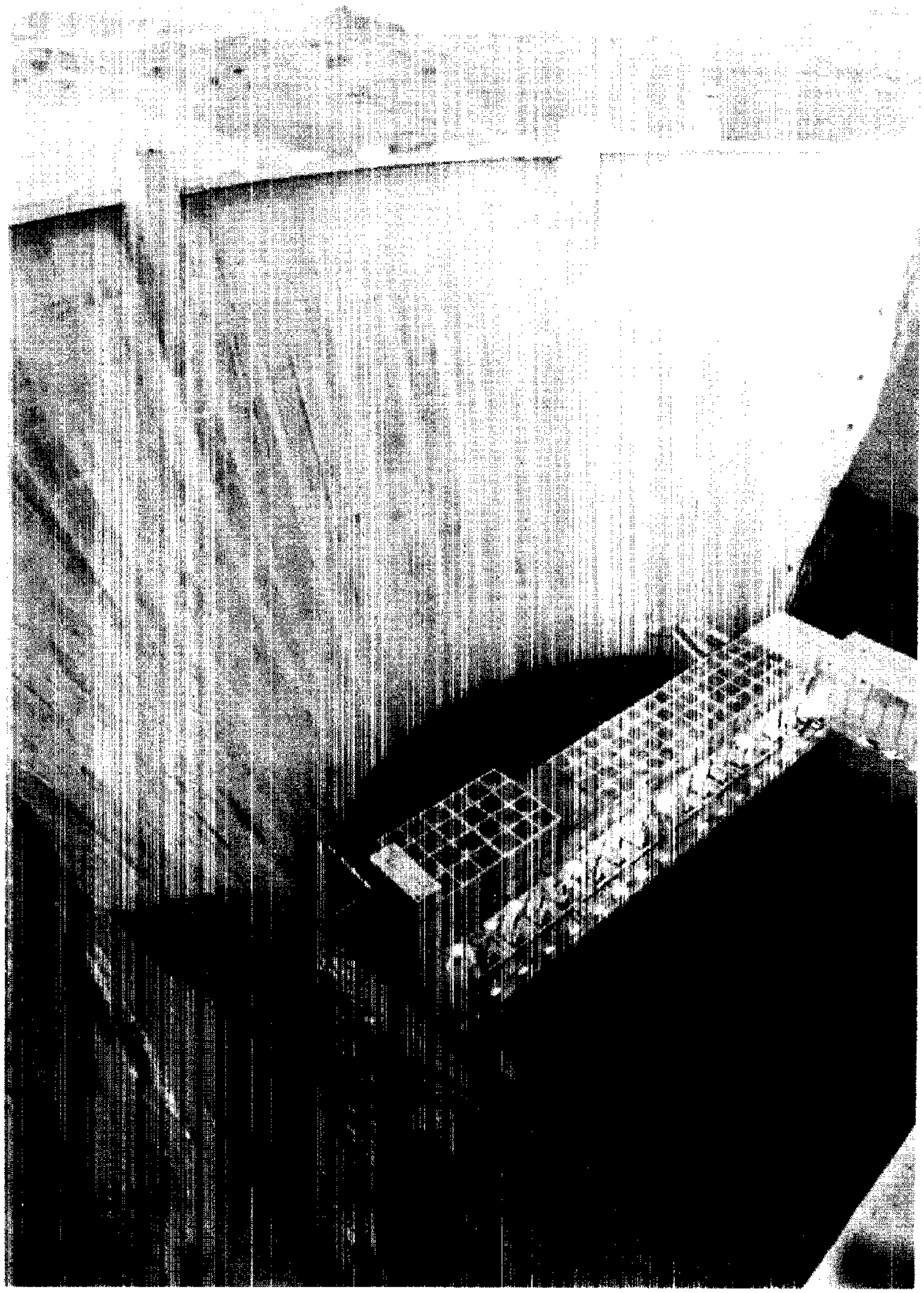
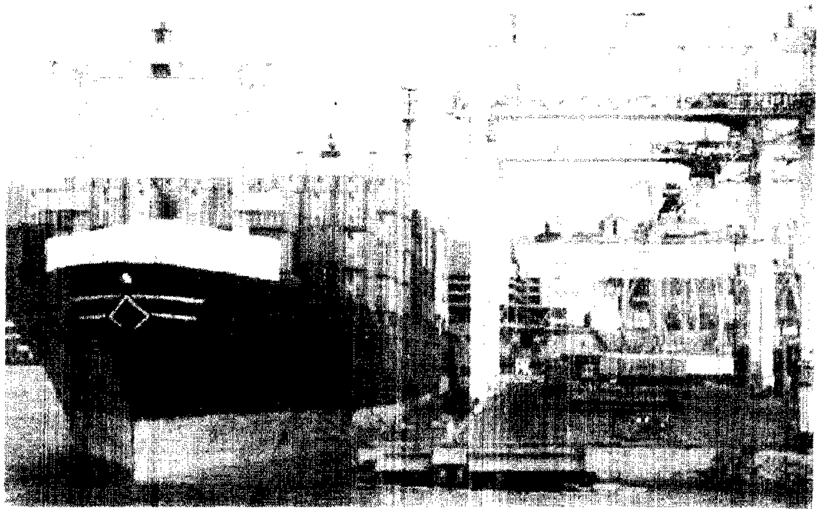
APPENDIX F

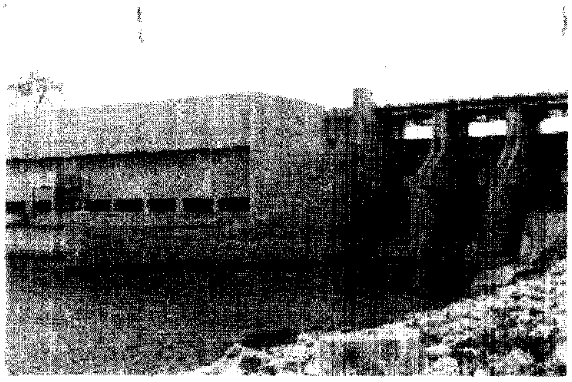
WATERWAYS AND PORTS



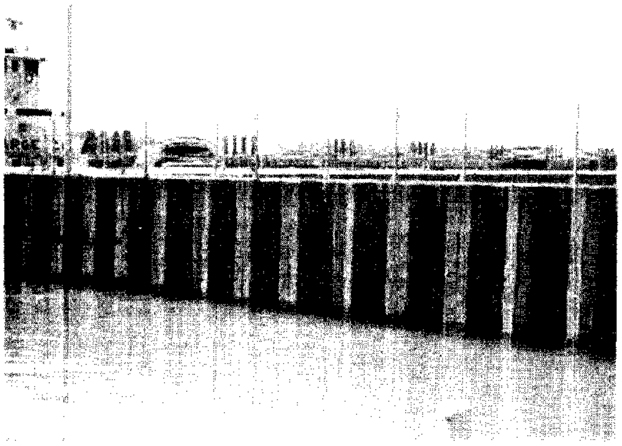


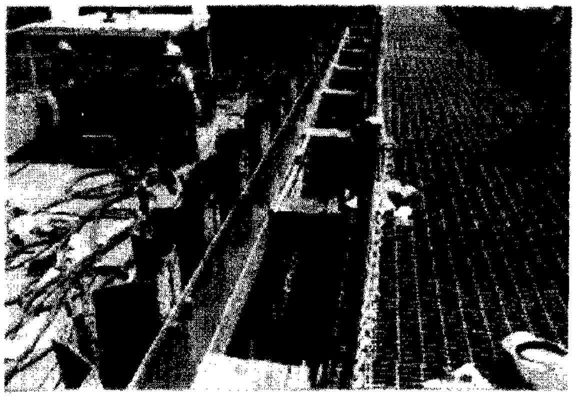
Port

Corroded columns at water line



Dam (concrete rebar corrosion)





Piling (steel corrosion)

APPENDIX F

WATERWAYS AND PORTS

MARK YUNOVICH[1] AND AARON J. MIERZWA[1]

SUMMARY

The United States has approximately 40,000 km (25,000 mi) of navigable waterways, 600 ports and locks, and 10,000 waterfront facilities. Corrosion is typically found in piers and docks, bulkheads and retaining walls, mooring structures, and navigational aids. Corrosion occurs on structures exposed to both fresh water and saltwater conditions.

There is no formal tracking of the corrosion-related costs, and the estimates show that the annual expenditures for corrosion control to be as high as $293.4 million. Corrosion is primarily controlled by the surface coating systems and sacrificial cathodic protection systems.

Corrosion is seen as a significant issue within waterways and ports. Unfortunately, due to budgetary constraints, funds for structural maintenance to protect against corrosion are often in short supply. For example, the U.S. Army Corps of Engineers owned or operated 276 lock chambers at 230 sites in 1998; however, only 191 of these sites with 237 lock chambers received funding for maintenance.

Examples of neglected structures include single-pile navigational aids that are left in service until the corrosion is so severe that failure occurs. Subsequently, not only is a new $15,000 navigational aid necessary, but also the remaining pole that exists underwater becomes a hazard and must be removed.

Structures with higher initial capital costs are more likely to be protected either by coatings and/or cathodic protection. Structures such as lock gates, dam gates, and other water-containing devices are also protected to ensure their proper operation.

In the past 25 years, waterways and ports have benefited from advances in the quality of the available coating systems. The choice and development of coatings have also been affected by environmental regulations specifying which coatings can be exposed to water streams. For example, regulations have minimized the amount of volatile organic compounds that can be used in coatings.

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[1] CC Technologies Laboratories, Inc., Dublin, Ohio.

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SECTOR DESCRIPTION

The United States has more than 7,750 commercial water terminals, 192 commercially active lock sites with 238 chambers, and 40,000 km (25,000 mi) of inland, intracoastal, and coastal waterways and canals.(1) Forty-one states, 16 state capitals, and all states east of the Mississippi River are served by commercially navigable waterways.(2) Public and private works associated with waterways and ports have corrosion-related issues in both freshwater and seawater environments.

Public and Private Works

Public works waterway structures, which are primarily operated and maintained by the U.S. Army Corps of Engineers, include locks, dams (see figure 1), navigational aids, levies, and dikes. These structures are on primarily freshwater lakes and rivers. Many freshwater public works related to irrigation and flood control are owned, operated, and maintained by state and local agencies such as the Tennessee Valley Authority (TVA) or the California Aqueduct.

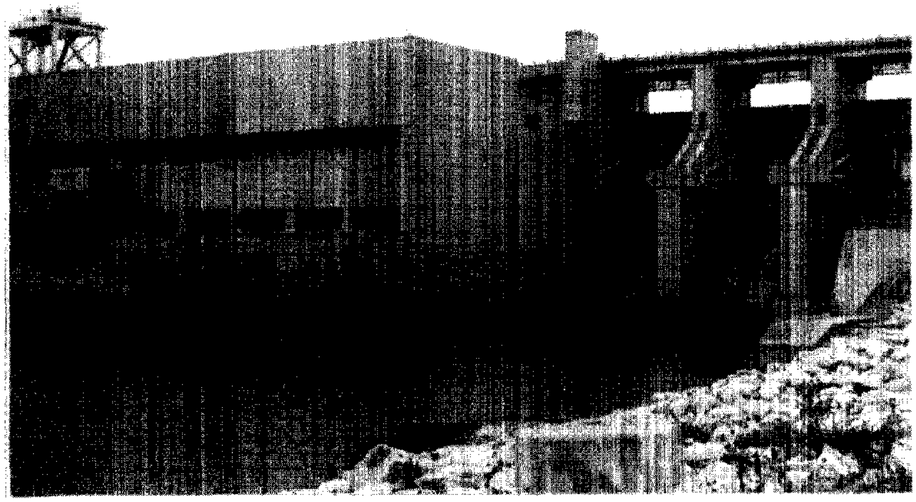

Figure 1. Example of a steel-reinforced concrete dam.

Public docks, piers, and bulkheads are mostly owned and maintained by port authorities. These public agencies have structures in both fresh water and seawater; however, most of the larger ports are in marine locations.

In addition, there are also a significant number of private terminals for loading grain and commodities (e.g., coal) owned by shipping companies and railroads. These private terminals are located in both freshwater and marine environments. The large size of most structures at port facilities requires that they be built with steel-reinforced concrete, steel, or a combination of both. The environment at seawater locations is significantly more severe than that at rivers and lakes due to the high chloride content in the seawater.

Not included in this sector are military installations and utility-owned hydroelectric power generation dams. Military installations that include a large number of piers and shipyard facilities are addressed in the Defense sector (Appendix BB), while utility-owned hydroelectric power generation dams are described in the Electrical Utilities sector (Appendix L) of this report.

AREAS OF MAJOR CORROSION IMPACT

Seawater

The reinforced-concrete structures exposed to the marine environment suffer premature corrosion-induced deterioration by chlorine ions in seawater. Corrosion is typically found in piers and docks, bulkheads and retaining walls, mooring structures, and navigational aids.

The marine environment can have varying effects on different materials depending on the specific zones of exposure. Atmosphere, splash, tide, immersion, and subsoil have very different characteristics and, therefore, have different influences on corrosion.(3) Figure 2 shows the relative metal loss for steel piling after 5 years of exposure to seawater at Kure Beach, North Carolina.

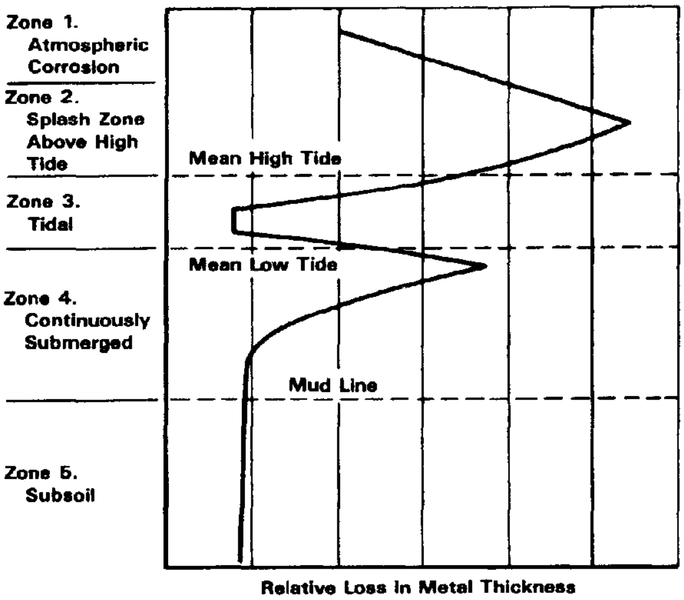

Figure 2. Corrosion profile of steel piling after 5 years' exposure in seawater at Kure Beach, North Carolina.(3)

Atmospherically exposed submerged zones and splash zones typically experience the most corrosion. These zones are found on piers and docks (ladders, railings, cranes, and steel support piles), bulkheads and retaining walls (steel sheet piling, steel-reinforced concrete elements, backside, and anchors on structures retaining dredged fill), and mooring structures and dams (steel gates, hinges, intake/discharge culverts, grates, and debris booms). Stationary navigational aids suffer from corrosion of support piles and steel-reinforced concrete pile caps. Floating steel buoys are subject to corrosion as well.

Fresh Water

Airborne or splash zone attack is normally not a problem at freshwater facilities; however, air pollution can cause potential problems. Under certain flow conditions, such as turbulent flow or cavitation, fresh water can cause severe corrosion to submerged metallic elements. Ice damage also can limit the effectiveness of coatings on bulkhead walls and support piling.

Piers and docks, bulkheads and retaining walls, locks, dams, and navigational aids exposed to freshwater environment experience corrosion-related problems. The most common areas of attack include submerged and splash zones on support piles (piers, docks, and navigational aids) and steel sheet piling (bulkheads and retaining walls). These zones are also found on locks (steel gates, hinges, intake/discharge culverts, valves, and sheet pile walls), dams (steel gates, hinges, intake/discharge culverts, grates, and debris booms), and navigational aids (anchorages).

Costs of Corrosion

U.S. Army Corps of Engineers-Maintained Structures

Some cost of corrosion information on lock and dam structures can be obtained from the U.S. Army Corps of Engineers' maintenance and capital budgets. In a 1986 study,(4) the total cost of corrosion to the Corps of Engineers in the Ohio River Division, the Civil Works Component, was estimated to be between 4 and 7 percent of the total annual operation and maintenance (O&M) budget. Using a typical value of 5 percent of the total 1999 Corps of Engineers O&M budget of $1.4 billion, the total annual corrosion-related maintenance cost was estimated at approximately $70 million.(5)

The above study further indicated that a large number of the structures maintained by the Corps of Engineers are currently at the end of their design life, which would require staggering replacement costs.

U.S. Public Ports

Public port authorities operate maritime cargo and cruise ship terminals along the Atlantic, the Pacific, and the Gulf coasts. Freshwater facilities are located in the Great Lakes region and on some major rivers. The American Association of Port Authorities (AAPA) also includes members from Canada and the Caribbean; however, the vast majority of seaports are located within the United States. The AAPA website(6) indicates that in the United States, there are 3,214 deep-draft ship berths located at 1,941 public and private terminals on coastal and inland waterways.

The AAPA Facilities Engineering Committee(7) indicated that corrosion costs are not tracked individually in O&M budgets and that cost data for the 1999 port expenditure survey were still being gathered. However, a previous survey revealed that the 83 port authority members in the United States had spent a total of $919 million on O&M in 1998.

The corrosion cost assessments can be made using the approximate cost (as a percentage of the total O&M budget) provided by the U.S. Corps of Engineers (5 percent). Since the Corps of Engineers maintains primarily freshwater structures, this value is most directly applicable to the freshwater ports.

Because marine structures are in a significantly more aggressive environment, corrosion costs are likely to be higher as coastal terminals have much higher atmospheric and splash zone corrosion rates. In addition, coating costs for berthing structures and cranes at saltwater marine terminals would be substantially greater than those for the freshwater facilities. Based on this information, it is estimated that approximately 5 percent of freshwater facility costs and 10 percent of saltwater marine port costs are corrosion-related.(5)

In 1998, about 20 percent of the 83 AAPA facilities were located in fresh water (mostly in the Great Lakes region); however, these freshwater structures were much smaller than the saltwater marine ports, such as New York or the Port of Long Beach. Adjusting for the size of the facilities, it is estimated that approximately 90 percent of the AAPA terminals are in saltwater environments and approximately 10 percent are in freshwater environments. Combined with the previous assumptions with respect to the fractions of the O&M budget attributable to corrosion, the estimated annual cost of corrosion-related maintenance in the U.S. public ports is $87.3 million.[2]

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[2] Calculated as (10% x 90% + 5% x 10%) x $919 million

The AAPA website(6) further reveals that, between 1997 and 2002, the U.S. public ports will spend $1.9 billion per year on construction and modernization, and that much of this infrastructure construction is necessary to accommodate growth and handling of the larger modern container ships. Even if only 5 percent of this expenditure is spent on replacing corrosion-damaged berthing facilities, $95 million can still be attributed to the annual cost of corrosion.

The analysis above indicates that the annual cost of corrosion in the public port authority sector of the ports and waterways can be estimated at $182.3 million ($87.3 million + $95 million). It should be noted that as there was no available concrete data, the estimate is based on the assumptions made by the authors; therefore, the annual expenditures may differ substantially from the estimate.

U.S. Coast Guard

The U.S. Coast Guard maintains navigational aids such as light structures and buoys that are continuously exposed to harsh environments in both fresh water and seawater.

According to the U.S. Coast Guard,(8) there are more than 21,000 navigation structures nationwide that range in size and complexity from simple unlit day beacons (a single wooden "telephone pole" driven into the bottom) to massive, multi-million dollar offshore lights and range structures.

The majority of the navigational aids are found in the Gulf Coast and are considered to be "simple" structures, such as a single-pile or a multiple-pile steel or wood construction.(8) Single-pile structures are not maintained and are, in fact, allowed to rust until they are replaced. Estimated costs are $15,000 per single-pile structure.(9)

Larger light structures are protected using epoxy coatings and zinc sacrificial anodes. New structure costs can range from $300,000 to $600,000, while the coating and sacrificial anode costs are estimated at $20,000 per system. The life expectancy of the coatings and sacrificial anodes are approximately 15 to 20 years.

Older lighthouses, initially constructed of iron in the 1800s and weighing approximately 600 tons, are still in use today. These massive structures require maintenance and sandblasting every 15 to 20 years at an estimated cost of $750,000 each.(9) There are 615 of these structures in the United States, with average annual routine maintenance expenditures of $750 per unit, for a total cost of $461,250 per annum. The combined cost of the lighthouse maintenance is therefore estimated at $23.5 million.[3]

The U.S. Coast Guard maintains foam, plastic, and steel buoys of different sizes and shapes in both fresh water and seawater. According to the U.S. Coast Guard,(8) approximately $2 million is spent each year to replace steel ocean buoys that cost between $15,000 and $18,000 each. It is estimated that there are 11,640 steel buoys with an expected service life of 40 years for each buoy. These buoys are often hit by boats and are continuously in harsh environments; however, epoxy and anti-fouling paints, which are to be reapplied every 6 years, can protect them. The estimated costs for labor and supplies to paint buoys are $5 million a year.

About 75 percent of river buoys are lost within a year of being put into service, the remainder of the river buoys often last 2 to 3 years.(8) The steel river buoys, made of sheet metal with a foam filling, cost between $170 and $330 each. Given the relatively small cost of the river buoys compared to the steel ocean buoys, river buoys are viewed as consumables and are replaced if they sink or are lost; therefore, they are not considered maintenance expenditures.

Annually, the U.S. Coast Guard spends approximately $2 million to purchase 5,000 to 7,000 replacement river buoys.(8)

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[3] Calculated as $750,000 / 20 x 615 + $460,000

Corrosion-Related Maintenance Costs

In 1999, the U.S. Coast Guard spent an estimated $60 million on the east coast(10) and $31 million in the Pacific(11) on maintenance costs. These costs include maintenance performed on land and sea facilities, corrosion-related repairs, and any other activity necessary to maintain the safety of the waterways.

Applying the corrosion-related O&M budget fractions estimated for the U.S. Army Corps of Engineers (5 percent for fresh water and 10 percent for saltwater) and a similar assumption that 90 percent of the structures maintained by the U.S. Coast Guard are in a saltwater marine environment and the remaining 10 percent are in a freshwater environment, the annual cost of corrosion-related maintenance for 1999 can be estimated at $8.6 million.

Total Costs

Total annual corrosion-related costs for this sector are shown in table 1.

Table 1. Total annual corrosion-related costs.

CATEGORY	COST ($ x MILLION)
U.S. Army Corps of Engineers	
Maintenance @ 5%	70.0
SUBTOTAL	**70.0**
U.S. Public Ports	
Corrosion-Related Maintenance	87.3
Corrosion-Related Replacements	95.0
SUBTOTAL	**182.3**
U.S. Coast Guard	
Lighthouse Maintenance	23.5
Replace Steel Ocean Buoys	2.0
Paint Buoys	5.0
Replace River Buoys	2.0
Corrosion-Related Maintenance	8.6
SUBTOTAL	**41.1**
TOTAL	**$293.4**

CORROSION CONTROL METHODS AND MANAGEMENT PRACTICES

Typical corrosion control methods for freshwater structures include coatings for atmospherically exposed steel and corrosion allowances for submerged and splash zone steel. Dielectric coatings are normally used for structural steel above water, while galvanizing is often used for railings, ladders, gates, and gratings. Copper-bearing steel alloys are sometimes utilized for structural elements and sheet pile walls. These alloys, which form a tenuous oxide film in the atmosphere, provide little help when buried or submerged. Cathodic protection (CP) is occasionally used on submerged steel elements.

Marine corrosion control methods also include coatings for atmospherically exposed steel elements and a corrosion allowance for submerged and splash zone steel structures. Specialty marine dielectric coatings are normally used for structural steel above and often below water. Although galvanizing is used for railings, ladders, gates, and gratings, non-ferrous alloys provide better service in the aggressive saltwater marine conditions. Marine structures commonly use CP to control corrosion on submerged steel. CP is occasionally used on atmospherically exposed steel-reinforced concrete, particularly in warm climates [see additional discussion on the subject in the "Highway Bridges" sector (Appendix D) of this report]. The most cost-effective corrosion control on submerged and splash zone steel is achieved by using CP in conjunction with a heavy dielectric coating. Although corrosion allowances are often used for saltwater marine structures, they are not as helpful as in fresh water because the corrosion damage tends to be more localized in the tidal zone (wet/dry cycling) and at the mud interface zone.

While corrosion may be seen as a significant issue within waterways and ports, due to budgetary constraints, funds for structural maintenance to protect against corrosion are often in short supply. For example, the U.S. Army Corps of Engineers owned or operated 276 lock chambers at 230 sites in 1998, but only 191 of these sites with 237 lock chambers received funding for maintenance-related projects.(2)

Examples of the neglected structures include single-pile navigational aids that are left in service until the corrosion is so severe that a failure occurs. Not only is a new $15,000 navigational aid necessary, the remaining underwater pole becomes a hazard and must be removed as well.

Structures with higher initial capital costs are more likely to be protected either by coatings and/or CP. These include lock gates, dam gates, and other water-containing devices, which are protected to ensure their proper operation.

In the past 25 years, waterways and ports have benefited from advances in the quality of the available coating systems. New technologies that have been developed include metallizing, application of epoxies, and 100 percent solids coatings.

The choice and development of coatings have also been affected by environmental regulations specifying which coatings can be exposed to water streams (e.g., regulations have minimized the amount of volatile organic compounds (VOC) that can be used in coatings. Coatings with 100 percent solid content have been developed that contain no volatile solvents (before, coatings with 25 percent to 50 percent solid content were used). In addition to the epoxy coatings, anti-foulants are applied to submerged sections of the structure to prevent microbiologically induced corrosion (MIC).

Epoxy coatings cost approximately $4.7 to $5.3 per L ($18 to $20 per gal), while anti-foulants are much more expensive at approximately $11.8 to $21.1 per L ($45 to $80 per gallon).(12) Environmental regulations have also led to a decreased amount of chemicals released from industrial installations along waterways, especially corrosive ones such as chlorine. The materials of construction for some water structures have changed as well. Piers and docks are no longer being constructed with wood, but instead are being constructed with steel-reinforced concrete. To improve the lifespan of the structure and prevent corrosion of the reinforcing steel, fusion-bonded epoxy-coated reinforcement or corrosion-inhibiting admixtures are sometimes utilized in the concrete mix.

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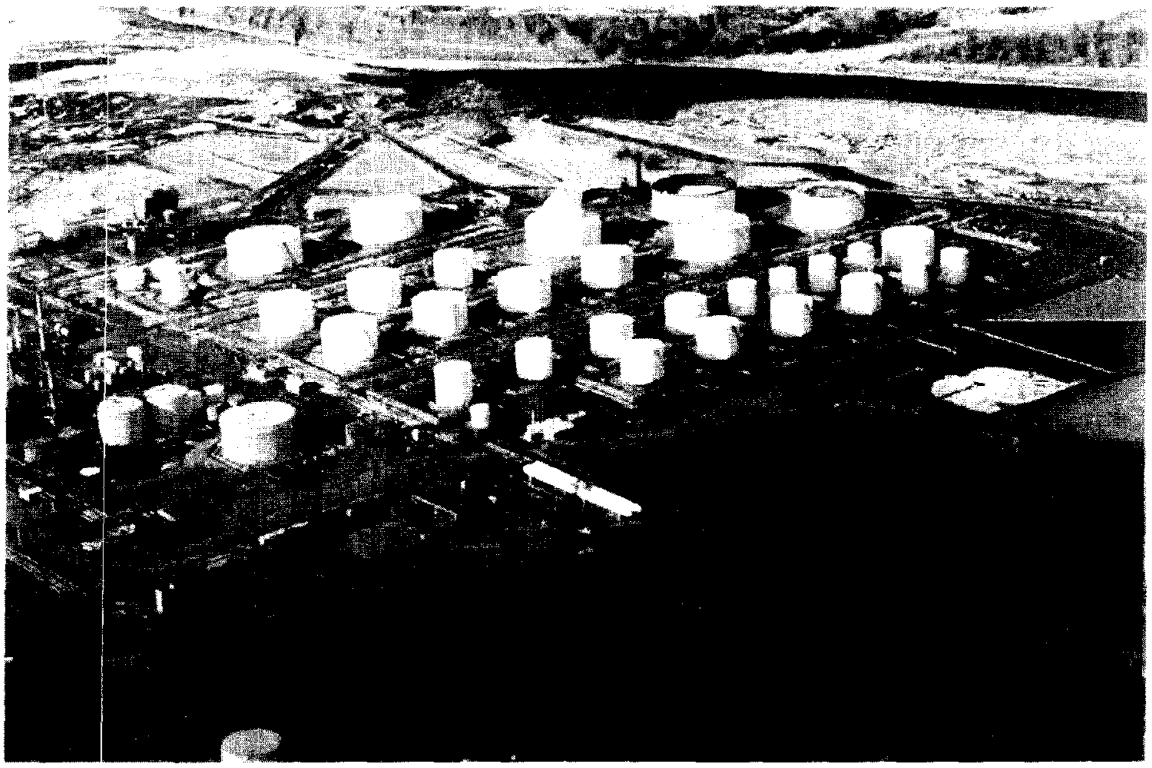
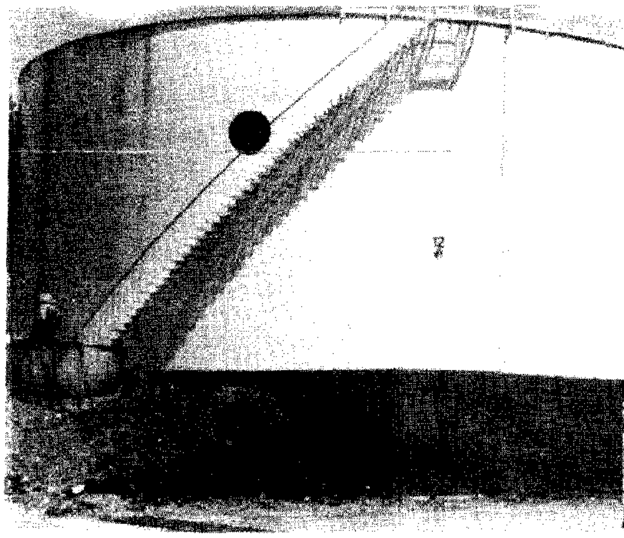
APPENDIX G

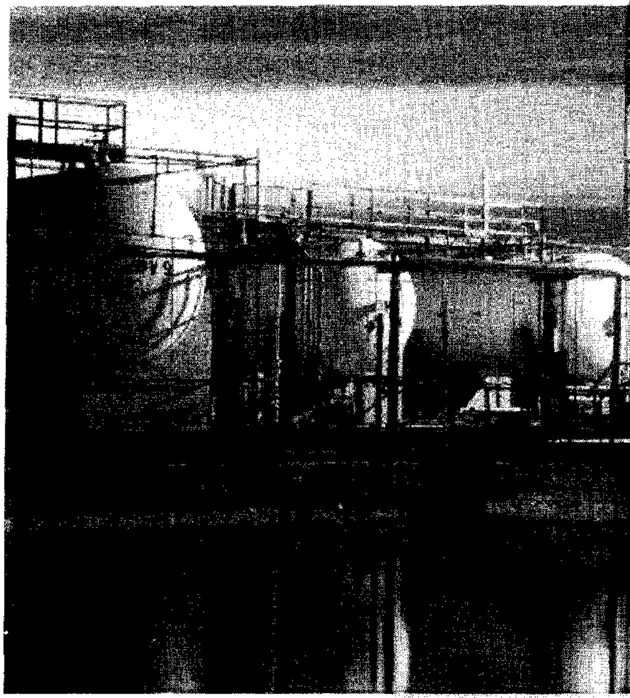
HAZARDOUS MATERIALS STORAGE



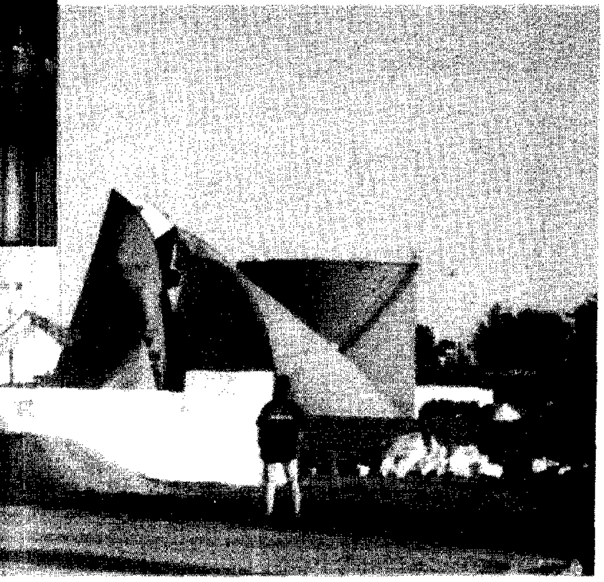


Aboveground storage tank

Lifting underground storage tank



Storage tanks



Collapsed storage tank

APPENDIX G

HAZARDOUS MATERIALS STORAGE

MICHIEL P.H. BRONGERS[1]

SUMMARY AND ANALYSIS OF RESULTS

Corrosion Control and Prevention

There are approximately 8.5 million regulated and non-regulated aboveground storage tanks (ASTs) and underground storage tanks (USTs) for hazardous materials (HAZMAT) in the United States. The regulated tanks can be divided into two groups: Spill Prevention Countermeasure and Control (SPCC)-regulated and Office of Underground Storage Tanks (OUST)-regulated. A total of 2.5 million tanks fall under SPCC regulations, 0.75 million tanks fall under OUST regulations, and 5.25 million are non-regulated tanks. HAZMAT tanks represent a significant investment, and maintaining their structural integrity for a longer service life is in the best interest of their owners. The U.S. Environmental Protection Agency (EPA) concerns itself with the environmental impact of spills from leaking tanks. In addition, the tank operators should be concerned about the potential economic impact of penalties and clean-up costs.

The total cost of corrosion for storage tanks is $7.0 billion per year (ASTs and USTs). The cost of corrosion for all ASTs was estimated at $4.5 billion per year. A vast majority of the ASTs are externally painted, which is a major cost factor for the total cost of corrosion. In addition, approximately one-third of ASTs have cathodic protection (CP) on the tank bottom, while approximately one-tenth of ASTs have internal linings. These last two corrosion protection methods are applied to ensure the structural integrity of the ASTs.

The cost of corrosion for all USTs was estimated at $2.5 billion per year. The largest costs are incurred when leaking USTs must be replaced with new tanks. The soil remediation costs and oil spill clean-up costs are significant as well. In the last 10 years, the most common problem associated with USTs occurred at gasoline service stations that did not have corrosion protection on their USTs.

The current sector study shows the following corrosion costs:

	ANNUAL CORROSION COST	DIVIDED OVER:
ALL ASTs	$4.5 billion	$2.8 billion for external coatings $1.2 billion for cathodic protection $0.5 billion for internal linings
ALL USTs	$2.5 billion	$1.4 billion for gasoline stations $1.1 billion for the remaining USTs

Since 1988, the number of OUST-regulated USTs has decreased from approximately 1.3 million to 0.75 million due to stringent regulations. During the same period, a trend of replacing multiple small USTs with fewer larger ASTs was evident. While USTs were being closed, repaired, or replaced to achieve the necessary compliance with regulations, the number of confirmed HAZMAT releases increased. The December 1998 deadline

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[1] CC Technologies Laboratories, Inc., Dublin, Ohio.

for UST compliance marked the date that owners were required to have corrosion control systems, overfill protection, and spill protection applied on all of their regulated USTs.

Opportunities for Improvement and Barriers to Progress

Experts have argued that focusing only on corrosion protection on the tanks is insufficient because the connected underground piping should have corrosion protection as well. In order to prevent future leaks, corrosion protection on associated piping and connectors should be applied, as specified in the Code of Federal Regulations.

The largest structural problem with ASTs is external corrosion of the tank bottoms that are sitting on-grade. New tanks are generally designed with a bottom coating and cathodic protection; however, the majority (70 percent) of ASTs have no cathodic protection at all, making them vulnerable to reduction in wall thickness because of external corrosion. Since corrosion of the AST exteriors is not so much a structural problem, exterior painting is repeated every few years at a significant expense. Studies showed that the cost of labor for surface preparation and painting is 80 percent of the total painting cost, and the cost of the paint is 20 percent of the total painting cost.

Internal linings on the walls and the bottoms of ASTs are commonly used to prevent a variety of corrosion problems. The most common problem is the presence of water at the bottom of a tank. Inspection of linings should be performed regularly, including disbondment testing and visual inspection for scratches. Damage to internal linings should be repaired as soon as possible to prevent leaks and to ensure the structural integrity of the tank.

Only 30 percent of existing ASTs have cathodic protection on their tank bottoms. Using cathodic protection in combination with coatings and the installation of tanks on well-draining soils provides good corrosion protection of AST tank bottoms. New tanks are usually designed with these corrosion protection systems; however, older ASTs generally do not have these systems in place. Retrofitting of older tanks with cathodic protection is possible using a variety of methods to place and configure anodes; however, a barrier to installing cathodic protection to existing tanks is that retrofits can be costly. Due to this high cost, retrofitting is often not done, even though the potential costs of oil spill remediation could be many times larger.

Approximately 60 percent (5.2 million) of the total number of HAZMAT tanks (8.5 million) are unregulated. The great majority of these tanks are used for home heating oil, LPG (liquid propane gas)/propane gas, and kerosene. Although the size of unregulated tanks is generally smaller than that of regulated tanks, the potential for more spills exists. The level of corrosion awareness is low with owners of unregulated tanks, and a mentality of "bury it and forget it" is common. This potentially large number of small spills is an invisible problem that affects many sites.

Recommendations and Implementation Strategy

The SPCC program for USTs has shown the effectiveness of a national approach to prevent and remediate HAZMAT releases. The SPCC program has increased awareness that corrosion protection can work, that it prevents environmental problems, and that a substantial cost-savings can be achieved over the life of the tanks.

A similar systematic approach should be applied to protect AST tank bottoms. Technologies to retrofit existing ASTs are available. Research regarding the cost benefits for retrofitting ASTs with cathodic protection, coatings, and well-draining grade soils is recommended to support this work.

The cost of replacing HAZMAT tanks with new tanks can far exceed the cost of repairing existing tanks for continued use. Existing methods can be used and new methods should be developed to measure and evaluate wall loss on aged USTs and AST tank bottoms, with the objective that corroded tanks may be repaired instead of replaced.

Summary of Issues

Increase consciousness of corrosion costs and potential savings.	There are 8.5 million aboveground storage tanks (ASTs) and underground storage tanks (USTs). The cost of corrosion for all ASTs is $4.5 billion per year. The cost of corrosion for all USTs is $2.5 billion per year.
Change perception that nothing can be done about corrosion.	The Spill Prevention Countermeasure and Control (SPCC) program for USTs has shown the effectiveness of a national approach to prevent and remediate hazardous materials releases.
Advance design practices for better corrosion management.	The use of cathodic protection in combination with coatings and the installation of tanks on well-draining soils allow for good corrosion protection of AST tank bottoms.
Change technical practices to realize corrosion cost-savings.	The mentality of "bury it and forget it" is common and should be changed to cost-effective corrosion-focused design, inspection programs at periodic intervals, preventive maintenance, and critical assessment of aged and corroded tanks with remaining safe service life.
Change policies and management practices to realize corrosion cost-savings.	A systematic approach similar to that for USTs should be applied to protect AST tank bottoms.
Advance life prediction and performance assessment methods.	Based on inspection data, engineering integrity assessments can be made to evaluate the integrity of existing USTs and ASTs for continued use.
Advance technology (research, development, and implementation).	A systematic approach should be applied to protect AST tank bottoms. Technologies to retrofit existing ASTs are available. Research to evaluate the cost benefits of retrofitting ASTs with cathodic protection, coatings, and well-draining grade soils is urgently needed.
Improve education and training for corrosion control.	The level of corrosion awareness is low with owners of unregulated tanks. A mentality of "bury it and forget it" is common and should be changed to prevent hazardous materials releases. There are 5.2 million out of 8.5 million tanks that are non-regulated.

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SECTOR DESCRIPTION

The Code of Federal Regulations, 49 CFR 173,(1) categorizes hazardous materials (HAZMAT) in nine classes: (1) explosives, (2) flammable and compressed gases, (3) flammable liquids, (4) flammable solids, (5) oxidizers, (6) poisonous materials, (7) radioactive materials, (8) corrosive materials, and (9) miscellaneous other HAZMAT. A significant portion of HAZMAT concerns petroleum and petroleum products (Class 3). The petroleum industry processes 65 percent of the energy that Americans consume. This includes vast quantities of transportation fuels, home heating oil, and industrial fuels, as well as petrochemicals used in the manufacture of countless consumer products.(2) Storage of bulk liquids is routinely done in buried and aboveground tanks. Small quantities of corrosive materials are stored in corrosion-resistant drums or containers.

Background

Almost every industry has a need to store hazardous materials. Example industries include farms, coal, metal and non-metal mineral mining, oil production, construction, manufacturing, chemical, petroleum refining, primary metals industry, railroad fueling, bus transportation, trucking, warehousing, water transportation services, air transportation, pipelines, electric utilities, petroleum bulk stations and terminals, fuel oil dealers, and commercial and industrial users. In addition to private and industrial users of HAZMAT tanks, both the state and federal government operate numerous storage tanks.

The federal government has an elaborate and complicated matrix of regulations regarding hazardous substances. The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980,(3) the Resource Conservation and Recovery Act (RCRA) of 1976,(4) and the Occupational Safety and Health Act (OSHA) of 1970(5) all provide definitions and classifications of hazardous materials. The Code of Federal Regulations, 40 CFR 280,(6) states that metal piping that routinely contains regulated substances and is in contact with the ground must be cathodically protected. Similarly, 49 CFR 195(7) contains the requirements for the transportation of hazardous liquids by transmission pipelines. Although transportation by transmission pipelines will be discussed elsewhere in this report, it is important that this CFR includes requirements for the associated piping and connectors at terminal facilities and stations that send and receive the hazardous liquids.

In addition to federal regulations, there are state and local regulations that may vary by state or county. There are literally thousands of materials that are regulated as hazardous; however, the largest single materials group in volume are the refined petroleum products. These refined petroleum products are affecting nearly every sector of the U.S. economy.

Underground storage tanks (USTs) for the handling and storage of petroleum and hazardous substances are regulated by the U.S. Environmental Protection Agency (EPA) office of underground storage tanks (OUST), (40 CFR 280).(6) OUST uses a definition of UST as those tanks that are buried underground to at least 10 percent of their height. Aboveground storage tanks (ASTs) that are 2.5 m^3 (660 gal) or larger, and USTs that are 159 m^3 (42,000 gal) or larger are regulated by the EPA oil spill prevention program (OSPP) in conjunction with the Spill Prevention Countermeasure and Control (SPCC) plan (40 CFR 112).(8) Under the EPA-SPCC definition, USTs are those tanks that are 100 percent buried.

Under the Clean Water Act (9) and the Oil Spill Pollution Act of 1990,(10) EPA is responsible for protecting the nation's waters from the adverse effects of oil spills. The SPCC regulation, which implements section 311(j) of the Clean Water Act, is designed to prevent discharges of oil from facilities and to contain such discharges when they occur. The regulation applies to "onshore, non-transportation-related facilities" that could reasonably be expected to discharge oil into navigable waters when such facilities have: (1) an aboveground oil storage capacity of more than 2.5 m^3 (660 gal) in a single container, (2) a total aboveground oil storage capacity of more than 5.0 m^3 (1,320 gal) in multiple containers, or (3) a total underground oil storage capacity of more than 159 m^3 (42,000 gal).

The incentives for good corrosion management are clear: maintaining structural integrity, preventing environmental spills, and preventing product contamination. The total number of aboveground and underground SPCC-regulated, OUST-regulated, and non-regulated HAZMAT storage tanks is approximately 8.5 million tanks. Obviously, these tanks represent an enormous investment, and maintaining their structural integrity for a longer service life is in the best interest of their owners.

The Water Enforcement Division of the U.S. EPA Office of Regulatory Enforcement and Compliance Assurance enforces the Oil Pollution Act of 1990. This law prohibits the discharge of threshold amounts of oil or other hazardous substances into navigable waters and requires facilities that store oil to prepare spill prevention plans and to adopt measures to keep accidental releases from reaching navigable waters.

A civil penalty policy was established for EPA litigation of violations. The settlement costs include dollar amounts for seriousness, culpability, mitigation, and history of prior violations. Penalties easily amount to millions of dollars because the size of the tank, the quantity and duration of the spill, negligence and/or willful misconduct, prompt response and mitigation, and previous incidents are considered as well. In addition, in cases where known economic impact would otherwise be minimal, the penalty amount may be increased to ensure that there is sufficient impact to specifically deter the violator from future violations. Also, the penalty amount may be increased if the violator obtained an economic benefit from avoiding or delaying necessary compliance.

Size of Storage Tank Population in the United States

SPCC-Regulated Facilities

In 1996, the EPA estimated the number of facilities subject to SPCC regulations based on the results of 1991 and 1995 surveys of U.S. oil storage facilities.(11) For the 1995 survey, the data were collected by sampling 215 of the 3,111 counties in the 48 contiguous states. Of the 215 counties, 20 stored large volumes of oil and were therefore considered to be "self-representing" in the sample design. The results obtained from the 20 counties were only extrapolated to the population of those counties. Due to the significant difference in total oil storage capacities in those 20 counties, including them with the other 195 counties as part of the overall extrapolation would have generated significantly lower confidence in the resulting estimates. In the 1995 survey, the EPA randomly selected 30,000 recipient facilities in 23 different industries who were likely to include facilities regulated by the EPA. Facilities using crude oil as well as those using refined petroleum products were included. A summary of the results is presented in table 1.

The facility capacity threshold was 5.0 m^3 (1,321 gal); therefore, the categories of study included 5.0 to 159 m^3 (1,321 to 42,000 gal) (aboveground only), 159 to 3,785 m^3 (42,001 to 1,000,000 gal), and more than 3,785 m^3 (1,000,000 gal). The number of facilities was estimated to be 505,000 in the 1991 survey and 386,661 in the 1995 survey. A 1996 estimate placed the adjusted number of facilities at 437,700. The survey data indicated that two categories constitute about 80 percent of the SPCC-regulated facilities: farms (42.2 percent) and oil production (37.3 percent). Manufacturing, transportation, and gas stations/vehicle fueling constitute 12 percent of facilities. All other industries combined make up 8 percent of the facilities. The farms comprise a sizable portion of the SPCC-regulated facilities, but this represents only 8 percent of the U.S. industry, as farms in general have smaller storage capacity, fewer tanks, and lower throughput levels than other types of facilities.

Table 1. National estimate of SPCC-regulated facilities in 1995, as determined by the EPA.[11]

TOTAL FACILITIES IN 1991	TOTAL FACILITIES IN 1995	TOTAL FACILITIES IN 1996 (ADJUSTED)	TANK LOCATION	SPCC-REGULATED FACILITIES	TANK VOLUME CATEGORY	TOTAL TANKS IN 1991	TOTAL TANKS IN 1996 (ADJUSTED)
505,000	386,661	437,700	Aboveground	> 2.5 m^3 (> 660 gal) in single tank, or > 5.0 m^3 (> 1,320 gal) in multiple containers	5 – 159 m^3 (1,321-42,000 gal)	3,141,340	2,373,276
					159 – 3,785 m^3 (42,001-1,000,000 gal)		
					> 3,785 m^3 (>1,000,000 gal)		
			Underground	0.416 – 159 m^3 (110 - 42,000 gal)	Regulated by OUST*		
				Combined capacity > 159 m^3 (> 42,000 gal)	159 – 3,785 m^3 (42,001-1,000,000 gal)	104,851	133,400
					> 3,785 m^3 (>1,000,000 gal)		

* OUST = Office of Underground Storage Tanks

SPCC-Regulated ASTs and USTs

The facilities covered in the SPCC studies included small aboveground (~ 10 m^3 on legs) tanks in the 5 to 159 m^3 (1,321 to 42,000 gal) category as well as large underground tanks in the > 159 m^3 (> 42,000 gal) category. The 1996 report separated tank characteristics by industry in the survey of sample facilities. The average number and size of tanks was calculated to provide an overall estimate using this small sample. Based on this estimate, 3,141,340 (1991) to 2,373,276 (1996 adjusted) aboveground tanks and 104,851 (1991) to 133,400 (1996 adjusted) underground tanks were present at facilities that exceed the combined capacity "42,000 gallons total" OUST regulatory limit. A very large number of small-capacity aboveground tanks at military installations, colleges, and oil production facilities are included in the AST estimates above. If industry categories with average tank capacities under 5.7 m^3 (1,500 gal) are removed, there are 1,067,485 (1991) to 1,124,748 (1996) ASTs in the United States. The 1995 SPCC survey data for both aboveground and underground regulated tanks are summarized in table 2.

The unplanned oil discharges reported in the SPCC survey were analyzed by the location of the failure. The survey showed that 138 (19.7 percent) of 702 reported unplanned oil discharges were caused by material damage as follows: 1 percent tank wall, 2 percent tank bottom, 6 percent tank roof, 7 percent tank piping, and 3 percent tank valve. Damage from loading arms, racks, and other parts accounted for 12 percent of the discharges. Valves, pumps, and other equipment caused 39 percent of the discharges. The remaining 30 percent had other discharge causes.

The unplanned oil discharges reported in the SPCC survey were further analyzed by the nature of the failure. The survey showed that 116 (16.8 percent) of 691 reported that unplanned oil discharges were caused by material failure as follows: 3 percent general structural failure, 1 percent bottom failure, 0.3 percent cold weather brittle failure, 2 percent weld/joint failure, 6 percent valve failure, and 5 percent corrosion. Failure from overfill, operator error, collision with mobile equipment, electrical malfunction, other mechanical failures, alarm failure, fire/explosion, vandalism, natural phenomena, and other failures accounted for the other discharges. This analysis shows that corrosion or other forms of material degradation in the tank construction account for approximately 17 percent of the large financial losses and environmental spills in SPCC-regulated facilities.

Table 2. Summary of 1995 SPCC survey data for both aboveground and underground regulated tanks.(11)

SIC CODE*	INDUSTRY		1995 SPCC SURVEY ESTIMATED NUMBER OF FACILITIES MEETING STORAGE CRITERIA
1	Farms		163,157
12,14	Coal Mining / Nonmetallic Mining		1,849
131	Oil Production		144,349
16	Contract Construction		7,167
20	Manufacturing	Food and Kindred Products	4,314
28		Chemical and Allied Products	3,281
29		Petroleum Refining and Related Industries	827
33		Primary Metals Industries	664
21-27,30-32,34-39		Other Manufacturing	15,526
401	Transportation	Railroad Fueling	16,492
411,413,414,417		Bus Transportation	
42,449		Trucking & Warehouse / Water Transp. Services	
458		Air Transportation	
491	Electric Utility Plants		2,638
5171	Petroleum Bulk Stations & Terminals		6,845
554	Gasoline Service Stations		12,996
751	Vehicle Rental		
5983	Fuel Oil Dealers		2,160
806	Hospitals		3,408
821	Education		
822	Colleges		
97	Military Installations		988
			386,661 TOTAL

*SIC = Standard Industrial Classification

Table 2. Summary of 1995 SPCC survey data for both aboveground and underground regulated tanks (continued).(11)

INDUSTRY	FACILITIES PERCENTAGE	COMMON PRODUCT	AVERAGE NUMBER OF TANKS PER FACILITY	TOTAL ESTIMATED NUMBER OF TANKS	PER FACILITY AVERAGE CAPACITY	PER TANK AVERAGE CAPACITY	TOTAL CAPACITY
	%		Number	Number	m^3	m^3	m^3 x million
Farms	42.2	Diesel	3.5	571,050	171.7	49.1	98.1
Coal Mining / Nonmetallic Mining	0.5	Diesel	4.9	9,060	8.8	1.8	0.1
Oil Production	37.3	Crude Oil	8.5	1,226,967	44.3	5.2	54.4
Contract Construction	1.9	Diesel	5.9	42,285	40.3	6.8	1.7
Food and Kindred Products	1.1	Other	12.7	54,788	162.3	12.8	8.9
Chemical and Allied Products	0.8	Other	8.5	27,889	492.4	57.9	13.7
Petroleum Refining and Related Industries	0.2	Other	65.0	53,755	5,363.1	82.5	288.3
Primary Metals Industries	0.2	Lube Oil	18.5	12,284	38.2	2.1	0.5
Other Manufacturing	4.0	Lube Oil	6.6	102,472	64.4	9.8	6.6
Railroad Fueling	4.3	Diesel	6.3	103,900	176.5	28.0	18.3
Bus Transportation	0.0	Lube Oil	2.0		1.5	0.8	
Trucking & Warehouse / Water Transp. Services	0.0	Lube Oil	5.1		557.0	109.2	
Air Transportation	0.0	Gasoline	6.8		128.4	18.9	
Electric Utility Plants	0.7	Lube Oil	8.8	23,214	1,792.7	203.7	41.6
Petroleum Bulk Stations & Terminals	1.8	Gasoline	10.4	71,188	618.1	59.4	44.0
Gasoline Service Stations	3.4	Gasoline	6.5	84,474	427.3	65.7	36.1
Vehicle Rental	0.0	Diesel	2.5		11.0	4.4	
Fuel Oil Dealers	0.6	Fuel Oil	5.9	12,744	73.2	12.4	0.9
Hospitals	0.9	Fuel Oil	7.0	23,856	41.2	5.9	1.0
Education	0.0	Fuel Oil	4.0		16.0	4.0	
Colleges	0.0	Fuel Oil	28.4		29.6	1.0	
Military Installations	0.3	Fuel Oil	48.9	48,313	90.6	1.9	4.4
	100.2% TOTAL**		**12.6 AVERAGE**	**2,468,239 TOTAL**	**10,348.6 TOTAL**	**24.4 WEIGHTED AVERAGE**	**618.6 TOTAL**

**Individual values do not add up to 100% due to rounding.

Table 2. Summary of 1995 SPCC survey data for both aboveground and underground regulated tanks (continued).[11]

INDUSTRY	AVERAGE AGE	TANKS WITH INTERNAL PROTECTION	TANKS WITH INTERNAL PROTECTION	TANKS WITH EXTERNAL PROTECTION (CP)	TANKS WITH EXTERNAL PROTECTION (CP)	TANKS WITH EXTERNAL COATINGS	TANKS WITH EXTERNAL COATINGS
	Years	%	Number	%	Number	%	Number
Farms	14	8.2	46,826	84.2	480,824	7.7	43,971
Coal Mining / Nonmetallic Mining	10	4.3	390	83.3	7,547	39.7	3,597
Oil Production	17	14.6	179,137	77.0	944,764	15.9	195,088
Contract Construction	17	5.6	2,368	91.6	38,733	43.2	18,267
Food and Kindred Products	14	4.1	2,246	81.0	44,378	43.6	23,887
Chemical and Allied Products	17	6.2	1,729	80.1	22,339	39.5	11,016
Petroleum Refining and Related Industries	39	8.7	4,677	93.5	50,261	20.8	11,181
Primary Metals Industries	19	1.1	135	78.4	9,631	15.8	1,941
Other Manufacturing	13	4.9	5,021	86.8	88,945	17.8	18,240
Railroad Fueling	21	15.7	16,312	92.0	95,588	23.0	23,897
Bus Transportation	2	***		***		***	
Trucking & Warehouse / Water Transp. Services	12	8.9		76.7		41.9	
Air Transportation	12	40.6		77.9		20.2	
Electric Utility Plants	23	6.2	1,439	95.2	22,100	19.0	4,411
Petroleum Bulk Stations & Terminals	20	11.6	8,258	80.5	57,306	26.5	18,865
Gasoline Service Stations	18	16.8	14,192	85.3	72,056	16.9	14,276
Vehicle Rental	3	20.0		80.0		0.0	
Fuel Oil Dealers	24	17.8	2,268	77.0	9,813	29.5	3,759
Hospitals	11	25.0	5,964	92.9	22,162	35.7	8,517
Education	13	22.4		74.5		19.1	
Colleges	13	5.0		89.4		15.5	
Military Installations	13	11.8	5,701	55.8	26,959	15.3	7,392
	16.78 **WEIGHTED AVERAGE**	**12.0% AVERAGE**	**296,663 TOTAL**	**80.8% AVERAGE**	**1,993,406 TOTAL**	**16.5% AVERAGE**	**408,304 TOTAL**

***No value reported.

OUST-Regulated USTs

The Code of Federal Regulations, 40 CFR 280,(6) contains the requirements for underground storage tank (UST) systems. The principal objective of the federal closure requirements is to identify and contain existing contamination and to prevent future releases from UST systems that are no longer in service. These federal regulations became effective on December 22, 1988. The deadline for compliance was December 22, 1998. Although this deadline has passed, many USTs still do not meet the requirements for leak detection, spill and overfill protection, and corrosion protection. UST owners or operators having these non-compliant USTs can be cited, as the result of official UST inspections, for violations and can be subject to penalty fees. To protect human health and the environment, UST owners and operators must take immediate action to upgrade, replace, or close any substandard USTs for which they are responsible.

USTs are not regulated by the Office of Underground Storage Tanks (OUST) when they are smaller than 0.416 m^3 (110 gal) in capacity and are not used to store heating oil that is utilized on the premises. Storage facilities that have a combined underground capacity larger than 159 m^3 (42,000 gal) are also not included in OUST's jurisdiction because they are regulated under the SPCC program. UST owners are required to notify the U.S. EPA of their tanks through EPA Form 7530-1. The information on this form includes the status of the UST (in use, temporarily closed, or permanently closed), the installation date, the estimated total capacity, the materials of construction, the piping material, the piping type, the substance currently stored, the installed release detection systems, and spill and overfill protection systems.

Based on the information supplied on the forms located on the U.S. EPA website,(6) OUST maintains a running total of the number of active tanks in their program, the total number of closed tanks, and the total number of confirmed releases (see table 3). The word "release" in this context refers to a gasoline or oil spill from a leaking UST. The vast majority of this population of regulated tanks are at retail gasoline stations.

Table 3. National totals of underground active tanks in the volume category 0.416 to 159 m^3 (110 to 42,000 gal), closed tanks, and confirmed releases, according to OUST.(6)

REPORTING TIME	NUMBER OF ACTIVE TANKS	ANNUAL CHANGE	NUMBER OF CLOSED TANKS	ANNUAL CHANGE	CONFIRMED RELEASES	ANNUAL CHANGE
1st Half FY 00	742,805	-	1,417,711	-	405,030	-
2nd Half FY 99	760,504	81,656	1,377,115	91,882	397,821	19,103
1st Half FY 99	824,461		1,325,829		385,927	
2nd Half FY 98	891,686	95,079	1,236,007	139,488	371,387	27,628
1st Half FY 98	919,540		1,186,341		358,269	
2nd Half FY 97	969,652	112,420	1,150,824	75,075	341,773	28,329
1st Half FY 97	1,031,960		1,111,266		329,940	
2nd Half FY 96	1,064,478	61,058	1,074,022	67,829	317,488	15,220
1st Half FY 96	1,093,018		1,043,437		314,720	
	AVERAGE	**87,553**	**AVERAGE**	**93,569**	**AVERAGE**	**22,578**

Indirect Corrosion Costs – Remediation of UST Spills

As a comparison to the OUST data, a 1997 American Petroleum Institute (API) survey, published in 1998,(2) was reviewed. In that API survey, the 14 participating companies reported on their 19,000 gasoline service station facilities with almost 74,000 tanks (average 3.9 tanks per station). In comparison with the 1,031,960

OUST-regulated tanks in 1997, the API numbers indicated that approximately 7.2 percent (74,000 / 1,031,960 x 100 percent) of the national UST population was represented.

The API survey reported the total estimated U.S. environmental expenditures and the expenditures on remediation and spills for the years 1990 through 1996 (see table 4). In 1996, the petroleum industry spent a total of approximately $8.2 billion on the environment, or $83 per U.S. household. The annual costs for remediation and spills were reported to vary between $947 million and $1.334 billion, as specified by the participants in the API survey. Between 1990 and 1996, on average, the remediation and spill costs were $1.171 billion, which is 12.4 percent of the total environmental expenditures. The remediation and spill costs in the API survey did not include the environmental expenditures for air, water, wastes, and other types of pollution, in exploration and production, transportation, refining, marketing, and research and development.

Table 4. Total U.S. environmental expenditures (in millions of dollars) from 1990 to 1996, as estimated by the American Petroleum Institute (API).(2)

	Exploration & Production	**Transportation**	**Refining**	**Marketing**	**Research & Development**	**Corporate Programs**	**Subtotal**	**Remediation & Spills***	**Total**
1990	1,525	666	3,710	440	175	147	6,663	1,124 (14.4%)	7,787
1991	1,553	737	4,118	646	227	121	7,402	1,332 (15.3%)	8,734
1992	1,566	966	5,808	641	214	78	9,273	1,250 (11.9%)	10,523
1993	1,563	972	5,698	742	227	246	9,448	1,198 (11.3%)	10,646
1994	1,559	872	5,933	732	175	194	9,465	1,177 (11.1%)	10,642
1995	1,322	809	5,509	508	156	141	8,445	1,169 (12.2%)	9,614
1996	1,582	1,013	3,958	432	103	187	7,276	947 (11.5%)	8,222
AVG	**1,524**	**862**	**4,962**	**592**	**182**	**159**	**7,425**	**1,171 (12.4%)**	**9,453**

*Aggregate amounts reported by participants in API's survey.

The report did not specify the origin of the remediation costs in terms of the root causes that lead to the remediation efforts; therefore, the remediation costs could not be directly related to corrosion costs. However, remediation is the term used for the clean-up of oil products and other hazardous materials that is necessary after leaking equipment is located. Leaks originate from holes and cracks in the tanks, pipes, and piping as they are formed by corrosion. Therefore, it is reasonable to assume that the environmental remediation costs are an indirect cost of corrosion. The API survey showed an estimate of these indirect annual corrosion costs as $1.171 billion per year.

Unregulated Tanks

Unregulated USTs are more difficult to quantify than the regulated tanks. There are a very large number of unregulated small USTs used for heating oil in homes, small businesses, utility backup generators, and for use on the premises in large businesses. In the March 2000 Hazardous Materials Program Evaluation (HMPE) report,(12) basic home heating oil survey data were reported, based on data provided by the Department of Energy. These data included the number of households in each category and the average cubic meters consumed annually by each household. The average delivery size (transport) and the annual number of deliveries were estimated by the Research and Special Programs Administration (RSPA) of the Office of Hazardous Materials Safety based on its understanding of home heating oil (distillate) and propane tank sizes.

The HMPE data showed that an estimated daily total of 89,420 deliveries (482,081 barrels) are made for distillate home heating oil, 56,057 deliveries (268,069 barrels) are made for liquid propane gas (LPG), and

7,712 deliveries (21,637 barrels) are made for kerosene. These estimates include single-family homes and mobile homes, and account for pick-up and delivery.

If the assumption is made that the average unregulated tank size is 1.893 m^3 (500 gal), and a tank is three-quarters filled [1.420 m^3 (375 gal)] with each delivery, the total number of unregulated tanks can be estimated as follows:

Heating oil tanks: 482,081 barrels/day x 365 days/year x 159 liters/barrel x 1 delivery / 1,420 liters x 1 tank / 6 deliveries per year = 3,283,752 tanks

LPG/propane tanks: 268,069 barrels/day x 365 days/year x 159 liters/barrel x 1 delivery / 1,420 liters x 1 tank / 6 deliveries per year = 1,825,984 tanks

Kerosene tanks: 21,637 barrels/day x 365 days/year x 159 liters/barrel x 1 delivery / 1,420 liters x 1 tank / 6 deliveries per year = 147,383 tanks

Summary of Tank Totals

The total estimated number of tanks is summarized in table 5. The regulated tanks are divided into SPCC-regulated and OUST-regulated tanks, and the numbers are based on several reports. The estimates for non-regulated tanks were determined based on the sales of various heating fuels.

Table 5. Summary of estimated total number of aboveground and underground storage tanks in the United States (see references 6, 11, 12, and 13).

	REGULATED BY	**YEAR**	**PRODUCT**	**LOCATION**	**NUMBER OF TANKS**
REGULATED TANKS	SPCC	1996	Petroleum products	ASTs	2,373,276
				USTs	133,400
	OUST	2000	Petroleum & HAZMAT	USTs	742,805
UNREGULATED TANKS	-		Heating oil	ASTs and USTs	3,283,752
			LPG/propane	mostly ASTs	1,825,984
			Kerosene	mostly ASTs	147,383
				TOTAL	**8,506,600**

Estimating Corrosion Costs

In order to estimate the total cost of corrosion for hazardous materials storage, corrosion experts Lary and Garrity(14-15) were asked to estimate the value of corrosion measures commonly taken for tanks. Table 6 summarizes these values, both for aboveground and underground tanks. Table 7 gives estimates of the purchase costs for new tanks as a comparison to the relative corrosion control costs per tank.

For aboveground storage tanks, the corrosion experts(14-15) estimated that 30 percent have cathodic protection (CP), 10 percent have internal linings, and 100 percent are externally coated. An internal lining is generally only applied for tanks that often change products, or that contain products with a large water ballast.

Table 6. Estimated corrosion control costs for aboveground and underground storage tanks.(14-15)

	CORROSION CONTROL	COST
ABOVEGROUND	External coating / painting	$\$86 / \text{m}^2$ ($\$8 / \text{ft}^2$)
	Internal flake glass polyester lining	$\$689 / \text{m}^2$ ($\$64 / \text{ft}^2$)
	CP for tank bottom on grade	\$15,000 for 30.5-m- (100-ft-) diameter tank
UNDERGROUND	Impressed-current CP	\$10,000 - \$12,000 / 3 tanks, inc. assessment
	Electricity for CP	\$234 / year for three tanks
	Inspection impressed-current CP	\$25 every 60 days, voltage and current reading
	Inspection impressed-current CP	\$800 / year for three tanks
	Sacrificial anode CP	\$250 / anode, design life is 20 years
	Inspection sacrificial anode CP	\$800 / 3 years, some states every year
	Internal lining	\$3,500 - \$7,000 / tank, inc. surface preparation
	Structural integrity assessment	\$2,000 - \$3,000 / three tanks in same pit
	Gain access to tanks	\$1,500 - \$2,000 / tank
	External coating	$\$10.76\ \text{m}^2$ ($1.00 / \text{ft}^2$), appearance coating on new tanks, to prevent flash rusting during transport

Table 7. Comparison of capital cost for new tanks with a capacity of 37.8 m^3 (10,000 gal).(14-15)

	MATERIAL	NEW COST PRICE
UNDERGROUND	Fiberglass tank	\$7,500
	Steel – single-wall tank, sti-P$_3$®	\$5,000 - \$6,000
	Steel – double-wall tank, sti-P$_3$®	\$10,000 - \$12,000
	Glass steel tank, heavily coated	\$8,000 - \$12,000

To simplify the calculations, they indicated that gas stations generally have three grades of gasoline (regular, plus, and premium), which are stored in three separate underground tanks. In most new installations, these three tanks are equipped with a single rectifier for impressed-current CP. They noted that the percentage (85.3 percent) of gasoline service stations with CP mentioned in the 1995 SPCC survey was probably a high estimate because, in recent years, many tanks have been replaced with fiberglass tanks. The SPCC survey data reported that of all reported ASTs and USTs included in the survey, the following forms of external protection were present: 18 percent no external protection, 65 percent painted / asphalt coating, and 10 percent CP. Lary and Garrity(14-15) estimated that at gasoline service stations, the current percentage of tanks with CP is approximately 30 percent.

A concern expressed by the experts was that, in many cases, the CP design is only focused on the tanks themselves, and not on the connected piping. They indicated that future corrosion leaks are likely in the piping between the tanks and the gasoline dispensers due to this lack of attention. For comparison, the 1995 SPCC survey showed that the location of piping of ASTs and USTs was as follows: 29 percent both aboveground and underground, 43 percent aboveground, 12 percent underground, and 16 percent reported to have "no piping." The data further showed that more than half of the piping is steel or iron, and about one-quarter is galvanized steel piping. The other piping materials used are fiberglass (FRP), copper, lead, aluminum, and a variety of plastics.

In general, tanks at gasoline service stations are USTs that are too small [< 159 m^3 (< 42,000 gal)] to be included in the SPCC survey. All piping (100 percent) of USTs at gasoline service stations is located underground. Similar to what the SPCC data showed, most piping at gasoline service stations is made of steel, iron, or galvanized steel. Galvanizing is only a temporary form of corrosion protection because the thin zinc layer is sacrificial, and after the zinc is consumed, the pipe has turned into bare, unprotected steel. A corrosion concern in the underground piping system is the presence of flexible couplings with an external stainless steel jacket. If these couplings are not isolated from the adjacent piping, galvanic corrosion may result from the more noble stainless steel at the expense of the piping. Similar concerns arise from stainless steel swing joints, fittings, and impact valves.

The SPCC data showed that the piping reported in that survey had the following forms of external protection: 35 percent painted / asphalt coating, 9 percent CP, 12 percent jacketed or wrapped, 42 percent "no protection," and 3 percent other forms of external protection.

AREAS OF MAJOR CORROSION IMPACT

Bulk storage of hazardous liquid and gaseous materials is normally done in large steel tanks. The largest aboveground tanks are used at refineries and manufacturing plants. These range from 15 m (50 ft) to more than 61 m (200 ft) in diameter and may have a capacity of more than 3,785 m^3 (1 million gal). Transportation and distribution terminals of storage facilities for these materials can have a mix of aboveground and underground tanks. Liquid petroleum products at the point of sale and at the point of use are normally stored in direct buried underground tanks ranging from 1.9 to 114 m^3 (500 to 30,000 gal) in capacity. Gases are typically stored in similarly sized aboveground tanks at the point of use. Hazardous chemicals are usually stored in vaulted underground tanks or aboveground facilities. Storage tanks for pressurized materials can be spherical in shape, while storage tanks for unpressurized materials can be constructed from welded steel plate (see figures 1a and 1b, respectively).

Figure 1a. Pressurized storage tanks.

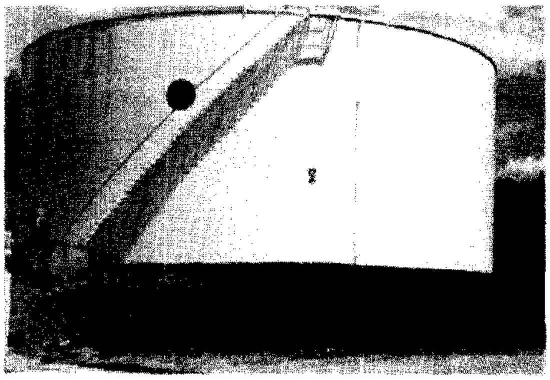

Figure 1b. Unpressurized storage tank.

Aboveground Storage Tanks

Large steel aboveground storage tanks (ASTs) are generally located on large tank farms of oil producers (see figure 2). Maintenance teams take care of external painting and internal and external corrosion inspections. Corrosion protection of ASTs is important for the preservation of large capital investments, the reduction of maintenance and inspection costs, and the assurance of system integrity for release prevention. ASTs are subject to a variety of internal and external corrosion mechanisms. In his book on ASTs,(16) Myers describes the different corrosion mechanisms and causes of corrosion (see figure 3).

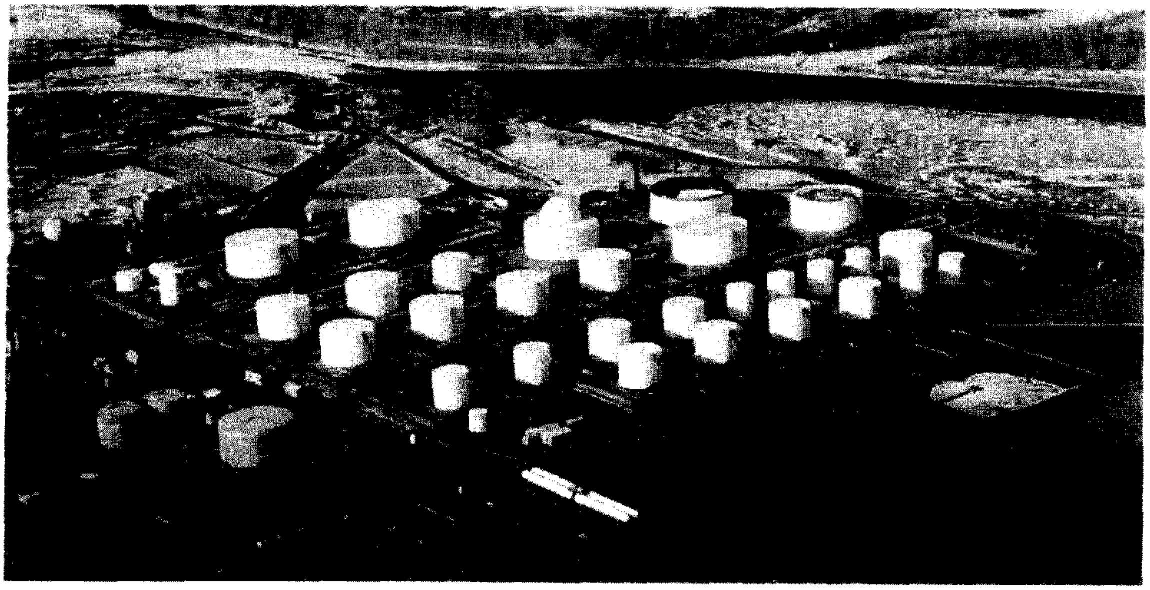

Figure 2. Example of an oil storage tank farm, showing multiple tanks of varying sizes.

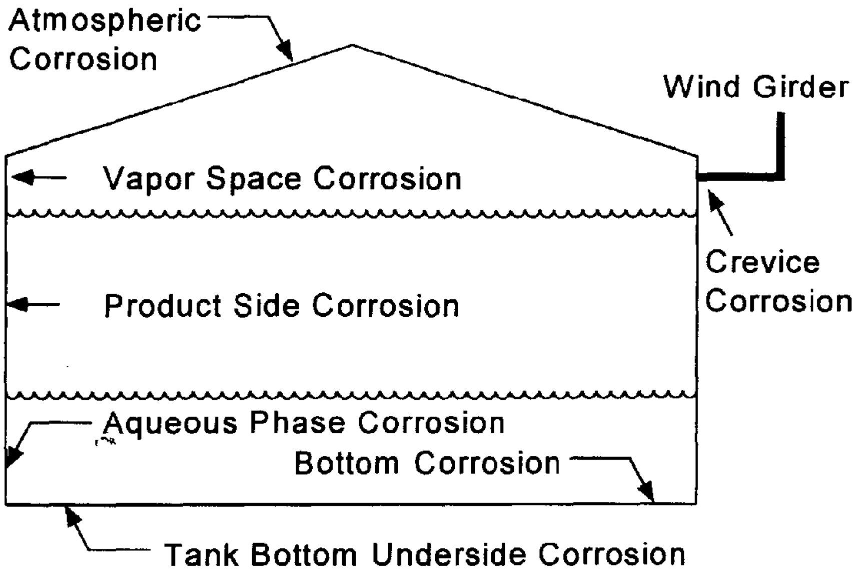

Figure 3. Internal and external corrosion modes that may occur at an aboveground storage tank.(16)

Internal Corrosion

There are several different corrosion conditions in the interior areas of an aboveground tank. Vapor phase corrosion can occur in the areas exposed to the vapor above the stored product, and includes general, crevice, and pitting corrosion, depending on the temperature and the characteristics of the material. Product side corrosion can occur on the internal wall plate when corrosive materials are stored. This type of corrosion includes general and pitting corrosion. At the interface of liquid and gas in a tank, the corrosion rate is often accelerated because the oxygen or moisture concentration gradient at the interface varies with depth into the liquid. Aqueous phase corrosion can occur when water contamination and settling in petroleum products result in a layer of water on the bottom of the tank. Although the product may be non-corrosive, the presence of contaminants such as sludges and deposits may result in internal bottom and wall general corrosion, crevice corrosion, and pitting corrosion damage. In addition, microbiologically influenced corrosion (MIC) can be a problem under anaerobic conditions. The internal corrosion problems are exacerbated by the stresses and flexing that the metal undergoes during fluctuations in product levels.

External Corrosion

Atmospheric corrosion of the external wall and the roof is a result of general corrosion and crevice corrosion damage. Aboveground tanks suffer from external corrosion as a result of the tank bottom sitting on a grade with a variety of corrosive padding materials or on a back-filled concrete ring wall. Both types of tank bottom supports can cause external pitting of the bottom plate steel. Small aboveground tanks suffer from external atmospheric corrosion, but to a lesser degree because they can be supported off the ground and the rounded surface minimizes crevice corrosion opportunities.

Underground Fuel Storage Tanks

Underground fuel storage tanks are a very large and dominant portion of the hazardous materials storage sector. Corrosion is estimated to be responsible for approximately 65 percent of tank failures, while 35 percent is due to other causes such as third-party damage.(13) Experience has shown that the vast majority of underground storage tanks (USTs) and piping failures are associated with external corrosion, while a small percentage can be attributed to internal corrosion.

One of the primary causes of external corrosion is exposure to corrosive soils. The electrical and chemical characteristics of soil and water are closely related to corrosivity. Variations in soil characteristics due to soil type, fill compaction, moisture content, bacteria, chloride concentration, etc. help establish corrosion cells. Over time, if untreated, this process can result in significant wall-thickness reduction and can cause leaks. The six o'clock position of USTs is one of the most critical locations because that is the rest point where the tank bottom touches the bottom of the hole dug for the tank. At that location, the layer of backfill is relatively thin; therefore, the soil characteristics can be different than in the adjacent soil, setting up conditions for macro-cell corrosion.

Similar to the aboveground tank phenomena, internal corrosion can occur from contaminants that settle on the tank bottom, under the stored product. Vapor phase corrosion is usually limited due to the relatively constant temperature. A particular tank failure type, which is sometimes reported for gasoline service stations, is localized internal corrosion at the location where the internal lining is damaged. The inspector's level-stick may cause mechanical damages to the lining, resulting in corrosion. Generally, a wooden pole is used to check the gas level in the UST. Lining damage occurs at the location where the pole hits the bottom of the UST.

CORROSION CONTROL METHODS

Aboveground Storage Tanks

Corrosion of tank bottoms, walls, roofs, and roof structures can pose dangers to their structural integrity. Corrosion may cause leaks that result in loss of product or pollution of the soil and water around a tank. Leaks can also make it possible for water to penetrate into the tank and contaminate the product itself.

Corrosion control and prevention can take many forms. It may take the form of a design detail, such as the application of a corrosion allowance to sophisticated lining systems and cathodic protection devices. Myers(16) listed the most common methods of corrosion control and prevention:

- linings ("bladder") / coatings (paints),
- corrosion allowances,
- design (avoidance of dissimilar metals, galvanic couples, improper materials, high fluid velocities in inappropriate places, caulking or seal welding of areas susceptible to crevice corrosion, roof design, etc.),
- sacrificial anodic systems,
- impressed-current cathodic protection, and
- use of high-alloy (corrosion-resistant) materials.

Tanks designed for materials that produce corrosive vapors often include roof and roof support structures (pontoons for floating roofs) that are made of corrosion-resistant materials. Petroleum tanks that are subject to a contaminated water layer are internally coated and cathodically protected on the bottom and partially along the wall. The external bottom corrosion of site-fabricated tanks (most tanks more than 4 m in diameter) can be controlled with a combination of select sand/concrete foundation pads, impervious liners, and cathodic protection. A list of corrosion control methods for aboveground storage tanks, as described by Myers,(16) is given in table 8.

Table 8. Corrosion control methods for aboveground storage tanks, based on Myers.(16)

CORROSION TYPE	CONTROL METHOD
UNIFORM CORROSION	Inhibitors Protective coating Cathodic protection
INTERGRANULAR CORROSION	Avoiding temperatures that can cause contaminant precipitation during heat treatment or welding
PITTING CORROSION	Protective coating Allowing for corrosion in wall thickness
STRESS CORROSION CRACKING	Reducing residual or applied stresses Redistributing stresses Avoiding misalignment of sections joined by bolts, rivets, or welds Use of materials of similar expansion coefficients in one structure Protective coating Cathodic protection
CORROSION FATIGUE	Minimizing cyclic stresses and vibrations Reinforcing critical areas Redistributing stresses Avoiding rapid changes in load, temperature, or pressure Inducing compressive stresses through peening, swagging, rolling, vapor blasting, chain tumbling, etc.

Table 8. Corrosion control methods for aboveground storage tanks, based on Myers[16] (continued).

CORROSION TYPE	CONTROL METHOD
GALVANIC CORROSION	Avoiding galvanic couples Completely insulating dissimilar metals (paint alone is insufficient) Using filler rods of same chemical composition as metal surface during welding Avoiding unfavorable area relationships Using favorable area relationships Cathodic protection Inhibitors
THERMOGALVANIC CORROSION	Avoiding non-uniform heating and cooling Maintaining uniform coating or insulation thickness
CREVICE CORROSION; CONCENTRATION CELLS	Minimizing sharp corners and other stagnant areas Minimizing crevices, especially in heat transfer areas and in aqueous environments containing inorganic solutions or dissolved oxygen Enveloping or sealing crevices Protective coating Removing dirt and mill scale during cleaning and surface preparation
EROSION; IMPINGEMENT ATTACK	Decreasing fluid stream velocity to approach laminar flow Minimizing abrupt changes in flow direction Streamlining flow where possible Installing replaceable impingement plates at critical points in flow lines Filters and steam traps to remove suspended solids and water vapor Protective coating Cathodic protection
CAVITATION DAMAGE	Maintaining pressure above liquid vapor pressure Minimizing hydrodynamic pressure differences Protective coating Cathodic protection Injecting or generating larger bubbles
FRETTING CORROSION	Installing barriers that allow for slip between metals Increasing load to stop motion, but not above load capacity Porous protective coating Lubricant
HYDROGEN EMBRITTLEMENT	Low-hydrogen welding electrodes Avoiding incorrect pickling, surface preparation, and treatment methods Inducing compressive stresses Baking metal at 93 to 148 °C (200 to 300 °F) to remove hydrogen Impervious coating such as rubber or plastic
STRAY-CURRENT CORROSION	Providing good lubrication on electric cables and components Grounding exposed components or electrical equipment Draining off stray currents with another conducting material Electrically bonding metallic structures Cathodic protection
DIFFERENT-ENVIRONMENT CELLS	Underlaying and backfilling underground pipelines and tanks with the same material Avoiding partially buried structures Protective coating Cathodic protection

Internal Coatings

Internal coatings protect the structural integrity of the tank by preventing internal corrosion. These coatings generally have a design life of 10 years or more for larger tanks. A coating system is selected based on the location within the tank: bottom, water layer, product exposed, vapor space, and roof structure. In addition, coatings are sometimes used to maintain product purity. Often, the internal bottom surface must be able to withstand the abrasive effects of slurry movement caused by internal flow patterns, mixers, or inlet and outlet flows, or by mechanical actions, such as by the movement of roof drain hoses lying on the tank bottom. A benefit of a bottom liner is that it reduces the cleaning effort when the tank is removed from service for repairs or for inspection.

External Coatings

Painting the exposed external surfaces of an aboveground storage tank provides corrosion protection, improved appearance, and reduced evaporation loss. Selection of the coating type depends on the tank operating temperature and the presence of insulation that contains minerals and salts that may cause corrosion. External coatings must be able to withstand the effects of weather, ultraviolet light, and industrial or marine atmospheres.

Cathodic Protection on ASTs

Aboveground storage tank (AST) farms have a network of CP rectifiers and anodes to protect the tank bottoms. The design of cathodic protection (CP) for new or existing ASTs can be done according to the API Recommended Practice for Cathodic Protection of Aboveground Storage Tanks.(17) Design considerations include the proximity to other metallic structures and existing CP systems, the type of grounding, the estimated remaining service life of the tank, the type and temperature of the stored product, the amount of product stored, the cycling rates, the method of tank bottom plate construction, the type of tank foundation, the type of secondary containment, if any, and the backfill soil characteristics. There are two types of CP: (1) sacrificial anode CP, by zinc or magnesium ribbon or ingot anodes, and (2) impressed-current CP, using perimeter, deep-buried, angle-drilled anodes or vertical, loop, or string under-tank anodes. Depending on the above parameters, the CP type, and the diameter of the tank, CP installation costs for an AST tank bottom may range from $10,000 to $25,000 per tank. Based on recent quotes, $15,000 would be considered average.

Underground Storage Tanks

Corrosion control of the external surfaces of underground storage tanks[2] can be achieved with a combination of cathodic protection and dielectric coating. However, an external coating must be applied when the tank is new. A buried tank cannot be retrofitted with an external coating unless it is removed from the ground. Internal corrosion protection, where required due to contamination or corrosive products, is commonly maintained with an internal liner, sometimes in combination with galvanic cathodic protection.

Cathodic Protection on USTs

CP is based on the reversal of the electrochemical current that occurs in the corrosion process. Two systems of CP are used: (1) sacrificial anode systems and (2) impressed-current systems.

The first system is based on the burial of anodes in the electrical proximity of the tank. The anodes are generally made of magnesium or aluminum, both of which are metals less noble than the steel of the tank. This forces the current to flow from the sacrificial anode (Al or Mg) to the cathode (tank). Over time, the anodes are consumed and must be replaced for continued corrosion protection of the tank.

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[2] Federal regulations define an underground storage tank as a tank system having a volume at least 10 percent of the system underground.

The second system is based on the application of an impressed current that is forced through anodes to the protected structure (the tank) by a current source of sufficient potential. Properly designed CP systems that are well-maintained and operate at the correct current density are a proven method of protecting tanks from the corrosive effects of contact with corrosive soils. In addition to protection of underground tanks, CP is also useful for aboveground double-bottom tanks and for internal corrosion protection.

CORROSION MANAGEMENT

The optimum corrosion methods for ASTs and USTs depend on the materials stored and on the exposure of the tanks to corrosive environments. Most tanks are constructed using welded steel, which must be protected from internal corrosion due to the tank content and from external corrosion due to exposure to moisture-rich environments such as soils or the atmosphere. This can be addressed with internal linings, external coatings, and cathodic protection. If designed, installed, and maintained properly, the life of a tank can be almost indefinite. However, tanks may experience unforeseen problems such as damaged coatings or long intervals between CP inspections.

Larger companies have corrosion experts as part of their staff and usually maintain schedules for regular inspection and maintenance. In recent years, however, the process industry, and particularly the oil and gas industry, has continuously and purposely decreased their research centers that had the necessary level of awareness and expertise. Currently, larger companies tend to outsource this type of work to contractors that work at a cheaper price. Although not proven, in the long run, this procedure may prove to be more costly as corrosion defects may go undetected for longer periods of time.

The incentives for better corrosion management are clear: improved structural integrity, fewer leaks to soil or water, and a decreased probability of moisture being introduced into the product. In general, new tank construction has some forms of corrosion design built in. The sti-$P_3^{®}$ tanks, polymer tanks, fiberglass tanks, and externally painted tanks are just a few examples. However, these tanks age and will need continued maintenance and inspection. Older tanks may not have these corrosion control systems, or the systems may be ineffective.

In recent years, the federal government has given a lot of attention to the environmental impact of leaking ASTs and USTs. The EPA Spill Prevention Countermeasure and Control (SPCC) plan and the EPA Office of Underground Storage Tanks (OUST) maintain databases on the number of active tanks. The remediation and spill costs for cleaning soil and water around leaking tanks can be significant. For example, according to the 1998 API report, these indirect corrosion costs were estimated in table 4 at $1.171 billion per year and are attributed to leaks caused by corrosion.

For this sector, three case studies were performed to estimate the total cost of corrosion for different types of tanks. The numbers are summarized in tables 9 and 10. The direct corrosion costs ($2.5 + $4.5 = $7.0 billion per year) are paid by the commercial owners of the tanks because they benefit from the structural integrity and long service lives of the tanks. The federal government regulates those tanks that have a potential environmental impact in an effort to recover the indirect costs of remediation and spills. The API report shows that this recovery method results in an annual spending of $1.171 billion by the oil industry.

Table 9. Corrosion costs for USTs at gas stations.(2,14-15)

WHICH TANKS	CORROSION ITEM	CORROSION COST ($ x million / year)	REFERENCE
USTs at gasoline service stations	Sacrificial CP	52	Case study 2 [Refs. 14-15]
	Impressed-current CP	137	
	Internal linings	79	
	Remediation and spill costs	1,171	1998 API report [Ref. 2]
	TOTAL	**$1,439**	

Table 10. Summary of corrosion costs divided by tank location and corrosion control method.(14-15,18)

WHICH TANKS	CORROSION ITEM	CORROSION COST ($ x million / year)	REFERENCE
All USTs	**TOTAL**	**$2,458**	Case study 1, EPA website [Ref. 18]
All ASTs	Tank bottom CP	1,231	Case study 3 [Refs. 14-15]
	Internal linings	472	
	External coatings	2,803	
	TOTAL	**$4,506**	

The sti-P_3® System

The Steel Tank Institute (STI) developed a specification for underground steel storage tanks, the so-called the sti-P_3® system.(19) This now popular specification was first developed in 1969 for STI by leaders in the field of corrosion engineering. It covers an external corrosion control system (termed sti-P_3®) for underground steel storage tanks. The system is a practical and economical means of extending the service life of underground tanks from a minimum of 30 years in corrosive soil conditions to an indefinite term in less severe environments. The design includes a safety factor that will allow for somewhat more than ordinary damage to the external coating of the tank from shipping and handling and other accidental coating holidays.

Traditionally, steel tanks used for underground storage of petroleum products have been protected with an inexpensive coating to prevent corrosion of the tank during storage of the tank aboveground and after installation underground. This practice has been adequate in some soils, but has invariably been unsatisfactory in corrosive soils. Previously, the known methods of applying stringent corrosion control to tanks were not feasible because they required handling by experienced corrosion personnel.

The sti-P_3® method of corrosion protection overcomes these problems and still retains all the advantages of a steel tank with its structural strength. The sti-P_3® system combines three basic methods of underground corrosion control, all of which are installed on the tanks during manufacture: (1) cathodic protection, (2) protective coating, and (3) electrical isolation of the tank from other underground metallic structures by use of non-conductive bushings or similar methods that isolate the tank electrically from the piping.

The salient feature of the design is that it is pre-engineered and is provided by the tank fabricator as an integral part of the tank. This aspect eliminates costly on-site engineering, misunderstood installation requirements, and concern over the effectiveness of the corrosion control used. Furthermore, the sti-P_3® system turns itself on after the tank has been buried and provides cathodic protection for a minimum pre-determined length of time in a given soil.

The methods employed by the sti-P_3® system to prevent exterior corrosion were developed by corrosion engineers and have been successfully used on pipelines and other underground structures for more than 50 years. Although the basic methods are quite different in their way of protecting steel underground, they are related and must be used in combination with each other to achieve complete protection. For example, protective coating should not be used alone because, in practice, no coating will be free of holidays. Some corrosion engineers submit that coating alone is approximately 75 percent effective against corrosion, whereas coating supplemented with cathodic protection results in a combined effectiveness that approaches 100 percent corrosion control.

The only practical approach to a pre-engineered CP system for this application is using sacrificial anodes attached to the tank in a manner similar to that employed for ship hull protection. The protective coating serves to reduce the amount of protective current needed for cathodic protection. Electrical isolation bushings or flange isolators are installed in each tank opening to prevent contact between the tank and other nearby metal structures, and to reduce the chance of stray current corrosion or excessive CP current demand.

Galvanic anodes develop their own protective current because of the natural potential difference between the anode metal and the metal being protected. This means that the anode system is self-activated after the tank is buried and that the CP current will continue to provide corrosion control until the anode is consumed by corrosion. Based on the estimate of the average current produced by the anodes in a given soil, the useful life of the anode system can be readily calculated.

Polymer Tanks

Polymer tanks are commonly used when people do not want to deal with the maintenance issue. The philosophy is to start from scratch with a corrosion-resistant material and to prevent corrosion altogether. The use of polymer tanks is an option if the stored quantity is less than 5.7 m^3 (15,000 gal). The tanks can then be constructed of molded polymers or fiber-reinforced thermoset polymers. High-density polyethylene (HDPE) is commonly used for chemical storage tanks and for chemicals that contain water. However, HDPE is not applicable for the storage of hydrocarbons or for long-term storage at temperatures higher than 50 °C. In this case, or if higher temperatures (50 to 200 °C) are a problem, fiberglass reinforced tanks made with resins, such as vinyl ester or epoxy, can be used. For more elevated temperatures (> 200 °C), metal storage tanks are the only solution.

Polymer storage tanks may be susceptible to forms of material degradation such as cracking and pinholes; therefore, they should be inspected regularly. Many fiberglass tanks that were produced in the early 1980s are not compatible with additive substances such as methanol or ethanol. Today, these liquids are commonly blended into gasoline and, therefore, many service stations are removing their fiberglass tanks to replace them with tanks constructed of corrosion-resistant materials.

CHANGES FROM 1975 TO 2000

In the last 25 years, the federal government has developed more and more regulations for HAZMAT storage. Rules that served as a foundation for current regulations include the Clean Water Act;(9) the Resource Conservation and Recovery Act;(4) the Comprehensive Environmental Response, Compensation, and Liability Act;(3) and the Oil Spill Pollution Act.(10)

After initial periods of survey studies, task force recommendations, and interim regulations, many of the ideas have matured into the current code of federal regulations. Examples are the regulations for USTs in 40 CFR 280,(6) the regulations for spill prevention countermeasures and control in 40 CFR 112,(8) and the regulations for transportation of hazardous liquids by pipeline in 49 CFR 195.(7)

In interviews with people from the HAZMAT storage industry, the opinion was expressed that the federal government is likely to expand from an exploratory function to a more strict enforcement function. Voluntary surveys, such as the 1995 SPCC survey, are expected to be replaced with mandatory questionnaires and inspection intervals appropriate to high-consequence areas. This predicted trend for tanks is already visible in efforts in the transmission pipeline industry, where risk-based assessment is based on failure probability and the location of pipelines in high-consequence areas.

The changes in regulations towards HAZMAT storage are mostly related to their environmental impact in case of an unplanned release. Schenke(20) reviewed these changes in a recent presentation. The EPA's oil pollution prevention regulation 40 CFR 112,(8) otherwise known as the Spill Prevention Countermeasure and Control (SPCC) regulation, applies to non-transportation-related facilities that have oil storage capacities above certain thresholds and are located such that a release could reasonably be expected to reach U.S. waters. The EPA estimated in 1996 that there were approximately 435,000 SPCC-regulated facilities.

In recent years, analyses of the causes and responses to large oil spills and other events have demonstrated the need to revise the regulation addressing the storage, transportation, and handling of oil and petroleum products, including the SPCC regulation that requires preparation and implementation of SPCC plans.

On January 2, 1988, the collapse of a 15,120-m^3 (4-million gal) aboveground storage tank owned by Ashland Oil Company resulted in a spill of approximately 2,839 m^3 (750,000 gal) of diesel fuel into the Monongahela River. Approximately 11,356 m^3 (3 million gal) of the diesel fuel, however, was contained in a secondary containment dike required by the existing SPCC regulation. This spill led to the formation of an interagency SPCC task force to review federal regulations governing oil spills from aboveground storage tanks and to recommend actions to improve the program.

In 1996, the EPA published the results of the 1995 Spill Prevention Countermeasure and Control (SPCC) plan survey. The data from this survey indicated that when a facility replaces a UST, the trend is toward replacing USTs with ASTs. In the 2 years before the survey, approximately 8 percent (5,062) of the SPCC-surveyed facilities replaced a total of 27,462 USTs with 17,195 new tanks, of which 56 percent were ASTs and 44 percent were USTs. The analysis also indicates that fewer tanks are being used to replace USTs. There are two possible explanations for this occurrence. If the amount of oil stored is unchanged, the majority of USTs are being replaced with ASTs of greater storage capacity. Another explanation is that the amount of oil stored has decreased and the USTs that were removed were not replaced.

For the period 1996 to 2000, the data from the EPA Office of Underground Storage Tanks showed this trend as well, in the form of the number of closed tanks per year (see table 8). In the last 5 years, the rate of closing USTs has been, on average, 93,000 USTs per year.

CASE STUDIES

Case Study 1. How Much Does It Cost to Upgrade, Replace, or Close UST Systems?

The information in this case study was taken from the website of the U.S. EPA Office of Underground Storage Tanks.(18) On this website, the EPA supplies "cost estimates" to upgrade USTs. All "cost estimates" are educated guesses. First, it is noted that cost estimates vary significantly depending on the circumstances of the specific UST site. Some of the controlling factors include:

- the nature of the surrounding soil and structures,
- labor costs (rural vs. urban, regional variations),
- length of downtime (installation may last several days),

- amount of labor required (especially time to break through existing site "covering pads"),
- reductions based on having work done at the same time (for example, having spill, overfill, and corrosion protection all installed at the same time), and
- differences between vendors, and inflation over time (these estimates reflect costs in early 1998).

Cost Estimates to Upgrade USTs

Table 11 shows cost estimates for upgrading USTs, as estimated by the EPA. For example, a cost estimate for a three-tank upgrade using spill buckets, butterfly valves, and impressed current alone would be approximately $12,700. With additional retrofits of an automatic overfill system, float valves, and internal linings, the total cost as illustrated in table 11 is $33,000.

Table 11. Approximate costs to add spill, overfill, and corrosion protection, based on a three-tank facility, labor costs, and 24 hours or less of downtime, as reported by EPA.[18]

COST	EQUIPMENT / LABOR
$1,200	3 Spill buckets
$1,500	3 Automatic shutoff (butterfly) devices
$5,000	Automatic overfill alarm (includes 3 probes and 1 automatic tank gauging system)
$300	3 Ball float valves
$15,000	Interior lining of 3 tanks (more than 24 hours downtime)
$10,000	Impressed-current system, including an assessment for three tanks (assuming no interfering structures)
$33,000	**TOTAL**

Cost Estimates to Replace USTs

Replacing an existing three-tank facility (gasoline service station) with three new USTs and piping would cost approximately $80,000 to $100,000 (includes closing the existing USTs and putting in new USTs), assuming that no cleanup is necessary. Replacement would also involve about 2 to 3 weeks of downtime.

Cost Estimates to Close USTs

Temporarily closing a UST involves no more expense than the costs for the required corrosion monitoring. If a UST is closed for more than 3 months, then the capping of all lines is required, except the vent lines. Closing USTs permanently, however, requires emptying and cleaning the tank, and either removing the UST or leaving it in place filled with an inert solid, all of which would cost approximately $5,000 to $11,000 (not including site assessments or cleanup).

Costs of Not Upgrading, Replacing, or Closing Substandard USTs

After the December 22, 1998 deadline, owners and operators of substandard UST systems who continue to operate their systems that are not in-compliance risk fines of up to $11,000 per day per violation. Owners and operators may also face potential soil and groundwater clean-up costs (which can exceed $1 million), financial liability for third-party damages, and legal fees.

Underground Storage Tanks – Total Cost of Corrosion

The EPA, through OUST, provides corrosion cost and spill clean-up information. The information posted on the EPA OUST website(18) indicated that the cost for upgrading USTs averages $2,700 for overspill protection ($400 for spill bucket + $500 for shut-off valve + $1700 for shut-off alarm + $100 for float valve) and $3,400 ($10,000 / 3 tanks) for impressed-current cathodic protection (CP) per tank. The average cost to permanently close a tank is $8,000 and the average cost of clean-up, when groundwater is contaminated (approximately one-half of the releases), is $125,000.

If these estimates are applied to the average annual change between 1996 and 2000, the annual cost of corrosion from regulated USTs can be calculated based on the information in table 3 as follows:

Installing impressed-current CP:	87,553 tanks/year x $3,400/UST	= $298 million/year
Closings:	93,569 tanks/year x $8,000/UST	= $749 million/year
Contamination cleanup:	22,578 tanks/year x 0.5 x $125,000/UST	= $1,411 million/year
	Average for 1996 to 2000	= $2,458 million/year

Based on the data reported for the first half of 2000, the estimated cumulative corrosion costs since the program began in 1988 can be calculated based on the information in table 3 as follows:

Installing impressed-current CP:	742,805 tanks x $3,400/UST	= $ 2.5 billion
Closings:	1,417,711 tanks x $8,000/UST	= $11.3 billion
Contamination clean-up:	405,030 tanks x 0.5 x $125,000/UST	= $25.3 billion
	Total since 1988	= $39.1 billion/program

Case Study 2. Annual Cost of Corrosion Protection for Three USTs at a Gas Station

The objectives of this case study are to estimate the average annual corrosion costs for a typical gas station and to estimate the total national corrosion costs for all gas stations combined. Gas stations generally have three grades of gasoline, which are stored in three separate underground tanks with a typical size of 37.8 m^3 (10,000 gal). According to the December 22, 1998 deadline, all installations of the underground tanks at gas stations have to be in compliance with the SPCC regulations. In the current project, estimates were made for the types of corrosion protection on underground tanks at gas stations. Most steel tanks (90 percent) have some form of CP, either sacrificial (estimated 60 percent) or impressed current (estimated 30 percent), while a small portion (10 percent) have an internal lining, and less than 1 percent have both modes of protection. These estimates assume that all USTs (100 percent) have some form of corrosion protection as required by the December 22, 1998 deadline under the SPCC regulations.

The corrosion protection estimates are consistent with the data reported in a 1997 API survey published in 1998.(2) In that API survey, the 14 participating companies reported that at the end of July 1997, 83 percent of their 19,000 gasoline service station facilities with almost 74,000 tanks (average 3.9 USTs per station) met the 1998 corrosion protection standards for USTs and associated piping. API reported that its members operate more than 35,000 gasoline service stations, approximately 20 percent of the U.S. total. This brings the national total to 175,000 gasoline service stations, which when multiplied by 3.9 (average number per station) results in a total of 682,500 USTs.

The number of large [> 159 m^3 (> 42,000 gal)] underground storage tanks can be estimated from the 1995 SPCC survey data, in which 12,996 facilities were designated as gasoline service stations meeting the criteria under the SPCC regulations, with a total of 84,474 tanks (see table 2). The number of smaller [0.416 to 159 m^3 (110 to

42,000 gal)] underground storage tanks can be estimated from the "1st Half of Fiscal Year 2000" data from EPA OUST as a total of 742,805 tanks (see table 3).

If it is assumed that all these tanks are located at gas stations, they are grouped as three per station, all tanks under the SPCC and OUST regulations are made of steel, 60 percent have sacrificial CP and 30 percent have impressed-current CP, and 10 percent have an internal lining, the following numbers would result, based on the information in table 3:

Total USTs:	742,805 + 84,474	=	827,279	tanks
Total gas stations:	827,279 / 3	=	275,760	gas stations
Stations with sacrificial CP:	275,760 x 60%	=	165,456	stations
Stations with impressed-current CP:	275,760 x 30%	=	82,728	stations
USTs with internal lining:	827,279 x 10%	=	82,728	tanks

New Installations – Cost of Sacrificial Anode CP

New installations are currently made using fiberglass tanks or steel tanks (sti-P_3® tanks). The sti-P_3® system combines three basic methods of underground corrosion control (all of which are installed on the tanks during manufacture): (1) cathodic protection, (2) protective coating, and (3) electrical isolation of the tank from other underground metallic structures by use of non-conductive bushings or similar methods that isolate the tank electrically from the piping. The CP system on sti-P_3® tanks is included by the manufacturer in the form of attached sacrificial anodes (two per tank at $250 each with a design life of 30 years). In most states, sacrificial anodes must be inspected once every 3 years, while in some states, this inspection is conducted once every year. The cost of the actual inspection is estimated at $800. All new tanks include a test station, making it possible to inspect them from the top of the tank without digging up the anodes. For older tanks and tanks that do not have a test station attached to them (estimated 20 percent), a one-time cost for gaining access to anodes connected to the tank and installing a test station is estimated at $2,500. This large cost is because the tanks are buried and the tanks are generally located under the concrete or asphalt pavement of the gas station. If the one-time installation costs are not included, the annual costs are estimated as follows:

6 x $250 / 30 years + $800 / 3 years = $317 / year

Nationally, the annual corrosion cost estimate is 165,456 stations with sacrificial CP x $317 per year = $52 million per year.

Old Installations – Cost of Impressed-Current CP

Older installations of the three tanks at gas stations can be equipped with a single rectifier for impressed current CP. Corrosion experts Lary and Garrity(14-15) were interviewed for the current project, and they estimated that, at gasoline service stations, the current (year 2000) percentage of tanks with impressed current CP is approximately 30 percent. The cost of electricity to operate the impressed-current system is calculated from the potential and current output, efficiency, and electricity costs (see table 12). After the initial costs of a new installation, the impressed-current CP system must be inspected annually by a corrosion expert. In addition, every 60 days, the current and potential readings must be taken from the rectifier. This last type of checking is generally done by a clerk working at the gas station. These values of installation and inspection are given in table 13. It is noted that these costs are minimum costs because they assume that the system operates well and that no additional maintenance is required. Table 14 combines the previous values to calculate a total annual corrosion cost.

Table 12. Calculation of annual cost for impressed-current CP for three underground tanks in the same pit. CP runs at 60 percent efficiency: power consumption is 1 / 0.60 = 1.67 times as much.(15)

Volts	20
Amps	10
Efficiency	60%
kW	0.333
$/ kWh	$0.08
$/ hour	$0.027
$/ day	$0.64
$/ month	$19.84
$/ year	$233.60

Table 13. Cost of installation and maintenance for impressed-current CP for three underground tanks in the same pit, as estimated by Lary and Garrity.(14-15)

INSTALLATION OF IMPRESSED-CURRENT CP	
$12,000	For three tanks, excl. assessment, design life 30 years
$2,000	Structural integrity assessment, for new construction of three tanks (one time for 30 years)
$467	Depreciation per year, average
BIMONTHLY INSPECTION IMPRESSED-CURRENT CP	
$25	Every 60 days, voltage and current reading
$150	Per year
ANNUAL INSPECTION IMPRESSED-CURRENT CP	
$800	Every year for three tanks, complete review

Table 14. Estimated total annual cost for impressed-current CP for three underground tanks in the same pit.

CORROSION ITEM	COST PER YEAR
Depreciation of UST CP	$467.00
Electric power	$233.60
Bimonthly inspection of impressed-current CP	$150.00
Annual inspection of impressed-current CP	$800.00
TOTAL	**$1,650.60**

Nationally, the annual corrosion cost estimate is as follows: 82,728 stations with impressed-current CP x $1,650.60 per year = $137 million per year.

Cost of Internal Lining of USTs

The cost of applying an internal lining in a UST is estimated at \$86 / m^2 (\$8 / ft^2). The size for a 37.8-m^3 (approximately 10,000-gal) tank can be approximated as follows: 2.5 m diameter x 7.6 m length. The internal surface for this tank is: (2 x 3.14 x $(2.5\ m)^2$ / 4) + (3.14 x 2.5 m x 7.6 m) = 69.5 m^2. This would bring the installation cost per tank to: 69.5 m^2 x \$86 = \$5,977 / tank. Similar estimates (\$5,000 to \$8,000) were made by Lary and Garrity(14-15) and by the EPA (\$15,000 /3 tanks) (see table 11).

Internal linings can last a long time, presumably more than 30 years. However, according to the SPCC regulations, internal linings require inspection after the initial 10 years and then every 5 years following that. This visual inspection requires a person to physically enter the empty underground tank. The estimated cost per inspection is \$2,500. Similar to the problem of gaining access to the underground sacrificial anodes, there is a problem with access to the manhole at the tank's 12 o'clock position. The cost of gaining access to the underground manhole of the tank is estimated at \$2,000. This cost is because the tanks are buried are generally located under the concrete or asphalt pavement of the gas station; therefore, in the initial 30 years of the internal lining, a total of five inspections are required at a cost of 5 x (\$2,500 + \$2,000) = \$22,500.

Nationally, for underground storage tanks with internal linings, the annual corrosion cost estimate is 82,728 tanks x (\$5,977 + \$22,500) / 30 years) = \$79 million / year.

In summary, the national annual total corrosion costs for underground tanks at gas stations is approximately \$268 million divided as follows:

60 percent USTs with sacrificial CP:	\$52 million / year	Average: \$317 / tank / year
30 percent USTs with impressed-current CP:	\$137 million / year	Average: \$1,656 / tank / year
10 percent USTs with internal linings:	\$79 million / year	Average: \$950 / tank / year

Case Study 3. Annual Cost of Corrosion Protection for ASTs

Corrosion experts Lary and Garrity(14-15) estimated that, from all aboveground storage tanks, 30 percent have CP on their tank bottom, 10 percent have internal linings, and 100 percent are externally coated (painted). Only the internal linings value is consistent with the 12 percent weighted average calculated from the 1995 SPCC survey data (see table 3). The values for CP and external linings are not consistent with the SPCC data of 80.8 percent and 16.5 percent, respectively. The apparent discrepancy comes from the fact that the SPCC data includes many sizes of ASTs and the largest USTs. For the following calculations, the percentages estimated by the experts are used rather than the derived SPCC values.

The 1995 SPCC survey data further showed that an estimated total of 2,468,239 aboveground and underground tanks are regulated under that program (see table 2). Table 5 shows that, of this number, approximately 95 percent are ASTs (EPA estimate = 2,373,276 tanks) and 5 percent are USTs (133,400 tanks). This is consistent with the earlier observation that SPCC-regulated USTs are mostly located at gasoline service stations, which in 1995 ccounted for an estimated 84,474 tanks.

If it is assumed that all ASTs are regulated under the SPCC, all these tanks are made of steel and are externally coated, 30 percent have impressed-current CP, and 10 percent have an internal lining, the following numbers would result, based on the information in table 2 and table 5:

Total ASTs:	2,468,239 - 133,400	=	2,334,839 tanks
ASTs with CP on tank bottoms:	2,334,839 x 30%	=	700,452 tanks
ASTs with internal linings:	2,334,839 x 10%	=	233,484 tanks
ASTs with external coatings:	2,334,839 x 100%	=	2,334,839 tanks

Cost of Impressed-Current CP on Tank Bottoms of ASTs

The cost of installing CP on the tank bottom is estimated at $15,000 for an AST of 30.5 m (100 ft) diameter (see table 6). In the current calculation, a design life for a tank bottom CP is approximately 30 years. It is also assumed that a single rectifier protecting one tank bottom runs at approximately the same output current and potential as a rectifier used for a gasoline service station with three tanks. The cost of electricity to operate the impressed-current system is calculated from the potential and current output, efficiency, and electricity costs (see table 15). After the initial cost of a new installation, the impressed-current CP system must be inspected annually by a corrosion expert. In addition, every 60 days, the current and potential readings must be taken from the rectifier. These values of installation and inspection are given in table 16. It is noted that these costs are minimum costs because they assume that the system operates well and that no additional maintenance is required. Table 17 combines the previous values to calculate a total annual corrosion cost.

Table 15. Calculation of annual cost for impressed-current CP for one 30.5-m- (100-ft-) diameter aboveground storage tank bottom. CP runs at 60 percent efficiency: power consumption is 1 / 0.60 = 1.67 times as much.(15)

Volts	20
Amps	10
Efficiency	60%
kW	0.333
$/ kWh	$0.08
$/ hour	$0.027
$/ day	$0.64
$/ month	$19.84
$/ year	$233.60

Table 16. Cost of installation and maintenance for an AST tank bottom CP, as estimated by Lary and Garrity.(14-15)

INSTALLATION OF IMPRESSED-CURRENT CP	
$15,000	For one 30.5-m- (100-ft-) diameter tank, excl. assessment, design life 30 years
$2,000	Structural integrity assessment, for new construction of one AST
$567	Depreciation per year, average
BIMONTHLY INSPECTION IMPRESSED-CURRENT CP	
$25	Every 60 days, voltage and current reading
$150	Per year
ANNUAL INSPECTION IMPRESSED-CURRENT CP	
$800	Every year for each tank, complete review

Table 17. Estimated total annual cost for impressed-current CP for a single AST tank bottom.

CORROSION ITEM	COST PER YEAR
Depreciation of AST CP	$567.00
Electric power	$233.60
Bimonthly inspection of impressed-current CP	$150.00
Annual inspection of impressed-current CP	$800.00
TOTAL	**$1,750.60**

Nationally, the annual corrosion cost estimate is as follows: 700,452 tanks x $1,750 / year = $1.226 billion / year.

Cost of Internal Linings of ASTs

Calculating the internal lining costs of ASTs is similar to calculating the internal lining costs for USTs done in the previous case study. For simplicity, it is assumed that all tanks have a volume of 37.8 m^3 (10,000 gal) and the cost of downtime is assumed to be zero.

The cost of applying an internal flake glass polyester lining is estimated at $689 / m^2 ($64 / ft^2) and the cost of applying an external coating is estimated at $86 / m^2 ($8 / ft^2) (see table 7). The internal surface for a 2.5-m-diameter, 7.6-m-long tank [37.8 m^3 (10,000 gal)] is 69.5 m^2. This would bring the internal lining installation cost per tank to 69.5 m^2 x $689 = $47,891 / tank.

Internal linings can last a long time, presumably more than 30 years. However, according to SPCC regulations, internal linings require inspection after the initial 10 years and then every five years following that. This visual inspection requires a person to physically enter the empty tank, at an estimated cost of $2,500 per inspection. Access to aboveground tanks is generally no problem; however, the tank must be empty. Therefore, in the initial 30-year period for the internal lining, a total of five inspections are required at a cost of 5 x $2,500 = $12,500.

Nationally, for tanks with internal linings, the annual corrosion cost estimate is 233,484 tanks x ($47,891 + $12,500) / 30 years) = $470 million per year.

Cost of External Coatings on ASTs

Calculating the external coating costs of ASTs is similar to calculating the internal lining costs for USTs and ASTs in the previous and the current case study.

The cost of applying an external coating is estimated at $86 m^2 ($8 / ft^2) (see table 6). The external surface for a 2.5-m-diameter, 7.6-m-long tank [37.8 m^3 (approximately 10,000 gal)] is 69.5 m^2. This would bring the external coating installation costs per tank to: 69.5 m^2 x $86 = $5,977 per tank. It is estimated that ASTs must be painted an average of once every 5 years.

Nationally, for tanks with external coatings, the annual corrosion cost estimate is 2,334,839 tanks x $5,977 per tank = $2.791 billion per year.

In summary, the national annual total corrosion cost for aboveground tanks is approximately $4.5 billion, as reported earlier in table 10 and as shown below:

30 percent ASTs with tank bottom CP:	$1,226 million / year	Average: $1,750 / tank / year
10 percent ASTs with internal linings:	$ 470 million / year	Average: $2,013 / tank / year
100 percent ASTs with external coatings:	$2,791 million / year	Average: $1,195 / tank / year

To put these average corrosion costs per tank in perspective, the inspection costs for AST tank bottoms, according to API Standard 653 "Tank Inspection, Repair, Alteration, and Reconstruction,"(21) are estimated at $30,000 to $50,000 per inspection. The cost for total replacement of one tank bottom is estimated at $200,000 to $500,000. The cost to build one 30.5-m- (100-ft-) diameter AST is estimated at several million dollars.

Case Study 4. Comparison of USTs Versus ASTs

The Steel Tank Institute (STI) compares USTs with ASTs on their website.(22) The comparison is made from the viewpoint of EPA regulations. Table 18 is a copy of the information on the STI website, without comments. The objective of including this information in the current report is to provide a direct comparison of the two types of tank regulations described in the chapter titled "Sector Description".

Table 18. Steel Tank Institute comparison of USTs versus ASTs.

UST (40 CFR 280)	**AST (40 CFR 112, SPCC)** **Based on SPCC Phase I proposed rules of October 22, 1991.**
Definition • Device constructed of non-earthen materials containing an accumulation of regulated substances, the volume of which is 10 percent or more underground.	Definition • Any tank not completely buried, including bunkered tanks.
Exemptions • Farm or residential less than 416 L (110 gal) • Heating oil used on premises • Flow-through process or separator • Stormwater or wastewater collection • Equipment for operational purposes such as hydraulic lift tanks and electrical equipment • Airport hydrant tanks	Exemptions • USTs under 40 CFR 280 • Onshore facilities that, due to their location, could not reasonably be expected to discharge oil into waterways • Vessels under DOT requirements
Size Limitations • Greater than 416 L (110 gal) (excluding field-constructed tanks)	Size Limitations • Individual containers greater than 2.5 m^3 (660 gal) • Container aggregates greater than 5.0 m^3 (1,320 gal) • UST aggregates greater than 159 m^3 (42,000 gal)
Primary Charter • Prevent release of regulated substances that can harm the environment, including soils and groundwater	Primary Charter • Prevent spills of oil by non-transportation-related onshore and off-shore facilities into U.S. surface waters and surrounding shorelines, including wetlands
Regulated Substance • Petroleum, including crude oil in its various natural or processed states, and motor and jet fuels, lubricants, petroleum solvents, distillate fuel oils • Substances defined in CERCLA, excluding hazardous wastes under Subtitle C	Regulated Substance • Oil in any form, including petroleum, sludges, oil refuse, crude oil, animal and vegetable oils

Table 18. Steel Tank Institute comparison of USTs versus ASTs (continued).

UST (40 CFR 280)	AST (40 CFR 112, SPCC) **Based on SPCC Phase I proposed rules of October 22, 1991.**
Corrosion • Tank protected per code of practice developed by nationally recognized association or independent testing lab, includes: • FRP • Composites • Cathodic Protection • Protection includes piping system	Corrosion • Partially buried tanks protected using coatings and cathodic protection • Piping protected as in 40 CFR 280 • Compatible with stored product
Structure • Prevent releases due to structural failure	Structure • Construction and materials must conform to industry standards in application of good engineering practices
Containment • Chemicals and other hazardous substances must include secondary containment to hold releases until detected and to prevent release into the environment • Some states also require containment of petroleum liquids	Containment • All facilities must be contained to prevent discharged oil from reaching navigable waters (includes double-wall steel, under recent interpretation) • Containment impervious to oil for 72 hours • Dike, curbs, and pits to contain largest tank, plus sufficient freeboard for bulk storage containers
Testing / Release Detection • Must detect release from any portion of tank and connected piping • Monitor every 30 days for tanks with automatic tank gauging, vapor and groundwater monitoring, and interstitial monitoring • Pressurized piping tests every year unless monitored monthly with tanks AND automatic line leak detection • Suction piping tested every 3 years unless monitored monthly • Testing for tightness every 5 years; if tank is not in conformance with other requirements, then annual tightness testing is required • statistical inventory reconciliation allowed as monthly release detection check	Testing / Release Detection • Integrity test of tanks every 5 years, and piping every year • Those with secondary containment must have integrity test every 10 years • Piping and valves examined monthly
Financial Responsibility • $1 million insurance	Financial Responsibility • No insurance required, although U.S. Senate and U.S. House are introducing language similar to 40 CFR 280

Table 18. Steel Tank Institute comparison of USTs versus ASTs (continued).

UST (40 CFR 280)	**AST (40 CFR 112, SPCC)** **Based on SPCC Phase I proposed rules of October 22, 1991.**
Clean-up • Report suspected and confirmed releases to implementing agency • Must take immediate action to prevent further release (within 24 hours) • Submit report of initial actions within 20 days and remove free product • Develop corrective action plan to clean-up contaminated soils and groundwater	Clean-up • Report spills immediately to National Response Center (40 CFR 110) • Materials and manpower for control and removal must be provided for facilities without secondary containment when secondary containment not practical. Professional engineer required to develop strong oil spill contingency plan • Owners/operators of large tank sites may have to submit a facility response plan for approval under 7-1-94 EPA's definition of "significant and substantial harm"
Overfill Prevention and Containment • Spill prevention equipment that prevents releases of product when transfer hose is detached • Overfill prevention equipment • Shut-off at 95% capacity • Alert operator at 90% capacity by restricting flow or triggering high-level alarm	Overfill Prevention and Containment • Fail-safe engineered to avoid spills
Other Requirements	Other Requirements • Security to minimize vandalism • Training for facility personnel to minimize operator error

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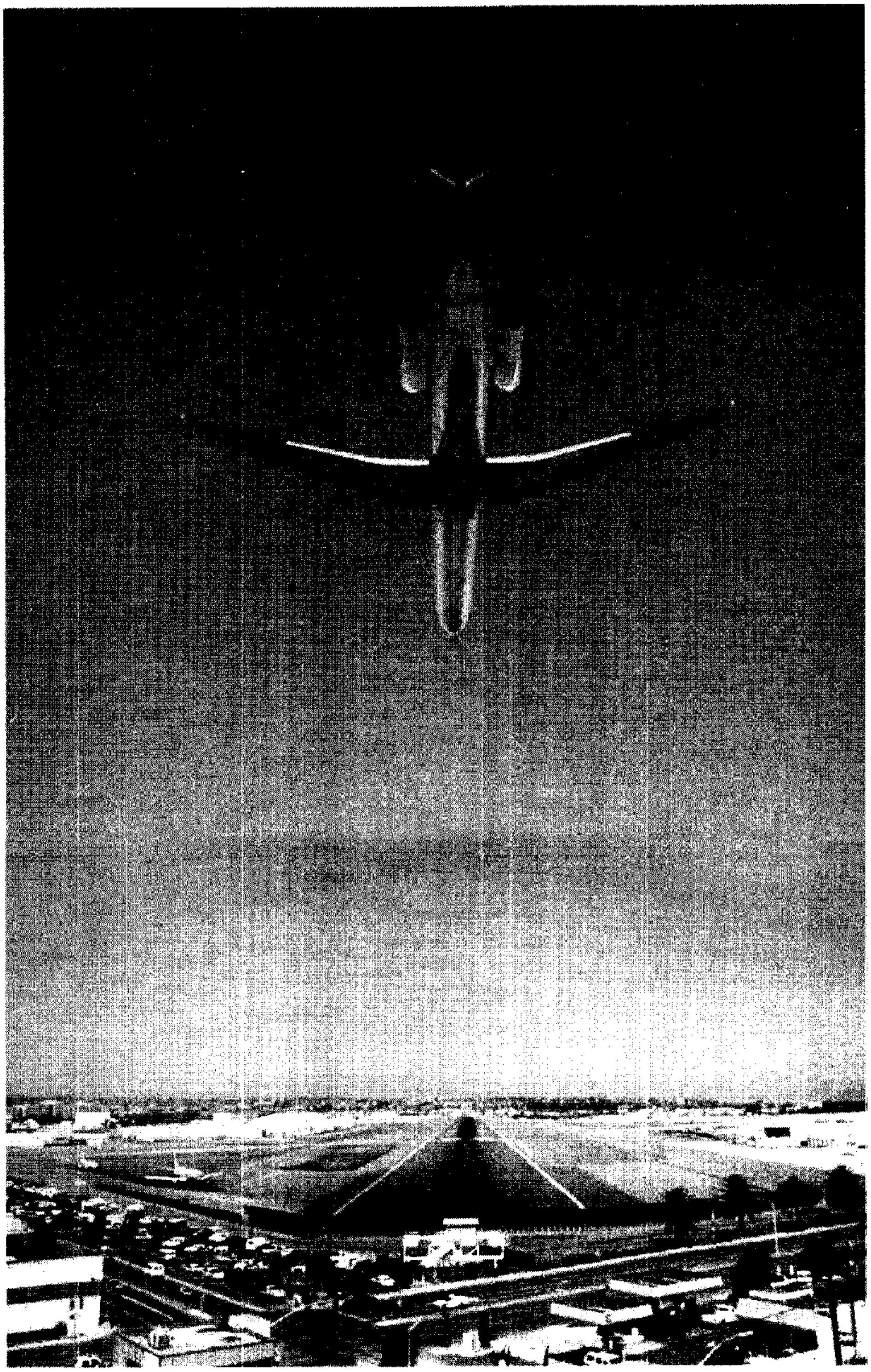
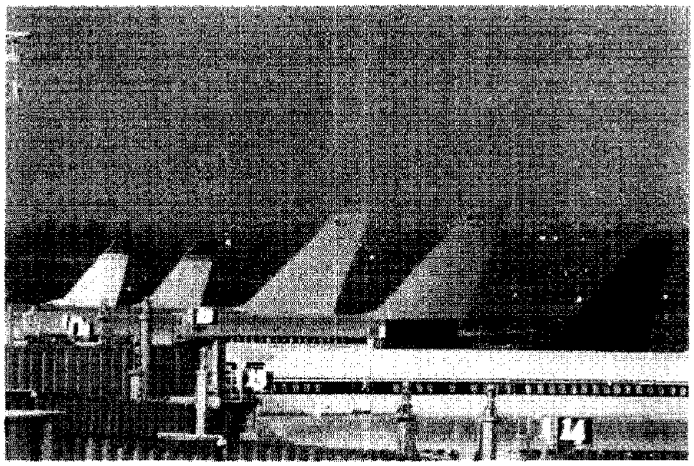
APPENDIX H

AIRPORTS



Boarding plane

Airport terminal



Gate area

Parking garage

APPENDIX H

AIRPORTS

MARK YUNOVICH[1]

SUMMARY

The United States has the world's most extensive airport system, which is essential to national transportation. Airports, which are among the most important and widely used facilities, play a major role in generating economic activity for the United States. According to the Bureau of Transportation Statistics, in 1999, there were 5,324 public-use airports and 13,774 private-use airports in the United States. The airports used by the scheduled air carriers are virtually all public facilities run by an agency of a state or local government, or a commission or port authority established by the state legislature. Since airports resemble small cities, they are organized accordingly, with departments for purchasing, engineering, finance, administration, etc.

A typical airport infrastructure is relatively complex, and components that might be subject to corrosion include the natural gas distribution system, jet fuel storage and distribution system, deicing storage and distribution system, water distribution system, vehicle fueling systems, natural gas feeders, dry fire lines, parking garages, and runway lighting. Generally, each of these facilities is owned or operated by different organizations and companies, and the impact of corrosion on an airport as a whole is not known or documented; however, the airports do not have any specific corrosion-related problems that have not been described in other sectors, such as corrosion in water and gas distribution lines, corrosion of concrete structures, and corrosion in aboveground and underground storage tanks.

Because of the diversity of airport facilities and different accountabilities, the costs due to corrosion are not apparent and, therefore, cannot be addressed in a systematic manner. In order for airports to reduce and control their corrosion costs, it is recommended that the airports establish databases that will allow engineers to track corrosion and corrosion costs and raise awareness.

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[1] CC Technologies Laboratories, Inc., Dublin, Ohio.

SECTOR DESCRIPTION

The United States has the world's most extensive airport system, which essentially consists of national transportation, commerce, and defense. Airports, which are among the most important and widely used facilities, play a major role in generating economic activity for the United States. Specifically, U.S. airports handle more than 3.2 million passengers and 38,000 metric tons of cargo each day.(1) As a result of this considerable passenger and cargo capacity, airports accrue an annual $380 billion in total economic activity nationwide. There are 1.6 million jobs at airports in the United States, with an additional 4.2 million jobs created in local communities. These jobs translate into total annual earnings of $155 billion. Moreover, airports generate $31.2 billion in local, state, and federal taxes.

According to the Bureau of Transportation Statistics, there were 5,324 public-use airports and 13,774 private-use airports in the United States in 1999 (see table 1).(1)

Table 1. U.S. airport statistics.(1)

	1980	1985	1990	1998	1999
Public Use					
% with lighted runways	66.2	68.1	71.4	74.8	76.1
% with paved runways	72.3	66.7	70.7	74.2	74.2
TOTAL	**4,814**	**5,858**	**5,589**	**5,352**	**5,324**
Private Use					
% with lighted runways	15.2	9.1	7.0	6.3	6.7
% with paved runways	13.3	17.4	31.5	33.2	31.8
TOTAL	**10,347**	**10,461**	**11,901**	**13,418**	**13,774**
TOTAL AIRPORTS	**15,161**	**16,319**	**17,490**	**18,770**	**19,098**
Certified					
Civil	ND	ND	ND	566	566
Military	ND	ND	ND	94	94
TOTAL	**730**	**700**	**680**	**660**	**660**

ND - not determined

Air transportation is the fastest growing transportation mode in the United States. Domestic passenger-miles of air travel more than doubled since 1980, while ton-miles of freight carried by air increased threefold. Airway system mileage increased from 545,600 km (341,000 mi) in 1980 to 630,400 km (394,000 mi) in 1995 (no estimates are available for 1996 and 1997).(1) Certified airports (those serving scheduled air carrier operations with aircraft seating more than 30 passengers), with virtually all of the passenger traffic and with the bulk of it concentrated in the 29 large hubs (75 airports), handled 431 million enplaned passengers in 1997. The top 10 busiest airports in the United States, on the basis of passenger enplanement, are listed in table 2.

The airports utilized by the scheduled air carriers are mostly public facilities run by a state or local government agency, such as the department of transportation, or a commission or port authority established by the state legislature and governed by a board of directors appointed by elected officials. Since airports resemble small cities, they are organized like a small city, with departments for purchasing, finance, engineering, etc.(2) They also have fire and police departments and handle such municipal duties as trash and snow removal.

Table 2. Top 10 busiest airports in the United States (1999).(3)

RANK	LOCID	AIRPORT NAME	ASSOCIATED CITY	ST	ENPLANEMENTS
1	ATL	William B. Hartsfield	Atlanta	GA	38,136,866
2	ORD	Chicago O'Hare Intl	Chicago	IL	34,050,083
3	LAX	Los Angeles Intl	Los Angeles	CA	30,830,915
4	DFW	Dallas/Fort Worth Intl	Dallas-Fort Worth	TX	27,990,212
5	SFO	San Francisco Intl	San Francisco	CA	19,249,988
6	DEN	Denver Intl	Denver	CO	18,039,836
7	DTW	Detroit Metropolitan	Detroit	MI	16,982,496
8	EWR	Newark Intl	Newark	NJ	16,927,048
9	PHX	Phoenix Sky Harbor Intl	Phoenix	AZ	16,781,835
10	MIA	Miami Intl	Miami	FL	16,531,295

AREAS OF MAJOR CORROSION IMPACT

A typical airport infrastructure is relatively complex, and the components that might be subject to corrosion include the following:

- Natural gas distribution system.
- Jet fuel storage and distribution system.
- Deicing storage and distribution system.
- Water distribution system.
- Vehicle fueling systems.
- Natural gas feeders.
- Dry fire lines.
- Parking garages.
- Runways and runway lighting.

Generally, each of these infrastructure components is owned and/or operated by different organizations and companies. Given the above, airports do not have any specific corrosion-related problems that cannot be found in other sectors of the national economy (e.g., corrosion of heat, ventilation, and air-conditioning systems; corrosion of a reinforced-concrete floor in a parking garage; or corrosion of buried metallic structures). The latter issue, corrosion of buried metallic structures, is primarily manifested in underground storage tanks (USTs) or buried fuel lines transporting fuel from the tank farms. Larger airports generate considerable volumes of wastewater during the deicing season and may have wastewater treatment facilities (which often are not owned by the airports).

The issue with USTs became particularly acute with the passing of an Environmental Protection Agency (EPA) regulation deadline in 1998, which mandates installation of corrosion protection on existing regulated USTs (see Appendix G, Hazardous Materials Storage).

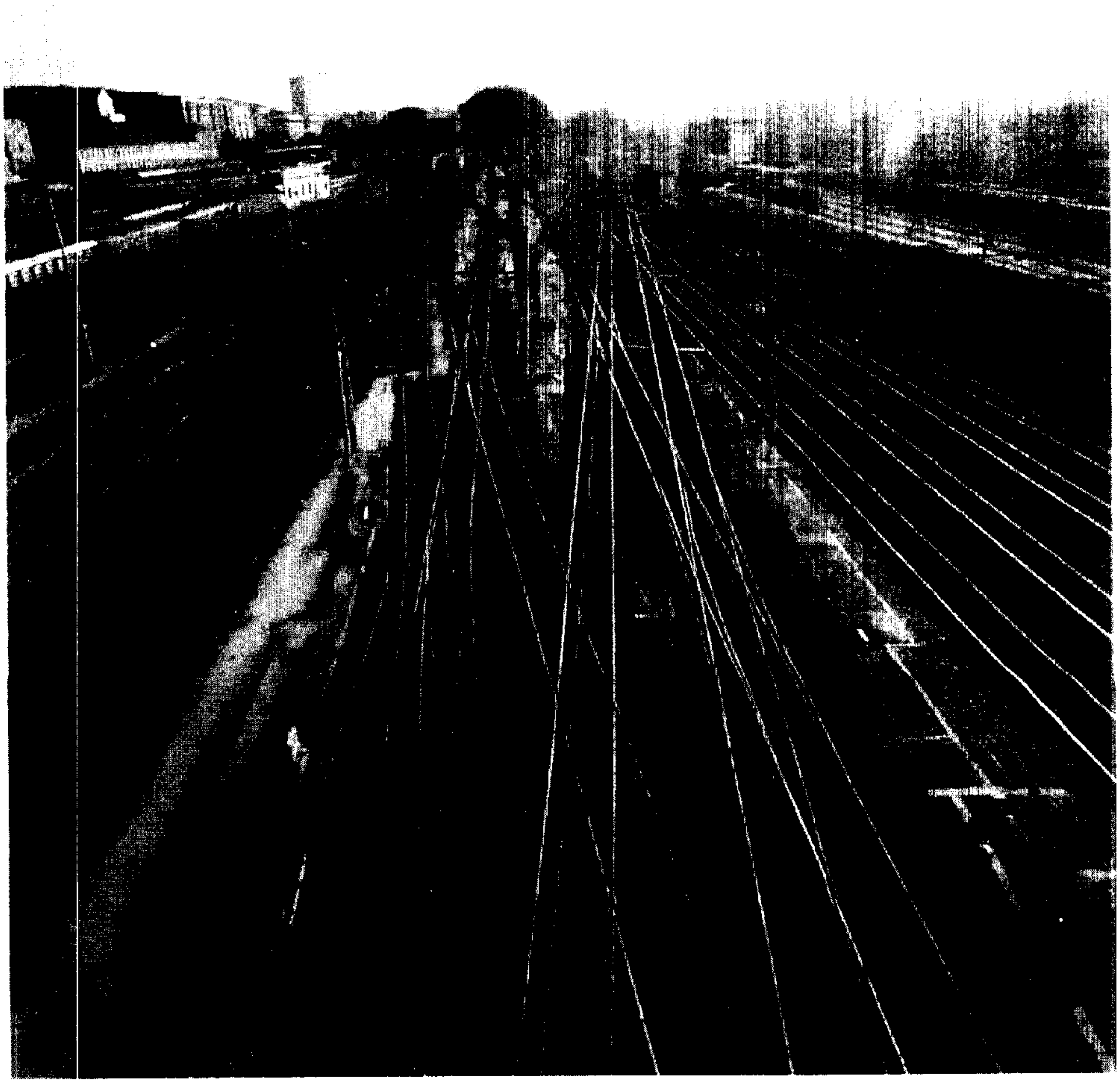
Considering that the scope of the problem is rather limited, there is no available information on corrosion control costs. For the most part, these costs are contained within the maintenance budgets, but are not tracked separately. To complicate the issue, in many cases, the structures subject to corrosion, such as tank farms, while technically owned by the airports, are leased by the airport tenants. The sources of funds are multiple, including rent and gross-receipt fees paid by the airport-based businesses, landing fees, and sometimes parking and fueling fees paid by the airlines. Sometimes a structure, such as a parking garage, is built for exclusive use by an airline and, therefore, is owned and maintained by it. Furthermore, outside contractors often perform whatever corrosion control maintenance is scheduled. Because a basis was not identified to estimate corrosion-related cost, no estimates were made. Given the lack of information on the subject, no estimates of corrosion-related costs were attempted.

REFERENCES

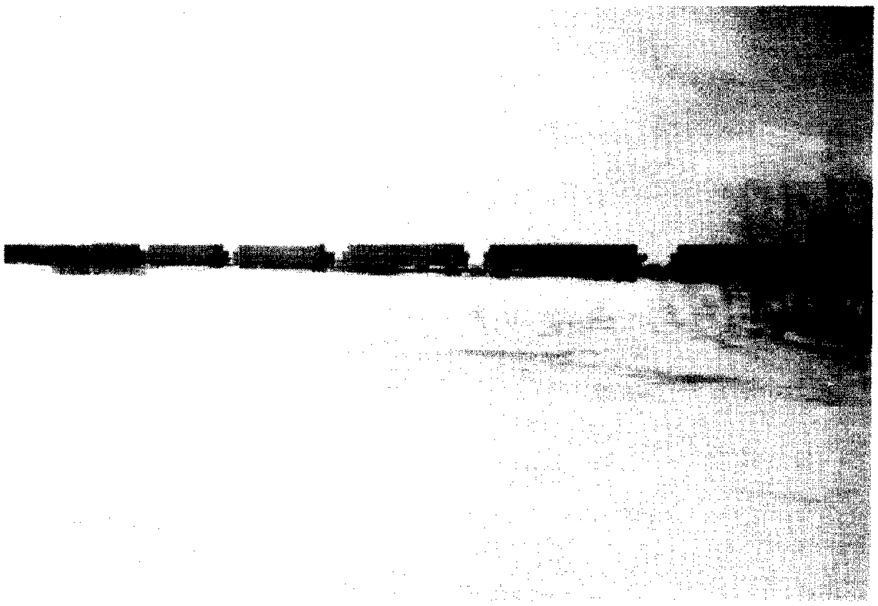
1. U.S. Bureau of Transportation Statistics data, 1999.
2. Chapter 7, Airports, *Airline Handbook*, www.air-transport.org, June 2000.
3. FAA DOT/TSC ACAIS database, 1999.

APPENDIX I

RAILROADS



Railroad tracks



Train with pipe sections

RAILROADS

MARK YUNOVICH[1]

SUMMARY

In 1997, there were nine Class I freight railroads (railroads with operating revenues of $256.4 million or more). These railroads accounted for 70 percent of the industry's 274,399 km (170,508 mi) operated. There were 35 regional railroads (those with operating revenues between $40 million and $256.4 million and/or operating at least 560 km (350 mi) of railroad). The regional railroads operated 34,546 km (21,466 mi). Finally, there were 515 local railroads (including switching and terminal railroads) operating more than 45,300 km (28,149 mi) of railroad.

The elements that are subject to corrosion include metal members, such as rail and steel spikes; however, corrosion damage to railroad components are either limited or go unreported. Therefore, a cost of corrosion could not be determined.

One area where corrosion has been identified is in electrified rail systems, such as those used for local transit authorities. Stray currents from the electrified systems can inflict significant and costly corrosion on non-railroad-related underground structures such as gas pipelines, waterlines, and underground storage tanks.

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[1] CC Technologies Laboratories, Inc., Dublin Ohio.

SECTOR DESCRIPTION

America's first common-carrier railroad, the Baltimore and Ohio (B&O), was chartered in Maryland on February 28, 1827. In another 2 years, the rail network grew to 48 km (30 mi). By 1848, 9,700 km (6,000 mi) of track were laid, mostly in the Northeastern United States. At the end of the century, this number grew to 306,000 km (190,000 mi) and, by 1916, there were 409,000 km (254,000 mi) of railroad track in this country.

Railroads were the first major industry in the United States to be the subject of economic regulation under the Interstate Commerce Act passed in 1887. The railroads remained under regulation for almost 100 years, until 1980, when the Staggers Rail Act was signed, which lifted some of the regulations.

In the most basic way, national railroads are divided into passenger and freight railroads. Passenger railroads are further separated into intercity railroads (with Amtrak, created by U.S. Congress in 1971, being the only U.S. company in this category) and those under the auspices of transit and suburban authorities.

The Surface Transportation Board (STB) defines Class I freight railroads as those with average operating revenues of $256.4 million or more. Those with revenues between $20.5 million and $256.4 million are classified as Class II railroads. Railroads with average operating revenues less than $20.5 million are considered Class III railroads. A brief summary of North American railroad statistics is presented in table 1.

Table 1. Basic facts of North American railroads (1999).

TYPE OF RAILROAD	NUMBER OF RAILROADS (INCLUDING CANADIAN)	KILOMETERS OPERATED	MILES OPERATED	NUMBER OF EMPLOYEES	FREIGHT REVENUE ($ x million)
Class I	9	191,891	119,239	178,222	$32,247
Regional	35	34,368	21,356	11,094	$1,586
Local	309	34,825	21,640	5,781	$856
Switching & Terminal	206	10,913	6,781	5,809	$606
Canadian	2	2,401	1,492	n/a	n/a
All Railroads	**561**	**274,399**	**170,508**	**200,906**	**$35,295**

n/a – data not available.

The following U.S. railroads (as of the end of 1999) were classified as Class I:[2]

- Burlington Northern and Santa Fe Railway Company.
- CSX Transportation.
- Kansas City Southern Railway Company.
- Norfolk Southern Corporation.
- Union Pacific R.R.

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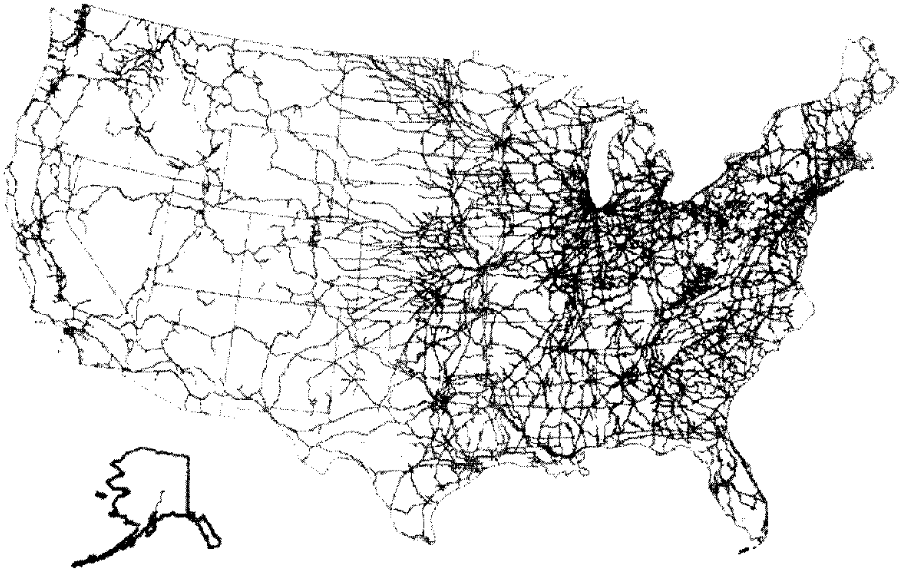
[2] The remaining four railroads are registered in Canada.

The Association of American Railroads (AAR) has estimated that while making up only 2 percent of the number of American railroads, Class I railroads employed approximately 89 percent of the industry workforce, operated 70 percent of the track, and generated 91 percent of the revenue in 1998.[(1)]

The sketch illustrating the density of coverage of railroads in the United States is shown in figure 1.



Rail network based upon 1997 National Transportation Atlas Databases published by the US DOT Bureau of Transportation Statistics

Figure 1. Railroad coverage in the United States.[(1)]

AREAS OF MAJOR CORROSION IMPACT

Published information with respect to corrosion-related issues in the industry is scarce. The elements of construction subject to corrosion include metal members, such as rail, steel spikes for wooden ties, etc. As far as the railroads are concerned, corrosion damage to the rail itself is limited and often goes unreported. One area where corrosion has been identified is in the electrified rail systems, such that as those used for local transit authorities. Barlo et al. (1995)[(2)] conducted a study on corrosion of electrified trains that covered a number of transit systems. It was estimated that the damage to the rail is primarily caused by stray current that occurs on the electrified rail systems.

The above-referenced 1995 review covered transit systems in Chicago, Jersey City (NJ), New York City, Washington, D.C., San Francisco, and Los Angeles. The systems were powered by 600V to 1000V direct current (DC), with the third positive rail, or overhead catenary wire, and the running rails providing a negative return. The transit authorities acknowledge that corrosion-related problems exist, as manifested by the accelerated corrosion of the insulators of the rail fasteners in Jersey City and New York City, or in the wood tie spikes in Chicago. For example, wood tie spikes need to be replaced after 6 months instead of the anticipated 25 years. In many instances, there was no formal tracking of corrosion-related costs. The estimates for the cost of corrosion made by the authors of this 1995 study suggest that the direct costs are small (less than 0.5 percent of the annual total non-vehicle costs). Additional expenditures included the *in situ* study of stray-current problems in Washington, D.C., and column footing reconstruction in Chicago.

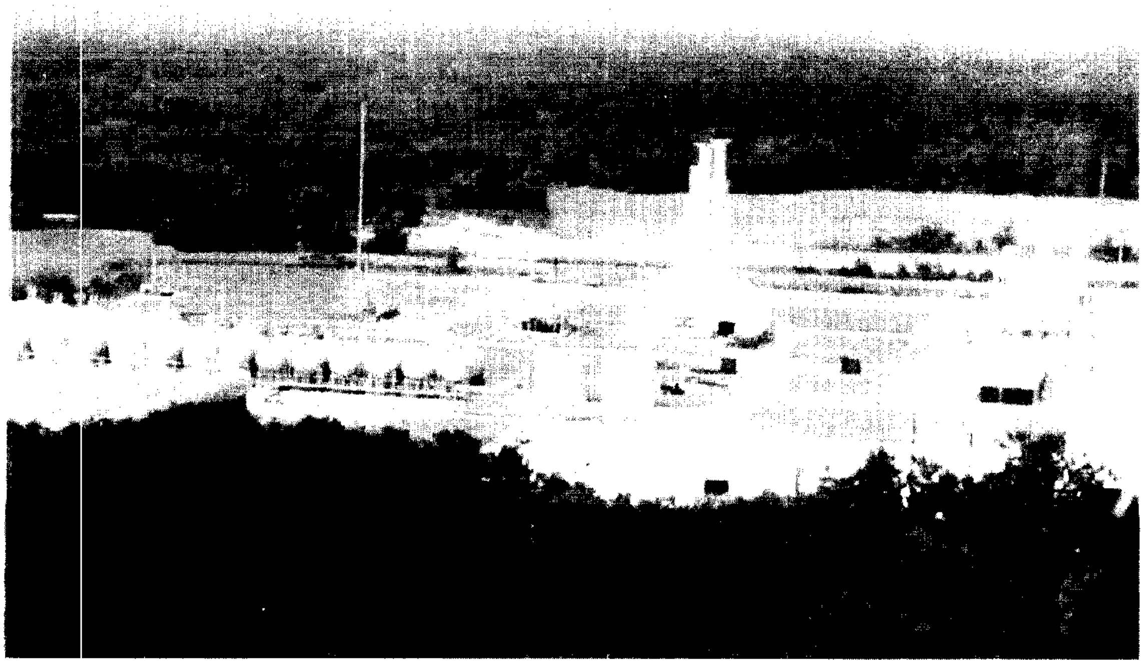
While ostensibly there is corrosion damage to other railroad-owned property, such as bridges, railyard structures, etc., from exposure to the elements, the railroad systems apparently do not consider it to be a major expense and, therefore, do not track this data. No estimate of the cost of corrosion to railroads was possible from the data obtained.

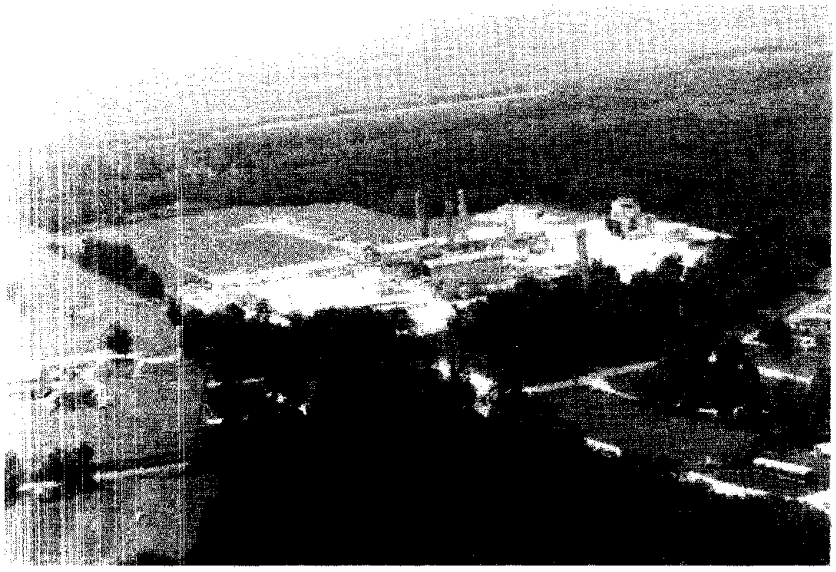
REFERENCES

1. Association of American Railroads Data, 2000.
2. T.J. Barlo and A.D. Zdunek, *Stray Current Corrosion in Electrified Rail Systems*, Northwestern University, May 1995.

APPENDIX J

GAS DISTRIBUTION




Gas distribution facility


Piece of gas pipeline with external corrosion


Ruptured gas pipeline

GAS DISTRIBUTION

NEIL G. THOMPSON, PH.D.[1]

SUMMARY

The natural gas distribution system includes 2,785,000 km (1,730,000 mi) of relatively small-diameter, low-pressure piping, which is divided into 1,739,000 km (1,080,000 mi) of distribution main and 1,046,000 km (650,000 mi) of services. There are approximately 55 million services in the distribution system. The typical distribution of piping diameters is between 40 mm and 150 mm (1.5 in and 6 in) for main distribution piping and 13 mm to 20 mm (0.5 in to 0.75 in) for service piping. A small percentage of distribution mains and services have a larger diameter pipe, typically for commercial and industrial application. The total cost of corrosion was estimated at approximately 10 percent of the operation and maintenance cost (approximately $5.0 billion).

Several different materials have been used for distribution piping. Historically, distribution mains were primarily made of carbon steel pipe; however, since the 1970s, a large portion of the gas distribution main lines have been made of plastic, mostly polyethylene (PE), sometimes polyvinyl chloride (PVC). A large percentage of mains (57 percent) and services (46 percent) are made of metal (steel, cast iron, or copper). The methods for monitoring corrosion on the lines are the same as those used for transmission pipelines; however, leak detection is widely used.

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[1] CC Technologies Laboratories, Inc., Dublin, Ohio.

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SECTOR DESCRIPTION

The Gas Distribution Pipeline sector is a part of the oil and gas industry. Figure 1 illustrates the different components of a natural gas production, transmission, storage, and distribution system. The components include production wells, gathering lines within the production fields, processing plants, transmission pipelines, compressor stations (periodically along the transmission pipelines), storage wells and associated gathering pipelines, metering stations and city gate at distribution centers, distribution piping, and meters at distribution sites (residential or industrial).

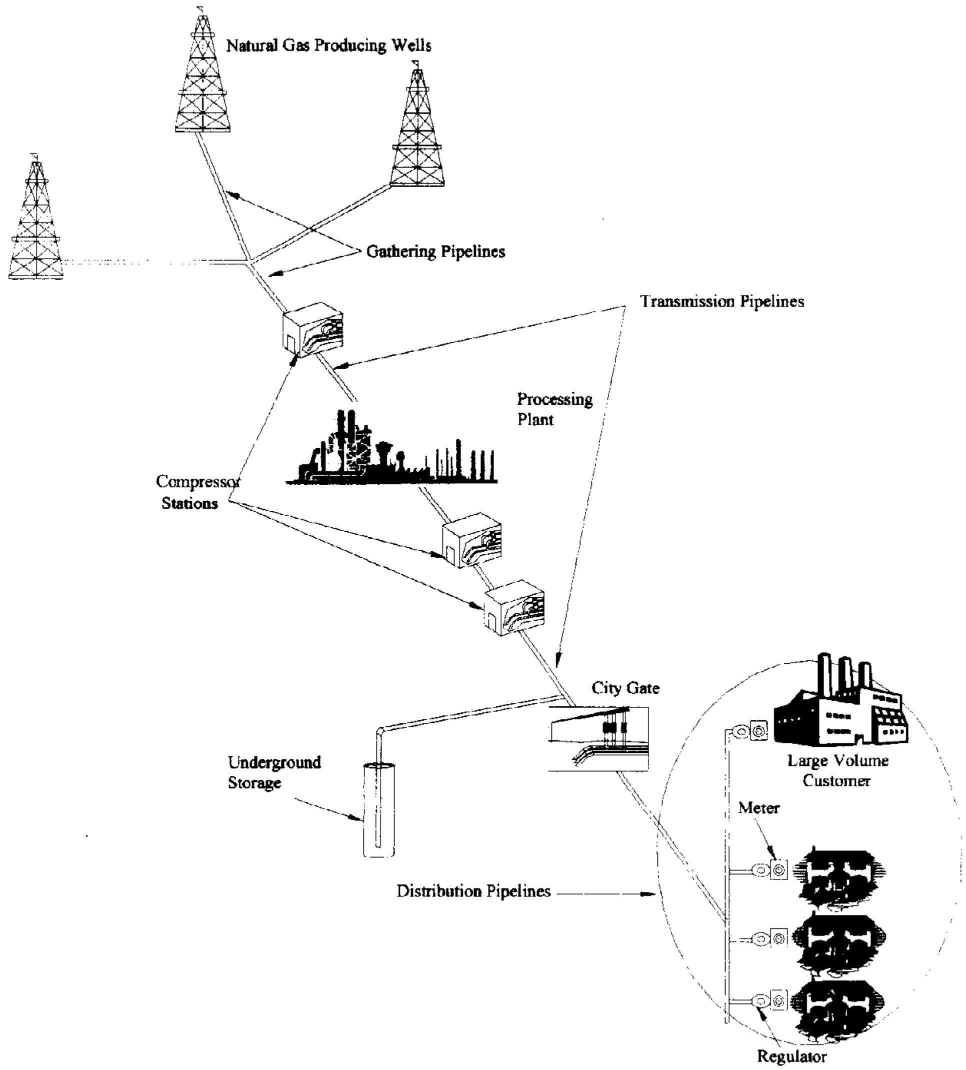

Figure 1. Components of a natural gas production, transmission, and distribution system.

In 1998, the distribution pipeline industry included 2,785,000 km (1,730,000 mi) of relatively small-diameter, low-pressure natural gas distribution piping, which is divided into 1,739,000 km (1,080,000 mi) of distribution main and 1,046,000 km (650,000 mi) of services.[1-2] There are approximately 55,000,000 services in the distribution system. Figure 2 shows the Distribution Pipeline sector in relationship to the oil and gas industry.

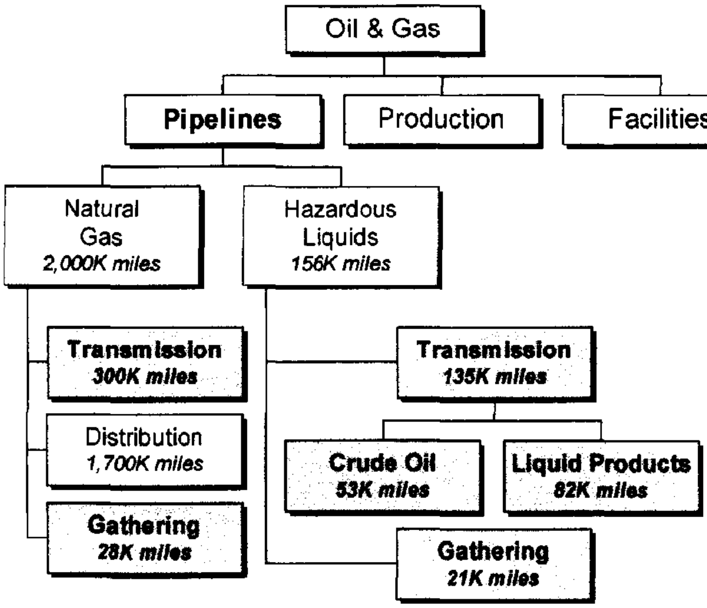

Figure 2. Chart describing the Oil and Gas Distribution Pipeline sector.

BACKGROUND

Several different materials have been used for main and service distribution piping. Historically, distribution mains were primarily carbon steel pipe; however, since the 1970s, a large portion of gas distribution mains have been plastic. Some steel mains are installed in small sections of an existing steel system, in certain "downtown" environments where the use of plastic pipe is restricted, and in some large-diameter [> 150 mm (6 in)] applications. Gas service piping has been constructed primarily of steel and plastic. Essentially, all service piping installed today is made of plastic. Table 1 gives the breakdown of the mains and services by material (1998).(2) Other than steel and plastic, there are some cast iron mains and copper services. The plastic pipe is primarily made of polyethylene, but some PVC piping has also been installed.

Table 1. Summary of miles of gas distribution main and number of services by material.

	STEEL	PLASTIC	CAST IRON	COPPER	OTHER	TOTAL
MILES OF MAINS	569,908	461,433	46,023	52	7,983	**1,085,399**
NUMBER OF SERVICES	23,814,222	28,506,127	51,090	1,497,638	1,099,929	**54,969,006**

1 mi = 1.61 km

Typical distribution piping diameters are between 40 and 150 mm (1.5 and 6 in) for mains and 13 and 20 mm (0.5 and 0.75 in) for services. A small percentage of mains and services is larger diameter pipe, typically for commercial and industrial applications. Tables 2 and 3 give the breakdown of distribution mains and service piping by diameter, respectively (1998).(2)

Table 2. Miles of gas distribution main by material and diameter.

MATERIAL	MILES OF MAIN BY DIAMETER						TOTAL MILES OF MAIN BY MATERIAL
	UNKNOWN	**2 in and Less**	**2 in to 4 in**	**4 in to 8 in**	**8 in to 12 in**	**Greater Than 12 in**	
Steel	98	297,246	162,312	93,452	24,632	5,971	583,711
Cast iron	2	1,845	20,030	18,513	3,644	1,989	46,023
Plastic PVC	7	18,572	2,756	189	2	0	21,526
Plastic polyethylene	57	335,691	88,152	15,757	234	16	439,907
Other	0	4,981	1,663	1,121	186	90	8,041
TOTAL BY SIZE	**164**	**658,335**	**274,913**	**129,032**	**28,698**	**8,066**	**1,099,208**

1 in = 25.4 mm, 1 mi = 1.61 km

Table 3. Number of gas distribution services by material and diameter.

MATERIAL	SERVICES BY DIAMETER						TOTAL NUMBER OF SERVICES BY MATERIAL
	Unknown	**1 in and Less**	**1 in to 2 in**	**2 in to 4 in**	**4 in to 8 in**	**Greater Than 8 in**	
Steel	534,778	16,620,181	6,420,831	221,997	15,384	1,051	23,814,222
Copper	3	1,012,850	484,366	417	2	0	1,497,638
Plastic PVC	110	1,035,730	160,684	1,459	33	1	1,198,017
Plastic polyethylene	140,429	24,001,942	3,106,968	53,603	5,071	97	27,308,110
Other	93,107	918,691	137,283	1,156	707	75	1,151,019
TOTAL	**768,427**	**43,589,394**	**10,310,132**	**278,632**	**21,197**	**1,224**	**54,969,006**

1 in = 25.4 mm

A large percentage of mains (57 percent) and services (46 percent) are metal (steel, cast iron, or copper) and corrosion is a major issue. For distribution pipe, external corrosion is the primary threat, although internal corrosion has been identified in some instances. The methods of corrosion monitoring on cathodically protected piping are similar to those described in the Transmission Pipeline sector, including pipe-to-soil potential and coating surveys. One difference is that in distribution systems, leak detection is an acceptable method of corrosion monitoring for these pipelines without cathodic protection (approximately 15 percent of the steel mains).(2) For gas distribution piping, corrosion mitigation is primarily sacrificial cathodic protection. Techniques such as in-line inspection are typically not an option for the relatively complex network of distribution mains and services. This makes integrity assessment of the piping difficult.

AREAS OF MAJOR IMPACT

Capital Costs

Because of the vast expanse of distribution piping [992,000 km (616,000 mi)] of metallic main piping and 25,300,000 metallic services], the corrosion-related capital cost of primary interest is the cost of the steel, cast iron, and copper main piping and service lines. The capital cost of the metallic portion of the gas distribution system was not available; making it impossible to calculate a cost of capital related to corrosion.

In order to provide justification for funding for corrosion control in maintaining the existing metallic piping system, a cost is calculated for replacing this infrastructure. The average cost of main replacement (1993 dollars) ranged from $328 per m ($100 per ft) in urban areas to $82 per m ($25 per ft) in developed areas, with an average of $105 per m ($32 per ft). The average cost of a service replacement was $950 per service.(3) It is assumed that the cost of replacement has not significantly increased since 1993 due to improved construction practices. This gives the replacement cost of the metallic gas distribution system as $128 billion [$104 billion for mains (992,000,000 m of metallic main x $105 per m) plus $24 billion for services (25,300,000 metallic services x $950 per service)]. Note that the replacement cost is based on replacement with plastic mains and services, which would be the case in the vast majority of situations.

Pipe Failures

Metal Pipe

Low-pressure gas distribution pipeline failures result in leaks rather than the catastrophic ruptures that may occur in high-pressure natural gas transmission pipelines. The primary concern is that a leak goes undetected and the gas collects in a confined space, eventually igniting and causing an explosion.

Table 4 gives the leak incidence by cause for distribution mains and services.(2) Corrosion was the cause of 40 percent of the leaks repaired on mains and 24 percent of the leaks repaired on services in 1998. The leak incidence as a result of corrosion was 8.4 leaks per 100 km (13.6 leaks per 100 mi) of metal main pipe and 3.9 leaks per 1,000 services. For comparison, the total 1998 leak incidence rate was 12 leaks per 100 km (19.3 leaks per 100 mi) of main pipe and 7.4 leaks per 1,000 services.

Table 4. Leak incidence by cause for distribution mains and services.

	NUMBER OF LEAKS REPAIRED BY CAUSE						TOTAL LEAKS
	Corrosion	**Third Party**	**Outside Force**	**Construction Defect**	**Material Defect**	**Other**	
MAINS	83,864	29,566	12,107	6,466	12,835	64,999	**209,837**
SERVICES	99,024	95,555	21,814	20,965	32,356	138,267	**407,981**

The vast majority of the 83,864 corrosion leaks on main pipes and the 99,024 leaks on services are generally detected and repaired without major incidents. Only 26 major incidents caused by corrosion were reported by natural gas distribution pipeline companies for the 5 years from 1994 to 1999 (5.2 incidents per year).(4) These incidents resulted in $4,923,000 in property damage, 4 fatalities, and 16 injuries [see Gas and Liquid Transmission Pipeline sector (Appendix E) for comparison tables and figures between natural gas distribution, natural gas transmission, and hazardous liquid transmission pipelines].

The cost of the 84,000 corrosion leaks on main pipes and the 99,000 leaks on services is significant. For gas mains, the cost of leak repair is estimated at between $1,200 and $2,500 per leak and the cost of service repairs is estimated at between $800 and $1,500 per leak.

The cost of the major incidents are estimated similarly to those for the Transmission Pipeline sector except that the lost product is minimal for low-pressure distribution companies and the legal costs are estimated to be less. Table 5 summarizes the estimated annual costs to gas distribution operators due to corrosion failures. It is estimated that corrosion failures cost the gas distribution operators between $383 million and $667 million annually.

Table 5. Summary of the cost of leaks for gas distribution systems.

	DESCRIPTION	**LOW ESTIMATE ($ x million)**	**HIGH ESTIMATE ($ x million)**
Fatalities	One fatality per year @ $1,000,000 to $4,000,000 per occurrence	1.0	4.0
Injuries	3.1 injuries per year @ $500,000 to $1,000,000 per occurrence	1.6	3.2
Added Legal	Legal issues and liability (civil and punitive) @ $50,000,000 to $75,000,000 per fatality and injury (4)	200	300
Property Damage	5.2 incidents per year @ $198,000 per occurrence	0.98	0.98
Non-Reportable Main Leaks	84,000 leaks @ $1,200 to $2,500 per occurrence	100.8	210.0
Non-Reportable Service Leaks	99,000 leaks @ $800 to $1,500 per occurrence	79.2	148.5
TOTAL COST OF GAS DISTRIBUTION PIPELINE FAILURES		**$383.58**	**$666.68**

Plastic Pipe

It is sometimes suggested that plastic pipe is safer than steel pipe due to corrosion of the steel pipe. Although plastic pipe failures are not in the scope of this study, the aging or degradation process of plastics may play an important role in plastic pipe failures and deserve some discussion here. Although degradation of plastic pipe has been studied, degradation processes that lead to plastic pipe failures in operation are not well documented. A recent advisory bulletin from the Research and Special Programs Administration (RSPA), U.S. Department of Transportation (DOT), on the vulnerability of older plastic gas distribution pipe (1960s to mid-1980s) to brittle-like cracking has brought to light the fact that plastic pipe is susceptible to certain aging and degradation processes.(5) The phenomenon of brittle-like cracking in plastic pipe as described in the NTSB report, and generally understood within the plastic pipeline industry, relates to a part-through crack initiation in the pipe wall followed by stable crack growth at stress levels much lower than the stress required for yielding, resulting in a very tight slit-like opening and gas leak. Although significant cracking may occur at points of stress concentration and near improperly designed or installed fittings, small brittle-like cracks may be difficult to detect until a significant amount of gas leaks out of the pipe and potentially migrates into an enclosed space, such as a basement. Premature brittle-like cracking requires relatively high localized stress intensification that may be the result of geometrical discontinuities, excessive bending, improper fitting assemblies, and/or dents and gouges. The report suggests that the combination of more durable plastic pipe materials and more realistic strength testing has improved the reliability of estimates of the long-term hydrostatic strength of modern plastic pipe and fittings. The report also documents that older polyethylene pipe, manufactured from the 1960s through the early 1980s, may fail at lower stresses and after less time than was originally projected.

The number of leaks in plastic (polyethylene) mains in 1993 was 36,948 per year, and in polyethylene services, it was 134,448 per year.(3) This gave a leak incidence of 8.5 leaks per 100 km (13.7 leaks per 100 mi) of polyethylene main and 6.21 leaks per 1,000 polyethylene services. In comparison to above, this suggests that leaks in plastic pipe occur at a similar (slightly less) incidence rate as leaks in distribution piping as a whole.

CORROSION MANAGEMENT

The best way to account for all of the operation and maintenance costs associated with corrosion is to examine the total operating and maintenance budgets for the gas distribution industry. The cost of operation and maintenance for gas distribution piping includes maintenance of both plastic and metallic pipe. The cost of only the metallic piping is being considered in this report. These costs typically include the costs associated with annual test point cathodic protection surveys, leak surveys, cathodic protection maintenance and upgrades (including materials), pipe inspection at excavations, casing and insulator inspection, record-keeping, training, and leak repair. It has been reported that the operation and maintenance budget for distribution pipeline companies is $26.06 billion (1997).(6) It is estimated that 10 percent of the operation and maintenance budget for a typical distribution company represents the cost of corrosion.(7) Therefore, the cost of the operation and maintenance corrosion-related expenditures is estimated at $2.61 billion per year (1997).

Furthermore, the assumption is made that the operation and maintenance cost of corrosion is the same portion of the total cost as calculated for the Gas and Liquid Transmission Pipelines sector (Appendix E) of this report (52 percent). Therefore, the total annual cost of corrosion for natural gas distribution pipelines is $5.0 billion ($2.61 billion = 52% x $5.0 billion).

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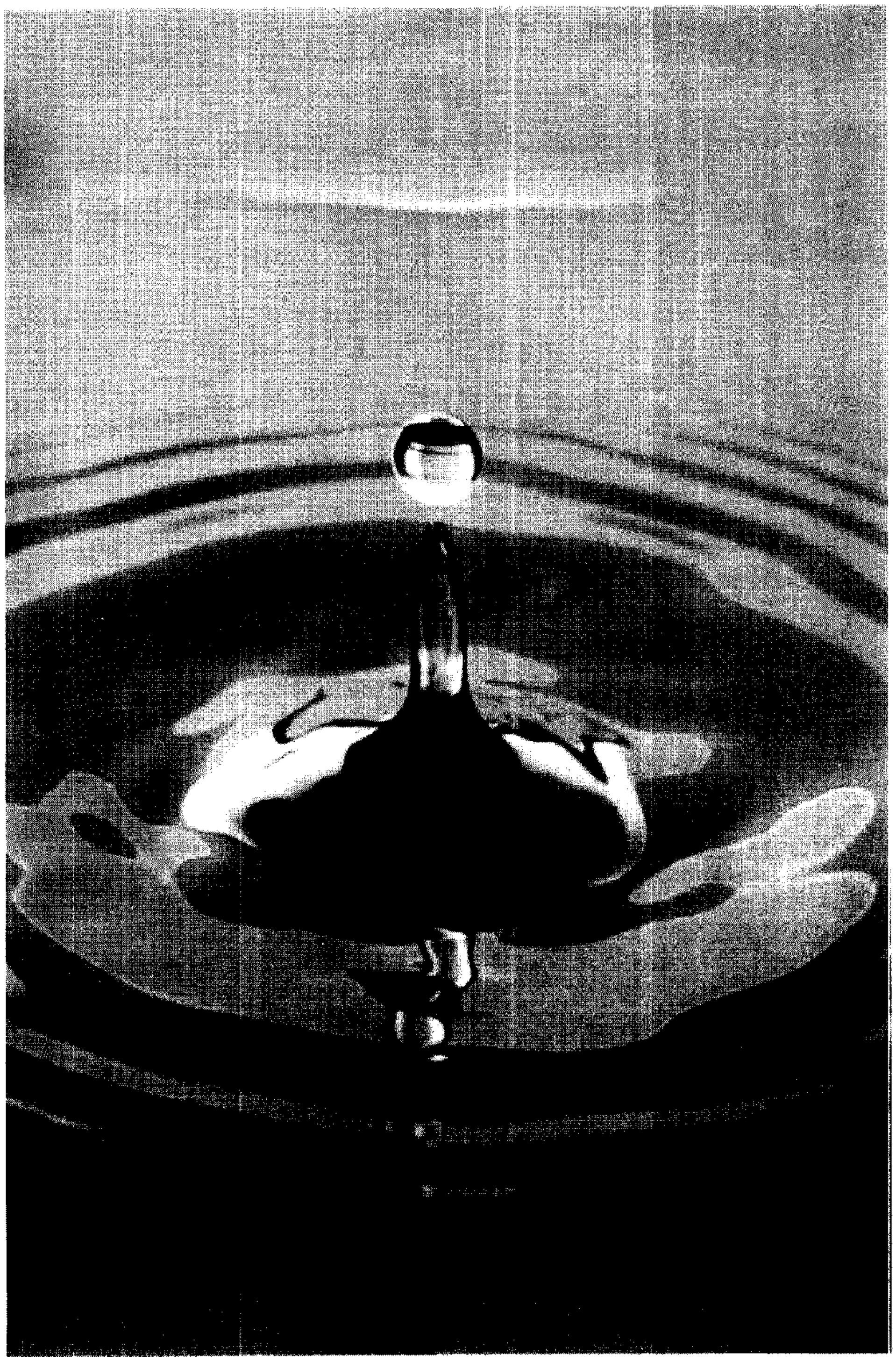
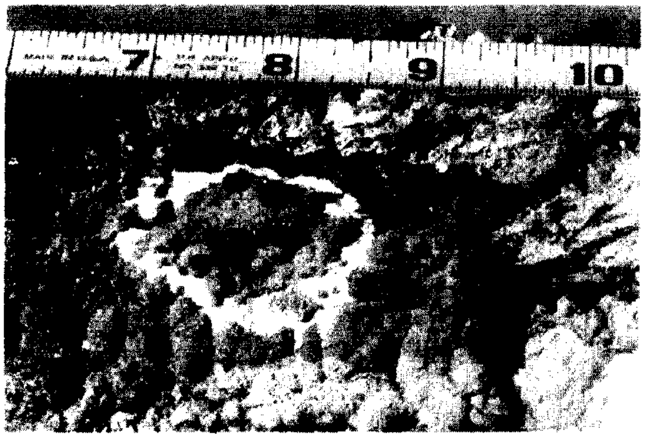
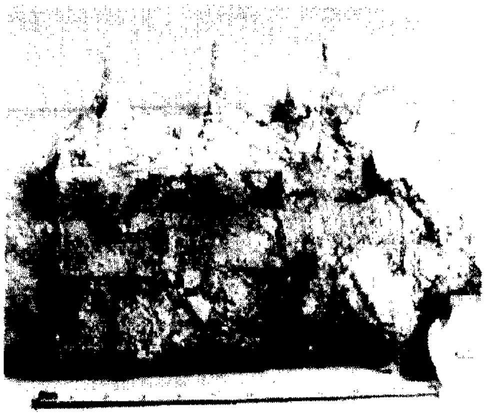
APPENDIX K

DRINKING WATER AND SEWER SYSTEMS



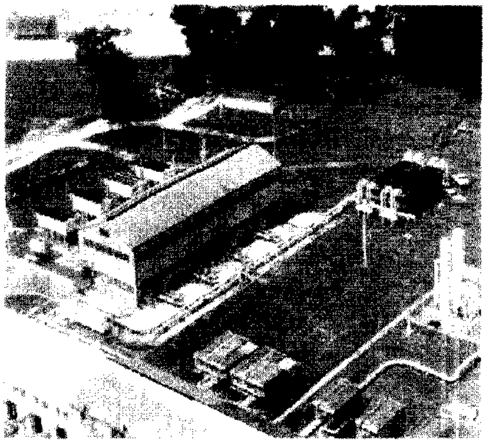


External corrosion on ductile iron pipe

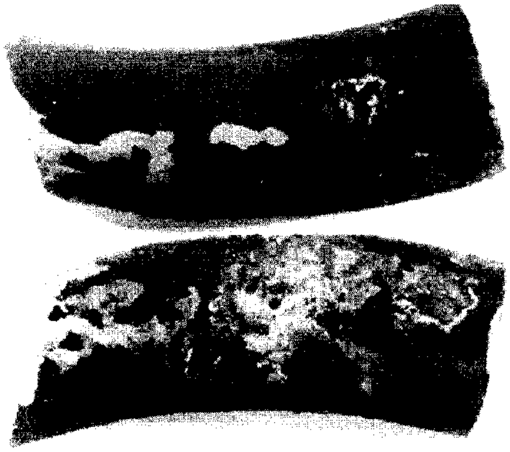


Two clamps on water main

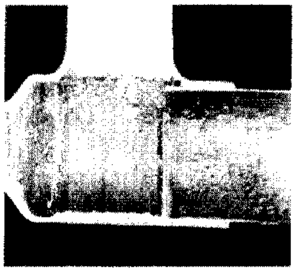
Water main break



Water treatment plant



Pit in copper tubing



Erosion-corrosion of copper water pipe

Stray current corrosion

DRINKING WATER AND SEWER SYSTEMS

MICHIEL P.H. BRONGERS[1]

SUMMARY AND ANALYSIS OF RESULTS

Corrosion Control and Prevention

Americans consume approximately 550 L of drinking water per person per day, for a total annual quantity of approximately 56.7 billion m^3. The treated drinking water is transported through 1.4 million km of municipal water pipes. The water pipes are subject to internal and external corrosion, resulting in pipe leaks and water main breaks.

The total cost of corrosion for the drinking water and sewer systems includes the cost of replacing aging infrastructure, the cost of unaccounted-for water, the cost of corrosion inhibitors, the cost of internal cement mortar linings, the cost of external coatings, and the cost of cathodic protection.

In March 2000, the Water Infrastructure Network (WIN) estimated the current annual cost for new investments, maintenance, operation, and financing of the national drinking water system at $38.5 billion per year, and that of the sewer system at $27.5 billion per year. The total cost of corrosion was estimated from these numbers by assuming that at least 50 percent of the maintenance and operation costs are to replace aging (corrosion) infrastructure, while the other 50 percent would be for system expansion. This results in an estimated cost of corrosion for drinking water systems of $19.25 billion per year and for sewer systems of $13.75 billion per year.

WIN stated that the current spending levels are insufficient to prevent large failure rates in the next 20 years. The WIN report was presented in response to a 1998 study by the American Water Works Association (AWWA) and a 1997 study by the U.S. Environmental Protection Agency (EPA). Those studies had already identified the need for major investments to maintain the aging water infrastructure.

In addition to the costs of replacing aging infrastructure, there is the cost of unaccounted-for water. One city reported a constant percentage of unaccounted-for water of 20 percent in the last 25 years, with 89 percent of its main breaks directly related to corrosion. Nationally, it is estimated that approximately 15 percent of the treated water is lost. The treatment of water that never reaches the consumer results in inflated prices (national lost water is estimated at $3.0 billion per year) and over-capacity in treatment facilities.

Adding these three major cost items results in a total annual cost of corrosion of $36.0 billion per year for drinking water and sewer systems combined.

Opportunities for Improvement and Barriers to Progress

Water transmission and distribution systems can be protected from internal corrosion by using corrosion inhibitors in combination with pH adjusters and alkalinity control. A second method of internal corrosion protection is the application of a cement mortar lining to iron-base pipes. External corrosion protection can be obtained from coatings and cathodic protection.

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[1] CC Technologies Laboratories, Inc., Dublin, Ohio.

The cost of corrosion inhibitors added to the drinking water is a percentage of the total treated water cost. AWWA estimated that the annual costs for corrosion inhibitor treatment ranges from $1.00 to $1.50 per residential consumer. With approximately 66 million residential customers, the total cost can be estimated at $82 million per year, which is 2.5 percent of the total annual treated water cost.

New iron and steel pipelines are commonly lined with cement mortar. Cement mortar linings are also used for rehabilitation of older ductile iron, cast iron, and steel water pipeline networks. The linings can eliminate small leaks in pipes and pipe connections as a result of the high resistance of cement mortar to pressure, enhance the hydraulic characteristics of the mains, and prevent further internal corrosion damage. Studies by AWWA show that the cost for water pipe rehabilitation by cement mortar lining ranges from 13 percent to 41 percent of the costs of total pipe replacement.

Several studies show that the direct cost of maintenance and repair of water pipes, and repaving after work is done is approximately 50 percent of the total budget of water departments. Repairs can be prevented if control methods are applied to the system. External corrosion can be effectively mitigated by the application of coatings and cathodic protection. Although these systems have problems of their own, the initial cost for installing coatings and cathodic protection on new systems is almost always warranted because large maintenance cost-savings can be achieved over the life of the piping system.

A major barrier to progress in corrosion management is the absence of complete and up-to-date information on all water systems. Limited communication between water utilities limits the awareness and implementation of available corrosion control technologies, such as new coating systems and cathodic protection. In addition, the lack of information complicates the process of prioritizing maintenance. AWWA maintains partial records on the water systems of its members, and the U.S. EPA collects data from voluntary questionnaires; however, most water utilities do not have complete records on all of their buried pipes. The pipe mileage length, pipe materials, pipe diameters, and their installation dates are, in many cases, unknown. At the local level, corrosion engineers maintain small databases with information on the nature of individual repairs, but often these records are not integrated in a larger data system. Computers provide the opportunity to maintain the records both in local and national databases.

A second barrier to progress in corrosion management is the lack of understanding and awareness of corrosion problems at the local level, and the limited time dedicated to solving corrosion problems. Often, an attitude is taken of burying the water pipe and forgetting about it until it fails. Investigations of corrosion-related parameters in drinking water are an important aid to water utilities. The data should be used to regularly re-evaluate the applied chemical treatment for internal corrosion protection. External corrosion protection can be evaluated by systematic inspection of coatings and inspection of the cathodic protection systems at regular intervals.

New developments in electronic equipment make internal inspection with cameras an option to evaluate the condition of pipe sections. These techniques, however, are not commonly used because they are still quite expensive, the equipment insertion into and extraction from the pipe is usually difficult, and the pipe may have internal obstructions or bends. In addition, analysis of the data is generally time-consuming and diffucult.

Recommendations and Implementation Strategy

It is recommended that a national effort be initiated in order to decrease the total amount of unaccounted-for water using several available methods. The objective of this effort would be to prevent increasing consumer prices and to more effectively use the capacity of treatment facilities. Furthermore, a decrease in unaccounted-for water will also decrease the total quantity of chemicals used to treat drinking water.

It is recommended that a national resource expertise be created where water utilities can get information about corrosion, where agencies can receive support to develop their corrosion protection plan, and where corrosion awareness training for employees is provided.

It is recommended that a national database be created to which all water utilities must submit complete records on changes to their systems. This will enable water utility managers to better understand the reasons for system growth, to accurately estimate pipe replacement rates, and to prioritize funding for corrosion maintenance and aging system rehabilitation.

Finally, it is recommended that regularly scheduled corrosion inspections be conducted on water treatment facilities, water tanks and towers, and water transmission and distribution systems. The inspections should evaluate the effectiveness of internal and external corrosion protection measures so that the integrity of the aging infrastructure is maintained at the lowest possible cost.

Summary of Issues

Increase consciousness of corrosion costs and potential savings.	The total cost of corrosion for drinking water and sewage systems is \$36.0 billion/year. This cost is divided in \$19.75 billion for drinking water systems, \$ 13.25 billion for sewage water systems, and \$3.0 billion in consumer costs for unaccounted-for water. The cost for added corrosion inhibitors is only a small part of the total cost: \$82.5 million/year.
Change perception that nothing can be done about corrosion.	Internal corrosion can often be prevented or slowed down if corrosion inhibitors are used in combination with a system of internal linings and coatings. External corrosion can be prevented and slowed down with the use of external coatings and the application of cathodic protection. In a case study reported by AWWA, it was reported that the costs for water pipe rehabilitation by cement mortar linings can be very economical compared with total pipe replacement. The costs of mortar linings ranged from 13 percent to 41 percent of the costs of total pipe replacement.
Advance design practices for better corrosion management.	Corrosion engineering will be more effective if training about corrosion is provided to maintenance personnel and water system designers. They will recognize corrosion problems in the design and after the system is in service. Also, they will be aware of the latest developments in corrosion technology, including inhibitors, coatings, and cathodic protection. In the last 25 years, major advances have been made in the development of new coating systems and corrosion inhibitors.
Change technical practices to realize corrosion cost-savings.	In many cases, no corrosion protection is applied, and the only corrosion allowance is in the wall thickness of the water system. The application of internal coatings and linings, corrosion inhibitors, external coatings, and cathodic protection have great potential to realize corrosion cost-savings. It is noted that the selection of the corrosion protection system is always related to the specific site and application.
Change policies and management practices to realize corrosion cost-savings.	It was found that most utilities maintain detailed information about their local system. However, nationally, the system information is not coupled. A complete and up-to-date national water system database could include data on unaccounted-for water and improve communication between departments and between individual utilities. In addition, corrosion knowledge could be more easily compared if coupled information would be available in a generally used format, and the assessment of the effectiveness of different corrosion control approaches could be improved.
Advance life prediction and performance assessment methods.	Currently, estimates for pipe replacement rates range from as low as 0.46 percent to as high as 5.0 percent. Utilities should gather relevant data to determine the pipe replacement rate, because it helps in the planning and budgeting for system maintenance. Improved modeling of pipe replacement would allow statistical analysis and predictive assessments for the performance of the system.

Advance technology (research, development, and implementation).	Most utilities do not have a proactive inspection plan to find leaks in their water pipes. Often, leaks are only repaired if they are so large that the water pressure drops significantly or if a flood occurs. This results in many leaks that go undetected for a long time and large losses of treated water. The development and implementation of technologies to detect leaks has the potential of large cost-savings. These techniques could include pressurization tests and internal inspection procedures. For internal inspection, the pipes need to be made accessible for the internal inspection tools.
Improve education and training for corrosion control.	Training should be provided to maintenance personnel so that they will identify corrosion problems in the field. Present corrosion protection techniques should be made accessible to field crews.

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SECTOR DESCRIPTION

Communities in the United States have always provided water to individuals and businesses using groundwater and surface water sources. The water infrastructure is divided into two separate and complementary systems: drinking water services and waste water services. These services consist of a continuously changing and expanding system of water sources, water storage, transmission piping, distribution piping, and treatment facilities. The water system consists of a range of materials in contact with water and soils that vary in quality, both temporally and from one part of the system to another. The utilities operating the individual systems provide water according to the quality standards set forth in the 1996 Safe Drinking Water Act (SDWA) amendments.(1)

Americans use a lot of water. Annually, about 56.7 billion m^3 (15 trillion gal) of drinking water serves approximately 66 million customers in the United States, with the average total water use rate per customer ranging between 473 and 662 L/capita/day [125 and 175 gal/capita/day (gpcd)]. Recent benchmark estimates by the American Water Works Association (AWWA) on indoor water use rates, indicated an average use rate of 245 L/capita/day (64.6 gpcd).(2) The average consumer cost for clean water ranges from $0.50 to $2.50 per 3.78 m^3 (1,000 gal). Corrosion inhibitors are chemicals that are dosed in small quantities and that provide a significant reduction in corrosion. Corrosion inhibitors cost approximately $5.29 per million L ($20 per million gal). The cost for corrosion inhibitors in water treatment is a very small percentage of the treated water cost.

The sewer system is approximately the same size as the drinking water system. The 1995 U.S. Geological Survey Circular(3) reported that approximately 16,400 publicly owned treatment facilities released some 155 million m^3 (41 billion gal) per day of treated wastewater nationwide during 1995.

Over the years, small systems have been combined to form larger systems for the economic benefits of scale. Large systems were interconnected to accommodate temporary demand in certain areas by transporting water from other areas. In the process of maintaining, replacing, upgrading, and combining water systems, many different construction materials and methods have been used. The current extensive and complex water system is a one-of-a-kind result of more than a hundred years of water system engineering. Therefore, maintenance of the existing structures for continued supply and the design and installation of new structures for system expansion pose major technical challenges.

Based on the AWWA Water Industry Database (WIDB),(4) Staples(5) reported in 1995 that the entire United States had approximately 1.4 million km (0.88 million mi) of municipal water piping. Table 1 shows an estimated profile of the different materials that make up these water pipes. (Similar information for wastewater systems was not found.) In 1998, the AWWA Research Foundation used the same database to estimate the total mileage at 0.97 million km (approximately 0.61 million mi), which is only 70 percent of the previous value. Staples estimated that new pipes are being installed at a rate which extend the system length by 1.5 percent per year, while an additional 0.5 percent is being replaced annually.

Table 1. Profile of different materials used for U.S. transmission water pipes, as determined from the 1992 AWWA water industry database.(4-5)

MATERIAL	PERCENTAGE
Cast Iron	48
Ductile Iron	19
Concrete and Asbestos Concrete	17
PVC	9
Steel	4
Other	2
TOTAL	99%

In the current research, it was found that most water utilities do not have complete records of all their buried pipes. The pipe mileage length, materials, and diameters, as well as installation dates, are in many cases, unknown. In many cases, this information is missing due to the age of the system and the change of organizations over the years. The lack of complete up-to-date information about all water systems complicates the process of prioritizing maintenance and the assessments for corrosion protection. The fact that computers have become commonplace in recent years provides the opportunity to maintain records in local databases and in a national database.

System reliability is of the utmost importance to water suppliers and their customers. Corrosion jeopardizes system reliability by causing leaks and breaks and by affecting water quality. Corrosion problems vary within a single system because many variables affect corrosion, such as pipe material, pipe age, pipe wall thickness, water additives, corrosion inhibitor treatment, soil chemistry, soil moisture content and/or local groundwater level, and stray currents.

Corrosion Cost Estimates

Because of the deterioration of the water infrastructure, a number of recent studies were conducted. The studies addressed the current and future needs for replacement and expansion of the infrastructure. Each study had a different scope and used different methods to collect the data and to calculate the current and future infrastructure needs.

In the following sections, three studies are reviewed that estimate the cost of drinking water and wastewater infrastructure in the United States. Table 2 summarizes and compares the three reports. The first two studies deal with drinking water systems only, while the third study includes both drinking water and wastewater. The three studies are:

- EPA Drinking Water Infrastructure Needs Survey, 1997.
- AWWA Report on Drinking Water Infrastructure Needs, 1998.
- Water Infrastructure Network (WIN) Report on Clean and Safe Water for the 21st Century, 2000.

EPA – Drinking Water Infrastructure Needs Survey – 1997

In 1997, the U.S. Environmental Protection Agency (EPA) presented the Drinking Water Infrastructure Needs Survey to Congress.(6) The objective of this study was to estimate the cost of maintenance of the U.S. drinking water system for a 20-year time period. The analysis of the data focused on the future infrastructure needs and whether these needs were due to system expansion (growth) or system deterioration (aging).

The EPA national survey estimated that the nation's 55,000 community water systems must invest a minimum of $138.4 billion (1995 dollars) over the next 20 years ($6.9 billion per year) to install a new infrastructure and upgrade or replace an existing infrastructure to ensure the provision of safe drinking water. Of this total, $12.1 billion (8.7 percent) would be needed immediately (distributed over the first few years) to meet the current SDWA requirements. All values in this study were reported in 1995 dollars. In addition, the report did not correct for financing costs as part of the anticipated capital investment costs.

In the EPA study, approximately 4,000 community water systems documented their infrastructure needs by filling out questionnaires. The questions included requests for information about currently deficient structures and future infrastructure projects. Table 3 shows the categories for investment considered in this study and the total need as determined from the questionnaires.

Table 2. 20-year water infrastructure needs in billions of dollars: Summary of the 1997 EPA report,(6) the 1998 AWWA report,(8) and 2000 WIN report.(9)

		1997		1998		2000			
		EPA		**AWWA**		**WIN**			
		Drinking water	**Sewage water**	**Drinking water**	**Sewage water**	**Drinking water**		**Sewage water**	
		NEED	**NEED**	**NEED**	**NEED**	**NEED**	**CURRENT**	**NEED**	**CURRENT**
Transmission & Distribution	**Maintenance**	77.2	-	325	-	27/year = 540 / 20 yrs	23/year = 460 / 20 yrs	27/year = 440 / 20 yrs	15/year = 300 / 20 yrs
	Operation	-	-	-	-				
Water Treatment	**Maintenance**	36.2	-	-	-				
	Operation	-	-	-	-				
Water Storage	**Maintenance**	12.1	-	-	-				
	Operation	-	-	-	-				
Water Source	**Maintenance**	11.0	-	-	-				
	Operation	-	-	-	-				
Other Water Needs	**Maintenance**	1.9	-	-	-				
	Operation	-	-	-	-				
Financing*		-	-	-	-	100	100	100	100
Capital Investments		-	-	-	-	380	210	360	150
TOTAL		138.4 (6.9 / year)	-	325 (16.3 / year)	-	1,020 (51 / year)	770 (38.5 / year)	900 (45 / year)	550 (27.5 / year)
		Billions of 1995 Dollars		Billions of 1997 Dollars		Billions of 2000 Dollars			
Infrastructure Replacement Rate		**User Specified**	-	**Uniform, 0.5 – 1.5%**	-	**Uniform, 0.5 – 1.5%**	-	**5.0%**	-

*Change in financing costs was not specified by WIN, and therefore the financing costs were given as constant ($100 billion / 20 years) in this table.

Table 3. Total 20-year capital investment needs by category, according to the 1997 EPA Drinking Water Needs Survey (in 1995 dollars).(6)

CATEGORY	TOTAL NEED ($ x billion)	PERCENTAGE
Transmission and Distribution	77.2	56
Water Treatment	36.2	26
Water Storage	12.1	9
Water Source	11.0	8
Other	1.9	1
TOTAL	**$138.4**	**100%**

In 2000, the EPA survey manager(7) explained that the database that served as a basis for the EPA report(6) contained details on 35,545 separate projects listed by the utilities interviewed. The project size ranged from several hundred dollars for rural systems to $699 million for the largest municipal systems. The size of the population served per system ranged from several tens to 15 million people. When the project costs were divided by the number of people served by the improvement, the costs ranged from pennies to $44,000 per person. From the 436 projects that were reported to cost more than $1,000 per person (i.e., $50 per year for 20 years), 158 projects served more than 1,000 people. Most of these relatively expensive projects included transmission and distribution line replacement or rehabilitation, while only a few of these projects were for source or treatment needs. Currently, work is underway on an updated version of the EPA Drinking Water Needs Survey.

AWWA – Infrastructure Needs for the Public Water Supply Sector – 1998

In 1998, the American Water Work Association (AWWA) presented the *Infrastructure Needs for the Public Water Supply Sector* report.(8) The objective of this report was to provide an assessment of the capital investment needs for the water supply community over the next 20 years. This AWWA report was written as a review of the 1997 EPA report, discussed previously, and was intended to be an independent assessment of the potential magnitude of the capital investment needs for water distribution and transmission systems.

AWWA recognized the concern in the drinking water community regarding how much additional investment will be needed over the coming decades for infrastructure upgrades. These infrastructure needs encompass both what is required by the 1996 SDWA amendments, as well as what will be needed to replace and rehabilitate aging water treatment and distribution facilities, regardless of federal regulatory mandates.

In contrast to the EPA report, AWWA examined current water transmission[2] system needs and other long-term infrastructure investment requirements for U.S. water utilities. AWWA commented in their report that the EPA study was solely based on the questionnaires returned by utilities. They indicated that it was therefore possible that many of the answers were based on the Capital Improvement Project (CIP) plans of the individual water systems. The AWWA report stated that the CIP plans typically have only a 5-year timespan, and as a result, the EPA estimates may have been low.

In the AWWA analysis, the expected mileage of pipe to be replaced annually was determined from the current amount of water pipe buried in the United States, multiplied by an average annual rate of replacement, as determined from various sources. The replacement rate signifies the fraction of pipe being replaced annually and can be used to estimate the total time required to replace the entire system once.

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[2] AWWA uses the word "distribution" pipe to refer to large-diameter underground pipe for transportation of water over long distances. In the current report, this pipe is called "transmission" pipe, while the term "distribution" is reserved for relatively small-diameter pipes in residences and businesses.

The 20-year infrastructure needs were calculated by multiplying the annual replacement rate, the total U.S. length of transmission pipe, the expected unit cost per meter of replaced pipe, and the time over which the replacement takes place (i.e., 20 years). Although the following equation appears simple, the actual calculation requires the application of ranges of data and a statistical analysis:

$$\text{20-Year Infrastructure Needs} = \text{Replacement Rate} \times \text{Kilometers} \times \text{Unit Cost} \times \text{20 years}$$

Based on the AWWA calculations, the anticipated 20-year capital needs for distribution systems of U.S. water utilities were estimated to be $325 billion (1998 dollars), or $16.3 billion per year. From the "Waterstats" database, the AWWA Research Foundation estimated in 1998 that approximately 0.89 to 1.06 million km (0.55 to 0.66 million mi) of transmission pipe are currently in service. The calculations for future spending in the drinking water infrastructure strongly depend on the estimated pipe replacement rates. The pipe replacement rate is defined as the percentage of the total length of water pipe in a system that is replaced in 1 year. For example, a replacement rate of 1.0 percent signifies that the entire system is replaced once every 100 years.

The estimated replacement rates ranged from 0.46 percent (entire system replacement once every 217 years) to 0.63 percent (entire system replacement once every 159 years) to 1.54 percent (entire system replacement once every 65 years) to 2.0 percent (entire system replacement once every 50 years). For their 20-year statistical analysis, AWWA used a replacement rate with a uniform distribution, assuming a minimum of 0.5 percent and a maximum of 1.5 percent. Approximately 26 percent to 45 percent of the transmission pipe has a diameter smaller than 20.3 cm (8 in), 54 percent to 72 percent is between 20.3 and 50.8 cm (8 and 20 in), and 0.4 percent to 2.2 percent is 50.8 cm (20 in) or greater. The range of estimated replacement costs for pipe varied from $289/m for 20.3-cm-diameter pipe ($88/ft for 8-in-diameter pipe) to $866/m for a 61-cm-diameter pipe ($264/ft for 24-in-diameter pipe). It was recognized that these values depend on many factors, including the location of the pipes, the current age of the system, and the local importance of the system. The calculations for the total expected amounts were made using a sensitivity analysis with the above-mentioned values. The AWWA study did not include estimates for treatment, storage, and source infrastructure needs. For the total infrastructure needs, AWWA calculated the infrastructure distribution needs for medium and large systems, and used the EPA estimate for small systems.[3]

To compare the EPA report with the AWWA report, both must be expressed in 1998 dollars. The $325 billion AWWA estimate is approximately 3.9 times that generated by the EPA for its 20-year assessment of transmission needs, amounting to $84 billion (1998 dollars) [$77.2 billion in 1995 dollars]. The reasons identified for the larger AWWA estimate were the undefined time period for the costs due to utilities probably reporting only 5- to 6-year needs, the underestimated or overlooked future costs due to the short period of capital investment plans, the unreported distribution needs of one-half to three-quarters of the surveyed large utilities, and the possible underestimation of large utilities. In addition, the EPA did not collect data on the miles of pipes in place, the types of pipes used, and the water system data, such as population served or total service area.

WIN – Clean and Safe Water for the 21st Century – 2000

In April 2000, the Water Infrastructure Network (WIN), a coalition of more than 20 drinking water suppliers, wastewater treatment companies, municipal and state government agencies, engineering organizations, and environmental groups, including AWWA, published a report called *Clean and Safe Water for the 21st Century.*(9) The objective of this report was to compare the current investments in water infrastructure with the investments that will be needed annually over the next 20 years to replace aging and failing pipes and to meet the mandates of the Clean Water Act and the Safe Drinking Water Act.

WIN handled the infrastructure replacement costs somewhat differently in the case of water supply compared to wastewater treatment. For water supply estimates, WIN adopted the method used by AWWA in their 1998 report.(8) This method used a simulation model to project the future costs of replacing distribution systems at then-current

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[3] EPA defines "large systems" as serving more than 50,000 people, "medium systems" as serving 3,301 to 50,000 people, and "small systems" as serving 3,300 people or fewer.

costs. Unfortunately, WIN failed to report how they re-evaluated the replacement rates estimated by AWWA. If the same replacement rates were used, then they would be in the range of 0.46 to 2.0 percent. For wastewater, WIN used a model based on a method first developed by the U.S. Department of Commerce.(10) The model assumed that 1/20 of the depreciated value of all wastewater systems nationwide would be replaced each year over the next 20 years. This means that WIN assumed a replacement rate of 5.0 percent for the wastewater sector. The reason for the large difference between the replacement rates for the two sectors was not given.

WIN estimated that there will be a total annual capital investment and financing need of $46 billion during the next 20 years. Therefore, the total estimated 20-year need is $920 billion. The $46 billion annual need value includes $24 billion for drinking water and $22 billion for wastewater infrastructure and capital investment financing. If operations and maintenance are added, the total annual need is $96 billion, which is equivalent to an estimated $1.920 trillion in 20 years. WIN refers to its source as Hagler Bailly Services, Inc., which based its estimates on data and analyses conducted by AWWA, the U.S. EPA, the U.S. Bureau of the Census, and the U.S. Department of Commerce; however, the details on the calculations were not included in their report.

Different from the EPA report, which addressed the drinking water transmission piping infrastructure only, and the AWWA report, which addressed drinking water transmission systems only, the WIN report addressed both drinking water and sewage water infrastructure. WIN reported that the costs of replacing aging water facilities with new ones are much greater than previous estimates by EPA. Table 4 shows the estimates for operations and maintenance (O&M) costs, financing costs, and capital investment costs.

Table 4. Combined annual drinking water and wastewater infrastructure needs, according to the 2000 WIN report.(9)

	INVESTMENT NEEDS ($ x billion)	**CURRENT INVESTMENTS ($ x billion)**	**SPENDING GAP (Year 2000 U.S. dollars) ($ x billion)**
Operations and Maintenance	49 (51%)	38 (58%)	11
Financing	10 (10%)	10 (15%)	0
Capital Investments	37 (39%)	18 (27%)	19
TOTAL	**$96**	**$66**	**$30**

Table 4 shows that a total annual investment gap of $30 billion exists. Filling this gap will require a redistribution of allocations from 58 percent 15 percent 27 percent to 51 percent 10 percent 39 percent for the three cost categories, respectively. This redistribution indicates a significant increase in capital investments, both in absolute value ($18 billion to $37 billion) and in percentage of the total costs (27 percent to 39 percent). It is noted that the $30 billion gap calculated above is $4 billion lower than the $34 billion gap presented in the WIN report itself. The reason for this gap is that the WIN report is unclear about the individual costs for current operations and maintenance, financing, and capital investments.

The cost of taking action to guarantee a sufficient water quantity and a satisfactory water quality is traditionally recovered through customer rate increases. WIN reports that local homeowners and industries currently pay more than $60 billion a year in water and sewer charges. It is WIN's opinion that federal funds are needed amounting to nearly a trillion dollars in critical water and wastewater investments over the next two decades. These federal funds are meant to prevent significant rate increases for large portions of the U.S. population.

Comparing the Three Reports

A comparison of the EPA report, the AWWA report, and the WIN report reveals that the estimated infrastructure costs were estimated by each organization using a different focus and different calculation methods. The estimated 20-year costs ranged from $138.4 billion (EPA, transmission pipe for drinking water only, no financing, no capital investments) to $325 billion (AWWA, drinking water transmission only, no financing, no capital investments) to $1.02 trllion for drinking water and $900 billion for sewage water (WIN, operations and maintenance costs, financing, and new capital investment costs included). Table 2 summarized and compared the three reports.

Estimating the Total Cost of Corrosion

In all three reports, the costs for replacement and the costs for system expansion are treated equally. In the current research, no reference to studies was found that would estimate the division of these costs any differently than 50 percent/50 percent; therefore, in the next calculation, it is assumed that at least 50 percent of the transmission and distribution maintenance needs are used to replace aging (corrosion) infrastructure, while the other 50 percent would be for system expansion.

The EPA study estimated that transmission and distribution water piping represented 56 percent of the total cost. Using the AWWA study cost of $325 billion per 20 years for transmission water piping gives an estimate of the total drinking water infrastructure of $580 billion per 20 years (100 / 56 x $325 billion). This number is comparable to the $540 billion estimated by WIN (see table 2).

WIN estimated the current annual cost for new investments, operations and maintenance, and financing of the national drinking water system at $38.5 billion per year, and of the sewer system at $27.5 billion per year, as explained in table 2. The total cost of corrosion was estimated from these numbers by assuming that at least 50 percent of the operations and maintenance costs are to replace aging (corrosion) infrastructure, while the other 50 percent would be for system expansions. This results in an estimated cost of corrosion for drinking water systems of $19.25 billion per year and for sewer systems of $13.75 billion per year. In addition to the cost of replacing aging infrastructure, there is the cost of unaccounted-for water. Nationally, it is estimated that approximately 15 percent of the treated water is lost. Adding these three major cost items results in a total annual cost of corrosion of $36.0 billion per year for drinking water and sewer systems combined.

AREAS OF MAJOR CORROSION IMPACT

Corrosion damage costs money, but so does corrosion control. Corrosion can occur at the treatment plant, throughout the distribution system, and in household plumbing. Wherever it occurs, it has effects that cost both the utilities and the consumers money. Corrosion results in pipe breaks and leaks; damage to water meters, plumbing components, and storage facilities; excessive repairs and replacement, increasing both operating and capital expenses; and water loss.

In the current sector study, the total annual corrosion cost for drinking and wastewater systems combined was estimated at $36 billion per year. In the past, estimates of the total annual cost of corrosion damage incurred by water utilities have ranged from $1.7 billion(11) up to 25 percent of total annual operating costs,(12) which has been estimated at $5 billion.(13) Estimates of the cost of corrosion damage to consumers ranges from roughly equal the cost to utilities(14) to double their cost.(15) The large variations in these estimates may have been because of limited data; however, in the current study, national estimates and extrapolations were used.

In 1989, Levin et al.(16) compared specific chemical treatments for internal corrosion control by modeling variables such as dosage rate and system size. Although this method can be used for individual systems, it cannot be easily extrapolated to estimate national corrosion costs. The above authors also included data from several studies that compared corrosion costs in the 1970s and early 1980s. In table 5, one column shows the percentage cost of corrosion damage that could potentially be avoided through improved water treatment, according to the various researchers cited.

Table 5. Estimates of annual per capita corrosion damage (1998 dollars*), as summarized in a 1989 overview article by Levin et al.[16]

STUDIES	ESTIMATED ANNUAL CORROSION DAMAGE (per capita)			CORROSION DAMAGE AVOIDABLE THROUGH WATER TREATMENT	ANNUAL PER CAPITA BENEFITS OF CORROSION CONTROL	ASSUMPTIONS/NOTES
	Distribution Systems	Residential	Total			
Kennedy Engineers (1973)	$8.36	-	$25.07**	30%	$7.52**	Assumed 30% potential reduction in corrosion damage and that distribution costs were one-third of total costs.
Hudson & Gilcreas (1976)	$10.02**	-	$39.06**	50%	$19.53**	They did not include increased operating costs. Per capita estimate assumes 200 million people are served by public water systems. Assumed that distribution costs were one-third of total costs.
Kennedy Engineers (1978)	-	$46.31**	$69.45**	20%	$13.89**	They calculated $6.17 per capita in savings to residence owners. Assumed residential costs were two-thirds of total costs.
Bennett et al. (1979) cited in Ryder (1980)	$14.10	-	$42.30**	20%	$8.46**	Assumed that 200 million people are served by public water systems and that distribution costs were one-third of total costs.
Energy & Environmental Analysis	$5.97	$11.96	$17.93	38%	$6.81	This is an admitted underestimate. It includes only damage to pipes (not damage to water heaters, increased operating costs, etc.).
Ryder (1980)	$1.76	$33.29	$35.04	25%	$8.76	Ryder ascribed 95% of corrosion damage to private owners.
Kirmeyer & Logsdon (1983)	-	$35.40**	$53.10**	40%	$21.24**	Assumed residential costs were two-thirds of total damage.
AVERAGE	-	-	**$40.28**	**32%**	**$12.31**	

*In the current table, all amounts reported by Levin et al. in 1985 were multiplied by 1.5 to calculate 1998 dollars.

**These estimates have been calculated by Levin, Schock, and Clark.[16]

In the following sections, the areas of major corrosion impact in the drinking water and sewer services sector are identified. These areas include water quality, water quantity, unaccounted-for water, water main line breaks, internal corrosion in water systems, and external corrosion in water systems.

Water Quality

The two greatest concerns of water utilities are the quality and the quantity of water supplied to customers. Water quality is determined by serviceability (color, taste, and odor) and the health requirements. Corrosion may affect both of these factors. All aspects of water quality can be affected by corrosion of water handling equipment and piping. For example, corrosion products from welded steel piping and iron piping may cause complaints about red or yellow "rusty" water, and internal corrosion of copper and lead piping and corrosion of joint soldering can pose health risks due to increased human exposure to these elements. Microbiologically influenced corrosion (MIC) may affect water quality, both in the health aspects and in the color, taste, and odor of the delivered water.

Water Quantity

The quantity of water is measured directly after it leaves the water treatment facilities and just before it reaches the consumer. In terms of corrosion, the relevant water quantity is that of the unaccounted-for water. The quantity of water reaching the customers can be significantly decreased by leaks in the system. Although the cause of a leak may be internal or external corrosion, or in general terms, "system aging," it is usually not strictly reported as such. Utilities report leaks in the water system as one of the major factors in unaccounted-for water.

Unaccounted-For Water

In the current research, corrosion experts and maintenance engineers at various water utilities were interviewed to give their estimates of unaccounted-for water. The estimates ranged from 5 percent to 40 percent, depending on whether unaccounted-for water included unauthorized use of water only, or if it included all water lost between the producer and the consumer. The water utility annual reports from Denver, CO,(17) Columbus, OH,(18) and El Paso, TX(19) were reviewed to obtain an estimate of unaccounted-for water. These reports indicated unaccounted-for water as approximately 5.34 percent (1999, treated versus sales), 19.39 percent (1972-1997, pumped versus metered), and 12.70 percent (10-year average, 1988-1997, pumped versus billed), respectively (see table 6). Considering the spread in these values, a national average of 15 percent unaccounted-for water was assumed for calculations in the current report.

A least-conservative estimate of the percentage of unaccounted-for water can be calculated from the difference between the amount of treated water and the amount of metered (paid for) water. Within the total quantity of unaccounted-for water, the percentage attributed to system aging or leaks is generally not known; however, based on the review of several utility annual reports, a reasonable estimate appears to be about 50 percent.

Unaccounted-for water consists of two categories: authorized and lost. Examples of authorized, unmetered water uses include firefighting, fire hydrant flushing, main line flushing, process water for water plants, irrigation of public areas such as parks and highway medians, and street cleaning. Unauthorized, unmetered uses include water theft through illegal connections. Other causes of unaccounted-for water include unmapped or forgotten piping, evaporation, reservoir seepage, reservoir overflow, and oversized or inaccurate water meters; therefore, small leaks or minimal water usage may not be registered. Meters are originally installed according to anticipated user patterns; however, if the consumer's patterns change, a utility rarely resizes a meter to match this. Most water utilities are well aware of the difference in produced and metered water, and have teams to find and repair leaks and faulty meters. However, the magnitude of their systems and their overall deteriorating integrity as the water systems age make it a difficult task.

Table 6. Summary of estimated fraction of unaccounted-for-water for selected U.S. cities, as reported in various sources.(17-19)

CITY	YEAR	DEFINITION	BILLED	UNACCOUNTED FOR	m^3 LOST	RETAIL PRICE	LOST REVENUE
			%	%	x million	\$ / m^3	\$ x million
Denve, COr	1999	Treated versus Sales	94.66	5.34	15.195	0.4438***	6.7
Denver, CO	1998	Treated versus Sales	92.66	7.34	21.531	0.4438***	9.6
Columbus, OH	1972-1997	Pumped versus Metered	80.61	19.39	28.341	0.8137**	23.0
El Paso, TX	1988-1997	Pumped versus Billed	87.30	12.70*	19.097	0.3461**	6.6
San Francisco, CA	-	Pumped versus Metered	-	5 to 10*****	-	-	-
UNITED STATES	**Annual**	**Total Lost Water**	**85%**	**15% of 56.7 billion m^3**	**8,505**	**\$0.3513********	**\$2,988**

*10-year average.

**1997 value.

***1999 value.

****Average value, as reported by Institute for Research in Construction (IRC).

*****Estimated by Steven Leonard, San Francisco Water Department.

Unaccounted-for water is a serious problem nationwide. The water that disappears represents lost revenues and increased costs for water utilities. On the other hand, unaccounted-for water losses may create the impression that additional water supplies and/or distribution systems are needed, when all that is really required is reducing waste in the system. Unaccounted-for water losses may also increase the infiltration of outside water into wastewater treatment plants, resulting in greater volumes to process and increased costs to be paid.

An approximate revenue loss calculation for unaccounted-for water is done by multiplying the estimated annual total quantity of 56.7 billion m^3 (15 trillion gal) of treated water by an estimated 15 percent unaccounted-for water and the cost of that water. A lower bound calculation is done by assuming an average treatment cost of about \$5.29/thousand m^3. In that case, the lost revenue cost for unaccounted-for water is: 56.7 billion m^3 x 15 percent x \$0.00529/m^3 = \$45 million. An upper bound calculation is done by assuming an average consumer cost of about \$0.3513/ m^3. In that case, the lost revenue cost for unaccounted-for water is: 56.7 billion m^3 x 15 percent x \$0.3513/m^3 = \$2.988 billion. These calculations show that the annual direct cost of unaccounted-for water ranges between \$45 million and \$3.0 billion.

Water Main Line Breaks

Transmission and distribution line breaks are another large factor affecting water quantity. The direct cost of a break depends on the material, labor and equipment costs of the excavation, the actual repair and/or replacement, and repaving. These costs are influenced by the emergency level of the break and the location of the break in the city. Indirect costs are calculated as the costs of the consequences to others and they are much more difficult to estimate. For example, a street under construction will cause time delays for the traffic passing there and businesses may be affected by the water shortage and claim the liability of the utility. Customers experience inconvenience from the outage because the system is temporarily out of service and the water will remain dirty for a period of time following the pipe break. Dealing with the customer complaints places a heavy burden on the service departments of utilities.

Internal Corrosion in Water Systems

Forms of internal corrosion in water systems include uniform corrosion, galvanic corrosion, localized corrosion, concentration cell corrosion, microbiologically influenced corrosion (MIC), and erosion-corrosion. Major internal corrosion can occur in pipes made of cast iron, ductile iron, steel, galvanized steel, and cement-based materials. Table 7 summarizes corrosion types for different piping materials and the possible tap water quality problems caused by them, as described by the AWWA Research Foundation in 1996 in a reference book on internal corrosion of water distribution systems.(20)

Negative health effects can result from corrosion of lead, corrosion of copper alloys and solder in water supply systems, and corrosion of copper plumbing in potable water systems. In the current report, an effort is made to provide background on the most significant corrosion mechanisms, as related to their cost impact.

Table 7. Corrosion and water quality problems caused by materials in contact with drinking water.(20)

MATERIAL	CORROSION TYPE	TAP WATER QUALITY DETERIORATION
Cast Iron	Uniform Corrosion	Rust Tubercles (Blockage of Pipe)
Ductile Iron	Graphitization and Pitting Under Unprotective Scale	Iron and Suspended Particles Release
Steel	Pitting	Rust Tubercles (Blockage of Pipe) and Iron and Suspended Particles Release
Galvanized Steel	General Corrosion	Excessive Zinc, Lead, Cadmium, and Iron Release and Blockage of Pipe
Asbestos Cement*	Uniform Corrosion	Calcium Dissolution, Possible Asbestos Fibers, and Increased pH
Concrete	Uniform Corrosion	Calcium Dissolution and Increased pH
Cement Mortar**	Uniform Corrosion	Calcium Dissolution and Increased pH
Copper	Uniform Corrosion	Copper Release
	Localized Attack	Perforation of Pipe and Leakage
	Microbiologically Influenced Corrosion (MIC)	Leakage From Pipes
	Corrosion Fatigue	Rupture of Pipe and Leakage
	Erosion-Corrosion	Leakage From Pipes
Lead Pipe	Uniform Corrosion	Lead Release
Lead-Tin Solder	Uniform Corrosion	Lead and Tin Release
Brass	Erosion and Impingement	Penetration Failures
	Dezincification	Blockage of Pipe
	Stress Corrosion Cracking (SCC)	Lead and Zinc Release
Plastic	Degradation by sunlight and microorganisms?	Taste and Odor

*No internal lining (e.g., tar).

**Used as internal lining of iron and steel materials.

External Corrosion in Water Systems

External corrosion of water systems may be caused by general corrosion, stray current corrosion, microbiologically influenced corrosion (MIC), and/or galvanic corrosion. Mitigation techniques include the application of protective coatings, wrapping pipe in a plastic, and the application of cathodic protection. The areas of major external corrosion impact are generally those where localized attack may take place, such as in the proximity of other systems (galvanic corrosion) or in areas where stray currents may occur.

Both dc and ac stray currents on a water line can cause corrosion. Stray current studies, for example, those performed by the AWWA Research Foundation,(21) show that the corrosion rate due to dc current is generally greater than the corrosion rate due to ac current. General external corrosion can be a problem in corrosive soil, particularly when there is low soil resistivity, high moisture content, and corrosive chemical species present. When piping is electrically continuous (welded steel piping), cathodic protection can be applied; however, that is generally not possible for discontinuous pipe (ductile iron, cast iron).

Plastic piping [for example, polyvinyl chloride (PVC) piping] does not show metallic corrosion, but its properties do deteriorate over time. In severely corrosive soils, PVC piping may be selected rather than a metallic piping material because it is inert to the chemical conditions. PVC has a lower density than steel and iron; therefore, it is relatively easy to handle in the field. However, PVC also has lower strength, and traditional welding is not possible. PVC has been used for a relatively short time, compared with steel and iron water lines. Therefore, there is limited data on the expected service life of PVC pipelines, and calculations of comparative total life-cycle costs were not found.

Cement-based piping deteriorates by corrosion of the reinforcement steel, which is often accelerated by chloride from salt-treated roads during winter. Corrosion occurs when the passive surface film that naturally forms on steel in high-pH concrete/cement breaks down in the presence of chloride. The corrosion product has greater volume than the original steel, creating internal stresses that cause cracking and spalling of the concrete/cement pipes.

CORROSION CONTROL METHODS

Table 8 summarizes the most commonly used corrosion control methods for water systems. For each component, several different control methods can be applied.

Table 8. Summary of most commonly used corrosion control methods for water systems.

COMPONENTS IN WATER SYSTEM	CORROSION CONTROL METHOD
Steel dams	Increased wall thickness
General water infrastructure	Corrosion inhibitors
	pH adjusters
	Alkalinity controllers
	Hardness controllers
Storage tanks	Cathodic protection (CP)
	Internal coatings
	External paint coatings
Ductile iron, cast iron, and steel pipes – Internal corrosion	Internal linings
	Internal inspection
Cement-based pipe	Internal lining – cement mortar
Ductile iron, cast iron, and steel pipes – External corrosion	Cathodic protection (CP)
	External coatings
	Corrosion coupons, test stations, corrosion data loggers
Lead pipe	Replacement with copper pipe
Copper pipe	Prevention, by improved tube production
Nonferrous alloys – Fittings, fixtures, joints	Replacement with corrosion-resistant components
Sewage pipes	Increased wall thickness

Corrosion Control in the Water Supply

Each water utility tries to have a sufficiently large supply of water to fulfill the needs of its customers. Rainwater is the main source for groundwater, while river water and lakes are the main source for surface water. Lakes and underground reservoirs are used to store large quantities of raw water for times when the water level in a river is too low. Infrastructure in and connected to the reservoirs includes dams, water-intake structures, and piping. Corrosion is generally not a very significant issue here. For example, metal dams are given a corrosion tolerance with regard to the thickness of the steel walls, allowing for metal loss due to general corrosion during the expected service life.

Corrosion Control in Water Treatment Facilities

The infrastructure of water treatment facilities is designed to remove contaminants from water. Figure 1 shows a schematic diagram of the drinking water treatment process.

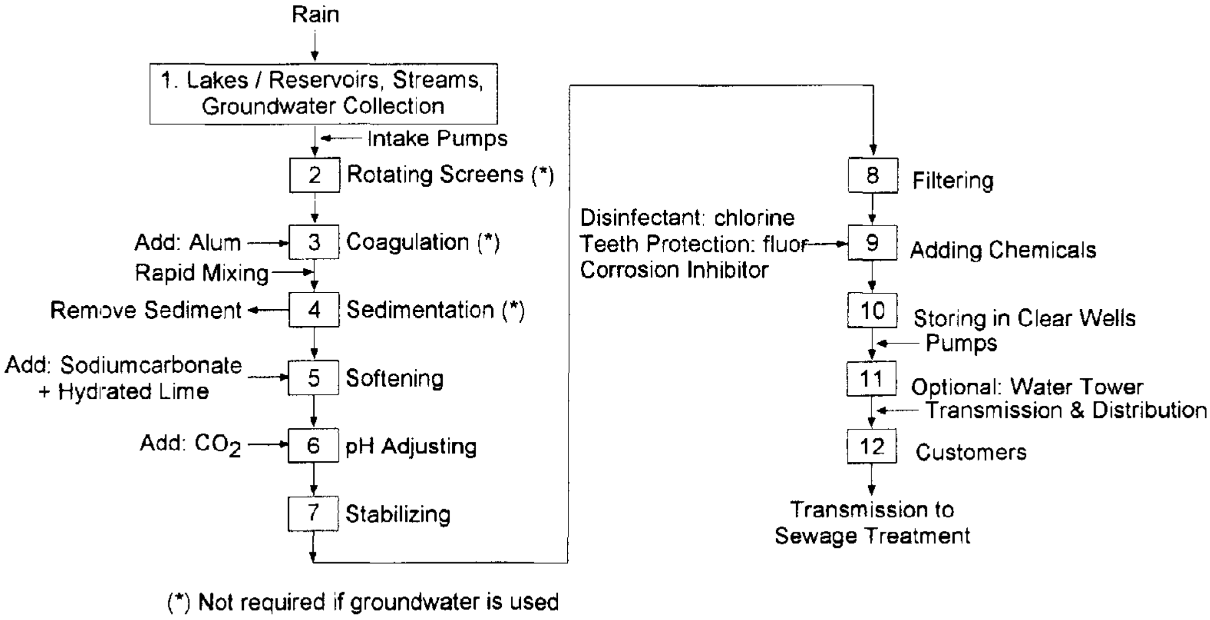

Figure 1. Schematic diagram of drinking water treatment process.

A series of filtration procedures and several chemical treatments are used in cleaning the raw water to prepare it for consumption. Mixing of different source waters is often used as an option to change quality and reduce corrosivity. In some cases, aeration can be used in drinking water treatment. In addition to removing hydrogen sulfide, methane, radon, iron, manganese, and volatile organic contaminants, aeration is effective for carbon dioxide (CO_2) removal. CO_2, in turn, directly affects pH and dissolved inorganic carbon, two parameters that significantly influence lead and copper solubility. Under the right water quality conditions, aeration can serve as a potential corrosion control treatment by removing CO_2 and subsequently increasing pH and decreasing dissolved inorganic carbon. The degree to which aeration affects corrosion depends on such raw water quality parameters as pH, dissolved inorganic carbon, and dissolved oxygen, as well as CO_2 removal efficiency.(22)

The chemicals used to treat the raw water and improve its quality include corrosion inhibitors, pH adjusters, and alkalinity and hardness controllers. The commonly used water treatment chemicals are soda ash, sodium bicarbonate, sodium hydroxide (caustic soda) plus carbon dioxide, lime, alkaline media filters, and combinations such as limestone slurry plus carbon dioxide plus sodium hydroxide. All U.S. water utilities are required to continuously monitor their water quality by taking and analyzing samples of their treated water. The samples are taken at regular time intervals and at different locations spread out over the system.

Corrosion Inhibitors, pH Control, and Alkalinity Adjusters

In addition to the necessity of water quality control according to the Safe Drinking Water Act (SDWA), the application of chemicals for pH adjustment is one of the main options of internal corrosion control. In many instances, however, pH control or pH and alkalinity adjustment are not sufficient to suppress corrosion problems. In these cases, corrosion inhibitors can be used for internal corrosion protection. Corrosion inhibitors are chemicals that are dosed in small quantities for a significant reduction in corrosion. The impact of inhibitors on water quality and their effectiveness on different materials are very complex.(23) The stringent limits concerning lead and copper, or other materials in drinking water, limit the use of inhibitors for corrosion control.

Categories of corrosion inhibitors for water treatment include naturally occurring inhibitors and human-added inhibitors. Natural inhibitors include natural organic matter, dissolved silica, and phosphate. Materials that can receive some degree of corrosion protection from natural inhibitors include iron, zinc coatings, lead, and copper. Added corrosion inhibitors are chemicals that are dosed in small quantities to obtain a passivating film on anodic sites to suppress the electrochemical corrosion reactions or to act to inhibit the cathodic reactions and, therefore, provide a significant reduction in corrosion rate. Added corrosion inhibitors include orthophosphates, molecularly dehydrated polyphosphates, bimetallic (zinc-containing) phosphates, silicates, and phosphate-silica mixtures.

Selection of Corrosion Inhibitors

The selection of the most cost-effective corrosion inhibitors is a complex task that depends on many interacting variables. The cost-effectiveness can be calculated by multiplying the relative effectiveness of the inhibitor, the necessary dosage rate (mg/L), and the price per weight ($/kg).

$$\text{Cost Effectiveness} = \text{Relative Effectiveness} \times \text{Dosage Rate} \times \text{Price Per Weight}$$

The inhibitor dosage rate depends on the local water condition and temporal factors, such as time of the year. It should be quantified in terms of percent reduction of corrosion and extension of useful life. Table 9 lists commonly used corrosion inhibitors for potable water systems, their dosage rates, and a comparative estimated inhibitor cost.(20) In 1995, the American Water Works Company (AWWC), a privately owned company serving about 5.1 million people, reported the costs of chemicals for their system.(24) These costs are included in table 9 and comparison shows that the estimates are in reasonable agreement with the AWWA estimates. AWWA estimated that if a treatment cost of $5.29 per thousand m^3 ($20 per million gal) is assumed, the annual costs for corrosion inhibitor treatment would range between $1.00 and $1.50 per residential consumer.

In a 1985 publication by Singley et al.,(25) typical annual chemical costs for corrosion control were presented, based on 1982 data from various chemical suppliers. These figures were used to estimate the cost range per year for an 11.4 thousand m^3-per-day [3 million gal-per-day (MGD)] plant and a 189 thousand m^3-per-day (50-MGD) plant. The results are given in table 10.

Phosphate and silicate corrosion inhibitors have been used, with or without pH control, to reduce metal release and to prolong the service life of distribution systems or domestic installations. If concentrations are limited, inhibitors may not avert localized corrosion (such as pitting) caused by material or installation faults, or they may not be able to reduce corrosion rates of the usual materials (galvanized steel, steel, cast iron, copper, or lead) sufficiently to extend the life span of a system beyond 75 to 100 years. Corrosion inhibitors are often necessary and can be very beneficial when concerns about water quality deterioration have to be resolved. However, there are secondary influences of corrosion inhibitors such as the impact of zinc orthophosphate on zinc levels in wastewater sludges, or phosphate levels in open reservoirs. Unfortunately, there is no simple solution for balancing water quality, health risks, system reliability, and environmental impact. Cooperation between plant owners and the concerned government agencies benefits system optimization for corrosion management.

Table 9. Commonly used corrosion inhibitors for potable water systems, dosage rates in milligrams per liter (mg/L), and comparative estimated inhibitor costs in 1994 dollars.(20,24)

INHIBITOR TYPE	DOSAGE RATE	INHIBITOR COST	TREATMENT COST ESTIMATED BY AWWA	TREATMENT COST ESTIMATED BY AWWC
	mg / L	$ / kg*	$ per million liters**	$ per million liters**
Lime	10 – 30	0.04	0.53 – 1.59	-
Caustic Soda	10 – 30	0.44	2.65 – 3.97	3.44 – 11.90
Soda Ash	10 – 30	0.27	4.42 – 13.23	3.97 – 4.76
Sodium Hexa-Metaphosphate	1 – 4 (PO_4)	2.00 (PO_4)	1.98 – 7.94	-
Bimetallic Phosphate	0.5 – 2 (PO_4)	3.33 (PO_4)	1.65 – 6.61	-
Zinc Orthophosphate	0.1 – 0.5 (Zn)	4.99 (PO_4)	0.53 – 6.61	2.12 – 4.50
Sodium Silicate	4 – 10 (SiO_2)	0.67 (SiO_2)	2.65 – 6.61	-
Carbon Dioxide	5 – 10	0.11	0.53 – 1.06	-
Phosphoric Acid	0.5 – 3 (P)	1.33 (PO_4)	0.79 – 4.76	-
Monosodium Phosphate	0.5 – 3 (P)	2.66 (PO_4)	1.59 – 9.52	-
Ortho-Polyphosphate Blend	0.2 – 1 (PO_4)	5.54 (PO_4)	1.06 – 5.29	-

*To obtain $/lb, multiply $/kg by 0.455.

**To obtain $/million gal, multiply $/million liters by 3.787.

Table 10. Typical annual chemical costs (1998 dollars) for common chemicals used for corrosion control based on data* from various chemical suppliers and reported by Singley et al.(25)

CHEMICAL	USE	FEED RATE	COST PER UNIT ($)	COST PER YEAR	
				11.4 THOUSAND m^3-PER-DAY (3-MGD PLANT) ($)	189 THOUSAND m^3-PER-DAY (50-MGD PLANT) ($)
Quicklime, CaO	pH adjustment	1 – 20 mg/L 8 – 170 lb/MG	95/ton bulk	416 – 8,798	6,750 – 146,550
Hydrated lime, $Ca(OH)_2$	pH adjustment	1 – 20 mg/L 8 – 170 lb/MG	117/ton bag 98/ton bulk	513 – 10,868 428 – 9,068	8,550 – 181,500 7,125 – 151,500
Caustic soda, NaOH (50% solution)	pH adjustment	1 – 20 mg/L 12 – 150 lb/MG	300/ton bulk	1,965 – 32,850	41,100 – 684,000
Soda ash, Na_2CO_3	pH adjustment	1 – 40 mg/L 8 – 350 lb/MG	24/cwt bag 228/ton bulk	2,103 – 91,980 999 – 45,563	35,100 – >1,500,000 16,650 – 759,000
Inorganic phosphates	Inhibitor	3 mg/L 25 lb/MG	98/cwt bag	26,700	445,500
Sodium silicate	Inhibitor	2 – 8 mg/L 17 – 67 lb/MG	8/cwt tank	1,395 – 5,505	23,250 – 91,800

*The values are given in 1998 dollars by multiplying the original data by 1.5. The costs do not include freight.

Corrosion Control in Water Storage Systems

After treating the raw water in treatment facilities, the clean drinking water can temporarily be stored in utility water towers in aboveground or underground tanks, or underground clear wells. The areas of major corrosion impact are internal corrosion of the storage towers and tanks, and external corrosion due to weather conditions. If left unattended, both internal and external corrosion may pose a structural risk due to loss of wall thickness. Therefore, regularly scheduled corrosion inspections of water tanks and water towers should be conducted. With regular maintenance, water tanks can have a useful life of more than 100 years.

The dominant forms of internal corrosion include general corrosion, galvanic corrosion, and microbiologically induced corrosion in standing water. The microbiological contaminants are regulated under the Surface Water Treatment Rule (SWTR) and the Total Coliform Rule (TCR). Corrosion control methods for these types of corrosion are cathodic protection and lining or painting of the interior of the tanks. Cathodic protection is usually performed on a project basis, while painting generally is performed as part of long-term maintenance programs.

External corrosion originates from moisture, rain, and changing weather. Generally, tanks and water towers are designed with a so-called corrosion allowance. This is an allowable rate of general corrosion. The corrosion rate can be determined by measuring the remaining wall thickness of a storage tank at given time intervals. If the corrosion rates are within the design limits and the remaining wall thickness is thick enough, then the tank is generally expected to be structurally fit for service. The common corrosion control method is painting the tower or tank. Deterioration of the appearance of water towers by external corrosion is another consideration for painting.

The costs for corrosion control for water storage tanks are determined by the type of cathodic protection and the type of protective coatings utilized. In 1991, Robinson(26) presented comparative case studies of the economics of corrosion protection systems. Robinson argued that many thousands of dollars are spent unnecessarily to re-coat and repair interior coatings when cathodic protection would mitigate further corrosion activity and prolong the necessity of coating maintenance. Using economic models, this author determined that long-term cost benefits can be realized with the application of cathodic protection to water storage tanks.

Corrosion Control in Water Transmission Systems

The water is pumped from the temporary storage or is pumped directly from the treatment facilities through large-diameter transmission water pipes. The transmission water piping system is regulated with large valves, where water quantities are measured using large-capacity water meters. The most common materials of construction for transmission pipe include cast iron, ductile iron, prestressed concrete, asbestos concrete, PVC, and welded steel piping. Except for PVC, all of the above materials contain ferrous metal components that must be protected.

Table 1 shows that approximately 67 percent of the U.S. transmission water lines are built from cast iron and ductile iron. Ductile iron pipe is manufactured in 5.5- or 6.1-m (18- or 20-ft) nominal laying lengths and 7.6- to 163-cm (3- to 64-in) diameters in a range of standard pressure classes and nominal wall thicknesses. Since its introduction in the marketplace in 1955, ductile iron pipe has been used extensively for drinking water and wastewater systems. Pipes are made from the manufactured sections of pipe, with a bell-and-spigot connection sealed with rubber O-rings.

The most common failure mechanisms of such pipes are uniform corrosion (external or internal), graphitization, and pitting under unprotected corrosion scales. Loose rust tubercles may cause blockage of a water pipe where these particles reach consumers. The only corrosion control methods for loose particles is prevention through the addition of corrosion inhibitors to protect the inside pipe walls or internal lining of the pipes. For ductile iron and cast iron pipes, a standard portland cement mortar lining is the most common internal lining. Other lining types include specialty cement mortars, epoxies, polyethylene, and polyurethane. In some instances, coal tar has been used for internal linings; however, concerns about possible health effects and oily organic residue given off by coal tar coatings limit their use.

Table 1 further shows that a steel pipe is only used for approximately 4 percent of the U.S. transmission water lines. The use of steel water pipe dates back to the California Gold Rush of 1849,(27) when it was produced from thin riveted wrought pipe that could be slipped together. In 1905, a pressure-locking seam pipe was developed. In the early 1930s, methods of automatically welded steel pipe from rolled stock were developed. Since World War II, U.S. manufacturers have primarily produced spiral-welding steel pipe. The most common corrosion control methods for external corrosion of steel pipes are coatings or coatings and cathodic protection.

Developments in electronic equipment make internal inspection with cameras an option to evaluate the condition of pipe sections. However, these techniques are still quite expensive, the equipment insertion into and extraction from the pipe is usually difficult, and the pipe may have internal obstructions or bends. In addition, analysis of the data is generally time-consuming and difficult.

Effect of Reduced Pipe Wall Thickness

Significant problems occur in older transmission pipes made from cast iron and ductile iron, as the wall thickness is reduced by corrosion until a leak occurs. Problems in newer iron pipes are similar to those found in older iron pipes, but occur after shorter periods of time because of decreased wall thickness. During the last 100 years, utilities have applied pipes of thinner wall because of the improved mechanical properties of steel; however, corrosion rates are generally independent of the strength of a material. For a given corrosion rate, a thinner wall will corrode through in less time than a thicker wall. Therefore, an effective corrosion control method is the selection of thicker wall pipe to provide a larger corrosion tolerance to wall thinning. Although thicker wall pipe is more expensive, this approach may be very cost-effective because of its long life and relatively low need for maintenance.

Degradation of Cement-Based Materials

Approximately 17 percent of the U.S. transmission water lines are built from concrete and asbestos concrete materials (see table 1). Pipes made from these materials are usually assembled on location from factory-made pipe sections. Internal steel reinforcement wires and bars (rebar), steel mesh, and steel plates are used to provide tensile strength. Cement-based pipes are susceptible to corrosion when aggressive ions, such as chloride, migrate to the steel surface. The corrosion products take up more volume than the original steel, causing cracking of the concrete, further accelerating corrosion.

In asbestos cement pipes, asbestos fibers are used as reinforcement for tensile strength. With these pipes, the main concern is the release of asbestos fibers into the drinking water. Other effects of cement-based material deterioration include calcium dissolution (increased water hardness), increased pH values, increased alkalinity, and migration of aluminum into the drinking water. A common corrosion control method for concrete pipe is the application of internal protection using a cement mortar lining, which can be applied as a factory lining or as an *in situ* lining. One method of determining the quality of a lining is to measure its calcium oxide (CaO) leaching resistance, a function of the mortar density.

Cement Mortar Linings

New iron and steel pipelines are commonly lined with cement mortar. Cement mortar linings are also used for rehabilitation of older ductile iron, cast iron, and steel water pipeline networks. The linings can eliminate limited leaks of pipes and pipe connections as a result of the high resistance of cement mortar to pressure, enhance the hydraulic characteristics of the mains, and prevent further internal corrosion damage. Table 11 shows the estimated costs for water pipe rehabilitation by cement mortar lining as a percentage of pipe replacement costs, as estimated by the AWWA.(20) The rehabilitation cost is broken down into four components: (1) cleaning and cement mortar lining; (2) excavation, pipe fitting, and restoration of the road surface; (3) materials; and (4) labor costs. The right column shows the percentage cost for rehabilitation compared with total pipe replacement.

Table 11. Estimated costs for water pipe rehabilitation by cement mortar lining, as a percentage of pipe replacement costs.[20]

INTERNAL DIAMETER		CLEANING AND CEMENT MORTAR LINING	EXCAVATION, PIPE FITTING, RESTORATION OF ROAD SURFACE	MATERIAL	LABOR COSTS AND RELATED COSTS	COSTS FOR REHABILITATION IN RELATION TO PIPE REPLACEMENT
cm	inch*	%	%	%	%	%
8-15	3-6	33	49	7	11	39.5
20-30	8-12	33	48	7.5	11.5	41
50	20	22	55	13	10	33.2
60-80	24-32	37	47	8	8	19.4
100-120	40-48	30	57	5	5	13

*Equivalent inch measurements are calculated in rounded inches.

External Corrosion of Transmission Piping

External corrosion mechanisms on transmission water piping include general or localized corrosion due to corrosive soils, galvanic corrosion through connections to other utilities and structures, MIC, ac stray current corrosion from power lines, and dc stray current corrosion from cathodic protection (CP) systems on nearby structures. Corrosion control methods to mitigate these forms of corrosion include the application of coatings and CP by installation of impressed current or sacrificial anode systems. External coatings on older water pipes include asphalt coatings and coal tar enamel coatings, while external coatings on new pipes include coal tar enamel coatings, polyethylene-based coatings, and fusion-bonded epoxy coatings.

Cathodic Protection and Coatings

The CP design should be executed by specialists. After the CP installation, regular inspection of the system is required. For CP to be applied effectively, the pipe must be electrically continuous, which is usually only partly true for the bell-and-spigot type of pipe. Welded steel pipes are generally electrically continuous; therefore, CP may be easier to apply to those pipes. CP protection of pipelines is typically more effective when used as a supplemental system to a coating system. Without a coating system, the amount of electrical current (from either a sacrificial or impressed-current CP system) is typically too large to make CP economically feasible for water systems. For prestressed concrete pipe, CP can be used to supplement the protection provided by the standard mortar coating in aggressive soil environments.[28] However, care must be taken not to overprotect the prestressing steel.

There exist two types of CP systems: impressed-current systems that require rectifiers and periodic direct assessment consisting of inspection, monitoring, and adjustment by trained operators, and sacrificial systems that require less attention. Because of the ease of operation, a sacrificial anode system (consisting of buried zinc or magnesium anodes) is generally preferred for welded steel pipe. Federal regulations specify the frequency and the specifics of monitoring of CP systems on interstate natural gas and oil product pipelines. For water lines, however, no such regulations exist; therefore, it is uncertain if cities and municipalities conduct the necessary CP monitoring.

Corrosion Control in Water Distribution Systems

Smaller diameter distribution pipes branch from the larger transmission pipes to supply the water to individual houses and businesses. The most common materials for distribution piping include ductile iron, PVC, copper, and piping. In these smaller diameter pipes, the corrosion problems and the corrosion control methods for ductile iron corrosion and the deterioration of PVC are similar to those described for the larger diameter pipes. A 1980 study performed for the Seattle (WA) Water Department[(29)] found that the cost of internal corrosion of consumer plumbing systems can be significantly higher than the cost of corrosion in large-diameter transmission systems. The study found that plumbing costs were 10 times higher for initial capital and 20 times higher for annual maintenance than transmission system costs.

A series of reports have suggested that increased use of chloramines for disinfection, as a means to reduce trihalomethane, accelerates corrosion and degradation of metals and elastomers common to distribution plumbing. In 1993, the AWWA Research Foundation[(30)] reported the results of a study comparing the oxidation effects of free and combined chlorine species on seven metal surfaces (mild steel, copper, brass, bronze, Pb/Sn solder, Sn-Sb solder, and Sn-Ag solder), seven basic elastomer types (natural rubber, acrylonitrilebutadiene, styrene-butadiene, chloroprene, silicone, ethylene-propylene, and fluorocarbon), and three thermoplastics. The results showed that, with few exceptions, solutions of chloramines produced greater material swelling, deeper and more dense surface cracking, a more rapid loss of elasticity, and greater loss of tensile strength than equivalent concentrations of free chlorine. Only the newly engineered, completely synthetic polymers developed specifically for their chemical resistance performed well in the chloramine exposures. The results further showed that, with regard to copper and its alloys, all tested chlorine disinfectants accelerated corrosion. In contrast to the elastomer experience, free chlorine exerted a higher oxidant effect than the chloramines. For solder, the rate of galvanic corrosion was only minimally influenced, while lead-free and tin-based solders were generally immune to chlorine attack.

In addition to ductile iron and PVC, materials such as copper and lead (used for piping) and brass (used for fixtures and connections) are used. Lead corrosion mechanisms include uniform corrosion and lead release. Copper corrosion mechanisms include uniform corrosion and copper release, localized-attack cold water pitting and hot water pitting, MIC, corrosion fatigue, and erosion-corrosion. Lead pipes and lead-tin solder exhibit uniform corrosion. Brass corrosion includes erosion-corrosion, impingement corrosion, dezincification, and stress corrosion cracking. The direct health impacts are due to increased copper, lead, and zinc concentrations in the drinking water. Mechanical problems due to corrosion include leaks from perforated pipes, the rupture of pipes, and the loss of water pressure due to the blockage of pipes by corrosion products. An example of a perforated copper plumbing pipe is shown in figure 2.

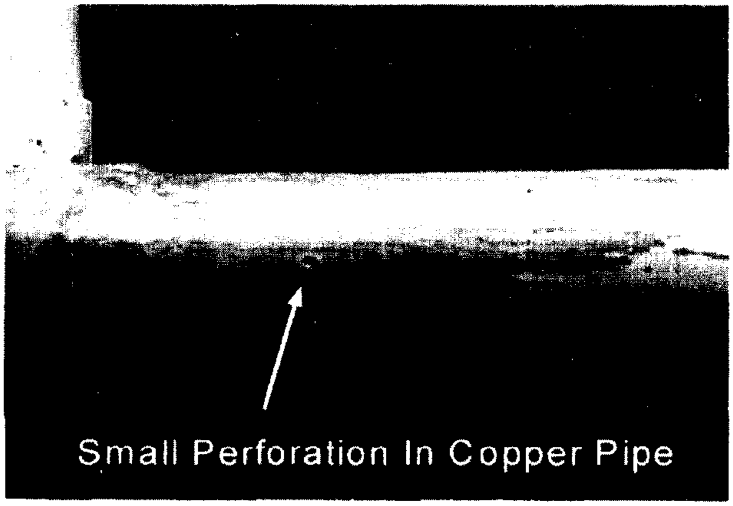

Figure 2. An example of a perforated copper plumbing pipe.

Corrosion Issues Related to the Lead and Copper Rule

In 1991, the U.S. EPA implemented the Lead and Copper Rule (LCR). The LCR was developed to minimize health risks associated with the public's exposure to the lead and copper in drinking water. This regulation requires a treatment technique and uses an "action level" for lead of 15 parts per billion (ppb) (15 µg/L) at the 90th percentile. The "action level" for copper is 1,300 ppb (1,300 µg/L). The action levels constitute the maximum allowable concentrations, beyond which a response is required. The type of response depends on the size of the system. Guidance and detailed interpretations of the rule are found in various documents.(31-33)

Corrosion of Lead Pipes and Solder Containing Lead

Lead is unusual among drinking water contaminants in that it seldom occurs naturally in water supplies such as rivers and lakes. The lead concentration in drinking water leaving water treatment plants is below the level of detection; however, lead can enter the water by corrosion or wear (erosion) of household brass fixtures, lead pipes, or lead solder. When water resides in plumbing more than 6 hours, testing has shown that lead levels can exceed the EPA action level of 15 ppb (15 µg/L) in some homes. Cold water lines usually have lower lead concentrations than hot water lines. Laboratory studies with lead pipe in the presence of corrosion inhibitors show that treatment of water with chemicals such as orthophosphate can aid in controlling lead leaching.(34) If the lead concentrations are too high, an alternative control method is to replace the home plumbing with new (copper) pipes.

Corrosion of Copper Pipes and Fixtures

Since World War II, copper has been the most common material for consumer plumbing because of its excellent characteristics, including ease of installation, low cost, and corrosion resistance. Copper accounts for 50 to 90 percent of all tubes installed in drinking water services in industrialized countries.(35) In the United States, this amounts to well over 160 million m (500 million linear ft) of copper water tubing installed each year. Copper tubing has progressively displaced alternative materials for pipe sizes that are up to about 50 mm (2 in) in diameter, at which it is competitively priced. The wall thickness of copper tubing is usually 1 mm (0.04 in) or greater in the lower range of diameters. Corrosion problems, although infrequent, can be severe for the affected consumers and systems. Failure of copper tubing by pitting, blue or green water problems, and, more recently, failure to meet the U.S. EPA action level for copper in tap water samples are major problems when they occur. Table 12 summarizes the occurrence of different corrosion mechanisms for copper pipes, as reported for the United States, by the AWWA Research Foundation.(20)

Table 12. Frequency of copper plumbing system failures, as a function of failure causes, reported in the United States in 1983.(10)

CAUSE OF COPPER TUBING FAILURE	FREQUENCY (%)
Pitting Corrosion	58
Erosion-Corrosion	24
Corrosion of Outer Surface Of Tubes	7
Faulty Workmanship	5
Fatigue	2
Other	4
TOTAL	**100%**

Corrosion control methods for copper corrosion include prevention by improved production techniques that give better cleanliness of the inner bore, removing carbon films that are said to initiate pitting. The predominant practice is to use iron grit as a blasting material to clean the inner bore. This process reduced the frequency of severe cases of pitting by 90 percent or more. Another option for an improved production technique is to preoxidize the inner bore, which removes any carbon present and produces an oxide scale that is said to improve corrosion resistance. Once the pipe is in place, chemical treatment of the water supply is a method used to reduce the corrosive attack on copper pipes.

Corrosion of Other Nonferrous Alloys

Nonferrous alloys are commonly used in domestic plumbing systems, either as fixtures, fittings, or in the making of joints. These alloys have been identified as a source of lead contamination in drinking water. Other chemical alloy elements of concern include copper, tin, zinc, antimony, and bismuth. The corrosion mechanisms vary greatly for each different alloy system and it is generally known that the local water composition influences the corrosion susceptibility of different alloys. Corrosion control methods for nonferrous alloys include preventive measures such as replacement of fixtures or a complete change of material design. In general, corrosion of nonferrous alloys is minimized by requiring plumbers to use industry-standard materials and workmanship when installing copper tubing systems.

Requirements to Perform Corrosion Control Studies

Under the Lead and Copper Rule, operators of most large systems are required to chemically analyze their water and conduct a corrosion control study to determine an "optimal" strategy for reducing lead release rates. Corrosion testing often consists of two distinct parts, including the environment (in this case, water) and a variety of materials in contact with the water. Table 13 lists some estimated costs of common laboratory testing of drinking water, as it relates to corrosion.

Table 13. Common laboratory testing of drinking water related to corrosion and estimated cost per test, based on utility data from Columbus, OH.(18)

TEST	COST / TEST
Weight Loss	$30
Total Metals Concentration	$20
Cation Concentration	$36
Anion Concentration	$36
Alkalinity	$12
Hardness	$10
pH	$5
Chlorine Concentration	$15

Documenting the internal condition of pipes can be performed through visual inspection, photomicrographs, weight loss measurements, pitting potential measurements, scale analysis, and corrosion probe data.(36) Predictions of corrosion rates for future water quality conditions can be obtained through pilot studies. Pilot tests can then be compared with field tests and used to estimate the service life of pipes.

Many utilities use metal release tests to measure the interactions of their treated water with different materials. Metal release tests (sometimes referred to as metal uptake tests) are designed to measure the accumulation of corrosion products in water flowing through a plumbing system or a distribution network. In its guidance manual on corrosion control studies, the U.S. EPA emphasizes the use of large pipe loops as both analytic and operational tools to evaluate release rates and select an appropriate control strategy. There are two basic systems in use: a closed loop system and a recirculation loop system. When used in a recirculating closed loop system, the metal release measurement can be interpreted as a point estimate of the corrosion rate. More commonly, metal release measurements support a pipe loop corrosion control demonstration study, where the intent is to simulate a residential plumbing system and evaluate the metal concentrations experienced at the consumer's tap under different corrosion control strategies. An important problem to focus on when determining lead levels is the protocol for sampling the water to determine the lead level. Stagnation time, flushing, and the specific conditions of the installation under consideration have an important influence on the results, while the measurement of the corrosion rate of lead is a relatively minor concern.

Corrosion Control in Sewage Water Systems

Sewage water is transported back to treatment facilities through a sewer water piping system that is connected to, but separate from, the drinking water system. The National Center for Environmental Research and Quality Assurance (The Office of Research and Development, U.S. EPA) reports that the current U.S. investment in sewage lines alone approaches $1.8 trillion.(37) Waste water is collected through relatively small-diameter pipes from bathrooms, kitchens, and sinks from each house and business and is then transported to treatment plants through larger diameter pipes. Rainwater will only enter the sewer system if it is collected through sewage grates collecting run-off water from streets and parking lots. All other rainwater and water used for activities such as watering a lawn or washing a car are simply absorbed by the earth, and do not run into the sewage system. Common materials of construction for sewage water systems include concrete piping, steel piping, and ductile iron piping.

The mechanisms of material degradation in sewage piping are generally similar to those in potable water systems. However, internal corrosion may be more severe because the water is not clean. In addition to the sewage waste, chlorine from salt winterizing treatments of roads comes into contact with the pipes. Cement-based piping deteriorates by corrosion of the reinforcement steel. The corrosion control method most commonly used in sewage piping is increased wall thickness. This is true for metal pipes and cement-based pipes. The thicker wall provides for a larger corrosion tolerance and, generally, a longer design life.

CORROSION MANAGEMENT

Corrosion Cost Estimates

The AWWA developed a six-step procedure for the assessment and control of internal corrosion of water distribution systems.(20) Figure 3 shows a flowchart illustrating the application of this method for internal corrosion.

Although the application of this method appears straightforward, working out the details for each system is quite complex. The procedure applies to older systems and does not consider corrosion prevention for new systems. It assumes that corrosion is already present and that the corrosion only occurs internally. Although the costs per system can be calculated reasonably accurately using this method, interactions with other systems are difficult to evaluate.

The system size, location, population served, materials used, water quality, and soil conditions all significantly influence corrosion susceptibility. The appropriate preventive strategies for corrosion control depend on the assessment of the local situations, options available to the local operators, available budgets (usually limited), and time frames.

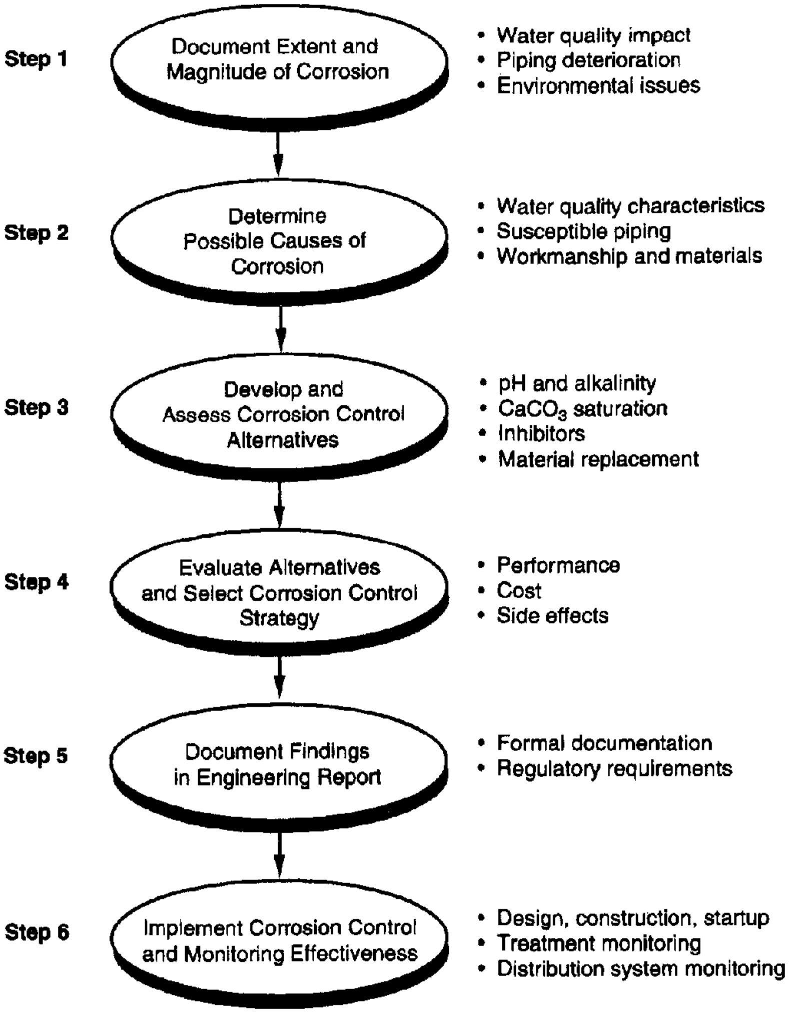

Figure 3. Corrosion control program implementation flowchart for internal corrosion.(20)

In 1993, Harrington(38) reported on methods to manage a corrosion control program. He presented 1992 to 1993 data showing a breakdown of water system leak repair costs and the resultant cost per average repair for the Marin Municipal Water District in California (see figure 4). For this chart, a total of 420 leaks were analyzed at an average repair cost of $3,640 per leak.

This figure shows that the direct costs of maintenance and repair ($724,000) and paving ($150,000) were roughly 57 percent of the total costs. The indirect costs of vehicles ($232,000), overhead ($211,000), and other indirect costs ($209,000) were roughly 43 percent of the total costs.

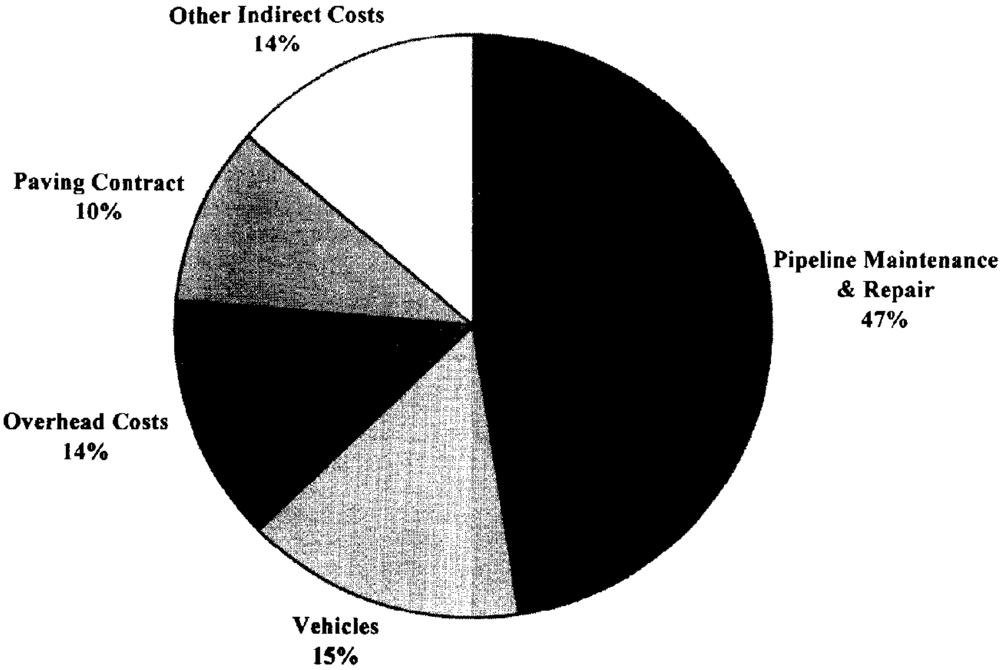

Figure 4. Pipeline repair costs for Marin Municipal Water District from 1992 to 1993, as reported by Harrington.(38)

Short-Term Corrosion Management

Short-term corrosion problems are often indicated by customer complaints, such as the occurrence of red or yellow "rusty" water, or a sudden decrease in water pressure. A reason for rust-colored water is generally the presence of corrosion products that have flaked off of the internal pipe walls, while a water pressure drop may be caused by a leak in the transmission or distribution system. Finding a leak in an underground pipeline is often difficult because the leak may start small and go undetected for a period of time. Once the leak is so severe that water is literally coming from the ground, it may cause a local flood. In addition to the lost water, the damage can be significant and the repair work is more than what would have been needed to fix a small leak. In cases where a leak occurs below a street, a large sinkhole may form due to the sand rinsing away from underneath the asphalt, posing an additional safety hazard.

Long-Term Corrosion Management

Long-term corrosion impact is generally indicated by integrity studies. Maintenance and inspection teams are dedicated to finding leaks and failures. Many utilities apply a specialized corrosion team to continuously monitor the water quality, using corrosion loops in which treated water circulates over weight loss coupons. The coupons are made from different materials, and they are exposed to various water flow rates. Periodically, these coupons are measured and average corrosion rates are determined. In addition to the weight loss coupons, water samples are routinely tested to ensure that the water quality is acceptable. The test results are used to make assessments about corrosion as well. For example, the pH of the water is important both for water consumers and for system integrity. The pH is kept within a predetermined range by adding pH adjusters to the treatment process. Dedicated corrosion groups mainly focus on corrosion prevention. They generally work with a fixed annual budget (a percentage of the total water utility budget).

Keeping Corrosion Data Records

The corrosion groups are also in charge of keeping records on the number and type of failures that occur in a system. The data are used to assess when maintenance or replacement is needed. An example of a rule of thumb used by some planners is that a water line is completely replaced if three failures occur in 1 year within one block. Otherwise, the pipe is repaired and will remain in place.

Although information on individual repairs may be collected, in the current research, it was found that most water utilities do not have complete records on all their buried pipes. The pipe mileage length, pipe materials, pipe diameters, and installation dates are, in many cases, unknown. In many cases, this information is missing because of the age of the systems and the changes in the organization over the years. The lack of complete up-to-date information about all water systems complicates the process of prioritizing maintenance and the assessments for corrosion protection. The fact that computers have become commonplace in recent years provides the opportunity to maintain records in local databases and in a national database.

Necessity of Long-Term Corrosion Planning

Because of the long life expectancy of water systems, a long-term vision for corrosion management is required. Unfortunately, some managers give in to short-term cost-savings over long-term investments. As an example, the average thickness of cast iron and ductile iron pipe has been continuously decreased over the last 100 years because thinner, higher strength pipe has become available. Clift[(28)] compared the change in wall thickness for 91.4-cm- (36-in-) diameter cast iron and ductile iron pipe, according to the AWWA specifications (see figure 5). These specifications showed that this thickness has been continuously reduced from 40 mm (1.58 in) in 1908 to about 9.7 mm (0.38 in) in 1991. Further reductions are due to service allowance, casting tolerance, and additional tolerance.

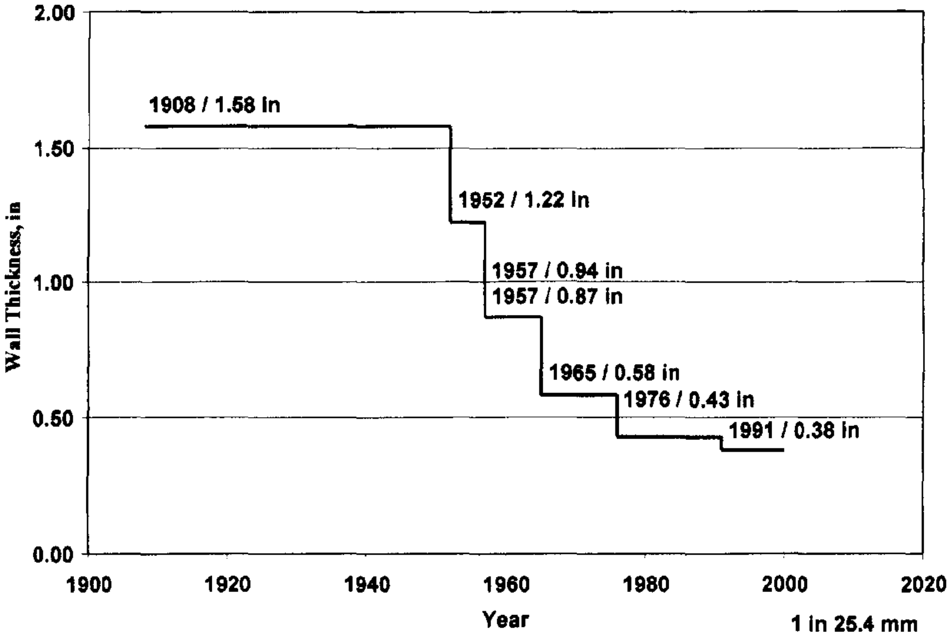

Figure 5. Actual size of AWWA specification thickness reductions for 0.925-m- (36-in-) diameter cast and ductile iron pipe, for 1.0 Mpa (150 psi) operating pressure, from 1908 to present.[(28)]

Unfortunately, corrosion rates are not significantly dependent on the strength of ductile iron or steel. As a result, thinner wall pipe will have a smaller corrosion tolerance than thicker wall pipe and will show more frequent failures. The failures cause high repair costs and inconveniences to the public. Extensive corrosion studies of buried pipe sections at more than 150 sites nationwide have shown that all ferrous pipe materials (including welded carbon steel pipes, cast iron, ductile iron, and wrought iron) corrode at approximately the same rate, assuming that general corrosion is the dominant mechanism.(39) The time to corrode through a pipe wall is directly proportional to the square of the wall thickness. That means that if the pipe wall thickness is reduced by 50 percent, the corrosion life will be reduced to 25 percent of the life of the original pipe thickness.

Although thicker wall pipe is more expensive, this method may be more cost-effective because it can prevent future customer complaints, unaccounted-for water through leaks, the need for continuous maintenance and inspection, and a lot of paper work for scheduling and reporting repair work. The use of thinner wall pipes requires additional corrosion protection in the form of coatings and cathodic protection (CP). In addition, the pipe sections must be bonded to be electrically continuous so that the CP will be effective.

Optimized Management by Combining Corrosion Control Methods

Increased wall thickness is one effective way of decreasing corrosion impact. Table 14 shows a summary of the most commonly used repair methods for water systems with corrosion damage. They include the addition of corrosion inhibitors, pH adjusters, alkalinity controllers, and hardness controllers to the water; the application of cathodic protection; internal coatings and linings; internal inspection; external coatings; and the application of monitoring systems such as corrosion coupons, test stations, and corrosion data loggers. To prevent any further problems in cases where lead and copper release is a concern, one may consider the complete replacement of the tubes, fittings, fixtures, and joints by corrosion-resistant components.

Table 14. Summary of most commonly used repair methods for water systems with corrosion damage.

WATER SYSTEM	DAMAGE	REPAIR METHOD
Any System	Small Corrosion Area or General Corrosion Over Large Area	Evaluate Structural Integrity If Fit for Service, Then Apply Coating to Protect Metal and Inspect According to Appropriate Schedule
	Localized Corrosion	Identify Root Cause of Localized Corrosion Remove Materials Causing the Corrosion Replace Damaged Material
Wall of Dam or Storage Tank	Wall Thinning	Evaluate Structural Integrity If Necessary, Reinforce Wall With Extra Steel
Metal Pipe	Small Leak	Clamp or Sleeve Around Pipe, or Replace Small Pipe Section
	Multiple Leaks	Replace Pipe Section
	Large Leak / Rupture	Replace Pipe Section
	Internal Corrosion	Apply Cement Lining
		Insert PVC Tubing in Pipe
	External Corrosion	Evaluate Structural Integrity If Fit for Service, Then Apply Coating to Protect Metal, and/or Apply Cathodic Protection To Reduce Corrosion Rate
Cement-Based Pipe	Reinforcement Corrosion	If Localized, Remove Loose Concrete, Re-Apply

Every system has its own requirements depending on the local conditions of the water (internal) and soils (external); therefore, a combination of the above-mentioned corrosion control methods must be carefully selected and consistently applied. Water line integrity managers should evaluate the effectiveness of the chosen mitigation program. Methods to check this include water sample measurements and evaluation of weight loss coupons, thorough review of customer complaints, and assessment of the reasons for unaccounted-for water.

The potential impact of failing systems should not be ignored. Large populations can be affected by a shortage in water supply. Prioritizing maintenance should be performed based on factors for each specific system, including the size of the population served, the location in rural or urban areas, the size of the system (large, medium, or small), the water quantity handled by that system, and the local water quality, which can be a function of seasonal activity.

CHANGES FROM 1975 TO 2000

Changed Need for Water Quantity

The changes in water systems can be summarized by recognizing the need for continuously increasing water quantity and continued concern regarding the impact of water quality on health. Water systems have very long design lives, typically 100 years or more, which relate to average replacement rates of 1 percent per year; therefore, the 25-year time period for water systems should be expanded to a longer time. Water utilities emphasize that a long-term view (20 to 50 years) for water supply is required for optimized maintenance.

One of the most significant changes is the growth in the U.S. population in the last 25 years and the anticipated continued growth into the future. In some areas of the country, the water supply is already strained. The capacity of water treatment, storage, transmission, and distribution will continue to increase. The interconnectivity of larger systems will provide the extra capacity needed during times of increased demand. Many cities have action plans in case of droughts, in which citizens are asked to limit their water usage. For example, during a drought, citizens are often encouraged to refrain from watering lawns and washing cars.

Changed Need for Water Quality

The second most significant change is in the increased awareness of water quality and the lower tolerance limits in water quality standards. The efforts made since the early 1970s to clean up environmental pollution to ensure safe water from surface water and groundwater sources are paying off. Ten years after the Lead and Copper Rule took effect, the actual achieved results are becoming visible. Comparison of U.S. rules and regulations with those of other industrialized nations and the results of international studies may direct the course of future actions. A concern of water utilities is the uncertainty around future requirements and regulations by the U.S. EPA and the federal government. Water managers are confronted with the task of optimizing the use of aging systems and system reliability, both of which are of the utmost importance to water suppliers and their customers. Each system requires the careful selection of one or more corrosion mitigation methods to ensure its continued operation. Changes in regulations make future financial planning for construction and maintenance a difficult job.

CASE STUDIES

Case Study 1. City of Columbus, Ohio – Analysis of Water Line Breaks

As an example of the manner in which a water utility can analyze its maintenance practises, the *1997 Operations Report* of the Division of Water, of the City of Columbus, Ohio, was investigated.(18)

Figure 6 shows the percentage of unaccounted-for water in Columbus, Ohio based on 25 years of record-keeping. The figure shows that the direct economic impact to the water utility is 20 percent less revenue. For 1997, the total water pumped to the city was 184 million m^3 (48.5 billion gal), while only 146 million m^3 [38.6 billion gal (79.4 percent)] were metered. To the customers, this means higher water prices in order to make up for the loss. In addition, the enormous effort of treating all this lost water is wasted by the unidentified leaks.

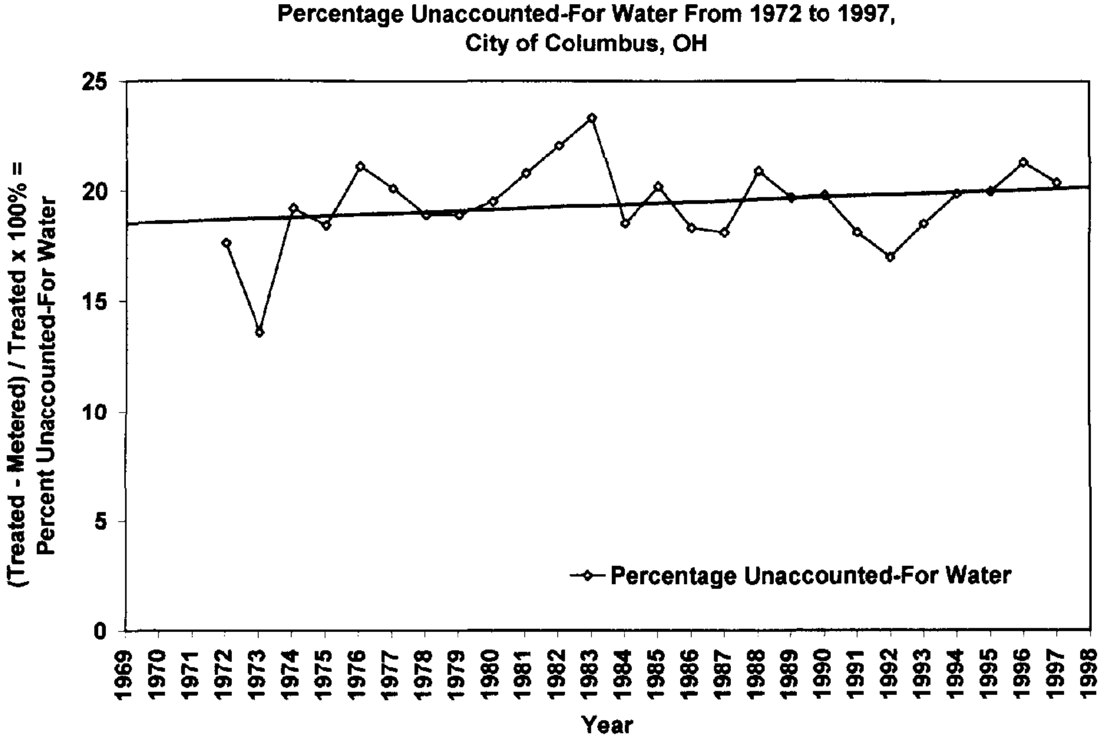

Figure 6. Percentage unaccounted-for water from 1972 to 1997 for the city of Columbus, OH.[18]

The city of Columbus, with approximately 1 million inhabitants, averages 500 to 800 significant water pipe breaks each year. Figure 7 shows that during the last 25 years, the number of line breaks is consistently rising. This increase in the annual number of main line breaks can most likely be attributed to the system's increasing size and age. Although Columbus consistently fixes these leaks at an approximate total annual cost of $9 million, the percentage of unaccounted-for water did not decrease during the last 25 years. If the leaks are detected and fixed earlier, the capacity of treatment facilities could be considerably smaller, contributing to greater efficiency and extra profitability for the system.

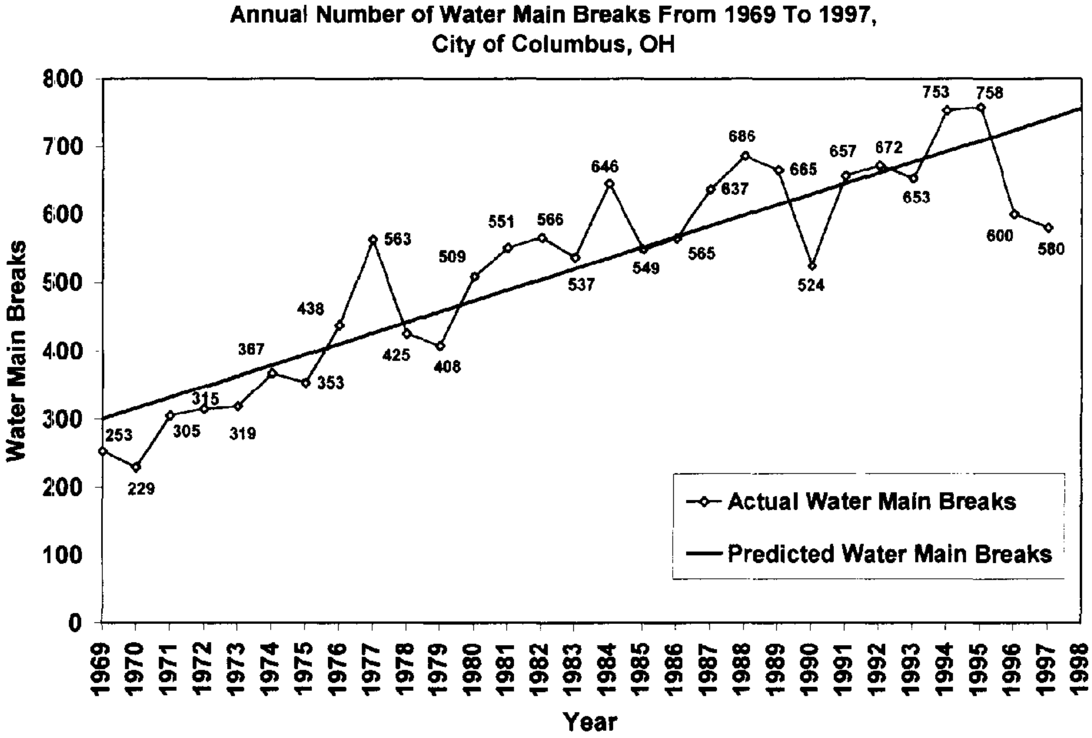

Figure 7. Number of actual and predicted water main breaks from 1969 to 1997 for the city of Columbus, OH.(18)

Tables 15a through 15d show analyses of the main line breaks that occurred in 1997, arranged by type of break, pipe materials age of pipe, and monthly distribution, respectively. Although the causes of leaks may be internal or external corrosion or, in general terms, "system aging," they are usually not strictly reported as such. However, a crack across a pipe, a split along a pipe, or a pit or hole in a pipe usually has corrosion as its cause. For example, a crack in a pipe that appears to be caused by soil movement would probably not have occurred if there was no wall loss from corrosion at that location.

Table 15a shows that 518 of the 580 breaks (89 percent) could be directly attributed to corrosion. Table 15b shows that 64 percent of these 580 breaks occurred on (gray) cast iron pipe, and another 29 percent occurred on galvanized pipe. Table 15c shows that the majority (78.8 percent) of the pipe breaks occurred on pipes that were between 30 and 75 years of age. The very old pipe category (> 75 years) shows a lower percentage of breaks because there is a lower percentage of such in the system. This table also indicates that for about 10 percent of the pipes, no data were available regarding their time of installation (age). Table 15d shows that the winter months have more water main breaks than the summer months. This is attributed to the external loads applied on the buried pipes when the surrounding soil freezes. A similar phenomenon occurs in the summer in states such as Texas and Arizona, where the soil loses a lot of its moisture. The external support soil around the buried pipes shifts due to the shrinking soil, resulting in an increased number of main line breaks in the summer months.

Table 15a. Type and number of water main breaks in 1997 for the city of Columbus, OH.(18)

TYPE OF BREAKS	NUMBER OF BREAKS	FRACTION (%)
Cracked Across Pipe	265	45.7
Split Along Pipe	80	13.8
Pit or Hole in Pipe	173	29.8
Cracked at Corporate Stop	2	0.3
Fitting or Joint Leak	44	7.6
Man-Made	5	0.9
Off-Set	3	0.5
Cut & Plug	8	1.4
Miscellaneous	0	0.0
TOTAL	**580**	**100%**

Table 15b. Pipe material and number of water main breaks in 1997 for the city of Columbus, OH.(18)

PIPE MATERIAL	NUMBER OF BREAKS	FRACTION (%)
Cast Iron	371	64.0
Galvanized Steel	170	29.3
Lead	1	0.2
Ductile Iron	19	3.3
Copper	4	0.7
PVC	12	2.1
Concrete	3	0.5
TOTAL	**580**	**100%**

Table 15c. Age of pipe and number of water main breaks in 1997 for the city of Columbus, OH.(36)

AGE OF PIPE	NUMBER OF BREAKS	FRACTION (%)
1-10	5	0.9
11-15	3	0.5
16-20	8	1.4
21-25	6	1.0
26-30	19	3.3
31-40	108	18.6
41-50	224	38.6
51-75	125	21.6
76-100	16	2.8
>100	6	1.0
Unknown	60	10.3
TOTAL	**580**	**100%**

Table 15d. Number of water main breaks per month in 1997 for the city of Columbus, OH.(23)

MONTH	NUMBER OF BREAKS	FRACTION (%)
January	119	20.5
February	55	9.5
March	25	4.3
April	34	5.9
May	25	4.3
June	35	6.0
July	34	5.9
August	35	6.0
September	30	5.2
October	47	8.1
November	71	12.2
December	70	12.1
TOTAL	**580**	**100%**

In 1997, the Columbus water department contracted with a third party to inspect large portions of their system for leaks. The survey covered 43 districts representing 1,720 km (1,069 mi) of pipeline. Seven of these districts were investigated further to locate the indicated leakage. The investigations resulted in the location of 69 leaks, the repair of which was projected to reduce system leakage by a total of about 8,328 m^3 per day (2.2 million gal per day) or about 3.0 million m^3 per year. This compares to about 1.65 percent of the 183 million m^3 (48.5 billion gal) annual total water pumpage, a savings of approximately $1.2 million, assuming an average consumer cost of about $0.40 per m^3 ($1.50 per 1,000 gal).

Case Study 2. City of Cleveland, Ohio – Downtown Water Main Break

On Monday, January 12, 2000, at 5:45 p.m., a large water main rupture on East 9th Street in Cleveland, Ohio spilled 95 thousand m^3 (25 million gal) of water onto Cleveland's downtown streets. The flood spread quickly, covering a large area under a few feet of water. The 91.4-cm-(36-in-) diameter cast iron pipe, originally constructed in 1913, was buried 1.8 m (6 ft) underground. It burst on a road that runs between two of the city's best-known landmarks, the Rock and Roll Hall of Fame and Jacobs Field. The break created a crater 6 m (20 ft) in circumference and 1.8 m (6 ft) deep. It took approximately 3 hours for workers to bring the break under control and 5 days to completely repair the failure. The rupture made headlines in the local news for several days.(40)

The rupture of the old water main caused major disruptions:

- Three cars were stuck in the water, which was up to 0.6 m (2 ft). The motorists were able to leave their cars safely, and one was able to drive his away after the flood.
- Rush-hour traffic was affected. Fire and police officials closed down part of East 9th Street.
- All Cleveland public and parochial schools, as well as Cleveland State University, were temporarily closed because of the break. The school district has 76,000 students.
- More than 70 businesses were affected, with one business owner estimating his losses at about $50,000. An owner of a pizzeria reported that his pizza couriers needed to pay more for parking farther away. A bakery owner reported that only half as many customers came to his store.

- People who live downtown and in several adjacent neighborhoods were forced to boil their drinking water as a precautionary measure.
- Emergency rooms at two hospitals had to turn away some people who were seeking medical attention. Hospital personnel were trying to preserve water for patients who had already been admitted.
- As the water receded, it left a muddy mess along East 9th Street. By 10 p.m., front-end loaders were removing mud and other debris from the road.
- Water and electric power were affected in downtown office buildings near the line break.

NewsNet5(40) published a background article investigating the history of the Cleveland pipes. The current rupture was fixed by replacing a 4-m (12-ft) section; however, Cleveland has 8,000 km (5,000 mi) of underground water pipe, most of it between 80 and 100 years old.

The ruptured pipe was made of cast iron, which made it subject to tuberculation. The Public Services Director of Lakewood, a city adjacent to Cleveland, said that they systematically replace all old pipes, while Cleveland focuses on cleaning out old pipes and relining them with concrete. The Cleveland Water Commissioner said, "We spend $6 million a year on rehabilitating pipes. We feel that's more cost-effective than coming in, tearing up, and disrupting streets." In both old pipes and new pipes, there is not a good way to predict where the next break is most likely to occur. Furthermore, just because a pipe is 90 years old does not mean that it is no good. Fluctuations in water pressure contribute to water main breaks. As long as the pressure is constant and the ground does not shift, the old pipes do very well. Shutting down all the lines affected by the break could mean more breaks in the future. Cleveland has spent a total of $1 billion over the past 20 years improving and rehabilitating the system, and that level of spending will continue.

Case Study 3. City of Martinez, California – Impact of the Lead and Copper Rule

The impact of the Lead and Copper Rule can be illustrated using the case of the city of Martinez, California. In 1993, this city was surprised by the high lead levels measured during the first round of monitoring.(41) The rule permits water utilities to consider how certain measures to control corrosion will affect other regulated water quality parameters. All of the corrosion control options called for the addition of modified chemicals following filtration; thus, they would not interfere with the primary disinfection process. However, because all the options require altering the finished water's pH, residual disinfection could be affected. This would need to be monitored. The addition of zinc orthophosphate would cause problems in the intake feed (additional flushing required), in the wastewater treatment facilities (one using wetlands, one using a furnace), and for consumers (taste problems in the transition period). After considering all parameters, pH adjustment by a small increase in the existing sodium hydroxide levels seemed to cause the least problems and was also the least expensive.

Case Study 4. City of Boulder, Colorado – Study of Nature and Extent of Corrosion

In 1982, a study was conducted for the city of Boulder, Colorado.(42) The purpose of the study was to evaluate the corrosion potential of the local water supply and analyze the extent of the corrosion problem throughout the distribution system. Water samples from the water treatment facilities and from a cross-section of homes in the city were collected and analyzed for the following corrosion-related parameters: pH, alkalinity, CO_2, chlorine, turbidity, temperature, calcium hardness, total dissolved solids, specific conductance, silica, dissolved oxygen, chloride and sulfate/alkalinity ratio, and color.

Metals were monitored to determine if their concentrations were sufficiently high to warrant concerns about health. Measured concentrations of metals were low in the water and were found to be within the EPA limits. Although the water is aggressive to the materials it contacts, the water quality was not shown to be a health risk. The results indicated that internal pipe corrosion was severe within Boulder and that two types of corrosion (general corrosion and pitting corrosion) were occurring. The cause of the internal corrosion was identified as insufficient concentrations of calcium and alkalinity, and the supersaturated levels of dissolved oxygen.

Investigations of corrosion-related parameters in drinking water are an important aid to water utilities. The appropriate action for improved corrosion control should be determined based on a complete review of the system and a thorough analysis of the data. Data from future monitoring of water quality and system conditions can then be compared with the baseline data. The data should also be used to re-evaluate the applied chemical treatment for corrosion protection at regular intervals to adjust the current corrosion practice to the best practice available for a specific system under changing conditions. Treating the water for internal corrosion protection by using corrosion inhibitors, pH adjustment, and alkalinity adjustment will result in a cost-savings due to improved system integrity.

Case Study 5. County Sanitation Districts of Los Angeles County, California – Anaerobic Selector and Carbon Dioxide Stripping

This case study is based on a study performed by the Joint Water Pollution Control Plant of the County Sanitation Districts of Los Angeles County,(43) and published on the web site of the Water Environment Research Foundation.(44)

The District's Joint Water Pollution Control Plant operates a High-Purity Oxygen-Activated Sludge (HPOAS) system, which consists of four trains of 189 thousand m^3 per day (50 MGD) of capacity each. Each train has four stages, with three surface aerators in each stage. This plant is a regional sludge management facility in which the treatment consists of primary and secondary treatments via the HPOAS system, sludge thickening, digestion, co-generation, and dewatering, and has a total rated capacity of 1.46 million m^3 per day (385 MGD) and a current flow of 1.32 million m^3 per day (350 MGD). The plant staff observed two problems: bulking sludge and corrosion.

The plant had consistent problems with sludge bulking and foaming due to filamentous organisms such as nocardia. The Sludge Volume Index (SVI) generally ranged from 200 mL/g to 250 mL/g, with occasional excursions up to 300 mL/g. Sludge settleability problems forced the plant to operate at low Mixed-Liquor Suspended Solids (MLSS) concentrations and Mean Cell Residence Times (MCRT), which made the process vulnerable to shock loading. This is important since the facility is downstream from many major industries, including several refineries.

Another operating challenge of the HPOAS system was corrosion of structures and piping. The plant staff observed concrete deterioration amounting to approximately 6.4 mm (0.25 in) of concrete loss, a condition which became progressively worse from the second to the fourth stage. In addition, mild steel effluent piping and metallic chain-and-flight components in the secondary clarifiers appeared to be exhibiting accelerated corrosion. Plant staff attributed this corrosion to a low pH condition brought about by the progressive increase in partial pressure of carbon dioxide through the HPOAS head space. As the carbon dioxide concentration in the MLSS increased, carbonic acid was created, depressing the mixed-liquor pH and leading to deterioration of concrete and corrosion of steel surfaces. While the in-plant corrosion impacts could be addressed relatively simply, potential corrosion of the 12.9 km (8 mi) of unlined effluent tunnels and outfall structures by low-pH plant effluent was a serious concern when all plant wastewater would be treated through secondary treatment facilities.

Accordingly, the plant staff modified the HPOAS system to address these concerns. To reduce filamentous microorganisms in the MLSS, thereby improving the MLSS settleability, plant staff converted the first stage of the HPOAS reactors to an anaerobic selector, since literature indicated that anaerobic selectors produce a biomass that settles well. Conversion to an anaerobic selector was accomplished by intermittent operation of the first-stage aerators and a reduction of aerator blade sizes. By intermittently operating the three surface aerator, 2 hours per day each, excess solids deposition in the bottom of the first-stage reactors was avoided. Furthermore, plant staff cut the mixer blades of the first stage to shorter blade diameters to reduce the dissolution of oxygen into the MLSS.

To address the problem of corrosion (i.e., low pH), the plant staff investigated several alternative chemical methods for elevating the mixed-liquor pH. Unfortunately, a significant amount of chemicals would be required at a significant cost. They then investigated what level of carbon dioxide concentration would be allowable to significantly reduce the likelihood of corrosion. They determined that a pH of 6.7 was required, which corresponded to a dissolved carbon dioxide level of less than 100 mg/L. To achieve this carbon dioxide concentration, the districts then decided to investigate physical methods of carbon dioxide stripping, and selected air stripping since it was the most cost-effective technology. To test the feasibility of fourth-stage air stripping, the fourth-stage vents of the HPOAS reactors were opened and the reactor headspace was purged by airflow from a 595-m^3/min (21,000-ft^3/min) fan. Only the first three stages were operated with an elevated oxygen atmosphere, enabling the fourth stage of the reactor to function as a conventional air-activated sludge reactor. These modifications were incorporated in both existing facilities and in the design of new facilities that will double plant capacity. Implementing these modifications to the HPOAS system has had several benefits:

- selector modifications reduced SVIs to routinely less than 100 and virtually eliminated bulking and foaming,
- air-stripping modifications raised the secondary effluent pH from 6.2 to 6.7. At this level, it is projected that it would take 75 years to corrode the concrete tunnels and outfalls to the depth of the rebar, and
- air stripping saved a minimum of $2 million per year over potential chemical methods of pH elevation.

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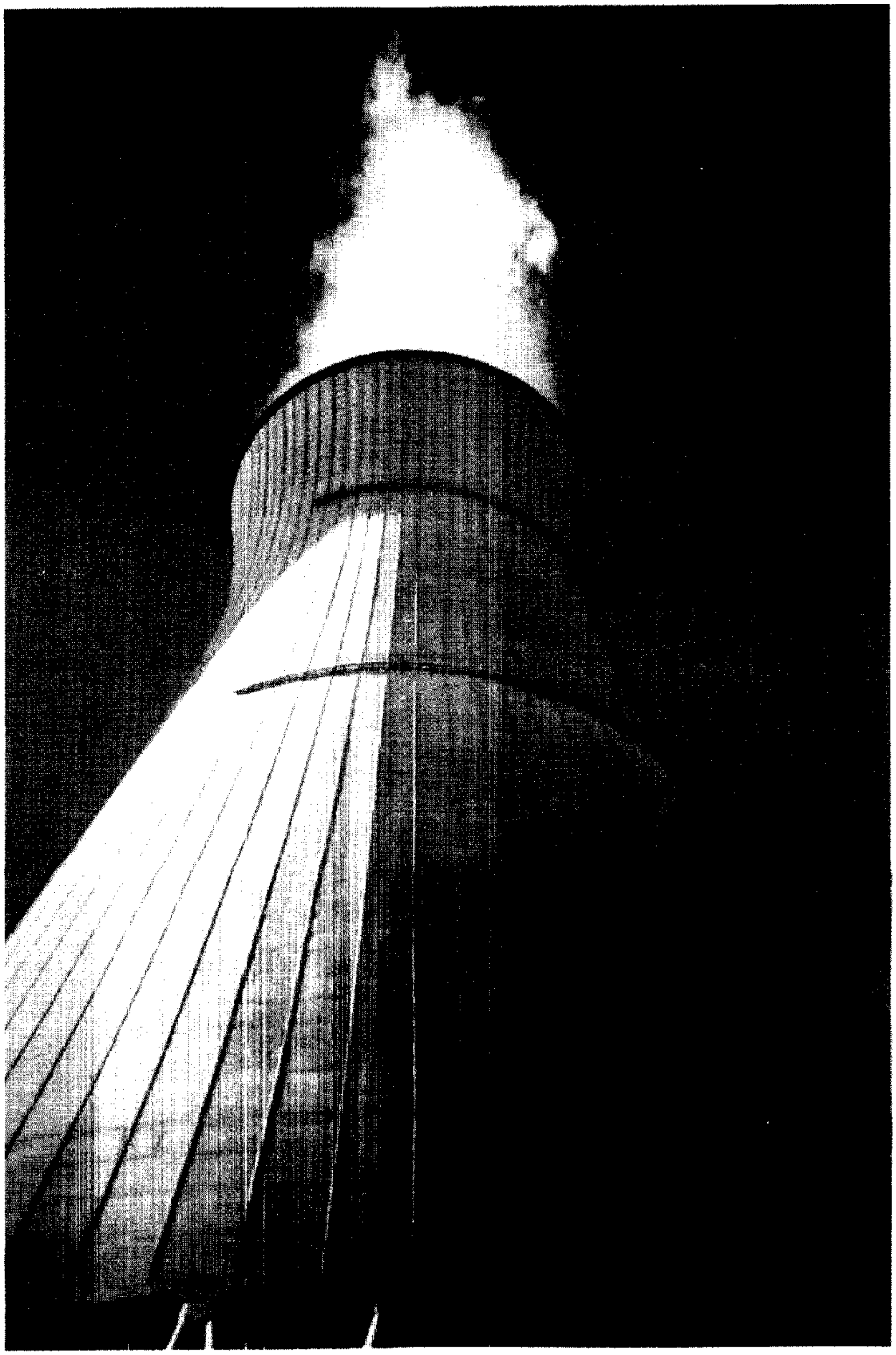
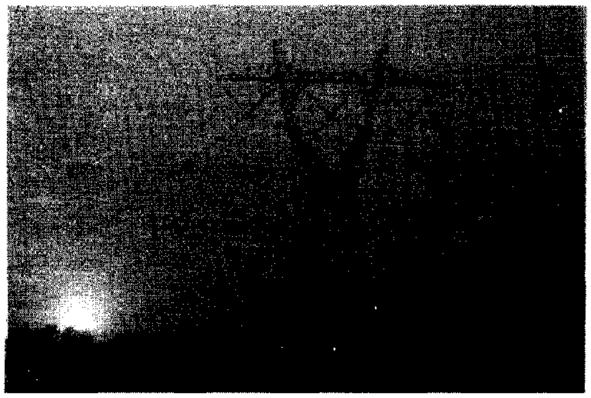
APPENDIX L

ELECTRICAL UTILITIES

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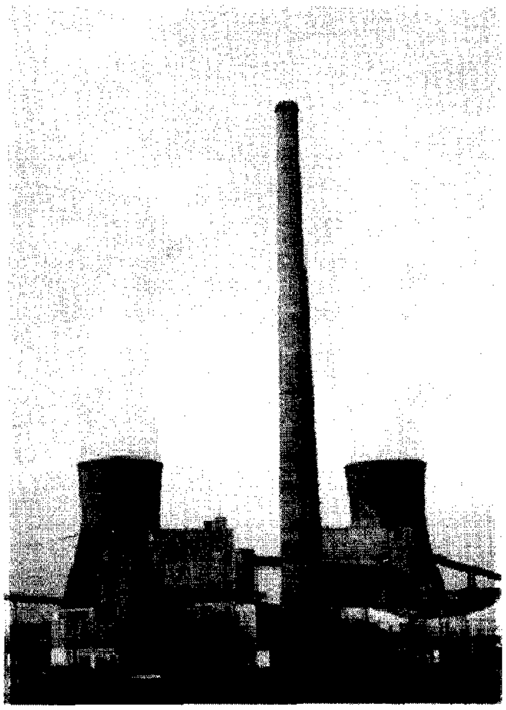
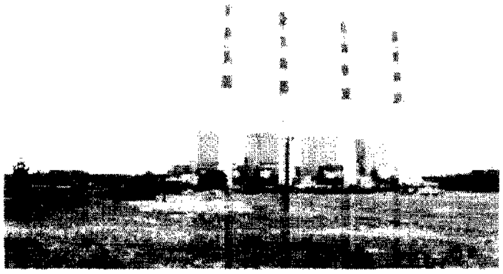
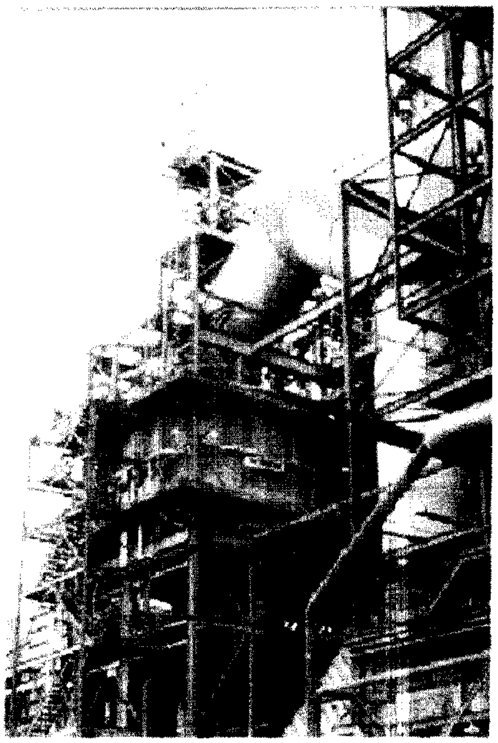
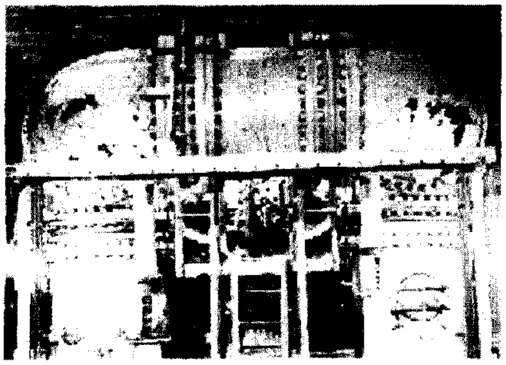

Stack and two cooling towers


Frozen water from leaking cooling water supply line


Power plant


Ducts in power plant


Corroded water piping in power plant

APPENDIX L

ELECTRICAL UTILITIES

GERHARDUS H. KOCH PH.D.[1]

SUMMARY AND ANALYSIS OF RESULTS

Corrosion Control and Prevention

The total cost of electricity sold in the United States in 1998 was 3.24 million gigawatt hours (GWh) at a cost to consumers of $218.4 billion. Electricity generation plants can be divided into seven generic types: fossil fuel, nuclear, hydroelectric, cogeneration, geothermal, solar, and wind. The majority of electric power in the United States is generated by fossil and nuclear steam supply systems. The fossil fuel sector (including gas turbines and combined cycle plants) is the largest, with a generating capacity of approximately 488 gigawatts (GW), and a total generation of 2.227 million GWh in 1998. In 1998, approximately 102 nuclear stations were operation, with a generating capacity of 97.1 GW and a total generation of 673,700 GWh.

Two different types of nuclear reactors are currently in use in the United States, namely the boiling water reactor (BWR) and the pressurized water reactor (PWR). The fuel for these types of reactors is similar, consisting of long bundles of 2 to 4 percent enriched uranium dioxide fuel pellets stacked in zirconium-alloy cladding tubes. The BWR design consists of a single loop in which the entering water is turned directly to steam for the production of energy. The PWR design is a two-loop system that uses high pressure to maintain an all-liquid-water primary loop. Energy is transferred to the secondary steam loop through two to four steam generators. The PWR also uses a wet steam turbine. The electric power industry uses three different types of fossil fuel power plants. The most common and widely used is the pulverized coal-fired steam power plant. Fuel oil can be used instead of coal. Gas turbines are usually smaller units that are used for peak loads and operate only for a few hours per day. Combined-cycle plants using both steam and gas turbines are generally used for baseload service, but also must be capable of addressing peak loads. Hydraulic power systems include both hydroelectric and pumped storage hydroelectric plants. In both processes, water is directed from a dam through a series of tapering pipes to rotate turbines that create electricity. In principle, the potential energy held in the dam converts into kinetic energy when it flows through the pipes. The concept behind the development of pumped storage plants is the conversion of relatively low-cost, off-peak energy generated in the thermal plant into high-value, on-peak power. Water is pumped from a lower to a higher reservoir when low-cost pumping is available from large, efficient thermal plant generation. It is released during periods of high power demand and displaces the use of inefficient, costly alternative sources of generation.

The total cost of electricity of $218.4 billion can be divided into operation and maintenance (O&M), depreciation, and forced outages. The corrosion-related cost of forced outages in the nuclear power industry was estimated at $670 million. The total cost of depreciation based on the 1998 Federal Energy Regulatory Commission (FERC) Form No. 1 data was $35.7 billion. Based on an evaluation of depreciation by facility type, a percentage due to corrosion was estimated. This cost percentage due to corrosion as part of the total utility depreciation in 1998 was 9.73 percent or $3.433 billion, with nuclear facilities at $1.546 billion, fossil fuel facilities at $1.214 billion, transmission and distribution at $607 million, and hydraulic and other power at $66 million. The corrosion portion of the annual O&M cost was estimated at $698 million for fossil fuel, $2.013 billion for nuclear facilities, and $75 million for hydraulic power, for a total of $2.786 billion. Thus, the total cost of corrosion in the electrical utilities industry in 1998 is estimated at $6.889 billion per year.

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[1] CC Technologies Laboratories, Inc., Dublin, Ohio.

A study for the Electric Power Research Institute[(4)] to estimate the cost of corrosion for electrical utilities estimated that the cost of corrosion to consumers of electricity was approximately $17.27 billion per year, which represents approximately 7.9 percent of the total cost of electricity to the consumers of $218.4 billion. The significant difference in the direct cost of corrosion to the utilities owners of about $6.9 billion and the cost to consumers of approximately $17.27 billion can be attributed to overhead and management costs and taxes.

Opportunities for Improvement and Barriers to Progress

Because of the complex and often corrosive environments in which power plants operate, corrosion has been a serious problem, with a significant impact on the operation of the plants. In the 1970s and 1980s, major efforts were made to understand and control corrosion in both nuclear and fossil fuel steam plants, and significant progress was made. However, with the aging of several plants, old problems persist and new ones appear. For example, corrosion continues to be a problem with electrical generators and turbines. Specifically, stress corrosion cracking in steam generators in PWR plants and boiler tube failures in fossil fuel plants continue to be problems. There are further indications that buried structures, such as service water piping, start to show leaks that cannot be tolerated.

Environmental requirements and deregulation of the power industry often result in less attention being paid to corrosion and deterioration of materials of construction. If corrosion issues are not addressed in a timely manner, these materials will corrode to the point that major repair and rehabilitation will be required. The cost of corrosion will then increase significantly.

Recommendations and Implementation

It is recommended that economic corrosion control programs to provide a strategic cost-effective approach be developed. These programs need to focus on the following areas: (1) implementation of corrosion control in equipment design and the application of corrosion-resistant alloys, (2) selection of proper on-line corrosion monitoring techniques, (3) implementation of corrosion maintenance programs, and (4) development of educational and training programs for corrosion control and prevention. The Electric Power Research Institute (EPRI) should develop programs to address these four items where they affect the entire electrical utilities industry. EPRI could further lend their expertise to assist individual utilities in developing tailored programs.

Of specific importance is the awareness of corrosion control and prevention that is raised among plant personnel at all levels by providing education and training. This provides the plant personnel with the necessary knowledge to make the right decisions to prevent or mitigate corrosion.

Summary of Issues

Increase consciousness of corrosion costs and potential savings.	Maintain and update corrosion cost records, which will raise awareness of the effects of corrosion on the bottom line. This should result in implementation of best engineering practices, which will reduce corrosion costs.
Change perception that nothing can be done about corrosion.	Educate engineers, technicians, and management on corrosion prevention strategies and methodologies.
Advance design practices for better corrosion management.	Selection of corrosion-resistant alloys and proper welding procedures are well defined to avoid corrosion and cracking-related failures. Coatings and cathodic protection are also available to help control corrosion.
Change technical practices to realize corrosion cost-savings.	Corrosion research on the technological needs of the electrical utilities industry will improve technical practices.

Change policies and management practices to realize corrosion cost-savings.	Corrosion prevention strategies and methodologies must be adapted by utilities management and be implemented. EPRI can be instrumental in developing industry standards.
Advance life prediction and performance methods.	Implement life-prediction models for fitness-for-service (FFS) and risk-based assessment (RBA) to ensure equipment integrity and remaining life.
Advance technology (research, development, and implementation).	Investigate the cause of unknown types of corrosion-related failures that are the result of new environmental restrictions and aging of plant equipment. The results of these studies must be made available to both management and engineering personnel in order to allow utilities to implement the most cost-effective measures. Implementation of on-line corrosion monitoring and inspection techniques should be emphasized.
Improve education and training for corrosion control.	NACE (National Association of Corrosion Engineers) International provides basic courses and certifications for corrosion technicians, engineers, and technologists. EPRI develops workshops for engineers on specific issues. General and targeted training and courses for management and engineering personnel will raise awareness of corrosion problems and the best ways to address them.

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SECTOR DESCRIPTION

The Battelle-NBS study indicated that the corrosion costs for the electric power industry in 1975 was approximately $4 billion or 0.24 percent of the gross national product (GNP).(1) In the mid-1980s, corrosion in steam-generating plants in the United States was reported to be responsible for about fifty percent of the forced outages and $3 billion annually in additional operating and maintenance (O&M) costs.(2) O&M includes general maintenance, repair, and replacement of corroded components, and corrosion activities such as inhibitor dosing, protective coating application, cathodic protection, water chemistry control, and corrosion monitoring. In the nuclear systems, the cost associated with exposure of maintenance staff to radiation was largely attributed to corrosion. Another significant contributor to the cost of corrosion is the cost of replacement power. When repair or replacement of a corroded component necessitates partial or complete shutdown of the plant, power must be purchased elsewhere to satisfy the customer demands.

DESCRIPTION OF THE DIFFERENT TYPES OF PLANTS

Electricity-generation plants can be divided into seven generic types: fossil fuel, nuclear, hydroelectric, cogeneration, geothermal, solar, and wind. The majority of electric power in the United States is generated by fossil and nuclear steam supply systems. The fossil fuel sector (including gas turbines and combined-cycle plants) is the largest. It has a generating capacity of about 488 GW and it had a total generation of 2.227 million GWh in 1998.(3) In 1998, approximately 102 nuclear stations were operational, with a generating capacity of 97.1 GW and they generated a total of 673.7 thousand GWh. The total cost of electricity sold in the United States in 1998 was $218.4 billion for 3.24 million GWh(3) at an average cost of $0.067 per kWh.

Nuclear Steam Supply Systems

Two different types of light-water reactors (LWR) are currently in use in the United States, namely the boiling water reactor (BWR) and the pressurized water reactor (PWR). The fuel for these types of reactors is similar, consisting of long bundles of 2 to 4 percent (by weight) enriched uranium dioxide fuel pellets stacked in zirconium-alloy cladding tubes. The BWR fuel assembly, however, has a smaller number of fuel pins and is surrounded by a metal flow channel. The larger PWR fuel assemblies are not enclosed.

The BWR design (see figure 1) consists of a single loop in which the entering water is turned directly into steam for the production of electricity. Since operating temperatures must remain below the critical temperature for water, steam separators and dryers are used with a "wet-steam" turbine.

The PWR design (see figure 2) is a two-loop system that uses high pressure to maintain an all-liquid-water primary loop. Energy is transferred to the secondary steam loop through two to four steam generators. The PWR design also uses a wet-steam turbine.

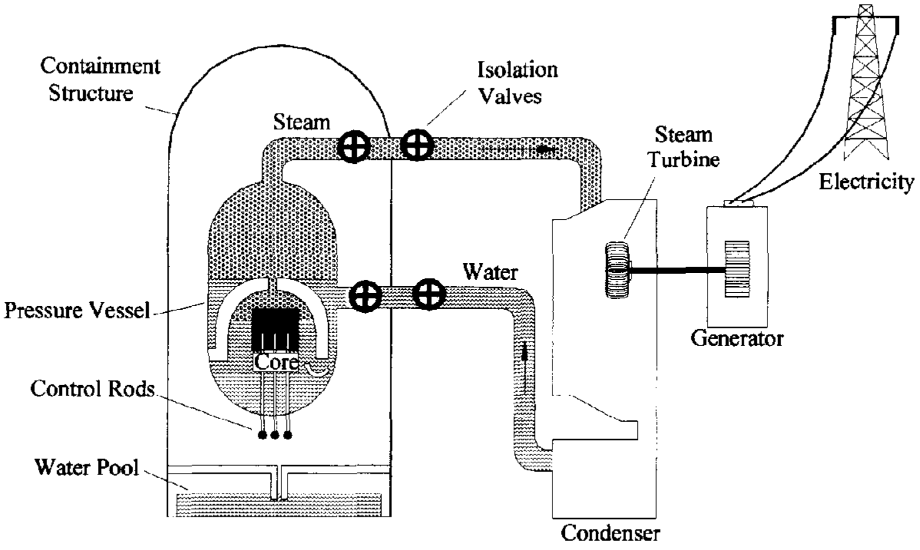

Figure 1. Schematic drawing of boiling water reactor (BWR).

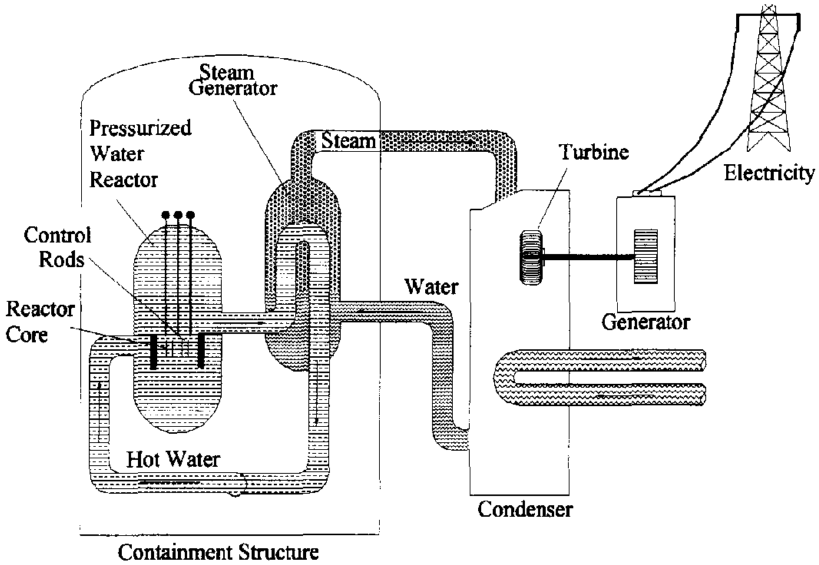

Figure 2. Schematic drawing of pressurized water reactor (PWR).

Fossil Fuel Steam Supply Systems

The electric power industry uses three types of fossil fuel power plants: coal-fired steam, gas turbine, and combined-cycle power plants. The most common and widely used is the pulverized coal-fired steam power plant. Fuel oil can be used instead of coal. The schematic drawing in figure 3 shows the basic operation of a steam-generating plant. Gas turbines are usually smaller units that are used for peak loads and operate for only a few hours per day. Combined-cycle plants using both steam and gas turbines are generally used for baseload service, but must be capable of addressing peak loads (see figure 4).

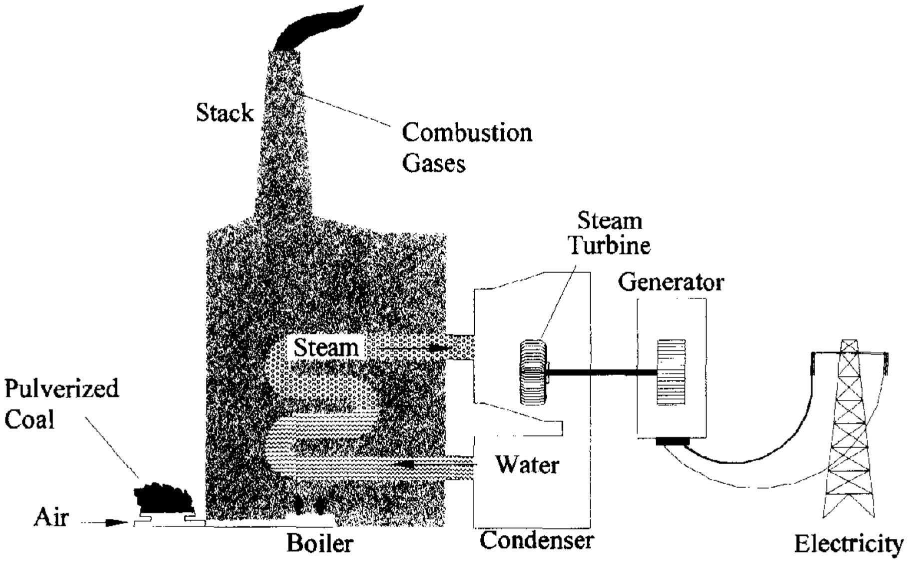

Figure 3. Schematic drawing of fossil fuel plant.

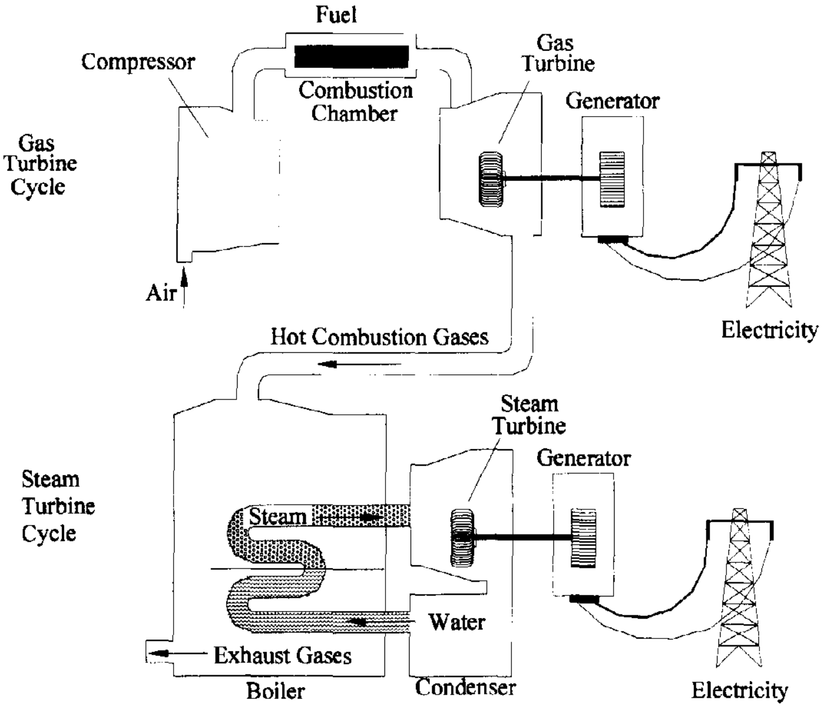

Figure 4. Schematic drawing of combined-cycle plant.

Hydraulic Plants

Hydraulic power systems include both hydroelectric and pumped storage hydroelectric plants. In both processes, water is directed from a dam through a series of tapering pipes to rotate turbines and create electricity. In principle, the potential energy held in the dam converts into kinetic energy when it flows through the pipes (see figure 5).

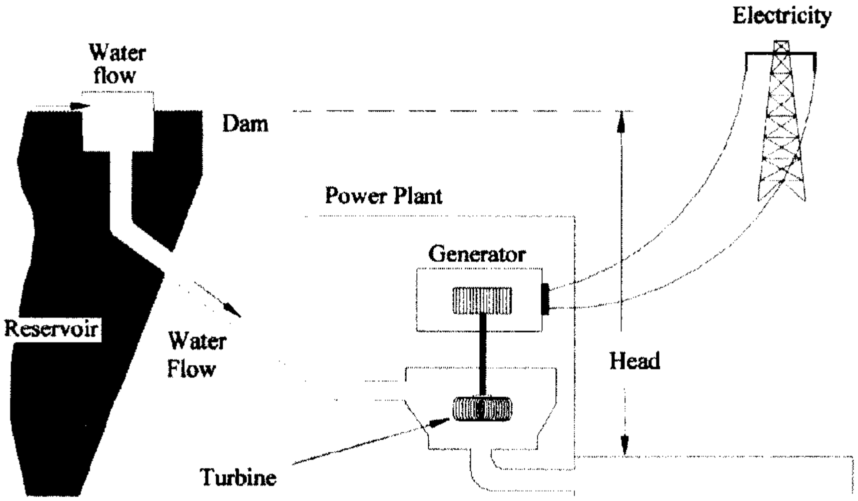

Figure 5. Schematic drawing of hydroelectric plant.

The concept behind the development of pumped storage plants is the conversion of relatively low-cost, off-peak energy generated in thermal plants into high-value, on-peak power. Water is pumped from a lower reservoir to a higher reservoir when low-cost pumping is available from large, efficient thermal plant generation. It is released during periods of high power demand and displaces the use of inefficient, costly alternative sources of generation. If the difference between the off-peak and on-peak energy cost values is large, the process can result in a savings. An additional benefit of pumped storage is the potential reduction in the need for additional peaking power generation capacity.

Transport and Distribution Systems

The electrical utilities transport systems include switchyard equipment, overhead towers, poles and conductors, and underground conductors and equipment. The types of structures and equipment that are included in electric distribution systems are switchgear and batteries, overhead towers, poles and conductors, underground conductors and equipment, transformers, connecting wires, meters, and street lighting.

AREAS OF MAJOR CORROSION IMPACT

The impact of corrosion on electric utility systems can be divided into the fraction of utility costs for depreciation and operation and maintenance that are attributable to corrosion. The estimated costs discussed for this sector are based on detailed analysis of facilities and work activities, using input from Duke Power, an energy company serving more than 2 million customers in North Carolina and South Carolina, and the Electric Power Research Institute (EPRI) reports, technical literature, and other utilities.(4) These fractions are then applied to the statistics for operation, maintenance, and depreciation of the entire utilities industry.

Total Cost of Operation, Maintenance, and Depreciation

The total 1998 cost of electricity of $218.4 billion can be divided into three main categories: operation, maintenance, and depreciation. The fraction of the cost for these categories for the major investor-owned and publicly-owned utilities for 1998 are reported in various government-compiled statistics.(4) Table 1 shows the distribution between the three categories and indicates that the majority of the cost is for the Operation category.

Table 1. Operation, maintenance, and depreciation costs for 1998.

CATEGORIES	PERCENT	COST OF ELECTRICITY ($ x billion)
Operation	75.2	164.3
Maintenance	8.4	18.4
Depreciation	16.3	35.7
TOTAL	**99.9%**	**$218.4**

Operation and Maintenance Costs by Facility Type

O&M costs, including fuel costs, are broken down by facility type using data published in Energy Information Administration, U.S. Department of Energy (EIA/DOE) reports. The latest report for major investor-owned utilities is for 1996.(5) Using data from that report and using data for 1996 from the latest report for publicly-owned utilities (1997),(6) provides the following cost data for O&M by facility or function type (see table 2).

The data indicate that the highest percentage of O&M cost is for the fossil fuel category, with the smallest percentage for hydraulic utilities.

Table 2. O&M costs for 1996.(5)

CATEGORY	PERCENT	1998 O&M COSTS ($ x billion)
Fossil Fuel	64.4	117.6
Nuclear	21.1	38.6
Hydraulic*	1.3	2.4
Other Power Generation	3.3	6.0
Transmission	3.0	5.4
Distribution	6.9	12.6
TOTAL	**100%**	**$182.6**

*Includes pumped storage.

Corrosion Percentage of Operation and Maintenance

In the following section "corrosion percentages" will be applied to the above costs to determine the cost of corrosion in 1998. To do this, corrosion percentages will be developed for both O&M and depreciation costs for each of the facility types

Nuclear Steam Supply Systems

The corrosion costs in nuclear plants are divided among three main categories:

1. Corrosion-related causes of partial power outages.
2. Corrosion-related causes of zero power outages.
3. Contribution of corrosion to O&M.

Partial Power Outages

Duke Power performed a detailed analysis of their operating and outage records to determine the total number of hours of lost production in 1998 at the seven PWRs and also the fraction due to corrosion.(6) Initially, the outage histories of Duke Power's Oconee, McGuire, and Catawba Nuclear Stations (seven PWRs) were reviewed for the 1998 calendar year with respect to partial power outages. These stations are PWRs with generating capacities of 2.541 GW, 2.2 GW, and 2.254 GW, respectively, which is 7.2 percent of the total nuclear generating capacity in the United States. The outages are defined as cases of power reduction at the plants without reaching the zero power threshold. It was assumed that a minimum loss of 5,000 MWh was required for any partial outage to be included. Although there are significant industry differences in the methodologies for converting MWh to dollars, an average cost of $17 per MWh is considered reasonable.

The total lost generation from partial power outages for the three nuclear stations in 1998 was 358.598 GWh. Of this lost generation, 6 percent or 21.389 GWh ($363,613) was attributed to corrosion-related issues. Extrapolating this cost to a total number of 102 nuclear steam supply systems, using the ratio of Duke Power nuclear generating capacity to total U.S. nuclear generating capacity yields a total estimated corrosion cost for partial power reduction of $5.05 million ($363,613 / 7.2%).

Zero Power Outages

Similarly, the outage histories at the Oconee, McGuire, and Catawba Nuclear Stations were reviewed for the 1998 calendar year with respect to zero power outages. These outages are defined as cases of power reduction at the nuclear plants that resulted in the generator being detached from the generation grid. The lost generation for zero power outages for the three stations in 1998 was 7,687 GWh, of which 35.6 percent or 2,740 GWh ($46,572,741) was attributed to corrosion-related causes. This represents 35.6 percent of the total zero power outage losses or 4.5 percent of the overall capacity for the three stations. Extrapolating this cost to the total number of 102 nuclear steam supply systems, using the ratio of Duke Power generating capacity (7.2 percent) to total U.S. nuclear generating capacity yields a total corrosion cost for zero power of $665 million ($46,572,741 / 7.2%).

Operation and Maintenance

For each nuclear station, the O&M cost is divided into specific work activities. For Oconee, McGuire, and Catawba, a total of 83, 83, and 91 work activities were reviewed, respectively. Table 3 ranks the activities with the 10 highest corrosion costs, as well as the remainder of the work activities. The corrosion cost estimates for the three Duke Power nuclear stations were made based on interviews with Duke Power subject matter experts.

Table 3. Top O&M activity costs at Duke Power's three PWR stations.

WORK ACTIVITIES	**COST**		**FRACTION ATTRIBUTED TO CORROSION**	**COST OF CORROSION**
	$	**%**	**%**	**$**
OCONEE NUCLEAR STATION				
Steam Generators	22,757,765	8.26	95	21,619,877
Maintenance Engineering Support	13,204,783	4.79	33	4,357,578
Radiation Protection	12,116,142	4.4	80	9,692,914
Mechanical Components	10,709,285	3.89	33	3,534,064
Maintenance Function Support	10,675,567	3.87	33	3,522,937
Work Control	6,073,111	2.2	33	2,004,127
Chemistry	5,570,659	2.02	60	3,342,395
Pipes	2,391,285	0.87	60	1,434,771
Coatings & Paintings	2,279,358	0.83	45	1,025,711
Decontamination	1,216,689	0.46	80	973,351
Remaining Activities	188,590,607	68.41	-	17,122,624
SUBTOTAL	**$275,585,251**	**100%**	**25%**	**$68,630,349**
MCGUIRE NUCLEAR STATION				
Maintenance Engineering Support	11,348,449	6.4	33	3,744,988
Radiation Protection	8,331,379	4.7	80	6,665,103
Work Control	7,555,778	4.26	33	2,493,407
Maintenance Function Support	7,089,933	4	33	2,339,678
Chemistry	5,460,571	3.08	60	3,276,343
Steam Generators	2,771,692	1.56	85	2,355,938
Maintenance Training	2,510,014	1.42	33	828,305
Coatings & Paintings	1,727,397	0.97	45	777,329
Pipes	1,286,856	0.73	60	772,114
Decontamination	656,478	0.37	80	525,182
Remaining Activities	128,507,745	72.51	-	12,063,839
SUBTOTAL	**$177,246,292**	**100%**	**20%**	**$35,842,226**
CATAWBA NUCLEAR STATION				
Work Control	9,225,851	4.84	33	3,044,531
Radiation Protection	8,800,640	4.62	80	7,040,512
Chemistry	6,595,992	3.47	60	3,957,595
Maintenance Engineering Support	5,518,379	2.89	33	1,821,065
Steam Generators	4,336,795	2.27	85	3,686,276
Maintenance Function Support	3,913,114	2.05	33	1,291,328
Mechanical Components	3,394,573	1.78	33	1,120,209
Pipes	2,763,982	1.45	60	1,658,389
Heat Exchangers	1,493,915	0.78	55	821,653
Decontamination	1,089,281	0.57	80	871,425
Remaining Activities	143,552,673	75.28	-	15,099,089
SUBTOTAL	**$190,685,195**	**100%**	**21%**	**$40,412,072**
TOTAL	**$643,516,738**		**TOTAL**	**$144,884,647**

The table indicates that steam generator costs are very large at Oconee Nuclear Station. About 95 percent of this cost was corrosion-related and can be largely attributed to corrosion of the sensitized Alloy 600 tubing, which needs more frequent inspection due to the risk of intergranular attack and stress corrosion cracking. Steam generator costs do not show up in the table for McGuire and Catawba Nuclear Stations; the lower cost is related to the use of more corrosion-resistant tube materials (either thermally treated Alloy 600 or Alloy 690). Radiation protection is a significant cost and is mostly due to corrosion, since the main source of radiation that must be dealt with is activated corrosion products. Finally, chemistry control is a significant cost. It is mainly attributed to corrosion since the primary function of chemistry control is to minimize corrosion damage.

The total corrosion-related O&M cost for the three Duke Power PWR stations in 1998 was $144.9 million. Extrapolation of the costs to the 102 nuclear units in the United States using the ratio of Duke Power nuclear generating capacity to total U.S. nuclear generating capacity results in a total cost of $2.013 billion ($144.9 million / 0.072).

Fossil Fuel Steam Supply Systems

Duke Power owns and operates eight fossil fuel and six combined-cycle plants, with total installed generating capacities of 7.573 GW and 2.081 GW, respectively. The fossil fuel stations have coal as fuel, while the combined-cycle units use natural gas. The basis for estimation of the O&M costs is the annual financial data documented by Duke Power and reported to the Federal Energy Regulatory Commission (FERC). The percentage of O&M cost attributed was obtained through interviews with Duke Power subject matter experts. Tables 4 and 5 show the 16 cost categories, which are defined in the Code of Federal Regulations.(6) The tables indicate that the majority of the production costs for the coal plants and combined-cycle plants are related to fuel costs, at approximately 82 and 83 percent, respectively. For the coal plants, the highest corrosion cost is for boiler maintenance at 30 percent, followed by maintenance supervising and engineering, maintenance of the electric plant, and maintenance of the steam plant at 15 percent each. Ten percent is related to the maintenance of structures. For the combined-cycle plants, the highest corrosion costs are in maintenance of the electric plant and maintenance supervising and engineering at 15 percent each and maintenance of structures at 10 percent. The percentage of generating capacity of combined-cycle plants is about 4.3 percent of the total generating capacity.

Table 4. O&M activity costs for Duke Power's coal-fired power plants.

WORK ACTIVITIES	COST		FRACTION ATTRIBUTED TO CORROSION	COST OF CORROSION
	$ x million	**%**	**%**	**$ x million**
Operations, Superv., and Eng.	12.514	1.82	2	0.250
Fossil Fuel	563.449	82.21	2	11.269
Steam Expenses	16.843	2.46	7.5	1.263
Steam – Other Sources	0	0	0	0
Stream Transferred (credit)	0.587	0.09	0	0
Electrical Expenses	10.509	1.54	3	0.315
Misc. Steam Power Expenses	13.258	1.93	2	0.265
Rents	0	0	0	0
Allowances	0	0	0	0
Maint. Superv. and Eng.	11.110	1.62	15	1.667
Maintenance of Structures	3.715	0.54	10	0.372
Maintenance of Boiler Plant	35.766	5.22	30	10.73
Maintenance of Electric Plant	15.921	2.32	15	2.388
Maintenance of Misc. Steam Plant	1.691	0.25	15	0.254
TOTAL	**$685.366**	**100%**	**4.2%**	**$28.773**

Table 5. O&M activity costs for Duke Power's combined-cycle plants.

WORK ACTIVITIES	COST		FRACTION ATTRIBUTED TO CORROSION	COST OF CORROSION
	$ x million	**%**	**%**	**$ x million**
Operations, Superv., and Eng.	0.523	1.41	2	0.010
Fossil Fuel	30.847	83.01	2	0.617
Steam Expenses	0	0	0	0
Steam – Other Sources	0	0	0	0
Stream Transferred (credit)	0.085	0.23	0	0
Electrical Expenses	1.890	5.09	3	0.057
Misc. Steam Power Expenses	0	0	0	0
Rents	0	0	0	0
Allowances	0	0	0	0
Maint. Superv. and Eng.	0.324	0.87	15	0.049
Maintenance of Structures	0.632	1.70	10	0.063
Maintenance of Boiler Plant	0	0	0	0
Maintenance of Electric Plant	2.951	7.94	15	0.443
Maintenance of Misc. Steam Plant	0	0	0	0
TOTAL	**$37.252**	**100%**	**3.3%**	**$1.239**

The total cost of corrosion in fossil stations with coal as fuel is estimated at $28.773 million and in combined-cycle plants at $1.239 million. Extrapolating these costs to the U.S. fossil fuel steam supply systems, using the ratio of Duke Power fossil fuel generating capacity, (4.3 percent) to the total U.S. fossil fuel generating capacity, results in $669.14 million ($28.773 million / 0.043) for the coal-fired plants and $28.81 million ($1.239 million / 0.043) for the combined cycle plants, for a total cost of corrosion of $698 million per year.

Hydraulic Production

Duke Power owns and operates 21 hydrostations. The individual power stations are relatively small, with a total generating capacity of 2.756 GW. As with the fossil fuel plants, the basis of the O&M costs is the annual financial data documented by Duke Power and reported to FERC. The percentage of the cost due to corrosion was estimated by Duke Power subject matter experts. Table 6 shows 11 cost categories, which are defined in the Code of Federal Regulations.(6) The highest costs are associated with electrical expenses at 26 percent, miscellaneous hydraulic power generation at 23 percent, and maintenance of reservoirs, dams, and waterways, and maintenance of the electric plant at 18 percent each. The highest corrosion cost is in the maintenance of the electric plant at 15 percent of the O&M cost. The electric plant includes waterwheels, turbines, and generators.

The total cost of corrosion in hydraulic power stations is estimated at $1.571 million. Extrapolating these costs to U.S. hydraulic power generation using the ratio of Duke Power hydraulic generating capacity (2.1 percent) to the total U.S. generating capacity results in a total cost of $75 million.

Table 6. O&M activity costs for Duke Power's hydraulic plants.

WORK ACTIVITIES	**COST**		**FRACTION ATTRIBUTED TO CORROSION**	**COST OF CORROSION**
	$ x million	**%**	**%**	**$ x million**
Operations, Superv., and Engr.	0.967	4.49	2	0.019
Water for Power	0	0	0	0
Hydraulic Expenses	0.745	3.46	5	0.037
Electrical Expenses	5.712	26.51	5	0.286
Misc. Hydraulic Power Gen. Exp.	4.987	23.15	2	0.1
Rents	0.251	1.17	0	0
Maintenance Superv. and Engr.	0.493	2.29	12	0.059
Maintenance of Structures	0.057	0.26	10	0.006
Maint. of Reserv., Dams, Waterw.	3.855	17.89	10	0.386
Maintenance of Electric Plant	3.847	17.86	15	0.577
Maintenance of Misc. Hydr. Plant	1.014	4.71	10	0.101
TOTAL	**$21.928**	**100%**	**7.2%**	**$1.571**

Depreciation Costs by Facility Type

The depreciation costs are broken down by facility type using data compiled from FERC Form No. 1 reports for major investor-owned utilities for 1998.(7) In addition to facilities for fossil fuel, nuclear and hydraulic power production, power transmission, and power distribution, the FERC data identify intangible plant, general plant, and common plant categories, which are combined as "miscellaneous and general." The hydraulic production plant category includes both conventional and pumped storage categories.

In the following sections, the fractions of depreciation due to corrosion are discussed for the different facility types. Increases in the original costs of these facilities due to corrosion result from two main factors: the increase in cost of individual items to make them more resistant to corrosion (e.g., increase in wall thickness and the use of more expensive material than carbon steel), and the use of redundant equipment to allow for downtime to accommodate corrosion-induced inspections, maintenance, and repairs. For all facility types, corrosion of property is considered to have no impact on the capital cost of land. Property is thus assigned a corrosion fraction of 0 percent.

Structures of all facilities include reinforced and prestressed concrete buildings, meta- roofed and metal-sided buildings, reinforced concrete docks, intake and discharge structures, etc. The main effects of corrosion on the capital costs of these items for all facilities are for initial protective coatings and for the use of more corrosion-resistant materials (e.g., aluminum siding versus steel sheet siding). Based on industry experience, the increase in cost due to corrosion of these facilities is about 2 percent.

Nuclear Steam Production

A detailed breakdown of capital costs for nuclear steam production plants provided in a Nuclear Regulatory Commission (NRC) report, is used as the basis for the analysis given below.(8) The estimated effect of corrosion on each of the major categories of structures, equipment, and property under Nuclear Steam Production facilities is discussed below.

Reactor Vessel and Reactor Coolant System (Nuclear Steam Supply System): Corrosion affects the initial cost of the reactor coolant system by requiring the use of either corrosion-resistant materials or corrosion-resistant cladding. Water chemistry control equipment that is used to control corrosion of the system and core is also an extra cost due to corrosion. This equipment includes make-up water purification equipment, letdown heat exchangers, demineralizers, and chemistry laboratory and chemistry monitoring equipment. Another design feature required mostly as a result of corrosion is the accommodation of post-shutdown radiation levels caused by the spread of irradiated corrosion products (crud). This requires many design features to provide shielding and to accommodate semi-remote maintenance. It is estimated that corrosion increases the cost of the reactor coolant system, including associated water chemistry control, by 20 percent.

Reactor Auxiliary Systems: Reactor auxiliary systems include emergency injection systems, chemical and volume control systems, radioactive waste treatment systems, etc. The radioactive waste treatment system is required mainly because of corrosion, i.e., to treat crud produced by corrosion. The other systems have to be made of corrosion-resistant materials in order to minimize the input of corrosion products into the core. It is estimated that corrosion increases the cost of these systems by 20 percent.

Turbine Generator System: Corrosion affects the turbine generator system mainly by requiring the design to be modified to prevent stress corrosion and corrosion fatigue of rotors, disks, blades, and bolting. This requires use of more resistant materials, tighter control of water chemistry, and special design features to reduce stresses and eliminate crevices (e.g., use of monoblock design versus shrunk-on-disk design). These features are estimated to increase the cost of the equipment by 20 percent.

Heat Exchangers and Piping: Corrosion, including erosion-corrosion or environmentally assisted cracking, affects the cost of heat exchangers, such as condensers, feedwater heaters, and moisture separators, by: (1) requiring the use of more corrosion-resistant materials (e.g., copper alloys, stainless steels, or titanium versus carbon steel) in many applications, (2) placing limits on flow velocities if carbon steel or copper are used, thereby increasing equipment size, (3) requiring the installation of flow baffles to prevent impingement effects, and (4) increasing required wall thicknesses to allow for corrosion, thereby decreasing efficiency and increasing original equipment size. For heat exchangers cooled using raw service-water, corrosion control concerns often require installation of water treatment systems (e.g., for biocides, or even the use of dual systems, with only one heat exchanger exposed to raw water and the other cooled using a closed cooling water system). For condensers, corrosion concerns often require the installation of sponge ball cleaning systems. These features are estimated to increase the cost of heat exchangers by 20 percent.

Corrosion, including erosion-corrosion or environmentally assisted cracking, affects piping systems by: (1) requiring thicker walls to provide corrosion allowances, (2) requiring the use of more corrosion-resistant materials in some areas, especially steam drains, (3) requiring the use of more corrosion-resistant materials for special applications such as valve seats and trim, and (4) requiring the use of more stress corrosion- and corrosion fatigue-resistant materials for special parts such as pump shafts, valve stems, and bolting. These features are estimated to increase the cost of piping systems by 10 percent.

The total effect of corrosion on heat exchangers and piping is estimated at 15 percent.

Electric Power and Instrumentation and Control: Corrosion affects the costs of electric power and instrumentation and control equipment mainly by requiring design features to exclude corrosive atmospheres and the use of special materials for some corrosion-sensitive parts, such as switches. These features are estimated to increase costs by 5 percent.

Miscellaneous Power Plant Equipment: This equipment includes the main condenser heat removal system, cranes for lifting and moving waterwheels and electric generators for maintenance, and machine shop equipment. Corrosion affects the original cost of this equipment by requiring the use of protective coatings and some design features to protect sensitive parts. These features are estimated to increase costs by 2 percent. Compiled corrosion cost estimates for nuclear steam production plants based on the above discussion are shown in table 7.

Table 7. Percentage of corrosion-related depreciation costs for nuclear steam production plants.

CATEGORY	PLANT COST %	CORROSION EFFECT, % OF PLANT COST	WEIGHTED % OF CORROSION EFFECT
Property	0.5	0	0.0
Structures, inc. Containment	26.3	2	0.5
Reactor Vessel & Reactor Core System	18.5	20	3.7
Reactor Auxiliary Systems	9.0	20	1.8
Turbine Generator	19.5	20	3.9
Heat Exchangers & Piping	7.0	15	1.1
Electric Power & Instrumentation, and Controls	11.5	5	0.6
Misc. Power Plant Equipment	7.7	2	0.2
TOTAL	**100%**		**11.8%**

Fossil Fuel Steam Production

A detailed breakdown of capital costs for fossil fuel steam production plants is provided in an NRC report and is used as the basis for the analysis given below.(7)

Boiler: Corrosion affects the initial cost of the boiler by requiring the use of thicker walls on the carbon steel-tubed water walls and by requiring the use of more expensive corrosion-resistant materials for the superheater and reheater tubes. However, use of the more expensive materials is also required to provide creep resistance; thus, the entire extra cost is not chargeable to corrosion. Water chemistry control equipment that is used to control corrosion of the boiler materials is also an extra cost due to corrosion. This equipment includes make-up water purification equipment, condensate demineralizers, and chemistry laboratory and chemistry monitoring equipment. It is estimated that corrosion increases the cost of boilers, including water chemistry control systems, by 10 percent.

Turbine-Generator System: Corrosion affects the turbine generator system mainly by requiring the design to be modified to prevent stress corrosion and corrosion fatigue of rotors, disks, blades, and bolting. This requires use of more resistant materials (e.g., alloy 17-4 PH versus carbon steel for blades), tighter control of water chemistry, and special design features to reduce stresses and eliminate crevices (e.g., use of monoblock design versus shrunk-on-disk design). These features are estimated to increase the cost of the equipment by 20 percent.

Heat Exchangers and Piping: Corrosion, including erosion-corrosion or environmentally assisted cracking, affects the cost of heat exchangers, such as condensers, feedwater heaters, and moisture separators, by: (1) requiring the use of more corrosion-resistant materials (e.g., copper alloys, stainless steels, or titanium versus carbon steel) in many applications, (2) placing limits on flow velocities if carbon steel or copper are used, thereby increasing equipment size, (3) requiring installation of flow baffles to prevent impingement effects, and (4) increasing required wall thicknesses to allow for corrosion, thereby decreasing efficiency and increasing original equipment size. For heat exchangers cooled using raw service-water, corrosion control concerns often require installation of water treatment systems (e.g., for biocides, or even the use of dual systems, with only one heat exchanger exposed to raw water and the other cooled using a closed cooling water system). For condensers, corrosion concerns often require the installation of sponge ball cleaning systems. These features are estimated to increase the cost of heat exchangers by 20 percent.

Corrosion, including erosion-corrosion or environmentally assisted cracking, affects piping systems by: (1) requiring thicker walls to provide corrosion allowances, (2) requiring the use of more corrosion-resistant materials in some areas, especially steam drains, (3) requiring the use of more corrosion-resistant materials for special applications such as valve seats and trim, and (4) using more stress corrosion- and corrosion fatigue-resistant materials for special parts, such as pump shafts, valve stems, and bolting. These features are estimated to increase the cost of piping systems by 10 percent.

The total effect of corrosion on heat exchangers and piping is estimated at 15 percent.

Coal-Handling Equipment: This equipment includes conveyor belts, pulverizers, and similar equipment. Corrosion is considered to have little impact on this equipment since most of the problems, and thus the design, are dominated by mechanical wear and fatigue. However, some original cost increase does result from the need for coatings. The corrosion impact on this equipment is estimated as 1 percent.

Flue Gas Systems: Flue gas systems, especially the wet flue gas desulfurization systems, are strongly affected by corrosion because of the corrosive nature of flue gas impurities (e.g., sulfur dioxide). This requires use of expensive corrosion-resistant materials for the scrubber equipment, such as the nickel-base alloys C-276 and C-22. It is estimated that flue gas systems with scrubbers are increased in cost by 50 percent as a result of corrosion.

Ash-Handling Equipment: Ash-handling equipment takes ash from the bottom of the boiler and transports it to locations where it can be transferred to off-site storage. The ash is typically handled as a water slurry to allow pumping or similar transport. While the slurries are corrosive, they are typically designed using carbon steels and are not affected much by anti-corrosion design considerations. The relatively small consideration given to corrosion is estimated to increase the cost of the equipment by 5 percent.

Electric Power and Instrumentation and Control: Corrosion affects the costs of electric power and instrumentation and control equipment mainly by requiring design features to exclude corrosive atmospheres and the use of special materials for some corrosion-sensitive parts, such as switches. These features are estimated to increase costs by 5 percent.

Miscellaneous Power Plant Equipment: This equipment includes the main condenser heat removal system, cranes for lifting and moving waterwheels and electric generators for maintenance, and machine shop equipment. Corrosion affects the original cost of this equipment by requiring the use of protective coatings and some design features to protect sensitive parts. These features are estimated to increase costs by 2 percent.

Compiled corrosion cost estimates for fossil fuel steam production plants based on the above discussion are shown in table 8. The values in the "Percent of Plant Cost" column are based on estimates contained in capital costs for a coal plant with flue gas desulfurization equipment, which were taken from a report developed for the NRC.(9)

Table 8. Percentage of corrosion-related depreciation costs for fossil fuel plants.

CATEGORY	PLANT COST %	CORROSION EFFECT, % OF PLANT COST	WEIGHTED % OF CORROSION EFFECT
Property	0.7	0	0.0
Structures	13.8	2	0.3
Boiler	23.9	10	2.4
Turbine Generator	16.3	20	3.3
Heat Exchangers & Piping	7.2	15	1.1
Coal-Handling Equipment	3.1	1	0.0
Flue Gas Systems	13.8	50	6.9
Ash-Handling Systems	1.8	5	0.1
Electric Power & I&C	11.8	5	0.6
Misc. Power Plant Equipment	7.6	2	0.2
TOTAL	**100%**		**14.8%**

Hydraulic Production (Including Pumped Storage)

The types of structures, equipment, and property included in this category are land; structures and improvements (e.g., office buildings); reservoirs, dams, and waterways; waterwheels, turbines, and generators; accessory electric equipment; miscellaneous power plant equipment; and roads, railroads, and bridges. The effect of corrosion on each of the major categories of structures, equipment, and property for hydraulic plants is discussed below.

Reservoirs, Dams, and Waterways: The main impact of corrosion on the original costs of these items is for initial protective coatings on reinforcing bars, and design and fabrication provisions to minimize corrosion of rebar, forms, etc. during the construction process. The estimated increase in cost due to corrosion is 1 percent.

Waterwheels, Turbines, and Generators: Corrosion affects waterwheels, turbines, and associated piping systems (e.g., valves) by requiring the use of corrosion- and erosion-corrosion-resistant materials such as specialty grades of stainless steels (e.g., Nitronic 60) for either the pressure boundary or for trim.(10) The electric generator is affected by the need to have a chemistry control system for the cooling water system, and by the need for protective coatings for steel parts. These features are estimated to increase the cost of the equipment by 10 percent.

Accessory Electric Equipment and Instrumentation and Control: Corrosion affects the costs of electric power and instrumentation and control equipment mainly by requiring design features to exclude corrosive atmospheres and the use of special materials for some corrosion-sensitive parts, such as switches. These features are estimated to increase costs by 5 percent.

Miscellaneous Power Plant Equipment: This equipment includes cranes for lifting and moving waterwheels and electric generators for maintenance, and machine shop equipment. Corrosion affects the original cost of this equipment by requiring the use of protective coatings and some design features to protect sensitive parts. These features are estimated to increase costs by 2 percent.

Roads, Railroads, and Bridges: Corrosion affects the original cost of this equipment by requiring the use of protective coatings, and some design features to provide for drainage to minimize water-induced corrosion. These features are estimated to increase costs by 2 percent.

Compiled corrosion cost estimates for hydroelectric production plants, including pumped storage, based on the above discussion are shown in table 9.

Table 9. Percentage of corrosion-related depreciation costs for hydraulic production plants.

CATEGORY	% OF PLANT COST	CORROSION EFFECT, % OF PLANT COST	WEIGHTED % OF CORROSION EFFECT
Property	10	0	0.0
Structures	5	2	0.1
Reservoirs, Dams, & Waterways	40	1	0.4
Waterwheels, Turbines, & Generators	25	10	2.5
Electric Power & I&C	5	5	0.3
Misc. Power Plant Equipment	5	2	0.1
Roads, Railroads, & Bridges	10	2	0.2
TOTAL	**100%**		**3.6%**

Other Production

The types of structures, equipment, and property included in this category are land, structures and improvements (e.g., office buildings), fuel holders and accessories, prime movers (e.g., diesels, combustion turbines), generators, accessory electric equipment, and miscellaneous power plant equipment. The effect of corrosion on each of the major categories of structures, equipment, and property is discussed below.

Fuel Holders and Accessories: Corrosion affects the initial cost of fuel oil tanks and oil pumping equipment by requiring the use of protective coatings and a small amount of water detection and removal equipment. It is estimated that corrosion increases the cost of this category by 3 percent.

Prime Movers: Corrosion affects the cost of combustion turbines (the main prime mover in this category) by requiring the use of more corrosion-resistant materials. This is estimated to increase the cost of the equipment by 5 percent.

Generators: Corrosion affects the cost of generators by requiring the use of more corrosion-resistant materials (copper alloys) for the cooling system and by requiring a water chemistry control system for the cooling system. In addition, coatings are used on steel parts to provide resistance to corrosion for the casing and support structure. These features are estimated to increase the cost of the equipment by 5 percent.

Electric Power and Instrumentation and Control: Corrosion affects the costs of electric power and I&C equipment mainly by requiring design features to exclude corrosive atmospheres and the use of special materials for some corrosion-sensitive parts, such as switches. These features are estimated to increase costs by 5 percent.

Miscellaneous Power Plant Equipment: This equipment includes cranes for lifting and moving waterwheels and electric generators for maintenance, and machine shop equipment. Corrosion affects the original cost of this equipment by requiring the use of protective coatings and some design features to protect sensitive parts. These features are estimated to increase costs by 2 percent.

Compiled corrosion cost estimates for other production plants based on the above discussion are shown in table 10.

Table 10. Percentage of corrosion-related depreciation costs for "other" facilities.

CATEGORY	% OF PLANT COST	CORROSION EFFECT, % OF PLANT COST	WEIGHTED % OF CORROSION EFFECT
Property	10	0	0.0
Structures	15	2	0.3
Fuel Holders and Accessories	10	3	0.3
Prime Movers	30	5	1.5
Generators	25	5	1.3
Electric Power & I&C	5	5	0.3
Misc. Power Plant Equipment	5	2	0.1
TOTAL	**100%**		**3.8%**

Transmission

The types of structures, equipment, and property included in this category are land, structures and improvements (e.g., office buildings), switchyard equipment, overhead towers, poles and conductors, underground conductors and equipment, and roads and trails. The effect of corrosion on each of the major categories of structures, equipment, and property for transmission facilities is discussed below.

Switchyard Equipment: Corrosion affects the initial cost of transformers and switching equipment by requiring the use of protective enclosures, protective coatings, and more corrosion-resistant materials for some applications. It is estimated that corrosion increases the cost of this category by 5 percent.

Overhead Towers, Poles, and Conductors: Corrosion affects the cost of this equipment by requiring the use of more corrosion-resistant materials, protective coatings, and cathodic protection systems for towers. This is estimated to increase the cost of the equipment by 5 percent.

Underground Conductors and Equipment: Corrosion affects the cost of this equipment by requiring the use of protective coatings and cathodic protection systems. These features are estimated to increase the cost of the equipment by 10 percent.

Roads and Trails: Corrosion is considered to have no impact on roads and trails. This category is thus assigned a corrosion fraction of 0 percent.

Compiled corrosion cost estimates for transmission plants based on the above discussion are shown in table 11.

Table 11. Percentage of corrosion-related depreciation costs for transmission facilities.

CATEGORY	% OF PLANT COST	CORROSION EFFECT, % OF PLANT COST	WEIGHTED % OF CORROSION EFFECT
Property	15	0	0.0
Structures	10	2	0.2
Switchyard Equipment	10	5	0.5
Overhead Towers, Poles, and Conductors	50	5	2.5
Underground Conductors and Equipment	10	10	1.0
Roads and Trails	5	0	0.0
TOTAL	**100%**		**4.2%**

Distribution

The types of structures, equipment, and property included in this category are land; structures and improvements (e.g., office buildings); switchgear and batteries, overhead towers, poles, and conductors; underground conductors and equipment; transformers, connecting wires, meters, and connections; and street lighting. The effect of corrosion on each of the major categories of structures, equipment, and property for transmission plants is discussed below.

Switchgear and Batteries: Corrosion affects the initial cost of switching equipment and batteries by requiring the use of protective enclosures, protective coatings, and more corrosion-resistant materials for some applications. It is estimated that corrosion increases the cost of this category by 5 percent.

Overhead Towers, Poles, and Conductors: Corrosion affects the cost of this equipment by requiring the use of more corrosion-resistant materials, protective coatings, and cathodic protection systems for towers. This is estimated to increase the cost of the equipment by 5 percent.

Underground Conductors and Equipment: Corrosion affects the cost of this equipment by requiring the use of protective coatings and cathodic protection systems. These features are estimated to increase the cost of the equipment by 10 percent.

Connecting Wires, Meters, and Connections: Corrosion requires the use of weathertight enclosures, protective coatings, and, in some applications, corrosion-resistant materials. These features are estimated to increase the cost of the equipment by 10 percent.

Compiled corrosion cost estimates for distribution facilities based on the above discussion are shown in table 12.

Table 12. Percentage of corrosion-related depreciation effect for distribution facilities.

CATEGORY	% OF PLANT COST	CORROSION EFFECT, % OF PLANT COST	WEIGHTED % OF CORROSION EFFECT
Property	10	0	0.0
Structures	10	2	0.2
Switchgear and Batteries	10	5	0.5
Overhead Towers, Poles, and Conductors	50	5	2.5
Underground Conductors and Equipment	10	10	1.0
Connecting Wires, Meters, and Connections	10	10	1.0
TOTAL	**100%**		**5.2%**

General and Miscellaneous

The types of structures, equipment, and property included in this category are land, structures and improvements (e.g., office buildings), office furniture and equipment, and tools and miscellaneous equipment of various types (e.g., shop, garage, laboratory, communications, and power-operated equipment). The effect of corrosion on each of the major categories of structures, equipment, and property for the general facilities is discussed below.

Property: Corrosion is considered to have no impact on land. Property is thus assigned a corrosion fraction of 0 percent.

Structures: Structures include reinforced concrete buildings, metal-roofed and metal-sided buildings, reinforced concrete docks, intake and discharge structures, etc. The main effects of corrosion on the costs of these items are for initial protective coatings and for the use of more corrosion-resistant materials (e.g. aluminum siding versus steel sheet siding). Based on industry experience, the increase in cost due to corrosion is approximately 2 percent.

Office Furniture and Equipment: Corrosion affects the initial cost of office furniture and equipment by requiring the use of protective coatings and more corrosion-resistant materials for a few applications. It is estimated that corrosion increases the cost of this category by 1 percent.

Tools and Miscellaneous Equipment: Corrosion affects the cost of this equipment by requiring the use of more corrosion-resistant materials, protective coatings, and weatherproof enclosures. This is estimated to increase the cost of the equipment by 5 percent.

Compiled corrosion cost estimates for general plants based on the above discussion are shown in table 13.

Table 13. Percentage of corrosion-related depreciation costs for general and miscellaneous facilities.

CATEGORY	% OF PLANT COST	CORROSION EFFECT, % OF PLANT COST	WEIGHTED % OF CORROSION EFFECT
Property	20	0	0.0
Structures	50	2	1.0
Office Furniture and Equipment	10	1	0.1
Tools and Miscellaneous Equipment	20	5	1.0
TOTAL	**100%**		**2.1%**

Summary of Corrosion Costs for Depreciation

Table 14 shows a summary of the depreciation costs, as calculated in the previous text. The table shows that the largest corrosion costs are incurred in nuclear and fossil fuel power generation, due to both the significant annual depreciation costs and the relatively large percentages of the cost attributed to corrosion. Power distribution systems and transmission systems have lower percentages; however, with their significant depreciation costs, there are still considerable corrosion costs. The corrosion costs for hydraulic and other power production are lower than for the other facility types, which is consistent with the smaller portion of the energy generated by those facilities.

Table 14. Summary of corrosion costs as part of depreciation costs by facility type for 1998 in the United States.

FACILITY TYPE	1998 DEPRECIATION COSTS ($ x billion)	CORROSION EFFECT, % OF COST	CORROSION COST ($ x billion)
Nuclear Steam Production	13.1	11.8	1.546
Fossil Fuel Steam Production	8.2	14.8	1.214
Hydraulic Production	0.9	3.6	0.032
Other Production	0.9	3.8	0.034
Transmission	2.7	4.2	0.113
Distribution	9.5	5.2	0.494
Miscellaneous and General	-	2.1	-
TOTAL	**$35.3**	**9.73%**	**$3.433**

*Includes pumped storage.

TOTAL COST OF CORROSION

The total direct cost of corrosion to U.S. electrical utilities owners can be divided into the corrosion fractions of forced outages, depreciation, and O&M. Table 15 shows the sum of these direct costs to be $6.889 billion per year.

Table 15. Summary of total cost of corrosion to the electrical utilities industry.

FACILITY	REASON FOR CORROSION COST	CORROSION COST PER YEAR ($ x billion)
Nuclear	O&M	2.013
	Depreciation	1.546
	Forced Outage	0.670
	SUBTOTAL	**$4.229**
Fossil Fuel	O&M	0.698
	Depreciation	1.214
	Forced Outage	0
	SUBTOTAL	**$1.912**
Hydraulic & Other Products	O&M	0.075
	Depreciation	0.066
	Forced Outage	0
	SUBTOTAL	**$0.141**
Transmission & Distribution	O&M	0
	Depreciation	0.607
	Forced Outage	0
	SUBTOTAL	**$0.607**
	TOTAL	**$6.889 billion**

A study for the Electric Power Research Institute (EPRI)(4) to estimate the cost of corrosion for the electrical utilities industry estimated that the cost of corrosion to consumers of electricity was approximately $17.27 billion per year, which represents approximately 7.9 percent of the total cost of electricity to consumers of $218.4 billion. The significant difference in the direct cost of corrosion to the electrical utilities owners of $6.889 billion and the cost to consumers of approximately $17.27 billion can be attributed to overhead and management costs and taxes.

CASE STUDY

Buried Condenser Circulating Water Piping

The following case study is presented to illustrate the possible reductions in corrosion-related costs that can occur from appropriate corrosion management.(11)

The Oconee Nuclear Station has three 846-MW PWRs. The buried condenser circulating water (CCW) piping system for each unit consists of four circulating water pumps, which take cooling water from a lake; two 335-cm-

(132-in-) diameter intake lines, which are buried for most of their length; a 472-cm- (186-in-) diameter line in the turbine building; 198-cm- (78-in-) diameter feeders to and from the condensers; and two 335-cm- (132-in-) diameter discharge lines, which are buried for most of their length. Also, the CCW includes an emergency discharge line. The buried lines are coated on both the outside diameter (OD) and inside diameter (ID) surfaces with a 0.41-mm- (16-mil-) thick coal tar epoxy coating.

A review of operating records indicated that from 1992 to 1999, three through-wall leaks or holes had occurred in the CCW piping:

- In 1992, standing water was found in the transformer yard, with substantial amounts of water flowing down the turbine basement wall. The source of the water was found to be a small hole in the emergency discharge line. The root cause of the leak was determined to be galvanic or pitting corrosion at a pinhole in the exterior coating, possibly accelerated by the close proximity of copper grounding wires in the transformer yard.
- In 1997, a through-wall hole was detected in one of the discharge pipes. The 2.5-cm- (1-in-) diameter hole was found during routine removal of the internal coating. The hole, which was located in a deep portion of the piping, 10.7 m (35 ft) below the surface and a few feet from the reinforced concrete turbine wall, had developed from the outside.
- In 1999, a through-wall hole was detected in one of the discharge pipes during routine removal of the internal coating. Again, it was determined that the hole had developed from the outside.

The risk of these leaks/holes developing in the CCW piping could be significant. The buried CCW piping is essential for maintaining production. Parts of the piping deliver water required for response to accidents, so they are required to be operational at all times. Leaks that form in the intake sections of the buried CCW piping could require a plant shutdown. Leaks that are tolerable from a nuclear safety point of view, e.g., a leak in the discharge piping, might still be unacceptable because of the economic consequences of the leak. For example, a leak in the discharge piping could wash away the soil supporting the pipe, eventually resulting in a cave-in. Thus, the performance goals for the CCW piping are to operate with 100 percent availability during plant operation, not to cause plant shutdowns or power reductions, not to experience leakage, and to cost-effectively maintain the piping while meeting the first three goals.

The CCW piping is both internally and externally coated with coal tar epoxy. Where the pipe diameter is sufficiently large to allow it, the internal coating is periodically inspected, and deteriorated coatings are blasted off and replaced. This, however, cannot be done with the outside surface of the buried piping. An estimate was made of the future occurrence of leaks/holes if no preventive actions were taken by fitting the three failure data points to a two-parameter Weibull distribution (see table 16). The table indicates that leaks will occur at an increasing rate with increasing service life. Thus, unless corrective measures are taken, it was predicted that there will be an increasing number of through-wall leaks/holes from exterior corrosion, which may eventually result in costly shutdowns.

Table 16. Projected buried CCW pipe through-wall leak events.

SERVICE YEARS	CUMULATIVE LEAKS	ANNUAL RATE OF LEAKS
18	1	0.15
23	2	0.3
25	3	0.4
40	17	1.6
60	81	5.2

In order to address the anticipated CCW pipe through-wall leak/hole events, options to monitor and control the external corrosion were explored. Upon review of several inspection and corrosion control methods, ranging from nondestructive inspection techniques, such as magnetic flux leakage, pressure and hydrostatic testing, and excavation of the pipe to recoat or replace, the following alternative approaches were selected for economic evaluation:

- Current maintenance practices of internal inspections and recoating of the internal surfaces of the large-diameter piping and fixing of the leaks as they occur.
- Cathodic protection program (for protection against corrosion on the external surfaces) added to the current maintenance plan.
- Current maintenance plan substantially extended to include nondestructive sampling inspections (spot checks) of pipe wall thickness. These would be performed from the internal surface of the tube.
- Cathodic protection and nondestructive sampling inspections added to the current maintenance plan.

Cost inputs were estimated for the following options to monitor and control corrosion on the various piping systems. The uncertainty of these estimates is considered to be high, on the order of 50 percent less to 100 percent more than the dollar amounts presented in the following paragraphs.

Cathodic Protection Design, Installation, and Operation: The costs to design and install cathodic protection on the intake piping, discharge piping, and emergency discharge piping were assumed to be $100,000, $100,000, and $30,000, respectively. The annual costs to operate these piping systems were assumed to be $20,000, $20,000, and $6,000, respectively.

Inspections: The annual cost of current visual inspections of the internal surfaces of the large-diameter piping is $2,000. The cost of performing sampling type nondestructive evaluation (NDE) of the external surface of the large-diameter piping is estimated at $100,000 initial cost and $10,000 annually, divided equally between intake and discharge piping. The cost of visual inspection of the internal surfaces of the emergency discharge piping is estimated at $100,000 initially, and $10,000 every 5 years. The cost of NDE of essentially all emergency discharge piping using smart pigs is estimated at an initial cost of $500,000, with an annual inspection cost of $10,000.

Failures: The cost of repairing a through-wall leak/hole is assumed to be $100,000. The cost of repairing an incipient leak, i.e. detected with NDE before the actual leak occurs, is assumed to be $50,000. The cost of repairing a major failure of an inlet or discharge pipe is assumed to be $2 million plus 10 days of lost production per event. The cost of repairing a major failure of the emergency discharge piping is assumed to be $1 million in indirect costs per anticipated event, with no lost production, and $500,000 in direct costs per anticipated event, with no lost production.

Preventive Repairs: The cost of recoating the inside surfaces of the inlet and discharge piping is assumed to be $2 million per unit, while the cost of recoating the internal surface of the emergency discharge piping is assumed to be $1 million.

Failure rates for the various piping systems, assuming different O&M approaches, were estimated with roughly the same uncertainty as the equivalent cost estimates. For example, for the case in which present practices are continued, the results of estimated rates of leak formation for the different piping systems are summarized in tables 17 and 18. The tables reflect the assumption that degradation of the coating and development of corrosion leaks/holes in the inlet pipe lag that of the discharge piping by a factor of two, because of lower temperatures.

Other failure rate estimates were made for piping with cathodic protection, sampling NDE, 100 percent remote NDE, and cathodic protection plus internal visual inspection. Finally, the probabilities of major failures and failures at local repairs were determined for current practices and for the various other inspection and corrosion control approaches.

Table 17. Projected through-wall leak/hole events in large-diameter buried CCW discharge piping and buried emergency discharge piping.

SERVICE YEARS	DISCHARGE PIPING (CUMULATIVE LEAKS/HOLES)	EMERGENCY DISCHARGE PIPING (CUMULATIVE LEAKS/HOLES)
25	2	1
30	3.5	1.8
40	11	5.5
50	27	13
60	54	27

Table 18. Projected through-wall leak events in buried CCW intake piping.

SERVICE YEARS	CUMULATIVE LEAKS/HOLES
37.5	2
45	3.3
60	11

Based on the estimated costs, failure rates, and failure probabilities, a life-cycle management economic model developed by EPRI (LCMVALUE, Version 1.0)(12) was used to calculate the net present value costs of the buried CCW piping for the life of the station, assumed to be 60 years. The results of the calculations are presented in table 19.

Table 19. Net present value costs for buried CCW piping ($ x thousand).

CASE	PREVENTIVE MAINTENANCE	CORRECTIVE MAINTENANCE	LOST PRODUCTION	CONSEQUENTIAL LOSS	TOTAL
Large-Diameter Discharge Piping					
Current Practices	$609	$1,289	$395	$0	$2,293
Cathodic Protection	$947	$129	$39	$0	$1,115
Sampling NDI	$717	$548	$3	$0	$1,268
Emergency Discharge Piping					
Current Practices	$146	$584	$0	$0	$730
Cathodic Protection	$247	$196	$0	$0	$443
100% Remote NDI	$731	$292	$0	$0	$1,023
Cathodic Protection + ID visual insp.	$364	$98	$0	$0	$462

Table 19. Net present value costs for buried CCW piping ($ x thousand) (continued).

CASE	PREVENTIVE MAINTENANCE	CORRECTIVE MAINTENANCE	LOST PRODUCTION	CONSEQUENTIAL LOSS	TOTAL
Large-Diameter Intake Piping					
Current Practices	$609	$277	$2,513	$0	$3,399
Cathodic Protection	$947	$28	$251	$0	$1,226
Sampling NDI	$717	$129	$1,241	$0	$2,087
Pipe Repairs					
Current Practices	$0	$230	$1,348	$0	$1,578
Cathodic Protection	$0	$44	$148	$0	$192
Cathodic Protection + NDI	$12	$31	$148	$0	$191
All Buried CCW Pipe Sections					
Current Practices	$1,364	$2,701	$4,256	$0	$8,321
Cathodic Protection	$2,141	$621	$438	$0	$3,200
Cathodic Protection + NDI	$1,887	$856	$1,428	$0	$4,171

*NDI – Nondestructive inspection.

Table 19 demonstrates that cathodic protection, with or without supporting NDE, has typically the highest preventive maintenance costs, which can be attributed to engineering, installing, and energizing the cathodic protection system. However, once in operation, the cathodic protection system represents the lowest corrective maintenance cost and by far the lowest cost due to lost production. Thus, cathodic protection of the buried sections of the CCW piping represents the most cost-effective corrosion management option for the piping.

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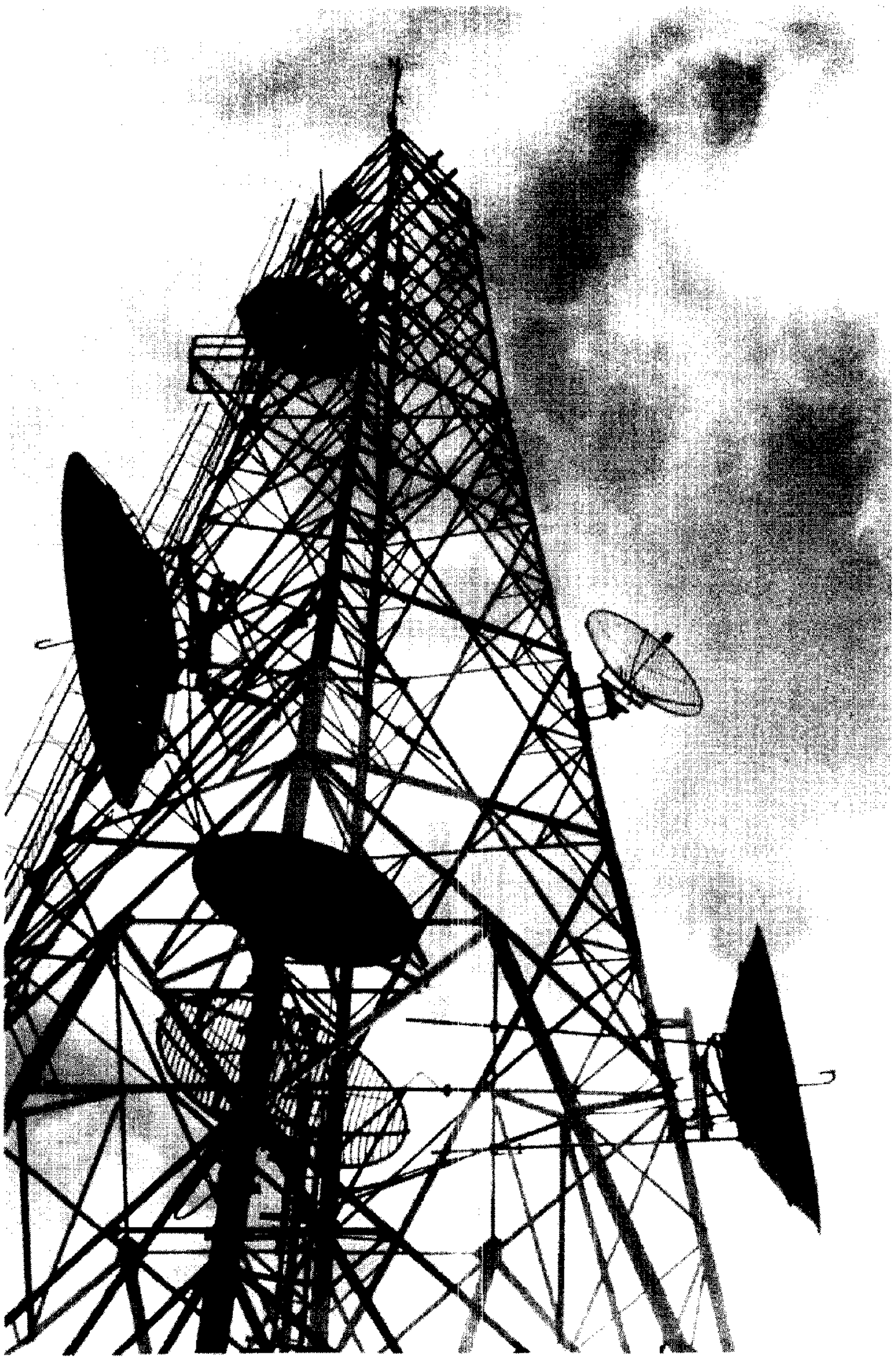
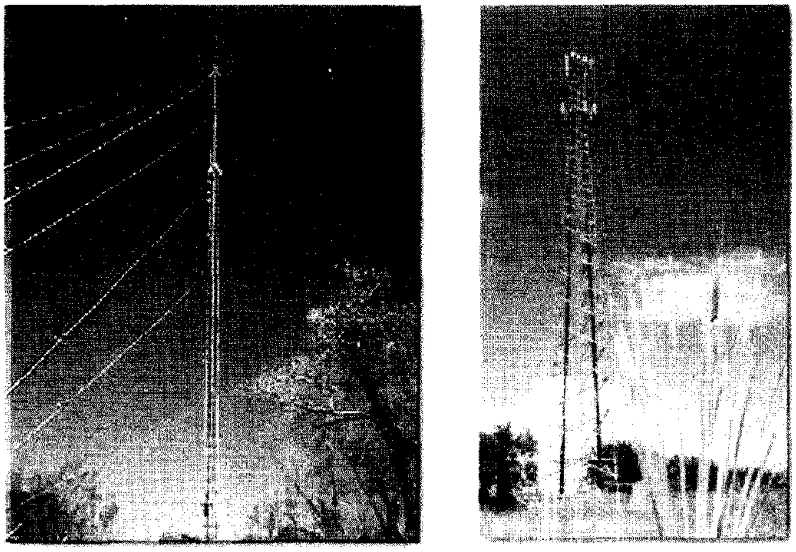
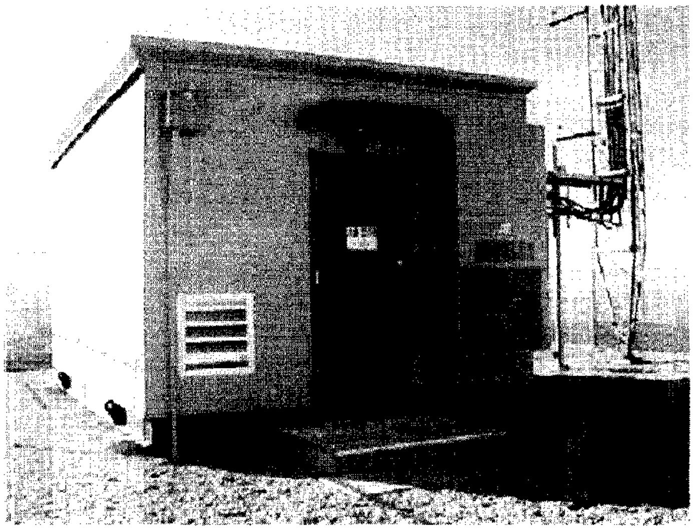
APPENDIX M

TELECOMMUNICATIONS





Transmission towers



Equipment shelter

Telephone

APPENDIX M

TELECOMMUNICATIONS

MICHIEL P.H. BRONGERS[1]

SUMMARY

The components that have an impact on corrosion of the telecommunications infrastructure in the United States include hardware, such as electronics, computers, and data transmitters, as well as the equipment shelters and towers used to mount antennas and dish-shaped transmitters and receivers. According to the U.S. Census Bureau, the total 1999 value of shipments of communications equipment was $84.6 billion.

Factors to be considered for the cost of corrosion are: materials of construction for towers and shelters and corrosion of grounding beds. No estimated cost of corrosion was determined for this rapidly changing sector due to lack of information. Many components are being replaced before physically failing because they become obsolete technology in a short period of time.

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[1] CC Technologies Laboratories, Inc., Dublin, Ohio.

SECTOR DESCRIPTION

This sector describes the impact of corrosion on the telecommunications infrastructure in the United States. The telecommunications infrastructure includes hardware such as electronics, computers, and data transmitters, as well as the equipment shelters and towers used to mount antennas and dish-shaped transmitters and receivers.

Wired communications systems include telephone and cable TV systems. Wireless communications systems include personal computer systems (PCS) and cellular telephones, broadcast and trunked radio systems, and a variety of other systems based on the transmission and reception of electromagnetic wave signals.

This sector description is limited to an identification of the areas expected to have the most corrosion problems. The telecommunications industry is relatively young and material replacement is often done because of technological changes rather than corrosion; therefore, no corrosion costs are reported in this sector.

Industrial Classification

The Standard Industrial Classification (SIC) system used by the U.S. Census Bureau(1) classifies the SIC 513 as "Broadcasting and Telecommunications Industries," which includes establishments providing point-to-point communications and the services related to that activity.

The SIC 5133 "Telecommunications" industry group comprises establishments primarily engaged in operating, maintaining, and/or providing access to facilities for the transmission of voice, data, text, sound, and full motion picture video between network termination points and telecommunications reselling. Transmission facilities may be based on a single technology or a combination of technologies. According to the 1997 Census, this industry group had 30,012 establishments, an annual revenue of $260.5 billion, an annual payroll of $47.5 billion, and approximately 1.0 million employees.

Size of Communications Equipment Sales

The U.S. Census Bureau reported that in 1999, the value of shipments for communications equipment totaled $84.6 billion(2) (see table 1). The Office of Telecommunications Technology, under the U.S. Department of Commerce, reported a comparable value for 1999 with $78.6 billion in total shipments.(3) Table 2 shows a list of typical telecommunications equipment.

Table 1. Value of shipments in 1999 for communications equipment, as reported by the U.S. Census Bureau.(2)

SHIPMENTS	VALUE OF SHIPMENTS	
	$ x billion	**%**
Communications systems and equipment	31.3	37.0
Other telephone and telegraph equipment	20.4	24.1
Telephone switching equipment	13.9	16.4
Carrier line equipment and non-consumer modems	9.1	10.8
Broadcast, studio, and related electronic equipment	3.9	4.6
Alarm systems	2.1	2.5
Other electronic systems and equipment	1.7	2.0
Vehicular and pedestrian traffic control equipment	1.0	1.2
Electronic teaching aids	0.7	0.8
Paging systems	0.3	0.4
Ultrasonic equipment	0.2	0.2
TOTAL	**$84.6**	**100%**

Table 2. U.S. telecommunications trade in 1998.(3)

PRODUCT		
NETWORK/TRANSMISSION EQUIPMENT	**CUSTOMER PREMISES EQUIPMENT**	**OTHER TELECOMMUNICATION EQUIPMENT**
Switches	Cellular telephones	Radio transceivers
Satellites	Videophones	Radio parts
Coaxial cable	Private branch exchange Switching apparatus (PBX)	Radio transmitters
Optical fiber/cable	Modems	Telegraphic apparatus
Line systems	Key systems	Radio receivers
Repeaters	Teleprinters	Antennas
	Handsets	Articles for instruments/networks
	Intercoms	Loudspeakers
	Wire with modular connectors	Earth stations
	Answering machines	Telephonic apparatus
	Pagers	Set-top boxes
	Facsimile machines	Television transmitters
	Telephone sets	
	Cordless telephones	

AREAS OF MAJOR CORROSION IMPACT

Hardware

Telecommunications hardware is the collective name for all the switchboards, electronics, computers, data transmitters, and receivers necessary to complete communications between people. Delicate electronic components must be protected from human and weather factors to be able to operate reliably over long periods of time. An expert in electronics manufacturing and corrosion contended that most failures of this type of equipment are caused by environmental factors. If electronics are not protected from moisture, corrosion of the delicate small parts will cause malfunctions.

It was found that most telecommunications hardware is placed and used inside buildings; therefore, it is expected that it will not be exposed to corrosive environments. In addition, electronic hardware becomes obsolete in just a few years. Therefore, the actual service life of consumer goods is often limited by rapid technological changes rather than by material degradation issues.

Telecommunications equipment with a longer design life includes the cables, connectors, and antennas used for the transmission and reception of electronic signals. These components may be placed outside and be buried so that they become exposed to environments such as soils and water, or they may be exposed to air and moist weather conditions. No data were found regarding the percentage of failures due to corrosion for each category.

A specific corrosion issue is a possibility at telephone facilities that maintain backup power systems in case of power outages. These facilities may have diesel fuel generators supplied by underground storage tanks (USTs). Leaking (UST) systems can cause contamination of groundwater supplies and can cause fires, explosions, and vapor hazards. Under the Resource Conversation and Recovery Act (RCRA), Subtitle I for Underground Storage Tanks, the owners and operators of underground storage tanks must have upgraded, replaced, or closed existing substandard

UST systems by December 22, 1998. Upgrading may involve adding spill, overfill, and corrosion protection to the UST system. More information about UST regulations is given in the sector that discusses hazardous materials storage.

Shelters

Telecommunications equipment is usually housed in a shelter in order to protect it from wind and weather. Shelters are structures without windows that can be climate controlled and contain large amounts of electronics, computers, and equipment, such as transformers.

Shelters are generally located in the immediate proximity of power stations and communications towers. Many antennas and towers are placed at high locations; therefore, a common place for shelters is on rooftops. Shelters are also placed at locations on the ground. Mobile telephony has created the need for many support antennas spread throughout the landscape. Along a major interstate highway, one can count approximately one communications tower per mile of road. Each tower has a shelter and a fence built around it, both of which protect this infrastructure.

Four construction materials are commonly used for communications shelters: steel, aluminum, fiberglass, and concrete. Wooden blocks or concrete blocks are used for their foundations. The capital cost for a shelter can range from $5,000 for a small metal box to $500,000 for a secured concrete building with steel doors. Prefabricated steel shelters for cellular telephone companies typically cost $20,000.(4)

Carbon steel shelters need to be painted to be protected from corrosion. Stainless steel shelters would not need painting; however, the initial material costs are higher than for painted steel. Elsewhere in this report, a full description is given on the cost of paint and its application and the cost comparisons of stainless steel versus carbon steel; therefore, no further details are given here.

Aluminum is mainly selected due to its favorable weight-to-strength ratio. On rooftops and on other mounted structures, the dead weight of the shelter can be important for structural purposes. Aluminum is generally considered to be corrosion-resistant in non-marine environments. The initial material costs are higher than that for carbon steel; however, surface painting is not necessary. For aesthetic appearances, an owner may select coated aluminum with a different color.

The wall construction of fiberglass shelters consists of a foam core with two skins of fiber-reinforced plastic. The fiberglass exterior is corrosion-resistant and, therefore, requires relatively low maintenance. However, the price of fiberglass shelters is generally higher than that of painted carbon steel and aluminum. The fiberglass surface may be molded for a better appearance (for example, using a brick pattern). Standard widths vary between 1 and 5 m (4 and 16 ft), and standard lengths vary between 2 and 7 m (6 and 24 ft). An advantage of fiberglass shelters is that they can be delivered pre-assembled.

The largest and strongest shelters are those constructed using concrete. They are usually secured shelters with steel doors. Montee of the AT&T Tower Group(4) stated that all concrete shelters have temperature- and humidity-controlled environments; therefore, corrosion is not an issue for the equipment place inside.

Heat and Humidity

For cellular telephone equipment, a refrigerator-sized cabinet can be placed near an antenna. The cabinets can be made of steel or aluminum. Corrosion protection is applied for cosmetic purposes because this type of technology generally becomes obsolete and is replaced before corrosion becomes a structural issue. Terry Keating of Lucent Technologies(5) explained that they apply a double system of galvanizing and painting for corrosion protection of their steel cabinets. Surface preparation through grinding and the application of zinc chromate primer is essential for galvanizing. The outdoor cabinets are built more robustly (of thicker gauge material) than the indoor cabinets and can cost twice as much. Cabinets in the range of $1,000 to $10,000 have an estimated corrosion cost of approximately 20 percent, according to Keating.

Significant effort is put forward to protect the equipment contained in the cabinets from moisture. The cabinets are sealed and cooled using passive air-to-air heat exchangers. Only in extreme cases do these cabinets have the more expensive active air-conditioning units.

Nationwide, an estimated 4,000 cabinets for cellular telephone equipment are in use. Their average price is around $5,000, and the estimated cost for corrosion protection for this type of cabinet is 20 percent; therefore, their estimated corrosion costs are approximately $4.0 million (4,000 x $5,000 x 0.20).

Towers

The transmission of signals is done best from antennas mounted at high places. To achieve this, four types of towers have been developed: (1) towers with guidewires, (2) self-supporting wireless towers, (3) tapered steel monopoles, and (4) aesthetic towers. The design, erection, inspection, and maintenance of telecommunications towers is a growing industry because more and more people have portable telephones that require a large number of relatively small towers to be constructed around the country.

Montee(4) explained that the large majority of telecommunications towers are of the self-supporting type. These towers have been constructed since the early 1960s and are made using hot-dipped galvanized steel. Now, 40 years later, negligible corrosion is observed on these towers. Up until the late 1980s, many of the self-supporting towers were painted red and white for daytime visibility and have a red beacon for nighttime. During that period, paint was reapplied every 7 years at a cost of $15,000 to $20,000 per tower; however, this was not for corrosion protection. Today, towers less than 152 m (500 ft) tall and equipped with strobe lights are not required to be painted.

The second largest group of towers is the guided (wire) towers. These towers have been in service for some time. Historically, guided towers were constructed using regular carbon steel and were sandblasted and repainted regularly. The continued operation of these existing, aging guided towers is a major corrosion concern because corrosion of the steel members may affect the structural integrity of the towers.

In recent years, wireless communications have emerged as a large industry with continued growth. Many cellular telephone companies are using monopole towers because they are less noticeable in the landscape and cities than self-supporting and guided towers. Additionally, the cost for monopoles with a height up to 46 m (150 ft) is comparable to that of self-supporting towers. A disadvantage of monopoles is that they cannot be expanded or strengthened after construction; however, that is a possibility for steel-framed towers.

The number of aesthetic towers is relatively low due to their added finishing costs; therefore, this type of tower is only used when other options would be unacceptable.

The antennas that are mounted to towers do not have significant corrosion problems, according to Montee.(4) Dish antennas are made from aluminum and are painted. Cellular telephone panel antennas have not yet shown problems; however, they were placed only a relatively short time ago. The whip antenna, which is 5.5-m (18-ft), 76-mm- (3-in-) diameter pole, is typically used for emergency 911 calls. The whip antenna has no corrosion problems but is prone to damage from lightning strikes.

One tower attachment engineer stated that the single largest corrosion problem in the telecommunication industry is the degradation of buried grounding beds and grounding rings around towers and shelters. These copper grounding systems are consumed over time by corrosive soil. Problems occur when the electrical connection between the grounding bed and the structure is interrupted, or when the corrosion advances so much that the electrical resistance of the bed becomes too great. To prevent electrical disconnection between the grounding and the structure, the traditional mechanical connections must be replaced with CADWELD® connections [American Welding Society (AWS) designation: Termit Welding (TW) process]. Galvanic corrosion due to connections between dissimilar metals is another factor related to copper ground beds.

The copper cables used for the telecommunications industry's electrical supply are encapsulated in plastic to prevent electrical shorts. The plastic also provides corrosion protection to the wires.

CASE STUDIES

Case Study 1. Inspection of Telecommunications Towers

The components and elements of a telecommunications network require regular maintenance. One of the most important parts is to ensure the structural integrity and safety of the telecommunications towers. On their website,(6) CGTI Pylones[2] specifies details for a maintenance and inspection program for telecommunications towers. The amount of maintenance is greater for towers with guidewires than for self-supporting towers.

The principal action is to regularly perform a visual inspection of the tower's external condition. The inspection must be done regularly during the life of the structure, for each installation of an additional loading, and after each important climatic event (tempest, hurricane, etc.) As a minimum, the first checking visit of each tower should be done, at the latest, 6 months after its installation and erection, while subsequent maintenance visits should be done each year. Based on the results of the inspection, maintenance and other such interventions can then be carried out.

CGTI Pylones reports the following detailed checklist for inspection visits (see table 3). For the current report, the corrosion-related items are italicized. The list shows that water traps, problems with grounding systems, and structural hazards from corroded areas are the most common problems. If the items are counted and the relative time spent on each of the tasks in a normal inspection is estimated, the inspection time spent on corrosion issues is calculated at approximately 25 percent.

Table 3. Checklist for inspection visits to telecommunications towers with guidewires, as reported by CGTI Pylones.(6)

MAIN STRUCTURE:
Check that there are no structural components missing.
Check that bars are neither warped nor holed nor split. In that case, defective part(s) shall be replaced.
Check that structural components are not oxidized.
Check that draining holes (pipe leg members, pipe lattice parts) are not blocked.
GUIDEWIRES:
Check guidewires and accessories.
Check that each cable that is part of the guidewire is neither broken nor warped.
Measure the tension of each guidewire by a strand dynamometer and to compare the result with the value stated in the manufacturer's files.
Check guidewire corrosion.
Check that the guidewire tightening system is properly greased.

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[2] CTGI Pylones is a French company that designs, constructs, maintains, and inspects telecommunications towers.

Table 3. Checklist for inspection visits to telecommunications towers with guidewires, as reported by CGTI Pylones[6] (continued).

BOLTING PARTS:
Check that there are neither bolts and nuts nor other bolting parts (washers, pins) missing. In that case, immediate corrective action is required.
Check bolt tightening.
Check that bolts are not oxidized.
Check anchorage rod in the concrete.
VERTICALITY AND ALIGNMENT:
Check structure verticality with the appropriate devices (such as theodolite).
Measurements should be made in two different planes with a 90° angle difference.
ANTENNAS AND ACCESSORIES:
Check that antennas and antenna supports are in good condition.
Check that coaxial cables are in good condition.
Check that fixing clamps are in good condition.
SAFETY COMPONENTS:
Check that access ladder is in good condition.
Check that all safety components are existing and complete.
Check the functioning of the fall arrestor system.
For a fall arrestor system with cable, check that the cable has not been overtightened (for instance, due to a fall).
Check the functioning of the anti-climbing door.
LIGHTNING AND EARTHING SYSTEM:
Check that all lightning and earthing components are existing and complete, including lightning arrestor, copper strip, and connection plate.
Check the earthing connection of coaxial cables.
Measure the resistivity of the earthing system.
NIGHT BEACONING:
Check that all beaconing components are existing.
Check condition and functioning of beaconing components (light bulb, energy cables, fixing parts, photoelectric cell, connections).
Check earthing of the night beaconing.
ANTI-CORROSION PROTECTION:
Check galvanization condition.
Check paint condition.
Check oxidization of the structure, bolting parts, and accessories.
For masts with guidewires, check oxidization of wires.
TOWERS IN SALTY ENVIRONMENTS:
Check the condition of the tower structure when located in a salty environment.
If rains are not sufficient to clean the tower of salt settlings, a regular wash of the tower structure shall be carried out.

Table 3. Checklist for inspection visits to telecommunications towers with guidewires, as reported by CGTI Pylones[6] (continued).

CONCRETE BLOCKS:
Check the condition of aboveground concrete block parts. There must not be any stagnant water.
Check the condition of anchor setting in the concrete block.
TOWER LOADING:
Report types, numbers, and heights of antennas currently installed on the tower.
Compare the result with the initial loading that has been considered in the structure design.

Case Study 2. Example of a New $3,000,000 Digital Television Facility

In February 1999, the Leblanc group announced the new construction of a digital television facility, which will be constructed on top of Farnsworth Peak in Lafayette, Colorado.[7] The total value of this new construction was $3,000,000, which was to be spent on the different components by the respective subcontractors. The contract included the tower, foundations, antennas, transmission lines, combiners, switching systems, and emergency power systems.

The contracting group was a consortium of eight stations, consisting of five commercial and three public broadcasters. The new 73-m (240-ft) tower, topped by a 22-m (72-ft) antenna system, provides a center of radiation approximately 1,500 m (5,000 ft) above Salt Lake City, Utah. In addition to the 8 digital television station antennas, 16 microwave dishes would be installed on the tower.

The tower selected in this case was a rugged, heavy self-supporting type. It was designed to withstand forces created by 250 km per hour (155 mi per hour) winds simultaneously with 7.6 cm (3 in) of radial ice. The base foundation was designed to withstand strong uplift forces. The legs at the tower base are fabricated from 25-cm-(10-in-) diameter solid round high-strength steel, and the face width at the top is 3.0 m (10 ft).

The main antenna was mounted inside a 1.5-m- (5-ft-) diameter glass-reinforced plastic (GRP) cylinder 22 m (72 ft) tall. The GRP cylinder has the advantage of significantly reducing the wind, while at the same time providing for easy access and maintenance regardless of the severe weather conditions incurred at the site.

In the design phase of this tower and antenna, no specific corrosion cost analysis was reported. However, it is obvious that the presence of the glass-reinforced cylinder is a choice of materials to protect the antenna from moisture and therefore corrosion. In this case, the cost of this corrosion protection could be estimated from the cost of the fiberglass construction, which is possibly 10 percent ($300,000) of the total construction costs.

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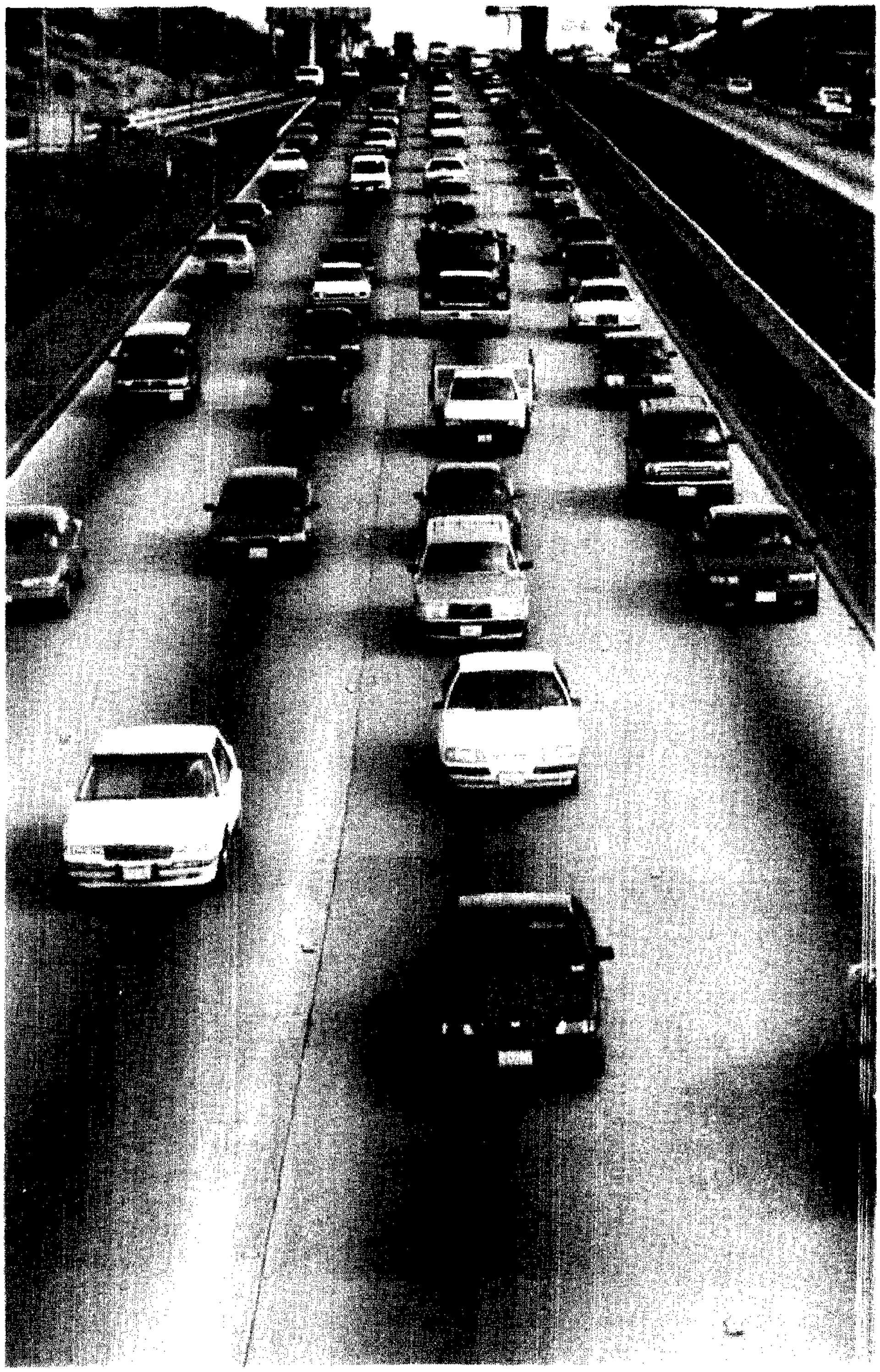
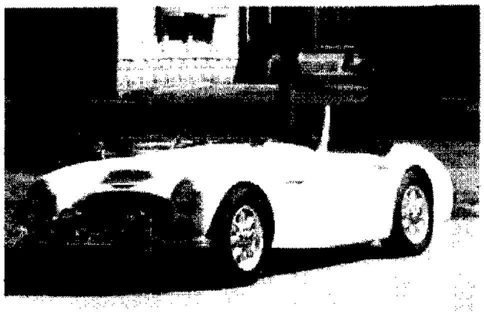
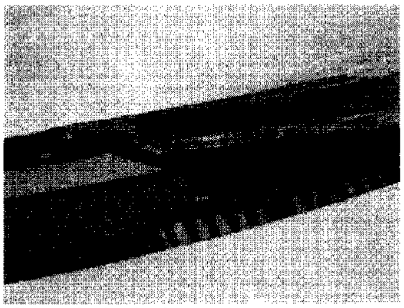
APPENDIX N

MOTOR VEHICLES

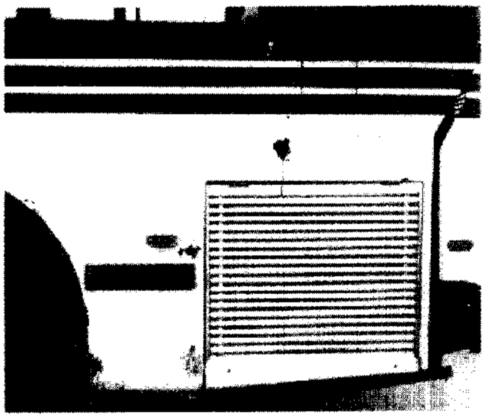


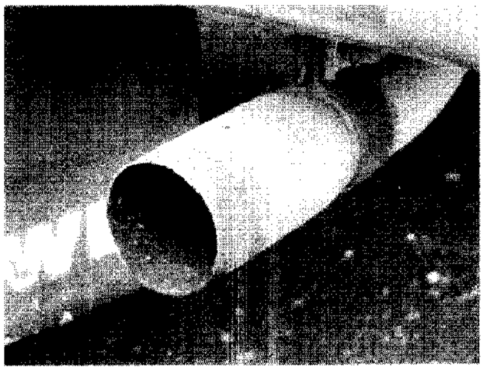

Well-maintained old-timer

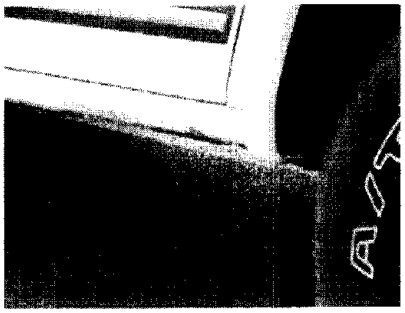

Corroded window wiper

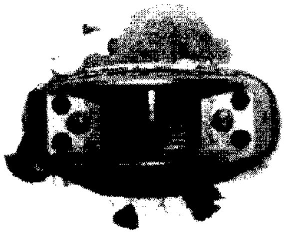

Commercial truck


Decorative coatings on recreational vehicles


Area of corrosion on a bus


Tailpipe


Corrosion under damaged coating


Corrosion at reflector


Corrosion under damaged coating

APPENDIX N

MOTOR VEHICLES

JOSHUA T. JOHNSON[1]

SUMMARY AND ANALYSIS OF RESULTS

Corrosion Control and Prevention

The corrosion-related cost to American consumers with regard to automobiles is estimated to be approximately \$23.4 billion per year. This is divided up into three components: (1) increased manufacturing cost due to corrosion-resistant materials and engineering (\$2.5 billion), (2) repairs and maintenance necessitated by corrosion (\$6.5 billion), and (3) corrosion-related depreciation (\$14.4 billion).

American consumers, businesses, and government organizations own more than 200 million registered vehicles. Assuming a value of \$5,000 for each vehicle allows an estimate that Americans have more than \$1 trillion invested in their motor vehicles, making our automobiles one of the largest investments collectively among Americans.

Until the late 1950s, corrosion of motor vehicles was a concern limited to marine environments; however, with the increased use of deicing salts, vehicles in snowbelt areas started to corrode and fall apart within years of their initial purchase. In the late 1970s, automobile manufacturers started to increase the corrosion resistance of vehicles by using corrosion-resistant materials, employing better manufacturing processes, and designing more corrosion-resistant vehicles through anti-corrosion engineering knowledge. Because of the steps taken by manufacturers, today's automobiles have very little visible corrosion, and most vehicles survive structurally until a vehicle wears out mechanically. The annual cost of corrosion in this sector, however, is substantial and more can be done to reduce this cost.

Opportunities for Improvement and Barriers to Progress

Very few opportunities exist for combating general corrosion in motor vehicles since the majority of the steps that could be taken to increase corrosion resistance have already been implemented. Motor vehicles could be made more corrosion-resistant; however, the significant cost increases would probably not be worth the small incremental benefits. As long as automakers learn from the past and the improvements made in the past 25 years are not removed, motor vehicle bodies should remain corrosion-resistant.

The few areas for improvement are in individual systems in automobiles. Automobile manufacturers have been upgrading the materials used for fuel and brake systems as well as the corrosion resistance of the electrical systems in automobiles. Many of the failures of electrical or electronic components in these systems are due to corrosion. Since the corrosion damage to these components is typically not visible, very little public outcry exists to increase the corrosion resistance beyond the slow product upgrading by the manufacturers.

Recommendations and Implementation Strategy

The most important recommendation that can be made in the automotive sector is that automobile manufacturers should not forget what made today's corrosion-resistant vehicles. To that end, every new vehicle

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[1] CC Technologies Laboratories, Inc., Dublin, Ohio.

produced should be designed to minimize corrosion, be built in a high-quality manner, and be constructed with corrosion-resistant materials where appropriate.

Current trends may force automobile manufacturers to increase the level of corrosion resistance in the electrical system and other component systems in new automobiles. One of these trends involves increasing the length of warranties on new automobiles. A second related trend is that automobiles are becoming more complex and more expensive; therefore, consumers are demanding longer life from automobiles to offset this higher cost. Better consumer understanding of the cause of electrical and other system failures may increase the pace in which these corrosion control upgrades are made; however, the competitive nature of the automobile industry ensures that the balance between corrosion resistance and cost will probably be met.

Summary of Issues

Increase consciousness of corrosion costs and potential savings.	Total cost of corrosion in the automotive sector is $23.4 billion.
Change perception that nothing can be done about corrosion.	Examine the cause of failure of electrical and other components. Convince the public that corrosion is still causing problems in automobiles.
Advance design practices for better corrosion management.	Increase the use of specialty metals in electrical systems and other components.
Change technical practices to realize corrosion cost-savings.	Continue to update technical practices based on new materials and design considerations.
Change policies and management practices to realize corrosion cost-savings.	Show management, through various studies, that small expenditures on corrosion can provide huge cost-benefits.
Advance life prediction models and performance assessment methods.	Assess the percentage of electronic component failures that are due to corrosion to determine the extent of the problem.
Advance technology (research, development, and implementation).	Use advanced alloys and materials from other industries for certain critical components.
Improve education and training for corrosion control.	Educate the public and technicians that not all corrosion on automobiles involves red rust.

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SECTOR DESCRIPTION

Background

Forty years ago, the streets and highways in the northern part of the United States were kept travelable by using abrasives and plowing to remove snow from the roads. Starting in the late 1950s, the use of sodium chloride and calcium chloride to help keep the roads clear became common in the snowbelt region of the United States. While the use of road deicing salts has allowed states and municipalities to keep roads and highways free of snow and ice and to make winter travel relatively safe, the use of deicing salts created a considerable problem for vehicle manufacturers and consumers. Before 1950, catastrophic corrosion of automobiles (i.e., corrosion damaging enough to end the life of the vehicle) was uncommon, particularly for those vehicles away from marine and coastal environments. By the 1970s, however, acid rain, the increased use of deicing salts, and thinner sheet metal in automobiles, which was used to reduce weight and increase fuel efficiency, had led to major body perforations within a few years of purchase. In the Battelle-NBS study, a significant part of the national cost of corrosion was assigned to the cost of premature replacement of personal and commercial motor vehicles.(1-2) Since the late 1970s, better designs, better materials, and better manufacturing practices have significantly increased the corrosion resistance of most motor vehicles.

As of 1995, there were more than 200 million registered vehicles on America's roads and highways.(3) These 200 million registered vehicles included 134,981,000 passenger cars, 65,465,000 trucks, 670,000 buses, and 18,195,000 trailers of various types. If each of these vehicles were assumed to have an average value of $5,000, the combined value of motor vehicles in the United States would be more than $1 trillion. This value represents one of the largest personal capital investments in the United States; therefore, the design and actual service life of these vehicles have a major impact on both personal finances and the national economy.

Corrosion Modes

Corrosion in motor vehicles is present in several different forms. The most obvious form of corrosion for vehicles is general corrosion of the painted steel body panels (see figure 1). This general corrosion can result in perforations in the body and can reduce the resale value of a vehicle due to the cosmetic effects of red rust. General corrosion also affects the underside and frame of a vehicle, leading to possible floorboard perforation and weakening of the frame.

Figure 1. Example of general corrosion of painted steel automobile body panel.

Pitting corrosion occurs when chlorides and other chemical species are in contact with metal. This can cause a corrosion reaction on a localized scale, resulting in several small, but potentially deep, pits. Pitting corrosion produces small cavities that can cause leaks in the radiator and in the muffler and tail pipe.

Galvanic corrosion occurs between dissimilar metals where one of the metals is electrochemically more active and corrodes, while the second metal is protected by the corroding metal. Galvanic corrosion was a cosmetic concern when more metal was used for trim and decoration on vehicles than is used today. Galvanic corrosion can be reduced through careful design and must be considered because of the number of different materials used in a motor vehicle.

Crevice corrosion occurs when a fluid enters a tight space between two surfaces, such as between a washer and a steel beam. This fluid can concentrate in a narrow crevice, resulting in highly accelerated corrosion in the crevice area.

Corrosion Causes

Several factors lead to the various types of corrosion in motor vehicles, specifically the design process, the manufacturing process, and the operating conditions.

Design Process

Designers of motor vehicles make a multitude of choices that influence how susceptible a vehicle may be to corrosion. During the design of the vehicle, engineers should strive to reduce dissimilar metal contacts, crevices, stresses, poor drainage, and locations where salt and dirt can build up. An example of a faulty design that allows road dirt and corrosion products to build up is shown in figure 2. The choice of materials in the design will also dramatically affect the corrosion performance of vehicles. The use of corrosion-resistant metals, coated steels, and polymers, as well as the avoidance of dissimilar metal contacts, will allow vehicles to operate for many years without significant corrosion problems. One of the most critical considerations in the design process that affects corrosion performance involves the choice of primers, paints, and sealers. The use of corrosion-resistant primers over the entire body and special chip-resistant coatings for the wheel well and the lower surface of the car have become standard in the industry in order to reduce the initiation of corrosion.

Figure 2. Photograph of poultice build-up of road contaminants in the wheel area of a bus.

Manufacturing Process

Several elements of corrosion protection added in the design phase can be rendered useless if the quality of the manufacturing is low. A few elements of the manufacturing process are of specific importance. First, the quality of the welding will affect the presence of crevices where corrosion can occur. Secondly, the surface pretreatment must be done properly to ensure good adhesion of the primer and the final coating. Finally, several of the special coatings, such as the chip-resistant coatings and the body sealants, are applied by hand and the quality of this work is highly dependent on the skill and attention of the applicator.

Operating Conditions

The corrosivity of the local environment will strongly affect the corrosion performance of the vehicle.(4-5) Figure 3 shows a map of the United States, pointing out the locations where corrosive environments are possible due to acid rain, deicing salts, or marine environments. In these corrosive environments, personal driving habits and diligent maintenance of the vehicle, such as regular washing and replacement of fluids, can have a significant effect on the reduction of corrosion.

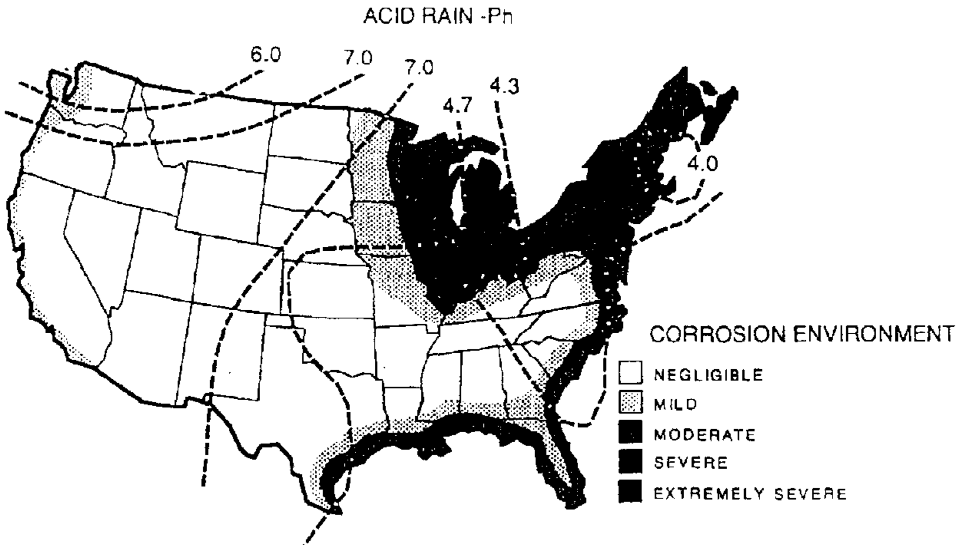


Figure 3. Level of corrosive environment and pH level due to acid rain in the United States.(4)

AREAS OF MAJOR CORROSION IMPACT

The primary cost of corrosion in the automotive sector can be broken down into three major elements:

1. The cost of corrosion engineering and materials added into the cost of new automobiles. These costs include corrosion-resistant materials such as galvanized steel and aluminum, coatings beyond what is needed for appearance, and testing of materials and designs.

2. The cost of repairs and maintenance due to corrosion. This includes the cost of repairing or replacing components of the car, such as radiators, exhaust systems, and electrical/electronic components, due to non-accident-related failures. This cost also includes the periodic

replacement of cooling fluids, which need to be changed due to the degradation of corrosion inhibitors rather than a loss of coolant function.

3. The detrimental cosmetic effects of corrosion causes reduced resale values, which often leads to premature replacement of the automobile. Corrosion damage is not likely to necessitate the replacement of a vehicle; however, the reduced value of a vehicle due to corrosion will cause major repairs such as engine or transmission replacement, which often costs more than the car's value. This leads to scrapping of automobiles that might have been worth repairing if corrosion had not occurred.

An additional cost element that was not calculated for this study is the cost due to reduced safety in automobiles due to corrosion. Deterioration of various systems in automobiles may lead to accidents or cause certain systems to be inoperable, which could lead to accidents. An example is corrosion of the electrical components of an anti-lock braking system (ABS), which can cause the system to become inoperable. If the driver was counting on the ABS system to help stop him or her on a wet road and the system was inoperable, an accident resulting in extensive damage and possible injury could result. Accidents that were caused by or influenced by corrosion have resulted in numerous injuries and many lawsuits. The resulting cost of this reduction in safety is probably an extremely high amount; however, it is nearly impossible to estimate. While an estimate was not prepared, the costs due to these incidents should be considered when justifying further corrosion resistance in automobiles.

In this sector discussion, the cost for each of the three elements above were determined in order to estimate the total cost of corrosion in the automotive sector. Element one was calculated by working with representatives from the major U.S. automakers to determine the amount spent on an average automobile for corrosion prevention. This average cost per vehicle was multiplied by the number of new motor vehicles sold annually in the United States in order to estimate the total cost.

Element two costs were determined by gathering data on the annual expenditures for replacement radiators, exhaust components, electrical/electronic components, and coolant. Estimates of what percentage of these repairs is due to corrosion were made so that the total cost of these repairs that are due to corrosion can be made.

Element three costs were determined by examining data on the value of used cars of the same make and model in different areas of the country. By comparing values in the Midwest, the Atlantic and Gulf Coasts, and the Southwest desert area, an estimate of the total depreciation due to corrosion was obtained.

Previous Cost Estimates

Several estimates of the cost of the corrosion protection built into new vehicles have been performed over the past 25 years. The Battelle-NBS study(1-2) reported that rust-resistant metals, special paint, protective coatings, and other corrosion control features added approximately $100 to the cost of a new automobile in 1975. This $100 figure represented approximately 2 percent of the cost of a new vehicle in 1975.

Special Report 235 from the Transportation Research Board (TRB), *Comparing Salt and Calcium Magnesium Acetate* (published in 1991) estimated the cost of corrosion protection built into each new automobile to protect automobiles from road salts.(6) Cost estimates per new vehicle were calculated at $250 to $800, based on the use of precoated steels and plastics, electrodeposited primers, splash shields, body and electrical sealers, special metals and coatings for the engine, ignition components and fuel systems, and special bumper supports and trim metals. An average value of $500 per vehicle represents approximately 3.5 percent of the average cost of a new vehicle in 1991.

This $500 figure can be multiplied by the number of new vehicles sold in 1991 in the United States to estimate the national cost of corrosion protection in automobiles. In 1991, approximately 8.8 million motor vehicles were sold; 5.4 million of those were cars. Thus, the total cost of corrosion, based on data from 1991, was estimated at \$4.4 billion per year (\$500 x 8.8 million).

Menzies (1991) examined the average depreciation in different regions of the country to estimate the average cost of corrosion due to road salts.(7) He compared automobiles in the North Atlantic region of the country to automobiles in the Southern Atlantic and Gulf Coast regions. This comparison was designed to ignore corrosion due to marine environments and only investigate corrosion due to road salts. By comparing the values of the same 12 vehicles, he came to an estimate of \$17 of corrosion damage per year for each vehicle in the snow belt region. Approximately 60 percent of the 200 million vehicles in the United States are in the "snow belt". By using Menzies' estimate, the cost of corrosion damage due to road salts was estimated at \$2.04 billion per year (60 percent x 200 million x \$17).

The TRB estimated that about half of the corrosion damage was due to road salts, while the other half was attributed to the effects of acid rain, marine environments, and other sources. This damage can be assumed to affect every vehicle in the country. If the average damage for non-road salt corrosion is the same as road salt corrosion, the estimate of \$17 per vehicle per year can be used. This leads to an estimate of \$3.4 billion per year.

Current Cost Estimates

Design and Manufacture

A major automobile manufacturer was approached for this project to calculate the cost of corrosion protection for an average vehicle. This cost estimate was made by identifying changes made to automobiles where corrosion was the primary factor for the change that caused a cost increase. A total of \$150 per vehicle was calculated with the largest portion of the cost being the cost of replacing plain steel with two-sided galvanized steel for all major inner and outer body panels and structural members. During the calculation, it was noted that several changes had been made to vehicles that have resulted in increased corrosion resistance; however, these changes were made primarily for other reasons, such as marketing, design, or performance. These costs were not included in the \$150 estimate.

This \$150 estimate is much lower than the \$500 estimate made during the 1991 TRB report. There are several reasons for this discrepancy. In 1991, automakers were still in the process of switching over to two-sided galvanized steel. The switch to two-sided galvanized steel was very costly because almost all aspects of the manufacturing were affected. In addition, the steel manufacturers charged a much higher price for two-sided galvanized steel at this time to cover the cost of modifying their facilities to manufacture the galvanized steel. Currently, since all of the changes have been made in the automobile factories and steel mills, the cost of using galvanized steel has dropped dramatically. Another change since 1991 is that less supplemental coating is needed to improve corrosion resistance in trouble areas. Because of improved design, fewer areas need these supplemental coatings. Improved design has also allowed manufacturers to use thinner (and lower cost) galvanizing than was used 10 years ago. Other changes, such as the use of plastic fuel tanks instead of galvanized steel, have also produced cost-savings over the past 10 years.

It is interesting to note that not only has the actual cost of corrosion protection fallen in the past 10 years, the cost of corrosion protection as a percentage of the price of a new vehicle has fallen dramatically as well. The \$150 found in this study is approximately 0.7 percent of the average price of a new automobile. The Battelle-NBS study put the cost of corrosion protection at about 2 percent of the total cost, while the 1991 TRB study found that the cost of corrosion protection was about 3.5 percent of the cost of a vehicle. Thus, the cost of corrosion protection as a function of automobile cost is the lowest it has been in more than 25 years. The two main reasons for this reduction are: (1) the price and complexity of vehicles have increased dramatically over the past decades, and (2) designers who now pay much more attention to avoiding corrosion problems and using intelligent designs dramatically reduces the need for extra coatings and other corrosion prevention additions. The end result of these changes is that today's vehicles are extremely corrosion-resistant and the cost of this protection is minimal as a percentage of the cost of a vehicle.

To evaluate the total cost of corrosion due to increased corrosion protection in automobiles, the number of new vehicles sold in 1999 can be multiplied by the $150 figure. In 1999, approximately 16.9 million motor vehicles were sold. The cost of corrosion based on the 1999 data is then $2.5 billion per year ($150 x 16.9 million).

Repair and Maintenance

Estimates from the American Automobile Manufacturers Association(3) indicate that approximately 17.5 million exhaust systems are replaced each year. Of these exhaust systems, it was estimated that 80 percent of the repairs (14 million exhaust systems) are the result of corrosion. The remaining 20 percent are replaced because of accidents or other physical impact damage. Estimates on the average cost of an exhaust system repair were obtained from several establishments that perform exhaust services. While the price of an exhaust repair can be extremely high, particularly on the more expensive cars, an estimate of $150 for the average exhaust repair/replacement was assumed. Multiplying this average cost by the number of repairs yields an annual cost of $2.1 billion (80 percent x 17.5 million x $150) due to the repair or replacement of corrosion-damaged exhaust systems.

Furthermore, estimates from the American Automobile Manufacturers Association(3) indicated that approximately 4 million radiators are replaced each year. Of these radiators, it is estimated that 50 percent, or 2 million, of the radiators are replaced due to corrosion. The other 50 percent are replaced due to front-end collisions or other damage. Estimates on the average cost of radiator replacement were obtained from several establishments, where it was found that the cost of radiator replacement could vary greatly, depending on the type of motor vehicle. An average cost of $300 per radiator was assumed. Multiplying this average by the number of repairs and replacements yields an annual cost of $600 million (50 percent x 4 million x $300).

Another aspect of corrosion repair and maintenance is the replacement of engine coolant. Manufacturers suggest that automotive coolant be replaced every 2 years, not because the coolant loses its effectiveness over time, but because the corrosion inhibitors added to the coolant lose their effectiveness over time, rendering the coolant corrosive. Taking into account that many people never change their coolant in their vehicle, or change it less often than the recommended time intervals, it was estimated that, on average, the coolant is changed every 4 years. Based on this estimate, it follows that 50 million of the 200 million vehicles will have their coolant changed every year. The cost of changing coolant is mostly a function of who performs the maintenance. Coolant flushes and fills cost approximately $40 when they are performed by a garage, while a "do-it-yourselfer" could complete the job for approximately $10. The average cost of coolant maintenance is then estimated at about $25 for each change. Multiplying the $25 cost by the 50 million cars serviced each year, an annual cost of $1.25 billion was estimated as the cost of corrosion due to coolant replacement.

A final aspect of repair and maintenance costs due to corrosion is in the area of corrosion damage to electrical components and electronics in an automobile. According to the Freedonia Group, the average automobile manufactured in 1997 contained $1,796 worth of electronics.(8) This amount is expected to grow to more than $2,400 worth of electronics per car by the year 2002. When older vehicles were considered, the average vehicle contained $1,406 worth of electronics in 1997. When multiplied by the 200 million vehicles in the country, it is estimated that $281 billion worth of electronics are present in automobiles.

Experts in automotive electronics indicate that almost all electronic failures are caused by corrosion, not by damage to the vehicle from an accident. The value of these failures is difficult to measure because, in most instances, corrosion is not recognized as the cause of the failure. If corrosion attacks a control board in a modern vehicle, the contacts in the circuit board could easily be destroyed and the board would require replacement. These boards, however, are not examined for the cause of failure, as the corrosion causing the failure would be microscopic in nature. Instead, the board is just replaced and the vehicle owner has no idea that corrosion caused the problem. Another difficulty in calculating the cost due to replacement of corroded electronics is that vehicle makers do not have information available on how many electrical components need to be replaced each year.

Due to the difficulties in obtaining accurate figures on the cost of corrosion of electrical devices in vehicles, an estimate was made by making a number of assumptions. The assumptions were discussed with experts in the automotive electronics field and were considered reasonable. The first assumption was that 50 percent of the failures in electronics were due to corrosion, with the remainder due to accidents and other damage to the electrical system. The second assumption made was that each vehicle, on average, undergoes $25 of electrical repairs per year. While many vehicles will not have an electrical failure during their lives, some repairs, such as repairing the control board for a dashboard system, can cost hundreds of dollars. Combining these assumptions with the 200 million vehicles in the country leads to a cost of $2.5 billion (50 percent x 200 million x $25) due to corrosion of electronics.

In summary, the estimated cost of corrosion due to repair and maintenance of exhaust systems, radiators, engine coolant systems, and automotive electronics was calculated to be $6.45 billion.

Cosmetic Damage

To assess the cost of corrosion due to cosmetic damage and depreciation, a study was conducted on the prices of used vehicles in different areas of the country, similar to the study performed by Menzies.(7) In 1999, 10 different passenger vehicles were used for this study to obtain a good representation of the U.S. vehicle fleet. The 10 vehicles investigated were the Honda Accord four-door LX, Chevrolet S10 Blazer, Chevrolet Lumina, Ford Taurus LX, Ford Escort LX hatchback, Dodge Grand Caravan LE, Toyota Corolla four-door LE, Buick Park Avenue, Pontiac Grand Am two-door SE, and the Volkswagen Jetta GL. Price estimates were made assuming typical equipment levels and mileage of 19,093 km (10,000 mi) per year. The 1999 price information was found for the following six different cities in different geographic areas: Boston, MA; Bangor, ME; Chicago, IL; Miami, FL; Las Vegas, NV; and Phoenix, AZ. By comparing the vehicle values in the marine and snowbelt environments with those in desert environments, a cost difference between the two areas could be calculated. This value difference can be assumed to be due to corrosion. An estimate for the total cost due to depreciation can be done based on the number of vehicles. Automobile model years from 1990 to 1996 were studied for each of the 10 vehicles in each of the markets to obtain the average amount of depreciation due to corrosion.

The results of the study for each vehicle are presented in table 1, where some cost observations were made based on the data. The average depreciation due to corrosion in the high corrosion areas (i.e., Boston and Bangor), where both marine conditions were prevalent and road salt was used, was $141.09 per vehicle per year. In the areas where either road salt (Chicago) or marine conditions (Miami) existed, the average cost of corrosion was $109.11 per vehicle per year. Using these averages and the fact that 20 percent of the vehicles in the United States are in the high corrosion areas and 40 percent of the vehicles are in the lower corrosion areas, an annual cost of corrosion of $14.4 billion was estimated [(40,000,000 vehicles x $141.09 per vehicle) + (80,000,000 vehicles x $109.11 per vehicle)]. This value appears to be much higher than the value that Menzies estimated. Menzies compared Northern Atlantic areas to Southern Atlantic areas to get an estimate of $17 per car due to road salt. Comparing the high corrosion areas to the lower corrosion areas in this study would be the same as the comparison that Menzies made. This comparison yielded a difference of $31.98, which, if present day values are considered, is very similar to the value that Menzies found.

Table 1. Results of used automobile value survey.

Honda Accord 4D LX

RESALE VALUE IN U.S. DOLLARS				PERCENTAGE CHANGE BETWEEN	
MODEL YEAR	BOSTON AND BANGOR	CHICAGO AND MIAMI	LAS VEGAS AND PHOENIX	BOSTON/BANGOR & LAS VEGAS/PHOENIX	CHICAGO/MIAMI & LAS VEGAS/PHOENIX
90	3,475	3,475	4,175	-16.77	-16.77
91	4,325	4,325	5,125	-15.61	-15.61
92	5,250	5,250	6,175	-14.98	-14.98
93	6,100	6,150	7,125	-14.39	-13.68
94	7,250	7,425	8,150	-11.04	-8.90
95	8,600	9,050	9,625	-10.65	-5.97
96	10,250	10,625	11,300	- 9.29	-5.97

Chevrolet S10 Blazer

RESALE VALUE IN U.S. DOLLARS				PERCENTAGE CHANGE BETWEEN	
MODEL YEAR	BOSTON AND BANGOR	CHICAGO AND MIAMI	LAS VEGAS AND PHOENIX	BOSTON/BANGOR & LAS VEGAS/PHOENIX	CHICAGO/MIAMI & LAS VEGAS/PHOENIX
90	2,625	2,625	3,200	-17.97	-17.97
91	4,195	4,195	4,970	-15.59	-15.59
92	5,190	5,190	6,065	-14.43	-14.43
93	6,185	6,235	7,160	-13.62	-12.92
94	7,160	7,335	7,985	-10.33	-8.14
95	10,970	11,495	12,195	-10.05	-5.74
96	12,445	12,845	13,520	-7.95	-4.99

Ford Taurus LX

RESALE VALUE IN U.S. DOLLARS				PERCENTAGE CHANGE BETWEEN	
MODEL YEAR	BOSTON AND BANGOR	CHICAGO AND MIAMI	LAS VEGAS AND PHOENIX	BOSTON/BANGOR & LAS VEGAS/PHOENIX	CHICAGO/MIAMI & LAS VEGAS/PHOENIX
90	2,170	2,170	2,620	-17.18	-17.18
91	2,770	2,770	3,345	-17.19	-17.19
92	3,395	3,395	4,095	-17.09	-17.09
93	4,195	4,245	4,945	-15.17	-14.16
94	5,215	5,365	5,890	-11.46	-8.91
95	6,295	6,545	7,120	-11.59	-8.08
96	7,395	7,695	7,995	-7.50	-3.75

Table 1. Results of used automobile value survey (continued).

Ford Escort LX

RESALE VALUE IN U.S. DOLLARS				PERCENTAGE CHANGE BETWEEN	
MODEL YEAR	BOSTON AND BANGOR	CHICAGO AND MIAMI	LAS VEGAS AND PHOENIX	BOSTON/BANGOR & LAS VEGAS/PHOENIX	CHICAGO/MIAMI & LAS VEGAS/PHOENIX
90	1,015	1,015	1,265	-19.76	-19.76
91	1,225	1,225	1,600	-23.44	-23.44
92	1,915	1,915	2,365	-19.03	-19.03
93	2,365	2,415	2,940	-19.56	-17.86
94	3,040	3,140	3,515	13.51	-10.67
95	3,825	4,010	4,285	-10.74	-6.42
96	4,710	4,960	5,135	-8.28	-3.41

Pontiac Grand Am 2D SE

RESALE VALUE IN U.S. DOLLARS				PERCENTAGE CHANGE BETWEEN	
MODEL YEAR	BOSTON AND BANGOR	CHICAGO AND MIAMI	LAS VEGAS AND PHOENIX	BOSTON/BANGOR & LAS VEGAS/PHOENIX	CHICAGO/MIAMI & LAS VEGAS/PHOENIX
90	2,060	2,060	2,485	-17.10	-17.10
91	2,545	2,545	3,095	-17.77	-17.77
92	2,595	2,595	3,170	-18.14	-18.14
93	3,265	3,315	3,915	-16.60	-15.33
94	3,820	3,945	4,395	-13.08	-10.24
95	5,130	5,355	5,680	-9.68	-5.72
96	6,280	6,555	6,805	-7.71	-3.67

Chevrolet Lumina

RESALE VALUE IN U.S. DOLLARS				PERCENTAGE CHANGE BETWEEN	
MODEL YEAR	BOSTON AND BANGOR	CHICAGO AND MIAMI	LAS VEGAS AND PHOENIX	BOSTON/BANGOR & LAS VEGAS/PHOENIX	CHICAGO/MIAMI & LAS VEGAS/PHOENIX
90	1,055	1,055	1,430	-26.22	-26.22
91	1,465	1,465	1,940	-24.48	-24.48
92	1,990	1,990	2,590	-23.17	-23.17
93	2,665	2,690	3,315	-19.61	-18.85
94	3,610	3,760	4,335	-16.72	-13.26
95	5,315	5,565	5,965	-10.90	-6.71
96	6,640	6,940	7,240	-8.29	-4.14

Table 1. Results of used automobile value survey (continued).

Dodge Grand Caravan LE

RESALE VALUE IN U.S. DOLLARS				PERCENTAGE CHANGE BETWEEN	
MODEL YEAR	BOSTON AND BANGOR	CHICAGO AND MIAMI	LAS VEGAS AND PHOENIX	BOSTON/BANGOR & LAS VEGAS/PHOENIX	CHICAGO/MIAMI & LAS VEGAS/PHOENIX
90	3,000	3,000	3,575	-16.08	-16.08
91	3,900	3,900	4,600	-15.22	-15.22
92	4,750	4,750	5,575	-14.8	-14.80
93	5,840	5,890	6,740	-13.35	-12.61
94	6,985	7,160	7,935	-11.97	-9.77
95	8,575	8,850	9,375	-8.53	-5.60
96	12,490	12,940	13,615	-8.26	-4.96

Toyota Corolla 4D LE

RESALE VALUE IN U.S. DOLLARS				PERCENTAGE CHANGE BETWEEN	
MODEL YEAR	BOSTON AND BANGOR	CHICAGO AND MIAMI	LAS VEGAS AND PHOENIX	BOSTON/BANGOR & LAS VEGAS/PHOENIX	CHICAGO/MIAMI & LAS VEGAS/PHOENIX
90	2,225	2,225	2,700	-17.59	-17.59
91	2,775	2,775	3,375	-17.78	-17.78
92	3,375	3,375	4,100	-17.68	-17.68
93	5,090	5,115	5,915	-13.95	-13.52
94	6,165	6,315	6,990	-11.80	-9.66
95	7,305	7,555	8,180	-10.70	-7.64
96	8,325	8,650	8,975	-7.24	-3.62

Volkswagen Jetta GL

RESALE VALUE IN U.S. DOLLARS				PERCENTAGE CHANGE BETWEEN	
MODEL YEAR	BOSTON AND BANGOR	CHICAGO AND MIAMI	LAS VEGAS AND PHOENIX	BOSTON/BANGOR & LAS VEGAS/PHOENIX	CHICAGO/MIAMI & LAS VEGAS/PHOENIX
90	1,950	1,950	2,450	-20.41	-20.41
91	2,375	2,375	2,950	-19.49	-19.49
92	3,200	3,200	3,800	-15.79	-15.79
93	4,175	4,200	4,925	-15.23	-14.72
94	5,150	5,325	5,850	-11.97	-8.97
95	7,020	7,420	7,870	-10.80	-5.72
96	8,120	8,420	8,770	-7.41	-3.99

Table 1. Results of used automobile value survey (continued).

Buick Park Avenue

RESALE VALUE IN U.S. DOLLARS				PERCENTAGE CHANGE BETWEEN	
MODEL YEAR	**BOSTON AND BANGOR**	**CHICAGO AND MIAMI**	**LAS VEGAS AND PHOENIX**	**BOSTON/BANGOR & LAS VEGAS/PHOENIX**	**CHICAGO/MIAMI & LAS VEGAS/PHOENIX**
90	2,250	2,250	2,725	-17.43	-17.43
91	4,320	4,320	5,095	-15.21	-15.21
92	5,415	5,415	6,315	-14.25	-14.25
93	6,640	6,690	7,690	-13.65	-13.00
94	8,190	8,365	9,315	-12.08	-10.20
95	10,065	10,390	11,215	-10.25	-7.36
96	12,190	12,540	13,265	-8.10	-5.47

Summary

Totaling the costs for new vehicle corrosion protection ($2.5 billion) plus corrosion-based repairs ($6.45 billion) plus corrosion depreciation ($14.4 billion) leads to an estimate of the cost of corrosion in automobiles of $23.4 billion dollars per year. The Battelle-NBS study estimated the cost of corrosion in automobiles at $6 billion, where $1 billion is attributed to new automobiles and $5 billion is attributed to used vehicles. The current estimate reflects how much more protection vehicle manufacturers are putting into new vehicles than was done 25 years ago. While the cost of corrosion in automobiles has increased in terms of straight dollar figures, there are approximately 55 percent more motor vehicles on the road today than in 1975. In addition, the average cost of a new vehicle is significantly higher today than in 1975 due to inflation and the increased complexity of motor vehicles. Considering these factors, the percentage of the gross domestic product (GDP) due to motor vehicle corrosion has decreased from 0.37 percent in 1975 to 0.27 percent in 1998.

CORROSION MANAGEMENT ASSESSMENT

The automobile industry, for the most part, has become one of the major success stories in corrosion engineering management over the past 25 years. While the total cost of corrosion is quite high, the decrease in cost, as a percentage of GDP, indicates the success of the industry in controlling both corrosion and the cost of preventing corrosion. The observation that the average cost of protecting a vehicle has fallen from $500 to $150, while providing a corrosion-resistant vehicle, attests to proper corrosion management practices. The product changes between 1975 and 2000 that led to increased corrosion protection are documented below. The most important change in the industry, however, is the integrated systems approach to total vehicle corrosion protection. Since 1975, the manufacturers have created a coordinated and balanced effort between advances in design, materials, and processing. As long as the lessons learned over the years are applied and a proper design is used with the appropriate materials and processing, vehicles should remain highly corrosion-resistant for years to come.

CHANGES FROM 1975 TO 2000

Extensive changes and advances have taken place since 1975 in several different areas in terms of increasing the corrosion performance of motor vehicles.(9) These changes can be broken down into materials, processing, and design. The end result of these advances are illustrated in figures 4 and 5. Figure 4 shows the change in the mean and median ages of automobiles from 1970 to 1994. The figure shows that there has been a consistently increasing average age of automobiles since 1970, with the mean age increasing from 5.6 years to 8.4 years and the median age increasing from 4.9 to 7.5 years. This trend is also shown in figure 5, which shows the percentage of vehicles remaining in service as a vehicle model year ages. Five model years are examined. They are 1966, 1971, 1976, 1981, and 1986. It can be clearly seen that the 1966 and 1971 automobiles showed the worst performance, while the 1976 and 1981 model years were improved, and the first 9 years of performance of the 1986 vehicles were better yet. The performance of the vehicles manufactured in the 1990s will probably be better yet due to the significant improvements that have been made over the past 25 years. The increased corrosion protection lifetime can also be demonstrated by table 2, which lists the length of the corrosion warranty for automobiles sold in the United States. The American Motor Company (AMC) offered the first 3-year warranty against perforation in the U.S. market in 1977. Today, almost every manufacturer offers at least a 5-year/100,000-mile warranty. One particular manufacturer (Audi) even offers a 12-year/unlimited mileage warranty against corrosion perforation. This increase in warranty length over the past 25 years is a clear indication of the confidence the manufacturers have in producing a corrosion-resistant vehicle.

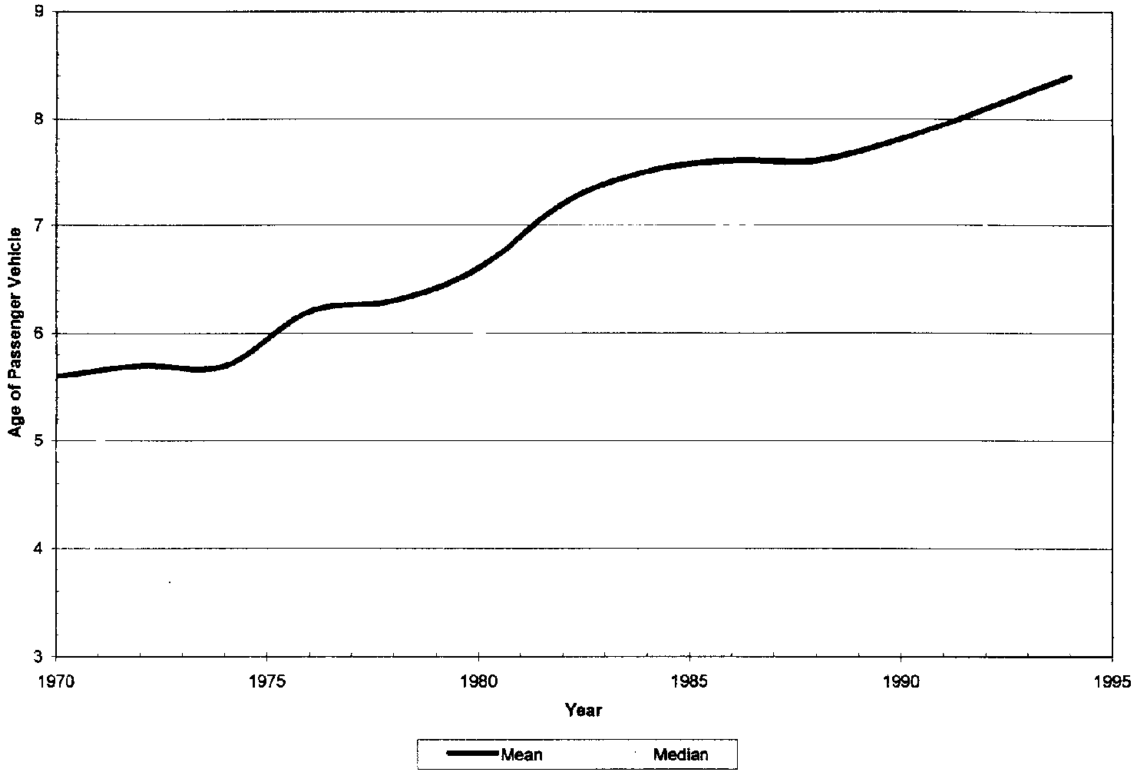


Figure 4. Average mean and median ages of passenger vehicles from 1970 to 1994.

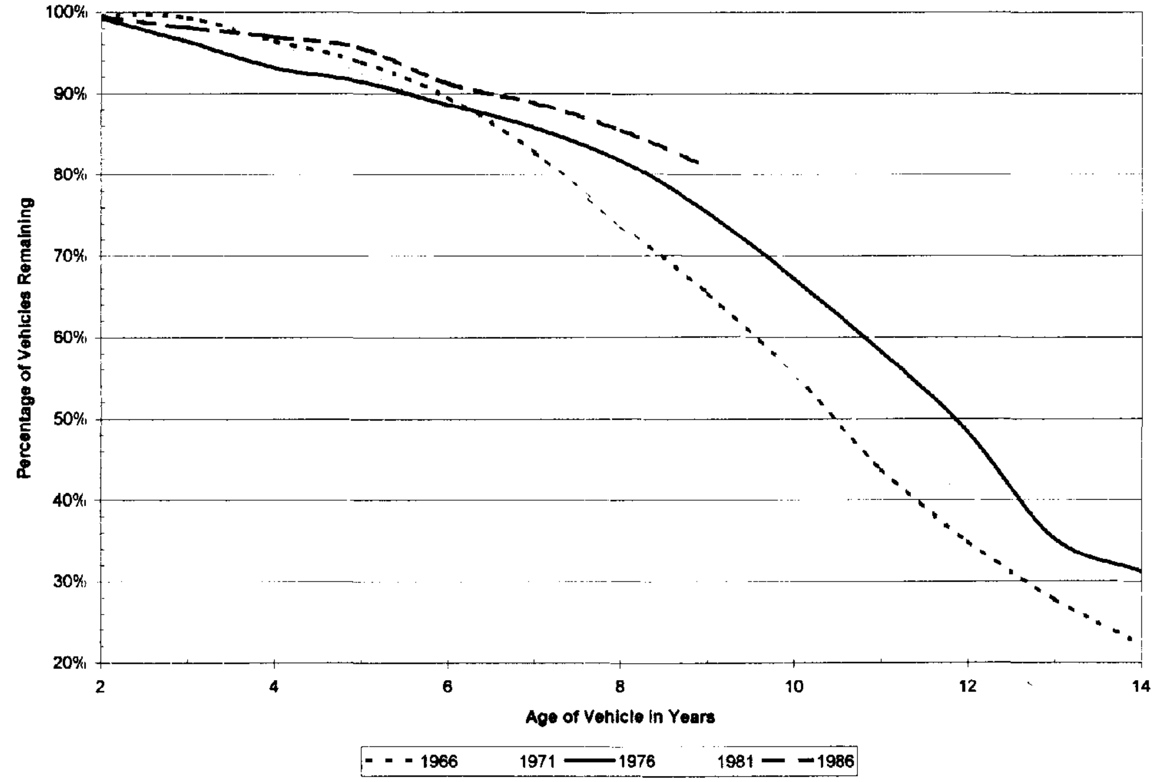


Figure 5. Percentage of vehicles remaining for the first 14 years of service for five different model years.

Table 2. Length of corrosion perforation warranties on model year 2000 automobiles sold in the United States.

MAKE	LENGTH OF WARRANTY		MAKE	LENGTH OF WARRANTY	
	YEARS	MILES		YEARS	MILES
Acura	5	Unlimited	Lincoln	5	Unlimited
Audi	12	Unlimited	Mazda	5	Unlimited
BMW	6	Unlimited	Mercedes-Benz	4	50,000
Buick	6	100,000	Mercury	6	Unlimited
Cadillac	6	100,000	Mitsubishi	7	100,000
Chevrolet	6	100,000	Nissan	5	Unlimited
Daewoo	5	Unlimited	Oldsmobile	6	100,000
Dodge	5	100,000	Plymouth	5	100,000
Ford	5	Unlimited	Pontiac	6	100,000
GMC	6	100,000	Porsche	10	Unlimited
Honda	5	Unlimited	Saab	6	Unlimited
Hyundai	5	Unlimited	Saturn	6	100,000
Infiniti	7	Unlimited	Subaru	5	Unlimited
Isuzu	6	100,000	Suzuki	3	100,000
Jaguar	6	100,000	Toyota	5	Unlimited
Kia	5	100,000	Volkswagen	6	Unlimited
Land Rover	6	100,000	Volvo	8	Unlimited
Lexus	6	Unlimited			

1 mi = 1.61 km

Materials

The most important change in materials over the past 25 years has been the transition from uncoated mild steel to zinc pre-coated steel and other corrosion-resistant metals. The first pre-coated steels used in the motor vehicle industry were hot-dip galvanized steels. These steels had good corrosion resistance, but they had a spangled surface, which resulted in a poor appearance after painting. Because of the painted appearance, these steels were only used in less visible areas of the car. Hot-dip galvanized steel is still used on most body structural members and the interior surface of major body outer panels.

Electrogalvanized steels became available in the mid-1970s. Once manufacturing capacity increased by the mid-1980s, most exterior body panels were made of electrogalvanized steel. Electrogalvanized steel is coated on both sides so it protects the panel from both cosmetic and perforation corrosion. The zinc coating is also smooth enough so that the steel may be painted after proper surface preparation is performed.

Some new pre-coated steel utilized what is referred to as a composite or "piggyback" coating. In these coatings, a thin layer of zinc or zinc alloy is applied to the steel and an organic barrier coating is applied over the zinc on the inside surface. These steels have the cosmetic corrosion protection of electrogalvanized steel and the increased perforation corrosion resistance because of the barrier coating.

Over the past 25 years, another change in materials has been the increased use of aluminum alloys as a replacement for steel. The benefit of using aluminum alloys in place of steel is twofold. First, aluminum alloys are much lighter than steel. Secondly, aluminum alloys are more corrosion-resistant. Aluminum alloys have seen limited use as a hood and rear deck lid material in the past because of the cost and strength of these materials as compared to steel. New designs and aluminum alloys have allowed at least two automobiles to be made entirely from aluminum, including the frame.

Polymers have also seen increased use, replacing steel as body panels. Polymer panels are corrosion- and dent-resistant, making them attractive to consumers. However, the automobiles must be designed to use the polymer panels, since the panels do not aid in the structural rigidity of the automobile.

Stainless steel use has increased over the past 25 years. Most of the exhaust system uses stainless steel or aluminized stainless steel for corrosion resistance. Increasingly, fuel systems have been made of galvanized or stainless steel.

The results of all of these changes in materials are summarized in table 3. This table shows the average weight of each material and the percentage of the automobile made of each material for a typical family car in 1978, 1985, and 1996. The table shows that the percentages of regular steel and iron have been reduced from 67.9 percent of a 1978 vehicle to 55.5 percent of a 1996 vehicle. The use of high-strength steel, stainless steel, plastics, aluminum, and copper, on the other hand, has dramatically increased from 1978 to 1996. These materials have replaced mild steels for greater strength, weight reduction, and corrosion resistance.

The demands on materials, due to the increased temperature and more aggressive conditions created by today's higher performance automobiles, have led to a new trend in the automotive industry. Automakers have started to turn to very expensive, high-performance alloys for some of the critical components in today's automobiles. An example of this is the flexible couplings used in exhaust systems. In order to achieve higher engine efficiency and lower emissions, the exhaust operating temperature has been increased over the years as corrosion rates have increased dramatically with temperature increases. Because of these temperature increases, the materials that have been used for flexible couplings (mostly stainless steel) are failing before the 10-year/100,000-mile warranties that most exhaust systems come with. The high temperatures and the high salt concentrations, along with the movement of the flexible couplings, have led to failures due to fatigue, corrosion fatigue, hot salt attack, chloride stress corrosion cracking, pitting, and general corrosion in 316 and 321 grades of stainless steel. To combat this attack, automakers have started to use nickel-based super-alloys such as Inconel® alloy 625LCF® and Incoloy® alloy 864™.

These alloys, while often more expensive than stainless steel, have shown excellent resistance to corrosion attack in the modern automotive exhaust environment.

Table 3. Weight of material in a typical family vehicle, 1978 to 1996.

MATERIAL	**1978**		**1985**		**1996**	
	Weight (lb)	**% of car**	**Weight (lb)**	**% of Car**	**Weight (lb)**	**% of Car**
Regular Steel	1,915	53.6	1,485	46.5	1409	43.5
High- and Medium-Strength Steel	133	3.7	217.5	6.8	287	8.9
Stainless Steel	26	0.7	29	0.9	46.5	1.4
Other Steels	55	1.5	54.5	1.7	38.5	1.2
Iron	512	14.3	468	14.7	389	12.0
Plastics and Plastic Composites	180	5.0	211.5	6.6	245	7.6
Aluminum	112.5	3.2	138	4.3	195.5	6.0
Copper and Brass	37	1.0	44	1.4	45	1.4
Powder Metal Parts	15.5	0.43	19	0.60	29.5	0.91
Zinc Die Castings	31	0.87	18	0.56	15.5	0.48
Magnesium Castings	1	0.03	2.5	0.08	5.5	0.17
Fluids and Lubricants	198	5.5	184	5.8	197.5	6.1
Rubber	146.5	4.1	136	4.3	139	4.3
Glass	86.5	2.4	85	2.7	94	2.9
Other Materials	120.5	3.4	99	3.1	99.5	3.1
TOTAL	**3,569.5**	**99.73%**	**3,187.5**	**100.4%**	**3,236**	**100.4%**

Source: *American Metal Market*, copyright 1996. Capital Cities Media Inc. 1 lb = 0.454 kg

The automotive industry has found several other applications where the additional cost of specialty metals may be worth the benefit gained. These areas include manifolds and tailpipes, catalytic converters, high-temperature fasteners, exhaust valves, airbag inflators, and other critical electrical components. The future use of these materials will depend on the benefits found in service and the changes in automotive technology that affect the corrosion conditions that automobiles encounter.

Processing

Many improvements have been made over the past two decades in the way that vehicles are finished. The first step in the finishing of a vehicle is the clean/phosphate process. During this step, the vehicle parts are treated in a mixture of zinc, phosphoric acid, and some proprietary additives to clean the surface for paining and leave a very thin layer of zinc phosphate coating. A better understanding and control of the bath parameters have allowed improvement of these coatings for better corrosion resistance and paint adhesion. Systems have also been optimized for vehicles with mixed-material bodies, such as aluminum, coated steel, and plastic.

The second step in the finishing process is the application of primer paint. Before 1975, all body paints were applied with air-spray atomizers. This method gave a good finish on the exterior of the car, but the interior area often received no coverage, which led to corrosion-prone areas. In 1976, PPG Industries introduced a cathodic electrodeposition (ELPO) primer process. This method ensured that every location on a primed part would be coated. Other advances in primer technology include using thicker "high-build" primers for increased corrosion protection and flaw-hiding capabilities.

The third step in the finishing process is body sealing and augmentation coatings. Vehicles have their body joints and exposed flanges sealed to reduce cosmetic and perforation corrosion. In the past, the work of sealing was done manually and was sensitive to the proficiency of the operator. Over the past 25 years, the sealing process has become a robotic operation to ensure the quality of the sealing job. Several augmentation coatings have been developed over the past 25 years to increase corrosion protection in particular areas of the vehicle. Among these are the anti-chip plastisols and urethane coatings that are applied in the rear of the wheel house before final painting. A second augmentation coating is the use of waxes applied to the interior body cavities. The earliest versions of these waxes were added by after-market rust-proofing companies using a handheld airless probe spray. Later, manufacturers started using waxes and applying them using automated wax coverage. These methods were less prone to operator error and increased the rust-through corrosion resistance.

The final step in the finishing process is the application of the topcoat. The topcoat is applied for cosmetic reasons and has little effect on the corrosion performance of the vehicle. There still have been advancements over the past 25 years that have led to better overall paint system performance. The use of robotic processing and control equipment has resulted in more uniform paint coverage and superior performance. Simplified vehicle design and optimization of the paint process have resulted in increased finish quality, which, in turn, increases corrosion resistance.

Design

Over the past 25 years, vehicle engineers have improved their designs to reduce the extent of corrosion. The designers have tried to remove crevices and locations where salt and soil can build up. Another concern of designers has been the removal of as many dissimilar metal contacts as possible. The number of "nose over" hoods, hood louvers, tuck-under areas, and other design features that promote chipping and corrosion have been reduced.

These changes, as well as the material and process changes, have greatly increased the corrosion resistance of American vehicles. Currently, vehicles in high-corrosion areas are driven 6 or more years with no signs of corrosion, compared to the 2 to 3 years common in the mid-1970s.

CASE STUDY

SAE Parking Lot Surveys

Introduction

While most observers and car owners would agree that automobiles have become much more corrosion-resistant over the past 25 years, it may be difficult to quantify the level of improvement. It may also be difficult to determine which of the changes made by automakers had the greatest effect on corrosion prevention and which changes had lesser effects. The Body Division of the Automotive Corrosion and Prevention (ACAP) Committee of the Society of Automotive Engineers (SAE) started a series of studies in 1985 to help quantify the improvements made in corrosion protection. These studies, along with information from the automakers on when corrosion-based improvements were made, can be used to determine the level of benefits resulting from the various changes made by automakers.

These studies were started in 1985 and consisted of biannual surveys of automobile body corrosion of vehicles in two college parking lots in Detroit. The survey consisted of checking approximately 20 body panels on each automobile for perforations, blisters, and surface rust. Five- and six-year-old automobiles were selected in the parking lots for study (the year of the automobile was determined from the vehicle identification plate found on the top of the dashboard of every vehicle). The vehicle sample size for each survey was between 200 and 800 vehicles.

The initial study was conducted in 1985 on 1980 and 1981 model year vehicles. All of the surveys were conducted in the fall, because the average age of the 1980 vehicles was 6 years old and the 1981 vehicles averaged 5 years old. Five- and Six-year old vehicles were selected for study for two main reasons. First, most corrosion prevention systems used by automakers would show some sign of failure at this point. Second, very few vehicles would have been scrapped due to corrosion or other causes within 5 or 6 years.

The surveys were performed by individuals from the ACAP committee from SAE using clear plastic grids to measure the size of any perforations, blisters, or surface rust found. Because these surveys were done in parking lots, without the owner present, no investigation was performed on the interior body panels of the car. Only visual defects that could be seen without disturbing the car were tallied. Along with the number, type, and size of the corrosion defects, the investigators recorded the vehicle identification number (VIN), mileage, and whether there was any evidence of rust-proofing or repainting done on the automobile.

Survey Results

Figure 6 shows the overall trends in blisters, perforations, and surface rust found during the 10 years covered by the survey period. Except for the anomaly between the third and fourth survey (SAE believed that the data from the third survey might have been skewed lower), the survey results indicate a consistent improvement in each type of defect. Significant reductions are seen in many of the areas, including a decrease in perforations from 20 percent in the first survey to 3 percent in the fifth survey. A decrease from 61 percent to 38 percent was seen in blistering and a decrease from 78 percent to 50 percent was seen in surface rust between the first and fifth surveys.

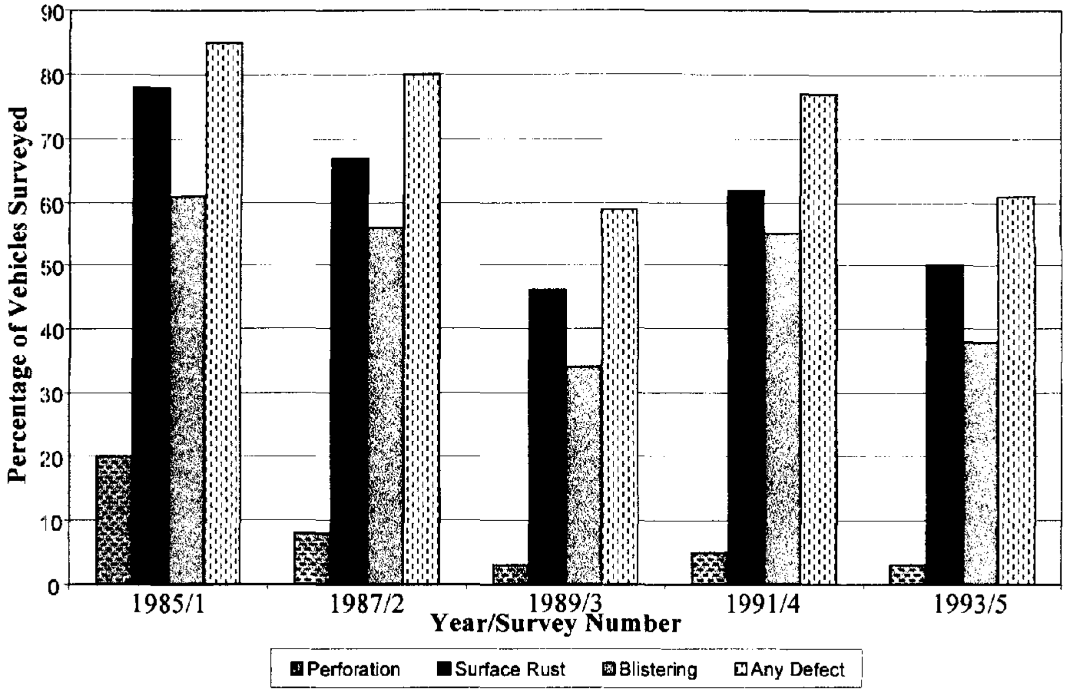


Figure 6. Percentage of vehicles with various types of corrosion defects for each of the five SAE ACAP surveys.

SAE was also able to correlate some of their results with automotive industry trends. One of the major areas examined was the change of materials used for panels. Prior to the 1980 model year, most vehicle body panels were made of uncoated carbon steel. Over the model years that the survey covered (1989-1999), major changes in manufacturing occurred. The first improvement was the use of pre-coated steel, which is steel that has a zinc-rich primer on the interior. These coatings gave way to steels that were coated on one side with zinc or a zinc alloy. Finally, automakers went to two-sided coated steel, which is used on almost all automobiles manufactured in the United States today.

The effect of these changes in materials was found to be dramatic. Figure 7 shows the average surface area of rust found on five major body panels that were either carbon steel, steel pre-painted with zinc-rich primer, or steel coated with zinc/zinc alloy. The data were from the 5- and 6-year-old vehicles surveyed in 1985 and 1993. The data clearly show that the amount of surface rust decreased dramatically when coated steels were used in place of plain carbon steels. This effect is further shown in figure 8, which shows the average number of perforations per automobile panel for the carbon steel, pre-painted, and zinc/zinc alloy-coated steel panels. The figure shows the superiority of pre-painted steel over plain carbon steel and that zinc/zinc alloy-coated steel is better. The SAE study did not differentiate between the two-sided and the one-sided zinc/zinc alloy-coated steel. It is likely that the two-sided steel would have resulted in an even higher performance.

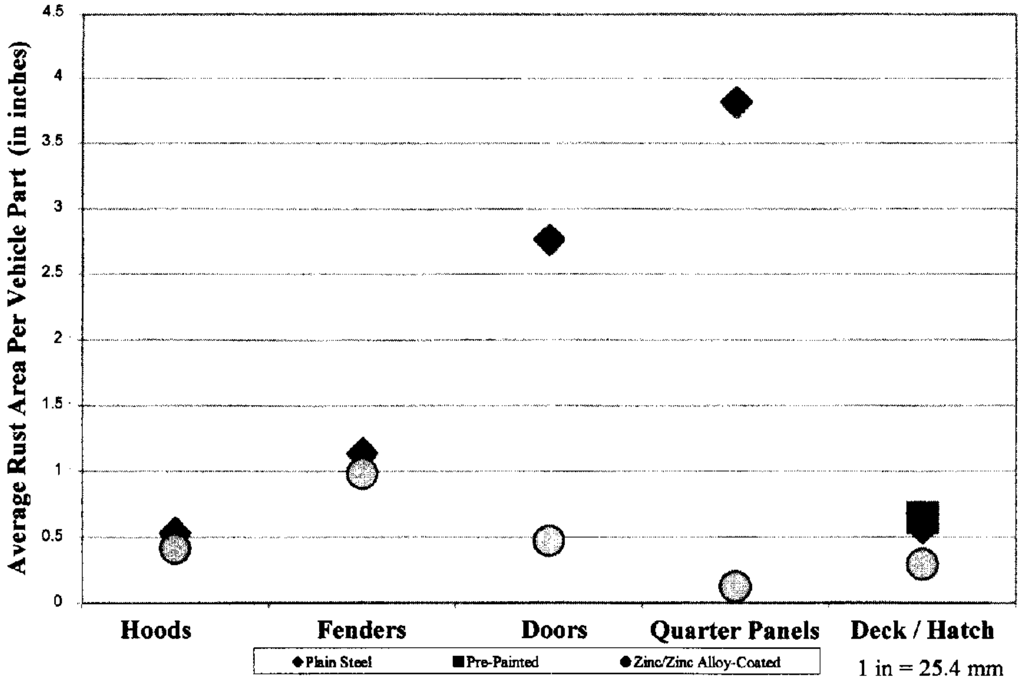


Figure 7. Average area of surface rust found on five different automobile body panels, comparing plain steel, pre-painted steel, and zinc/zinc alloy-coated steel.

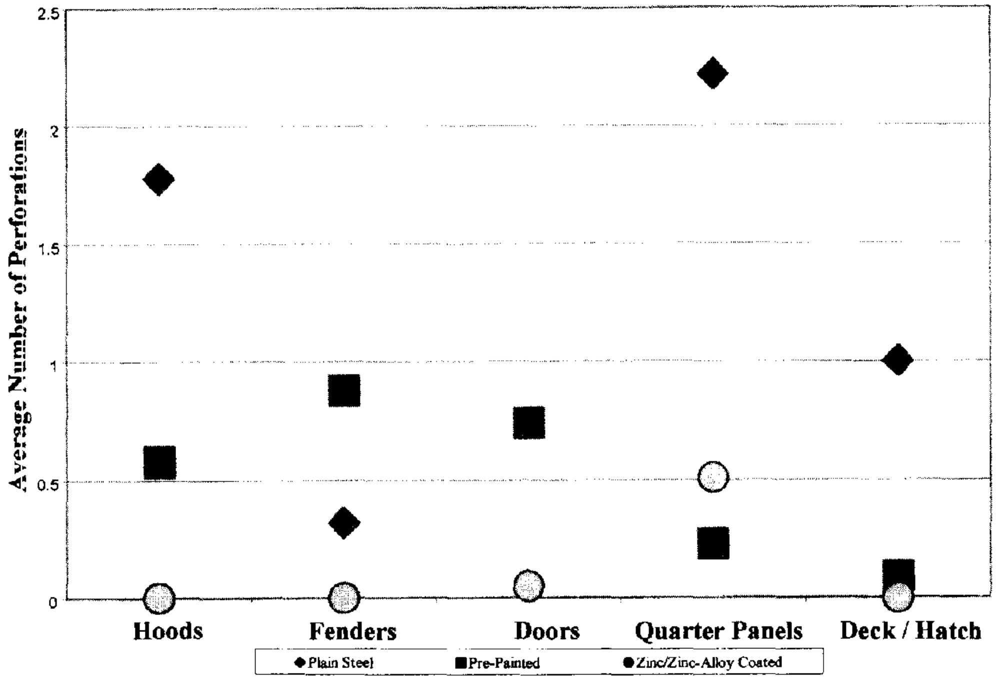
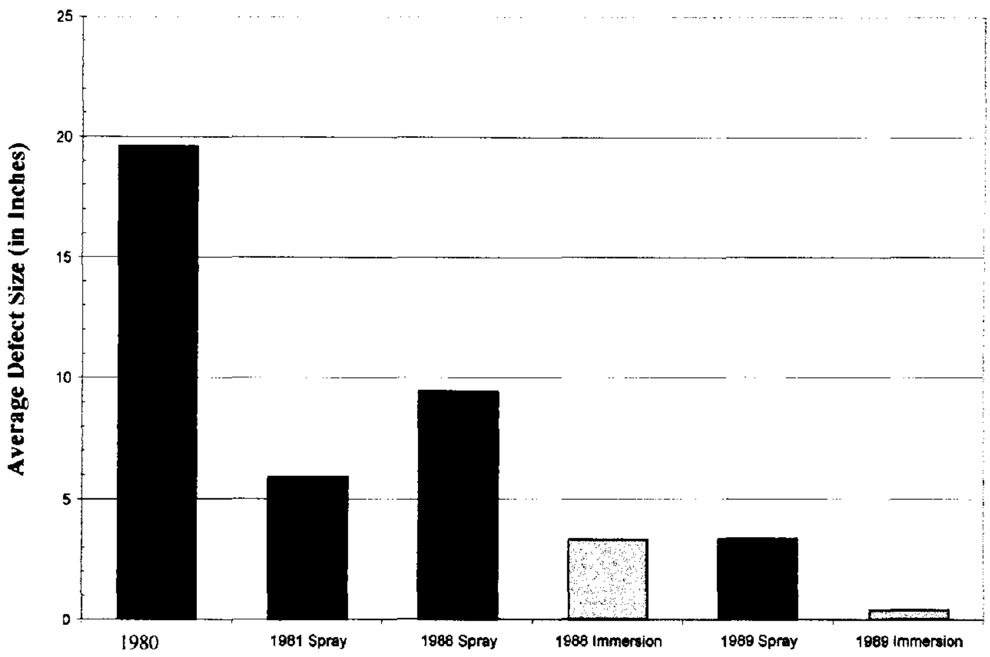


Figure 8. Average number of perforations found on five different automobile body panels, comparing plain steel, pre-painted steel, and zinc/zinc alloy-coated steel.

In terms of corrosion resistance, another major change made by automobile manufacturers in 1980 was the improvement made in the phosphating process. During the 1980s, the composition of the phosphate baths changed with the addition of manganese, nickel, and zinc to the baths, resulting in improved coating performance and corrosion resistance. A second major change in phosphating came with the change from spray systems to immersion systems. The immersion system allowed for more even coverage, as well as the ability to coat the entire surface, as compared to spray systems that could not reach tight spaces or interior locations. The changes in the chemical composition proved to be too difficult to evaluate because of the multiple changes and because the make-up of each manufacturer's bath is proprietary and difficult to track. It is possible, however, to examine the difference between the spray and the immersion systems.

All of the cars in the first study in 1985 were phosphated using the spray process that was standard in the 1980 and the 1981 model year automobiles. In the 1993 survey, nearly half of the automobiles were phosphated with an immersion system. Figure 9 compares the average defect area per car for automobiles with immersion and spray phosphate treatments. The age of the 1990 and the 1998 model year cars averaged 6 years, while the 1991 and the 1989 model year automobiles averaged 5 years. The figure indicates that cars that had immersion phosphating performed had significantly lower areas of corrosion-related defects, even for automobiles from the same model year.



1 in = 25.4 mm

Figure 9. Average size of corrosion defects for automobiles that had undergone spray phosphating or immersion phosphating.

Another change in the automotive industry that led to increased corrosion resistance is the change in primers and paints used on automobiles. One measure of the improvement of paint systems and corrosion protection is that the survey revealed that 47.7 percent of 1980 model year automobiles had been repainted within 6 years, while only 10.6 percent of the 1988 model year automobiles were repainted after 6 years, which is a dramatic improvement over a relatively short time.

The use of electrocoat or e-coat paints and primers was another technology that increased in use in the 1980s. Electrocoated paint is applied by placing the part to be coated in a paint bath and applying a current to the part to draw the paint onto the part. This method allows very even paint coverage and allows complete coverage, even on small areas or interior areas that sprays would not cover. To investigate the effect of electrocoated paints, the non-repainted 1980 and 1981 models were grouped together and the non-repainted 1988 and 1989 models were grouped together. All of the 1988 and 1989 model year automobiles were electrocoated, while about half (52.2 percent) of the 1980 and 1981 automobiles were electrocoated. The survey found that the amount of surface rust was approximately three times higher on the 1980 and 1981 automobiles and the number of perforations was almost two times higher on the 1980 and 1981 automobiles than on the 1988 and 1989 automobiles where 100 percent of the vehicles were electrocoated. Some of these differences are the result of differences in the zinc coating on the steel and phosphating; however, the use of electrocoated paint systems has had a noticeable effect on corrosion resistance.

Summary

The results of the SAE ACAP parking lot surveys indicate that the frequency and extent of corrosion have decreased with the new technologies used by the automotive industry for corrosion control. This decrease is probably because of changes in design, materials, phosphating, and coating practices. The members of the committee also drew several specific conclusions from the survey data and analysis:

- The increase in the use of zinc metallic precoating has contributed to reductions in perforation when these coatings are on the inside of the panel.

- Metallic coatings on the interior of the panels are more effective in reducing perforations than paint coatings.
- Increased use of two-sided precoated steels has contributed to decreases in blistering and surface rusting.
- Increased use of immersion phosphating systems has contributed to the improvement in corrosion resistance of the vehicles surveyed. Blistering and surface rusting have been reduced 40 to 70 percent and no perforations were seen on 5- and 6-year-old cars phosphated using an immersion system.
- Improvements in materials use, design, phosphates, and paints have resulted in a dramatic decrease in the percentage of repainted cars at 5 and 6 years of age over the survey period. The reduction in repainted vehicles from model years 1980-1981 to 1988-1989 was approximately 70 percent.
- The overall improvement in corrosion performance over this 10-year survey period may be greater than the data reveals because of the considerable number of vehicles that were repainted in early surveys.

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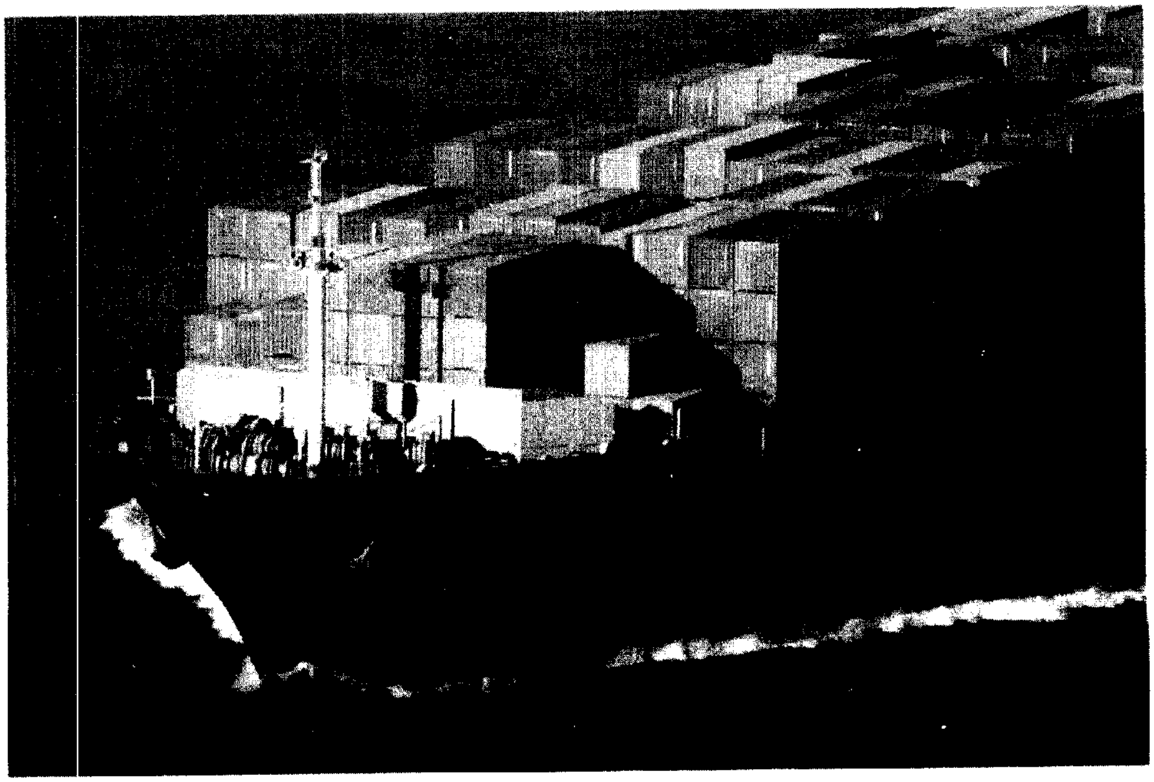
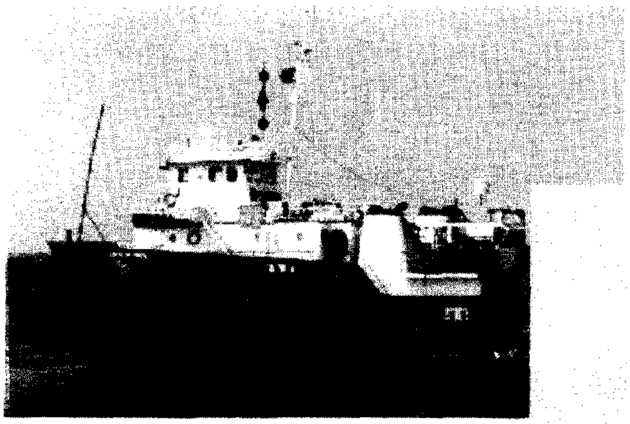
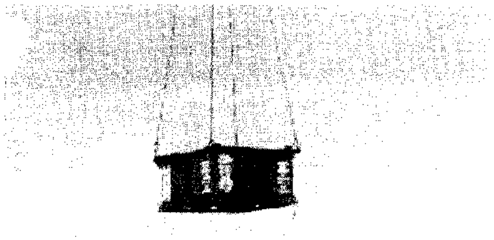
APPENDIX O

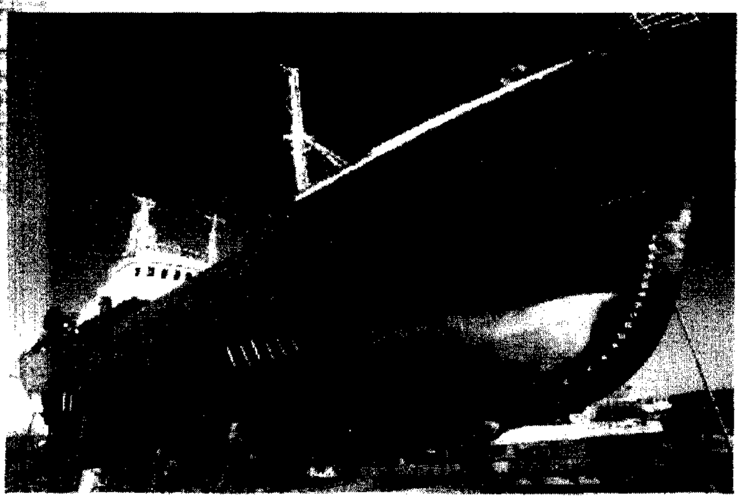
SHIPS





Corrosion of ships in marine enviroments





Painting of ship hull

SHIPS

JOSHUA T. JOHNSON[1]

SUMMARY AND ANALYSIS OF RESULTS

Corrosion Control and Prevention

The size of the shipping industry can be measured by the number of miles that ships sail and the tons of cargo they haul (ton-miles). The U.S. flag fleet can be divided into several categories as follows: (1) Great Lakes with 737 vessels at 99.82 billion ton-km (62 billion ton-mi), (2) inland with 33,668 vessels at 473.34 billion ton-km (294 billion ton-mi), (3) ocean with 7,014 vessels at 563.5 billion ton-km (350 billion ton-mi), (4) recreational with 12.3 million boats, and (5) cruise ships with 122 boats serving North American ports (5.4 million passengers).

The annual corrosion-related costs of the U.S. marine shipping industry is estimated at $2.7 billion (see figure 14). This cost is divided into costs associated with new construction ($1.12 billion), maintenance and repairs ($810 million), and corrosion-related downtime ($785 million). Because of the nature of the shipping industry, it is difficult to estimate the national cost of corrosion. Most ships that serve U.S. ports do not sail under the U.S. flag, but under those of nations with less restrictive laws and taxation. Furthermore, the shipping industry is very diversified in terms of size, cost, and cargo. Finally, the shipping industry is primarily a commodity industry where short-term profits are often more important than long-term savings on assets.

Opportunities for Increased Integrity, Durability, and Savings

New coatings, designed to last for the entire lifetime of the ship, have been developed. These coatings are more expensive than the coatings that have traditionally been used; however, they require less maintenance and repairs than other coatings. These coatings also reduce the need for repairs to the steel as the ship gets older. Additional opportunities exist in the manufacture of double-hulled tankers. The first generation of double-hulled oil tankers has had significant corrosion problems that were not considered before they were built (this is documented in the case study). By studying the differences between single- and double-hulled tankers, improvements can be made to the new double-hulled tankers to keep them corrosion-resistant for years to come.

Barriers to Progress and Effective Implementation

The nature of the shipping industry is the major barrier to implementation of additional corrosion-reduction practices. Ships are bought and sold often enough that most original owners know that they will not be keeping the ship long enough for corrosion to become a problem. Because of this, most ships are not built with the best materials and coatings and will require more maintenance later in the ship's life.

Recommendations and Implementation Strategy

Compared to other industries, the cost of corrosion in this sector is relatively small for the extent of the industry; however, improvements can still be made. Studies showing that better coatings reduce the amount of future repairs and extend the maintenance cycle before repairs are required may help to convince companies that investment in coating systems is worthwhile.

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[1] CC Technologies Laboratories, Inc., Dublin, Ohio.

Summary of Issues

Increase consciousness of corrosion costs and potential savings.	Total cost of corrosion in the shipping industry is $2.7 billion.
Change perception that nothing can be done about corrosion.	Enhance the knowledge of case studies showing that using proper coatings during construction is more cost-effective than later repairs.
Advance design practices for better corrosion management.	Ensure that designs using high-tensile-strength steel contain enough steel to allow for some corrosion.
Change technical practices to realize corrosion cost-savings.	Use modern epoxy coatings on appropriate areas during construction of new ships.
Change policies and management practices to realize corrosion cost-savings.	Build more corrosion resistance into new construction for lower repair costs and higher resale values later.
Advance life prediction models and performance assessment methods.	Perform cost-benefit analyses on the long-term effects of employing greater corrosion management.
Advance technology (research, development, and implementation).	Materials and design principles from more high-tech industries may prove to be useful for specific applications.

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SECTOR DESCRIPTION

Background

The world's ships can be divided into five general categories based on the cargo the ships carry and the type of work performed on the vessel. The first category is tankers and carriers, which includes oil tankers, chemical tankers, liquefied gas carriers, and ore carriers. There are 9,321 tankers and carriers in service, which constitutes 10.8 percent of the world's ships. The tankers and carriers have a total gross tonnage of 168,011,588 metric tons (185,200,000 tons). While other categories of ships contain more ships by number, the size of the tankers and carriers, particularly the oil super-carriers, cause these vessels to make up 34.8 percent of the world's total ships by tonnage. The second category of ships is the bulk cargo ships, which are designed to hold large amounts of loose cargo such as grain. These ships make up 7.3 percent of the total ships by number and 29.3 percent of the ships by tonnage. The third category of ships is the container ships, which are cargo ships designed to carry their cargos in large packed containers. This category of ships includes 23.4 percent of the ships by number and 16.3 percent of the ships by tonnage. The fourth category of ships is the fishing vessels, which includes both fishing ships and the mobile fish processing ships. A considerable number of these ships exist. There are 23,711 in the world, accounting for 27.6 percent of the world's ships by number; however, they account for only 2.4 percent by tonnage because of the small average size of these vessels. The fifth category consists of the remainder of the ships, including tugs, ice breakers, scientific research vessels, ferries, and cruise ships. Figures 1 and 2 offer a graphical account of the percentage of ships by type, with figure 1 showing the percentage based on the number of ships and figure 2 showing the percentage based on tonnage. In these figures, the categories are divided into slightly more specific groups, such as chemical tankers.

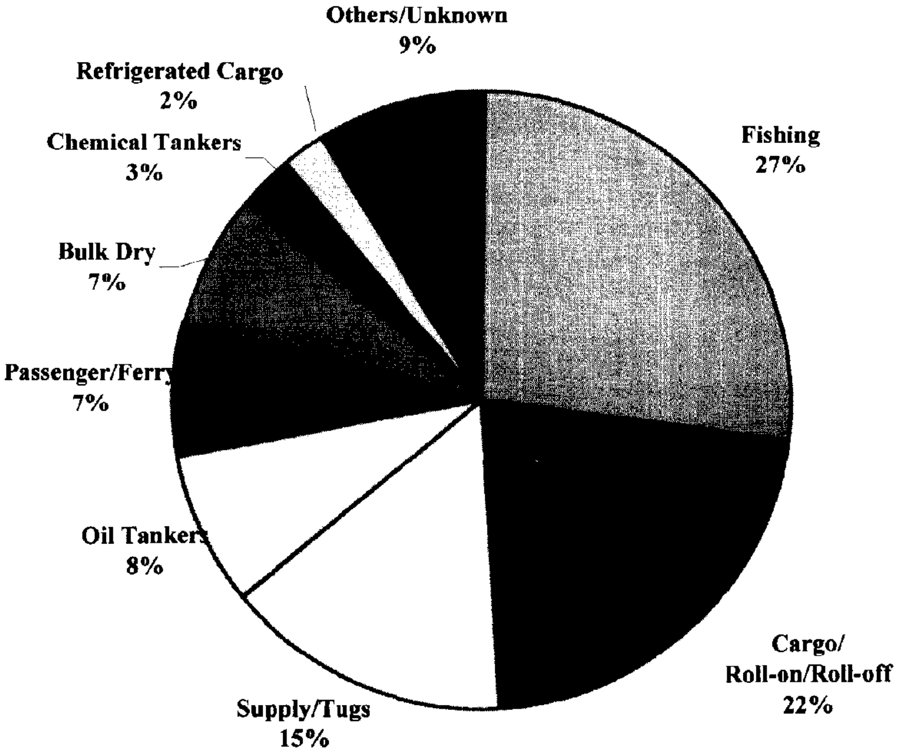

Figure 1. Percentage of the world's fleet by class of ship, based on the number of ships.

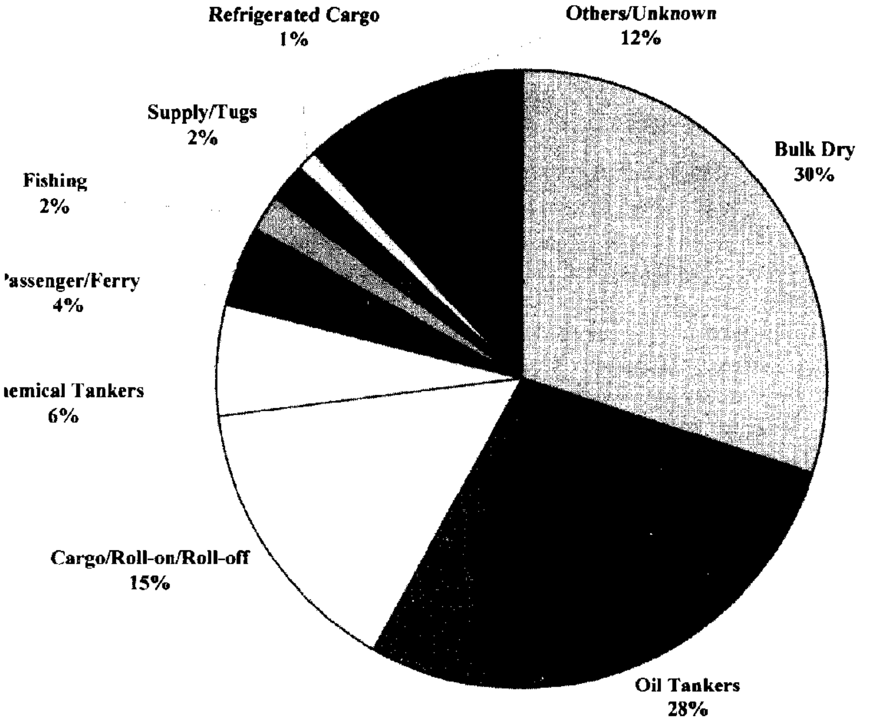

Figure 2. Percentage of the world's fleet by class of ship, based on gross tonnage.

The purpose of a ship is to be in transit between landmasses. Because of the international nature of the shipping industry, it is difficult to determine which ships should be included in a study on the cost of corrosion in the United States. A further complication is that ships do not need to be registered in the countries where they conduct their business. It is the result of laws and regulations in both the United States and other countries that ships are often registered in countries where they will never operate. Ships are commonly registered in nations such as Liberia and Panama and are operated under what is known as flags of convenience. Table 1 lists the registration of the 20 largest merchant fleets in order of gross tonnage. The table clearly shows that some very small countries, such as Panama, Liberia, Malta, the Bahamas, and Cypress, have registered merchant fleets larger than more industrialized, large nations. Liberia, for example, is slightly larger in area than Tennessee and has a GDP of $2.8 billion, which is 0.0033 percent of the U.S. GDP.(1) Liberia, however, has 408 registered oil carriers, while the United States has only 108 oil carriers. Malta is an even smaller nation, roughly twice the size of the District of Columbia; however, Malta has 356 registered bulk dry cargo ships compared, to 15 registered in the United States.

Another reason for not considering only U.S. registered ships is based on various marine legislation, such as the Jones Act of 1920. The Jones Act affects ships that trade between ports in the Unites States. These ships, according to the Jones Act, must be built in the United States, be owned by citizens of the United States, and be operated by American crews. The cost of these requirements has caused most ships traveling to the United States to be flagged in foreign countries, even if they do the majority of their business in the United States. The cruise ships operating in the United States out of Florida, Texas, and Alaska are good examples of this. The vast majority of the passengers on these vessels are citizens of the United States; however, all of the ships are registered in Panama, Liberia, Norway, or other nations. A second result of these laws is that ships flagged in the United States are often much older and more likely to suffer from corrosion problems than ships that are registered in other countries. The average age of a U.S.-flagged ship is 23 years old, which is older than any of the fleets in table 1 except for Greece.(2)

Table 1. Number of registered ships and aggregate gross tonnage for the 20 largest merchant fleet nations.

WORLD RANK	COUNTRY OF REGISTRATION	NUMBER OF SHIPS	AGGREGATE GROSS TONNAGE
1	Panama	6,143	98,222,372
2	Liberia	1,717	60,492,104
3	Bahamas	1,286	27,715,783
4	Greece	1,545	25,224,543
5	Malta	1,416	24,074,712
6	Cypress	1,602	23,301,517
7	Singapore	1,677	20,370,399
8	Norway	750	19,918,331
9	Japan	8,922	17,780,396
10	China	3,214	16,503,355
11	United States	5,626	11,851,660
12	Russia	4,723	11,089,922
13	Philippines	1,726	8,508,313
14	Germany	1,158	8,083,620
15	Saint Vincent	1,317	7,875,497
16	Italy	1,329	6,818,632
17	India	947	6,777,102
18	Marshall Islands	207	6,441,843
19	Turkey	1,135	6,251,395
20	Hong Kong	391	6,170,705

Due to what is known as "flags of convenience," as well as the various international maritime laws, it was decided, for the purposes of this study, to assign a percentage of the total cost of corrosion of ships worldwide as the U.S. cost of corrosion. U.S. residents pay an increased price in goods shipped into the country and U.S. companies pay more to export their goods to make ships more corrosion-resistant and to make corrosion repairs to ships. The U.S. Bureau of Transportation Statistics reports that U.S. waterborne exports and imports accounted for approximately 21 percent of global waterborne trade.(3) Assuming that half of the cost of the voyages can be attributed to the United States, approximately 10 percent of the world maritime cost would be attributable to the United States based on foreign trade.

The United States also transports almost the same amount of materials by ship in domestic trade (1,071 million metric tons foreign versus 1,010 million metric tons domestic).(3) The size of the shipping industry can be measured by the number of miles that ships sail and the tons of cargo they haul (ton-miles). The U.S. flag fleet can be divided into several categories: (1) Great Lakes with 737 vessels at 99.82 billion ton-km (62 billion ton-mi), (2) inland with 33,668 vessels at 473.34 billion ton-km (294 billion ton-mi), (3) ocean with 7,014 vessels at 563.5 billion ton-km (350 billion ton-mi), (4) recreational with 12.3 million boats, and (5) cruise ships with 122 boats serving North American ports (5.4 million passengers).(1)

Domestic trade routes, however, tend to be significantly shorter than foreign routes (by a factor of approximately 10); therefore, approximately 5 percent of the world's maritime costs can be attributed to U.S. domestic shipping. Based on foreign and domestic trading, 15 percent of the corrosion costs of the world's ships is assessed as the cost of corrosion for the U.S. shipping industry.

Corrosion Modes

Corrosion of ships is the result of several different types of corrosion. The most common one is general corrosion or wall thinning of the hull due to seawater attack. Studies have shown that the rate of this form of corrosion is approximately 0.1 mm (4 mils) per year.(4) At this corrosion rate, it would take approximately 62 years to have a reduction of 6.4 mm (0.25 in). Because of this slow rate, general corrosion is normally not a consideration in a ship's design life.

Galvanic corrosion occurs between two metals with dissimilar electrochemical potentials. In this form of corrosion, one of the metals is more electrochemically active and corrodes, while the second metal is protected by the corroding metal. The metals can even be of the same material if the electrochemical potential of one of the materials has been changed due to stresses or differential aeration. Previous studies have indicated that most hull corrosion is galvanic in nature.(5)

Salt spray and atmospheric corrosion can severely attack external ship components. Coatings provide the primary corrosion control and maintenance of these coatings is required at regular intervals.

Direct chemical corrosion attack occurs when certain chemicals are present in the internal holds and tanks of transport ships. Elements such as chlorine and sulfur can readily attack the steel and cause accelerated corrosion and pitting.

Corrosion in ships can also be caused by microbiologically influenced corrosion (MIC). In this type of corrosion, microbial organisms present in the environment can accelerate corrosion. For example, sulfate-reducing bacteria (SRB), which are present in the stagnant water of many harbors, can build up on the hulls of ships. Other corrosion-causing bacteria, such as acid-producing and anaerobic bacteria, are also present in ballast tanks as well as in the liquid products that some tankers carry. These microbes cause a localized change in the environment, which can promote aggressive pitting and other types of corrosion.

AREAS OF MAJOR CORROSION IMPACT

The primary cost of corrosion in the ships sector can be broken down into two major elements:

1. The cost of corrosion engineering and materials added into the cost of a new ship. These costs include corrosion-resistant materials and coatings, as well as cathodic protection systems installed during construction.
2. The cost of repairs, maintenance, and downtime due to corrosion. These costs include the replacement of steel, removal and reapplication of coatings, and installation of additional cathodic protection equipment. Also included is the revenue lost from the ship being out of service while repairs and maintenance are being performed.

Cost Estimates

New Ship Construction

The majority of the corrosion prevention cost on new ship construction results from the application of coatings to the hulls, decks, and, most importantly, ballast and storage tanks. The actual cost of the coating is a relatively small part of the cost for applying a coating. The largest portion of the cost of coating application comes from the extensive surface preparation needed to prepare steel for coating. Most modern coatings require extensive surface grit blasting to remove all of the corrosion, mill scale, and other products on the steel.(6) Without the proper surface preparation, the coating will not properly adhere to the steel surface and corrosion problems will be much more likely.(7) Another large portion of the application cost of a coating is in the labor needed to properly apply the coating. The coating must be hand-applied to corners and other areas to ensure coverage of the edges when the coating shrinks while drying.(8)

It has been estimated that, for most ships, the cost of applying the coatings to a ship is 7 percent of the total cost of the ship.(7) While the cost of applying a proper coating is expensive, Weber found that it was 4 to 14 times more expensive to replace corroded steel than to apply a coating during construction and maintain that coating.(9) The cost for the coatings applied for oil carriers is slightly higher, at 10 percent of a ship's construction cost. Oil tankers require better coatings than most of the industry due to the corrosive nature of chemicals, such as the hydrogen sulfide present in crude oils. Based on discussions with representatives of a major cruise line, the cost of coatings for cruise ships is also approximately 10 percent. Based on discussions with industry experts, cruise ships require better coatings for tanks that hold the wastewater from their passengers. An estimate was made that cathodic protections systems and corrosion-resistant materials add an additional 3 percent to the new build cost of ships. For most classes of ships, the total cost of corrosion protection for new construction can be estimated at 10 percent of the total construction cost, with oil tankers and cruise ships having slightly higher corrosion protection expenditures at 13 percent. The exception to this general number is the class of chemical tankers, because the storage tanks in these ships are made of stainless steel in order to be resistant to the chemicals that they transport. Because of this need, the literature estimates that the cost of corrosion protection for a chemical tanker is 30 percent of the new build cost.(7)

To estimate the total cost of corrosion for new ship construction, data on the number of ships in the world were combined with an estimate of the average cost of a vessel for each type of ship and the percentage of the construction cost attributable to corrosion protection. This information is reported in table 2. To calculate an average cost per year, the number of ships was multiplied by the estimated vessel cost and the percentage of the vessel cost attributable to corrosion. The sale price of several new and used vessels of various ages were used to estimate the average cost for each class of ship.(7,9-10) This resulting value was then divided by 25 years, which is the average design life of many ships, to obtain an average cost per year. As indicated in the table, the world cost of corrosion from new ship construction is approximately $7.5 billion per year. If 15 percent of the world cost is attributable to the United States, the cost of corrosion from new ship construction in the United States is estimated at $1.12 billion.

Table 2. Average corrosion cost per year due to new construction for each of the major types of ships.

TYPE OF SHIP	NUMBER	% COST OF CONSTRUCTION DUE TO CORROSION	AVERAGE COST OF VESSEL ($ x million)	AVERAGE CORROSION COST PER YEAR ($ x million)
Oil Tankers	6,920	13	50	1,799
Chemical Tankers	2,471	30	50	1,483
Bulk Dry	6,252	10	20	500
Cargo/Roll-on/Roll-off	18,611	10	15	1,117
Fishing	23,711	10	5	474
Supply/Tugs	12,954	10	11	570
Refrigerated Cargo	1,441	10	6	35
Cruise	337	13	200	350
Passenger/Ferry	5,386	10	24	517
Others/Unknown	7,724	10	20	618
			WORLD TOTAL	$7,463

Repair and Maintenance

The second portion of the cost of corrosion in the shipping industry is the cost of corrosion repairs and maintenance, as well as the downtime needed to perform these repairs.(3,9) Table 3, based on literature and discussions with industry experts, shows the average estimated cost of annual repairs for each class of ship with the cost of the downtime associated with the cost of the repairs. To calculate the total costs, the number of ships of each type was multiplied by the repair and downtime estimates. The total cost for repairs for the world shipping sector was calculated at $5.4 billion, while the cost of downtime was estimated at $5.2 billion. The U.S. portion of these costs would be estimated at $810 million for repairs and $785 million for downtime.

From the cost estimates of new construction and repair maintenance, the total cost of corrosion in the shipping industry can be estimated. The yearly cost of increased corrosion resistance in new ship construction in the United States was estimated at $1.12 billion, and the cost of repairs and maintenance was estimated at $810 million, with the cost of downtime at $785 million. Therefore, the total cost of corrosion for the U.S. shipping industry is estimated at $2.7 billion per year.

Table 3. Estimated average corrosion cost per year due to maintenance, repairs, and downtime for each of the major types of ships.

TYPE OF SHIP	NUMBER	AVERAGE CORROSION REPAIR COST PER SHIP ($ x thousand)	TOTAL YEARLY REPAIR COST ($ x million)	AVERAGE CORROSION DOWNTIME COST PER SHIP ($ x thousand)	TOTAL YEARLY DOWNTIME COST ($ x million)
Oil Tankers	6,920	200	1,384	140	969
Chemical Tankers	2,471	300	741	140	346
Bulk Dry	6,252	50	313	56	350
Cargo/Roll-on/Roll-off	18,611	50	931	73	1,303
Fishing	23,711	25	593	20	474
Supply/Tugs	12,954	50	648	50	648
Refrigerated Cargo	1,441	50	72	50	72
Cruise	337	200	67	1,000	337
Passenger/Ferry	5,386	50	269	56	302
Others/Unknown	7,724	50	386	56	433
		WORLD TOTAL	**$5,404**	**WORLD TOTAL**	**$5,234**

CORROSION CONTROL METHODS

Corrosion control can be accomplished in the design phase, the manufacturing phase, and the operation phase of a ship.

Design

There are several elements of design that can reduce the amount of corrosion that a ship will undergo in its lifetime. The first of these elements is the basic structural design of a ship. Designing a ship to have minimal surface discontinuities, such as sharp corners, will reduce the surfaces where coatings are most likely to fail.

Designs can also be made to minimize locations with stress concentrations, which can act as crack initiation sites, and locations where coatings can crack. It is also important to design a ship so that all surfaces of the tank interior can be accessible so that later coating and surface inspections can be performed. Crevices that can collect dirt and form corrosion cells should also be avoided during the design phase.

Another element of design that can influence corrosion prevention is the design of the welds. Proper sizing of the welds and planning the sequence of the welds can reduce stress concentrations and distortions of the hull. Past experience has shown that lap joints have been prone to failure on older ships; therefore, butt welded joints should be used whenever possible. Designs should also avoid intermittent spot welding since this form of weld is more prone to corrosion.

The most important element of corrosion protection is a proper coating selection. A coating should be selected during the design phase based on the function of the ship, the type of tanks used, and the expected life of the ship. Due to the high cost of coating application, care should be taken in choosing the proper coating. Possible coating choices include:(10)

- Epoxies:
  - Coal tar epoxy
  - Silicone-modified epoxy
  - Electrodeposition epoxy
  - High solids epoxy over a waterborne epoxy zinc primer
  - Pure amine epoxy
  - Epoxy amides
  - Epoxy amino/amides
  - Hydrocarbon (wax) -modified epoxy amides and epoxy amines
  - High solids (low molecular weight epoxy resins) epoxy
- Thermoplastics:
  - Thermal-spray thermoplastics
  - 100 percent solids rust-preventive wax
- Others:
  - Coal tar polyurethanes
  - Polyurethane (aliphatic polyol) topcoats
  - Zinc silicates
  - Alkyd paints
  - Calcium sulfate alkyd

Solvent-free epoxies are much more expensive coatings than the coal tar epoxies or the solvent-borne epoxies previously used in ship construction. Solvent-free epoxy costs, on average, $6.60 per square meter for the epoxy, compared to coal tar epoxies and solvent-borne epoxies that cost, on average, $1.80 and $2.80 per square meter respectively. For the amount of coating needed to coat a ship, it is approximately $150,000 more expensive to use solvent-free epoxy over coal tar epoxy and $120,000 more expensive to use solvent-free epoxy over solvent-borne epoxy. On vessels that cost $70 million to $80 million, the use of solvent-free epoxy would be a very small increase in terms of percentage cost. Most of the cost in a coating application is in the cost of grit blasting the steel and applying the coating, which generally costs about the same for any type of epoxy coating.

However, the additional $150,000 during construction can pay major dividends during the operational life of the ship. If the cheaper coal tar epoxy coating is used during construction, the coating will have to be reapplied two or three times during the life of the tanker. To perform the re-coating, the tanks would first have to be cleaned and grit-blasted before the coating is applied. The total cost of such a job on a large tanker would be approximately $3 million.

If cathodic protection systems or other corrosion prevention equipment are going to be used on a ship, it should be incorporated in the design phase. A cathodic protection system is a secondary defense against corrosion when holidays or cracks form in the coating. Cathodic protection systems use either sacrificial zinc anodes or impressed-current systems to mitigate corrosion that occurs. If cathodic protection is applied properly, the steel on the ship will be the cathode and corrosion will be mitigated. Other corrosion prevention equipment and materials include inert gas systems (to keep corrosive gases out of holds) and corrosion inhibitors.

Manufacturing

There are several elements of ship fabrication and manufacturing that will affect the corrosion performance of a ship. The first of these elements are the structural tolerances of construction. The ship classification societies, such as Lloyd's Register of Shipping, the American Bureau of Shipping, and Nippon Kaiji Kyokai, have published tolerance standards with which ships built according to their classification systems must comply. These tolerances permit gaps up to a certain width (3 mm) and misalignments up to one-half of the plate thickness.(11) Keeping the gaps and misalignments under this level will help reduce the possibility of stress concentrations and other possible causes of structural failure. Adherence to good painting practices in terms of application and curing, not adherence to the least proper temperatures to ensure a good solvent release in the wet stage, will ensure that the coatings have as low an internal stress level as possible and this will ensure a longer service life.

One phase of the manufacturing process that greatly affects corrosion performance is the surface preparation prior to the coating application. Almost all coatings used in the marine industry adhere to the metal by mechanical adhesion; thus, it is important to have a surface that readily bonds with the coating in order to protect the metal. There are two important elements to surface preparation. The first element is that the surface preparation must clean the surface thoroughly by removing all salt, dirt, and chemicals on the steel surface. The second element is to create a textured or anchor-pattern surface so that the coating can mechanically adhere to the surface. The preferred method of surface preparation is grit blasting. The coating manufacturer will provide information regarding the degree of surface profile that must be achieved by blasting.

Once the surface has been prepared, the coating can be applied to the metal. The quality of the coating application can have a lasting effect on the corrosion performance of a ship; therefore, the directions of the coating manufacturer must be closely followed. One of the most important parts of the coating application is hand-finishing, where a painter with a brush coats the corners, angles, and edges. This must be done because surface tension causes drying coatings to draw away from sharp edges. Because of this, coatings are thinner in the corners, angles, and edges; therefore, extra coating must be applied by stiping to ensure proper coating thickness. Care must also be taken to ensure that the coating is not too thick. This can lead to solvent and thinner retention, film cracks, and gas pockets.

Operation

The last element of corrosion control are the actions of the owner and the crew during the operation of the ship. The coating represents the most important part of corrosion control on a ship, so maintaining the integrity of the coating during operation is vital to corrosion control. Damage to coatings can be caused in many different ways, including:

- Wear caused by crew members and equipment moving through the tank.
- Wear caused by water sloshing in partially filled ballast tanks.
- Wear caused by mud silt and other debris that accumulate in the tanks.
- Aggressive corrosion caused by high-temperature cargos.
- Abrasion of the ballast tanks caused by sloshing sand.

To ensure that a ship operates through its design life, it is essential that the operator does everything possible to keep the coatings intact. It is also essential to inspect the coating on a regular basis so that repairs can be made when needed, while the damage is minimal.

CHANGES FROM 1975 TO 2000

Several major changes in corrosion control technologies, environmental legislation, and ship design have led to dramatic changes in corrosion control approaches in the marine industry over the past 25 years.

The most important change over the past 25 years has been the change in coatings for marine use. There have been two primary driving factors in these changes over the past decades including, changes in environmental laws limiting the use of lead, chromates, and certain volatile organic compounds (VOCs) and the formulation of better performing multi-part epoxies and other coatings. These factors have led to high solid epoxies of different types being the number one choice for coatings in marine applications. These coatings are both more effective and more expensive, than the coatings used 25 years ago. These coatings also require more extensive surface preparation than earlier coatings greatly increasing the costs of application and repair.

Another major change over the past few decades is the switch to high-strength steel and other materials with higher strength-to-weight and thickness ratios than the standard carbon steel. This change has allowed the structural elements of ships to be made thinner, allowing ships with the same size hull to have more internal room to hold cargo. The downside to this development is that less corrosion is needed to reduce the structural integrity of elements made of thinner high-strength materials than when the elements were made from carbon steel. High-strength steels often have corrosion rates that are the same as or higher than those of carbon steels; therefore, it is more important to protect high-strength steel elements, otherwise, the risk of corrosion failure can be high. This was revealed by several failures of structural components in the late 1970s and the early 1980s.

Another change has been the increased use of double-hulled tankers over the single-hulled variety. Double-hulled tankers are designed to essentially have a ship inside of a ship to reduce the risk of a ship sinking or a loss of cargo. Due to well-publicized failures, such as the Exxon Valdez, regulations in the United States have led to the exclusive use of double-hulled tankers in coastal waters. While leaks into the water should not occur with doubled-hulled tankers, these ships have been found to have their own corrosion problems. The space between the inner and outer hulls of these tankers is often used for ballast water to balance the tankers. These areas often have coating damage and corrosion problems due to the conditions in these tanks. Moreover, these areas are difficult to inspect due to several hull supports and other structures between the inner and outer hulls. Operators have also noticed increased corrosion damage to the actual oil tanks due to what is referred to as the thermos effect. Corrosion is a temperature-sensitive process. For each 10 °C increase in temperature, the corrosion rate can be estimated to double. Oil is pumped into tankers at relatively warm temperatures [approximately 46 °C to 55 °C (115 °F to 130 °F) or hotter]. In single-hulled tankers, the ocean water surrounding the oil would lower the temperature quickly to the local water temperature. On double-hulled tankers, however, the hull acts as insulation and the ballast tanks stay in the high-temperature condition longer, which results in higher corrosion rates.

CASE STUDIES

Case Study 1. Double-Hulled Tankers

On March 24, 1989, the Exxon Valdez ran aground in Prince William Sound, Alaska, causing 42 million L (11 million gal) of crude oil to be spilled. The clean-up cost billions of dollars and, in the hope of avoiding a similar accident, the U.S. Congress passed the Oil Pollution Act in 1990. This law required all new tankers operating in the

United States to be built with a double hull. Most other industrial nations passed similar laws so that today almost all carriers are built with a double hull.

Because of the limited experience with doubled-hulled carriers before 1990, the first double-hulled carriers were very similar to their single-hulled predecessors. Owners and operators of the new tankers found much more serious corrosion after the first 5 years of operation than expected from their experiences with single-hulled carriers. This has caused a re-evaluation of the causes of corrosion in these ships, as well as a re-evaluation of the methods for corrosion protection.

Differences Between Single- and Double-Hulled Carriers

As the name implies, a double-hulled ship is built with an additional inner hull. The area between the two hulls can be used for ballast, but not for cargo. The purpose behind the double hull is that if the outer hull is pierced, the cargo will still not leak out of the ship.

Adding an additional layer of steel also increases the size of the tanker, the weight, and the amount of steel needed to create a ship that will carry the same amount of oil. Because of volume and weight concerns, naval architects often decided to use more high-tensile strength (HT) steel in the design of the new double-hulled tankers. HT steel has mixed results because the higher strength, thinner steel plates can be used to maintain the standards of the classification societies; however, corrosion becomes more of a concern since there is less steel to corrode before a leak or other failure occurs. Another problem with HT steel is that the thinner plates tend to flex more with natural water waves and other sea motions. This flexing can cause the surface rust and scale to fall away and expose new bare steel to the corrosive conditions. If this process is repeated many times, rapid wall loss can occur. Owners have reported double the usual corrosion rate on some HT steel plates, which has some owners and operators concerned.

Along with the dimensional differences between single- and double-hulled tankers, operators have found differences between the environments in the cargo tanks. The main difference in the environment is that the cargo tanks in double-hulled tankers are often warmer due to what has been called the thermos effect. Many of the leading oil-producing regions, including the Middle East, West Africa, the Gulf of Mexico, and the South Pacific, are in high-temperature areas. When the oil is loaded into a tanker, it generally cools over the voyage to the temperature of the surrounding water. This temperature change often only takes a couple of days for a single-hulled tanker; however, for a double-hulled tanker, the outer hull can act as an insulator and it may take 20 to 30 days for the temperature of the cargo to reach sea temperature. The temperature may never reach sea temperature on short voyages. These higher temperatures are a problem for two reasons. First, corrosion rates often follow an Arrhenius behavior, where the corrosion rate doubles for every 10 °C increase in temperature; therefore, if the average temperature of the tank is 20 °C warmer, then the average corrosion rate is quadrupled. A second problem with higher temperatures is that many of the coatings, particularly tar epoxies, do not handle high temperatures well and will degrade more rapidly.

Case Study 2. Corrosion in Cargo Tanks

Most of the corrosion on the bottom of crude cargo tanks is in the form of pitting. Similar corrosion is found in crude cargo tanks on single-hulled tankers, double-hulled tankers, and refinery storage tanks. Crude oil contains a small percentage of water that will settle over time to the bottom of a storage tank. If the crude oil contains H_2S or other chemicals, acid will be formed from the water and the acid will attack the bottom of the tank.

The water on the bottom of the tank can also lead to corrosion because of the various microbes in the water. Several types of bacteria exist in the water and the crude oil product, including acid-producing bacteria (APB) and sulfate-reducing bacteria (SRB). The APB and other forms of bacteria can lead to corrosion; however, their most harmful effect is often the creation of ideal conditions in which the SRBs may attack. Under proper conditions, the SRBs can multiply rapidly and concentrate in colonies on the bottom of the tank. The SRB damage steel by removing sulfates from the crude oil and reducing the sulfates to sulfides that concentrate underneath the SRB and attack the steel, causing pits in the areas under the SRB colonies. Microbiologists have found that the SRB generate the highest level of sulfides at 37 °C to 41 °C (99 °F to 106 °F). This finding, along with the thermos effect noted above, might explain why more rapid pitting has been found on the first generation of double-hulled tankers.

The other areas in crude storage tanks where considerable corrosion occurs are at the top of the tank or the ullage space. The corrosion in these areas tends to be in the form of a general attack rather than pitting; however, the difficulty of inspecting and repairing these regions makes the corrosion of these areas a major concern. The top portions of the crude tanks are often made of HT steel and the flexing/descaling problem discussed previously is a concern in these areas.

Two different corrosion mechanisms affect the top of tanks, depending on whether the tank is filled with cargo or is empty for the ballast voyage. While the tank is filled with crude, the ullage space is filled with inert gas that should limit corrosion. The crude, however, will release different gases, including hydrogen sulfide, which can combine with minute traces of water and oxygen to form concentrated sulfuric and sulfurous acids. These acids will attack the steel of the tank and cause the general corrosion of the steel.

During the ballast voyage, the entire tank is filled with inert gas, which tends to be saturated with water vapor. This water vapor will often condense during the voyage and absorb any remaining sulfur-containing compounds, as well as carbon dioxide and nitrous oxides, to form various acids that attack the steel.

Case Study 3. First-Generation Corrosion Treatment for Cargo Tanks

The first double-hulled tankers' cargo tanks were protected in the same manner as the cargo tanks on single-hulled tankers. Most often this involved not using a coating to line the crude oil cargo tanks and using only a single-layer tar epoxy coating on the water ballast tanks. In the many years of carrying crude oil in single-hulled tankers, the corrosion rate was found to be somewhat constant, and owners treated tank corrosion as an operating expense. It was known that repairs and steel replacement would have to be performed after the third special survey when the ship was 12 years old; however, owners of the early double-hulled tankers found significant corrosion and pitting at the first special survey after only 5 years. The owners of these tankers, assuming that they would be similar to single-hulled tankers, had not budgeted for such extensive maintenance so early in the life of the tanker. This led to new interest in understanding and controlling the corrosive environment in double-hulled tankers.

Knowledge of the conditions that led to increased corrosion in the first generation of double-hulled tankers allowed naval architects to design protection systems to reduce this level of corrosion. Several options for reducing corrosion could be implemented, such as building the tanks of stainless steel or removing the water vapor from the inert gas. These options, however, would be incredibly costly; therefore, the only cost-effective option would involve coating the bottom and top surfaces of the cargo tanks, as well as using better coatings on the ballast tanks.

These coatings should have certain characteristics to increase their effectiveness and longevity in preventing corrosion and malfunction for the entire design life of the tanker. High-temperature resistance is one of the most important characteristics for a coating for use in crude tanks. A coating should be able to be resistant to temperatures of at least 70 °C (158 °F) and resistance to 90 °C (194 °F) may be advisable as further deepwater exploration increases, since the deeper the oil, the hotter the oil reservoir. Another important coating characteristic is resistance to bacteria and MIC. The coating used must be able to resist the acid waste products of the APB and the sulfide waste products of the SRB. If these bacteria are not allowed to reproduce on the surface of the tank, MIC should be minimal. Another characteristic of the proper coating is that it should resist the acid attack that occurs in the ullage spaces during voyages. Because of the flexing of the HT steel, it is important that the coating used be very flexible and does not become brittle and break off over time as the ship flexes. The final characteristic for a proper tank coating is that the coating should have a service life greater than 20 years. Solvent-free epoxies have been found to have all of these characteristics and are now becoming the coating of choice for Japanese and Korean shipyards when building tankers.

Some owners quickly realized the need for coatings with these characteristics and had their tankers built with these coatings; however, the use of coatings did not become nearly universal until 1998. The most common coatings used by shipbuilders are normally modified epoxies, coal tar epoxy, or solvent-borne epoxy. These coatings have been used by the majority of shipbuilders for 30 years, so when coatings were needed for the inside of the crude tanks, these products were often used. The problem with these coatings is that they are products with a medium life span designed to provide protection for only 8 to 10 years, which is considerably shorter than the design life of these vessels. They also are not resistant to the temperatures often seen in double-hulled tankers. Another concern is that these coatings are not very resistant to the bacteria that lead to pitting corrosion on the bottom of the tanks.

The mandated use of double-hulled tankers led to many ships being constructed before there was knowledge of the service conditions that the ships would see. The industry has realized in only the past few years the differences between single- and double-hulled tankers and the modifications to the crude tanks that must be made to minimize the repairs needed during the design life of a ship. The use of solvent-free epoxy on the top and bottom of a crude tank should lead to a significant decrease in the amount of corrosion detected in the first and additional special survey inspections performed on these vessels. The improvement in the understanding of the corrosion conditions experienced in the crude tanks and ballast tanks of oil tankers should lead to safer and longer lasting ships in the future.

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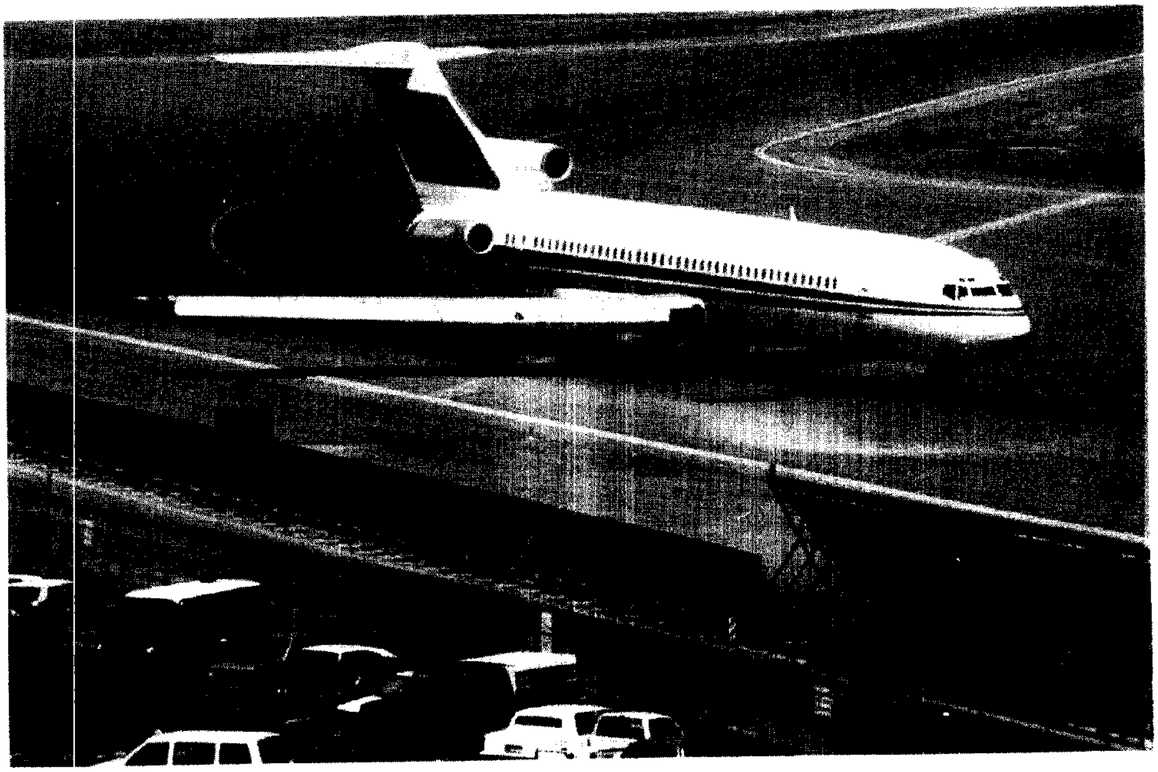
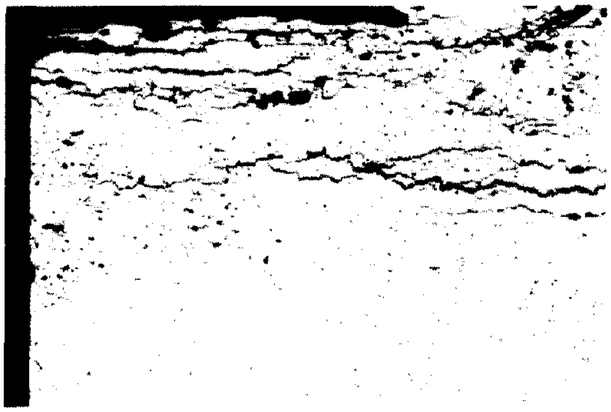
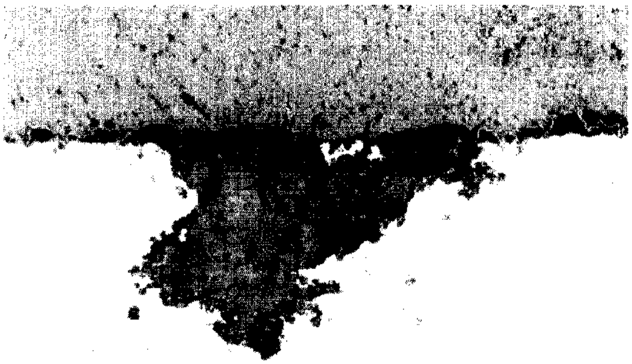
APPENDIX P

AIRCRAFT





Exfolation corrosion in aircraft structural member



Pitting in aluminum

Aircraft aluminum corrosion

Wing repair

Maintenance

SEM photo of corrosion fatigue of aluminum alloy

APPENDIX P

AIRCRAFT

GERHARDUS H. KOCH, PH.D.[1]

SUMMARY AND ANALYSIS OF RESULTS

Corrosion Control and Prevention

In 1998, the combined aircraft fleet operated by U.S. airlines was more than 7,000, of which approximately 4,000 were turbojets. At the start of the "jet age" (1950s-1960s), little or no attention was paid to corrosion and corrosion control. These aircraft are characterized by a design that primarily addressed strength and fail-safe criteria. Aircraft from this era that are still in use include the B-707, DC-8, DC-9, B-727, L-1011, DC-10, and the earlier models of the B-737 and B-747. The second generation of jet aircraft built in the 1970s and 1980s incorporated some corrosion control; however, major emphasis was placed on the incorporation of damage tolerance standards into the design. This generation of aircraft includes the B-737 (-300, -400, and -500); B-747-400; B-757; B-767; MD-81, -82, and -83; MD-88; MD-11; and F-100. As part of the durability standards, airframe manufacturers started to use corrosion-inhibiting primers and sealants. Moreover, the Federal Aviation Administration (FAA) issued Airworthiness Directives (ADs) related to corrosion control in design and maintenance.

The third generation of jet transport aircraft includes the B-777 and the new generation B-737 (-600, -700, and -800). In addition to the key characteristics of the first- and second-generation aircraft, the third-generation aircraft are characterized by the incorporation of significant improvements in corrosion prevention and corrosion control in design.

The total annual (1996) cost of corrosion for the U.S. aircraft industry was estimated at $2.225 billion, which includes the cost of design and manufacturing at $0.225 billion, corrosion maintenance at $1.7 billion, and downtime due to corrosion at $0.3 billion. With the availability of new corrosion-resistant materials and an increased awareness of the impact of corrosion on the integrity and operation of jet aircraft, the current design life of 20 years can be extended without jeopardizing structural integrity and significantly increasing the cost of operations.

Opportunities for Improvement and Barriers to Progress

One of the major concerns of the aircraft and airline industry is the aging of several types of aircraft beyond the design life of 20 years. This aging of the fleet has been the subject of considerable attention by the industry and the government for many years, and has resulted in increased maintenance efforts on the aging aircraft. In April 1988, the sudden decompression of an Aloha Airline B-737-200 airplane and the subsequent separation of the fuselage skin resulted in more focused attention on the problems associated with aging aircraft.

In order to prevent similar incidents on other airplanes, manufacturers, airline operators, and other aviation industry representatives formed the Airworthiness Assurance Working Group to develop all measures considered necessary to ensure the continued safety of aging aircraft. Individual working groups for each aging aircraft model were directed to develop Corrosion Prevention and Control Programs (CPCPs). The recommendations developed in the CPCPs were incorporated in the mandatory Airworthiness Directives (ADs) issued by the FAA. These ADs

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[1] CC Technologies Laboratories, Inc., Dublin, Ohio.

define a baseline program for each aircraft model, establishing minimum requirements for airline operators to prevent or control corrosion that may jeopardize continuing airworthiness.

Significant improvements have been made in the corrosion design and manufacturing of new airplanes. Aircraft manufacturers have implemented many key design improvements over the past 25 years, ranging from the use of more corrosion-resistant materials, to improved adhesive bonding processes, to the use of sealants in fastener holes and on faying surfaces, to the control of spillage of galley and lavatory fluids. Because of the significance in the corrosion design and manufacturing of aircraft, the design service life of new generation aircraft was moved from 20 to 40 years. Despite these improvements, several concerns remain that impede progress in effective corrosion control. Although state-of-the-art materials are available, there appears to be a reluctance to incorporate them into new designs. For example, the corrosion- and stress corrosion cracking-prone aluminum alloys 7075-T6 and 2024-T3 are still widely used despite the availability of new corrosion-resistant aluminum alloys with equal strength and fatigue properties.

A major problem is the corrosion maintenance of the aging aircraft fleet. Although it was stated by a major domestic U.S. airline that . . . *"the degree to which an airline aggressively pursues corrosion prevention from the beginning of an airplane's maintenance life is the single most important measure affecting future maintenance costs,"* corrosion maintenance is often not performed adequately. Traditionally, corrosion has not been given sufficient attention with respect to structural integrity. This may have been due to the lack of understanding of the corrosion process and the inability to predict the nucleation and growth behavior of corrosion. Corrosion has therefore not been incorporated in the damage tolerance assessments, and an approach of "find it and fix it" has generally been accepted. This approach leads to extensive corrosion of both structural and non-structural parts, which significantly increases the cost of maintenance. Moreover, as airframes continue to age, corrosion will increasingly affect the structural integrity of these airframes.

Furthermore, state-of-the-art corrosion control techniques that are available are often not applied to older aircraft because of regulation, lack of awareness, education, and technology transfer.

Recommendations and Implementation Strategy

For many years, the importance of corrosion and corrosion control has been underestimated, and a "find it and fix it" approach to corrosion maintenance has generally prevailed. It must be understood that if corrosion is not taken care of in a timely manner, an airplane, as an important asset and with regard to its structural integrity, will be threatened. While it is the responsibility of the airframe manufactures to implement the newest available technology to mitigate corrosion, the operators must have a corrosion control program in place throughout the life of the airplane. The "find it and fix it" approach must be replaced by a more fundamental approach that is based on an understanding of the corrosion process and the ability to predict and monitor its behavior.

Corrosion prediction models need to be developed in order to define a cost-effective corrosion integrity program. In addition, development of improved inspection and monitoring techniques is needed to expand the capabilities in order to detect and monitor flaws from an early stage.

Summary of Issues

Increase consciousness of corrosion costs and potential savings.	Implement corrosion control programs early in the life of the airplane. Consciousness should be present at the design phase at all operator levels – from maintenance technicians to upper management.
Change perception that nothing can be done about corrosion.	The industry is well aware of the corrosion problems, but needs to put in more effort to do something about it.
Advance design practice to realize corrosion cost-savings.	The newest generation of airplanes has increased their design service life from 20 years to 40 years by incorporating corrosion control in the design. Research and development for corrosion-resistant materials and corrosion control methods need to continue.
Change technical practices to realize corrosion cost-savings.	Incorporation of state-of-the-art inspection and monitoring techniques in a corrosion management strategy will be key.
Change policies and management practices to realize corrosion cost-savings.	The "find it and fix it" approach should be amended by a prevention and control approach.
Advance life prediction and performance assessment methods.	The development of corrosion life prediction and performance models is critical to cost-effective structural integrity management. Effective predictive models are currently not available.
Advance technology (research, development, and implementation).	The needed technology advances include a better understanding of the corrosion process in aircraft materials and improved inspection and monitoring techniques.
Improve education and training for corrosion control.	Provide education to design and maintenance personnel in order to gain a better understanding of corrosion and be cognizant of current corrosion-resistant materials and corrosion control techniques. Training courses for maintenance technicians are necessary if effective corrosion maintenance is desired.

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Background

According to data presented in the 1999 edition of the *Aviation & Aerospace Almanac*, the combined aircraft fleet operated by U.S. airlines in 1998 totaled 7,478.(1) These include fixed-wing turboprop and turbojet, and rotary wing aircraft. Of this total number of aircraft, 3,973 are turbojet aircraft, which are divided into 29 different types for domestic and international service. Table 1 shows a 1997 listing of the major U.S. carrier fleets with the number and average age of the fleets' airplanes.(1)

Table 1. Major carrier jet fleets in 1997, as reported in the *Aviation & Aerospace Almanac*.(1)

CARRIER	NUMBER	AGE	CARRIER	NUMBER	AGE	CARRIER	NUMBER	AGE
ALASKA			**DELTA (cont.)**			**UNITED**		
B-737	31	6.9	L-1011	53	17.7	A-319*		
MD-80	44	7.7	MD-11	12	4.0	A-320	35	2.1
Total	**75**	**7.4**	MD-80	119	6.4	B-727	74	17.7
AMERICA WEST			MD-90	12	1.4	B-737	225	11.9
A-320	25	5.6	**Total**	**538**	**11.7**	B-747	56	14.1
B-737	61	12.0	**FEDERAL EXPRESS**			B-757	92	4.8
B-757	14	10.0	A-300-600	19	1.5	B-767	42	8.8
Total	**100**	**10.1**	A-310	29	12.7	B-777	16	1.4
AMERICAN			B-727	159	22.5	DC-10	52	21.4
A-300-600	35	7.2	B-747	2	19.6	**Total**	**592**	**11.5**
B-727	81	19.7	DC-10	34	17.1	**UNITED PARCEL SERVICE**		
B-757	90	4.7	MD-11	21	3.6	B-727	53	27.8
B-767	71	7.9	**Total**	**264**	**17.7**	B-747	16	24.1
DC-10	35	22.2	**NORTHWEST**			B-757	57	4.5
F-100	75	3.8	A-320	50	5.1	B-767	9	0.7
MD-11	16	4.4	A-330			DC-8	9	28.0
MD-80	260	8.6	B-727	46	17.8	**Total**	**144**	**16.5**
Total	**663**	**9.4**	B-747	43	15.5	**U.S. AIR**		
CONTINENTAL			B-757	48	7.2	B-737	203	10.4
A-300	4	16.2	DC-9	180	26.3	B-757	34	6.2
B-727	30	20.5	DC-10	37	22.5	B-767	11	7.5
B-737	132	11.5	MD-80	8	15.1	BAE-146	4	11.3
B-757	71	1.8	**Total**	**412**	**18.9**	DC-9	72	23.7
B-777*			**TWA**			F-100	40	5.8
DC-9	28	24.3	A-330*			F-28	13	12.1
DC-10	18	20.1	B-727	47	24.1	MD-80	31	14.7
MD-80	67	11.9	B-747	15	25.8	**Total**	**408**	**12.3**
Total	**350**	**11.9**	B-757	1	0.3	**SOUTHWEST**		
DELTA			B-767	14	12.4	B-737	241	8.1
B-727	129	19.7	DC-9	58	25.6	**Total**	**241**	**8.1**
B-737	67	11.8	L-1011	13	22.6			
B-757	88	7.9	MD-80	52	9.7			
B-767	58	8.3	**Total**	**200**	**19.9**			

Source: GKMG Consulting Services, Inc. **Data not available.*

The table shows that several types of airplanes are currently operating beyond the typical design life of 20 years. This aging of the commercial fleet has been the subject of considerable attention by industry and government for many years and has resulted in increased maintenance efforts for the aging aircraft. In April 1988, the sudden decompression of an Aloha Airline B-737-200 airplane and the subsequent separation of its fuselage skin [see the 1988 National Transportation Safety Board (NTSB) report](2) has resulted in more focused attention on the issue of aging aircraft. Although this incident was primarily attributed to widespread fatigue damage (WFD), the NTSB report addressed all factors that contributed to the structural deterioration of the airframe, including corrosion.

In order to prevent similar accidents in future airplanes, manufacturers, operators, and other aviation industry representatives joined together in September 1988 to form an Aging Aircraft Task Force Steering Committee (later called the Airworthiness Assurance Working Group).(3-5) Its charter was to develop all measures considered necessary to ensure the continued safety of aging airplanes. In order to accomplish this, the Airworthiness Assurance Working Group sponsored an industry-wide Structures Task Group for each aging airplane model. These included the following airplanes: Airbus A300; Boeing 707/720, 727, 737, and 747; British Aerospace BA1-11; Douglas DC-8, DC-9/MD-80, and DC-10; Fokker F-28; and Lockheed L-1011. Each group reviewed the various corrosion control practices with the primary objectives of maintaining airworthiness in an economical manner and establishing minimum procedures for preventing or controlling corrosion.

The working groups were directed to develop Corrosion Prevention and Control Programs (CPCPs). The recommendations developed in the CPCPs were incorporated in the Airworthiness Directives (ADs) issued by the Federal Aviation Administration (FAA). These ADs defined a baseline program for each airplane model, establishing minimum requirements for airline operators to prevent or control corrosion that may jeopardize continuing airworthiness. The baseline program includes definitions of corrosion, program implementation requirements, and mandatory reporting systems.

The mandatory CPCPs were intended to supplement each operator's existing maintenance program. The corrosion programs are self-adjusting in that findings of unacceptable corrosion levels require operators to adjust the tasks. These maintenance program adjustments should preclude recurrence of unacceptable corrosion findings. The adjustments may include actions such as reduced repetitive task intervals and/or improved corrosion treatments. The anticipated cost per individual airplane to comply with the mandatory CPCPs was calculated in 1992 by the FAA prior to issuance of the ADs and is shown in table 2.(5) The table shows the annual cost per aircraft type based on a 6-year major overhaul cycle.

Table 2. Annual estimated cost (1992) to implement corrosion airworthiness directives for an individual airplane.(5)

MODEL	AD NUMBER	COST (IN $) (Based on a 6-Year Cycle)	U.S. AD FLEET SIZE AFFECTED
A-300	94-18-02	44,000	54
BAC-1-11	93-02-14	38,500	45
B-707/-720	90-25-07	80,640	74
B-727	90-25-03	80,000	1,143
B-737	90-25-01	38,720	232
B-747	90-25-05	188,800	65
DC-8	92-22-07	105,700	222
DC-9/MD-80	92-22-08R1	87,100	1,016
DC-10	92-22-09R1	51,900	244
F-27	94-15-11	28,880	55
F-28	94-05-02	29,600 (based on a 4-year cycle)	46
L-1011	93-20-03 95-21-07	139,700 14,000	117

Corrosion Modes

Corrosion in an aircraft manifests itself in several different forms. Pitting and crevice corrosion are the most common forms of corrosion in the 2000 and 7000 series aluminum alloys, which are the principle materials of construction. Pitting corrosion produces deterioration of the airframe structures in localized areas and can have high penetration rates. Pits often create stress concentrations, which may reduce the fatigue life of a component. Crevice corrosion, by itself, is more destructive than pitting corrosion. Crevice corrosion occurs when a corrosive fluid enters and is trapped between two surfaces, such as a joint, a delaminated bondline, or under a coating. Both pitting and crevice corrosion, when unchecked, can readily develop into exfoliation corrosion or intergranular stress corrosion cracking. Exfoliation corrosion is a form of intergranular corrosion where corrosion attack occurs along the grain boundaries of elongated grains, causing a leaf-like separation of the metal grain structure (see figure 1). This form of corrosion often initiates at unprotected end grains, such as at fastener holes and plate edges.

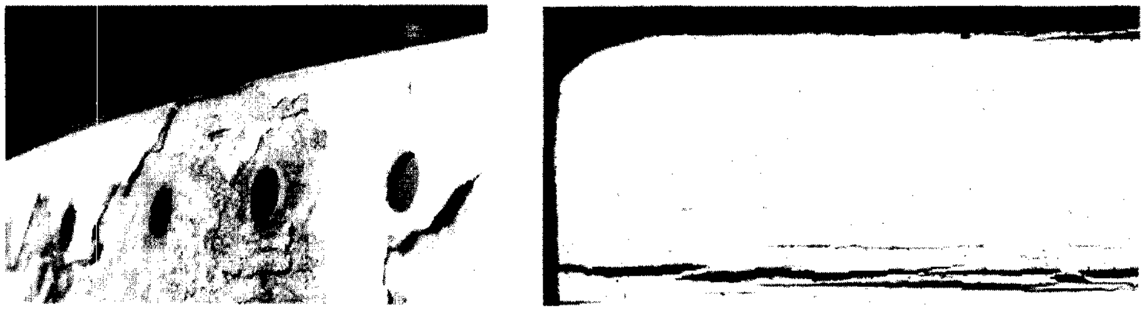


Figure 1. Exfoliation corrosion around fastener holes in aluminum alloy 7075-T6 fuselage section.

Intergranular stress corrosion cracking occurs when stresses are applied perpendicular to the susceptible grain boundaries. More so than pitting and crevice corrosion, susceptibility to exfoliation corrosion and intergranular stress corrosion cracking depends on alloy type, heat treatment, and grain orientation. Other common forms of corrosion include fretting corrosion, which occurs when two surfaces rub at high frequency and low amplitude in the presence of a corrosive environment, and galvanic corrosion, where dissimilar metals such as aluminum and steel are in direct contact. Isolating the different metals, which can be accomplished by proper design and assembly, can prevent both forms of corrosion.

Corrosion Causes

There are many contributing causes of corrosion in commercial aircraft.(6-7) Figure 2 shows some of the typical causes and sources of corrosion, which are divided into the two main categories of manufacturer and operator. The first potential source of corrosion is in the basic design process. Material selection, finishes, and structural configuration can have a significant impact on the corrosion performance of an airplane. During the design phase, attention must be paid to the basic principles of corrosion-conscious design, such as the selection of corrosion-resistant materials, the avoidance of dissimilar metal contact, crevices, stresses, and poor drainage. In addition, the selection of sealants and finish systems is an important part of a corrosion-conscious design. For example, the use of corrosion-inhibiting primers and sealants on fasteners and faying surfaces has become common practice for new airplanes, and the elimination of crevices is now required by "faying surface sealing" of all joints that are prone to corrosion. Corrosion-inhibiting compounds are routinely applied in the final assembly of many aircraft components, such as the inside fuselage crown and lower lobe, pressure bulkheads, pressure deck, under lavatories and galleys, wheel wells, wing-empennage cove areas, dry bays, empennage torque box interiors, and under fairings.

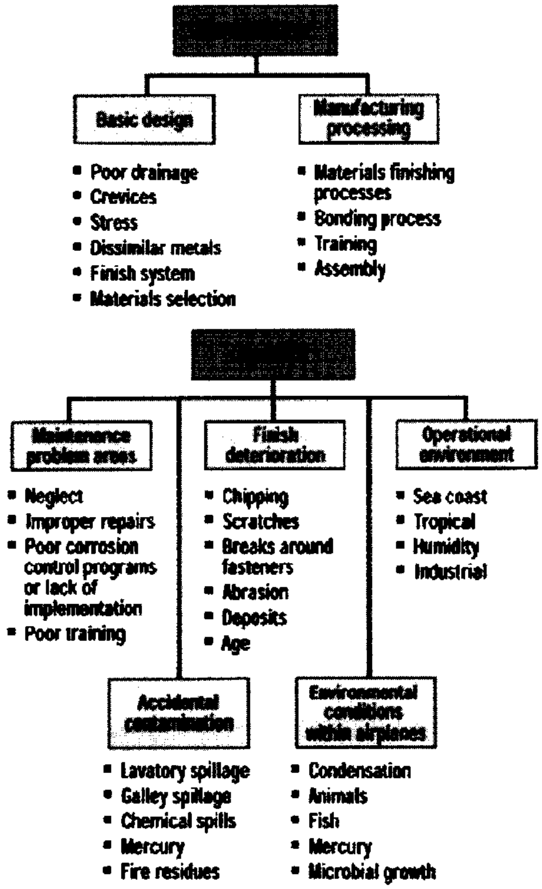


Figure 2. Typical causes and sources of corrosion.(7)

Another potential source of corrosion problems is in the manufacturing process. Specifically, the assembly and finishing processes can determine whether a specific component will be subject to premature corrosion. Of particular importance is the proper surface pretreatment and application of protective coatings and sealants, which must offer long-term durability in order to provide adequate corrosion protection.

Once airplanes are in the hands of operators, many factors, including operating conditions and maintenance practices, determine the corrosion performance of the airplanes. Operational environments such as marine, tropical, high humidity, and industrial can be extremely corrosive to the outside of an aircraft. Furthermore, during operation, the protective surface finishes can deteriorate by chipping, scratching, breaking around fasteners, abrasion, and aging. Environmental conditions inside an airplane can be even more damaging. For example, lavatory spillage, galley spillage, chemical spills, animal waste, microbial growth, fire residue, and corrosive cargo such as fish (saltwater) can create extremely corrosive conditions inside an airplane. Condensation that forms on the inside of the fuselage is also a potential source of internal corrosion. Boeing(8) has conducted an inspection of airplanes with the most severe moisture problems and found that as a result of moisture uptake in insulation blankets in B-737-300 airplanes, the weight had increased by an average of 36 kg (79 lb).

CORROSION CONTROL METHODS

Corrosion control can be accomplished in the design and manufacturing phase as well as in the operation and maintenance phase of the airplane.

Design and Manufacturing

Proper design for corrosion control must include the selection of materials, coatings, sealants, and corrosion-inhibiting compounds. In addition, consideration must be given to the avoidance of dissimilar metal contacts, access for maintenance, and proper drainage.

Material Selection

High-strength aluminum alloys are the most widely used airplane material because of their high strength-to-weight ratio. However, these alloys and the low-alloy, high-strength carbon steels are the two groups of airplane materials that are most susceptible to corrosion. Clad aluminum alloy sheets and plates are used where weight and function permit, while corrosion-resistant alloys and tempers are used to increase the resistance of the alloys to exfoliation corrosion and stress corrosion cracking. For example, the aluminum alloy 7055-T7751 plate, which is not susceptible to exfoliation corrosion, has replaced the alloy 7150-T651 plate on upper wing skins. Major structural forgings of aluminum alloys and steel may be shot-peened to improve their fatigue and stress corrosion life. Titanium alloys such as Ti-6Al-4V are used in severe environments, such as floor structures under entryways, galleys, and lavatories. Stainless steels are used where possible; however, a number of highly loaded structural components such as landing gears and flap tracks have to be made of low-alloy, high-strength steel. Fiber-reinforced plastics, which find wider application, are corrosion-resistant, whereas carbon fiber-reinforced plastics (CFRP) can induce galvanic corrosion in attached aluminum structures. An example of an application of CFRP is the Boeing 777 CFRP floor beam design where an aluminum splice channel is used to avoid attaching the floor beam directly to the primary structural frame (see figure 3).(7)

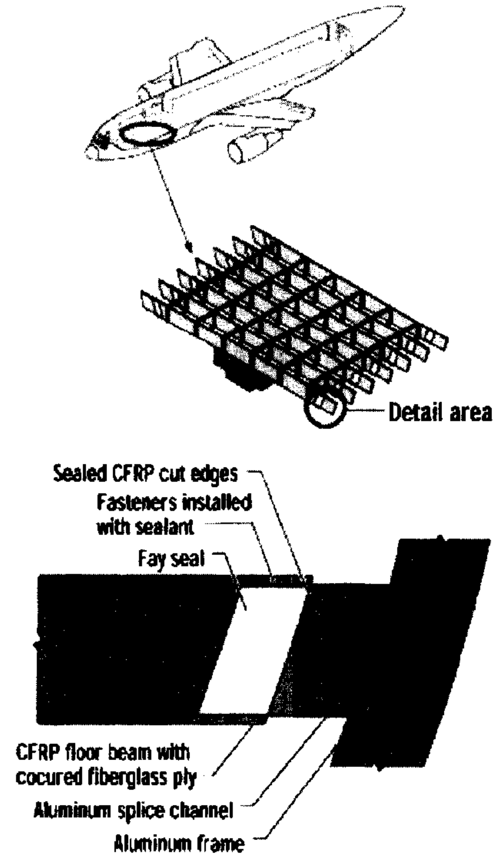


Figure 3. Boeing 777 design incorporating carbon fiber-reinforced plastic.(7)

Coating Selection

The most practical and effective means of protecting against corrosion is in the application of appropriate coatings. The coating system for aluminum alloys usually consists of an appropriate surface, such as an anodized surface with a corrosion-inhibiting primer. A commonly used process for anodization is phosphoric acid anodizing. The morphology of this film is such that primer adheres well. The corrosion-inhibiting primers that are generally used include Skydrol-resistant epoxies formulated for general use, resistance to fuel and hydraulic fluids, or for use on exterior aerodynamic surfaces. Exterior surfaces of the fuselage and vertical stabilizer are painted with a Skydrol-resistant, decorative polyurethane topcoat over a urethane-compatible epoxy primer that resists filiform corrosion. Titanium and stainless steel are cadmium plated and primed if they are attached to aluminum or steel parts. This is done in order to prevent galvanic corrosion of the aluminum or the steel.

Drainage

Effective drainage of the entire airplane structure is important in preventing fluids from becoming trapped in crevices. The entire lower pressurized fuselage is drained by a system of valved drain holes. The fluids are directed to these drain holes by a system of longitudinal and cross-drain paths through the stringers and frame shear clips. Figure 4 shows examples of improvements made in drainage.$^{(7)}$

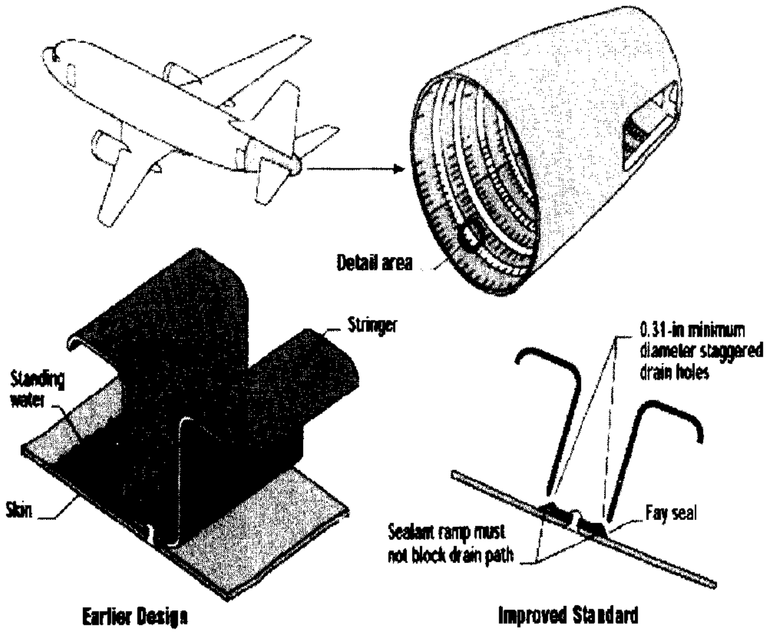


Figure 4(a). Lower lobe frame shear-tie drainage.

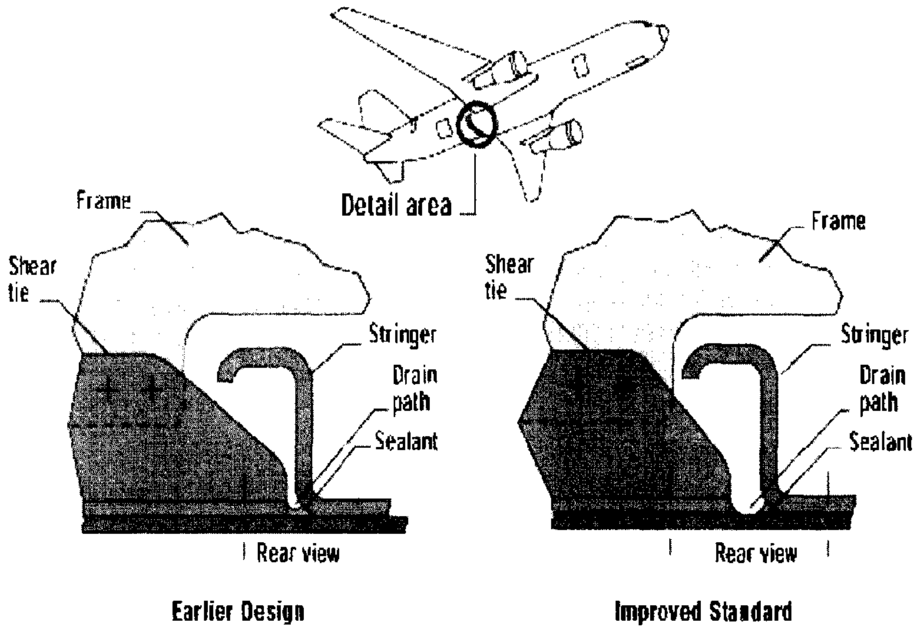


Figure 4(b). Lower lobe stringer drainage and sealing.(7)

Sealants

The potential for lap joint or joint crevice corrosion is eliminated by applying a sealant to the faying surfaces of the joints. A polysulfide sealant is typically applied to such areas as skin-to-stringer and skin-to-shear tie joints in the lower lobe of the fuselage, longitudinal and circumferential skin splices, skin doublers, the spar web-to-chord and chord-to-skin joints of the wing and empennage, wheel well structure, and pressure bulkheads. High-strength steel and titanium fasteners on the exterior of the airplane and fasteners that penetrate the pressurized portion of the fuselage are installed with a sealant. Finally, fillet seals are used in severe corrosion environments.

Corrosion-Inhibiting Compounds

Although the previously discussed design aspects provide most of the corrosion protection for airplanes, corrosion-inhibiting compounds (CICs) are widely used to provide additional protection, particularly when periodically applied in service. Typically, CICs are initially applied in areas that are prone to corrosion, such as in the lower lobe of the fuselage. In current production, CICs are applied to most aluminum structures. CICs are petroleum-based compounds that serve to displace water or serve as a coating. The water-displacing CICs are sprayed onto a structure to penetrate faying surfaces and keep water away from crevices. These CICs must be reapplied every few years to remain active, depending on the environment in which the airplane has been operating. The more viscous heavy-duty CICs are sprayed on as well, but they form a much thicker film and have less penetrating ability. They are used on parts of the airplane that are most prone to corrosion.

Access for Maintenance

The new generation aircraft are designed to provide easy access for frequent maintenance and corrosion inspections.

Operation and Maintenance

Design features and protective finishes applied during manufacturing and by operators after delivery of an aircraft should ensure a safe and economical service life; however, the aircraft requires continuous and appropriate maintenance by the operator to minimize corrosion. A proper corrosion maintenance program should prevent or eliminate conditions that can cause corrosion. These conditions include:

- trapped moisture,
- wet insulation blankets,
- plugged drain holes and passages,
- chipped or missing paint,
- loss of protective finish, and
- corrosive cargo.

Much corrosion can be avoided by proper and timely application of sealants and CICs. Particularly when components such as lavatories and galleys are removed for maintenance or repair, close attention should be paid to the proper sealant application procedures when these components are replaced. Moreover, maintenance programs should be able to detect corrosion at an early stage so that expensive repairs and replacement can be avoided. Nondestructive inspection (NDI) techniques that are being utilized include ultrasonic testing, eddy current testing, optical testing, and radiography. When corrosion is detected, it is removed by blending it out. When cumulative blend-out has reached an allowable limit (10 percent of the total thickness), the section or part will be replaced. Currently, there are efforts underway to further refine existing NDI techniques and to develop new techniques to be able to detect smaller flaws, as well as flaws and corrosion that are hidden within the structure and cannot be readily detected with current NDI techniques. Until recently, corrosion control of airplanes was based on the principle of "find and fix." However, even if all corrosion can be found, it cannot be completely eliminated. Thus, in an effort to control corrosion in an economical manner, corrosion is now being managed by a combination of selective blend-out and application of corrosion-preventive or water-displacing compounds.

CORROSION MANAGEMENT METHODS

Fleet Definition

The current operating fleet can be divided into three generations. The first generation are jet transport airplanes that were designed in the 1950s and 1960s where some of these are still in operation. These airplanes include the B-707, DC-8, DC-9, B-727, L-1011, and the earlier production models of the B-737 (-100, -200), B-747 (-100, -200, -300, SP), and the DC-10. They are characterized by a design that primarily addressed strength and fail-safe criteria while little or no attention was paid to incorporating corrosion protection into the design.

The second generation of jet transport airplanes, which were designed in the 1970s and the 1980s, include the B-737 (-300, -400, -500); B-747 (-400); B-757; B-767; MD-81, -82 and –83; MD-88; MD-11; and F-100. In addition to the strength and fail safety requirements, these airplanes are characterized by the incorporation of durability and damage tolerance standards into the design. It was realized that corrosion in aircraft was becoming an economic burden and could possibly become detrimental to the structural integrity of the airplane. Thus, as part of the durability standards, airframe manufacturers started to use corrosion-inhibiting primers and sealants for the faying surfaces of lap joints and fastener holes. Moreover, the Federal Aviation Administration (FAA) issued Airworthiness Directives (AD) related to corrosion control in design and maintenance.

The third generation of jet transport airplanes include the B-777 and the new generation B-737 (-600, -700, and -800) and B-747 (-400). In addition to the key characteristics of the first- and second-generation airplanes, these airplanes are characterized by the incorporation of significant improvements in corrosion prevention and corrosion control in design.

Corrosion Definition

The corrosion control program in the AD defines three levels of corrosion. It should be noted that the various modes of corrosion are not included in these definitions. Only the total loss of material, which affects the load-carrying capacity of a structure, is defined.

Level One Corrosion

- Corrosion damage occurring between successive inspections that is local and can be reworked or blended out within the allowable limits, as defined by the manufacturer.
- Corrosion damage that is local and exceeds allowable limits, but can be attributed to an event not typical of the operator's usage of other airplanes in the same fleet (e.g., mercury or acid spill).
- Operator experience over several years has demonstrated only light corrosion between successive inspections, and latest inspection and cumulative blend-out now exceed allowable limit.

Level Two Corrosion

- Corrosion occurring between successive inspections that requires rework or blend-out of structural elements as defined by the original equipment manufacturer's structural repair manual.

Level Three Corrosion

- Corrosion found during the first or subsequent inspections that is determined (normally by the operator) to be a potentially urgent airworthiness concern that requires expeditious action.
- In addition to the degree of corrosion, the extent of corrosion is taken into consideration. The appearance of corrosion on a single skin panel, single stringer, or single frame, where it does not affect any adjacent members, is defined as local corrosion. Widespread corrosion is defined as corrosion on two or more adjacent frames, chords, stringers, or stiffeners.
- The baseline program is designed to eliminate severe corrosion on airplanes and to control corrosion of all primary structures to Level One or better, meaning minor corrosion that never affects the airworthiness of the aircraft. Level Two and Level Three Corrosion must be reported to the airplane manufacturer, who uses the reported data to determine any actions required to ensure continuing airworthiness and economic operation.

Maintenance Schedule

A typical maintenance program begins with nightly inspections of each airplane, which consists of a detailed visual inspection and a review of the pilot's report. There are then scheduled periodic inspections:

A Check – This is a more detailed visual inspection conducted every 4 to 5 days after 65 to 75 flying hours. The interior and the exterior of each airplane is visually checked for general condition and any obvious damage, with particular attention given to areas where exposure to accidental or environmental damage may have occurred.

B Check – This check occurs approximately every 30 days. Specific access panels are removed for inspection. In addition to engine servicing, other safety and airworthiness items are checked as well.

C Check – This is performed every 12 to 18 months after the aircraft has flown about 5,500 hours. It is an in-depth, extended, heavy structural and maintenance check.

D Check – This is the most comprehensive inspection, conducted after 20,000 to 25,000 flying hours. The paint is removed from the exterior, and the interior of the airplane is completely stripped to allow for close inspection of all structural members of the fuselage.

AREAS OF MAJOR CORROSION IMPACT

The corrosion cost in the aircraft sector can be broken down into three major elements.

- Cost of engineering and materials that are incorporated into a new aircraft. Only in the past 10 years have airframe manufacturers paid serious attention to the corrosion-conscious design and manufacturing of aircraft. Corrosion awareness has been evidenced by selection of more corrosion-resistant materials, specific design features, and the application of corrosion-inhibiting compounds and sealants.

- Cost of maintenance and unscheduled downtime. A significant percentage of the corrosion cost in this sector can be attributed to maintenance of the older airframes, which have little or no corrosion protection incorporated into their structures.

- Loss in asset value (depreciation). Depending on the level of attention paid to corrosion during the various maintenance activities, resale or lease values may vary considerably.

Design and Engineering

Few cost data are available on corrosion-specific engineering and manufacturing of aircraft. However, for one of the latest models, the B-777, some cost information is available(9), that can be extrapolated to the fleet.

The cost of incorporating corrosion control in the structural design of the B-777 was estimated at 100,000 engineering-hours for a total cost of approximately $20 million. The required testing and material to support this design adds another $5 million. Therefore, the total cost to design a corrosion-tolerant airplane of the size of the B-777 can be estimated at $25 million. In order to implement the corrosion design features, approximately 113 kg of corrosion-inhibiting compounds are needed. At a current cost of $238/kg, the total cost per airplane is approximately $30,000. Furthermore, about 200 hours of technician labor are required to apply these compounds for an estimated labor cost of $15,000. Therefore, the total cost per airplane to install corrosion-inhibiting compounds is $45,000.

Extrapolation of the numbers obtained for one particular airplane to the entire fleet is based on the following statistics:

1. In 1998, U.S. manufacturers delivered eight different jet aircraft: B-737, B-747, B-757, B-767, B-777, MD-11, MD-83, and MD-90.

2. The total number of jet aircraft built in the United States in 1998 is 544.

3. It is assumed that each type of aircraft delivered in 1998 has similar corrosion design features and design costs ($25 million).

4. The cost to implement the corrosion design is the same for each of the aircraft types ($45,000 per aircraft).

Based on these statistics, the total design cost for the eight types of U.S.-built jet aircraft delivered in 1998 is estimated at $200 million and the corrosion fraction of the total manufacturing cost for 544 airplanes delivered in 1998 is estimated at $25 million (544 x $45,000). This gives a total design and engineering cost of $225 million.

Maintenance and Unscheduled Downtime

Maintenance Costs

Maintenance cost is part of the total operating cost. The total operating cost also includes flying operations, passenger services, aircraft and traffic servicing, promotion and sales, depreciation, and amortization. Table 3 shows the total annual operating and maintenance expenses for domestic and international U.S. carriers.(10)

Table 3. Operation and maintenance expenses of U.S. air carriers for calendar years 1977–1997.(10)

	DOMESTIC			INTERNATIONAL		
Year	**Operating Expenses ($ x million)**	**Maintenance Expenses ($ x million)**	**Maintenance Expenses (% of Total)**	**Operating Expenses ($ x million)**	**Maintenance Expenses ($ x million)**	**Maintenance Expenses (% of Total)**
1977	$15,166	$2,001	13.2%	$3,852	$450	11.7%
1978	$17,172	$2,155	12.5%	$4,355	$498	11.4%
1979	$21,522	$2,457	11.4%	$5,505	$571	10.4%
1980	$26,409	$2,758	10.4%	$6,766	$616	9.1%
1981	$29,051	$2,822	9.7%	$6,574	$540	8.2%
1982	$29,476	$2,709	9.2%	$6,452	$512	7.9%
1983	$31,186	$2,878	9.2%	$6,693	$548	8.2%
1984	$33,812	$3,176	9.4%	$7,485	$677	9.9%
1985	$36,311	$3,604	9.9%	$7,984	$768	9.6%
1986	$39,959	$4,475	11.2%	$8,458	$901	10.7%
1987	$43,925	$4,951	11.3%	$10,226	$1,096	10.7%
1988	$47,739	$5,643	11.8%	$12,403	$1,332	10.7%
1989	$52,460	$6,184	11.8%	$14,954	$1,724	11.5%
1990	$58,983	$6,921	11.7%	$18,915	$2,051	10.8%
1991	$56,939	$6,703	11.8%	$19,884	$2,094	10.5%
1992	$59,138	$6,906	11.7%	$21,716	$2,107	9.7%
1993	$60,921	$6,990	11.5%	$21,596	$1,916	10.4%
1994	$63,558	$7,274	11.4%	$21,693	$2,036	9.4%
1995	$66,224	$7,670	11.6%	$22,216	$2,253	10.1%
1996	$71,460	$8,276	11.6%	$24,147	$2,615	10.8%
1997	$75,615	$9,443	12.5%	$25,154	$2,878	11.4%

Source: GKMG Consulting Services, Inc., based on carrier Form 41 filings with U.S. DOT.

Note: Details may not add up to totals because of rounding, including scheduled and non-scheduled services for all certificated route air carriers and excluding supplemental air carriers, commuters, and air taxis.

The operating costs listed in the table are averages of specific aircraft with varying ages, with the older airplanes requiring higher maintenance than the newer airplanes. It is clearly indicated in the table that over the past 20 years, the percentage average cost of maintenance has not changed significantly, varying between 8 and 13 percent of the total operating cost. For example, in 1997, the total operating costs were approximately $76 billion for domestic operations and $25 billion for international operations. The maintenance expenses, which include corrosion maintenance expenses, were about $9.5 billion for domestic operations and $3 billion for international operations (12.5 percent and 11.4 percent, respectively, of the total operating expenses).

According to the Air Transport Association (ATA) Annual Report of 1998, the operating costs of individual airplanes varied greatly.(11) Table 4 shows the average operating cost per hour for the most common U.S.-operated aircraft in 1997. The table indicates a wide range of operating costs – from $1,409 for a DC-9-10 to $6,447 for a B-747-100. Assuming that the average maintenance cost for that year is 12 percent (refer to table 3), an average maintenance cost can be calculated.

Table 4. Aircraft operating costs – 1997.(11)
(Figures are averages for most commonly used models.)

TYPE OF AIRCRAFT	AIRCRAFT OPERATING COST PER HOUR	MAINTENANCE COST PER HOUR @ 12% OF OPERATING COST
B-747-100	$6,447	$773.64
B-747-400	$6,859	$823.08
B-747-200/-300	$7,300	$876.00
B-747-F	$7,497	$899.64
L-1011-100/-200	$3,720	$446.40
B-777	$4,241	$508.92
DC-10-10	$5,281	$633.72
DC-10-40	$4,746	$569.52
DC-10-30	$6,078	$729.36
MD-11	$6,406	$768.72
A-300-600	$5,237	$628.44
L-1011-500	$3,829	$459.48
B-767-300ER	$3,558	$426.96
B-757-200	$2,675	$321.00
B-767-200ER	$3,348	$401.76
MD-90	$1,636	$196.32
B-727-200	$2,504	$300.48
B-727-F	$4,993	$599.16
A-320-100/-200	$2,177	$261.24
B-737-400	$2,124	$254.88
MD-30	$2,087	$250.44
B-737-300	$1,918	$230.16
DC-9-50	$1,923	$230.76
B-737-100/-200	$1,904	$228.48
B-737-500	$1,743	$209.16
DC-9-40	$1,500	$180.00
DC-9-30	$1,988	$238.56
F-100	$2,002	$240.24
DC9-10	$1,409	$169.08

Source: Air Transport Association (ATA) Annual Report, 1998.

Table 5 shows the maintenance costs for individual aircraft operated by U.S. carriers.(12) The data shown in this table indicate significant deviations from the numbers shown in table 4, which are based on 12 percent of the average operating cost of individual airplanes. The difference is particularly obvious for the older aircraft. For example, the total maintenance cost for the B-747-200 is shown in table 5 as $2,384 per block hour, while the same cost is shown in table 4 as $876. Similarly, for a B-727-200, table 5 shows a maintenance cost of $832 versus a cost of $321 in table 4. For the newer airplanes, the costs stated in the two tables are much closer. For example, the hourly maintenance costs for the B-747-400 is $1,206 and $823 in tables 5 and 4, respectively. The increase in maintenance cost discrepancy with the age of the airplane could be attributed to anincrease in corrosion and fatigue inspection and maintenance as the airplane ages.

Moreover, table 5 indicates significant differences in maintenance costs for specific aircraft operated by different airlines. For example, the hourly cost to maintain a B-747-200 is $2,675 by Northwest Airlines and $1,541 by United Airlines. This difference in maintenance cost data is primarily the result of a difference in airframe maintenance costs. In addition, it may be noted that the depreciation of the United B-747-200 is more than twice that of the Northwest B-747-200. The maintenance costs suggest a difference in maintenance practices between the two operators. Assuming that the aircraft are of approximately the same age, a higher maintenance cost and also a lower rate of depreciation would indicate Northwest Airlines' intent to own or lease these aircraft for a longer time than United Airlines.

Table 5. 1998 Maintenance cost (per block hour) for individual aircraft.(12)
(AK-Alaska; AA-American; CO-Continental; DL-Delta; NW-Northwest; TW-TWA; UA-United Airlines; HP-America West; WN-Southwest; US-US Airways)

B-727-200	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number		78	22	129	40	23	75				367	
Airframe Maint ($)		373	482	190	243	686	473					340
Engine Maint ($)		219	110	151	230	44	220					177
Maint Burden ($)		484	314	203	56	364	458					315
Total Maint ($)		1,076	906	544	529	1,094	1,151					832
Block Hours/Day		8.1	9.8	8.8	7.6	8.2	8.3					8.4
Maint / Day ($)		8,716	8,879	4,787	4,020	8,971	9,553					6,989
B-737-100/-200	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number			3	54			25	18	37	64	201	
Airframe Maint ($)			240	114			222	206	921	259		343
Engine Maint ($)			12	106			146	207	33	84		96
Maint Burden ($)			134	131			422	182	42	356		216
Total Maint ($)			386	351			790	595	996	699		636
Block Hours/Day			9.1	10.1			7.8	9.7	10.5	9.3		9.6
Maint / Day ($)			3,513	3,545			6,162	5,772	10,458	6,501		6,288
B-737-300	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number			92	21			101	46	207	85	552	
Airframe Maint ($)			159	113			146	245	123	151		147
Engine Maint ($)			6	238			179	241	132	181		140
Maint Burden ($)			88	209			381	110	42	246		150
Total Maint ($)			253	560			706	596	297	578		437
Block Hours/Day			10.2	9.4			10.3	11.3	11.2	10		10.6
Maint / Day ($)			2,581	5,264			7,272	6,735	3,326	5,780		4,632

Table 5. 1998 maintenance cost (per block hour) for individual aircraft (continued).$^{(12)}$

B737-400	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number	37									54	91	
Airframe Maint ($)	69									68		68
Engine Maint ($)	4									209		112
Maint Burden ($)	26									22		24
Total Maint ($)	99									299		204
Block Hours/Day	11.6									9.6		10.4
Maint / Day ($)	1,148									2,870		2,122

B737-500	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number			67				57		24		148	
Airframe Maint ($)			94				327		137			188
Engine Maint ($)			207				179		12			161
Maint Burden ($)			159				401		42			228
Total Maint ($)			460				907		191			577
Block Hours/Day			10.1				9.8		11.1			10.1
Maint / Day ($)			4,646				8,889		2,120			5,828

B747-100	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number							5				5	
Airframe Maint ($)							421					421
Engine Maint ($)							352					352
Maint Burden ($)							845					845
Total Maint ($)							1,618					1,618
Block Hours/Day							10.2					10.2
Maint / Day ($)							16,504					1,6504

B747-200	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number					25		9				34	
Airframe Maint ($)					724		394					639
Engine Maint ($)					968		343					808
Maint Burden($)					983		804					937
Total Maint ($)					2,675		1,541					2,384
Block Hours/Day					9.6		9.2					9.5
Maint / Day ($)					25,680		14,177					22,648

B747-400	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number					10		34				44	
Airframe Maint ($)					361		396					388
Engine Maint ($)					549		143					235
Maint Burden ($)					508		604					583
Total Maint ($)					1,418		1,143					1206
Block Hours/Day					12.6		12.6					12.6
Maint / Day ($)					17,867		14,402					15,196

B757-200	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number		95	32	97	48		96	13		34	415	
Airframe Maint ($)		119	143	98	256		229	172		195		165
Engine Maint ($)		276	5	192	212		95	184		251		182
Maint Burden ($)		115	79	174	152		418	137		137		203
Total Maint ($)		510	227	464	620		742	493		583		550
Block Hours/Day		10.7	10.4	11.5	11.6		11	13		10.7		11.1
Maint / Day ($)		5,457	2,361	5,336	7,192		8,162	6,409		6,238		6,105

Table 5. 1998 maintenance cost (per block hour) for individual aircraft (continued).(12)

B-767-200	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number		30		15		11	19			12	87	
Airframe Maint ($)		418		130		491	372			212		338
Engine Maint ($)		178		381		84	224			115		196
Maint Burden ($)		449		304		708	596			112		437
Total Maint($)		1,045		815		1,283	1,192			439		971
Block Hours/Day		10.3		10.4		12.6	10.9			13.9		11.3
Maint / Day ($)		10,764		8,476		16,166	12,993			6,102		10,972

B-767-300	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number		45		68		4	27				144	
Airframe Maint ($)		151		140		142	120					140
Engine Maint ($)		183		193		103	197					188
Maint Burden ($)		147		223		246	368					225
Total Maint ($)		481		556		491	685					553
Block Hours/Day		13.7		13		13.5	12.8					13.2
Maint / Day ($)		6,590		7,228		6,629	8,768					7,300

B-777	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number							34				34	
Airframe Maint ($)							391					391
Engine Maint ($)							–					–
Maint Burden ($)							403					403
Total Maint ($)							718					718
Block Hours/Day							13.6					13.6
Maint / Day ($)							9,765					9,765

Fokker-100	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number		75								40	115	
Airframe Maint ($)		199								123		173
Engine Maint ($)		81								173		112
Maint Burden ($)		145								417		236
Total Maint ($)		425								713		521
Block Hours/Day		8.7								8.2		8.5
Maint / Day ($)		3,698								5,847		4,429

L-1011-1-250	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number				23							23	
Airframe Maint ($)				318								318
Engine Maint ($)				267								267
Maint Burden ($)				349								349
Total Maint ($)				934								934
Block Hours/Day				9.8								9.8
Maint / Day ($)				9,153								9,153

L-1011-1-500	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number				14							14	
Airframe Maint ($)				315								315
Engine Maint ($)				264								264
Maint Burden ($)				367								367
Total Maint ($)				946								946
Block Hours/Day				9.1								9.1
Maint / Day ($)				8,609								8,609

Table 5. 1998 maintenance cost (per block hour) for individual aircraft (continued).[12]

MD-11	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number		11		15							26	
Airframe Maint ($)		619		230								375
Engine Maint ($)		313		131								199
Maint Burden ($)		505		255								348
Total Maint ($)		1,437		616								922
Block Hours/Day		11.2		13.9								12.7
Maint / Day ($)		16,094		8,562								11,709

DC-9-30	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number			21		116	34				48	219	
Airframe Maint ($)			272		324	288				188		282
Engine Maint ($)			46		192	168				229		182
Maint Burden ($)			169		233	389				382		286
Total Maint ($)			487		749	845				799		750
Block Hours/Day			8.6		7.7	8.4				8.3		8.0
Maint / Day ($)			4,188		5,767	7,098				6,632		6,000

DC-10-30	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number		5	30		16		8				59	
Airframe Maint ($)		461	533		327		1039					526
Engine Maint ($)		514	426		535		576					482
Maint Burden ($)		501	507		133		726					423
Total Maint ($)		1,476	1,466		995		2,341					1,431
Block Hours/Day		9.4	11.4		11.5		9.4					11.0
Maint / Day ($)		13,874	16,712		11,443		22,005					15,741

MD-80	**AK**	**AA**	**CO**	**DL**	**NW**	**TW**	**UA**	**HP**	**WN**	**US**	**TOTAL**	**AVE**
Number	39	260	69	120	8	72				31	599	
Airframe Maint ($)	236	169	328	109	403	151				68		175
Engine Maint ($)	96	90	73	99	–	113				–		84
Maint Burden ($)	134	186	213	124	626	239				431		196
Total Maint ($)	466	445	614	332	1,029	503				420		455
Block Hours/Day	11.3	10	9.4	9.9	8.2	10.3				9		10.1
Maint / Day ($)	5,266	4,539	5,772	3,287	8,438	5,181				3,780		4,596

Maintenance Trends

An analysis of 25 years of the DOT Form 41 commercial fleet maintenance cost data indicated that for all aircraft types, the maintenance cost for engines remained relatively constant.[13] However, trend diagrams, such as those shown in figure 5, clearly indicate that airframe maintenance costs started to increase in the mid-1980s, which coincided with the fleet leader reaching its design life of 20 years. The maintenance trend diagram in figure 5 represents the maintenance costs of 60 Boeing Classic 747-100/-200 airplanes for a period of 25 years. According to the diagram, the average fleetwide Boeing Classic 747 airframe maintenance grew at an annual rate of 7 percent from 1985 to 1998. A summary diagram in figure 6 shows that the increase in maintenance cost growth rates over the life of an airframe ranges from 3.5 percent for the DC-9 to 9 percent for the DC-10. Figure 6 also shows the average age of five different aircraft as a function of cost per flight-hour. The arrows in the figure indicate that the oldest aircraft or fleet leaders are the B-747 and the B-727. The figure shows the high airframe cost of the B747 and DC10 components compared with those of the smaller DC-9, B-737, and B-727 airframes.

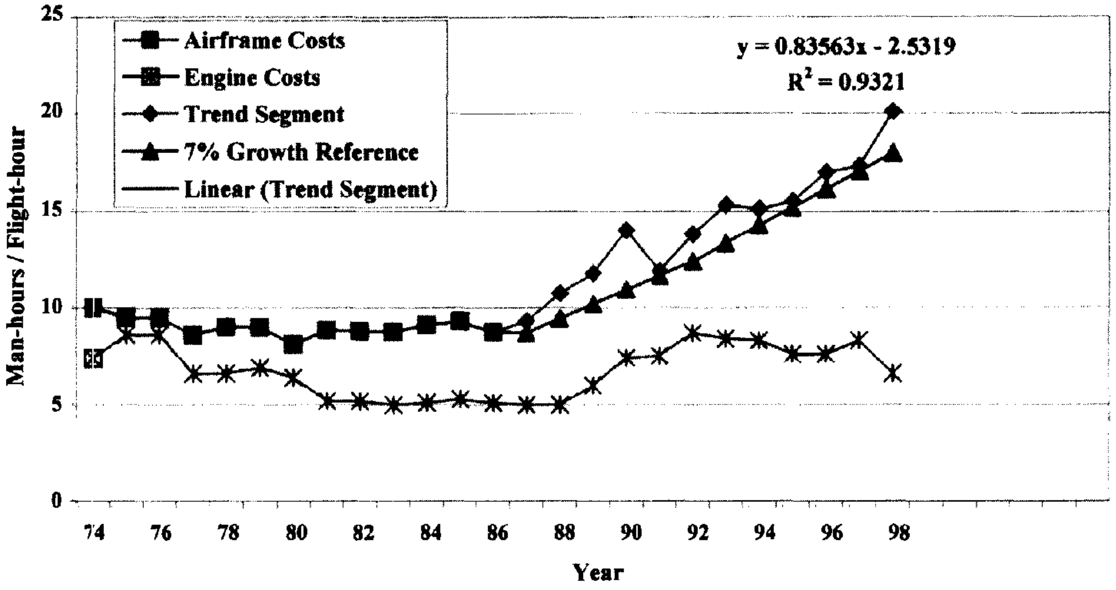


Figure 5. Maintenance trend analysis – B-747-100/-200.(13)

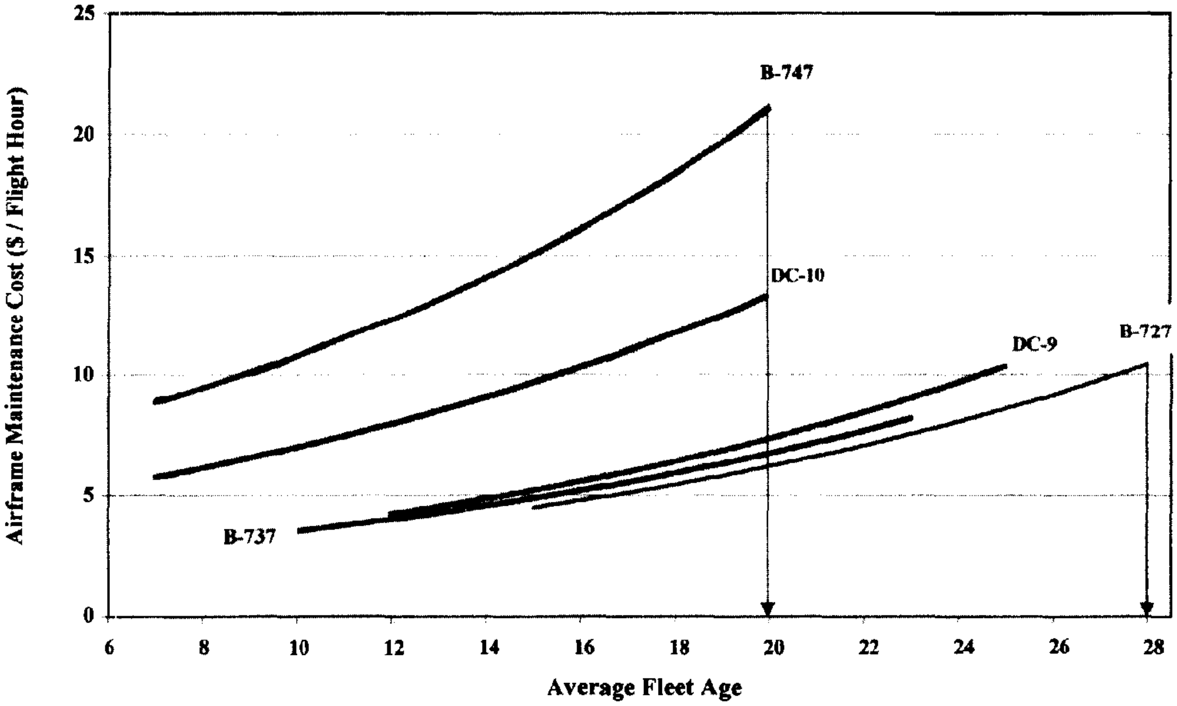
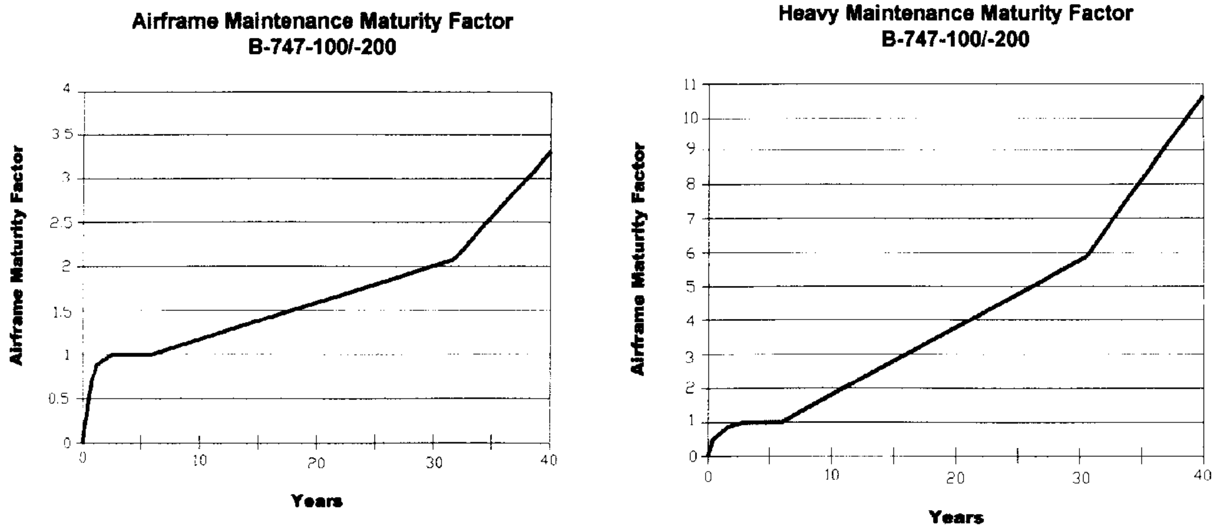


Figure 6. Maintenance trend analysis showing airframe maintenance cost per flight-hour as a function of average fleet age.(13)

Airplane Maturation

The level of maintenance depends on the age of an airplane. The service life of an airplane can be divided into three different phases: the newness phase, the mature phase, and the aging or post-design life phase. The airplane mature phase is defined as beginning at the end of the first major comprehensive maintenance cycle (D-check) and lasting through the second maintenance cycle.(14) The mature phase starts at about the fifth or sixth year of operation and ends arbitrarily at 25,000 flight-hours. For an aircraft utilized about 2,500 hours per year, the newness phase lasts for the first 5 to 6 years, and the mature phase occurs the following 5 to 6 years. Beyond this point, industry maintenance cost data indicate that an airframe enters its aging phase. Boeing has developed an analytical/empirical model to predict the maintenance costs of different types of aircraft. Figure 7 shows the results of the model in the form of maturation diagrams. The figure shows the airframe maturity factor as a function of the age of specific aircraft. This factor is an age-related multiplying factor for a total aircraft maintenance cost (see table 6). Assuming that most of the maintenance costs are incurred during depot maintenance, maturity diagrams for light (A- and B-checks) and heavy maintenance (C- and D-checks) were developed. These are indicated in figure 7 as airframe and heavy maintenance maturity factor diagrams.



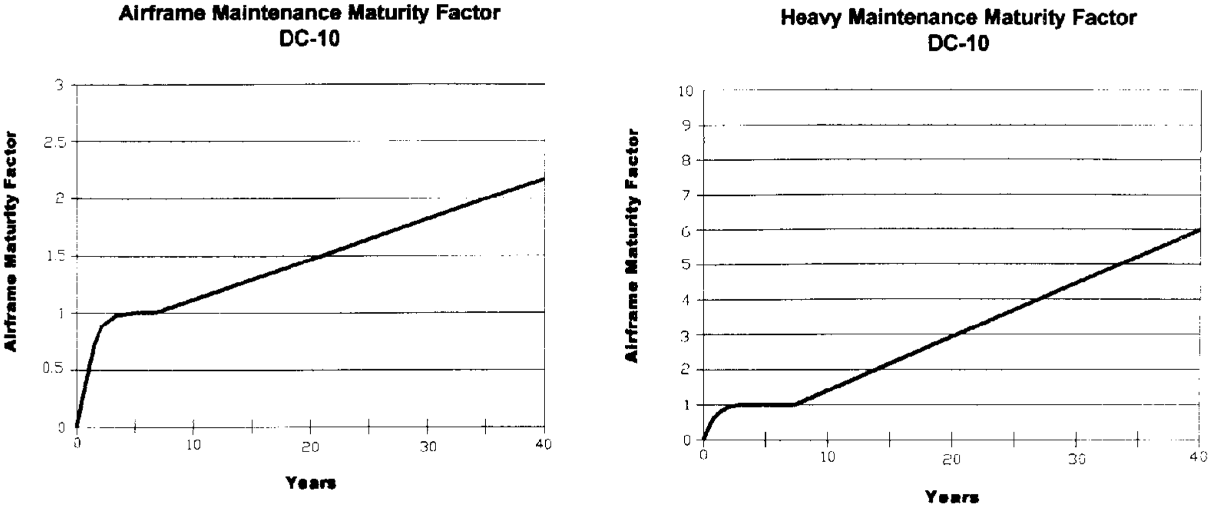


Figure 7. Airframe maintenance and heavy maintenance maturity diagrams.(14)

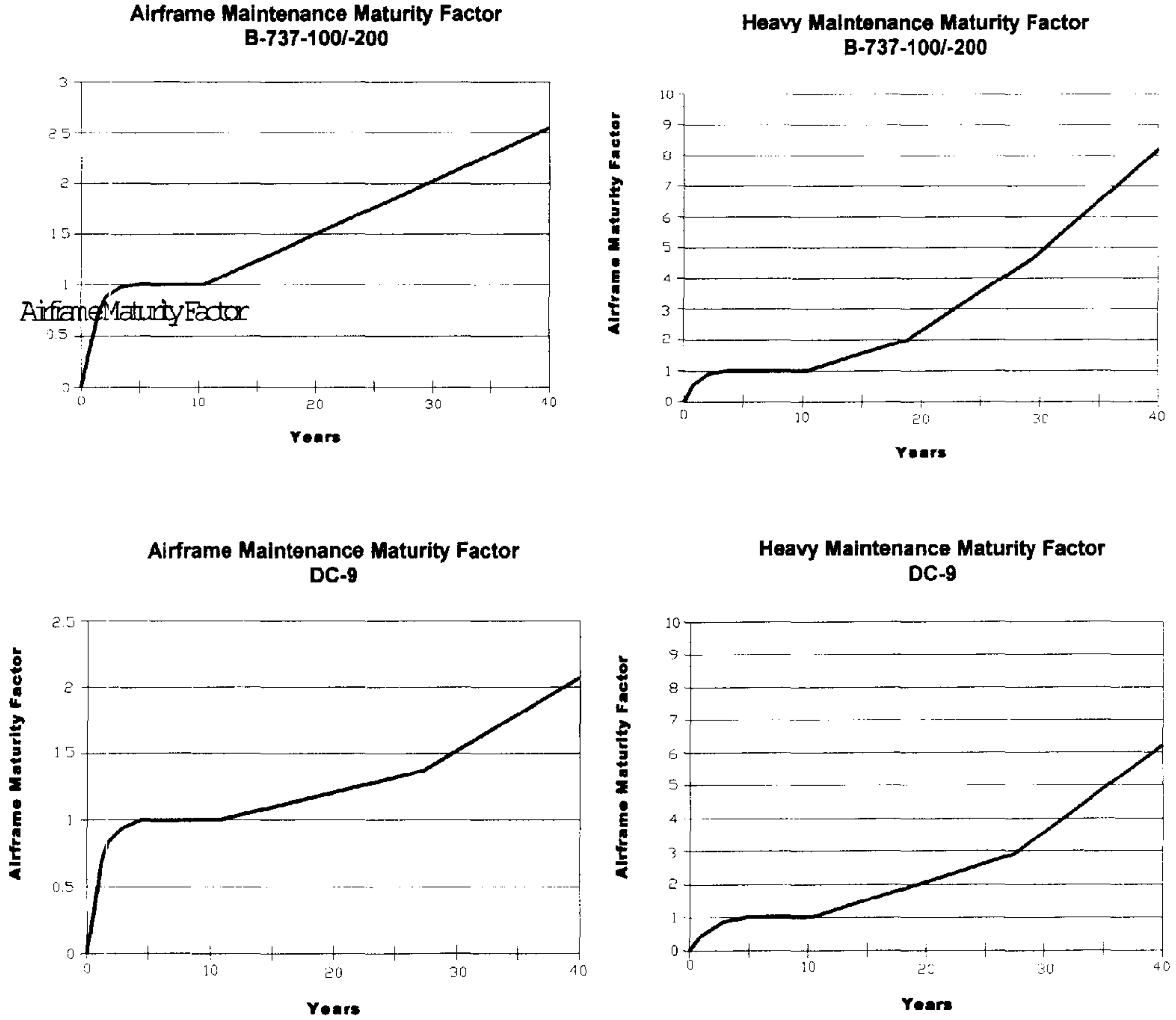


Figure 7. Airframe maintenance and heavy maintenance maturity diagrams (continued).(14)

The estimated mature maintenance costs in 1999 in dollars per flight-hour (maturity factor = 1) are shown in table 6.(15) The total maintenance costs shown in the table are based on labor and material for the airframe and the engine, as well as shipping and handling. Based on the curves and the estimated maturation maintenance cost, the average annual maintenance cost of an airplane can be calculated. For example, if at year 35 the airframe maturity factor is 2 and the heavy maintenance maturity factor is 6, one would multiply the mature values in current dollars by those factors to predict the average annual costs when the airplane is 23 years old. It should be noted that in the aging phase, the rate of increase of both the airframe maturity factor and the heavy maintenance maturity factor varies significantly for the different airplanes, but that the escalation of maintenance cost is dominated by the medium (C-check) and heavy (D-check) maintenance cost increases.

The diagram in figure 5 and the data indicating a maturity factor of 1 in table 6 refer to the total maintenance cost, which includes corrosion- and fatigue-related maintenance. These two modes of deterioration are intertwined and, therefore, are important factors to be considered as the Corrosion Prevention and Control Programs (CPCPs) and aging programs are implemented. Metal is appropriately removed when corrosion is detected; as a result of this removal, the airframe becomes less fatigue-resistant and this leads to an increased number of non-routine repairs during the heavy checks. The cost numbers in table 6 are estimates and do not include the maintenance burden. The reported cost numbers in table 5 include the maintenance burden, which results in a higher total maintenance cost.

Table 6. Estimated mature maintenance cost in 1999 (U.S. dollars per flight-hour).(15)

AIRPLANE	737-200	737-300	737-700	747-200	747-400	DC10-30	DC8-55F	DC9-30
LABOR								
Airframe	62.67	65.59	52.68	186.89	180.34	154.42	181.82	59.53
Engine	15.68	13.80	11.22	72.91	56.49	53.78	39.48	16.74
LABOR (Subtotal)	**78.35**	**79.39**	**63.90**	**259.80**	**236.83**	**208.20**	**221.30**	**76.27**
MATERIAL								
Airframe	46.58	46.63	42.24	201.13	234.57	159.96	145.04	46.49
Engine	55.26	109.09	100.04	511.83	511.48	432.07	92.20	57.19
Shipping/Handling	7.13	10.90	9.96	49.91	52.22	41.44	16.61	7.26
Contractor's Surcharge	–	–	–	–	–	–	–	–
MATERIAL (Subtotal)	**108.96**	**166.63**	**152.23**	**762.86**	**798.28**	**633.47**	**253.84**	**110.95**
TOTAL DIRECT	**187.31**	**246.02**	**216.13**	**1,022.67**	**1,035.11**	**841.67**	**475.14**	**187.22**
OVERHEAD	**188.03**	**190.55**	**153.36**	**623.53**	**568.40**	**499.69**	**531.13**	**183.05**
TOTAL MAINTENANCE	**$375.34**	**$436.57**	**$369.49**	**$1,646.20**	**$1,603.51**	**$1,341.36**	**$1,006.27**	**$370.27**

Fleet Costs

In 1983, the International Air Transportation Association (IATA) conducted a survey of international carriers on the cost of aircraft corrosion.(16) The IATA document, *Guidance Material on Design and Maintenance Against Corrosion of Aircraft Structures*, dated November 1983, states that the cost of aircraft corrosion can be expressed in several ways:

- Direct corrosion cost per flight-hour is between $8 and $20, depending on the operator and aircraft type (not including maintenance overhead), based on 1982 costs.
- Corrosion fraction of direct airframe maintenance costs is between 6 and 8 percent.
- Total annual direct cost for IATA member airlines would be close to $200 million based on 1982 operations.

The above-reported values represent the costs for a range of airlines and aircraft types. The lower value is very conservative and is largely based on one operator's actual modification cost alone. The higher value is more likely to be closer to the actual corrosion cost since it is based on a breakdown of actual modification, routine maintenance, and inspection costs. Furthermore, it was stated in the document that the major cost component associated with corrosion prevention and control is the cost of labor. An additional cost that is not reflected in the IATA numbers is the unscheduled downtime.

When assuming that in 1982 the cost of corrosion was 8 percent of the total maintenance cost [$3,221 million for domestic and international carriers (see table 3(11))], the total cost of corrosion in 1982 dollars can be estimated at $257 million. This cost is close to the IATA estimate of $200 million.

In table 7, the total 1996 maintenance expenses are presented for the various major national, regional, and cargo airlines.(10) Presently, the cost of corrosion maintenance is estimated at between 8 percent of the total maintenance expenses for new airplanes and 20 percent of that of old airplanes.(9) Assuming that the average corrosion maintenance expense is 15 percent of the total maintenance expense, the corrosion maintenance expense for the different carrier groups was calculated. The total maintenance expense of $11.5 billion in table 7 is in approximate agreement with the total maintenance expense shown in table 3. Table 3 shows that the total maintenance expenses in 1996 and 1997 are $10,891 billion and $12,321 billion, respectively.

Summing up the estimated 1996 corrosion maintenance costs results in a total expense of approximately $1.7 billion. This number includes labor, materials, and consumables, but does not include the cost of unscheduled downtime.

Table 7. U.S. carriers' maintenance expenses (1996 dollars).(10)

CARRIER	MAINTENANCE EXPENSE ($ x million)	% OF TOTAL OPERATING EXPENSES	CORROSION MAINTENANCE COST @ 15% OF MAINTENANCE EXPENSE ($ x million)
AK	116.9	8.83	17.5
America West	199.4	11.56	29.9
AA	1,873.5	13.00	281.0
CO	665.0	11.63	99.7
DL	1,114.8	8.86	167.2
NW	1,125.2	12.81	168.8
WN	353.9	10.75	53.1
TW	455.1	13.55	68.3
UA	2096.9	13.02	314.5
US	935.6	11.82	140.3
TOTAL MAJOR	**$8,936.2**	**11.58%**	**$1,340.4**
AirTran Airlines	82.5	28.37	12.4
Aloha	40.2	17.67	6.0
American TransAir	99.1	13.46	14.9
Frontier	33.3	19.85	4.7
Hawaiian	95.9	23.84	14.4
Midway	22.2	13.00	3.3
Midwest Express	32.8	12.06	4.9
Reno	48.3	11.38	6.8
World	66.0	22.55	9.9
TOTAL NATIONAL	**$515.4**	**18.02%**	**$77.3**
Air Wisconsin	27.0	19.69	4.1
Atlantic Southeast	68.6	22.46	10.3
Continental Express	78.4	20.08	11.8
Executive	23.1	20.28	3.5
Horizon	62.8	21.05	9.4
Simmons	78.1	17.03	11.7
Trans States	29.7	16.24	4.5
TOTAL REGIONAL	**$367.8**	**19.55%**	**$55.2**

Table 7. U.S. carriers' maintenance expenses (1996 dollars) (continued).[10]

CARRIER	MAINTENANCE EXPENSE ($ x million)	% OF TOTAL OPERATING EXPENSES	CORROSION MAINTENANCE COST @ 15% OF MAINTENANCE EXPENSE ($ x million)
Arrow Air	33.7	36.09	5.5
Atlas	26.1	7.57	3.9
DHL	105.3	9.17	158.0
Emery	62.3	28.03	9.4
Evergreen	43.5	19.45	6.5
Federal Express	850.9	7.19	127.6
Polar Air Cargo	87.3	25.89	13.1
Southern Air Transport	85.6	46.63	12.8
UPS	410.0	22.69	61.5
TOTAL CARGO	**$1,707.7**	**22.52%**	**$256.1**
GRAND TOTAL	**$11,527.1**		**$1,729.1**

Source: GKMG Consulting Services, Inc.

Unscheduled Downtime

A typical cost for U.S. domestic operations is $2,500 per delay/interruption-hour.[9] When an annual downtime for an older airplane, such as a B-727, of 40 hours is assumed, an additional cost of $100,000 can be estimated. Assuming that airplanes at or beyond their design service life of 20 years (a total of 1,034 according to table 1) have an average annual downtime of 40 hours and assuming that 50 percent results from corrosion, the total annual downtime cost due to corrosion is approximately $50 million (1,034 planes x 40 hours per plane x $2,500 per hour x 0.5).

Older airplanes will also be subject to increased scheduled and unscheduled maintenance downtime to incorporate modifications, to comply with aging aircraft programs, and to complete increased maintenance required as the airplane ages. For example, comparing the B-727 with the B-737-500, the revenue loss for a B-727 due to scheduled and unscheduled maintenance can range from 15 to 25 flight-days. Using the same definition for older airplanes and assuming that 50 percent of unscheduled maintenance (13 days) is due to corrosion, a total corrosion-related cost can be estimated at $250 million. Finally, a 2.5 percent reduction in passenger load factor is assumed on the B-727 to address the loss of passengers at full load due to performance degradation, and some reduction in revenue can be assumed due to passenger preference issues. The resulting cost could not be estimated.

Corrosion Maintenance Costs for Older Airplanes

The following empirical equations are used by Boeing to calculate the cost of corrosion maintenance for the older individual aircraft B-727-100/-200, B-737-100/-200, and B-747-100/-200:

Corrosion Maintenance Cost = Routine Maintenance + Non-Routine Repair + Parts and Consumables

For the B-727-100/-200 and the B-737-100/-200, the values are estimated as:

Routine Maintenance	4,500 h x $X per hour
Non-Routine Repair	3,000 h x $X per hour
Parts and Consumables	$4,500

where X = technician's cost (estimated at $65/hr)

For the B-747-100/-200, the values are estimated as:

Routine Maintenance	20,000 h x $X per hour
Non-Routine Repair	80,000 h x $X per hour
Parts and Consumables	$80,000.

where X = technician's cost (estimated at $65/hr).

The cost calculations are based on a 6-year period, which is the typical period between heavy maintenance (D-check).

The corrosion maintenance costs for the B-757 and B-767 are similar to that of the B-727-100/-200 and the B-737-100/-200.

The newer versions of the B-737 and the B-747, i.e. B-737-300/-400, B-737-600/-700/-800, and B-747-1400, have a 3 to 16 percent less total corrosion maintenance cost than the older versions of these airplanes. Finally, the B-777 has similar corrosion maintenance costs to the B-737-800. Table 8 summarizes the results of the corrosion maintenance costs calculated.

Table 8. Total cost of corrosion maintenance per year.

AIRPLANE TYPE	CORROSION COST
B-727-100/-200	$88,750
B-737-100/-200	$88,750
B-747/100/-200	$1,096,667
B-757	$88,750
B-767	$88,750
B-737-300/-400	$86,088
B-737-600/-700/-800	$74,976
B-747-400	$921,200
B-777	$74,976

According to one major airline, the average cost of corrosion maintenance is approximately $200,000 per airplane per year or 10 to 12 percent of the total maintenance cost.

Loss in Asset Value (Depreciation)

Depending on the level of attention paid to corrosion during the various maintenance activities, resale or lease values of aircraft may vary. The resale value of a pre-owned plane is directly affected by its (possibly corroded) appearance and any corrosion-related defects an inspector or appraiser may observe. In the current sector description, no estimate was made due to the large variety in planes and many other factors that play a role in the resale value of aircraft.

Total Cost of Corrosion

The total cost of corrosion for U.S. aircraft is estimated at $2.225 billion, including $0.225 billion for design and engineering, $1.7 billion for corrosion-related maintenance, and $0.3 billion for unscheduled downtime. No cost estimate was established for loss of asset value (depreciation).

CORROSION MANAGEMENT ASSESSMENT

Significant improvements have been made in the corrosion design of new airplanes. The airframe manufacturers have implemented many key design improvements over the past 25 years. Figure 8 shows some of these improvements for the B-747 since the early 1970s.(9) The improvements range from the replacement of corrosion-prone materials, such as aluminum alloy 7075-T6, to improved adhesive bonding processes, to the use of sealants in fastener holes and on faying surfaces, to the control of spillage, such as galley and lavatory fluids. Other airplane models have made similar improvements.

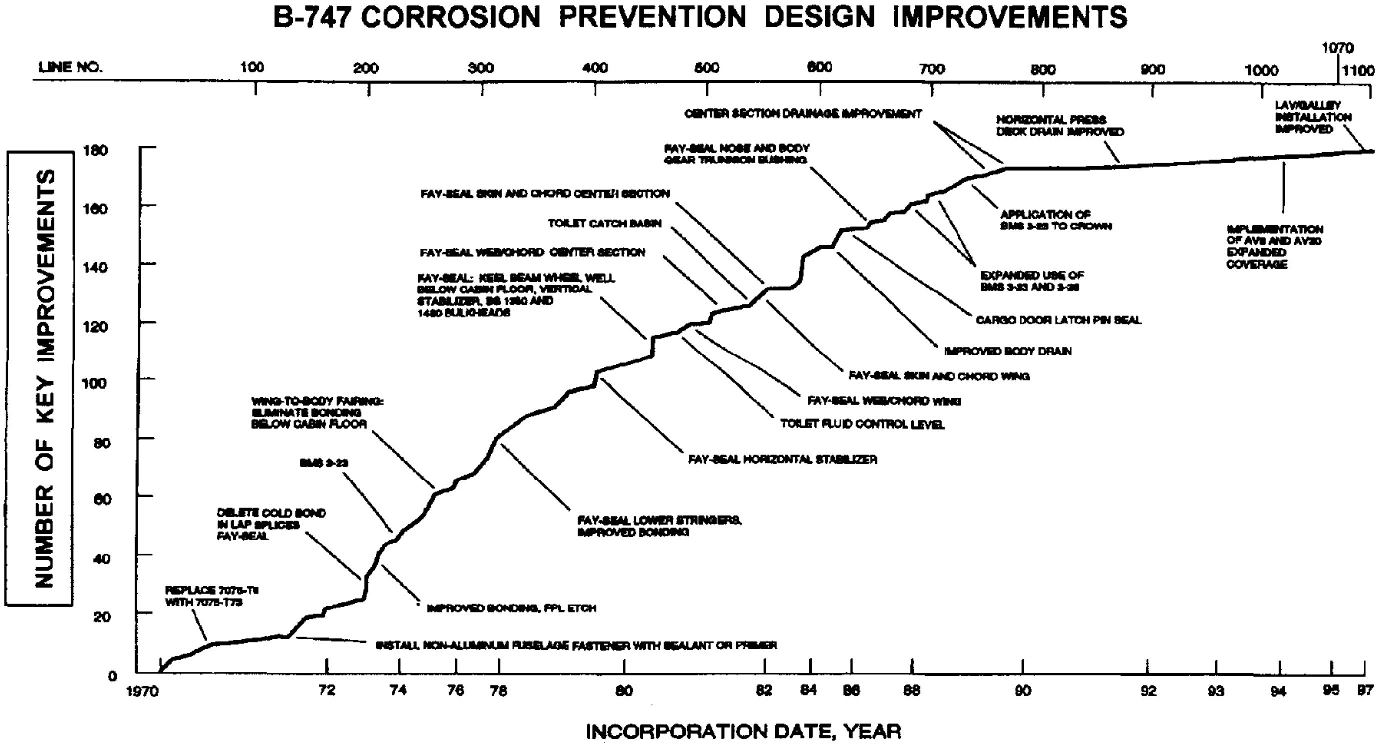


Figure 8. B-747 corrosion prevention design improvements.(9)

It must be understood that aggressive maintenance can mitigate and perhaps prevent corrosion in aging airplanes. In fact, a major U.S. domestic airline has stated that the degree to which an airline aggressively pursues corrosion prevention from the beginning of an airplane's maintenance life is the single most important measure affecting future maintenance costs.(17) In the same statement, it was pointed out that exposure to humid, coastal ground environments, as well as certain corrosive cargo materials, can play a very significant role, especially when accompanied by a less-than-aggressive approach to corrosion prevention and control. Some airlines with available resources, who are planning to keep their aircraft for many years, must be aggressive in their approach to preventing corrosion, especially when the airframe is exposed to harsh environments. However, if resources are unavailable, or the airplanes are expected to be sold, maintenance practices will seldom go beyond the minimum regulatory requirements. These issues will affect the maintenance cost escalation when the airplane has reached its aging phase, but also will affect the starting point at which the airplane will enter its aging phase.

Moreover, it is important that airlines apply state-of-the-art corrosion control techniques, even to the older airplane. The definitions used to describe the levels of corrosion (Levels 1, 2, and 3) are inadequate to characterize corrosion on an aircraft. Recent research examining corrosion in the lap joint of both commercial and military aircraft has indicated that metal loss alone cannot be relied upon as a measure of the severity of corrosion. Certain types of corrosion that do not contribute to significant loss in mass, such as pitting and intergranular corrosion, can have a significant detrimental effect on fatigue life.

Maintenance practices vary depending on the type of airline. For example, one major U.S. airline tracks corrosion problems by tail number of the aircraft and trend data to determine threshold levels for maintenance actions for the fleet. Inspections are performed on letter checks (major inspections) under FAA requirements every 9 months to 1 year. Because flight profiles and utilization cycles are very close for all the aircraft and since local basing environments have little influence on corrosion and other maintenance factors, all aircraft in the fleet are considered equal. As a result of this, the airline is able to predict the maintenance requirements of all of their airplanes with high accuracy, while maintaining at least 88 percent efficiency in their maintenance operations. Other airlines manage the maintenance of the airplanes in a different manner. For example, most of them do not track or manage any specific unique corrosion problems. In fact, the majority of the airlines perform better inspections specific to each type of airplane.

Generally, the maintenance manuals that go with the individual B-747-100 airplanes are used to conduct corrosion maintenance, and these maintenance procedures have typically not been updated to present standards. Specifically, when galleys and lavatories are removed, they are often not reinstalled properly using state-of-the-art sealants and CICs. However, if the corrosion control techniques described in the maintenance manuals for new generation airplanes (i.e., B-747-400) would be applied to the older airplanes, better corrosion control management can be accomplished. Finally, training and education of maintenance engineers and technicians play an important role in the corrosion management of airplanes. Only if these engineers and technicians are fully aware of all the aspects of corrosion inspection and maintenance of airplanes and have an understanding of the impact of good corrosion management on maintenance cost and structural integrity can airplanes be economically and safely operated beyond their design lives.

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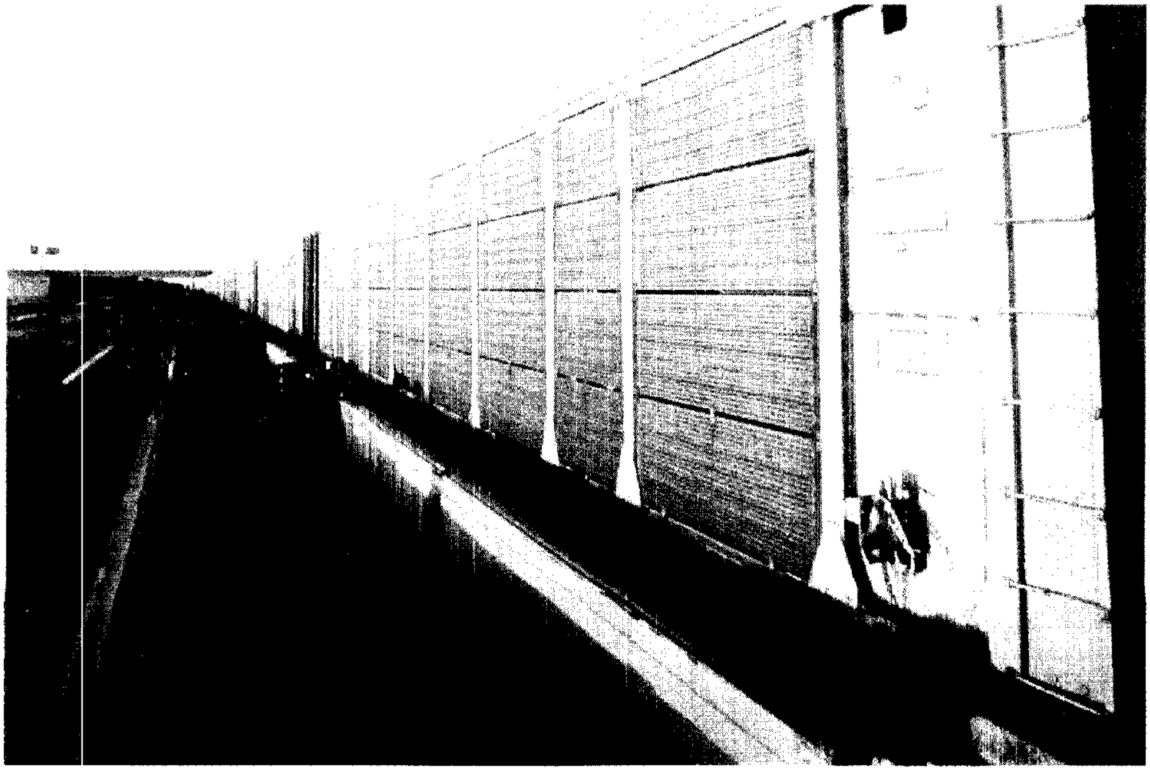
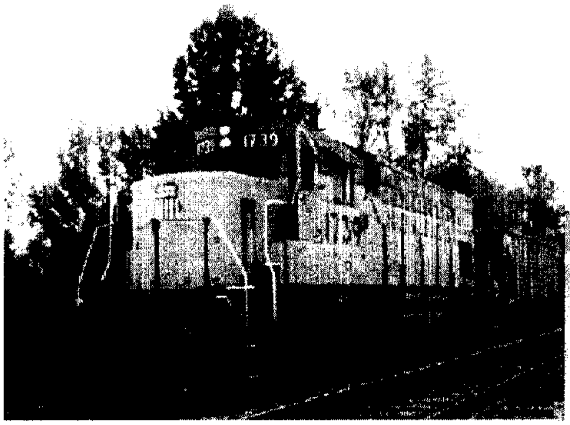
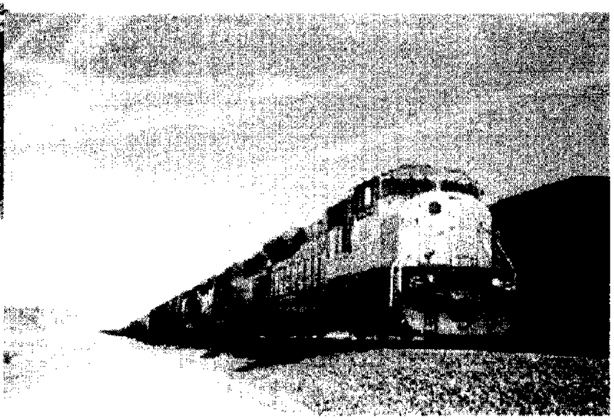
APPENDIX Q

RAILROAD CARS

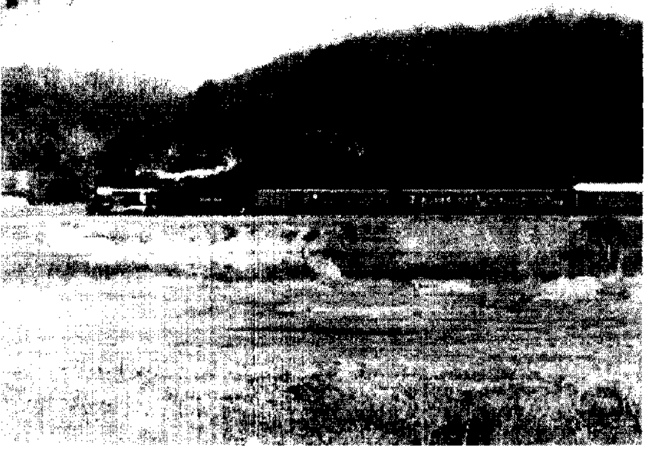




Modern-day locomotive



Corroded locomotive



Reconditioned railroad cars

APPENDIX Q

RAILROAD CARS

MARK YUNOVICH[1]

SUMMARY AND ANALYSIS OF RESULTS

Corrosion Control and Prevention

Railroad cars typically suffer from both external and internal corrosion. While external corrosion, which is primarily due to atmospheric exposure, is a concern, car appearance takes precedence. External corrosion is controlled by the application of coating systems (epoxies with or without a urethane coat) directly to metal. Certain categories of cars, particularly tank cars, are almost all leased by the shippers; therefore, the lessees often choose to apply only an exterior paint system to address aesthetics.

Internal corrosion is caused by an aggressive cargo, such as coal, sodium chloride, or various acids. The rate of corrosion has to be controlled, not only for the obvious reasons of prolonging the service life of a car, but also to prevent contamination of the transported product (e.g., food products or high-purity chemicals). Protection from internal corrosion is achieved by using coating systems or rubber linings. As an alternative, cars for certain corrosive cargo services are manufactured from corrosion-resistant materials, such as aluminum or stainless steel (raising the price of a car twofold), or undergo component upgrades (such as valves made from stainless steel rather than from carbon steel).

When it comes to corrosion, there are a limited number of regulations imposed on the industry. Tank cars are required to be periodically inspected for corrosion damage to the shell and the heads. The time frame of these inspections, the test techniques, and the acceptance criteria are left to the discretion of the owner. The most common inspection intervals for the cars transporting benign commodities are 10 years, and the cars used in an aggressive commodity service are typically inspected once every 5 years.

Based on the limited corrosion cost information, it is estimated that the total annual corrosion-related maintenance costs amount to approximately $504 million (broken down into $258 million for external coatings and 246 million for internal coatings and liners).

Opportunities for Improvement and Barriers to Progress

It seems that the current corrosion control practices in the industry are fairly uniform in that they are limited to replacing the exterior/interior coatings and linings as they degrade in service. Despite the availability of the more expensive and longer-lasting coating systems, which would yield lower life-cycle costs, the savings are apparently not high enough to justify the diligent care. On the other hand, the annual industry cost for new railcars is between $1.2 billion and $2.4 billion (although it is impossible to determine how many are bought as replacements); therefore, even a modest extension of a car's service life could result in considerable savings.

Interviews with the industry experts suggest that partially due to the perceived limited impact of the problem on revenue (less than 1 percent of revenue) and partially due to the complex ownership structure, the railroad companies and shippers do not track corrosion-related costs.

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[1] CC Technologies Laboratories, Inc., Dublin, Ohio.

Recommendations and Implementation Strategy

Considering that there are almost 1.5 million railroad cars in service today, there is a significant opportunity for the reduction of corrosion-related costs in the railroad car industry. In order to reduce the costs, however, the industry should first make an attempt to estimate the magnitude of the problem, which means that the costs of the exterior and interior protective systems must be documented.

Summary of Issues

Increase consciousness of corrosion costs and potential savings.	It appears that the industry is not particularly concerned with the corrosion-related costs, apparently because of the perceived insignificance in terms of cost (estimated to be less than 1 percent of the revenue). The complex ownership structure (many cars are not owned by the railroads) further complicates the tracking of the costs. Data on corrosion costs can be obtained from the protective systems manufacturers.
Change perception that nothing can be done about corrosion.	The general attitude with respect to corrosion is that it is a "nuisance". Investments in the protective systems are regarded as a "necessary evil" and are made without giving much consideration to the life-cycle costs. If corrosion costs were tracked with more accuracy, the industry would be in a position to acknowledge the scope of the issue and would be able to realize significant savings through utilizing effective and efficient corrosion control solutions. The corrosion issues are not heavily regulated by the government.
Advance design practices for better corrosion management.	The primary focus of government regulations are on the safety of the railroad cars in the event of an accident and the cars are designed to have specific containment features (such as an outer shell for the tank cars). Corrosion is commonly addressed by constructing cars with a built-in corrosion allowance (extra thickness). The coating systems currently used for the cars are not necessarily developed for this application. Through cooperation with the coatings suppliers, the industry could explore the issue of developing protective coatings and linings specifically for the railroad cars.
Change technical practices to realize corrosion cost-savings.	To reduce the corrosion-related costs, it will be beneficial to increase the frequency of the car inspections. The potential cost-savings through early corrosion detection and prevention should, of course, be balanced with the increased expenditures of the more frequent inspections, which, as mentioned above, require the tracking of corrosion costs.
Change policies and management practices to realize corrosion cost-savings.	
Advance life prediction and performance assessment methods.	No data available.
Advance technology (research, development, and implementation).	The industry acts as the end-user of the corrosion control technology developed elsewhere (coating manufacturers). It may be beneficial to enter into closer cooperation with the protective coating producers to develop coatings specifically for the railroad cars.
Improve education and training for corrosion control.	The first step should be to assess the magnitude of the problem in the industry through accounting for the corrosion-related costs.

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SECTOR DESCRIPTION

The Class I railroads in the United States consist of freight railroads with average operating revenues of $256.4 million or more. Class I railroad volume in 1998 was 2.21 trillion ton-km (1.38 trillion ton-mi). The U.S. railroads transported nearly 26 million carloads, including nearly 8.8 million intermodal trailers and containers. Class I railroads operated 20,261 locomotives, which hauled a fleet of 1,315,667 cars with an aggregate capacity of 127.8 million tons (140.9 million short tons). U.S. railroads owned and maintained more than 211,200 route km (132,000 route mi) in 1998. Class I railroads owned and operated 191,701 km (119,813 mi) and 156,691 km (97,932 mi), respectively.(1)

The Association of American Railroads (AAR) has estimated that, while making up only 2 percent of American railroads, Class I railroads employed more than 89 percent of the industry workforce, operated 70 percent of the track, and generated 91 percent of the revenue in 1998.(1) Table 1 and table 2 summarize the make-up and use of the railroad car fleet.

Table 1. Railroad car fleet statistics (number of cars).

TYPE	TOTAL ALL OWNERS	CLASS I RAILROADS	OTHER RAILROADS	CAR COMPANIES AND SHIPPERS
Covered hoppers	382,313	151,879	21,447	208,990
Tank cars	232,425	914	37	231,474
Gondolas	197,972	114,675	17,628	65,669
Hoppers	164,506	98,014	16,598	49,894
Box cars	156,633	92,983	47,276	16,374
Plain box	26,594	1,324	11,441	13,829
Equipped box	130,039	91,659	35,835	2,545
Flat cars	143,758	89,171	13,229	41,358
Refrigerator cars	29,645	23,574	3,766	2,305
Others	8,412	4,394	1,678	2,340
TOTAL	**1,472,297**	**668,587**	**168,935**	**634,778**

Table 2. Aggregate railroad car use data (in freight car-miles).

CAR TYPE	FREIGHT CAR-MILES (x thousand)
Hopper (covered)	5,091,536
Flat	3,577,710
Box (equipped)	2,507,341
Gondola (plain)	2,374,349
Hopper (open top, general service)	2,052,092
Flat (multi-level)	2,000,852
Gondola (equipped)	1,239,295
Tank (under 22,000 gal)	1,236,102
Hopper (open top, special service)	1,222,205

Table 2. Aggregate railroad car use data (in freight car-miles) (continued).

CAR TYPE	FREIGHT CAR-MILES (x thousand)
Tank (22,000 gal and over)	1,112,346
Flat (all other)	954,520
Box (plain 50 ft and longer)	460,390
Refrigerator (non-mechanical)	378,455
All other car types (total)	373,977
Refrigerator (mechanical)	212,776
Flat (general service)	17,558
Box (plain, 40 ft)	247
TOTAL	**24,811,751**

1 gal = 3.79L, 1 ft = 0.305 m, 1 mi = 1.61 km

Covered hoppers make up the greatest proportion of the car fleet (28 percent) and transport the most total freight. Tank cars are the second largest segment of the railroad car fleet (18 percent), but transport a disproportionately smaller amount of the load; however, on a per car basis, both of these car types are at the bottom of the group (see table 3). Table 1 suggests that railroads own very few of the tank cars (99.6 percent are owned by the leasing companies or the shippers).

Table 3. Average annual miles per railroad car.

TYPE	MILES PER CAR (x thousand)
Flat cars	31.5
Refrigerator cars	19.9
Hoppers	19.9
Equipped box	19.3
Gondolas	18.3
Plain box	17.3
Covered hoppers	13.3
Tank cars	10.1

1 mi = 1.61 km

The types of commodities transported by the railroads are shown in table 4. Coal has traditionally been the most frequently transported commodity. In fact, it makes up approximately 27 percent of the carloads. A distant second is the chemicals and allied products category (6.5 percent).

Table 4. Volume of transported commodities.(1)

COMMODITY GROUP	CAR LOADS (x thousand)
Coal	7,027
Chemicals and allied products	1,680
Motor vehicles and equipment	1,546
Farm products	1,404
Food and kindred products	1,282
Non-metallic minerals	1,256
Metals and products	671
Lumber and wood products	645
Waste and scrap material	581
Pulp, paper and allied products	547
Petroleum and coke	483
Stone, clay and glass products	475
Forwarder and shipper association traffic	376
Metallic ores	311
Other carloads	7,421
TOTAL CARLOADS ORIGINATED	**25,705**

AREAS OF MAJOR CORROSION IMPACT

The largest costs to the industry are due to corrosion of the exterior and interior of the railroad cars.

External Corrosion

External corrosion of the cars is primarily due to atmospheric exposure. While corrosion damage is still a concern, car appearance takes precedence; therefore, the car manufacturers/lessees often choose to apply an exterior paint system to address the issue of aesthetics. The paint systems are typically "direct-to-metal" (DTM) epoxy or epoxy with a urethane coat. This epoxy substrate adds protection against ultraviolet radiation.

Internal Corrosion

The most common method of internal corrosion prevention is the use of coating systems and rubber linings for internal surfaces. The use of linings and interior coatings is aimed not only at prolonging the service life of the car fleet, but also at precluding the contamination of the transported commodity by corroding metal substrate. Considering that certain types of commodities may be rather corrosive (e.g., chemicals), these corrosion prevention measures are an absolute necessity. While the largest segment of the freight has historically been coal, chemicals and allied products amount to the second largest group of transported goods, while food and kindred products make up 5 percent of transported goods (see table 4). The latter two groups of commodities are either corrosive or sensitive to contamination. Approximately 130,000 of the covered hopper cars are used for transporting plastic pellets, which require liners to preserve product purity. The liner life is 8 to 10 years.(2)

Transportation of coal presents a problem because, when mixed with moisture, it becomes highly acidic and corrosive to the carbon steel. There are indications that a large number of cars can be significantly affected by this problem.(2) Corrosion is likely to be further advanced by the use of the thawing sheds during the winter months in cold climates, in which the cars are heated to thaw the coal. By some estimates, there are about 100,000 cars used for coal service; therefore, the problem may be quite extensive.(2)

Another type of aggressive commodity is sodium chloride (rock salt). The cars used for transporting rock salt suffer from advanced corrosion attack and last for approximately only 3 years.(2) The high cost of rehabilitation of salt cars (see the Corrosion Control Costs section below) created a trend toward using unlined, covered hopper cars previously utilized to transport grain for rock salt service. When corrosion becomes considerable, the cars are scrapped. Since such a process cannot continue indefinitely, more and more rock salt is expected to be hauled by trucks and barges, as the revenue seems to be insufficient to justify the corrosion-related replacement/rehabilitation costs.

In order to accommodate the properties of the cargo, in addition to the use of coatings and linings, certain components of the cars, such as valves, undergo an upgrade from the lower corrosion-resistant carbon steel to the higher resistant steel grades, such as stainless steel.

As mentioned above, rubber linings are often used for strong acids (concentrated hydrochloric, phosphoric). In cases of extremely aggressive cargoes, such as nitric acid, the entire tank car body is manufactured from stainless steel (Type 316L).

CORROSION CONTROL COSTS

The cost of external coating was estimated from the data collected through the railroad car manufacturers and leasing companies (the data is summarized in table 5). The most commonly used types of coatings are DTM epoxy and epoxy/urethane, the former being the cheaper alternative and the latter being the more expensive alternative. The cost of exterior coatings also varies for different types of cars, with an average of about $2,500 per car. According to industry sources, the exterior coatings are typically alkyd- or epoxy-based and the expected service life is approximately 8 to 16 years.

Interior coatings can typically be found on covered hoppers and tank cars, as these tend to be used for the transporting of chemicals and other purity-sensitive products or chemically aggressive commodities. One type of internal coating is spray-applied vinyl esters, used for most types of acidic services (certain strong organic and inorganic acids), caustic commodities, salts, and oxidizers. Spray-applied, modified, cold-set epoxy coatings are typically used for preserving the product purity of such chemicals as solvents (such as benzene, alcohol, and toluene), oil products, and food. High-temperature baked epoxy coatings, due to the process through which they are applied, require that if the internal coating is to be replaced at some point, the external coating would have to be replaced as well (on the cars without external insulation).

Table 5. Corrosion-related maintenance costs for railroad cars.

RAILROAD CAR TYPE	TOTAL (ALL OWNERS)	EXTERNAL COATINGS REPAIRS, EVERY X YEARS	COST PER CAR	INTERNAL COATING/LINER REPAIRS, EVERY X YEARS	COST PER CAR
Covered hoppers	382,313	8-10 (pellet cars)	$2,800	8-10	$3,500
Tank cars*	232,425	8-10	$2,200-$2,600	8-10	$3,400
	sulfuric acid service			4-8	$4,300 (non-insulated)
	~10,000 rubber-lined		$2,600	10	$15,000

Table 5. Corrosion-related maintenance costs for railroad cars (continued).

RAILROAD CAR TYPE	TOTAL (ALL OWNERS)	EXTERNAL COATINGS REPAIRS, EVERY X YEARS	COST PER CAR	INTERNAL COATING/LINER REPAIRS, EVERY X YEARS	COST PER CAR
Gondolas*	197,972				
Hoppers*	164,506	10 (coal service)	$10,000 (steel replacement)		
	~50,000 lined	15-20 (food service)	$2,000	10	$2,500-$3,000
		10-15 (chemical service)	$3,000	5-10	$2,500-$3,500
Box cars*	156,633				
Plain box	26,594	15-20	$2,200	15-20	$750-$1,000
Equipped box	130,039	10-15	$2,500	10-15	$1,500
Flat cars*	143,758	10-15 (auto rack)	$6,000		
		15-20 (articulated)			
Refrigerator Cars*	29,645	8-10	$2,500	wood interior	
Others*	8,412				

*Some information was not available.

The Code of Federal Regulations (CFR) 180.509(d) mandates that tank cars undergo periodic internal and external inspection to check for corrosion damage to the shell and the heads. Paragraph 180.509(c) dictates that the inspection intervals are determined by the next commodity to be transported by the car. The frequency of inspections, the test techniques, and the acceptance criteria are at the owner's discretion. Such intervals for the unlined/uncoated or lined/coated cars transporting benign commodities are typically 10 years. If the next transported commodity is hazardous (as defined by listing in Appendix B of DOT-E 12905), the operator/owner of an unlined/uncoated tank car has to adjust the selected inspection interval, depending on the inspection results (5-year intervals if less than half of the shell thickness reduction allowance remains). Cars can be condemned due to general or localized corrosion attack.

It is estimated that about 40 percent of the tank cars have an interior coating and 10 percent have a rubber lining.(3) The cost of an interior coating (such as phenolic resin) is estimated to be about $3,500 per car, with a service life ranging between 2 and 15 years before a complete overhaul is required. The cost of a rubber lining is much higher (about $14,000 per car), with a service life of 8 to 20 years.

The cars used to transport aggressive commodities (such as the rock salt mentioned above) may require rehabilitation of the car body, which may cost between $10,000 and $15,000. When coupled with an additional $6,000 for the lining and a short service life of 2 years, such rehabilitation may be considered uneconomical. The type of purchased/leased cars is dictated by the type of cargo. Regulations significantly restrict shippers from using the same car for transporting different types of commodities without cleaning the car interior (e.g., one cannot transport chemicals and food products back-to-back).

The cost of car component upgrading (such as valves and fixtures) from carbon to stainless steel is approximately $3,000 per car. The cost of an all-stainless steel tank car increases the new car price nearly twofold, from approximately $60,000 to approximately $120,000.

Given the lifetime of coatings (see table 5), it was assumed that every year, on average, approximately 7 percent (once every 15 years) of the total fleet undergoes exterior coating replacement at an average cost of $2,500 per car and 10 percent (once every 10 years) of the internally coated fleet undergoes interior coating/lining replacement at a cost of $3,000 per car. This study estimated the annual cost of corrosion-related maintenance to be $504 million (see table 6).

Table 6. Estimated internal and external coating costs for railroad cars.

	ALL OWNERS	**FREQUENCY**	**COST**	**TOTAL COST**
	quantity	**% / year**	**$ / application**	**$ x million / year**
External Coating	1,472,297	7	2,500	258
Internal Coating	821,371	10	3,000	246
			TOTAL	**$504**

To contrast this number with the capital expenditures on the new car fleet, some approximate estimates can be made (only for the cars owned by the Class I railroads, which effectively excludes the tank cars). With an average car cost of approximately $30,000 and the number of purchased cars varying between 40,000 and 80,000 for the past 3 years, buying new cars costs $1.2 billion to $2.4 billion annually (4.3 to 8.6 percent of the operating expenses for all Class I railroads). As the cost of maintenance of the existing car fleet is small in comparison to the new car purchases, the benefits of extending the service life of an average car could be considerable.

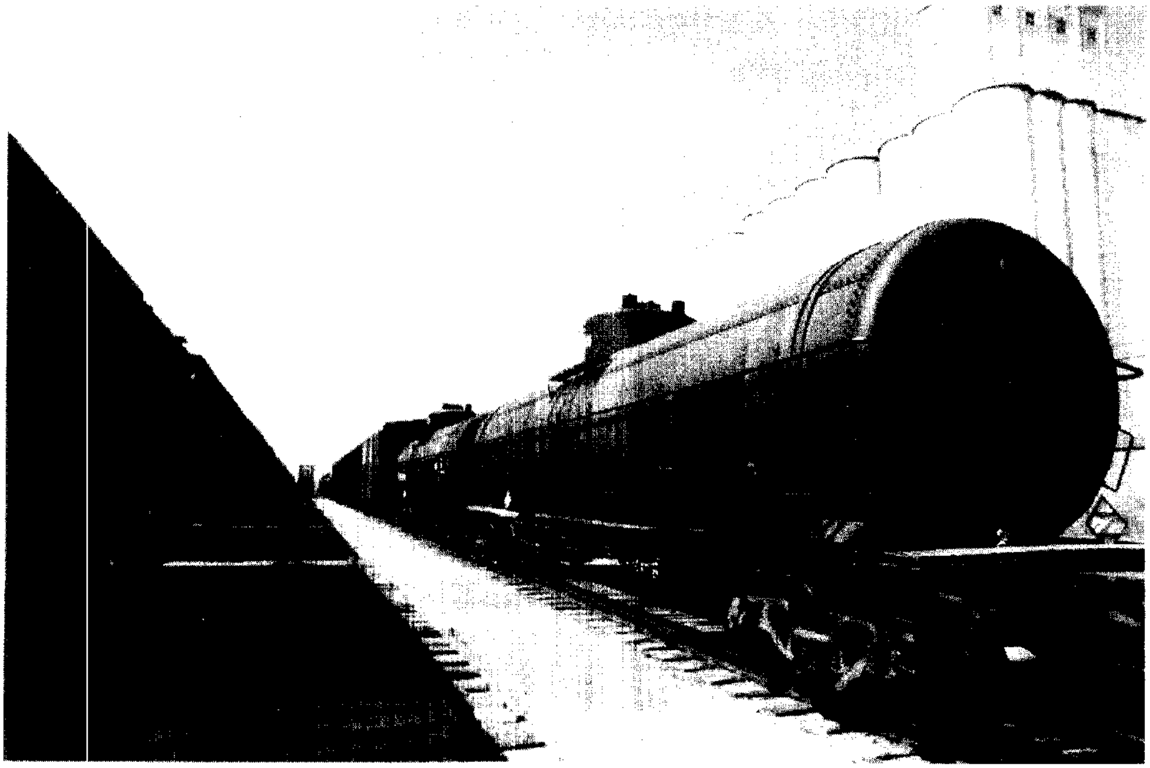
Information regarding specific company practices with respect to corrosion control is very scarce and not easily obtainable for a variety of reasons, including lack of tracking or reluctance to release information regarded as proprietary. The data obtained suggest that current corrosion maintenance practices in the industry are fairly uniform in that they are limited to replacing the exterior/interior coatings and linings as they degrade in service. Since many of the cars are leased (almost all tank cars are), at times, the lessors replace the coatings due to aesthetic considerations. More expensive (and longer-lasting) coatings could ostensibly yield lower life-cycle costs; however, the savings are apparently not high enough to justify the diligent care, or railroad companies are simply not motivated to spend any time looking into the issue.

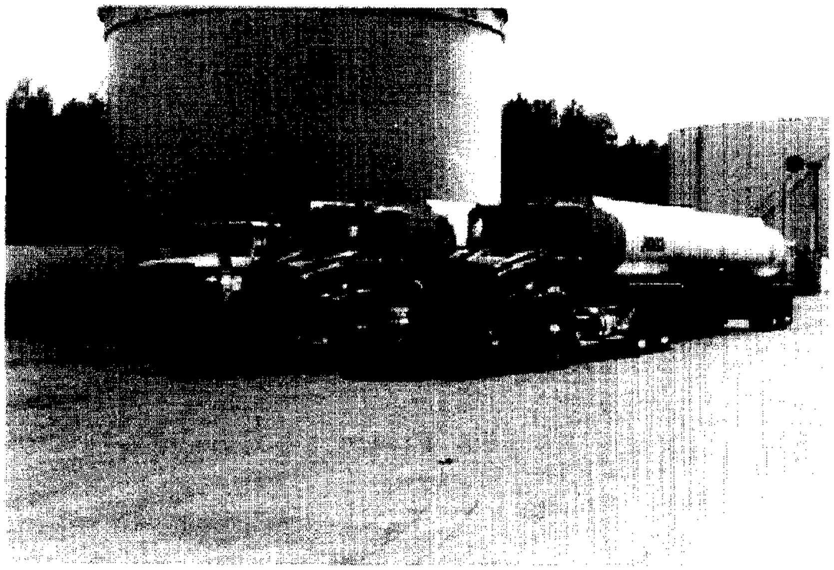
REFERENCES

1. Association of American Railroads data, 2000.
2. Coating industry expert, Personal Communication, June 2000.
3. Tank car leasing company executive, Personal Communication, June 2000.

APPENDIX R

HAZARDOUS MATERIALS TRANSPORT

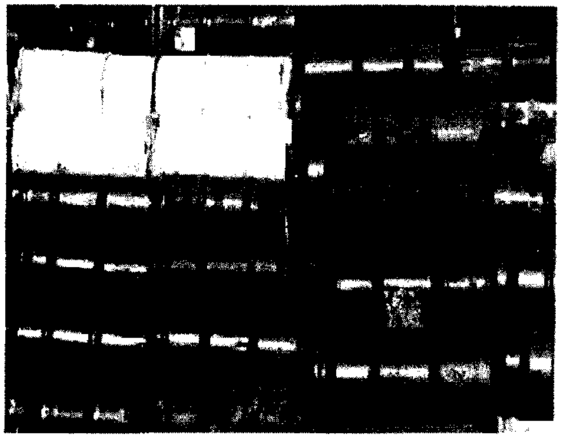




Trucks for transport of hazardous materials

Stainless steel tanks for highway trucks

Corroded storage drum



Storage drums

APPENDIX R

HAZARDOUS MATERIALS TRANSPORT

MICHIEL P.H. BRONGERS[1]

SUMMARY AND ANALYSIS OF RESULTS

Corrosion Control and Prevention

Each year, approximately 2 billion metric tons of hazardous materials are produced in the United States. The amount of hazardous materials shipments is approximately 3 billion metric tons. Bulk transport of hazardous materials involves overland shipping by tanker truck, rail tank car, and specialized containers that are loaded on vehicles. Over water, ships loaded with specialized containers, tanks, and drums are used. In small quantities, hazardous materials require specially designed packaging for truck and air shipments.

The total cost of corrosion for hazardous materials transportation is at least $887 million per year. The elements of the annual corrosion cost include the cost of the transporting vehicles ($400 million per year), the cost of specialized packaging ($487 million per year), and the direct and indirect costs ($0.5 million per year and an unknown value, respectively) of accidental releases and corrosion-related transportation incidents.

According to the 1997 Vehicle Inventory and Use Survey (VIUS), there are a total of 403,000 trucks (including pick-up trucks) dedicated to hazardous materials transport in the commercial trucking fleet. Together, these trucks constitute only 0.55 percent of the total number (72.8 million) of commercial trucks. Hazardous materials trucks are responsible for 39.9 billion km (24.8 billion mi) of driven distance per year. In 1998, the Research and Special Programs Administration (RSPA) of the U.S. Department of Transportation (DOT) reported that 195,000 trucks (excluding pick-up trucks), 238,000 train cars, and 11,000 vessels (sailing under both U.S. and foreign flags) were dedicated to hazardous materials transport. The total cost to equip vehicles for corrosive hazardous materials was estimated at approximately $400 million per year.

The cost of hazardous materials packaging can be estimated by analyzing the replacement rates of steel pails and steel drums. In 1998, a total of 91.3 million new steel pails were produced with a total value of $290 million, and a total of 32.3 million new steel drums were produced with a total value of $684 million. Similar data for the last 10 years show that these replacement rates are typical. Two possible reasons for replacement of pails and drums are damage from handling and damage from corrosion. If it is assumed that 50 percent of the replacements are corrosion-related, then the cost of corrosion was $145 million for pails and $342 million for drums.

All accidental releases of hazardous materials during transportation must be reported to the U.S. DOT. Packaging failure was identified as the primary cause of 15 to 35 percent of all hazardous materials transportation incidents. Corrosion-related incidents are those accidental releases of hazardous materials where corrosion of the containers was identified as the root cause of the incident. In 1998, the corrosion-related incidents were approximately 1.35 percent of the total number of reported hazardous materials incidents.

The average direct cost of property damage in corrosion-related transportation incidents is only $0.5 million per year; however, the indirect costs of packaging failures are probably significant, although they go unreported. Indirect costs of corrosion-related incidents include the costs related to human injuries (average of eight injuries per year), fatalities (average of one death per 3 years), lost product (no data), and clean-up activities (no data).

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[1] CC Technologies Laboratories, Inc., Dublin, Ohio.

Summary of Issues

Increase consciousness of corrosion costs and potential savings.	The total cost of corrosion for hazardous materials transport is at least $0.89 billion per year. This total cost includes the cost of dedicated hazardous materials vehicles at $400 million per year and the corrosion cost of steel pails and drums at $487 million per year. The direct cost of hazardous materials transportation incidents is $0.5 million per year, while the indirect cost of hazardous materials transportation incidents is probably many millions of dollars.
Change perception that nothing can be done about corrosion.	No issue identified in current study.
Advance design practices for better corrosion management.	No issue identified in current study.
Change technical practices to realize corrosion cost-savings.	No issue identified in current study.
Change policies and management practices to realize corrosion cost-savings.	Adjust the U.S. Department of Transportation report form in order to gather more information about the long-term impact of corrosion, such as related hazardous materials incidents.
Advance life prediction and performance assessment methods.	No issue identified in current study.
Advance technology (research, development, and implementation).	No issue identified in current study.
Improve education and training for corrosion control.	No issue identified in current study.

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SECTOR DESCRIPTION

This sector includes the transportation of hazardous materials (HAZMAT) other than of the transportation of hazardous gases and liquids by buried pipelines, which will be discussed as a separate sector (see Appendix E). The storage of HAZMAT is described in a separate sector as well (see Appendix G).

Bulk transportation of HAZMAT involves overland shipping by tanker truck and rail tank car and by specialized containers that are loaded onto vehicles. Over water, ships loaded with specialized containers, tanks, and drums are used. In small quantities, HAZMAT requires specially designed packaging for truck and air shipments. Table 1 lists primary areas of the HAZMAT transportation industries.

Table 1. Primary areas of the HAZMAT transportation and storage industries.

TRANSPORTATION MODE		LOADING / UNLOADING FACILITIES	TANKS AND CONTAINERS
LAND	Trucks	Manufacturers and Users	Tanker trucks
	Trains	Stations	Tanker train cars
WATER	Ships	Docks	Drums and movable tanks
AIR	Airplanes	Airports	Special containers

Background

The Hazardous Materials Transportation Act (HMTA) of 1974(1) authorized the U.S. Department of Transportation (DOT) to regulate the transportation of HAZMAT over land, sea, and air. Within U.S. DOT, the Research Special Programs Administration (RSPA) issues the Hazardous Materials Regulations (HMR) and provides training, enforcement, technical support, information, and policy guidance to protect the transportation community and the general public against the safety risks inherent in transporting HAZMAT.

In the last 25 years, the federal government has developed more regulations for HAZMAT transport. The regulations for workplace safety are given in the Occupational Safety and Health Act (OSHA).(2) The Code of Federal Regulations, 49 CFR 173,(3) contains the requirements for HAZMAT transportation, including the requirements for shipping, packaging container design, and labeling. The code defines nine hazard classifications assigned for distinct HAZMAT (see table 2).

Table 2. Hazard classifications assigned for distinct HAZMAT.(3)

CLASSIFICATION	MATERIALS
Class 1	Explosives
Class 2	Flammable and Compressed Gases
Class 3	Flammable Liquids
Class 4	Flammable Solids
Class 5	Oxidizers
Class 6	Poisonous Materials
Class 7	Radioactive Materials
Class 8	Corrosive Materials*
Class 9	Miscellaneous Hazardous Materials

*Includes materials corrosive to human skin.

Class 5 and Class 8 materials require shipping and storage containers that are resistant to corrosion to prevent internal damage. However, most of the materials listed in table 2 can become corrosive to a mild steel container when they are contaminated with moisture. Depending on the environment, materials from all nine categories must be shipped and stored in containers that are protected from external corrosion damage.

The Office of Hazardous Materials Safety (OHMS) and the Research and Special Programs Administration (RSPA) of the U.S. DOT reported(4) that there are at least 300 million HAZMAT shipments of more than 3.1 billion metric tons annually in the United States (see table 3 and table 4). While approximately 43 percent of all HAZMAT tonnage is transported by truck, approximately 94 percent of the individual shipments are carried by truck. Transportation by air, while almost negligible in terms of tonnage, also has a share of individual shipments that greatly exceeds its percent of tonnage carried. While less than 1 percent of all HAZMAT tonnage is transported by air, approximately 5 percent of all HAZMAT shipments are transported by air. In contrast, significant amounts of HAZMAT tonnage are carried by rail, pipeline, and water modes, and, in some markets, these are the only modes that haul HAZMAT products; yet, the total number of shipments for all three of these bulk commodities is less than 1 percent.

Table 3. Daily and annual number of domestic HAZMAT shipments, movements, and tonnage shipped, specified by product group.(4)

PRODUCT GROUP	DAILY SHIPMENTS (quantity)	DAILY MOVEMENTS[2] (quantity)	ANNUAL SHIPPED (metric tons)	ANNUAL MOVED (metric tons)
Chemicals & Allied	500,000	900,000	0.53 billion	0.85 billion
Petroleum Products	300,000	300,000	2.60 billion	3.03 billion
Other	10,000	10,000	0.01 billion	0.02 billion
TOTAL	**> 800,000**	**> 1,200,000**	**> 3.1 billion**	**> 3.9 billion**

1 ton = 1,000 kg

Table 4. Daily number of domestic HAZMAT shipments, movements, and tonnage moved, specified by mode of transportation.(4)

TRANSPORTATION MODE	DAILY SHIPMENTS (quantity)	DAILY MOVEMENTS (quantity)	DAILY MOVED (metric tons)
Highway	768,907	1,154,450	3,794,970
Air	43,750	87,500	8,098
Rail	4,315	12,945	1,136,748
Water	335	670	2,545,850
TOTAL	**817,307**	**1,255,565**	**7,485,666**

1 ton = 1,000 kg

According to RSPA,(4) the amount of HAZMAT produced each year in the United States is close to 2 billion metric tons, while the amount shipped is closer to 3 billion metric tons. This relationship suggests that every ton of

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[2] Based on the 1993 U.S. Census Bureau Commodity Flow Survey (CFS) shipment distribution data for standard transportation commodity classification (STCC) 28; 1995 CMA tonnage figures (SIC 28); 1995 U.S. EPA hazardous waste shipment and manifest data; 1996 U.S. DOE Energy Information Administration data; 1996 Waterborne Commerce Statistics; and 1997 BTS Air Carrier Traffic Statistics.

HAZMAT, on average, is shipped 1.5 times. RSPA reported a ratio of 0.64 for chemicals and allied products transportation, excluding other HAZMAT shipments.

Since the early 1990s, the federal regulations for transportation of small packages of HAZMAT have been performance-oriented, rather than specific about the shape of a container or about the packaging materials to be used. The specifications for larger packages are more design specific. To be able to operate in today's global marketplace, U.S. DOT has focused on harmonizing its rules and regulations with international standards.

In 1997, the Vehicle Inventory and Use Survey (VIUS)(5) reported that a total of 403,000 trucks, ranging from pick-ups and vans to heavy combination trucks (see figure 1), are in the commercial HAZMAT fleet (see table 5). This shows that 0.55 percent (403,000 HAZMAT trucks / 72.8 million total trucks) are involved in HAZMAT transport. Together, these HAZMAT trucks are responsible for approximately 39.9 billion km (24.8 billion mi) of travel per year.

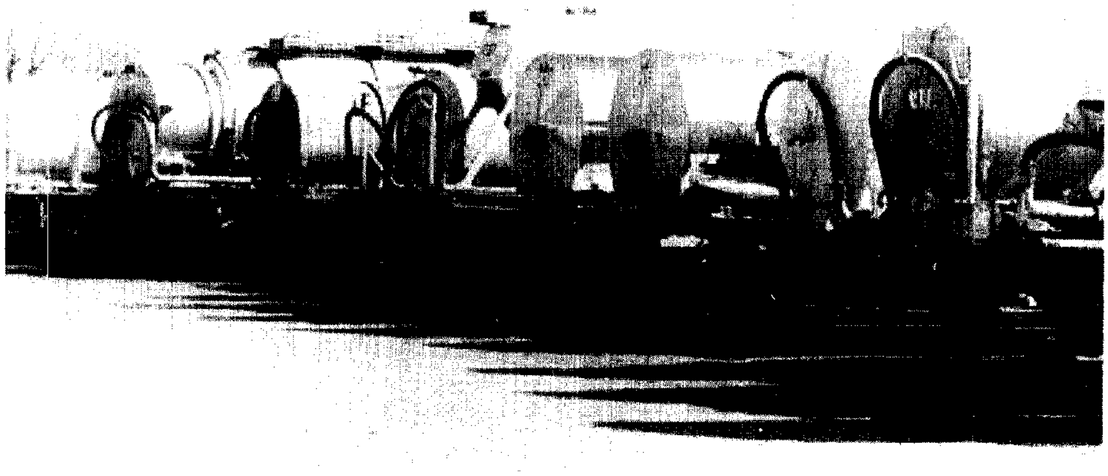

Figure 1. Example of stainless steel tanks for road transport.

Table 5. Number of registered trucks transporting HAZMAT in 1997, as reported in the VIUS.(5)

HAZARDOUS MATERIALS CARRIED	1997 TRUCKS (x thousand)	PERCENT
Total Trucks Carrying Hazardous Materials	403.3	0.55
No Hazardous Materials Carried	71,182.8	97.78
Not Reported	1,214.1	1.67
TOTAL TRUCKS*	**72,800.2**	**100%**

*Values rounded to nearest thousand.

Table 6 lists the number of trucks used for each category of HAZMAT transport. The numbers of trucks listed in this table should not be confused with the 403,000 total trucks in the previous table, because many trucks can be used for multiple HAZMAT classifications.

Table 6. Number of registered trucks transporting HAZMAT in 1997, specified by HAZMAT classification, as reported in the VIUS.(5)

HAZARDOUS MATERIALS CARRIED		1997 TRUCKS (x thousand)
Class 1	Explosives 1.1 (formerly explosive A)	7.2
	Explosives 1.2 (formerly explosive B)	3.8
	Explosives 1.3 (formerly explosive C)	4.5
	Explosives 1.4 (formerly dangerous)	37.3
	Explosives 1.5 (formerly blasting agents)	22.7
	Explosives 1.6 (formerly dangerous)	25.3
Class 2	Flammable gas	115.3
	Nonflammable gas	83.0
	Poisonous gas	34.1
	Flammable	218.0
Class 3	Combustible	127.5
Class 4	Flammable solid	65.4
	Spontaneously combustible (formerly flammable solid)	41.4
	Dangerous when wet	47.4
Class 5	Oxidizer	90.8
	Oxygen	39.0
	Organic peroxide	46.5
Class 6	Poison (formerly poisons A and B, solids, and liquids)	70.9
	Keep away from food	49.6
Class 7	Radioactive	19.2
Class 8	Corrosive	159.2
Class 9	Miscellaneous hazardous materials	53.5
-	Hazardous materials not specified	40.6

In the previous paragraphs, an estimate of 403,000 HAZMAT trucks was given based on the 1997 VIUS.(5) However, in 2000, RSPA published data(6) regarding the dedicated HAZMAT fleet in the United States based on a long list of databases (see Appendix V of that report). RSPA reported that 195,000 trucks, 238,000 train cars, and 11,000 vessels (both under U.S. and foreign flags) are dedicated to HAZMAT transport. The RSPA numbers are smaller, but do not conflict with the VIUS data because VIUS includes small pick-up trucks and vans in its count.

Cost of Corrosion

No detailed information was found on the initial costs to equip a vehicle for HAZMAT transport or on the costs of operation and maintenance of HAZMAT vehicles. Dedicated HAZMAT vehicles are designed differently than regular trucks and are constructed using materials that are compatible with the HAZMAT contents; therefore, the cost of HAZMAT trucks is significantly greater than the cost of regular trucks. If it is estimated that $10,000 is the cost to equip one vehicle for HAZMAT transport and the average useful life per truck is 10 years, then the total cost of corrosion of HAZMAT vehicles is approximately $0.4 billion per year (400,000 trucks x $10,000 per truck every 10 years).

Shippers are required to report HAZMAT incidents to the U.S. DOT using the Hazardous Materials Incident Report DOT Form 5800.1 whenever there is an unintentional release of a HAZMAT. The information from all submitted forms is collected in the Hazardous Materials Information System (HMIS) incident database, which is maintained by RSPA and includes data reported by carriers over the past 30 years. Table 7 shows the number of, as well as the consequences resulting from, serious incidents for 1990 through 1998.(7) In 1998, there were roughly 15,000 reported HAZMAT incidents related to HAZMAT shipments, resulting in 13 deaths and 198 injuries.

On DOT Form 5800.1, the shippers are requested to give a description of the packaging failure for each incident. In addition to "vehicle collision," "improper loading," and several other checkboxes, there is an option to indicate "corrosion" as one of the contributing factors for the packaging failure. It is important to realize the difference between the contents of a package involved in an incident (corrosive materials were the contents in 35.7 percent of the 1998 incidents) and the root cause of an incident (corrosion was indicated as a contributing factor in 1.35 percent of the 1998 incidents).(8)

In general, the incident report gathers the hard "physical" costs associated with the damages generated by the spill, but not the intangible costs that we recognize as being associated with each incident. Such intangible costs may include the costs of executing paperwork and the lost time of production. Therefore, some types of factor can be added to the reported damages when looking at the overall impact cost of the incident.

For the current project, RSPA conducted a special query of the HMIS incident database. The results are included in table 7. As an example, the RSPA query(9) showed that in 1998, for 205 (1.34 percent) of the 15,322 incidents, corrosion was indicated as a contributing factor with a combined cost of $517,710. A total of 79 (38.3 percent) of these 206 corrosion-related incidents had a reported damage cost of $0, while 45 incidents had a cost between $0 and $100, and 81 incidents cost more than $100.

Table 7. Number of, and consequences resulting from, serious incidents involving HAZMAT transport for 1990 through 1998, as reported in the HMIS database(7) and the RSPA query.(9)

YEAR	TOTAL REPORTED INCIDENTS	NUMBER OF				AMOUNT OF PROPERTY DAMAGE	CORROSION WAS CONTRIBUTING FACTOR		PROPERTY DAMAGES IN CORROSION-RELATED INCIDENTS	
		SERIOUS INCIDENTS	FATALITIES	INJURIES	PERSONS EVACUATED					
1990	8,879	402	8	423	12,123	$32,353,276	142	1.60%	$289,710	0.90%
1991	9,110	403	10	439	10,502	$38,350,611	127	1.39%	$304,866	0.79%
1992	9,310	375	15	600	29,186	$35,164,057	150	1.61%	$517,388	1.47%
1993	12,830	357	15	627	18,237	$22,801,551	206	1.61%	$409,214	1.79%
1994	16,087	429	11	577	18,398	$44,185,413	216	1.34%	$5,966,850****	13.50%
1995	14,743	409	7	400	11,444	$30,903,281	233	1.58%	$456,957	1.48%
1996	13,950	464	120*	1,175**	19,556	$46,849,243	205	1.47%	$317,791	0.68%
1997	13,994	417	12	225	24,587	$33,393,504	210	1.50%	$536,746	1.61%
1998	15,322	429	13	198	9,181	$45,497,550	205	1.34%	$517,710	1.14%
Average	12,692	409	23	518	17,024	$36.6 million	188	1.49%	$1.0 million	2.60%
TOTAL	114,225	3,685	211	4,664***	153,214	$329 million	1,694	-	$9.3 million	-

*110 deaths were the result of a ValuJet incident in 1996.

**A single rail incident in Montana involving chlorine resulted in injuries to 787 people.

***In summarizing incident injuries for the biennial report, RSPA combines hospitalization (serious) injuries with minor injuries.

****In 1994, there was one rail incident involving arsenic acid liquid, with a total damage cost of $5,255,000 (Product Loss: $5,000, Carrier Damage: $250,000, Public/Private Property: $0, Decontamination/Cleanup: $5,000,000).

Limitations in HAZMAT Incident Data

There are two factors that could lead to low cost estimates for the incidents: (1) most incidents are small and (2) there are limitations to estimates of long-term impact because the information is collected immediately at the time and location of the incident.

The majority of the incidents reported to RSPA are minor and do not cause much damage or disruption. Even at 2 hours per incident (one for cleanup, one for reporting), the labor cost could be as low as $50, leaving $50 for materials lost or used during cleanup, for a total cost of $100 per incident. Since it was a minor spill and purely accidental, there may be no need for any managerial follow-up or corrective action such as safety training. To correct for small incident costs, (79 + 45) x $100 = $12,500 per year can be added to the $517,710 mentioned above.

The second reason for the low cost is the manner in which the information is collected. The question, as presented on DOT Form 5800.1, asks for the amount of loss or damages due to the HAZMAT as they relate to (a) Product Loss, (b) Carrier Damage, (c) Public/Private Property Damage, (d) Decontamination/Cleanup, and (e) Other. Most respondents do not take these types of costs into consideration when they are completing the form because the actual event descriptions do not correspond with the requested categories. Some costs may be under-reported since the forms are required within 30 days of the incident and the true costs may not be known until later. Additionally, the societal costs of evacuations, highway closures, lost work time, etc. are not reported on the incident report form; therefore, a cost correction factor could not be determined from this data.

Evaluation of HAZMAT Incident Reports

In March 2000, the U.S. DOT published a department-wide evaluation of the HAZMAT transportation programs.(6) The objective of that report was to document and assess the effectiveness of the department's HAZMAT transportation safety programs. The U.S. Coast Guard, the Federal Aviation Administration (FAA), the Federal Motor Carrier Safety Administration (FMCSA), the Federal Railroad Administration (FRA), and the Research and Special Programs Administration (RSPA) provided their input.

The Hazardous Materials Program Evaluation (HMPE) team analyzed all 13,950 incident reports for 1996 to determine their root cause. In table 8, the RSPA values, which were generated from the incident report forms that are filled out by HAZMAT shippers, are compared with the HMPE values, which were estimated by the team members, who all had inspection backgrounds. The HMPE team concluded that a larger percentage (34.6 percent) of the incidents are attributed to packaging failure than are indicated by the RSPA values (15.4 percent).

Table 8. Distribution of HAZMAT incident causes, as determined by RSPA and HMPE and reported in a 1996 RSPA-HMIS incident remarks subsystem report.(7)

CAUSE	RSPA-DETERMINED CAUSE	HMPE-DETERMINED CAUSE
	% of Total	**% of Total**
Human error	80.7	61.0
Packaging failure	15.4	34.6
Vehicle accident/derailment	2.4	2.6
Other	1.5	1.8
TOTAL	**100%**	**100%**

AREAS OF MAJOR CORROSION IMPACT

RSPA's Office of Hazardous Materials Safety (OHMS) published a list of the Top 50 hazardous materials in a 1998-1999 summary of HAZMAT transportation incidents.(8) The corrosive materials that were most often involved in HAZMAT incidents in 1998 included sodium hydroxide solutions, basic inorganic liquids, hydrochloric acid solutions, acidic inorganic liquids, phosphoric acid, caustic alkali liquids, acidic organic liquids, potassium hydroxide solutions, sulfuric acid, cleaning liquids, hypochlorite solutions, basic organic liquids, liquid amines, and ammonia solutions.

Internal Corrosion

Internal corrosion of tankers usually only requires mitigation when an oxidizer (Class 5) or a corrosive material (Class 8) is transported. Internal corrosion from settled contamination is limited because of high throughput and product movement during transportation. Internal corrosion of tankers can be a problem during long periods of storage if they are not cleaned properly first.

In 1998, the value of shipments of new steel pails totaled $289.8 million and the value of shipments of new steel drums was $684.2 million (see table 9).(10) The quantity of new steel pails was 91.3 million (average $3.17 per pail) and the quantity of new steel drums was 32.3 million (average $21.19 per drum).

Table 9. Summary of shipments of steel pails and drums from 1989 to 1998, as reported by the U.S. Census Bureau.(10)

	STEEL PAILS			STEEL DRUMS		
	QUANTITY (x thousand)	**VALUE ($ x thousand)**	**AVERAGE $ / PAIL**	**QUANTITY (x thousand)**	**VALUE ($ x thousand)**	**AVERAGE $ / DRUM**
1998	91,341	$289,768	$3.17	32,293	$684,242	$21.19
1997	88,940	$279,449	$3.14	34,107	$722,101	$21.17
1996	60,443	$200,681	$3.32	34,334	$706,084	$20.57
1995	71,896	$162,992	$2.27	33,279	$685,499	$20.60
1994	86,478	$208,406	$2.41	34,857	$681,972	$19.56
1993	85,899	$202,460	$2.36	33,474	$672,948	$20.10
1992	76,794	$178,850	$2.33	33,336	$632,616	$18.98
1991	72,645	$180,408	$2.48	33,970	$668,692	$19.68
1990	75,242	$195,669	$2.60	36,388	$701,615	$19.28
1989	80,693	$205,834	$2.55	35,966	$667,024	$18.55

Two possible reasons for replacement of pails and drums are damage from handling and damage from corrosion. If it is assumed that 50 percent of the replacements are corrosion-related, then the cost of corrosion in 1998 was $145 million for pails (50 percent of $290 million) and $342 million for drums (50 percent of $684 million).

Shipping containers, such as drums and pails, can suffer internal corrosion damage and failure when corrosive materials are shipped. Normally, internal corrosion is not a problem when materials are shipped from the manufacturer because the proper container material is used and the container materials are normally transported in a relatively short period of time. However, contaminated or corrosive materials can cause failures when stored beyond the material's shelf life. The corrosion failure of drums containing hazardous waste tends to be more of a problem. Typically, the problem occurs when wastes are mixed or when waste is contaminated and stored in containers made of non-compatible materials (see figure 2).

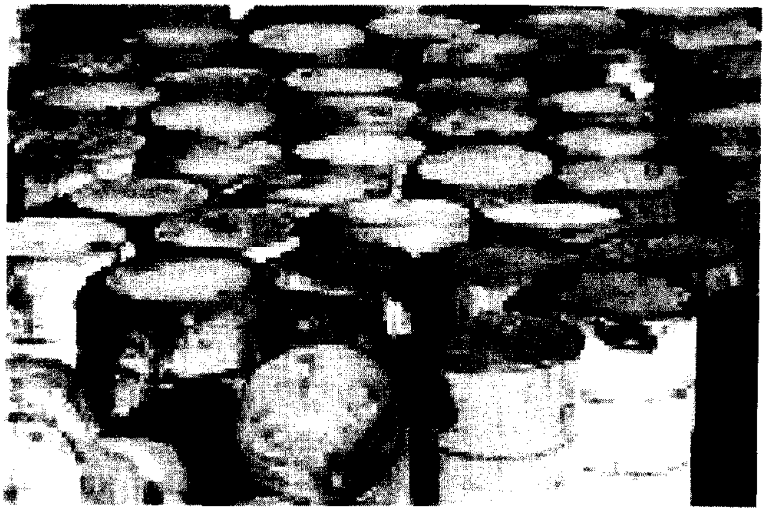

Figure 2. Storage drums for short-term storage can suffer both internal and external corrosion if they are stored for longer periods of time.

External Corrosion

In the transportation industries, external corrosion of tanker trucks and rail car-mounted tanks is a consideration. Both general and pitting corrosion from the atmosphere and splash water from the roadway or rail bed can affect the tank's structural integrity and tightness. This problem is particularly severe in areas of the country with chloride sources such as road salt or airborne marine atmosphere, and high concentrations of airborne industrial pollution. The common mitigation technique involves painting of the tanks.

CORROSION CONTROL

Corrosion control methods for tanker trucks and rail car-mounted tanks include linings and corrosion allowances for internal corrosion. In cases where corrosive materials are to be transported, corrosion-resistant alloys are used. In extreme cases, rubber bladder tanks have been used on flatbed trailers or rail cars. External corrosion is controlled with coatings and designs that minimize crevices. For example, crevice corrosion can be prevented by placing a horizontal tank with a circular cross-section on legs, thereby avoiding direct contact with other surfaces.

CASE STUDY

Hydrochloric Acid Leak in Train Tanker ($30,200)

This case study illustrates the direct cost of a failed liner in a train tanker containing a corrosive liquid. In addition, this case study shows what type of problems can be encountered and how different agencies work together to remediate a HAZMAT incident. The information reported here was taken from a single HAZMAT incident report from the HMIS database.(7)

On May 21, 1998, a chemical transportation safety manager of a large railroad company was contacted by a car foreman in Colton, CA, who reported that a train tank car was leaking from the bottom portion of the car. The manager drove to the Colton receiving yard, located the tank car on a yard track, and observed the tank car leaking a steady stream of product, estimated to be 30 to 38 L (8 to 10 gal) per hour, from the center bottom portion of the car. The billing information for this car showed that the car was not fully loaded and that the contents were a residue. The leak appeared to be at the weld that attaches the protective skid plate to the bottom of the tank car. The San Bernardino, CA, Fire Department was notified due to the toxic nature of the product vapors. Arrangements were made with the train company's HAZMAT emergency response contractor, who responded with a team of people and equipment to assist in remediation of the problem.

Due to the location of the tank car in the receiving yard, access was limited, which required moving the tank car. As there was a hospital directly north of the receiving yard, it was determined that the tank car would have to be moved east, which would place the tank car adjacent to the main switching yard. The highway patrol closed Interstate 10 and the Ceder Avenue overpass while the tank car was being moved, which was accomplished by 6 a.m. The area where the tank car was to be placed and the repair shop were evacuated. Once the tank car was placed, an entry team removed the valving from the product liquid line on the top of the car and placed a containment system to capture the leaking product underneath the car. During this process, the leak at the bottom of the car stopped and restarted several times. A vacuum truck was brought in and set up with a PVC "stinger" to access any free product through the tank car's liquid line. No product was obtained during this process, which further confirmed that the tank car liner had failed. It appeared that the liquid was between the tank liner and the tank shell.

Several attempts were made to putty the weld at the side plate, which only resulted in the leak moving to other areas of the weld. At this point, arrangements were made with a local tank car repair shop to receive this car. The repair shop had a containment pit that would accommodate the leaking tank until it could be purged. A makeshift containment system was constructed under the tank car to prevent any further spreading of product during the move. The tank car was then moved as a single unit with a yard switch engine and was sent to the containment area by 11 p.m. Two 208-L (55-gal) drums of free product were captured during this event. The waste and a batch of contaminated soil were delivered to a facility for proper disposal.

The total reported cost for this HAZMAT incident was $30,200. This cost was the direct cost incurred by the train company, and probably included the cleanup costs and repair costs for the tanker car. However, the indirect costs related to the actions taken by the fire department, the police department, and the lost time of the travelers on Interstate 10 were not included in the total cost.

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9. Query of HMIS Database, Email Communication with Kevin Coburn, Manager of Hazardous Materials Information System, Office of Hazardous Materials Safety, Research and Special Programs Administration, U.S. Department of Transportation, Washington, D.C., September 2000.

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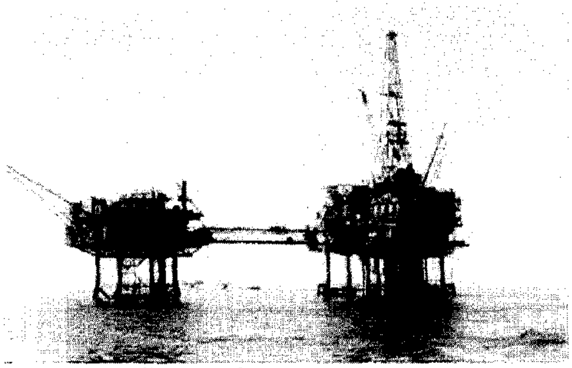
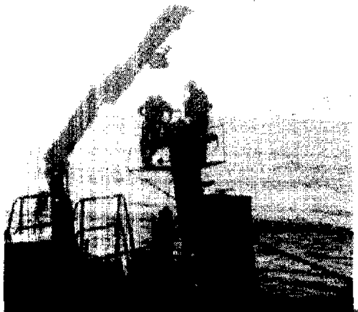
APPENDIX S

OIL AND GAS EXPLORATION AND PRODUCTION


Offshore oil drilling platform


Hoist and cage


Oil tanker


Internal corrosion of oil pipe


Lowering pipe


Maintenance

OIL AND GAS EXPLORATION AND PRODUCTION

GREGORY R. RUSCHAU, PH.D.[1] AND MOHAMMED A. AL-ANEZI[2]

SUMMARY AND ANALYSIS OF RESULTS

Corrosion and Prevention

Domestic oil and gas production can be considered a "dinosaur industry" in the United States because most of the significant onshore oil and gas reserves have been exploited. The significant recoverable reserves left to be discovered and produced in the United States are probably limited to less convenient locations, such as deepwater offshore, remote arctic locations, and difficult-to-manage reservoirs with unconsolidated sands. Materials and corrosion control technologies used in traditional onshore production facilities have not significantly changed since the 1970s. The materials and corrosion control technologies required for the more difficult production areas must be more reliable due to the excessive cost of replacement or failure in these locations. Of course, the commodity price of oil will continue to dictate whether or not these new developments will even be considered.

Downhole tubing, surface pipelines, pressure vessels, and storage tanks in oil and gas production are subject to internal corrosion by water, which is enhanced by the presence of CO_2 and H_2S in the gas phase. Internal corrosion control is the major cost item. The total annual cost of corrosion in the oil and gas production industry is estimated to be $1.372 billion, broken down into $589 million in surface pipeline and facility costs, $463 million annually in downhole tubing expenses, and another $320 million in capital expenditures related to corrosion.

Opportunities for Improvement and Barriers to Progress

The majority of the cost-savings for any oil production facility is the prevention of failure in one of the production arteries (downhole tubing, surface pipelines, production vessels). Money lost through lost production far outweighs expenses associated with maintenance.

The high "lifting" costs associated with oil and gas production in the United States put the industry at a distinct disadvantage compared to the Middle East and the former Soviet Union, where the only barriers to increased production are investment capital and political complications. To remain competitive with the world market, maintenance costs must be kept to a minimum. Also, the conservative culture in the oil patch seldom allows for a new, unproven technology to be embraced.

Recommendations and Implementation Strategy

A large portion of the costs for internal pipelines lies in the use of corrosion inhibitors. Optimization of inhibitor usage could be accomplished through the use of more advanced inhibitor treatment schemes, such as active monitoring systems connected to inhibitor pumps to increase or decrease dosage as the corrosivity increases or decreases. Even passive systems could be developed that more accurately couple inspection and monitoring data with treatment schemes.

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[2] Saudi Arabian Oil Company (Saudi ARAMCO), Dhahran, Saudi Arabia.

The use of corrosion-resistant alloys is currently limited by the high initial capital investment associated with these materials. The development of lower alloy, less expensive corrosion-resistant alloys, particularly for offshore applications, would increase reliability of the major arteries. This development will be inexorably linked to the commodity price of oil.

The use of high-strength, non-metallic composite materials with high-pressure and high-temperature capabilities would significantly reduce the need for corrosion control measures though they may pose other structural limitations. These composites must be produced economically yet remain reliable, and must also gain wider acceptance in the industry for applications other than water handling within the oil and gas industry.

Summary of Issues

Increase consciousness of corrosion costs and potential savings.	A much larger percentage of new domestic oil and gas production will come from remote locations (deepwater offshore, etc.) where corrosion failures will be much more costly to fix. In addition, secondary and tertiary recovery techniques will increase the corrosivity of existing fields. Many problems could potentially be solved simply by using the available improved technologies if there were better awareness of the existence of these technologies. Computerized expert systems and knowledge management tools should be utilized to educate and inform about state-of-the-art materials for corrosion control.
Change perception that nothing can be done about corrosion.	Much of the oil field production technology is based on tried-and-true designs and, as a whole, the industry is extremely conservative. The use of new innovative production strategies would necessarily be accompanied by a more innovative approach to corrosion control.
Advance design practices for better corrosion management.	Advances in materials technology, borrowed from other industries such as aerospace, offer alternatives to conventional designs. Innovative production schemes (such as downhole separation) could reduce the corrosivity of production streams early in the process.
Change technical practices to realize corrosion cost-savings.	Upfront consideration of corrosion control in new construction should be based on all aspects of life-cycle costs, not simply present worth calculations. The total consequences of a leak (including lost production, a more negative public image, and increased scrutiny from regulators) must be factored into these decisions.
Change policies and management practices to realize corrosion savings	Management must be made aware that the lack of immediate corrosion problems does not justify a reduction in expenditures on mitigation, monitoring, and inspection. Throwing money at the problem after a leak occurs should not be considered a cost-effective strategy.
Advance life prediction and performance assessment methods.	More accurate life prediction methods will better enable accurate life-cycle cost estimates when considering the use of advanced alloys and composites. Use of reservoir simulation models, applied to water-cut increases and field souring mechanisms, will help in predicting the behavior of aging fields and would allow for prevention measures to be implemented before the problems take hold.
Advance technology (research, development, and implementation).	Remote monitoring systems for internal corrosion would enable early detection of corrosion control in even the most remote locations. The development and utilization of so-called low-alloy steels would fill the void between carbon steel and expensive corrosion-resistant alloys.
Improve education and training for corrosion control.	Engineering design firms, not oil companies, are designing new platforms and production facilities. Basic education in oil field corrosion control technology needs to be brought into these firms as early as possible in the design of oil production facilities.

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SECTOR DESCRIPTION

The domestic U.S. oil industry is based on a finite resource – petroleum crude, thereby, having a limited growth potential. However, the oil industry is expected to remain an industrial force in the U.S. economy for years to come.

Oil production in the United States in 1998 consisted of 3.04 billion barrels (bbl).(1) The per-barrel price of oil has fluctuated greatly over the past 20 years; however, overall it has remained steady. In fact, the price has dropped steadily when adjusted for inflation. Fortunately, the infrastructure costs for producing oil have come down dramatically in the past 25 years, primarily due to advanced technologies that enable much more of the oil in place to be produced. These advancements have saved the domestic oil industry by allowing it to compete on a commodity basis with cheap foreign oil.

Recent History of Oil and Gas Production

Oil and gas are commodities; therefore, the amount of activity in oil and gas production rises and falls with the commodity price.

Figure 1 shows the price comparison between West Texas Intermediate (WTI) crude oil and the San Joaquin Valley (SJV) crude oil from 1991 to 2000, with the difference between the two prices for crude oil plotted as the "differential". WTI crude, also referred to as light sweet crude, is the benchmark most often quoted by investors in the commodity sector. SJV is heavy crude oil, which requires more expensive processing and refining. SJV's spot price is generally well below the WTI crude.

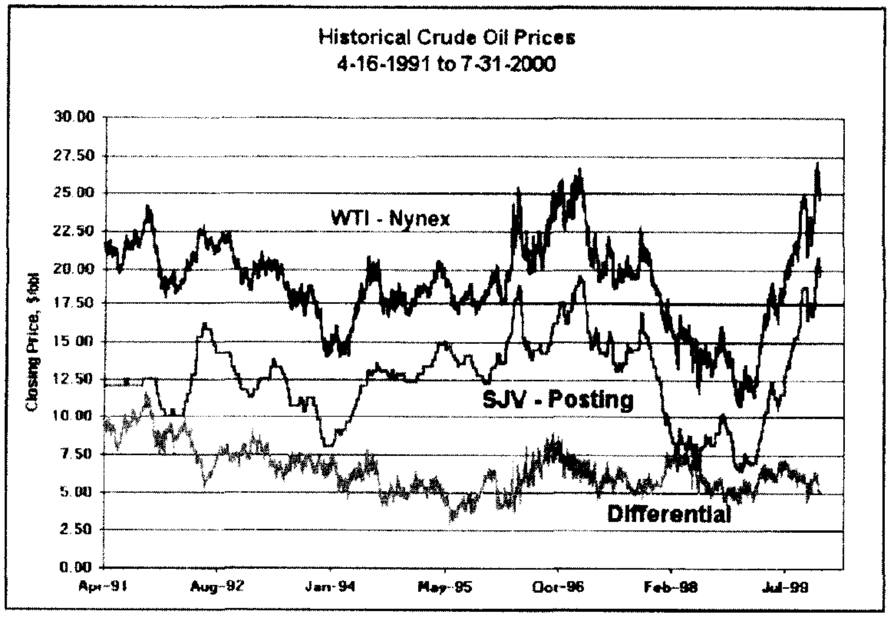

Figure 1. Oil prices in the 1990s.(2)

Table 1 presents the oil production of different countries since 1970. The data show the decline in oil production in the United States balanced by the rise in oil production of most other countries, especially within the Organization Petroleum Exporting Countries (OPEC) cartel. The exception to this is Iraq, whose production has suffered since the Gulf War.

Table 1. Worldwide oil production from 1970–1996.(3)

CRUDE OIL PRODUCTION									
	thousand barrels per day								
	1970	1980	1990	1991	1992	1993	1994	1995	1996
Non-OPEC "Western"									
United States	9,648	8,597	7,355	7,417	7,171	6,847	6,662	6,560	6,471
Canada	1,305	1,424	1,518	1,548	1,604	1,677	1,742	1,806	1,820
Mexico	420	1,936	2,648	2,774	2,668	2,673	2,685	2,722	2,854
Norway	0	528	1,620	1,876	2,144	2,264	2,580	2,782	3,086
United Kingdom	2	1,619	1,850	1,823	1,864	1,922	2,469	2,565	2,633
OPEC									
Algeria	976	1,020	794	803	772	747	750	764	816
Indonesia	855	1,576	1,289	1,411	1,346	1,327	1,319	1,498	1,516
Iran	3,831	1,662	3,252	3,358	3,455	3,671	3,585	3,612	3,675
Iraq	1,563	2,514	2,080	283	425	448	550	600	600
Kuwait	2,983	1,661	1,235	200	1,050	1,870	2,000	2,007	2,060
Libya	3,321	1,830	1,374	1,509	1,493	1,361	1,380	1,390	1,403
Nigeria	1,090	2,058	1,811	1,867	1,902	1,905	1,883	1,890	2,014
Saudi Arabia	3,789	9,903	6,414	8,223	8,308	8,087	8,000	8,074	8,083
United Arab Emirates	691	1,702	2,117	2,416	2,322	2,195	2,223	2,205	2,217
Venezuela	3,708	2,165	2,085	2,350	2,314	2,335	2,463	2,609	2,955
Other Non-OPEC									
China	602	2,113	2,769	2,785	2,835	2,908	2,961	3,007	3,127
Kazakhstan	NA*	NA	515	530	515	460	405	415	460
Russia	NA	NA	10,325	9,220	7,915	6,875	6,315	6,135	6,010

*NA – Not available

Figure 2 shows that worldwide oil production continues to increase. Figure 3 and figure 4 show the decline in the annual oil production for the lower 48 states and Alaska, respectively. Production costs, of which corrosion control is an increasing percentage, continue to limit domestic production as more oil is imported.

Production costs are not tied directly to commodity price, so when commodity prices drop, the solution is often to abandon or shut down the more difficult, less prolific production wells. When the commodity price fell to below $10 a barrel in 1998, an estimated 100,000 wells in the United States were shut down or abandoned. Because the initial cost of recommissioning these wells would be quite high, most of these are permanently shut down.

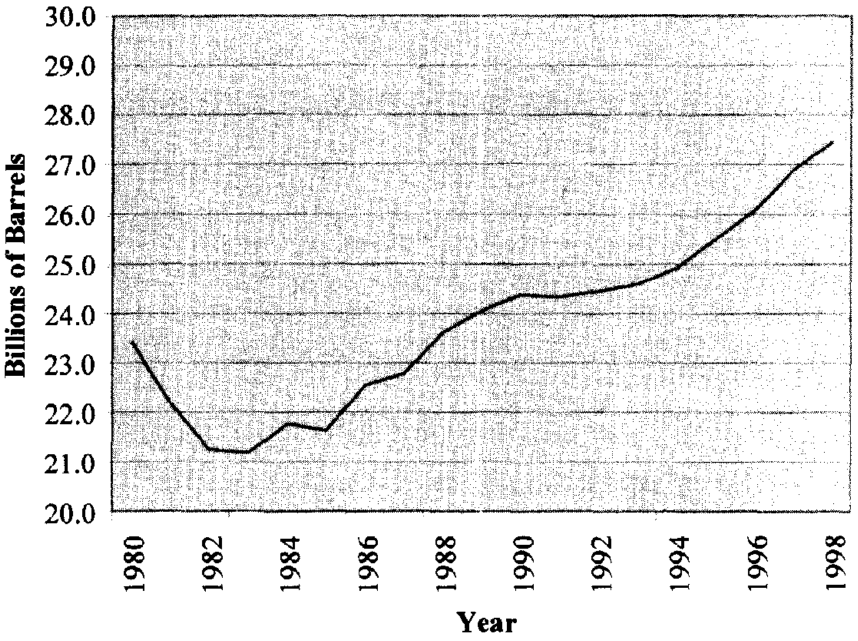

Figure 2. Annual world crude oil production.[3]

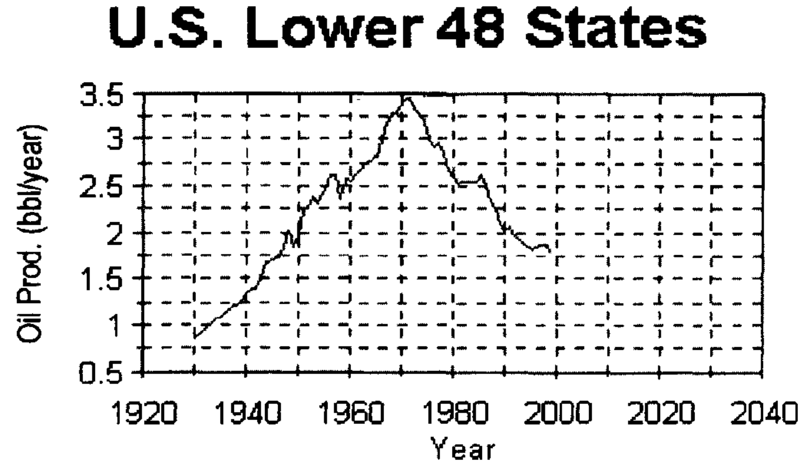

Figure 3. Crude oil production in the lower 48 states.[4]

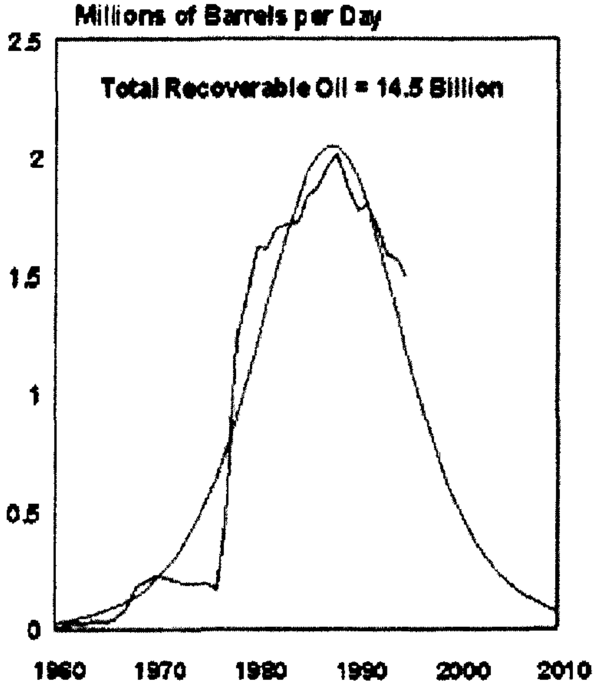

Figure 4. Annual crude oil production in Alaska.[4]

Technology of Oil and Gas Production

While oil and gas production has undergone a number of rebirths in its more than 100-year history, the elements of the process remain relatively constant. Oil is found in reservoirs deep underground or beneath the ocean floor, and is extracted vertically through relatively small-diameter, high-pressure tubing. The process extracts oil, water, and mixed gases (simple hydrocarbons, CO_2, and H_2S, possibly also small quantities of N_2 and inert gases) from the rock formations. A sketch of a typical oil field gathering system is shown in figure 5.

Once at the surface, the production stream runs through a control wellhead into horizontal flow lines, normally of larger diameter and running at lower pressures. The flow lines carry the three phases into a separator vessel in which the gas phase flashes to the upper portion. The oil occupies the middle portion and the water drops to the bottom. Gas from the top may be reinjected into the reservoir, refined and marketed, or flared. Water is normally reinjected into the reservoir, and the oil is sent to a pipeline for delivery to a refinery, tanker terminal, or transmission pipeline system. Other oil field processes include gas processing and reinjection, seawater injection, and natural gas liquid (NGL) stripping and blending.

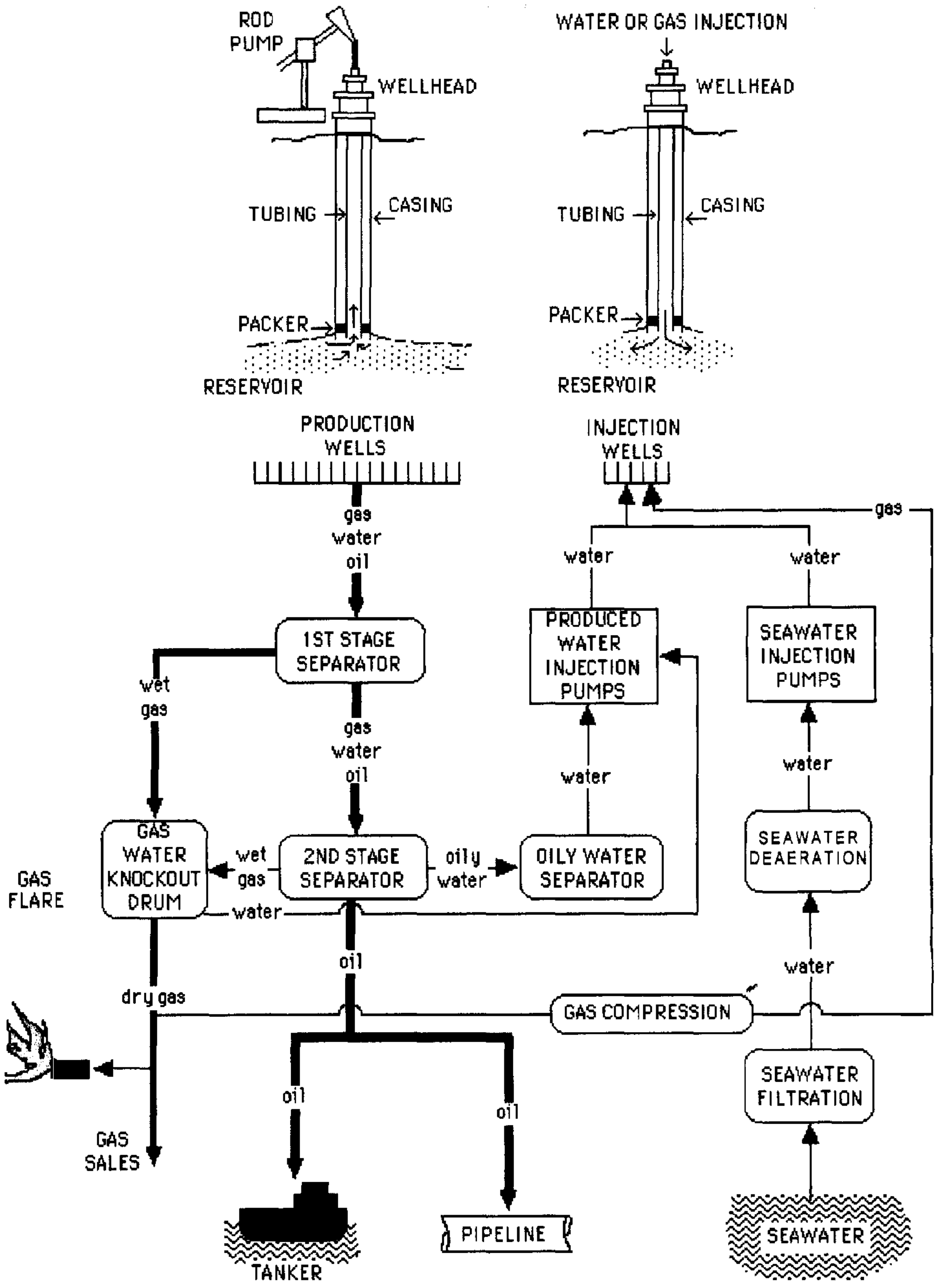

Figure 5. Typical oil and gas production flow diagram.

AREAS OF MAJOR CORROSION IMPACT

Corrosion in Oil Field Environments

Oil field production environments can range from practically zero corrosion to severely high rates of corrosion.(5) Crude oil at normal production temperatures (less than 120 °C) without dissolved gases is not, by itself, corrosive. The economics of controlling corrosion in many oil fields are dependent on efficient separation of crude oil from other species. While the rates may vary, the species causing the most problems are nearly universal. CO_2 and H_2S gases, in combination with water, define most of the corrosion problems in oil and gas production. Other problems include microbiological activity and the solids accumulation.

The mechanisms of CO_2 corrosion are generally well defined; however, the reality inside a pipeline becomes complicated when CO_2 acts in combination with H_2S, deposited solids, and other environments. H_2S can be highly corrosive, but can, in some cases, form a protective sulfide scale that prevents corrosion. Microorganisms can attach to pipe walls and cause corrosion damage. Solids, such as formation sand, can both erode the pipeline internally and cause problems with under-deposit corrosion, if stagnant.

Oxygen is not found in oil reservoirs and much is done to ensure that no oxygen enters the production environment; however, in many cases, a few parts per million (ppm) of oxygen will enter the pipelines, greatly exacerbating corrosion problems.

External corrosion problems in oil and gas production normally are similar to those found in the pipeline industry, but since the lines are shorter and smaller in diameter, their economic impact on the total cost of production is limited. Atmospheric corrosion of structures and vessels is a problem for offshore fields and those operating near marine environments. Improvements in the quality of protective coatings for offshore environments have dramatically reduced the frequency of repainting platforms and tanks.

TRENDS IN DOMESTIC OIL PRODUCTION

As previously described, the annual production of crude oil depends mainly on the cost of extraction, the amount of oil in the ground, and its price in the global market. In order to compete economically, production costs must be decreased using advanced technologies.

A consequence of the advanced technologies that enables higher total production from a reservoir has been an increase in the corrosivity of oil production environments. Secondary and tertiary recovery techniques applied to old oil fields enable them to produce economically for many years after their predicted decline. The drilling of wells in deep water and in otherwise inaccessible areas offshore, adds to the complexity of production. Corrosivity is increased for the following reasons:

- Oil, water, and gas are produced in every oil field. Water is reinjected downhole to maintain reservoir pressure and stability, and often water flooding (using seawater or fresh water sources) is used to drive oil out of the formation. As a field ages, the water cut, or the ratio of water to oil in the fluids produced, increases to levels of 95 percent or higher depending on the economics of production. As the oil industry matures and the number of old oil fields relative to new fields increases, the amount of water produced increases and the internal corrosion increases.
- Water injection from seawater or fresh water sources contributes to "souring" of oil fields with H_2S, usually resulting in an increase in the corrosion rate, which sometimes requires a complete change in the corrosion strategy. These water sources may necessitate biocide

injection and will require deaeration to avoid introducing new corrosion mechanisms into the existing system.

- Tertiary recovery techniques are often based on miscible and immiscible gas floods. These gas floods invariably contain a high percentage (often 100 percent) of CO_2, which dramatically increases the corrosivity of the produced fluids.
- Due to the high cost of failure and the inability to rehabilitate facilities in deep water, offshore production in deep water necessitates the use of high-alloy steels and other more exotic corrosion control measures. A similar need for advanced measures exists in the production of high-pressure, high-temperature offshore oil and gas fields where conventional corrosion mitigation is not possible.

The American Petroleum Institute (API)(6) has recently forecast that there are approximately 200 billion barrels of recoverable oil remaining in the United States and the continental shelf associated with the United States, or about 70 years of production at current rates. This "recoverable" oil includes mostly difficult production, such as deep water, unconsolidated sands, heavy oils, remote arctic fields, and tertiary recovery on existing fields.

Corrosion in oil and gas production varies from location to location. Corrosion can be classified into one of three general categories of internal corrosion caused by the produced fluids and gases, external corrosion caused by exposure to groundwater or seawater, and atmospheric corrosion caused by salt spray and weathering offshore. Of these, internal corrosion is the most costly since internal mitigation methods cannot be easily maintained and inspected.

Overall corrosion costs can most easily be evaluated on a cost per barrel of oil produced basis. In this way, as new wells are drilled or unproductive wells are shut down, the sinusoidal variation in total spending for a particular production area makes more sense.

Oil field production can be divided into downhole costs, including vertical tubing and miscellaneous accessories and surface facilities, which include horizontal piping, production vessels, and storage tanks. Another category would be offshore production costs, including downhole and surface components; however, there is the added expense of offshore platforms or subsea production equipment.

Operational Expenditures

Downhole Tubing

Corrosion economics for the oil wells in the majority of the U.S. onshore oil fields are characterized by very low mitigation costs and carefully monitored replacement and/or failure costs. This is contrary to operations offshore and in the arctic, in which the costs of lost production and/or the high cost of replacement make corrosion prevention a higher priority.

The figures for a typical onshore operation in the United States, consistent with API data, provide the following:(7)

- the average failure rate is 0.6 failures per year per well,
- approximately 30 percent of all failures are corrosion-related, and
- the average cost of a failed well is $3,000.

Using these numbers, there are 0.18 corrosion-related failures annually per well in the United States and the failure cost due to corrosion is $540 per well for every well in the United States. API statistics reported that there are currently 553,000 operational oil wells in the United States and 304,000 gas wells. The cost of corrosion for the downhole portion of the oil and gas industry is then:

0.18 failures x $3,000 per failed well = $540 per well

53,000 oil wells + 304,000 gas wells x $540 per well = $463 million.

Surface Production and Processing

A major American oil field, which produces 270,000 bbl per day (4 percent of total daily domestic production), provided some estimates with regard to the current (1999) annual corrosion costs in different aspects of production (see table 2).

Table 2. Detailed annual costs of corrosion for one large oil field.[8]

	COST ($ x thousand)
INSPECTION COSTS	
Overhead	$492
Tangential Radial Tomography Inspection	$1,409
Ultrasonic Inspection	$361
Other	$1,054
TOTAL INSPECTION	**$3,316**
MONITORING COSTS	
Coupons	$924
Bacteria Monitoring	$13
Laboratory Analysis	$40
TOTAL MONITORING	**$977**
REPAIRS	**$600**
ENGINEERING STAFF	**$1,416**
CORROSION INHIBITOR (chemical alone)	**$13,533**
TOTAL	**$19.84 million**

Another field, operated by the same company and producing 246,000 bbl per day, reported the following costs (see table 3):

Table 3. Costs for various corrosion expenses for one large oil field.[9]

CORROSION EXPENSE	COST ($ x thousand)
Inspection, monitoring, and staff costs	$9,625
Repairs	$1,350
Corrosion inhibitor (chemical alone)	$7,200
TOTAL	**$18.175 million**

The average distribution of these costs is shown in figure 6.

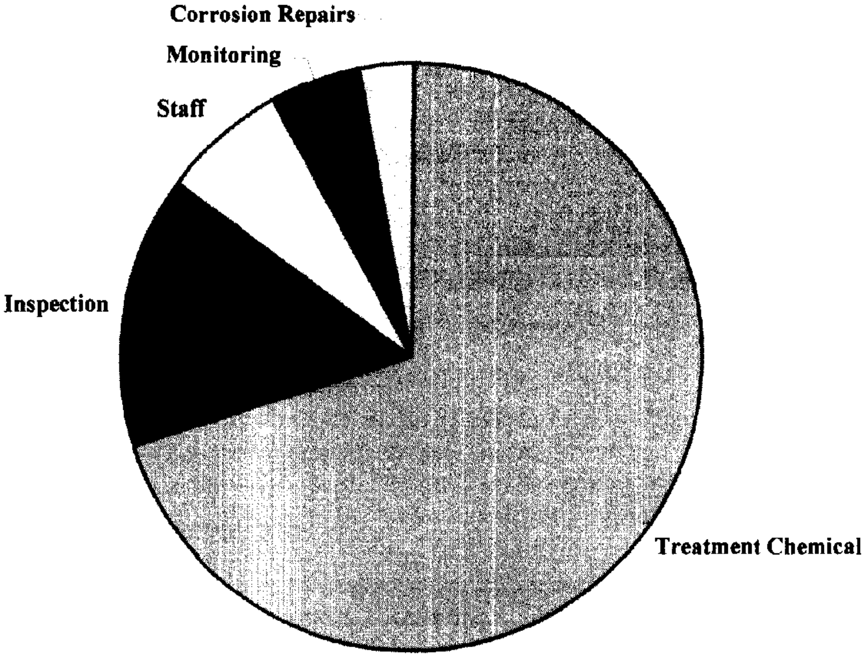

Figure 6. Cost of corrosion in oil production field by activity.

The choice of corrosion control activity would vary greatly with production environment, area, and company philosophy; therefore, some oil fields will use very little treatment chemicals, although the cost of alternatives (alloys, plastic liners, etc.) will fill this void.

Because the extent of internal corrosion in a particular oil field environment is largely a function of the amount of water produced, as a field ages and the water cut increases, corrosion control will become more costly. Increased water often is accompanied by increased levels of bacteria and H_2S, and in cases where miscible gas is reinjected, increased levels of CO_2. Below are figures expressed in terms of corrosion costs per barrel of produced fluid:

Average cost/bbl of produced oil:	$0.20
Average cost/bbl of produced water:	$0.07 to $0.09

The total amount of crude oil and natural gas liquids (NGLs) produced in the domestic United States is approximately 7.9 million bbl per day (*Oil & Gas Journal*, Aug. 2, 1999). Using the figures supplied above for a cost per barrel, that translates into a $1.58 million-per-day cost of corrosion for upstream oil production facilities, or an annual cost of $577 million annually. This figure includes only infield piping and facilities, and does not include cross-country pipeline transportation.

Capital Expenditures

Onshore

A report on internal corrosion for the oil and gas industry in the United States(10) estimated that the annual capital expenditures were $4.0 billion, of which $320 million (8.0 percent) were directly related to corrosion control. The most significant area for these expenditures was the use of corrosion-resistant alloys (CRAs) in downhole tubing and downhole equipment. Other capital expenditures include galvanizing; (OEM) coatings; and alloy valves, fittings, and equipment internals for surface facilities.

Offshore

Offshore oil and gas production works on a different economic basis than onshore production. First, the cost for doing any construction, maintenance, or inspection offshore can be up to 10 times higher than the cost of performing the same activities onshore. The material costs naturally become a smaller percentage of the total cost of the corrosion mitigation operation.

Second, because offshore drilling and completion costs are so much higher than onshore costs, only offshore wells with a high potential production and a long service life are drilled and completed. Field equipment service life must be longer to keep the operations economical; therefore, the facilities and piping must be designed to avoid replacement.

Finally, offshore production requires either expensive subsea completion technology or the construction of a platform to support the production equipment. Not only does the process equipment need corrosion mitigation, but the support infrastructure also needs protection and maintenance. It has been estimated that 60 percent of all maintenance costs in offshore production are corrosion-related.(11)

Offshore capital expenditures (CAPEX) represent a much higher proportion of costs offshore relative to onshore. A detailed study of the cost of corrosion for two particular offshore production fields(11) estimated that the cost of corrosion for the offshore facilities was $0.40 per barrel produced in comparison to $0.20 for onshore facilities.

The offshore fields studied utilized CRAs for tubulars and pipelines. This incrementally represented 6.6 percent of the total construction costs in this field. The operational expenditures (OPEX) were therefore minimized, limited to inspection and maintenance painting, and amounted to only $35,000 annually, or $0.0015 per bbl. The other field, which utilized CRAs but had a greater percentage of coated/cathodically protected carbon steel, showed an OPEX of $0.05 per bbl. In general, it was concluded that the CAPEX was directly related to the corrosivity, while OPEX was proportionally related to the life of the field.

Production offshore in the United States is only about 2 percent of total domestic production. This number is expected to grow incrementally over the next 15 years. Currently, offshore wells being drilled in the United States make up 15 percent of all new production wells. As onshore production declines, the offshore wells, particularly deep-water wells, will offer a frontier for domestic production.

SUMMARY

The total cost of corrosion in the U.S. oil and gas industry is estimated at:

$577 million in surface facilities + additional 2% for offshore OPEX = $589 million,
8% corrosion costs x $4 billion total CAPEX = $320 million, and
153,000 oil wells + 304,000 gas wells x $540 per well for downhole OPEX costs = $463 million.

The total estimated annual cost of corrosion in the oil and gas industry is therefore $589 million + $320 million + $463 million = $1.372 billion.

CASE STUDY

Installation of a Subsea Gathering System for a Natural Gas Production Field

The pipeline design for a new gas production facility for a major oil company(12) consisted of several short 20-cm- (8-in-) diameter subsea gathering lines (flow lines), emptying into a 19-km (30 mi), 50-cm- (20-in-) diameter subsea transmission gas pipeline (trunk line). The pipeline was to bring wet gas from an offshore producing area to a dehydration facility onshore with a design life of 20 years.

The internal corrosion rate of the pipeline system was estimated, through the use of corrosion prediction models, to be 300 to 400 mils per year (mpy); an unacceptably high rate for standard carbon steel pipelines. Because of the corrosivity of the system, several corrosion mitigation options were considered. These options were:

- Carbon steel treated with a corrosion inhibitor.
- Internally coated carbon steel with a supplemental corrosion inhibitor.
- 22 percent Cr duplex stainless steel.
- 625 corrosion-resistant alloy (CRA).

An economic evaluation of each of these included risk assessments and life-cycle cost estimates.

Options for Flow Lines

In the case of bare carbon steel with a supplemental corrosion inhibitor, the installed cost of a line was estimated to be $763,000. Based on the corrosivity of the system, it was predicted that half of the flow lines would have to be replaced over the life of the field. The cost of replacing the lines, based on present-worth calculations, was $549,000, for a total cost of $1.312 million. In addition, the risk of losing corrosion control due to malfunction of the injection system was considered to be quite high. External corrosion protection through coating and cathodic protection was $490,000.

For internally coated carbon steel with a supplemental corrosion inhibitor, the installed cost of a line was $1.033 million. Part of this cost would be the installation of internally coated, weldable sleeves that fit into the ends of the pipeline sections to provide a 100 percent coated line. The supplemental corrosion inhibitor was necessary to inhibit uncoated spots (holidays) in the pipeline. Either installation damage or in-service damage may cause the holidays. Again, external corrosion protection through coating and cathodic protection was $490,000.

For duplex stainless steel, the installed costs were calculated to be $1.77 million; however, due to the duplex stainless steel allowing for higher production velocities, it was calculated that 15-cm- (6-in-) diameter flow lines could be used, which would result in a 25 percent savings, reducing the installed cost to $1.33 million. The higher velocities were the result of a perceived lower amount of solids built up from scale and corrosion products. In addition, the lower external surface area to be coated and cathodically protected reduced this additional cost to $370,000.

The 625 CRA was the only option that would not require external coating and cathodic protection. The cost of this option, which was not given serious consideration, was estimated to be $11.3 million for a 20-cm- (8-in-) line and $8.5 million for a 15-cm- (6-in-) line.

Options for the Trunk Line

All of the above were considered as possible alternatives for the 50-cm (20-in) pipeline.

Bare carbon steel with corrosion inhibitor was not considered to be a technically sound option because maintenance pigging facilities, necessary for solids removal, were not possible with a subsea completion. The effectiveness of a bare carbon steel system with inhibitor is severely curtailed by the presence of solids, which build up inside the pipeline. Pigging facilities also allow in-line inspection pigs to be run, providing a way to monitor corrosion inhibitor effectiveness and subsequently adjust the inhibitor dosage when needed.

Internally coated carbon steel with supplemental corrosion inhibitor was estimated to cost $15.26 million installed, but required the specially coated internal sleeves to bridge the coating across the welds. Again, the supplemental corrosion inhibitor was necessary to inhibit holidays in the pipeline. A corrosion rate at the holiday, based on experience and statistical models, was estimated to be 2 mpy. A 32-mm (1/8-in) corrosion allowance was added to the steel as insurance against inhibitor delivery problems as well as start-up problems.

The duplex stainless steel pipeline was estimated to cost $19.84 million installed. Costs for large-diameter duplex pipes are proportionally much higher than for the 15-cm to 20-cm (6-in to 8-in) piping evaluated for flow line usage.

For all of these cases, external coating and cathodic protection would again be necessary to prevent external corrosion. The cost of this was estimated at $7.84 million or an additional 46 percent over the installed cost of each pipe.

The 625 CRA was not seriously considered for this application because of the high initial cost, estimated to be $77 million.

Risk Factors

The chance for success was estimated from known field histories of each technique, as well as analysis of the corrosivity of the system and the level of sophistication required for successful implementation (see table 4).

Table 4. Estimated probability of success for different material selection options.

OPTION	CHANCE FACTOR FOR SUCCESS
Bare Carbon Steel + Inhibitor	65%
Coated Carbon Steel + Supplemental Inhibitor	90%
Duplex Stainless Steel	95%
625 CRA	98%

Based on these risk factors, it was decided that the attractive economics of the coated carbon steel with a supplemental corrosion inhibitor was preferred over the duplex stainless steel, despite the perceived higher risk of the coated system.

Table 5. Total installed cost for all pipelines (bold underline indicates options that were selected).

LINE DESCRIPTION		BARE CARBON STEEL ("NO CORROSION" CASE)	CARBON STEEL WITH CORROSION INHIBITOR	COATED CARBON STEEL WITH SUPPLEMENTAL CORROSION INHIBITOR AND CORROSION ALLOWANCE	DUPLEX STAINLESS STEEL ALLOY (22% CR)	625 ALLOY
Flow Lines	Pipe + Internal Corrosion Protection	$970,000	$1,310,000	$1,030,000	8 in dia = $1,770,000 **6 in dia = $1,330,000**	8 in dia = $8,850,000 6 in dia = $6,650,000
	Cathodic Protection and External Coating	0	$490,000	$490,000	8 in dia = $490,000 **6 in dia = $370,000**	0
Trunk Lines	Pipe + Internal Corrosion Protection	$9,260,000	N/A	**$11,160,000**	$17,160,000	$77,000,000
	Cathodic Protection and External Coating	0	$7,840,000	**$7,840,000**	$7,840,000	0

N/A – not available

1 in = 25.4 mm

The "No Corrosion" case in the first column indicates the physical cost of installing a steel pipeline so that the additional costs due to corrosion control measures can be more clearly seen. The costs for cathodic protection (CP) and external coating are add-ons to the pipe, since the considerations for external corrosion are different and completely separate from the considerations for internal corrosion.

The total cost for the pipelines in the gas field was [$1,330,000 for 15-cm (6 in) duplex SS flow line] + [$370,000 for CP and external coating on 15-cm (6-in) duplex SS flow line] + [$11,160,000 for internally coated trunk line] + [$7,840,000 for CP and external coating on the trunk line] = $20,700,000 for the pipelines in the field. In the "no corrosion" case, the total cost is $970,000 for flowline + $9,260,000 for trunk line = $10,320,000 for the pipelines in the field. Therefore, corrosion concerns doubled the cost of the pipeline installations in the field.

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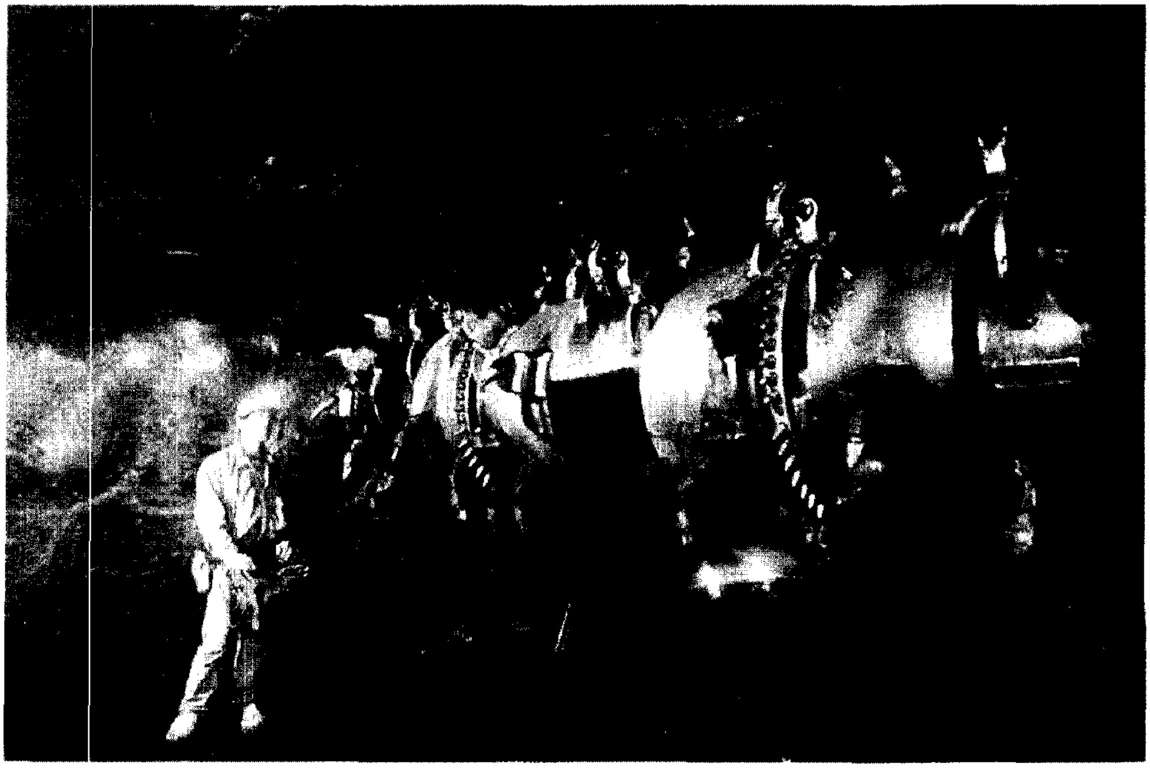
APPENDIX T

MINING



Gravel yard

Backhoe

Open-pit mining

Earth mover

MINING

AARON J. MIERZWA[1]

SUMMARY

Corrosion in the mining industry is not considered a significant issue. Interviews with several mining engineers indicated that equipment wear and tear was the primary concern in maintaining the equipment. Although various forms of corrosion could be identified in mining machinery, corrosion is not considered to be a life-limiting factor for this equipment. Maintenance painting is, however, heavily relied upon to control corrosion, and it is estimated that an average of $93 million is spent annually on maintenance painting for the coal mining industry.

In the few instances where corrosion has been considered to be a problem, the mining industry has relied heavily on past experience and the knowledge of equipment suppliers to quickly resolve any issues so that production is not interrupted. Engineers with corrosion knowledge and expertise are not kept on staff; however, if circumstances require additional help, corrosion consultants are hired.

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[1] CC Technologies Laboratories, Inc., Dublin Ohio.

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SECTOR DESCRIPTION

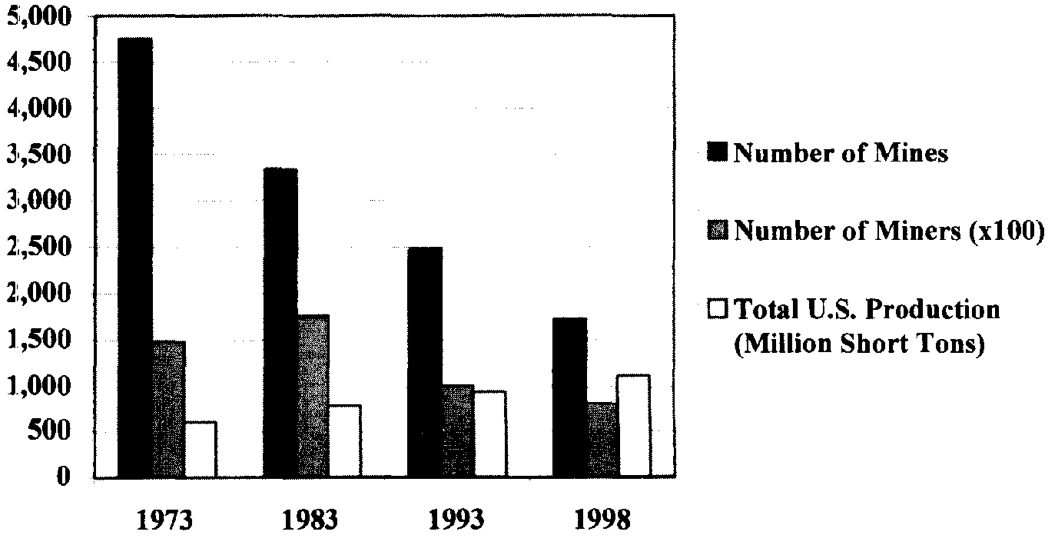
The United States mines and processes coal and more than 2,500 known minerals.(1) Each American relies on more than 21,000 kg (46,000 lb) of mined materials, including 3,400 kg (7,500 lb) of coal energy per year.(2)

The mining, mineral processing, and extractive metallurgy industries possess the ingredients for an extremely corrosive environment. Water, grinding media, dissimilar materials, oxygen, wide pH range, and the presence of many corrosive species in solution contribute to the corrosion-related difficulties that the mining industry deals with on a continuous basis.

This sector report includes information on the mining of metallic materials, industrial minerals (non-fuel, non-metal), and coal. Industry statistics and corrosion issues within the industry are discussed below.

Mining Industry Statistics

Total mining production in the United States was estimated at $59.3 billion in 1998.(2) Figure 1 shows that the trend of the mining industry over the past 25 years is to use fewer employees in fewer mines, but with greater production.(3)



1 short ton = 2,000 lb = 0.9072 metric tons

Figure 1. U.S. trends for the mining industry from 1973 to 1998.(3)

The total mining production values in 1998 for metals, industrial minerals, and coal are shown in figure 2. Industrial minerals such as dimension stone, clay ceramic, refractory minerals, and chemical and fertilizer minerals comprised more than 48 percent of the total mining production in U.S. dollars, while coal comprised 33.2 percent and metals 18.7 percent. The quantities and values of specific metals mined are shown in table 1.

In 1998, U.S. exports of principal minerals and products, excluding mineral fuels, totaled $31.4 billion, while imports totaled $65.4 billion.(5)

It is estimated that $2.1 billion of processing equipment to support the mining industries are developed and shipped annually.(1)

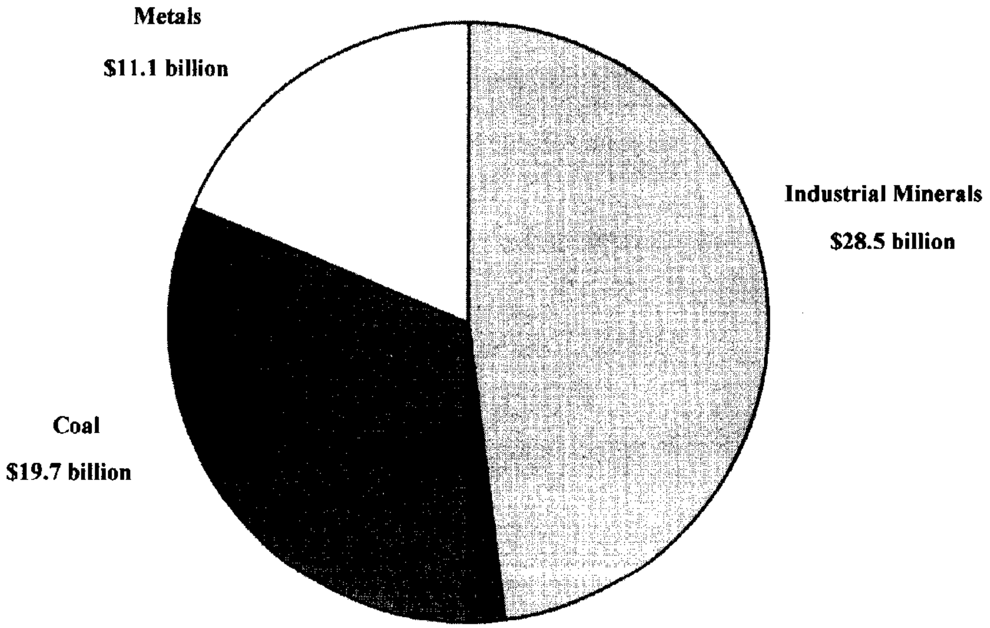


Figure 2. Total mining production values for the United States in 1998, as reported by the U.S. Geological Survey.(4)

Table 1. 1998 Metal production in the United States, as reported in March 2000 by the U.S. Geological Survey.(5)

MINERAL	QUANTITY (metric tons)	VALUE ($ x million)
Beryllium concentrates	6,080	*
Copper	1,860,000	3,220
Gold	366	3,480
Iron ore, usable	63,200,000	1,970
Iron oxide pigments, crude	46,100	7.3
Lead	481,000	480
Magnesium metal	106,000	344
Nickel ore	-	-
Palladium	10.6	98.6
Platinum	3.24	38.8
Rare-earth metal concentrates	5,000	14.4
Silver	2,060	339
Zinc	722,000	819
Antimony, bauxite, manganiferous ore, mercury, molybdenum, titanium, tungsten, vanadium, zirconium	-	590
TOTAL	-	**$11,400**

*No value reported.

Corrosion in the Mining Industry

Corrosion within the mining industry can be characterized as corrosion enhanced by abrasion. It is also difficult for corrosion engineers to plan for corrosion because mine atmospheres and waters are unique and vary widely from one mine to another; therefore, each mine experiences relatively different corrosion-related problems.

Aerobic and anaerobic microorganisms present in mining water also contribute to the extremely corrosive environments.(6) Aerobic species produce sulfuric acid, making the environment very acidic. Anaerobic microorganisms reduce sulfate and sulfides by using available hydrogen and producing hydrogen sulfide (H_2S).

Although corrosion does exist in the mining industry, the industry does not consider it to be a serious issue. Engineers from several mining companies who were interviewed could not provide any information on instances where corrosion problems were a critical issue. Past experiences and equipment suppliers provide these process engineers with enough information to keep the mining industry processing its metallic minerals, industrial minerals, and coal.

Maintenance painting is heavily relied upon to prevent corrosion. American Electric Power(7) estimated that it spends between $0.5 million and $1 million annually for maintenance painting in order to produce approximately 8.2 million metric tons (9 million short tons) of coal. Correlating this to the 1.0142 billion metric tons of coal (1.1176 billion short tons) that were produced nationwide in 1998,(4) it can be estimated that between $62 million and $124 million (average $93 million per year) was spent on maintenance painting for the coal mining industry.

While mine engineers are not involved in serious corrosion issues, literature on the subject lists several areas of major concern due to personnel safety and continuation of production. These areas are listed below.

AREAS OF MAJOR CORROSION IMPACT

The corrosive environment of the mining industry limits the life span of the processing equipment and as a result, decreases production and endangers the lives of employees within the mine. Examples of mining equipment that undergo corrosion are discussed below.

Wire Rope

Wire ropes are used extensively in the mining industry to help hoist equipment. Mine workers also depend on this rope for their safety. Wire rope undergoes both corrosion and abrasion, which will degrade the mechanical properties of the wire and, thus, reduce its load-bearing capability and cause it to fail.

A statistical study of mine-hoist wire ropes showed that 66 percent of the ropes exhibited the greatest strength loss in the portion of the rope in contact with the shaft environment during its service life.(8) The Mine Safety and Health Administration (MSHA) of the U.S. Department of Labor requires that wire ropes in service be visually examined for structural damage, corrosion, and improper lubrication or dressing.(9) MSHA also requires performance of careful nondestructive testing (NDT) every 6 months and sites one instance where a contractor reported that four ropes were in acceptable condition for use in an elevator shaft. However, less then 6 weeks later, one of the four 12.7-mm- (0.5-in-) diameter) ropes broke and another was severely corroded with several broken wires.(10)

Wire ropes within the mining industry are routinely replaced every 18 to 36 months, depending on environmental conditions and use over time. These wire ropes are mainly made of carbon steel; however, due to their susceptibility to corrosion and wear, stainless steel and synthetic fiber ropes are becoming more widely used instead.(6)

Roof Bolts

In the mining industry, roof bolts provide support in underground mines by tying the lower layer to a stronger layer located above the main roof. In the United States, more than 120 million low-carbon steel roof bolts are used per year and are a major area of concern with regard to corrosion because a failure of the roof bolt is hazardous and could result in the loss of lives.(6) In sulfide mines, roof bolts have been reported to fail within 1 year due to sulfide stress corrosion cracking

Pump and Piping Systems

Corrosion within pump and piping systems is another critical issue in the mining and mineral processing industries. The most common form of corrosion is uniform attack; however, pitting, crevice corrosion, intergranular corrosion, dealloying, galvanic corrosion, and cavitation are each possible, depending on the processing environment.

Erosion-corrosion in the milling process is another critical issue. Particulates are often carried in a corrosive medium through pipes, tanks, and pumps. The presence of these particulates erodes and removes the protective film of the metal and exposes the reactive alloy to high flow velocity, thus accelerating the corrosion mechanism.

Mining Electronics

According to the Connaisseur Corporation Pty. Ltd.,(3) the effects of corrosion in electrical and electronic systems in modern mines are often overlooked; however, the harsh environment of the mining industry often causes electrical equipment to fail after a short period of time.

Acid Mine Drainage

When pyrite and other sulfide minerals are oxidized by exposure to oxygen and water, ferrous ions and sulfuric acid are produced. The ferrous ions further react to form hydrated iron oxide and more acidity. This acid formation lowers the pH of the water, making it unable to support many forms of aquatic life and to become corrosive to surrounding structures. The acid mine drainage can cause corrosion problems in structures such as pipes, well screens, dams, bridges, water intakes, and pumps. In 1993, a survey by the U.S. Forest Service estimated that 8,050 to 16,100 km (5,000 to 10,000 mi) of domestic streams and rivers are impacted by acid drainage.(11)

In comparison, in 1995, the Pennsylvania Department of Environmental Protection reported that 3,902 km (2,425 mi) of stream in Pennsylvania did not meet EPA-mandated in-stream water quality standards due to mineral extraction.(12) This significant amount affected streams in Pennsylvania, compared with the nationally estimated amount, can be explained by the fact that this state has a relatively large portion of the U.S. coal industry.

CORROSION CONTROL METHODS

Material selection is the most important general form of corrosion prevention. Choosing the correct material based on the environment decreases the amount of corrosion and lengthens the life span of the equipment. While material selection is the most important general approach to corrosion prevention, several other methods of corrosion protection are used in the mining industry. They include protective coatings, corrosion inhibitors, and electrochemical techniques such as cathodic protection.

CORROSION MANAGEMENT

Corrosion-related issues in the mining industry are dealt with immediately when problems arise that can cause a slowdown in production. As corrosion-related issues develop, the mining industry relies almost entirely on past experience and vendor input to assist with a quick remedy to the problem. Corrosion engineers are not common in mines. When major corrosion problems are encountered, mining companies will contract the help of external contractors or corrosion consulting firms.(13)

CASE STUDY

Example of Cost Analysis of Organic Coatings

Andrew(14) performed a cost-benefit analysis for both the initial and long-term costs associated with four organic coating systems used in the mining industry. Alkyd, vinyl, and epoxy coatings were each analyzed with various forms of surface preparation (e.g., surface blasting or no surface blasting) and coating thicknesses. It is recognized that the values presented in this case study are merely estimates and should not be extrapolated beyond the current example; however, the presented method to compare systems is a valid approach to analyze long-term costs.

Organic coatings will react differently depending on the environment to which they are exposed.(15) Alkyd resins are oil-based coatings that have excellent adhesion to poorly prepared surfaces, but are not chemically resistant. They are mainly used for dry exterior uses. Vinyl coatings are easily recoated, are low in toxicity, but are highly volatile. They are mainly used under conditions where equipment is frequently exposed to either saltwater or fresh water and acidic chemicals. Epoxies are similar to alkyds, but are more chemically resistant and correspondingly more expensive. They are used in applications that involve exposure to fresh water, saltwater, or chemicals such as mineral spirits, lower alcohols, glycols, etc.

The surface preparation and thickness of the coating also play important roles in the amount of corrosion protection provided. Abrasive blasting produces a surface anchor pattern, which allows for better adhesion between the substrate and the coating. The thickness of the coating will also determine the amount of protection that the coating will provide. The thicker the coating, the longer it will last.

The initial costs, maintenance costs (touch-up versus replacement), and maintenance frequency of four painting systems with the different organic coatings, surface preparations, and coating thicknesses are estimated by Andrew(14) (see table 2). These cost estimates are relative with respect to the variable "P", which is the basic cost of the carbon steel item for which corrosion protection is required.

The two-coat, 100-µm (4-mil) alkyd coating system with no abrasive blasting has the lowest initial cost, but must be touched-up annually and be replaced every 2 years. As the abrasive blasting is performed and the coating thickness increases, the initial cost increases. However, the maintenance frequency decreases.

Table 2. Cost analysis of four coating systems.(14)

COATING SYSTEM	INITIAL COST	MAINTENANCE COST		MAINTENANCE FREQUENCY	
		TOUCH-UP	REPLACEMENT	TOUCH-UP	REPLACEMENT
2-coat alkyd/no blasting 100 μm (4 mil)	0.2P	0.1P	0.3P	Yearly	Every 2 years
3-coat vinyl/no blasting 175 μm (7 mil)	0.5P	0.3P	0.6P	Every 2 years	Every 4 years
3-coat vinyl/with blasting 175 μm (7 mil)	0.7P	0.3P	0.6P	Every 3 years	Every 6 years
3-coat epoxy/with blasting 250 μm (10 mil)	0.9P	0.4P	1.1P	Every 4 years	Every 8 years

Note: "P" is the basic cost of the carbon steel item requiring corrosion protection.

Table 3 evaluates the estimated costs and maintenance frequencies of the four coating systems over a 20-year period. The three-coat, 175-μm (7-mil) vinyl coating with abrasive blasting is the most cost-effective, while the same system with no abrasive blasting is the most expensive due to the necessary maintenance. Figure 3 shows this data in graphical form.

Table 3. Cost evaluation of four coating systems over a 20-year period.(14)

COATING SYSTEM	INITIAL COST	MAINTENANCE COST	TOTAL COST (20 YEARS)
2-coat alkyd/no blasting 100 μm (4 mil)	0.2P	4.0P	4.2P
3-coat vinyl/no blasting 175 μm (7 mil)	0.5P	4.3P	5.0P
3-coat vinyl/with blasting 175 μm (7 mil)	0.7P	2.6P	3.4P
3-coat epoxy/with blasting 250 μm (10 mil)	0.9P	3.4P	4.3P

Note: "P" is the basic cost of the carbon steel item requiring corrosion protection.

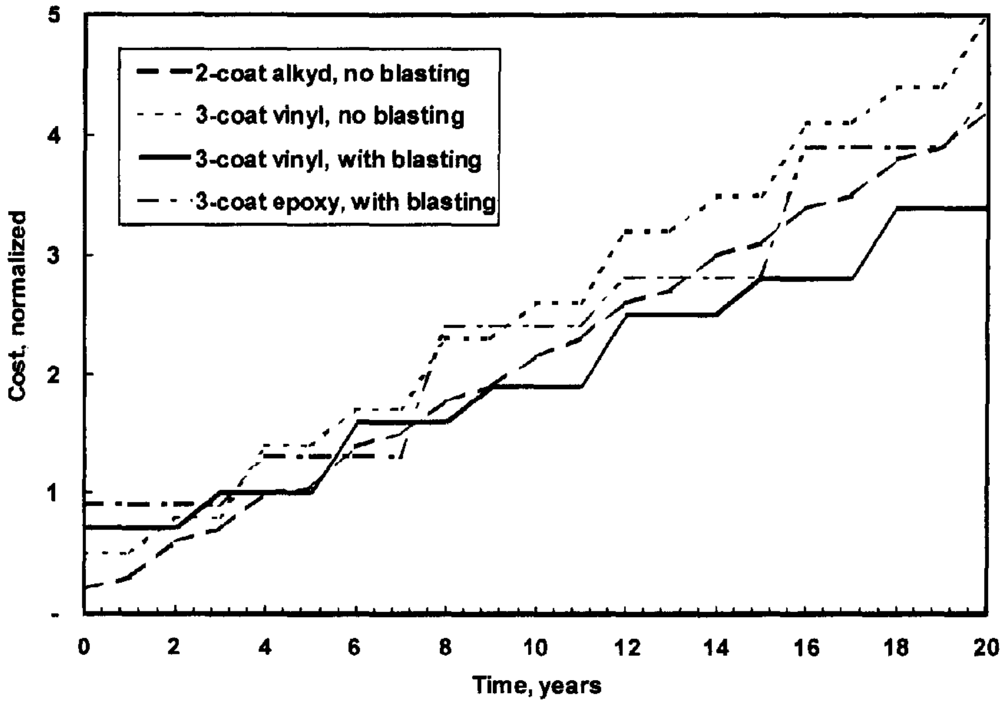


Figure 3. Comparison of relative cumulative costs for four typical painting systems.(14)

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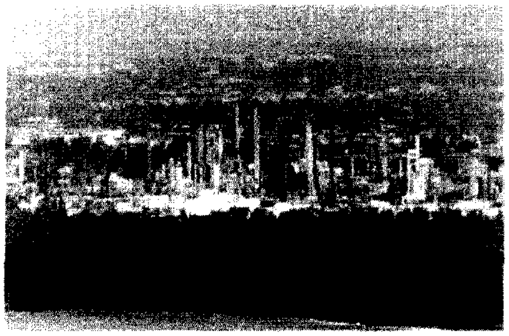
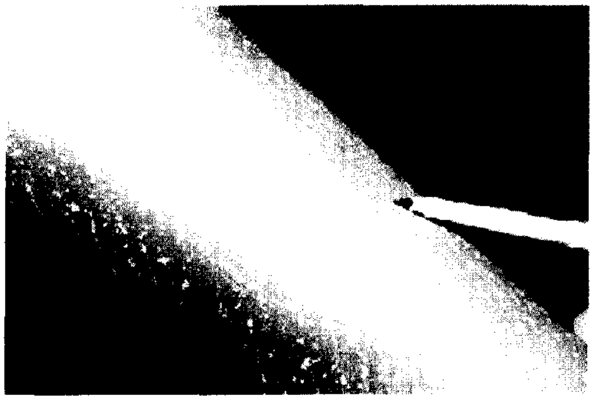
APPENDIX U

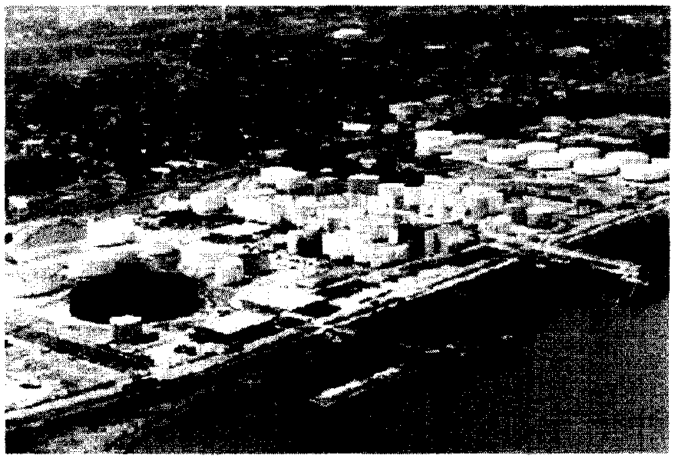
PETROLEUM REFINING



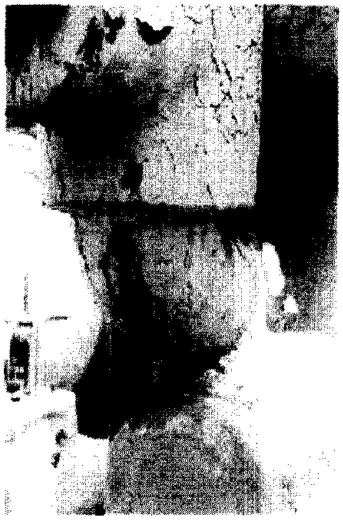
Refineries



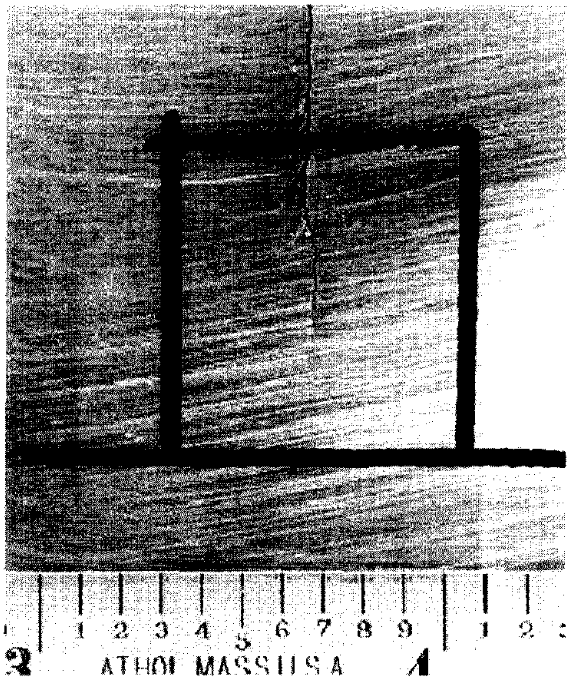
Pitting on stainless steel piping



Tank farm for storage of liquids



Disbonded coating on piping



Stress corrosion crack in stainless steel

PETROLEUM REFINING

GREGORY R. RUSCHAU, PH.D.[1] AND MOHAMMED A. AL-ANEZI[2]

SUMMARY AND ANALYSIS OF RESULTS

Corrosion Control and Prevention

Petroleum refining is an industry that is undergoing intense amounts of scrutiny in the United States from regulatory agencies and environmental groups. As a result, releases of pollutants caused by corrosion leaks are becoming a high-consequence event. The Clean Air Act of 1990 has forced refineries to implement a number of costly measures to reduce their impact on the environment, both in the types of products they produce and the manner in which they operate.

The total cost of corrosion control in refineries is estimated at $3.692 billion. Of this total, maintenance-related expenses are estimated at $1.767 billion annually, vessel turnaround expenses account for $1.425 billion annually, and fouling costs are approximately $0.500 billion annually. The costs associated with corrosion control in refineries include both processing and water handling. Corrosion-related issues regarding processing include the handling of organic acids (broadly referred to as napthenic acid corrosion) and sulfur species, particularly at elevated temperatures, as well as water carried over in processing vessels and pipelines. Water handling includes concerns with corrosives such as H_2S, CO_2, chlorides, and high levels of dissolved solids.

Opportunities for Improvement and Barriers to Progress

As with oil production, the lifeblood of a refinery is the production system. Failure in any processing vessel, particularly the major feedstock lines, costs significantly more in lost production than the cost of prevention and maintenance. Unlike oil and gas production, refining margins are dictated on both ends by commodity prices since the input feedstock crude oil is purchased at the market price and the output product is sold at each individual commodity price.

Because the economics of refining are wholly dependent on world market prices, the amount spent on corrosion control is dictated by current economic conditions in the industry. Since 1981, the number of operating refineries in the United States has dropped from 324 to 163. The industry has seen a trend toward refining more highly acidic oils (which can be refined at a higher margin) since the early 1990s, which increases potential corrosion problems, but may extend the economic life of some existing refineries.

Recommendations and Implementation Strategy

The majority of pipelines and vessels in refineries are constructed of carbon steel. Opportunities for significant savings exist through the use of low-alloy steels and alloy-clad vessels, particularly as increasingly higher fractions of acidic crude are refined.

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Increasing regulation and pressure from environmental groups have essentially forced the refiners to implement defensive strategies. This is compounded by overseas market forces such as the Organization of Petroleum Exporting Countries (OPEC), which can control the price of feedstock crude oil, making long-term planning difficult. In a commodity price-driven industry that is struggling to compete in the world market, investment in more effective corrosion control strategies often takes a backseat to across-the-board cost-cutting measures.

Summary of Issues

Increase consciousness of corrosion costs and potential savings.	Federal regulations such as the Clean Air Act of 1990 have increased operating costs due to stricter controls on releases. In addition, more acidic crude oil is being refined because of the higher net margins possible; a stronger approach to corrosion control will enable these more aggressive crudes to be safely refined in the United States, otherwise, the refining industry will continue to move overseas.
Change perception that nothing can be done about corrosion.	A longer-term vision must be incorporated into facility design and maintenance to enable U.S. refiners to remain competitive. This includes the use of some exotic materials, such as ceramics, which can provide a longer service life in high-temperature operations.
Advance design practices for better corrosion management.	More efficient processing vessel design would reduce the carryover of corrosives from one process to the next. Improved water separation, CO_2 stripping, etc. would help isolate the problem areas and would allow corrosion control efforts to be focused farther upstream.
Change technical practices to realize corrosion cost-savings.	Fitness-for-service principles will need to be applied to vessel inspections rather than following existing protocol, which may be inadequate. Risk-based models would enable the maintenance staff to prioritize inspections.
Change policies and management practices to realize corrosion cost-savings.	Management may have to shift its focus from ensuring compliance with existing regulations to a more active strategy to prevent releases. Zero-leak policies and programs would be implemented in plants to emphasize commitment to this strategy.
Advance life prediction and performance assessment methods.	Flexible life prediction models are needed that can show how a change in the feedstock crude affects all vessels downstream. Also needed are improved inspection and monitoring techniques for in-plant piping systems, both for aboveground and buried lines.
Advance technology (research, development, and implementation).	Processes in refineries are largely computer-controlled, but corrosion control methods lag behind in technology. Computer-aided mitigation systems, perhaps integrated with existing process control modules, could be used to track the changing corrosivity of existing processes.
Improve education and training for corrosion control.	Requiring contract services such as nondestructive inspection companies, maintenance painters, and corrosion control specialists to provide NACE-certified personnel or at least personnel who meet some minimum training/education requirements before they are allowed to work on-site would improve the level of knowledge in the industry.

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SECTOR DESCRIPTION

Petroleum is the single largest source of energy for the United States. When measured in British thermal units, the nation uses twice as much petroleum than either coal or natural gas, and four times more petroleum than nuclear power, hydroelectricity, and other renewable energy sources. On average, every citizen in the United States consumes 9.1 kg (20 lb) of petroleum per day. This primary dependence on petroleum for energy has been a reality for decades, with petroleum's share of the domestic energy mix peaking at 49 percent in 1977.

REFINING CAPACITY OF THE UNITED STATES

U.S. refineries represent approximately 23 percent of world production. The United States has the largest refining capacity in the world, with 163 operating refineries, having declined from a high of 324 refineries in 1981 and 205 refineries in 1990.(1)

Most refineries in the United States are concentrated on the west and gulf coasts, primarily due to access to major sea transportation and shipping routes. The majority of the oil distillation capacity is currently centered in large, integrated companies with multiple refining facilities. About 25 percent of all facilities are small operations producing fewer than 50,000 barrels per day, representing 5 percent of the total output of petroleum products annually.

In 1970, U.S. refineries supplied just under 15 million barrels of refined product per day. In 1996, U.S. refiners supplied more than 18 million barrels per day of refined petroleum products. Total daily crude oil refining capacity by the end of 1999 was 16,511,871 barrels per day. U.S. refiners rely on both domestic and foreign producers for crude oil. Historical trends over the last 10 years indicate that imports of crude oil have been rising steadily.

Future refining capacity in the United States is predicted to increase slightly and level off in the next 20 years, as shown in figure 1. The curve illustrates how the United States experienced a steep decline in refining capacity in the years following 1981. Between 1981 and 1989, the number of U.S. refineries fell from 324 to 204, representing a loss of 3 million barrels per day (MMBD) in operable capacity, and a concomitant increase in refining capacity utilization from 69 to 86 percent.

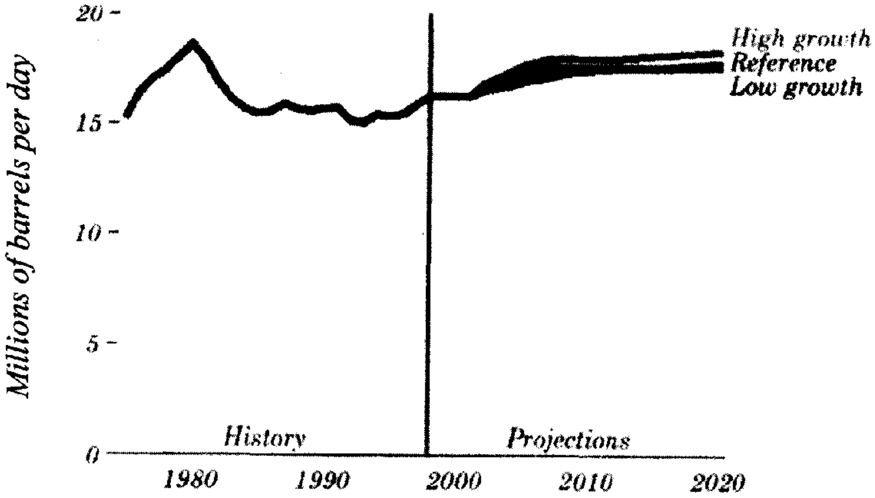

Figure 1. Past and predicted future refining capacity in the United States.(2)

Refined Products

Table 1 shows the average daily throughput of U.S. refineries in 1997.(3) On an annual basis, this translates into a total of 5.7 billion barrels[3] of refined product. Approximately 90 percent of all crude oil entering a petroleum refinery is converted to fuel products, with the remaining 10 percent divided into non-fuel products such as asphalt, lubricants, and waxes and petrochemicals such as polymer feedstocks and industrial solvents. Gasoline production alone accounts for more than 46 percent of all production, as shown in figure 2.

Table 1. U.S. daily average supply and disposition of crude oil and petroleum products, January 1997.(3)

COMMODITY	FIELD PRODUCTION (thousand barrels per day)			REFINERY PRODUCTION (thousand barrels per day)			UNACCOUNTED-FOR IMPORTS (thousand barrels per day)		
Crude Oil	6,402						7,492		
NGLs and LRGs*	1,782			528			246		
Pentanes Plus		302						53	
LPGs**		1,480			528			193	
Ethane/Ethylene			634			26			
Propane/Propylene			520			519			
N Butane/Butylene			165			-28			
			161			11			
OTHER LIQUIDS	267						740		
Other Hydrocarbons/Oxy		247						77	
Ounfinished Oils								421	
Mogas Blend. Comp.***								242	
Avgas Blend. Comp.****		20							
FINISHED PETRO PROD.	19			15,075			1,285		
Finished Mogas	19				7,288			320	
Reformulated						2,217			136
Oxygenated						134			0
Other						4,937			184
Finished Avgas					16			0	
Jet Fuel					1,491			100	
Naptha-Type									0
Kerosene-Type						1,491			100
Kerosene					118			3	
Distilate Fuel Oil					3,119			293	
≤0.05 Sulfur						1,751			94
>0.05 Sulfur						1,368			198
Residual Fuel Oil					801			211	
Naptha Petro Feed					180			106	
Oth Oils Petro Feed					240			206	
Special Napthas					47			10	
Lubricants					168			7	
Waxes					21			1	

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[3] 1 barrel = 158 L.

Table 1. U.S. daily average supply and disposition of crude oil and petroleum products, January 1997 (continued).[3]

COMMODITY	FIELD PRODUCTION (thousand barrels per day)			REFINERY PRODUCTION (thousand barrels per day)			UNACCOUNTED-FOR IMPORTS (thousand barrels per day)		
Petroleum Cake					638			2	
Asphalt & Road Oil					322			26	
Still Gas					585				
Misc. Products					41				
TOTAL	8,470			15,603			9,763		

*Natural Gas Liquids and Lead Replacement Gasolines
**Liquefied Petroleum Gas
***Motor Vehicle Fuel
****Aviation Fuel

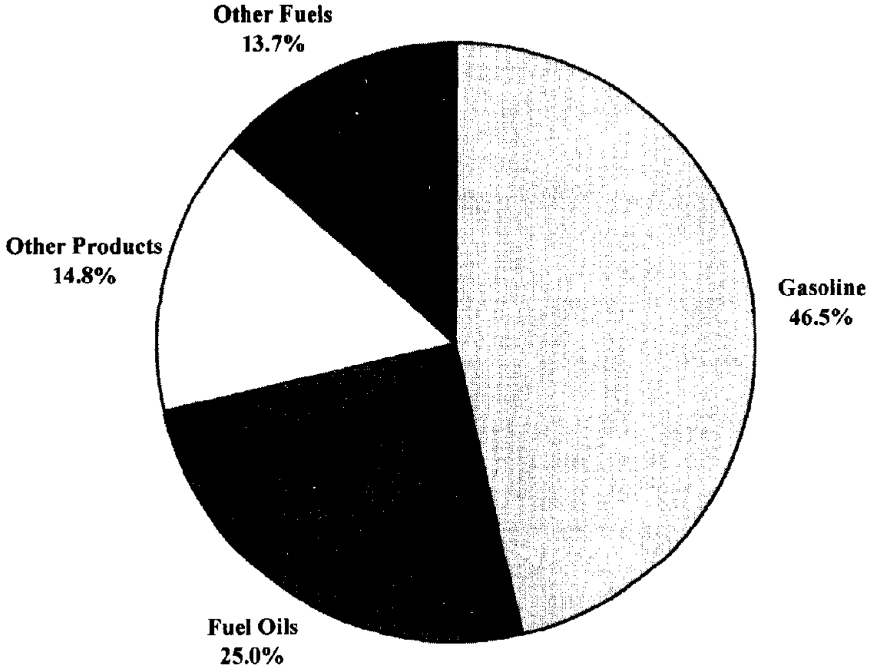


Figure 2. 1996 Outputs from refineries by end-product usage.

Types of Crude Oil

Crude oils are complex mixtures containing many different hydrocarbon compounds that vary in appearance and composition from one oil field to another. Crude oils range in consistency from water to tar-like solids, and in color from clear to black. An average crude oil contains about 84 percent carbon, 14 percent hydrogen, 1 to 3 percent sulfur, and less than 1 percent each of nitrogen, oxygen, metals, and salts. Crude oils are generally classified as paraffinic, naphthenic, or aromatic based on the predominant proportion of similar hydrocarbon molecules. Mixed-base crudes have varying amounts of each type of hydrocarbon. Refinery crude base stocks usually consist of mixtures of two or more different crude oils. Table 2 lists some typical properties for crude oil sources from around the world.

Crude oils are also defined in terms of API (American Petroleum Institute) gravity number. The higher the API gravity number, the lighter the crude. For example, light crude oils have high API gravities and low specific gravities. Crude oils with low carbon, high hydrogen, and high API gravity are usually rich in paraffins and tend to yield greater proportions of gasoline and light petroleum products. Crude oils with high carbon, low hydrogen, and low API gravities are usually rich in aromatics. Crude oils that contain appreciable quantities of hydrogen sulfide or other reactive sulfur compounds are called sour. Those with less sulfur are called sweet. Some exceptions to this rule are the West Texas crudes, which are always considered sour regardless of their H_2S content, and the Arabian high-sulfur crudes, which are not considered sour because their sulfur compounds are not highly reactive.

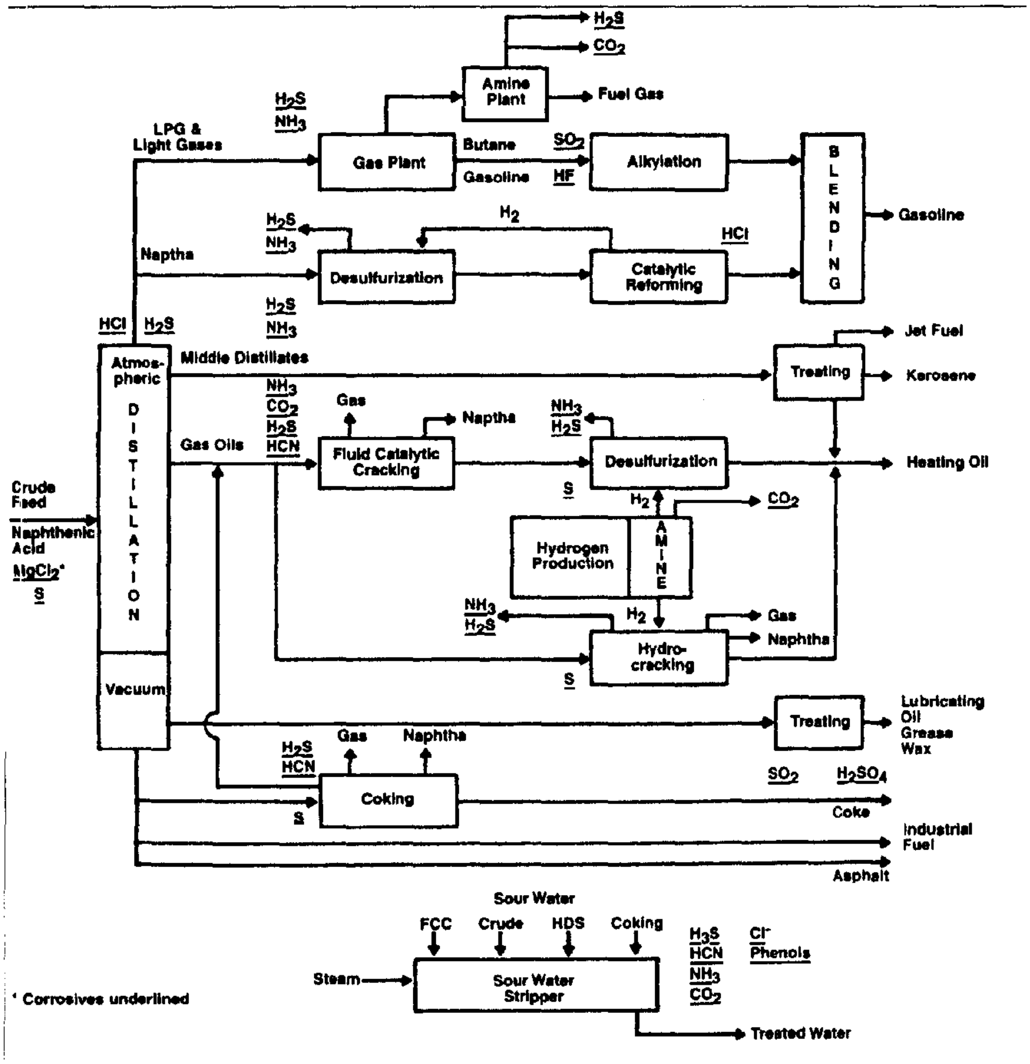
For refining operations, the acidity of the crude oil is an important consideration for economic reasons. A number of organic acids may be present in crude oil feedstocks. The extra costs associated with handling high-acid crudes can be offset by a lower feedstock cost. Acidity is defined in terms of the total acid number (TAN), which is a measure of the number of milligrams of potassium hydroxide (KOH) needed to neutralize 1 g of sample. A TAN exceeding 1.5 to 1.8 mg KOH/g is considered corrosive; however, corrosion problems can occur in crudes with TAN numbers as low as 0.3 for several reasons, including velocity and the nature of the acidic species present.

Table 2. Typical approximate characteristics and properties and gasoline potential of various crudes.(4)

CRUDE SOURCE	PARRAFINS (%VOL)	AROMATICS (%VOL)	NAPTHENES (%VOL)	SULFUR (%WT)	API GRAVITY (APPROX.)	NAPH. YIELD (% VOL)	OCTANE NUMBER (TYPICAL)
Nigerian (light)	37	9	54	0.2	36	28	60
Saudi (light)	63	19	18	2	34	22	40
Saudi (heavy)	60	15	25	2.1	28	23	35
Venezuela (heavy)	35	12	53	2.3	30	2	60
Venezuela (light)	52	14	34	1.5	24	18	50
USA Midcont. Sweet	-	-	-	0.4	40	-	-
USA (W.Texas Sour)	46	22	32	1.9	32	33	55
North Sea (Brent)	50	16	34	0.4	37	31	50

Elements of the Refining Operation

Petroleum refining begins with the desalting (dehydration) of feedstock followed by distillation, or fractionation, of crude oils into separate hydrocarbon groups. The resultant products are directly related to the characteristics of the crude oil processed. Most distillation products are further converted into more usable products by changing the size and structure of the hydrocarbon molecules through cracking, reforming, and other conversion processes as discussed in this sector. These converted products are then subjected to various treatment and separation processes, such as extraction, hydrotreating, and sweetening to remove undesirable constituents and improve product quality. Integrated refineries incorporate fractionation, conversion, treatment, and blending operations, and may also include petrochemical processing. An outline of the refining process is shown in figure 3.



* Corrosives underlined

Figure 3. Flowchart diagram of a typical refining process.(5)

Crude oil often contains water, inorganic salts, suspended solids, and water-soluble trace metals. As a first step in the refining process, to reduce corrosion, plugging, and fouling of equipment and to prevent poisoning the catalysts in processing units, these contaminants must be removed by desalting (dehydration). The two most typical methods of crude oil desalting – chemical and electrostatic separation – use hot water as the extraction agent. In chemical desalting, water and chemical surfactants (demulsifiers) are added to the crude and heated so that salts and other impurities dissolve into the water or attach to the water, and are then held in a tank where they settle out. Electrical desalting is the application of high-voltage electrostatic charges to concentrate-suspended water globules in the bottom of the settling tank. Surfactants are added only when the crude has a large amount of suspended solids. Both methods of desalting are continuous. A third and less common process involves filtering heated crude using diatomaceous earth.

After desalting, crude oil is continuously drawn from the top of the settling tanks and sent to the crude distillation (fractionating) tower. Fractionation (distillation) is the separation of crude oil in atmospheric and vacuum distillation towers into groups of hydrocarbon compounds of differing boiling-point ranges called fractions or cuts.

Conversion processes change the size and/or structure of hydrocarbon molecules. These processes include decomposition (dividing) by thermal and catalytic cracking, unification (combining) through alkylation and polymerization, and alteration (rearranging) with isomerization and catalytic reforming.

Treatment processes are intended to prepare hydrocarbon streams for additional processing and to prepare finished products. Treatment may include the removal or separation of aromatics and naphthenes, as well as impurities and undesirable contaminants. Treatment may involve chemical or physical separation such as dissolving, absorption, or precipitation using a variety and combination of processes, including desalting, drying, hydrodesulfurizing, solvent refining, sweetening, solvent extraction, and solvent dewaxing.

Formulating and blending is the process of mixing and combining hydrocarbon fractions, additives, and other components to produce finished products with specific performance properties.

Other refinery operations include light-end recovery, sour-water stripping, solid waste and wastewater treatment, process-water treatment and cooling, storage and handling, product movement, hydrogen production, acid and tail-gas treatment, and sulfur recovery. Auxiliary operations and facilities include steam and power generation; process and fire water systems; flares and relief systems; furnaces and heaters; pumps and valves; supply of steam, air, nitrogen, and other plant gases; alarms and sensors; noise and pollution controls; sampling, testing, and inspecting; and laboratory, control room, maintenance, and administrative facilities.

AREAS OF MAJOR CORROSION IMPACT

A refinery operation may have in excess of 3,000 processing vessels of varying size, shape, form, and function. In addition, a typical refinery has about 3,200 km (2,000 mi) of pipeline, much of which is inaccessible. Some of these pipelines are horizontal; some are vertical; some are up to 61 m (200 ft) high; and some are buried under cement, soil, mud, and water. The diameters range from 10 cm (4 in) up to 76 cm (30 in).

Water-Related Corrosion

Crude oil desalting and distillation generates considerable wastewater. Typical wastewater flow from a desalter is approximately 8 L (2.1 gal) of water per barrel of oil processed. This water contains accelerative corrosive components such as H_2S, CO_2, chlorides, and high levels of dissolved solids. The wastewater also contains a fraction of crude oil, which may be recovered during the water treatment process.

In addition to generated wastewater, cooling water (either fresh water or saltwater) is used extensively in refining operations. The corrosivity of the cooling water varies greatly depending on the process, so it is difficult to describe typical cooling water problems; however, corrosivity is highly dependent upon the level and type of dissolved solids and gases in the cooling water, including chlorides, oxygen, dissolved gases, and microbes. Cooling water temperature can also affect corrosivity.

Processing-Related Corrosion

The top section of a crude unit can be subjected to a multitude of corrosive species. Hydrochloric acid, formed from the hydrolysis of calcium and magnesium chlorides, is the principal strong acid responsible for corrosion in the crude unit top section. Carbon dioxide is released from crudes typically produced in CO_2-flooded fields and crudes that contain a high content of naphthenic acid.

Low molecular fatty acids such as formic, acetic, propionic, and butanoic acids are released from crudes with a high content of naphthenic acid. Hydrogen sulfide, released from sour crudes, significantly increases corrosion of the crude unit top section. Sulfuric and sulfurous acids, formed by either oxidation of H_2S or direct condensation of SO_2 and SO_3, also increase corrosion.

Mitigation of this type of corrosion is performed by process changes, material upgrading, design changes, and injection of chemicals such as neutralizers and corrosion inhibitors. Process changes include any action to remove or at least reduce the amount of acid gas present and to prevent accumulation of water on the tower trays. Material upgrading includes lining of distillation tower tops with alloys resistant to hydrochloric acid. Design changes are used to prevent the accumulation of water. They include coalescers and water draws. The application of chemicals includes the injection of a neutralizer to increase the pH and a corrosion inhibitor. The presence of many weak acids, such as fatty acids and CO_2, can buffer the environment and require greater use of neutralizers. Excess neutralizers may cause plugging of trays and corrosion under the salt deposits.

A dew-point probe is typically placed in a location at least 38 °C (100 °F) above the calculated dew-point temperature. The probe elements are then cooled internally by cold-air injection and the temperature at which the first liquid drop forms is determined for the actual conditions in the tower. The injection point and the amount of chemicals used depend on the knowledge of the temperature in the tower where condensation starts. With the number of corrosive species present, the calculated dew point may be much lower than the actual dew point.

Naphthenic Acid Corrosion

High-temperature crude corrosivity of distillation units is a major concern of the refining industry. The presence of naphthenic acid and sulfur compounds considerably increases corrosion in the high temperature parts of the distillation units and, therefore, equipment failures have become a critical safety and reliability issue. Naphthenic acid is the generic name used for all of the organic acids present in crude oils. Most of these acids are believed to have the chemical formula $R(CH_2)nCOOH$, where R is a cyclopentane ring and n is typically greater than 12. In addition to $R(CH_2)nCOOH$, a multitude of other acidic organic compounds are also present; however, not all of them have been analyzed to date.

Isolated deep pits in partially passivated areas and/or impingement attack in essentially passivation-free areas are typical of naphthenic acid corrosion (NAC). Damage is in the form of unexpected high corrosion rates on alloys that would normally be expected to resist sulfidic corrosion. In many cases, even very highly alloyed materials (i.e., 12 Cr, AISI types 316 and 317) have been found to exhibit sensitivity to corrosion under these conditions. NAC is differentiated from sulfidic corrosion by the nature of the corrosion (pitting and impingement) and by its severe attack at high velocities in crude distillation units. Crude feedstock heaters, furnaces, transfer lines, feed and reflux sections of columns, atmospheric and vacuum columns, heat exchangers, and condensers are among the types of equipment subject to this type of corrosion.

Sulfur

Other than carbon and hydrogen, sulfur is the most abundant element in petroleum. It may be present as elemental sulfur, hydrogen sulfide, mercaptans, sulfides, and polysulfides. Sulfur at a level of 0.2 percent and greater is known to be corrosive to carbon and low-alloy steels at temperatures from 230 °C (450 °F) to 455 °C (850 °F).

At high temperatures, especially in furnaces and transfer lines, the presence of naphthenic acids may increase the severity of sulfidic corrosion. The presence of these organic acids may disrupt the sulfide film, thereby promoting sulfidic corrosion on alloys that would normally be expected to resist this form of attack (i.e., 12 Cr and higher alloys). In some cases, such as in side-cut piping, the sulfide film produced by H_2S is believed to offer some degree of protection from naphthenic acid corrosion.

In general, the corrosion rate of all alloys in the distillation units increases with an increase in temperature. Naphthenic acid corrosion occurs primarily in high-velocity areas of crude distillation units in the 220 °C to 400 °C

(430 °F to 750 °F) temperature range. No corrosion damage is usually found at temperatures greater than 400 °C (750 °F), probably due to the decomposition of naphthenic acids or protection from the coke formed at the metal surface.

Velocity and, more importantly, wall shear stress are the main parameters affecting NAC. Fluid flow velocity lacks predictive capabilities. Data related to fluid flow parameters, such as wall shear stress and the Reynold's Number, are more accurate because the density and viscosity of liquid and vapor in the pipe, the degree of vaporization in the pipe, and the pipe diameter are also taken into account. Corrosion rates are directly proportional to shear stress. Typically, the higher the acid content, the greater the sensitivity to velocity. When combined with high temperature and high velocity, even very low levels of naphthenic acid may result in very high corrosion rates.

CORROSION CONTROL METHODS

High-temperature crude corrosion is a complex problem. There are at least three corrosion mechanisms:

1. furnace tubes and transfer lines where corrosion is dependent on velocity and vaporization, and is accelerated by naphthenic acid,
2. vacuum column where corrosion occurs at the condensing temperature, is independent of velocity, and increases with naphthenic acid concentration, and
3. side-cut piping where corrosion is dependent on naphthenic acid content and is inhibited somewhat by sulfur compounds.

Mitigation of process corrosion includes blending, inhibition, materials upgrading, and process control.

Blending may be used to reduce the naphthenic acid content of the feed, thereby reducing corrosion to an acceptable level. Blending of heavy and light crudes can change shear stress parameters and might also help reduce corrosion. Blending is also used to increase the level of sulfur content in the feed and inhibit, to some degree, naphthenic acid corrosion.

Injection of corrosion inhibitors may provide protection for specific fractions that are known to be particularly severe. Monitoring needs to be adequate in this case to check on the effectiveness of the treatment. Process control changes may provide adequate corrosion control if there is the possibility of reducing charge rate and temperature.

For long-term reliability, upgrading the construction materials is the best solution. Above 288 °C (550 °F), with very low naphthenic acid content, cladding with chromium (Cr) steels (5 to 12 percent Cr) is recommended for crudes of greater than 1 percent sulfur when no operating experience is available. When hydrogen sulfide is evolved, an alloy containing a minimum of 9 percent chromium is preferred. In contrast to high-temperature sulfidic corrosion, low-alloy steels containing up to 12 percent Cr do not seem to provide benefits over carbon steel in naphthenic acid service. Type 316 stainless steel [greater than 2.5 percent molybdenum (Mo)] or Type 317 stainless steel (greater than 3.5 percent Mo) is often recommended for cladding of vacuum and atmospheric columns.

Materials in Refinery Construction

The selection of materials for refinery construction depends on the type of refinery, the type of crude oil handled, and the expected service life for each vessel.(6) As with all materials selection, the life-cycle cost must be considered in addition to purchase price. Table 3 lists some common alloys and their material costs relative to carbon steel.

Table 3. Comparison of the relative costs of various alloys.(7)

ALLOY CLASS	EXAMPLE	CONSTITUENTS										COST RATIO(9)
		Ni	Cr	Mo	Fe	Co	Ti	Cu	Cb	Al	V	
Carbon Steel	C10				> 94							0.2
Low-Alloy Steel	1-1/4Cr 1/2Mo		1.25	0.5	balance							0.25
Fe-Ni-Cr + Mo	Type 316L	13.0	17.0	2.3	balance							1.0
	Alloy 800H	32.5	21.0		4.6							-
	20Cb-3	35.0	20.0	2.5	balance			3.5				3.8
Ni-Cr-Mo	Alloy C2	54.0	15.5	16.0								6.0
	Alloy C276	57.0	16.0	16.0	5.5							
	Alloy C4	54.0	16.0	15.5	3.0							
	Alloy 625	60.0	21.5	9.0					3.7			6.3
Ni-Cr-Fe	Alloy G	45.0	22.2	6.5	19.5			2.0				6.4
	Alloy 600	76.0	15.0		8.0							-
Ni-Mo	Alloy B2	balance	1.0	28.0	2.0	1.0						11.6
Ni-Cu	Alloy 400	65.1						32.0				-
Nickel	Alloy 200	99.9										-
Co-Base	ULTIMET (R)	9.0	26.0	5.0	3.0	54.0						27.2
Ti-Base	Ti-6Al-4V						90			6.0	4.0	-

Carbon Steel

Carbon steel is by far the most common structural material in refineries due primarily to a combination of strength, availability, relatively low cost, and a resistance to fire. The low-alloy steels are specified for applications that require higher properties than can be obtained with carbon steels. The workhorse refinery alloys for elevated temperature service greater than 260 °C (500 °F) contain 0.5 to 9.0 percent chromium plus molybdenum. Normally, at least 5 percent chromium is required to resist oxidation at temperatures in excess of 430 °C (800 °F). Currently, most refineries use 9Cr-1 Mo tubes in coker heaters. For carbon steel and low-alloy steel, creep becomes a design consideration at about 430 °C (800 °F) and 480 °C (900 °F), respectively. These alloys are used for pressure vessels, piping, exchangers, and heater tubes.

Austenitic Stainless Steel

The austenitic structure provides a combination of excellent corrosion, oxidation, and sulfidation resistance with high creep resistance, toughness, and strength at temperatures greater than 565 °C (1050 °F). They are, therefore, often used in refineries for heater tubes and heater tube supports, and in amine, fluid catalytic cracking (FCC), catalytic hydro-desulfurization (CHD) sulfur, and hydrogen plants.

They are susceptible, however, to grain boundary chromium carbide precipitation "sensitization" when heated in the range of 540 °C (1000 °F) to 820 °C (1500 °F). Where "sensitization" is to be avoided, refineries prefer to use the stabilized grades of Type 347 (with Cb) or Type 321 (with Ti).

The susceptibility of the austenitic stainless steels to stress corrosion cracking limits their use and requires special precautions during operation and at downtime. At downtime, the precautions taken to prevent stress corrosion cracking are either alkaline washing with a dilute soda ash and low-chloride water solutions and/or nitrogen blanketing. The austenitic stainless steels are used for corrosion resistance or resistance to high-temperature hydrogen or sulfide damage. Solid stainless steel vessels are rarely constructed. Strip-lined, stainless-clad, or lined vessels are found in hydrocracking and hydrotreating services. Austenitic stainless steels also find service as tubing in heat exchangers exposed to corrosive conditions.

Ferritic and Martensitic Steels

Other chromium-iron stainless steels with little or no nickel form crystallographic structures different from austenitic. This stainless steel alloy contains less than 0.10 percent C, 11 to 13 percent Cr, balance Fe, and a ferritic structure. When the ferritic stainless alloys are modified, they may be hardened and become what is called "martensitic" by heat treatment. The ferritic and martensitic stainless steels are classified by the American Iron and Steel Institute (AISI) as the 400 series. The most common alloys from this series found in refineries are types 410, 410S, 405, and 430 stainless steels. A common stainless steel for trays and lining in crude service is Type 410 stainless steel.

Other Alloys

The principal non-ferrous alloys in refinery processing equipment are the copper-based and copper-nickel alloys; however, the use of copper-based alloys in NH_3 or NH_4 environments should be avoided.

Although admiralty brass was the original saltwater condenser tube material, it was found to be susceptible to erosion-corrosion, particularly at tube ends. Aluminum brass, containing 2 percent aluminum, was found to be somewhat more resistant to erosion in saltwater. Inhibition with arsenic is necessary to prevent de-zincification, as in the case of admiralty brass. The stronger naval brass is often selected as the tube sheet material when admiralty brass tubes are used in condensers. Generally, a bronze is a tin alloy of copper, although the term has been widely used for other alloys, including some brasses. Cast brass or bronze alloys for valves and fittings are usually copper-tin-zinc compositions, plus lead for machinability. Aluminum bronzes are often used as tube sheet and channel material for exchangers with admiralty brass or titanium tubes exposed to cooling water.

The 70/30 copper-nickel alloy is used for exchanger tubes when better saltwater corrosion resistance than in aluminum brass is needed, or when high metal temperatures in water-cooled exchangers may cause de-zincification in brass. Monel is a nickel-copper alloy with 67 percent nickel and 30 percent copper. Monel has very good resistance to saltwater and, under non-oxidizing conditions, to acids such as hydrochloric and hydrofluoric acids. Monel has a better high-temperature resistance to cooling water than does 70/30 copper-nickel. Monel cladding and Monel trays are commonly specified at the top of crude towers to resist HCl vapor and where the temperature is below 205 °C (400 °F). Over 205 °C (400 °F), nickel-based alloys are attacked by H_2S. For high temperature strength and/or corrosion resistance, several nickel-based alloys are used for special applications such as expansion bellows in FCC process units (Alloy 625), stems in flue gas butterfly valves (Alloy X 750), and in springs exposed to high-temperature corrosives (Alloy X).

Titanium has excellent resistance to seawater, and it is also used for tubing in crude tower overhead condensers. Overall, the use of titanium is extremely limited due to the high cost and the availability of suitable, more economic alternatives.

CORROSION MANAGEMENT

Economics of Refining

Although the individual components are quite complicated, the large-scale economics of refining operations can be defined in simple terms. Gross margin is the difference between the output of a refinery (refined products) and the cost of the feedstock (crude oil and other chemicals). The net margin is the gross margin minus the operating costs. Figure 4 illustrates the last 20 years of margins in the refinery industry.

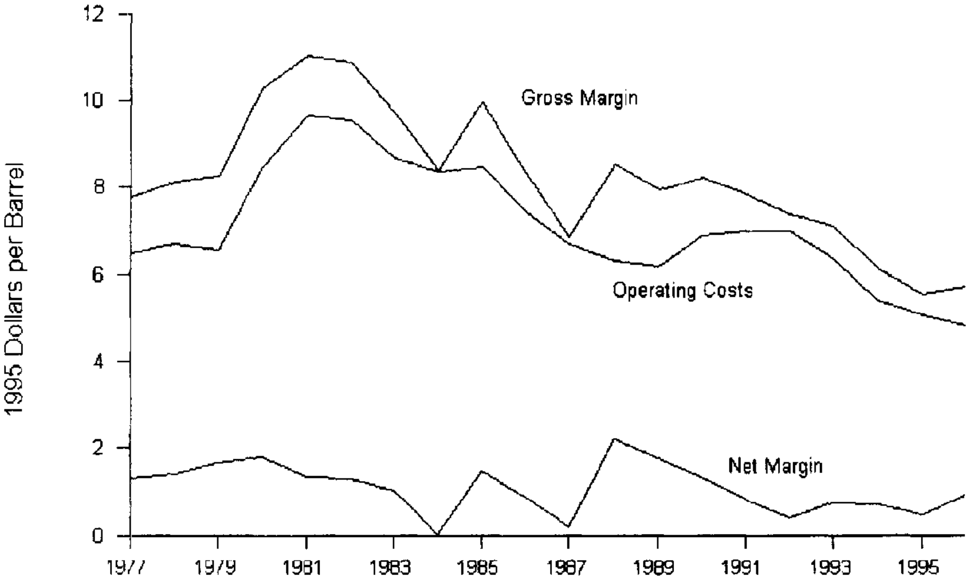


Figure 4. Margins of U.S. refiners since 1977.[8]

Capital Expenditures

The capital intensity of a process refers to the amount of capital needed to produce a unit of product. For U.S. refining operations, capital intensity is measured by the ratio of net property, plant, and equipment (i.e., the balance sheet value of productive long-term assets adjusted for depreciation) to refinery capacity (barrels per calendar day of crude distillation capacity). Adjusted for general inflation (via the implicit gross domestic product deflator), the refiners' capital expenditures for U.S. refining doubled from 1989 to 1992.

A surge in capital expenditures occurred in the late 1970s through the early 1980s. During this period, the major U.S. companies upgraded their refineries to process heavier, more sulfurous crude oil inputs into relatively greater proportions of lighter products, particularly gasoline. These investments were largely premised on wide price spreads between higher and lower quality crude oils and lighter and heavier refined products.

The decline in the price spread between differing qualities of crude oils in the 1990s contributed to the overall deterioration in the gross margin evidenced in figure 4. The price decline between crude oils of differing qualities was especially adverse for refiners who invested heavily in refinery upgrades to yield higher proportions of light products. The refiners directed much of the surge in their refining investments in the late 1970s to the early 1980s toward increasing their capability to process heavier, more sulfurous crude oils. For example, the capacity for increased processing of heavy sour crude inputs, relative to basic crude distillation capacity, rose from 22 percent in 1974 to 30 percent in 1980 to 47 percent in 1993.

Unlike the earlier surge in refinery investments, the upswing in capital expenditures in the 1990s appeared to be largely driven by increased expenditures for pollution abatement.[8] In particular, the Clean Air Act Amendments of 1990 required production of oxygenated gasolines by late 1992, lower sulfur diesel fuels by late 1993, and reformulated gasoline by January 1, 1995. The share of total U.S. refining capital expenditures for pollution abatement increased from slightly more than 10 percent shortly before the Clean Air Act Amendments of 1990 to more than 40 percent in recent years.

Although pollution abatement requirements clearly reduced the rate of return to refining/marketing assets, these requirements appear to account for only a small part of the steep decline in the rate of return to U.S.

refining/marketing operations in the 1990s. The increase in pollution abatement operating costs over this period was $0.07 per barrel of refined products sold, or 5 percent of the $1.52 per barrel decline in the net margin.

The cost of extra capital expenditures for corrosion control can be included in the operational expenditures for refinery operations. If an operator chooses a corrosion-resistant alloy vessel for a refinery operation, then the extra annual cost of this vessel amortized over the life of the vessel is included in the operational expenditures. If an operator chooses carbon steel for the vessel, then the cost of corrosion control measures, such as anodes, chemical treatment, and monitoring, are the only measurable capital expenditures, but annual costs of upkeep will greatly increase operational expenditures. Economic justifications for such expenditures based on life-cycle costs continue to be part of corrosion control decisions for refinery operations.

Operational Expenditures

The operating costs of refineries have steadily decreased in recent years due to technological advances and improvements in efficiency. The 1996 operating costs were an average of $5.51 per barrel (bbl).(9)

It should be noted that direct costs for corrosion prevention and mitigation are extremely difficult to obtain, as these are kept very "close to the vest" by the refining industry. While the reasons for this are unclear, it can be assumed that the intense scrutiny that the entire petrochemical industry undergoes by environmental regulators and community watchdogs has created a situation in which refiners prefer not to divulge the magnitude of their corrosion problems. Thus, information for this sector has been gathered from a combination of some published surveys and government sources.

One particular study(10) focused on operating costs at a single small refinery (53,000 barrels/day), concentrating on the costs related to environmental protection. This project quantified air emissions, water discharges, and other wastes generated at the facility. Moreover, it identified a range of options to reduce or prevent those releases, some of which appeared more cost-effective than those required by existing rules.

At most refineries, operating costs are dominated by crude oil. Even small fluctuations in the price of crude oil can overshadow other operating costs of the refinery. As a result, it is customary at the refinery level to track "non-crude operating costs," excluding the cost of feedstock. The non-crude operating costs of this refinery are shown in table 4.

Table 4. Environmental costs at a refinery.

ENVIRONMENTAL COST CATEGORY	PERCENTAGE OF 1992 NON-CRUDE OPERATING COSTS
Waste Treatment	4.9
Maintenance	3.3
Product Requirements	2.7
Depreciation	2.5
Administration, Compliance	2.4
Sulphur Recovery	1.1
Waste Disposal	0.7
Non-Recurring Costs	4.0
TOTAL	**21.6%**

The analysis estimates that total environmentally related costs are 21.6 percent of total non-crude operating costs. This total focuses primarily on capital, operating, and maintenance costs, and excludes contingent liability costs. If these costs were added, the total could be higher. Remediation expenses are recorded as "non-recurring costs."

At the outset of the project, prior to conducting the analysis, environmental personnel informally estimated environmentally related costs at only 3 percent of the total non-crude operating costs. The magnitude of this difference, as well as the magnitude of the costs, indicates the value of identifying and tracking environmental costs.

Maintenance costs (40 percent of which can be attributed to corrosion control) were estimated in the study(10) to be 3.3 percent (rounded to 3 percent) of the non-crude operating costs (table 4). When scaling up to all processes, this figure becomes:

0.03 fraction maintenance costs / 0.216 fraction environmental operating costs = 13.9% of the total operating costs due to maintenance

$5.51/bbl operating costs(9) x 13.9% = $0.76/bbl maintenance costs

$0.76/bbl maintenance costs x 40% due to corrosion control = $0.31/bbl operating costs for corrosion control

When multiplied by the annual refinery output in the United States (5.7 billion barrels in 1997), the total cost of corrosion is ($0.31 x 5.7 billion =) $1.767 billion per year.

Vessel turnarounds, during which a processing vessel is emptied, inspected, repaired (if necessary), and put back into service, are mandatory in most cases due to U.S. Department of Transportation (DOT) regulations, primarily due to suspected corrosion damage inside the vessels. The costs for these operations are capitalized rather than included in the maintenance budget.

One refiner estimated the total cost of the turnarounds at one of their refineries (a 260,000-bbl per day plant).(4) For the 3,000 processing vessels in this refinery, the total cost of turnarounds (5-year intervals for each individual vessel) was $118 million. Therefore, turnaround costs per barrel are:

($118,000,000/yr x 1 turnaround/5 years) / (260,000 bbl/day x 365 days/yr) = $0.25/bbl

$0.25/bbl x 5.7 billion bbl/yr = $1.425 billion/yr for turnaround costs

It should be noted that the trend in this activity is to move toward risk-based inspections and longer intervals (10 to 20 years) between turnarounds, which would significantly reduce the cost of corrosion maintenance, but increase the risk factor dramatically. The validity of this strategy is yet to be determined since the number of incidents with vessels outside the standard 5-year window will, in the future, help to define the proper risk assessment.

Fouling

In addition to mitigation and maintenance costs, the component of lost production due to corrosion and related problems must be considered. Fouling is the leading cause of diminished efficiency and productivity in refineries. Fouling is a deposit buildup in refinery processes that impedes heat transfer and/or reduces throughput. The energy lost due to this inefficiency must be supplied by burning additional fuel or reducing feed.

It is estimated that the cost penalty of fouling is in excess of $2 billion annually.(11) While most fouling is caused by the deposition of heavier hydrocarbon species coming directly from the crude oil, a small undetermined percentage is related to corrosion and scale deposits, either actively participating as loose corrosion products or by scale acting as a substrate for hydrocarbon deposition.

It is not known exactly how much fouling is related to corrosion versus that related to deposits, which affect only production rates. In the Drinking Water and Sewer Systems sector of this report (Appendix K), 50 percent of the costs of fouling were corrosion-related. Applying this factor to the water handling half of the refining process, the fouling-related corrosion costs in the refining sector are estimated to be $2 billion total costs x (1/2 fluid volume on water handling portion of refining process x 50% corrosion-related fouling costs = $0.5 billion.

The estimate of the total annual cost of corrosion in refining applications is therefore:

$1.767 billion	operational costs for corrosion
$1.425 billion	turnaround costs
$0.500 billion	fouling costs
$3.692 billion	total cost of corrosion

Acidic Crude Oils

As was discussed earlier, the refiners' willingness to accept the more corrosive, acidic crude oils has heavily influenced U.S. refinery operations due to the lower cost of the feedstock.

It can be anticipated that the growth in expenditures for corrosion can be expected to increase at the rate of the acidity in the crude oil refined. Therefore, this cost is part of the incremental maintenance cost, but in the near future, this will become a significant expenditure.

For a typical carbon steel distillation column running acidic crude oil, there are additional costs associated with corrosion coupons and probes for monitoring, nondestructive testing and analysis, and chemical treatment. It should be noted that these costs, shown below in figure 5, have a wide variance associated with them.

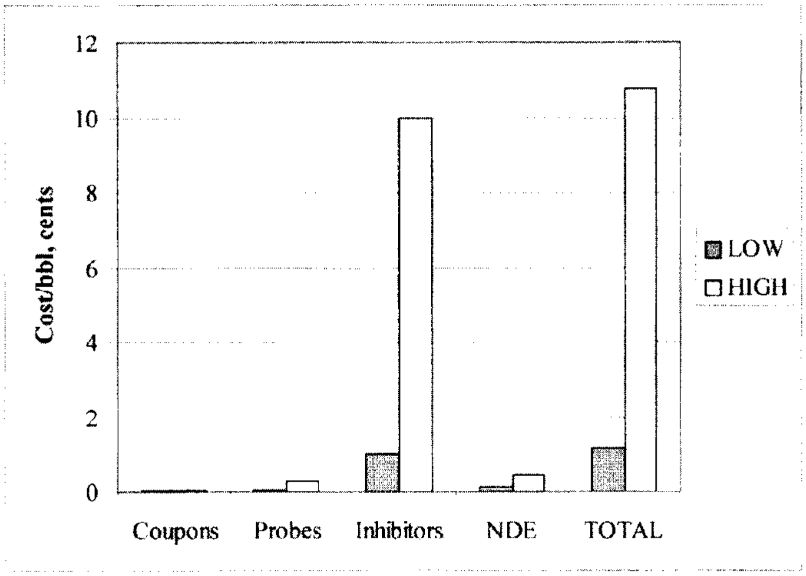


Figure 5. Incremental costs for corrosion control of carbon steel distillation column.(12)

The total cost for chemical treatment and all associated costs in the column range from $0.01 per bbl to a high of $0.11 per bbl. The figure is dominated by the chemical cost of the inhibitors. One study estimated that the total inhibitor cost associated with refinery operations in the United States was $246 million in 1998.(13)

Alternatively, a metallurgical upgrade in susceptible areas for a $120,000-bbl per day refinery is estimated to be $12 million to $20 million, which could be economically feasible if the refinery has a long-term commitment to processing acidic crudes. Based on a 20-year design life (typical for alloys), the incremental costs become $0.18 to $0.30 per bbl (higher than the costs for treatment with corrosion inhibitor, but comparable). The increased chance for success with the use of alloys relative to corrosion inhibitor treatments makes these options worth further study.

Failure Costs

The costs associated with catastrophic failures are very difficult to quantify since they include the costs of equipment replacement, production loss, and sometimes lost lives and litigation. In addition to the direct costs, indirect costs in publicity and increased scrutiny cannot be quantified.

Analyzing processing industry data for August 2000,(14) 9 incidents (fire, explosion, leak, or emergency shutdown) were reported at refineries in the United States out of a total of 52 total incidents during that month. The cause of each is still being investigated, but all of these incidents resulted in some loss of production and a significant economic impact.

CASE STUDY

Corrosion-Related Failure in Refinery

This example clearly illustrates the hazards associated with amine absorber pressure vessels used in refineries. On July 23, 1984, a refinery at Romeoville, Illinois, owned and operated by the Union Oil Company of California, experienced a disastrous explosion and fire.(10,15) An amine absorber pressure vessel ruptured and released large quantities of flammable gases and vapors. Seventeen lives were lost, 17 individuals were hospitalized, and more than $100 million in damages resulted.

The National Bureau of Standards (NBS) conducted a detailed investigation, which included chemical analyses, fracture mechanics analyses, stress corrosion cracking (SCC) susceptibility tests, and hydrogen cracking susceptibility tests. Preliminary NBS test results indicated that the subject plate material (ASTM A516, Grade 70 carbon steel) of the amine absorber was susceptible to hydrogen-induced cracking. Furthermore, repair welds that were done in the field and that had not been stress relieved, were especially sensitive to amine-induced corrosion and cracking. Figure 6 is an example of SCC both parallel and perpendicular to the weld, but not in the weld. The propagation of the crack clearly distinguishes SCC and reflects the different stresses along the weld area.

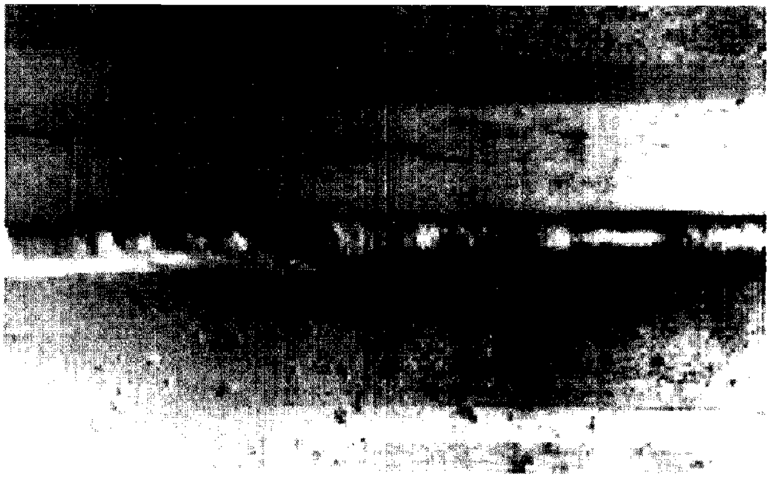


Figure 6. Stress corrosion cracking near a weld.

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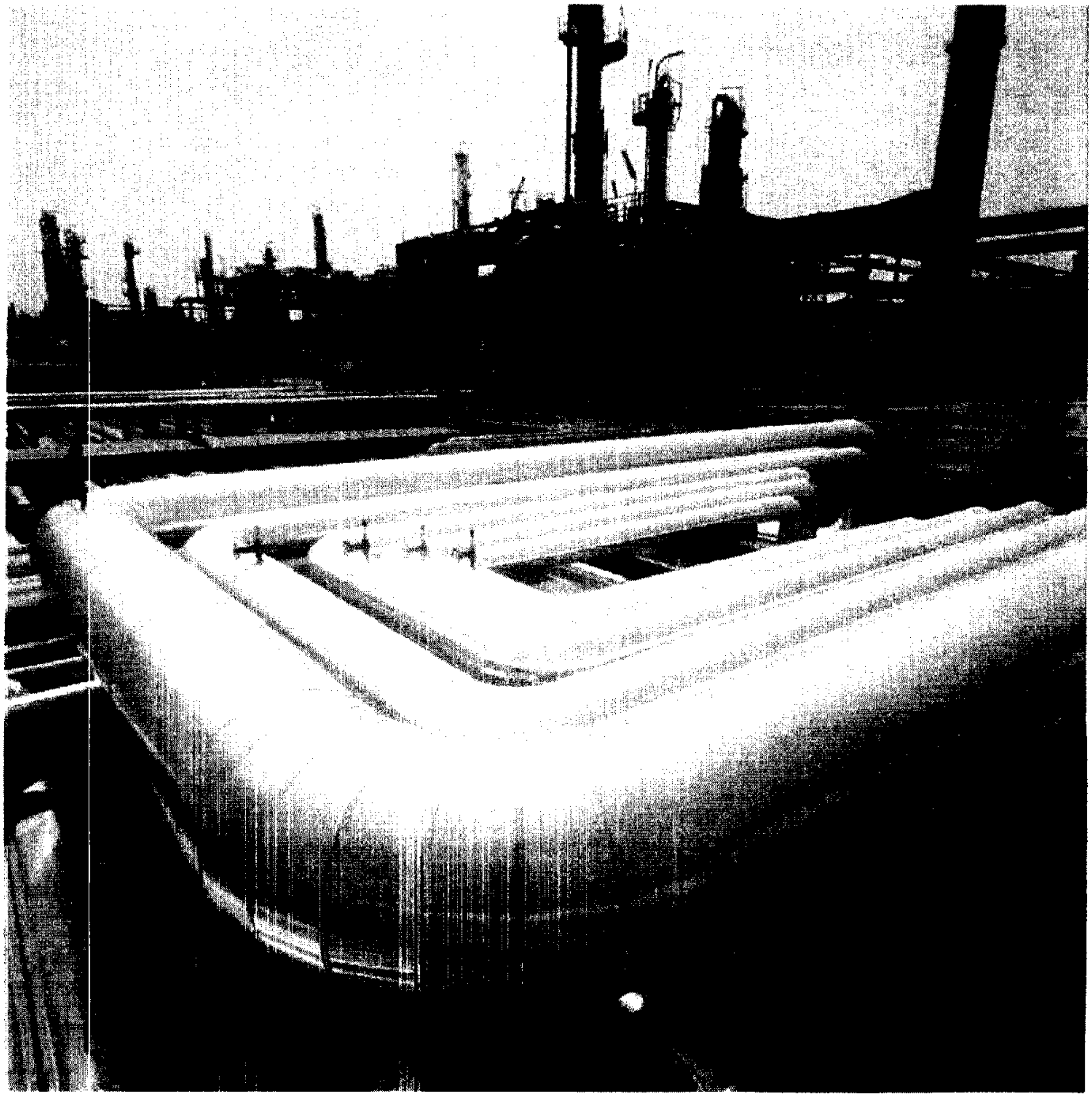
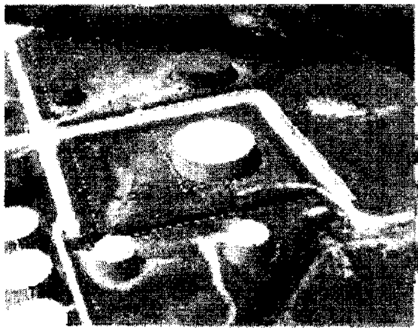
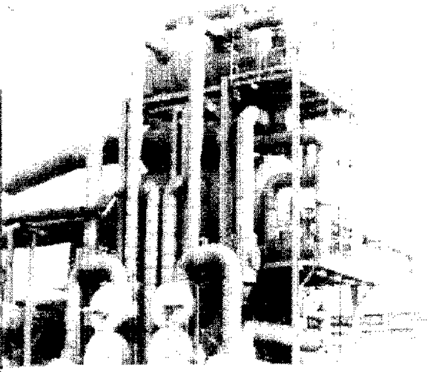
APPENDIX V

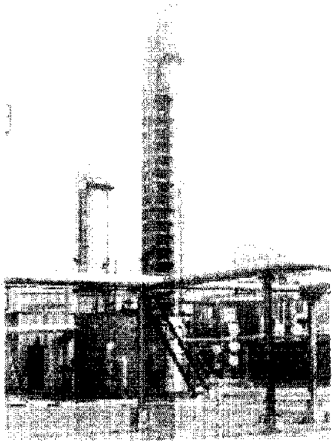
CHEMICAL, PETROCHEMICAL, AND PHARMACEUTICAL



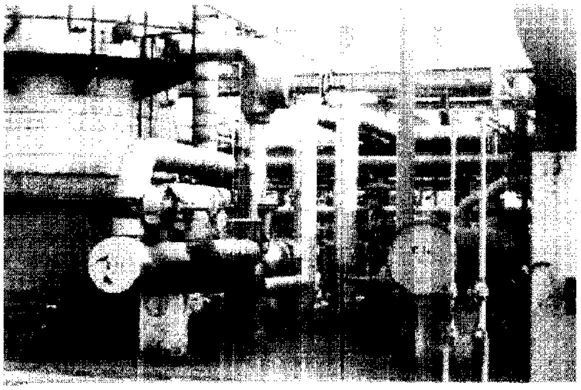


Tank storage

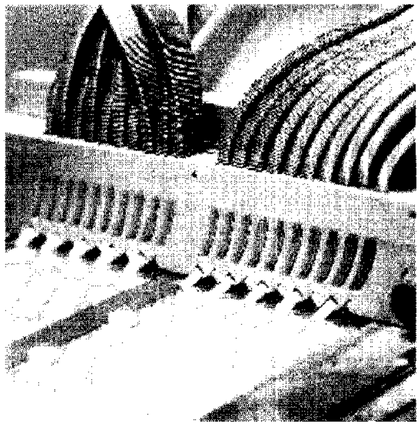




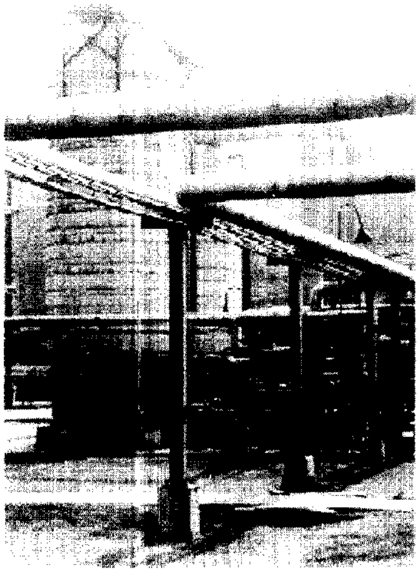
Distillation column



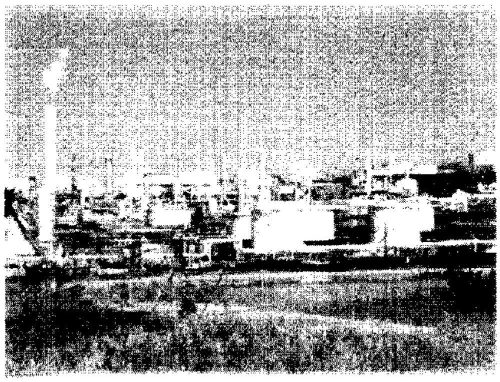
Chemical plant



Pill manufacturing



Storage tanks and piping



Chemical plant

Creep rupture of reformer tube

APPENDIX V

CHEMICAL, PETROCHEMICAL, AND PHARMACEUTICAL

MICHIEL P.H. BRONGERS[1] AND IVELISSE TUBENS[1]

SUMMARY AND ANALYSIS OF RESULTS

Corrosion Control and Prevention

The total capital expenditures for the chemical industry are $15.061 billion, with $604 million to $1.807 billion per year in corrosion costs. For the petrochemical industry, the total capital expenditures are $1.837 billion with $73 million to $220 million per year in corrosion costs. For the pharmaceutical industry, the total capital expenditures are $4.399 billion, with $176 million to $528 million per year in corrosion costs. Therefore, the three industries combined have total capital expenditures of $21.297 billion in 1997, with $853 million to $2.555 billion in annual corrosion costs. The estimated average direct corrosion cost is $1.7 billion per year (8 percent of total capital expenditures). Again, it is noted that these cost are direct costs and are based on actual capital expenditures.

No calculation was made for the indirect costs of production outages or indirect costs related to catastrophic failures. The costs of operation and maintenance related to corrosion were also not included in the $1.7 billion per year estimate.

Opportunities for Improvement and Barriers to Progress

In the past few years, the industry has concentrated its efforts on minimizing corrosion failures and related costs. The key corrosion control methods include the use of corrosion-resistant alloys, the use of corrosion monitoring techniques, and the implementation of planned maintenance. Corrosion-resistant alloys are gaining a widespread acceptance in the chemical industry. Although these alloys are more expensive than carbon steel, they can prevent high failure costs in the long run. Corrosion monitoring techniques are implemented in process streams in order to ensure the integrity of the equipment. Planned maintenance consists of scheduled shutdown periods in order to inspect all equipment and to refurbish or replace equipment that has failed due to corrosion or other mechanisms. Shutdown periods are generally scheduled in advance and are short in duration in order to minimize inspection costs and production losses.

Many chemical companies are using risk-based inspection procedures to minimize the likelihood of failure in pressure equipment or equipment containing hazardous materials. Such models determine the risk level on high-risk equipment based on the consequences and propensity to failure. The safety of surrounding infrastructure near the plant and the welfare of individuals are taken into consideration.

Convincing plant operators that a more expensive corrosion-resistant material will provide a significant cost benefit in the long run often presents a barrier to corrosion management. The design process of a chemical plant should incorporate a model predicting the probability of corrosion-related failure and low, moderate, and high corrosion risks. Such a model allows corrosion engineers to focus on equipment with a high corrosion risk and to select a cost-effective corrosion-resistant material. Selection of the appropriate material can prevent safety and legal issues that are a consequence of corrosion-related failures.

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[1] CC Technologies Laboratories, Inc., Dublin, Ohio.

Recommendations and Implementation Strategy

Development of corrosion control programs to provide a strategic cost-effective approach is required. These programs need to focus on implementing corrosion-resistant alloys in equipment design, selecting proper on-line corrosion monitoring techniques, implementing maintenance programs, and developing an educational and training program for corrosion control and prevention. Advanced planning and scheduling can help prevent excessive corrosion costs and catastrophic failures.

The use of corrosion-resistant alloys in conjunction with on-line corrosion monitoring has been shown to reduce corrosion costs. Proper alloy selection depends on the application and process. On-line corrosion monitoring provides an indication of the corrosion severity of the environment and allows for remediation measures to be taken.

Maintenance programs are critical to the operational safety and integrity of plant equipment. Optimization of maintenance programs is essential in order to comply with the current operational demands of equipment.

Increased awareness of corrosion control and prevention methods by management, engineers, and technicians through the provision of education and training gives these individuals the necessary knowledge to make the right decisions to mitigate or prevent corrosion.

Summary of Issues

Increase consciousness of corrosion costs and potential savings.	Regular efforts on maintaining and updating corrosion cost records will result in the ability to identify the most cost-effective practices. Implementation of best engineering practices will also reduce corrosion costs.
Change perception that nothing can be done about corrosion.	Educate engineers, technicians, and management on corrosion prevention strategies and methodologies.
Advance design practices for better corrosion management.	Improve procedures for material selection of corrosion-resistant alloys and design proper welding procedures to avoid corrosion- and cracking-related failures. Inhibitors, coatings, and cathodic protection are also available methods to help control corrosion.
Change technical practices to realize corrosion cost-savings.	Corrosion research on the technological needs of the chemical industry will help to improve technical practices.
Change policies and management practices to realize corrosion cost-savings.	Corrosion prevention strategies and methodologies will need to be incorporated into industry standards.
Advance life prediction and performance methods.	Implement life prediction models for risk-based assessment (RBA) and fitness-for-service (FFS) to ensure equipment integrity and remaining life.
Advance technology (research, development, and implementation).	Investigate the cause of unknown types of corrosion-related failures to prevent their reoccurrence. Implement on-line corrosion monitoring and inspection techniques.
Improve education and training for corrosion control.	NACE (National Association of Corrosion Engineers) International provides basic courses and certifications for corrosion engineers and technicians.

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SECTOR DESCRIPTION

The chemical, petrochemical, and pharmaceutical industries play a major role in the U.S. economy by providing a wide range of products. Chemical, petrochemical, and pharmaceutical industries can be defined by the types of products they manufacture. The chemical industry includes those manufacturing facilities that produce bulk or specialty compounds by chemical reactions between organic and/or inorganic materials. Examples of products from the chemical industry are alkalies, chlorides, fertilizers, plastics and resins, paints, soaps, and inks. The petrochemical industry includes those manufacturing facilities that create substances from raw hydrocarbon materials such as crude oil and natural gas. Examples of products from the petrochemical industry are aromatics and industrial gasses that are not made in a refinery. The pharmaceutical industry formulates, fabricates, and processes medicinal products from raw materials and is involved in grinding, grading, and milling of botanical products. In its industrial processes, the pharmaceutical industry uses more batch operations than are used in the chemical industry.

The number of operational facilities (establishments) varies depending on the size definition of a plant. The U.S. Census Bureau classifies establishments based on the type of product that a facility produces. According to the 1997 Census,(1) the U.S. chemical, petrochemical, and pharmaceutical industry together had more than 13,000 establishments, 877,000 employees, and a total value of shipments of $406.9 billion (see table 1). The total reported capital expenditures were $21.3 billion.

The current sector description focuses on the corrosion cost in the manufacturing facilities of the chemical, petrochemical, and pharmaceutical industries. Information about related topics can be found in the Petroleum Refining sector (Appendix U), Hazardous Materials Storage sector (Appendix G), and Food Processing sector (Appendix Y) of this report.

Chemical Manufacturing Industry

The largest single industrial process in the chemical industry is the production of chlorine and caustic soda from common salt. The majority of the chlorine (70 percent) is used in the manufacturing of organic chemicals, 15 percent is used in pulp and paper production, 8 percent is used in the production of other inorganic chemicals, and the other 7 percent is used in the production of miscellaneous products. The most significant users of caustic soda are the organic chemicals industry (30 percent) and the inorganic chemicals industry (20 percent), while the pulp and paper industry uses approximately 20 percent for pulping wood chips and other processes. The remaining caustic soda is used in the production of soaps and cleaning products, and in the oil and natural gas production industry as an additive to drilling fluid. Chlorine is a very aggressive chemical species that is difficult to store and transport; therefore, it is often produced near the end users, which are primarily chemical manufacturers and pulping operations.

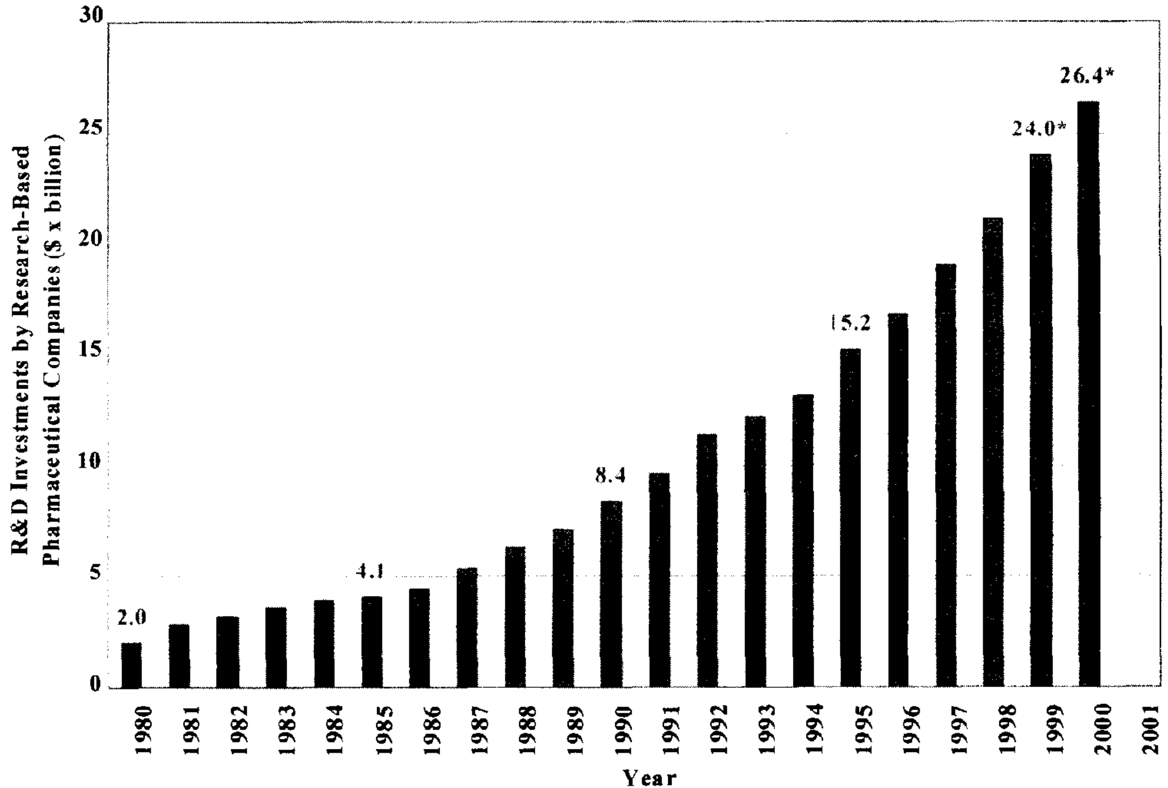
Petrochemical Manufacturing Industry

The hydrocarbon processing (petrochemical) industry manufactures hydrocarbons such as ethylene, propylene, and butylenes made from refined petroleum or liquid hydrocarbon, and cyclic aromatic hydrocarbons such as benzene, toluene, styrene, xylene, ethyl benzene, and cumene made from refined petroleum or liquid hydrocarbons.(1) Petroleum products include fuels, finished non-fuel products, and chemical industry feed stocks. Nearly 90 percent of the petroleum products used in the United States are fuels, with gasoline accounting for approximately 43 percent of the total. The remaining 10 percent is used for feed stocks for the manufacturing of fertilizers, pesticides, paints, waxes, detergents, thinners, cleaning fluids, refrigerants, latex, hard plastics, rubber compounds, and other miscellaneous products.

The hydrocarbon processing industry (HPI) consists of plants involved in the production of petrochemicals and chemicals, refining, gas processing, synfuel, and a variety of other products. In 1999, the U.S. hydrocarbon processing industry had a budget of $3.1 billion for capital spending, $4.0 billion for maintenance spending for equipment and materials, and $16.1 billion for operations.(2) Corrosion costs are considered as part of the operational maintenance costs.

Pharmaceutical Manufacturing Industry

According to the Pharmaceutical Research and Manufacturers of America (PhRMA) Annual Report 2000-2001, research-based pharmaceutical companies spent $26.4 billion on research and development in 2000.(3) This amounts to 17 to 21 percent of the sales of these companies, which is a significant amount in comparison with other industries that generally spend between 3 and 12 percent on research and development. The majority of this monetary amount is invested in health-related concerns and development of new drugs rather than on corrosion issues in the drug manufacturing process. On average, it takes 12 to 15 years and costs $500 million to discover and develop a new drug. Figure 1 shows the trend in pharmaceutical research and development since 1980 based on data from the PhRMA Annual Survey 2000.



*Estimated Value

Figure 1. Research and development expenditures by research-based pharmaceutical companies based on 2000 survey, as reported by PhRMA.(3)

AREAS OF MAJOR CORROSION IMPACT

The corrosion types experienced in the chemical manufacturing industry, the petrochemical manufacturing industry, and the pharmaceutical manufacturing industry are similar in many respects. The most common types of corrosion include caustic and chloride cracking, oxidation, sulfidation, corrosion under thermal insulation, ammonia cracking, and hydrogen-induced cracking (HIC). Primary causes of contamination in pharmaceutical manufacturing include corrosion of embedded iron particles in vessel walls, failures of glass linings, and corrosion under insulation.

According to J&H Marsh and McLennan, Inc., in the HPI market data 2000 report,(4) the majority (approximately 45 percent) of large losses are due to mechanical failure of equipment. Piping, tanks, reactors, process drums and towers, pumps and compressors, heat exchangers, heaters, and boilers are equipment that fail regularly.

The most important raw material for the HPI industry is crude oil, which often contains a fraction of water. Corrosive species that can be present in the oil/water mixture include sulfur compounds, chlorides, ammonia, sulfuric acid, hydrochloric acid, polythionic acid, carbonic acid, phosphoric acid, naphtenic acid, and cyanides. Although these species are treated for removal, traces remain and split, and combine or convert into numerous corrosive compounds or elements. Water, used in huge volumes by HPI plants for cooling, heating, and purifying process streams, is another source of corrosives and foulants. Chlorides, sulfates, magnesium, and calcium dissolved in water-cooling systems can cause scale, sludge, and corrosion. Water in the process stream can accelerate corrosion because it acts as an electrolyte and it dissolves and hydrolyzes certain materials.

Dillon(5) discusses three groups of corrosion. Group I consists of corrosion that can be readily identified upon visual examination. Group II consists of corrosion that may require supplementary means of examination. Group III consists of corrosion that usually should be verified by optical or electron microscopy, although sometimes it may be apparent to the naked eye.

Group I consists of general, localized, and galvanic corrosion. Localized corrosion includes both pitting and crevice corrosion. Group II consists of velocity effects, such as erosion-corrosion and cavitation; intergranular attack (IGA), where grain boundaries are preferentially attacked; and dealloying corrosion. Group III includes cracking phenomena and high-temperature corrosion. Cracking phenomena include stress corrosion cracking (SCC), hydrogen-assisted cracking (HAC), liquid metal cracking (LMC), and corrosion fatigue.

In 1997, the Materials Technology Institute (MTI) of the Chemical Process Industries, Inc., published a compilation of experiences of corrosion failure mechanisms in process industries.(6) The study found that cracking was the most frequent failure mode. It ranged from 27 to 36 percent of the corrosion failure modes reported. General corrosion was the next most frequent (17 to 26 percent), followed by local attack (12 to 20 percent). For local attack mechanisms, pitting was the most frequent failure mode, followed by intergranular corrosion. The study further found that steel and stainless steel were involved in the majority (48 to 61 percent) of the SCC failures reported.

The MTI report(6) listed the corrosion failure mode with an average frequency of occurrence. Table 1 shows a summary of the average failure mode frequency collected from five companies that participated in the MTI compilation. The data represent statistical information collected from more than 1,272 failures.

The "cracking" failure mode in table 1 includes SCC, fatigue cracking, and caustic cracking. Table 2 shows the distribution of SCC failures over different materials of construction. Chlorides were the most frequently identified cause of stainless steel cracking, while caustics and nitrates were the most frequently identified cracking agents for steel.

The study reported that one source had told the investigators that there were nearly as many mechanical failures as corrosion failures in their database (670 corrosion versus 568 mechanical). While no detailed information was available, a 50-50 distribution between mechanical and corrosion failures appeared to hold true for the other databases for which both kinds of data were included.

Table 1. Average failure mode frequency as reported in a 1997 MTI compilation of experiences, based on data from five companies.[(6)]

FAILURE MODE	AVERAGE FREQUENCY (%)
Cracking	36
General Corrosion	26
Local Attack	20
Temperature Effects	7
Velocity Effects	5
Voltage Effects*	3
Hydrogen Effects	2
Biological	0
TOTAL	**99%**

*Voltage effects include galvanic, stray current, and "macro cell" effects. The latter refers to currents encountered in a caustic chlorine cell house.

Table 2. Average frequency of stress corrosion cracking failures for different materials, as reported in a 1997 MTI compilation of experiences, based on data from five companies.[(6)]

MATERIAL	AVERAGE FREQUENCY (%)
Stainless Steels	61.4
Steel	30.4
Copper Alloys	4.3
Nickel Alloys	2.8
Titanium	0.7
Tantalum	0.3
TOTAL	**99.9%**

CORROSION COSTS

The 1997 economic census reports the total capital expenditures for chemical, petrochemical, and pharmaceutical manufacturing industry categories (see table 3). In the table, the materials costs are estimated as a percentage of the annual capital expenditures for each industry category. The corrosion costs were then estimated as a percentage of the materials costs. Based on personal communication with approximately 10 plant maintenance and corrosion engineers from various chemical companies, an estimated 20 to 40 percent of the capital expenditures is spent on materials. This range was estimated considering the fraction of construction material costs versus the fraction of labor to build plants. An estimated 20 to 30 percent of the material costs is directly related to corrosion. This range was estimated from the extra costs of upgrading regular materials (often carbon steel) to more corrosion-resistant materials (such as stainless steels) in areas where corrosion could be an issue. It is noted that the above estimates were made using the engineering judgment of the interviewed people and that these estimates could not be verified with existing databases.

Table 3. Estimated annual corrosion costs as a percentage of material costs and total capital expenditures for the chemical, petrochemical, and pharmaceutical manufacturing industries, based on data from the 1997 U.S. Census.(1)

INDUSTRY	ESTABLISHMENTS	EMPLOYEES	TOTAL VALUE OF SHIPMENTS	RELATIVE MARKET SHARE (in terms of dollars)	TOTAL CAPITAL EXPENDITURES	ESTIMATED MATERIALS COSTS		ESTIMATED CORROSION COSTS	
						Lower Limit: 20% of Capital Expenses	Upper Limit: 40% of Capital Expenses	Lower Limit: 20% of Material Costs	Upper Limit: 30% of Material Costs
	number	number	$ x million / year	%	$ x million / year	$ x million / year		$ x million / year	
CHEMICAL MANUFACTURING INDUSTRY									
Inorganic Dye and Pigment Mfg.	74	8,608	$3,734	0.9%	$212	$42	$85	$8	$25
Synthetic Organic Dye and Pigment Mfg.	112	8,314	$2,530	0.6%	$119	$24	$48	$5	$14
Alkalies and Chlorine Mfg.	39	4,859	$2,645	0.7%	$284	$57	$114	$11	$34
Carbon Black Mfg.	22	1,769	$990	0.2%	$89	$18	$36	$4	$11
All Other Basic Inorganic Chemical Mfg.	638	53,419	$17,255	4.2%	$839	$168	$336	$34	$101
Gum and Wood Chemical Mfg.	63	2,267	$815	0.2%	$33	$7	$13	$1	$4
Cyclic Crude and Intermediate Mfg.	50	8,020	$5,975	1.5%	$651	$130	$260	$26	$78
Ethyl Alcohol Mfg.	38	1,756	$1,230	0.3%	$34	$7	$14	$1	$4
All Other Basic Organic Chemical Mfg.	676	89,261	$53,542	13.2%	$3,787	$757	$1,515	$151	$454
Plastics Material and Resin Mfg.	532	61,035	$44,574	11.0%	$2,920	$584	$1,168	$117	$350
Synthetic Rubber Mfg.	143	12,009	$6,060	1.5%	$391	$78	$156	$16	$47
Cellulosic Organic Fiber Mfg.	6	4,802	$1,097	0.3%	$47	$9	$19	$2	$6
Noncellulosic Organic Fiber Mfg.	100	37,085	$11,912	2.9%	$595	$119	$238	$24	$71
Nitrogenous Fertilizer Mfg.	143	5,483	$3,764	0.9%	$574	$115	$230	$23	$69
Phosphatic Fertilizer Mfg.	61	8,878	$5,749	1.4%	$248	$50	$99	$10	$30
Fertilizer (Mixing Only) Mfg.	445	8,712	$3,314	0.8%	$71	$14	$28	$3	$9
Pesticide & Other Agricultural Chem. Mfg.	260	13,994	$11,420	2.8%	$437	$87	$175	$17	$52
Paint and Coating Mfg.	1,495	53,091	$19,175	4.7%	$415	$83	$166	$17	$50
Adhesive Mfg.	692	21,737	$7,330	1.8%	$241	$48	$96	$10	$29
Soap and Other Detergent Mfg.	807	31,158	$17,811	4.4%	$465	$93	$186	$19	$56
Polish and Other Sanitation Goods Mfg.	728	21,989	$8,369	2.1%	$154	$31	$62	$6	$18
Surface Active Agent Mfg.	211	9,471	$6,992	1.7%	$289	$58	$116	$12	$35

Table 3. Estimated annual corrosion costs as a percentage of material costs and total capital expenditures for the chemical, petrochemical, and pharmaceutical manufacturing industries, based on data from the 1997 U.S. Census (continued).[1]

INDUSTRY	ESTABLISHMENTS	EMPLOYEES	TOTAL VALUE OF SHIPMENTS	RELATIVE MARKET SHARE (in terms of dollars)	TOTAL CAPITAL EXPENDITURES	ESTIMATED MATERIALS COSTS		ESTIMATED CORROSION COSTS	
						Lower Limit: 20% of Capital Expenses	Upper Limit: 40% of Capital Expenses	Lower Limit: 20% of Material Costs	Upper Limit: 30% of Material Costs
	number	number	$ x million / year	%	$ x million / year	$ x million / year		$ x million / year	
CHEMICAL MANUFACTURING INDUSTRY (cont.)									
Toilet Preparation Mfg.	729	63,816	$24,334	6.0%	$577	$115	$231	$23	$69
Printing Ink Mfg.	565	13,026	$4,140	1.0%	$90	$18	$36	$4	$11
Explosives Mfg.	101	7,770	$1,318	0.3%	$34	$7	$14	$1	$4
Custom Compounding of Purchased Resin	832	27,573	$7,800	1.9%	$285	$57	$114	$11	$34
Photographic Film, Paper, Plate, & Chem. Mfg.	310	39,032	$12,829	3.2%	$567	$113	$227	$23	$68
Other Misc. Chemical Product & Preparation Mfg.	1,149	35,897	$1,149	0.3%	$613	$123	$245	$25	$74
SUBTOTAL	**11,021**	**654,831**	**$287,853**	**70.7%**	**$15,061**	**$3,012**	**$6,027**	**$604**	**$1,807**
PETROCHEMICAL MANUFACTURING INDUSTRY									
Petrochemical Mfg.	54	10,943	$20,534	5.0%	$1,108	$222	$443	$44	$133
Industrial Gas Mfg.	642	12,492	$5,231	1.3%	$729	$146	$292	$29	$87
SUBTOTAL	**696**	**23,435**	**$25,765**	**6.3%**	**$1,837**	**$368**	**$735**	**$73**	**$220**
PHARMACEUTICAL MANUFACTURING INDUSTRY									
Medicinal and Botanical Mfg.	338	23,378	$11,920	2.9%	$771	$154	$308	$31	$93
Pharmaceutical Preparation Mfg.	837	115,781	$67,520	16.6%	$2,493	$499	$997	$100	$299
In Vitro Diagnostic Substance Mfg.	226	36,502	$8,146	2.0%	$704	$141	$282	$28	$84
Biological Product (Except Diagnostic) Mfg.	364	23,285	$5,686	1.4%	$431	$86	$172	$17	$52
SUBTOTAL	**1,765**	**198,946**	**$93,272**	**22.9%**	**$4,399**	**$880**	**$1,759**	**$176**	**$528**
TOTAL	**13,482**	**877,212**	**$406,890**	**100.0%**	**$21,297**	**$4,260**	**$8,521**	**$853**	**$2,555**
									AVERAGE CORROSION COST: $1.7 billion per year

Table 3 shows that the total capital expenditures for the chemical manufacturing industry are $15.061 billion, with $604 million to $1.807 billion per year in corrosion costs. For the petrochemical manufacturing industry, the total capital expenditures are $1.837 billion, with $73 million to $220 million per year in corrosion costs. For the pharmaceutical manufacturing industry, the total capital expenditures are $4.399 billion, with $176 million to $528 million per year in corrosion costs. Therefore, the three industries combined have total capital expenditures of $21.297 billion in 1997, with $853 million to $2.555 billion in annual corrosion costs. The estimated average direct corrosion cost is $1.7 billion per year (8 percent of total capital expenditures). Again, it is noted that these cost are direct costs and are based on actual capital expenditures.

No calculation was made for the indirect costs of production outages or indirect costs related to catastrophic failures. The costs of operation and maintenance related to corrosion were also not included in the $1.7 billion per year estimate.

During the current sector study, it was found that many people referenced the 1978 Battelle-NBS report,(7) which estimated corrosion costs as 5 percent of the gross domestic product (GDP) of the industry. According to the Bureau of Economic Analysis, the GDP in 1998 for manufacturing of non-durable goods in the chemical industry totaled $223.5 billion per year ($168.4 billion for chemicals and allied products, plus $55.1 billion for rubber and miscellaneous plastic products). If the Battelle-NBS assumption were correct for the current sector, the 5 percent of the $223.5 billion per year total value of shipments for the chemical, petrochemical, and pharmaceutical industry combined would yield corrosion costs of $11.2 billion per year. However, based on the knowledge that the total capital expenditures are $21.3 billion per year, this estimate is probably too large. Rather, the estimated $1.7 billion per year corrosion costs should be interpreted as [$1.7 billion / $223.5 billion x 100% =] 0.76 percent in this sector, instead of 5 percent.

This apparent discrepancy of data can be explained from increased productivity on one side and improved corrosion control and protection on the other side. It is likely that more product is being produced at a lower cost and that the fraction of corrosion-related cost has decreased since 1975.

CORROSION CONTROL METHODS

In the book *Corrosion, Volume 2: Corrosion Control*,(8) a corrosion control model for chemical and petrochemical plants is described. The model distinguishes five phases: (1) plant and process design, (2) construction stage checks, (3) planned maintenance, (4) corrosion monitoring, and (5) remedial action and diagnostic work (see figure 2).

Phase 1. Plant and Process Design

Plant and process design involves the influencing of the materials of construction, equipment design, process conditions, and recommended operating practices to minimize the risk of corrosion. A commonly used rule of thumb is: "design corrosion out, don't design corrosion in."

In large companies, an internal project team may design the plant, otherwise contractors provide the design. In either case, the corrosion engineer must be involved from the inception of the project. Otherwise, the materials of construction will have to be chosen to satisfy process conditions, which may have been decided upon without consideration of the economic balance between process efficiency and capital costs of the plant.

Contractor designs will be in the context of a competitive bidding situation and in-company checks of the design should cover not only design errors, but also cases where calculated risks have been taken, which may not, however, be acceptable to the operating company. The effort required to specify the materials schedule for a new plant or to check a design very much depends on how much experience there is with similar or identical units in operation. Factors such as process conditions and raw material sources are taken into consideration before extrapolating the experiences of another unit.

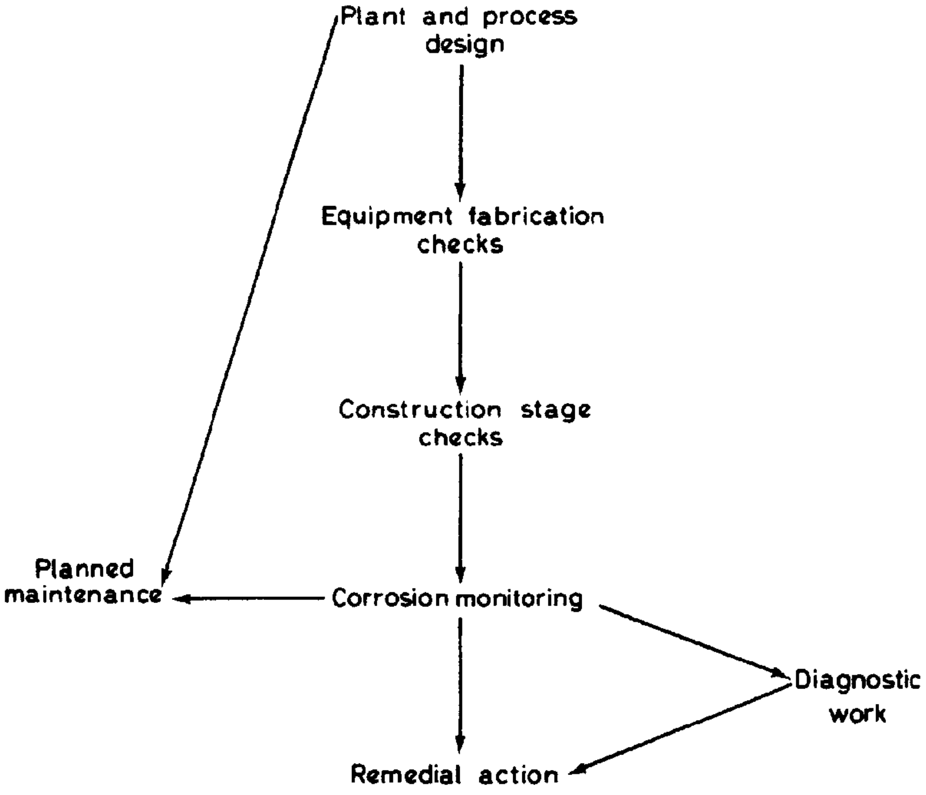


Figure 2. Phases of corrosion control.[8]

Corrosion-Resistant Alloys

The use of corrosion-resistant alloys (CRA) has gained a wide acceptance in the chemical process industry. While this is true, an often encountered problem of corrosion engineers in the chemical industry is convincing their management that a more expensive material will actually prevent problems and save money in the long run. Table 4 shows a comparison of the relative costs for various alloys. As mentioned before, not all alloys are equally resistant to all environments. It must also be noted that a more expensive alloy does not necessarily mean that it will provide more corrosion resistance. For example, there are situations where regular carbon steel will perform very well and an alloyed steel will not. Alloy constituents (nickel and chromium) and fabrication procedures determine the cost of the material. The cost ratio is based on a 6.4-mm- (0.25-in-) thick plate and Type 316L stainless steel is used as the cost reference, i.e., ratio 1.0.

For example, nickel-chromium-molybdenum (Ni-Cr-Mo) alloys have been used in reactor vessels in the production of acetic acid for more than 20 years. These alloys are a cost-effective alternative to nickel chromium (Ni-Cr) stainless steels because of good resistance to oxidizing corrosive media; Ni-Mo alloys have good resistance to reducing corrosive media. Molybdenum, in combination with chromium, stabilizes the passive film in the presence of chlorides, and is especially effective in increasing resistance to pitting and crevice corrosion.

Table 4. Comparison of the relative costs of various alloys.(9)

ALLOY CLASS	EXAMPLE	CONSTITUENTS										COST RATIO(9)
		Ni	Cr	Mo	Fe	Co	Ti	Cu	Cb	Al	V	
Carbon Steel	C10				> 94							0.2
Low Alloy Steel	1-1/4Cr 1/2Mo		1.25	0.5	balance							0.25
Fe-Ni-Cr + Mo	Type 316L	13.0	17.0	2.3	balance							1.0
	Alloy 800H	32.5	21.0		4.6							-
	20Cb-3	35.0	20.0	2.5	balance			3.5				3.8
Ni-Cr-Mo	Alloy C2	54.0	15.5	16.0								6.0
	Alloy C276	57.0	16.0	16.0	5.5							
	Alloy C4	54.0	16.0	15.5	3.0							
	Alloy 625	60.0	21.5	9.0					3.7			6.3
Ni-Cr-Fe	Alloy G	45.0	22.2	6.5	19.5			2.0				6.4
	Alloy 600	76.0	15.0		8.0							-
Ni-Mo	Alloy B2	balance	1.0	28.0	2.0	1.0						11.6
Ni-Cu	Alloy 400	65.1						32.0				-
Nickel	Alloy 200	99.9										-
Co-Base	ULTIMET (R)	9.0	26.0	5.0	3.0	54.0						27.2
Ti-Base	Ti-6Al-4V						90			6.0	4.0	-

Piping Design Considerations

In piping design, three dominant conditions may lead to corrosion problems: water traps, dead legs, and high velocities.(10) Figure 3 shows a typical area of plant piping, where some of the pipes run horizontal and where bends are common.

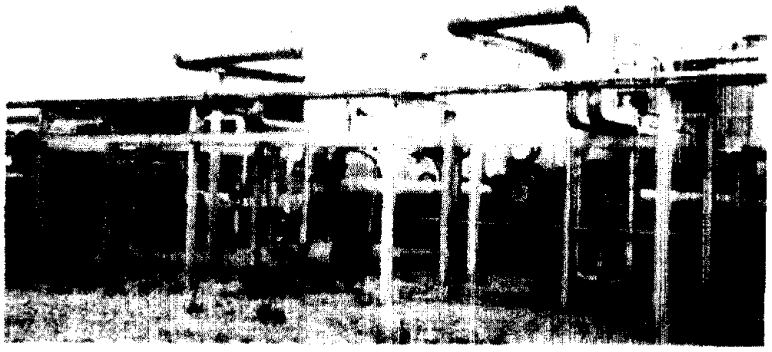


Figure 3. Typical plant piping in a petrochemical plant.

Water traps are low sections of the piping system where water stagnates and accumulates, causing corrosion. Water traps should be the first area to be inspected. Pitting corrosion is one of the most frequently occurring corrosion mechanisms at water traps. It may be possible to minimize low sections by slanting the pipe or by installing drain valves at the low points that are periodically drained.

Dead legs are the regions of the piping system where the fluid is stagnant. Pitting corrosion may occur in environments where stagnant particles are deposited on a metal surface. Once initiated, the pits grow until they penetrate through the metal wall, causing a leak. Pitting is especially dangerous in pressurized systems because a leak may release aggressive or flammable chemicals under high pressure. Dead legs can be minimized in the piping by eliminating dead ends in piping manifolds, providing drains so that stagnant deposits can be flushed, designing pipes with elbows rather than tees, placing valves to have the shortest dead legs, and placing branch lines off from the top rather than from the side.(10)

Velocity effects include cavitation and erosion-corrosion. Cavitation corrosion occurs when vapor bubbles are formed and collapse in a fluid medium due to changes in pressure. Cavitation may cause significant wall loss at the locations where the bubbles impact the metal. Erosion-corrosion occurs when the protective scale of a metal is removed due to high-velocity flow or turbulence. Elbows, tees, and internal protrusions such as valves and weld beads are locations where erosion-corrosion may occur. In general, fluid piping should be designed with large diameters to transport the quantity of material required; however, process changes over time may change the fluid volume transported through the piping. A location that never had a problem may then become susceptible to erosion-corrosion.

Phase 2. Construction Stage Checks

An inspection system to ensure that fabricators are working according to design codes and that their quality-control systems are operating effectively is of considerable value. At the construction stage, checks are made for materials correctly specified, but wrongly supplied; on-site welding quality heat treatments carried out as specified; and damage to equipment, especially where vessels have been lined (see figure 4). Mistakes can arise in two ways:

1. Assembled items are supplied in the wrong material by the fabricator due to a mix-up in his identification system.
2. Common items such as valves, piping, and welding electrodes that may be supplied for a large plant in half a dozen material specifications can become mixed up due to poor identification marking.

When specifying equipment to fabricators, it should be remembered that equipment may be exposed on-site before erection and temporary corrosion protection measures should be considered. Any pre-commissioning treatments to equipment that are specified by the design, e.g., descaling, must be carried out. Such details can make for a smooth start-up and minimum trouble during the early operational period of a new plant.

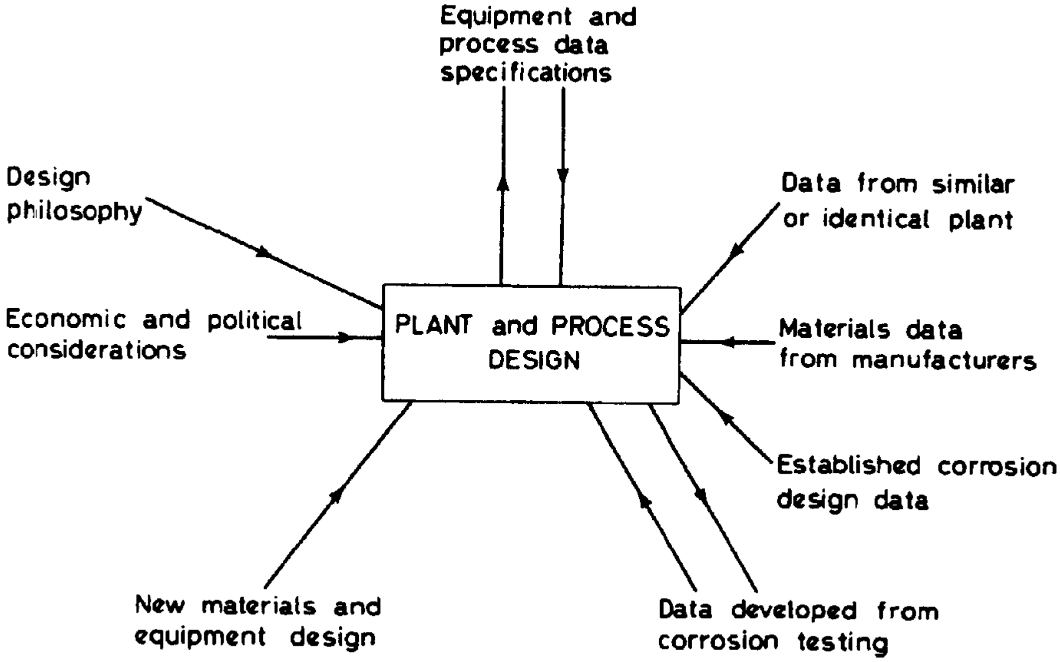


Figure 4. Factors influencing plant and process design.$^{(8)}$

Phase 3. Planned Maintenance

Planned maintenance or regular replacement of plant equipment to avoid failure by corrosion, etc. is an essential adjunct to design and constitutes the third phase of control (see figure 5). The design philosophy determines the emphasis placed on controlling corrosion by this means, as opposed to spending additional capital at the construction stage to prevent corrosion taking place. Where maintenance labor costs are high or spares may be difficult to procure, a policy of relying heavily on planned maintenance should be avoided.

Planned maintenance consists of scheduled shutdown periods in order to inspect all equipment and refurbish or replace equipment that has failed due to corrosion or other failure mechanisms. The shutdown periods are generally scheduled well in advance. The shutdowns are short in duration since inspection costs and production losses are the determining cost factors for the economic value of the scheduled shutdown.

A maintenance policy can be planned using a discounted cash flow (DCF) calculation over the life cycle of the plant. In some cases, the costs of regular replacements, including maintenance labor costs and lost revenues during downtime, are less than the extra initial capital cost of a more durable material. Regular maintenance of lower grade equipment can be preferable over minimum maintenance of expensive (specialty) equipment.

Periodic reviews are necessary to determine if the currently applied corrosion control methods need to be modified. For example, coatings on vessels or piping systems can deteriorate over time; therefore, they must be replaced. Inhibitor doses frequently need to be adjusted when environmental or process changes occur. Regular inspection periods will give an operator a sense of safety and assurance about the status of the equipment.

In the pharmaceutical industry, process tanks, pipes, and valves are routinely electropolished to reduce the adhesion of a product and to decrease the risk of bacterial growth in crevices. Packaging of pharmaceutical products is also important in order to minimize damage due to corrosion by spilled products; therefore, desiccant bags filled with highly active drying materials are often used as a means of protection. In addition, the atmosphere inside the packaging can be maintained at a level of relative low humidity so that corrosion can be avoided.

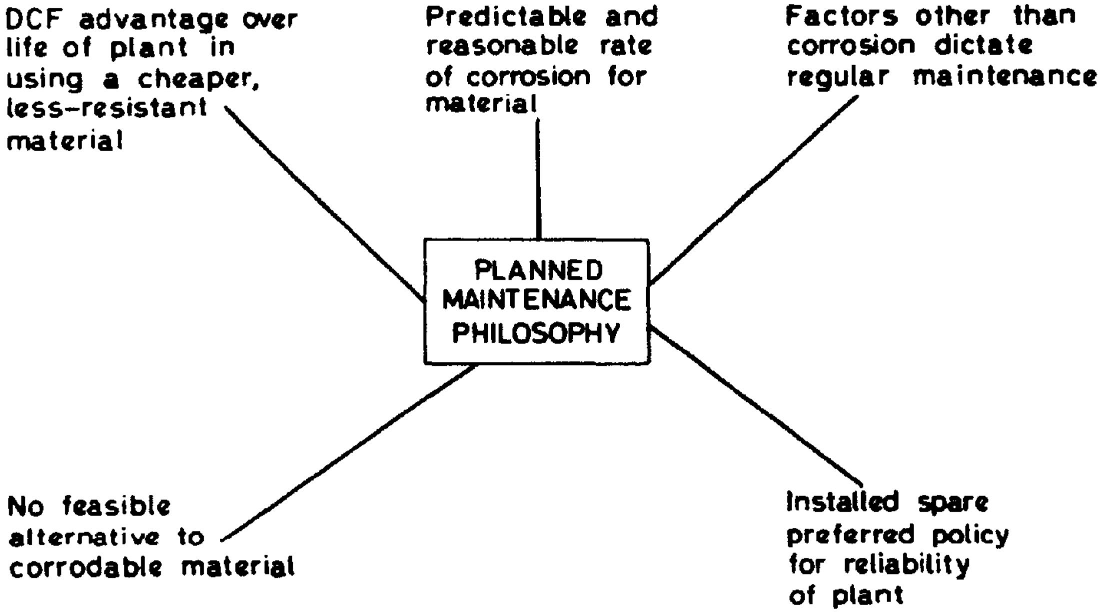


Figure 5. Factors contributing to a policy of planned maintenance.[8]

Phase 4. Corrosion Monitoring

Corrosion monitoring is the practice of checking and measuring the degree of corrosion of process equipment by the use of "probes" that are inserted into the process stream and a variety of other inspection techniques, such as visual inspection, thickness measurement and crack detection, weight loss coupons, and sentinel holes (see figure 6). Corrosion monitoring probes can be mechanical, electrical, or electrochemical devices. In many of these monitoring techniques, probes can become affected by oil or paraffin deposits, causing erroneous readings. Corrosion monitors should be regarded as part of the plant instrumentation and should be located in areas of high corrosion risk or where corrosion damage can be hazardous or costly. Monitoring should include a schedule of inspections once the plant is commissioned.

Corrosion monitoring using probes can be divided in continuous monitoring and non-continuous monitoring. Continuous monitoring is advantageous because corrosion rates can be determined immediately, while periodic monitoring provides average data and may miss an event if there is a short-term upset in the system. Non-continuous corrosion monitoring is traditionally performed during turnaround and in conjunction with vessel entry.

Table 5 lists common corrosion monitoring techniques and some advantages and disadvantages associated with each technique. The cost of a monitoring technique depends on labor, equipment, installation, and data processing. Selection of a compatible monitoring system depends on the environment and the process conditions.

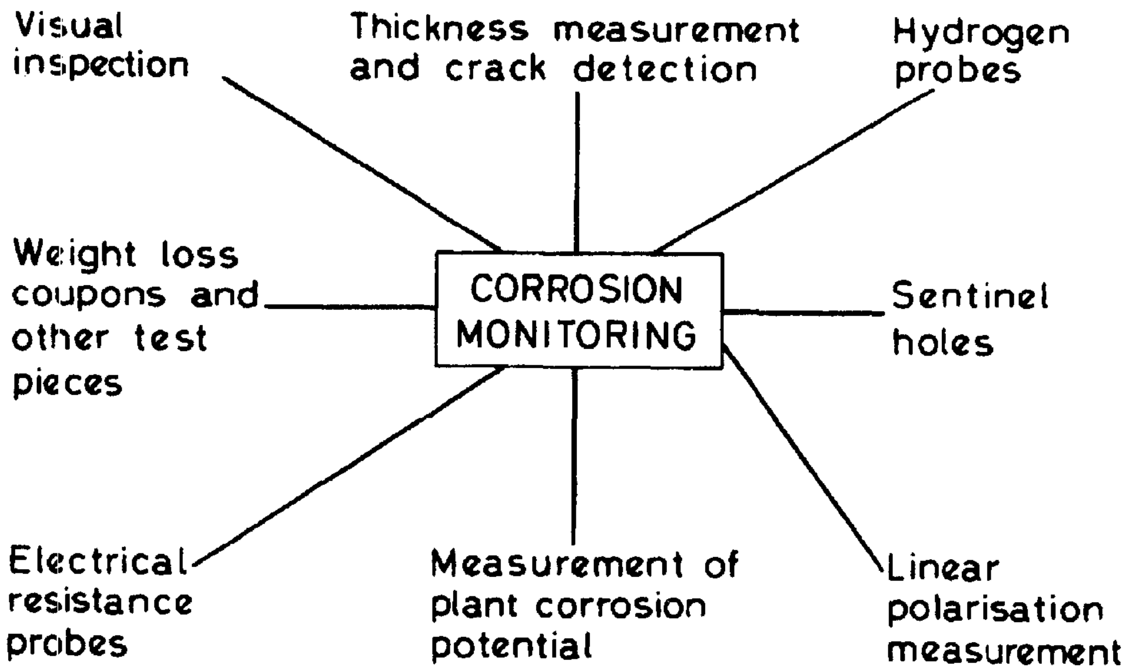


Figure 6. Techniques for monitoring corrosion in a process plant.[8]

Table 5. Corrosion monitoring techniques.

TECHNIQUE	ADVANTAGES	DISADVANTAGES
Weight Loss Coupons and Holders	Easy to use and implement Can test multiple specimens	Risk associated with people inserting/extracting the specimens Average corrosion rate
Radiography	Produces permanent record of corrosion damage Low initial cost	Requires careful implementation to prevent health hazards Holes, voids, and discontinuities affect x-ray attenuation
Magnetic Particle Testing	High reliability Provides integrity and safety assessment No disruption to system Lowers manufacturing costs	Limited to certain areas Measures only surface defects
Liquid Penetrant Testing	Low cost Simple equipment	Measures only near surface
Ultrasonic Shear Wave	Measures cracking in welds	Good technical skills required Inspection limited to area
Ultrasonic Testing (UT)	Automated operation Electronic recording Detect minute defects	No permanent record
On-Site Metallography	Assesses condition of equipment before refurbishing or repairing	High cost

Table 5. Corrosion monitoring techniques (continued).

TECHNIQUE	ADVANTAGES	DISADVANTAGES
Acoustic Emission	Low cost Rapid inspection Permanent test record On-line testing	Background noise can alter data Highly ductile materials yield low-amplitude emissions
Remote Field Eddy Current Inspection	Automated inspection	Volumetric test Percent wall loss only
Tank Floor Scanner	Detects corrosion and external/internal defects on aboveground storage tank floors	Follow up with UT Does not quantify data
Linear Polarization Resistance (LPR)	Direct measurement of metal loss and corrosion rate Frequent measurements	High cost Corrosion may deteriorate probe Special instrument necessary for high-resistivity environments

Phase 5. Remedial Action and Diagnostic Work

Corrosion monitors by themselves only warn of corrosion and must be coupled with the fifth phase of control, called remedial action and diagnostic work, to be effective. In some cases of corrosion, the remedial measure is known or easily deduced; however, in others, diagnostic work has to precede a decision on remedial action (see figure 7).

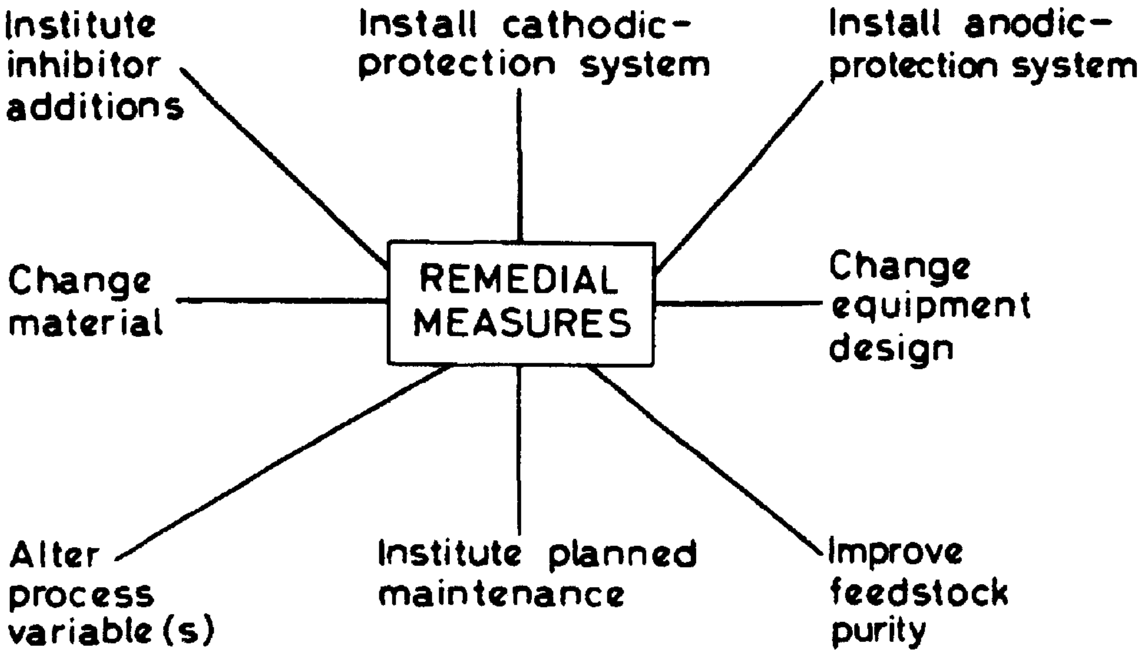


Figure 7. Options for remedying corrosion problems in a process plant.(8)

When the remedial action is not apparent, then diagnostic work has to precede a decision on remedial action. Further investigation or testing may take place in order to determine the root cause of the corrosion failure. For example nondestructive techniques (NDT) such as radiography, magnetic particle testing, liquid penetrant, acoustic emission, and ultrasonic testing may be used to detect cracks.

Options for remedial measures include: complete replacement of the equipment, using a corrosion-resistant alloy or clad material, or application of anodic protection (AP), coatings, or corrosion inhibitors.

CORROSION MANAGEMENT

The Environmental Protection Agency (EPA) has a Risk Management Program (RMP) that addresses worker safety, pollution prevention, and local emergency preparedness and response.(11) The American Petroleum Institute (API) applies Recommended Practice 750, which requires companies to employ process safety management (PSM) in controlling process hazards.(12) The American Institute of Chemical Engineers (AIChE) Center for Chemical Process Safety provides loss prevention information and support services.(13) The Responsible Care (RC) Program of the U.S. Chemical Manufacturers Association (CMA) is being adopted by hydrocarbon processing industry (HPI) companies in many countries around the world. Through these programs, there has been a significant decline in the number of HPI loss incidents and money in recent years. More companies are now focusing on loss prevention.

Risk-Based Inspection

Many chemical companies are using a form of risk-based inspection (RBI) to heighten the mechanical integrity of their plants. RBI is a methodology that systematically prioritizes pressure equipment risk levels so that leak detection and repair programs can be classified relative to the risk associated with each piece of equipment. RBI is both a quantitative and a qualitative process for systemically combining both the likelihood of failure and the consequences of failure to establish a prioritized list of high-risk equipment.(14) High-risk equipment includes pressure vessels, short piping, and toxic lines. To handle inspection requirements, a variety of portable and fixed detection and data collection instruments are utilized. Risk is the product of both the likelihood of failure and the consequences of a failure.

The probability that failure will occur can be estimated from the frequency of accidents that have occurred in the past. The consequences of a failure depend on the pressure equipment; the location of the plant; the population density surrounding the plant; and the nature, amount, and concentration of the chemicals being released.

Risk can be modeled into concentric areas around a plant. The proximity of an infrastructure and the population density and the potential for environmental damage are factors that affect the risk levels. Other factors that influence risk may include wind direction or possible escape routes. In figure 8, infrastructure X_1 has a risk of 10^{-1} because the probability of this neighboring structure being affected is extremely high. If there is an explosion in the plant, then this infrastructure may be seriously damaged, while a chemical spill or a gas release can severely injure people. In contrast, the infrastructure X_6 has a low risk (10^{-6}) because it is located a larger distance from the chemical plant. The force of an explosion will be less and a chemical release is likely to be significantly diluted before it reaches this location.

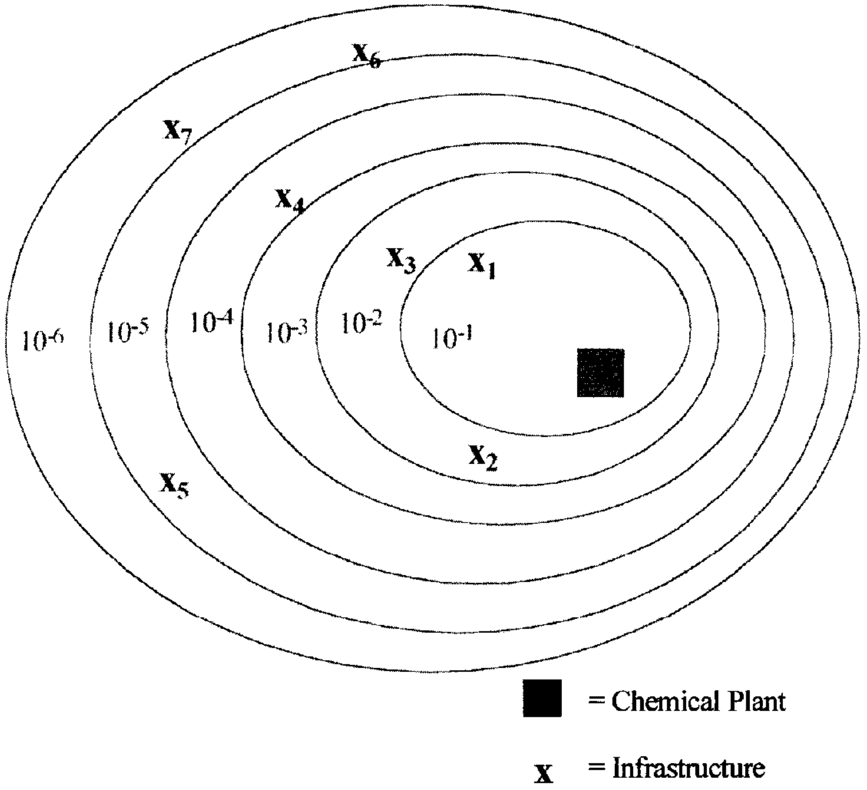


Figure 8. Illustration of risk density around a chemical plant.

Water Management

In addition to regulatory compliance requirements, plants have economic incentives to maximize water re-use by cleaning and recycling process unit effluent streams. Companies are using improved water and process treatment chemicals, and computerized programs and services, as well as separation and filtration technologies. Significant use is being made of off-line and on-line cleaning equipment, materials, and services. Some companies are outsourcing their water treatment requirements to suppliers and service companies.

Product Quality in the Pharmaceutical Industry

In the pharmaceutical industry, corrosion deposits are not acceptable in the products. For example, corrosion products containing chromium and nickel from stainless steels are not allowed to enter the process stream. In the manufacturing of Vitamin C, copper must be eliminated because copper in aqueous solutions accelerates the decomposition of Vitamin C, while stainless steel is not used to handle Vitamin B_6 hydrochloride (even though corrosion rates may be low) because trace amounts of iron are objectionable.(15)

The U.S. Food and Drug Administration (FDA) takes measures to ensure the safety of all approved prescription drugs. The drug development and approval process involves careful and methodical procedures to evaluate safety risks in four distinct stages. The four stages are a pre-clinical safety assessment, a pre-approval safety assessment in humans, a safety assessment during FDA regulatory review, and post-marketing safety surveillance.(3) The FDA review ensures that the product quality standards will be met during product manufacturing.

Product Quality in the Chemical Industry

The chemical industry produces a large variety of products. A large portion is made in bulk; therefore, low amounts of corrosion impurities are generally not a problem. In processes that manufacture small amounts of specialized chemicals and use batch processes, product quality may be more affected where corrosion is present; therefore, more effort is required to keep these processes corrosion-free or with low corrosion rates.

CHANGES FROM 1975 TO 2000

This section discusses the changes in the field of corrosion that have occurred in the chemical, petrochemical, and pharmaceutical industries during the last 25 years. The corrosion engineers interviewed for the current research indicated that the dominant factors changing the attitude of the industry toward corrosion include the availability of materials with improved corrosion resistance, a better understanding of corrosion phenomena, and the implementation of new electronic corrosion monitoring techniques.

Metallurgy and the effects of various alloying elements are better understood today than 25 years ago. Low-alloy steels are used when applicable because of their cost benefits; however, in more severe or critical cases, common stainless steels have become suitable materials due to their availability, moderate cost, relatively light weight, good strength, and overall acceptable corrosion resistance. The need for alternate materials rises as issues of production and higher product quality become increasingly important.

Monitoring techniques have advanced significantly as well. Today, measurements can be taken more quickly; using smaller sensors; and stored in handheld electronic devices or portable computers, or be sent to the control room in digital or analog form by wire or digitally using wireless technology. By using these computerized sensors, an operator can monitor local corrosion conditions at any time.

In the corrosion cost analysis of the current sector description, reference was made to the 1978 Battelle-NBS report on corrosion costs. The analysis showed that the direct cost of corrosion determined from the capital expenditures of the chemical, petrochemical, and pharmaceutical industries has decreased relative to the corrosion cost 25 years ago. More product is being produced at a lower cost, while corrosion prevention and control methods have improved significantly.

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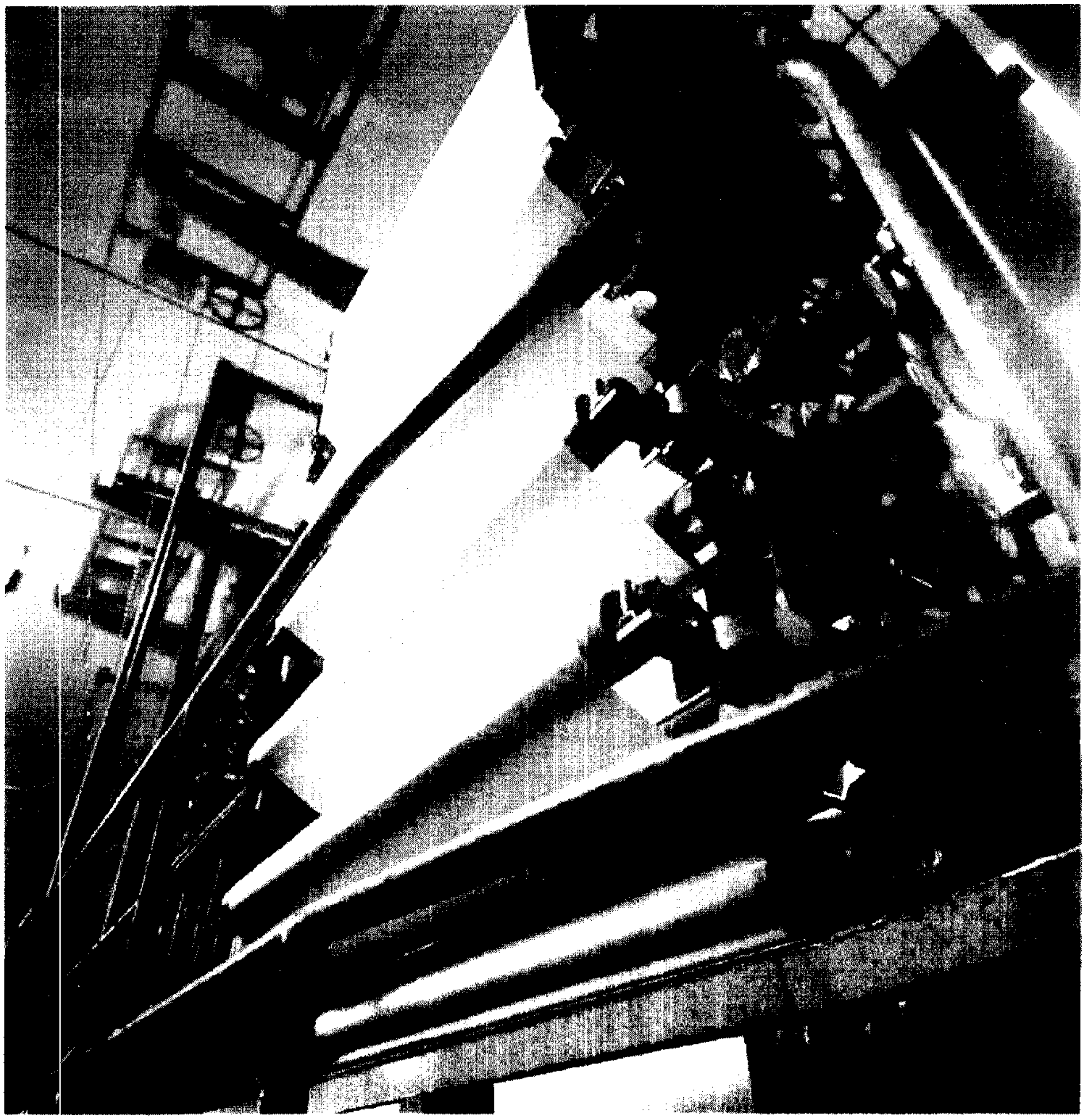
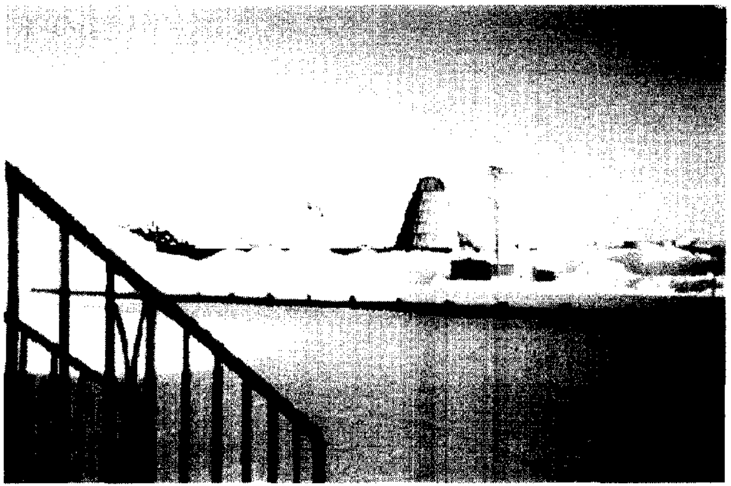
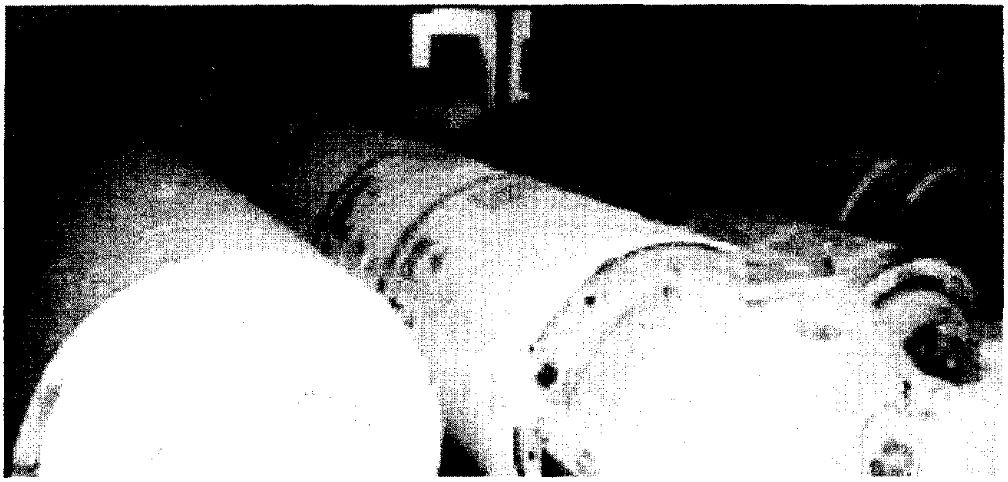
APPENDIX W

PULP AND PAPER

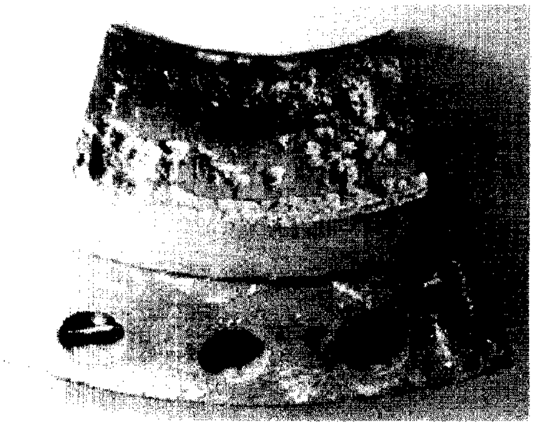




Pulping plant



Suction rolls



Corrosion of vessel wall

Microbiologically influenced corrosion

APPENDIX W

PULP AND PAPER

MICHIEL P. H. BRONGERS[1] AND AARON J. MIERZWA[1]

SUMMARY AND ANALYSIS OF RESULTS

Corrosion Control and Prevention

The $165 billion pulp, paper, and allied products industry supplies the United States with approximately 300 kg of paper per person per year. More than 300 pulp mills and more than 550 paper mills support its production. A typical pulp mill uses approximately 64 m^3 of water per metric ton of pulp, and the combined pulp and paper manufacturers release approximately 100 thousand metric tons of toxic chemicals per year into the air, water, or land.

The total annual corrosion costs for the pulp, paper, and paperboard industry, as determined as a fraction of the maintenance cost, is approximately $1.97 billion to $9.88 billion (average $5.928 billion per year). These estimates are between 1.2 percent and 6.0 percent of the total sales for the entire U.S. pulp and paper industry. The cost of corrosion for the pulp industry was only estimated at approximately $808.5 million per year.

Paper production consists of a series of processes and can be roughly divided according to the five major manufacturing steps: (1) pulp production, (2) pulp processing and chemical recovery, (3) pulp bleaching, (4) stock preparation, and (5) paper manufacturing. Each manufacturing step has its own corrosion problems related to the size and quality of the wood fibers, the amount of and temperature of the process water, the concentration of the treatment chemicals, and the materials used for machinery construction. Examples of corrosion affecting production are: (1) corrosion products polluting the paper and (2) corrosion of rolls scarring the sheets of paper. Corrosion of components may also result in fractures or leaks in the machines, causing production loss and safety hazards.

Opportunities for Improvement and Barriers to Progress

Major changes in the paper-making process have occurred in the period from 1975 to 2000. Today's digital world requires much-increased production of pulp and paper. Paper recycling and environmental issues concerning chemical releases have forced the pulp and paper industry to change their processes. The fierce competition within the pulp and paper industry has resulted in many company mergers, a smaller total number of pulp and paper mills, and significantly increased production capacity per mill. Furthermore, factories are no longer allowed to "run a river through their plant" and dump the processed water back into the environment without cleaning it first. There is a clear trend of decreasing the amount of process water, recycling and reusing the water in closed-loop systems, and cleaning the water before releasing. This results in a more corrosive process environment.

Paper mills in the United States are traditionally constructed of a combination of carbon steels and stainless steels. In general, production systems run cleaner if all machinery in contact with the process stream would be constructed of corrosion-resistant alloys, which effectively reduce the general corrosion rate. Although stainless steel can be susceptible to other forms of corrosion, such as stress corrosion cracking of weld heat-affected zones, the use of stainless steel reduces the formation of thick corrosion scales and significant wall loss can be prevented.

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[1] CC Technologies Laboratories, Inc., Dublin, Ohio.

An important barrier to immediate implementation of a complete change from carbon steel to stainless steel is the value of this investment. To resolve this, companies gradually exchange their equipment, when processupgrades are made. Pulp and paper mills are factories that involve a series of consecutive pieces of equipment, each with a different useful service life. At the end of the service life, when production is severely affected by the age of the equipment, equipment is completely replaced.

The European paper and pulp industry has demonstrated success in using a chlorine-free bleaching process for selected pulp grades. Substitutes for chlorine include ozone, oxygen, and peroxide. The Mestä-Rauma pulping plant was opened in Europe in 1996, and is one of a kind as it is made entirely of stainless steel. By using this material for each process, the maintenance costs associated with equipment are significantly reduced in comparison to those for carbon steel equipment. The capital investment for this pulping plant was $550 million. The capital investment costs for a new state-of-the-art integrated mill are estimated at $1 billion.

Recommendations and Implementation Strategy

A large portion of the corrosion cost lies in maintenance of carbon steel components. In many paper mills, corrosion management is concentrated around the maintenance groups, which primarily deal with all outages, replacements, and equipment inspections. The objective of the maintenance work is to ensure that production runs continuously. While some mills may have dedicated corrosion engineers on staff, most do not. It is recommended that awareness among maintenance engineers be increased so that corrosion maintenance can be conducted cost-effectively and in a timely manner. Furthermore, it was shown in the case study (Metsä-Rauma pulping plant) that replacement of the carbon steel components with stainless steel significantly reduces the corrosion maintenance costs. Hence, despite a higher initial cost, the use of corrosion-resistant alloys is recommended.

Summary of Issues

Increase consciousness of corrosion costs and potential savings.	Total corrosion maintenance costs range between $1.97 billion and $9.88 billion. The corrosion cost for pulping is only $808.5 million.
Change perception that nothing can be done about corrosion.	All-stainless steel equipment effectively reduces the general corrosion rate.
Advance design practices for better corrosion management.	Use more corrosion-resistant alloys. Prevent pulp build-up.
Change technical practices to realize corrosion cost-savings.	Regular inspections and preventive maintenance have proven to be effective in maintaining uninterrupted operation.
Change policies and management practices to realize corrosion cost-savings.	Corrosion is dealt with from a maintenance point of view. The "do nothing" approach is not the most cost-effective method.
Advance life prediction and performance assessment methods.	The current approach of do nothing and replace equipment at the end of a service life allows for upgrades; however, accurate life predictions may prevent unscheduled outages.
Advance technology (research, development, and implementation).	There are currently no all-stainless steel plants in the United States. Integration of this material in the pulp and paper industry would follow the European example.
Improve education and training for corrosion control.	Maintenance personnel deal with corrosion once failure has occurred. Few companies have dedicated corrosion engineers on staff.

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SECTOR DESCRIPTION

Background

The pulp and paper industry is a vital part of the U.S. economy. In 1998, the United States used an estimated 318 kg (700 lb) of paper per person(1-2) per year.[2] This included newspapers and magazines, toilet paper, printer and copier paper, tickets, receipts, pictures, stamps, packaging paper, and various other products. In 1998, the U.S. paper and allied products industry reported total sales of $164.9 billion, with $3.6 billion in earnings. In addition, in 1998, the wood pulp, paper, and paperboard industry ran at capacities of 93.6 percent, 92.3 percent, and 92.2 percent, respectively. According to the U.S. Environmental Protection Agency (EPA),(3) approximately 16 percent of the world's pulp mills were located in the United States.

The Lockwood-Post's Directory, which provides annual statistics on the U.S. pulp and paper industry,(1) reported the total number of pulp and paper mills in the United States and Canada (see figure 1). The ratio of these two major components of the paper-making process appears to be similar for the two countries. Paper mills and pulp mills are often located on the same site and owned by the same company. In addition, the mills may be connected and have processes that are partially integrated. Therefore, this count may vary according to the method used to determine what is considered as "one mill." The production amount of the different paper products (pulp, paper, and paperboard) produced in U.S. mills from 1993 to 1999, shown in figure 2, remains relatively constant.

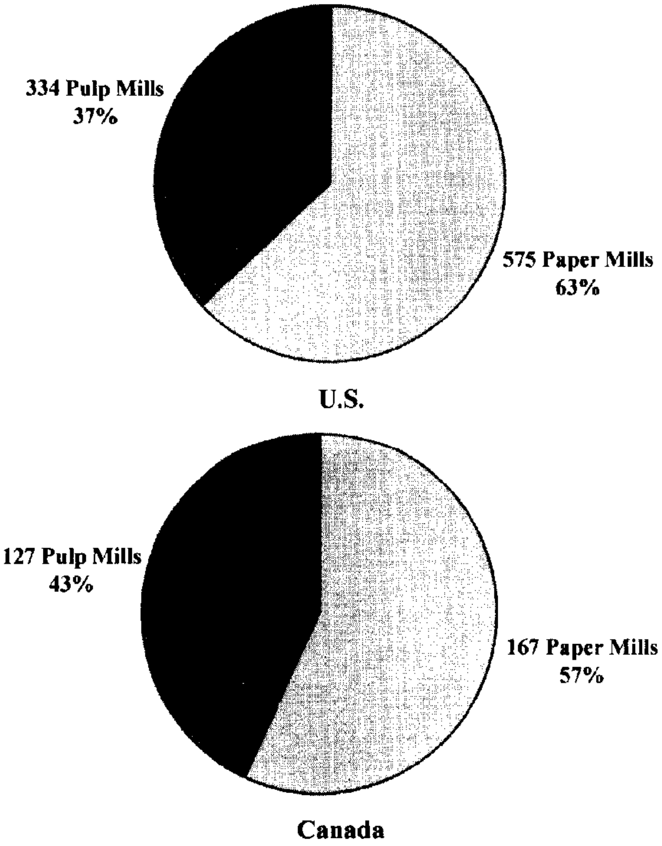

Figure 1. The division of paper and pulp mills in the United States and Canada in 2000.(1)

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[2] Based on 91.66 million short tons (83.2 metric tons) of paper and paperboard used (paper and paperboard produced minus exports plus imports)(1) within the United States, divided by the U.S. Census Bureau's estimate of 266 million people within the United States in 1997.(2)

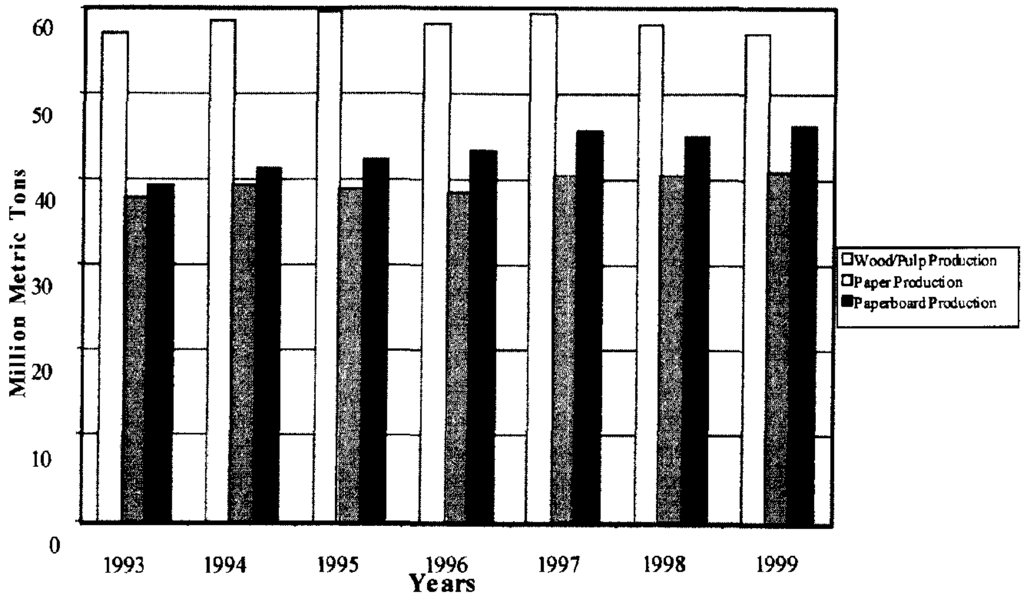

Figure 2. Total production of wood pulp, paper, and paperboard in the United States for the period 1993 to 1999 in metric tons.[1]

Although the production of paper products has remained relatively constant over the years, the market prices of pulp, printing and writing paper, and containerboard have fluctuated significantly. This fluctuation has had a direct effect on capital investment and asset management strategies. The website http://paperloop.com[4] provides a monthly price index of the average prices of major commodity grades, an example of which is shown in figure 3. The figure shows the considerable price fluctuations, even on a monthly basis. A price increase or decrease of 25 percent over a 6-month period is not uncommon.

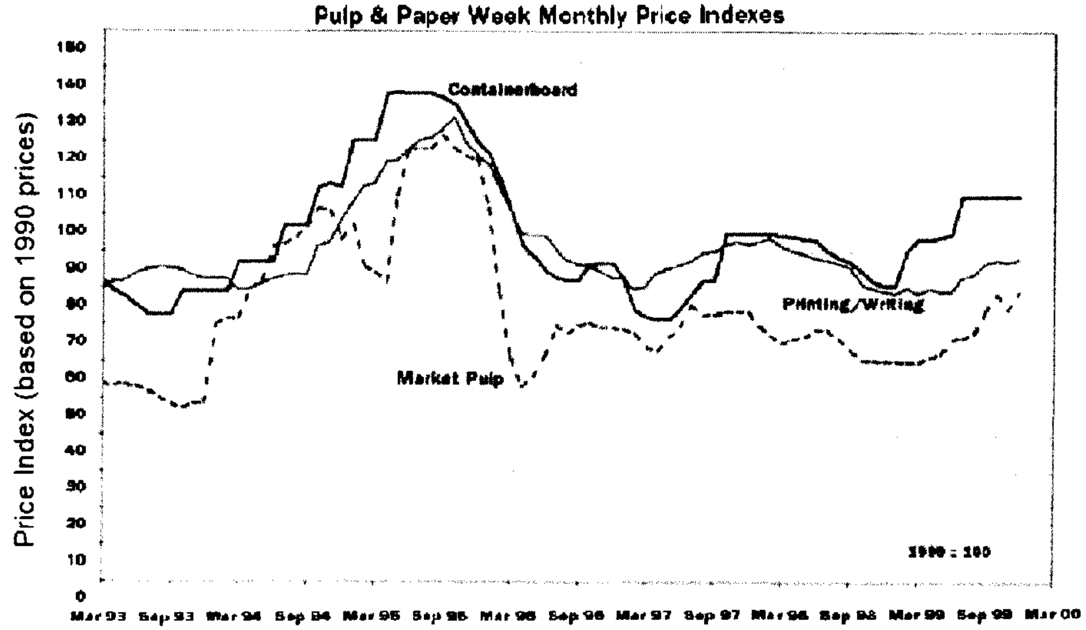

Figure 3. *Pulp & Paper Week* monthly price index for March 1993 to March 2000.[4]

Environmental Issues

Water Usage

Environmental issues involving the pulp and paper industry require that water usage by pulp and paper mills be reduced because they are among the largest industrial process water users in the United States. A typical pulp mill uses about 64 m^3 (17,000 gal) of water per ton of pulp produced, which is a decrease from approximately 379 m^3 (100,000 gal) per metric ton in the 1940s.(3) Today, the pulp and paper industry uses a lower volume of process water, recycles and reuses more water, and cleans water before releasing it, all in an effort to reduce costs as well as respond to increasingly strict environmental regulations.

Chemical Usage and the Cluster Rule

In 1995, according to the EPA,(5) the combined pulp and paper manufacturers released a total of 105.5 million kg (232.6 million lb) of toxics release inventory (TRI) chemicals into the air, water, or land. The top five highest amounts of TRI chemicals released in 1995 are listed in table 1.

Table 1. Top five highest amounts of toxics release inventory (TRI) chemicals released in 1995 by pulp and paper facilities.(5)

CHEMICAL	TOTAL NUMBER OF RELEASES	AVERAGE RELEASE PER FACILITY (in metric tons)
Methanol	62,657	358
Hydrochloric Acid	11,022	68
Ammonia	6,643	34
Sulfuric Acid	5,864	40
Chloroform	4,464	55

The environmental hazards related to the TRI chemicals led the EPA to create the pulp and paper cluster rule,(6) which limits the total allowable amount of chemicals released through process water, exhaust gases, and solid waste. Because of the cluster rule, operational processes are closed to a greater degree than in the past, creating more aggressive conditions and increasing corrosion-related problems.

AREAS OF MAJOR CORROSION IMPACT

The paper-making process consists of various steps, from pulp production to paper manufacturing, as illustrated in figure 4. The following sections discuss the impact of corrosion during the five major steps of this process: (1) pulp production, (2) pulp processing and chemical recovery, (3) pulp bleaching, (4) stock preparation, and (5) paper manufacturing.

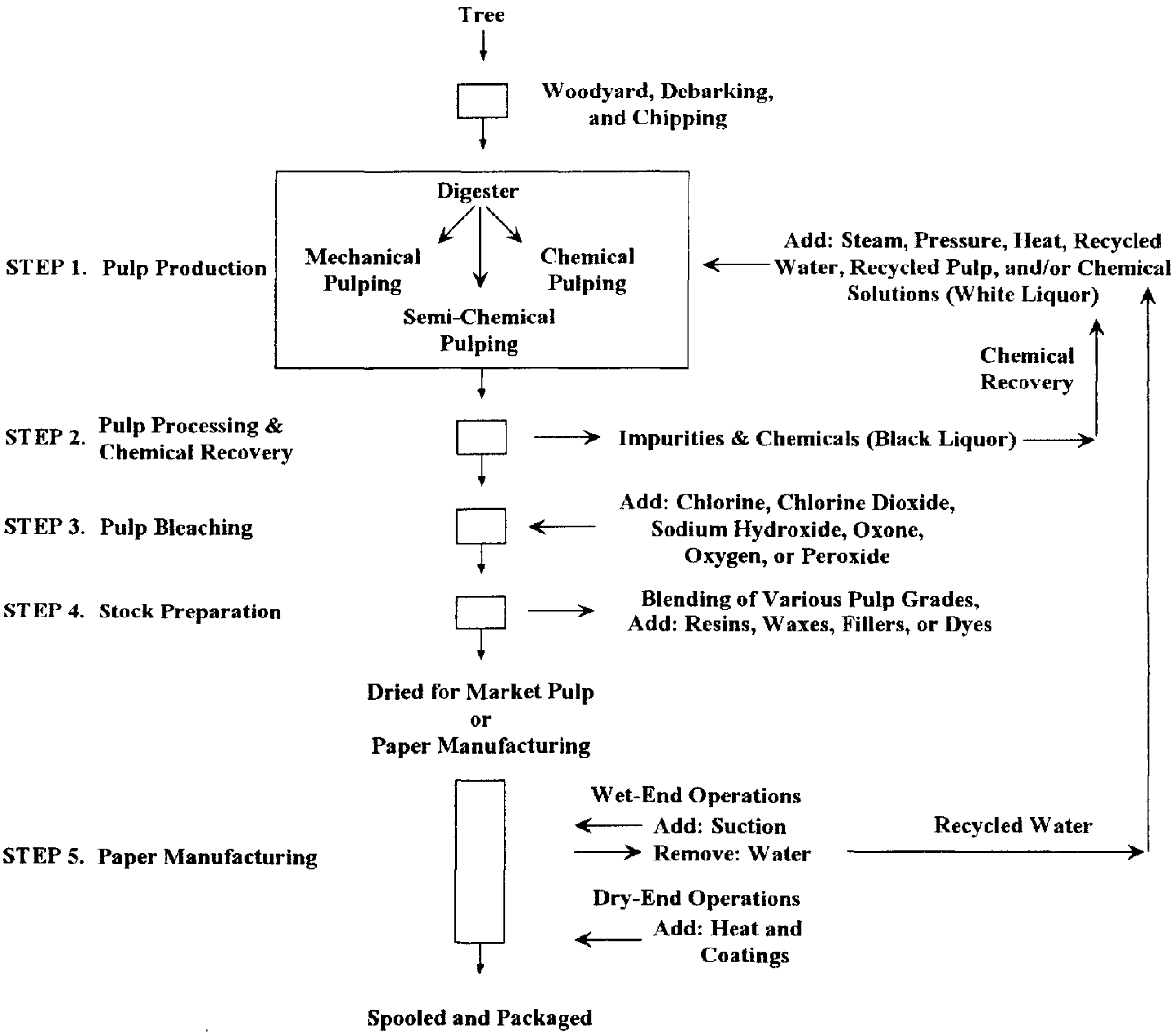

Figure 4. Flow diagram for the paper-making process.

Step 1. Pulp Production

There are several different methods of pulp production to make different strengths and grades of paper. The most common classifications are chemical, mechanical, or semi-chemical pulping techniques. The Lockwood-Post's Directory(1) reported that in 1998, 58.2 million metric tons (64.2 million short tons) of wood pulp were produced in the United States. Of that, 49.4 million metric tons [54.4 million short tons (84.7 percent)] were produced through chemical pulping techniques, 5.3 million metric tons [5.9 million short tons (9.1 percent)] were produced through mechanical pulping techniques, and the remaining 3.6 million metric tons [4.0 million short tons (6.2 percent)] were produced through semi-chemical pulping techniques (see figure 4). In the following paragraphs, these three pulping processes are described in more detail, based on the 1995 EPA Office of Compliance Sector Notebook Project for the pulp and paper industry.(7)

Mechanical Pulping

Mechanical pulping utilizes steam, pressure, and high temperatures instead of chemicals to tear the fibers. The fiber quality is greatly reduced because mechanical pulping creates short, weak fibers that still contain the lignin that bonds the fibers together. The presence of the lignin limits the amount that the pulp may be bleached because the lignin binds with the bleaching chemicals. Newspaper and paperboards are typical products of the mechanical pulping process. Mechanical pulping requires materials such as 300 series stainless steel to prevent corrosion.

Semi-Chemical Pulping

Semi-chemical pulping techniques use weak chemical solutions composed of sodium sulfite (Na_2SO_3) and sodium carbonate (Na_2CO_3) to help digest the lignin in the pulp. In addition to the chemical solutions, mechanical refining is used to separate the fibers.

Chemical Pulping

Chemical pulping uses various chemicals to produce long, strong, and stable fibers and to remove the lignin that bonds the fibers together. The chemicals used will vary depending on the type of chemical pulping used. In the United States, there are two main types of chemical pulping performed: Kraft (sulphate) pulping and sulfite pulping. The corrosion rate in these processes can be significant depending on the amount and kind of chemicals and the type of materials used.

Lockwood-Post's Directory(1) reported that chemical pulping is approximately 85 percent of the total pulping industry. Within this total, Kraft pulping produced approximately 83 percent [49.2 million metric tons (54.2 million short tons)] of the pulp processed in the United States in 1997. In this process, the lignin bonds of the pulp are dissolved by using alkaline sulfide in a digester at approximately 170 °C (338 °F) for 4 hours. Traditionally, carbon steel has been used as a material of construction. However, because of erosion from particles in the solution and corrosion from an increase in sulfur content due to system closures, stainless steel types 304L and 316L have been used as cladding for the carbon steel digesters. Although stainless steels are generally considered resistant to Kraft liquors, regular inspection must be performed because intergranular stress corrosion cracking (IGSCC) may occur in the heat-affected zone (HAZ) of the weldments.(8) Specific stainless steel grades used in Kraft pulping digesters and connecting pipes are duplex stainless steels 2205 and 2304 and austenitic stainless steel 312.(8)

The sulfite pulping process produced approximately 1.9 percent [1.1 million metric tons (1.2 million short tons)] of the pulp processed in the United States in 1997.(1) This acid pulping process uses cooking liquor of sodium bisulfite or magnesium bisulfite in a pulp digester with a pH of 3.(8) Type 316 stainless steel is normally used as a minimum alloy because the sulfur dioxide can degrade to sulfuric acid. Sulfuric acid can lead to corrosion of stainless steels depending on the temperature, pressure, and pH of the system. SCC has been observed in the HAZ of weldments in the pulp digesters in the presence of sodium hydroxide. Because of stress corrosion cracking susceptibility of the austenitic stainless steels, duplex stainless steel 2205 is often used in pressure vessels and tanks.

Step 2. Pulp Processing and Chemical Recovery

To further remove impurities and recycle the cooking liquor, also known at this stage as black liquor, the pulp is processed through a series of washes. The removal of the black liquor takes place in washers and is necessary to reduce the chemical costs of the liquor, generate energy from pulp residue burned in the recovery boiler, and prevent the cooking liquor from binding to the bleach chemicals. In addition, by recycling the cooking liquor back into the pulping process, environmental issues and costs are negated since there are no chemicals that must be discharged from the system.

Kraft Pulping Chemical Recovery

To recover chemicals from the black liquor, the slurry goes through a chemical recovery process, such as the Kraft pulping chemical recovery. The liquor passes through evaporators, recovery boilers, and causticizers to eventually produce white liquor.

The first step of chemical recovery is the evaporation process, which increases the concentration of solids from approximately 15 percent to more than 60 percent. The concentrated slurry contains approximately 50 percent organic solids and 6 percent total sulfur in the form of sodium sulfate (Na_2SO_4) and sodium thiosulfate ($Na_2S_2O_3$) and is placed into a recovery boiler. The organic solids are burned for energy while the inorganic process chemicals, also know as smelt, flow through the floor of the recovery boiler to be recausticized. Mills with high levels of closure operate at high levels of sodium chloride (NaCl). Typically, the NaCl concentration in black liquor is approximately 12 percent in closed systems.

Corrosion on the fireside of the recovery boiler is accelerated by the presence of reduced sulfur species. The hydroxide mixtures present within the black liquor are extremely corrosive to the recovery boilers, which are typically made of Type 304L stainless steels.(9) Several phenomena in the recovery section cause different forms of corrosion to occur simultaneously, including: (1) corrosion under ash build-up, (2) corrosion in the thin condensation layers, and (3) high-temperature metal/gas interactions.

1. Ash build-up on the heat exchanger tubes can occur in recovery boilers when the incineration of the liquid waste is incomplete. The deposited ashes decrease the efficiency of the heat exchanging process. Under-deposit corrosion may occur in the form of crevice corrosion or pitting.

2. Condensation can occur in the ductwork between the recovery boiler and the off-gas scrubbers when the hot gases cool down to a temperature below their flash point, before reaching the scrubber. Localized attack in the condensate phase can be very severe (>1,000 mpy)[3] and can be accelerated by the alternating process of condensation and revaporization. The concentration of corrosive species in the thin condensed layer is highest just before complete revaporization.

3. High-temperature metal/gas interactions in the recovery boiler include oxidation, carburization, and sulfidation. The kinetics of these processes vary with the concentrations of the burned black liquor waste and the temperature in the recovery boiler. High-temperature gaseous attack does not require an aqueous or molten salt electrolyte. Continued scale growth at the metal surface results in progressive metal consumption and decreased wall thickness of the boiler tubes and boiler walls.

Recausticizing

Recausticizing is the process used to transform the inorganic smelt recovered from the recovery boiler into white liquor so that the chemicals may be recycled. According to Westin,(10) the recycled inorganic chemicals are discharged as molten smelt from the recovery boiler and then dissolved using water to form green liquor. Any unwanted substances are precipitated out. Lime is then added to the clarified green liquor to produce sodium hydroxide (NaOH) from the remaining sodium carbonate (Na_2CO_3). The resulting solution (white liquor) contains sodium hydroxide, sodium sulfide (Na_2S), and a solid phase of calcium carbonate (lime mud). Before the white liquor is recycled back to the digester, the white liquor is clarified further to remove the lime mud.

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[3] 1,000 mpy = 1,000 mils per year = 1 in per year.

Sulfite Pulping Chemical Recovery

An alternative process is sulfite pulping chemical recovery. The chemical recovery system of sulfite pulping differs from that for the Kraft process discussed previously. The magnesium-based and calcium-based recovery systems are the most corrosive recovery systems for sulfite pulping.(11) Pitting and crevice corrosion under scale deposits are the major corrosion concerns. The sulfite pulping process contains greater amounts of sulfite (SO_3), hydrogen sulfide (H_2S), and hydrochloric acid (HCl) than those used in the Kraft pulping process. Because of the presence of these corrosive species, the internal portions of the recovery boilers and the evaporators are generally constructed of reinforced plastics, Type 316L stainless steel, Type 317L stainless steel, or nickel-based alloys. To prevent pitting and crevice corrosion, scale build-up should be prevented, wet-dry zones should be avoided, and chloride concentrations should be kept to a minimum.

Step 3. Pulp Bleaching

Pulp bleaching is performed on the pulp in order to increase its brightness. Bleaching is an extremely corrosive process that is executed under acidic conditions with strong oxidants such as chlorine, chlorine dioxide, sodium hydroxide, and hydrogen peroxide. In 1993, roughly half of the 65 metric tons (72 million short tons) of pulp used in paper production in the United States was bleached.(7)

Traditional Bleaching Techniques

The EPA(7) describes the bleaching process as normally having three to five stages in which the pH of the pulp is alternated between acid and alkaline conditions. During the acid cycle, chemical reactions between the bleach and the lignin bonds turn the pulp lighter in color. During the alkaline cycle, the reaction products from the acid stage are removed.

According to Thorpe,(8) chlorine dioxide has similar corrosivity to chlorine. Suitable materials for bleach washers using chlorine and chlorine dioxide are super austenitic 6 percent to 7 percent molybdenum stainless steels such as 25-4 SMo or 25-6 Mo. Routine cleaning, maintaining a high surface quality, and pickling of weldments with nitric and hydrofluoric acid help protect against corrosion.

Environmentally Friendly Techniques

In recent years, less chlorine and more sodium hydroxide have been used for bleaching. Currently, chemical pulps and the de-inking of secondary fibers are the primary users of chlorine bleaching techniques. The European paper and pulp industry has demonstrated success in using a totally chlorine-free bleaching process for selected pulp grades.(7) Such substitutes for chlorine are ozone, oxygen, and peroxide.

Duplex 2205 stainless steel is used to prevent SCC in the oxygen delignification process between 90 °C (194 °F) and 120 °C (248 °F).(8) However, bleaching processes that include ozone or peroxide generally require Type 316 stainless steels.(12)

Step 4. Stock Preparation

After bleaching, the pulp is processed into (liquid) stock that can be transferred to a paper mill. This processing is performed to get the required paper product and quality specified. It can include blending various pulps together, beating and refining, dispersion in water, and the addition of any wet additives such as resins, waxes, fillers, or dyes for coloring.(7)

Many pulp mills have a paper mill adjacent to them; therefore, transferring the products is not costly. The pulp mills, which produce market pulp, dry the pulp and transfer it by truck, train, or ship. The equipment used to store and transport the pulp can undergo crevice corrosion and pitting; therefore, they are usually completely or at least partially clad with Type 304L stainless steel.

Step 5. Paper Manufacturing

The creation of the paper is performed through wet-end and dry-end operations. These are discussed below.

Wet-End Operations

Using a paper production machine (see figure 5), the processed pulp is converted into a paper product.

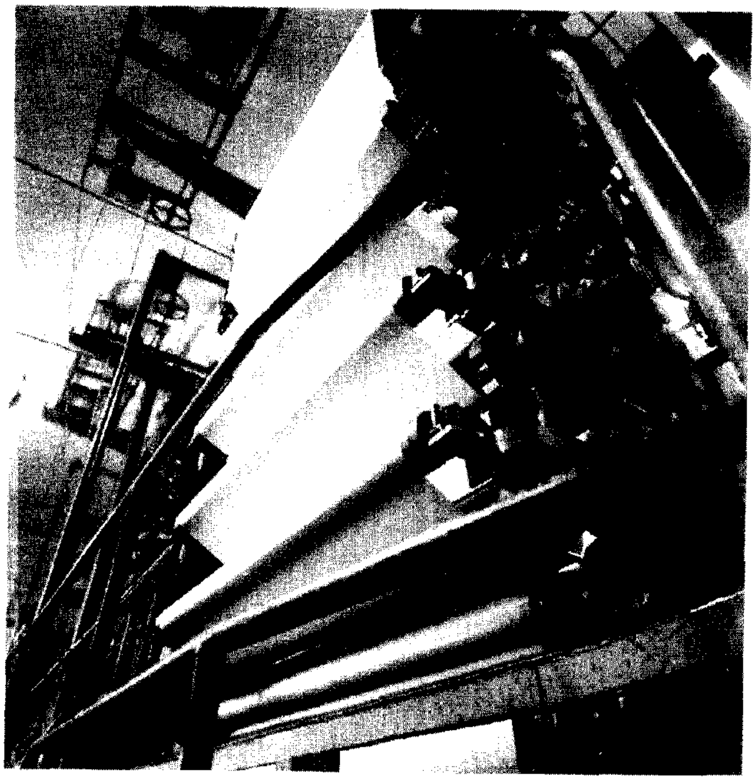

Figure 5. Paper machine used to transform processed pulp into paper product.

At the beginning of this stage, the water content of the paper is greater than 99 percent.(13) The most common machine utilized is the Fourdrinier paper machine.(7) In the wet-end operation, the slurry of pulp is deposited onto a continuously, moving belt that suctions the water from the slurry using gravity, vacuum chambers, and vacuum rolls. The continuous sheet then moves though additional rollers that compress the fibers and remove the residual water.

Thorpe(8) describes the traditional process as having a stock with a pH of 4.5 to 6. These paper machines process water, known as white water, which contains sulfate (200 to 500 ppm) and chloride (100 to 200 ppm), with little or no recycling. With recycling, the sulfate content can increase to 1,000 ppm, the chloride content can increase to 400 ppm, the dissolved organic compounds can increase to 1,000 ppm, and the temperature can vary between 50 °C (122 °F) and 60 °C (140 °F).

The suction rolls, which are used to remove the water from the paper as it begins its drying process, experience general corrosion, fatigue failures, pitting, and microbiologically influenced corrosion (MIC) due to exposure to stock and white water, deposits of paper fiber present in crevices, and bacterial growth. In addition, the inside diameter of the drilled holes within the suction rolls experience fatigue failures due to the presence of high stress concentrations. Studies have also shown that sodium thiosulfate ($Na_2S_2O_3$) in stock and white water systems can result in severe pitting.(14)

According to Thorpe,(8) the drilled holes in the suction roles, along with crevices and deposit sites, experience the growth of microbes as a result of high temperatures [40 to 50 °C (104 to 122 °F)], dissolved organic materials, and dissolved inorganic salts. Microbiological attack occurs beneath deposits on the microbiological slime and increases with the degree of closure of the paper mill.

To prevent general corrosion, fatigue failures, and MIC within the suction rolls, duplex stainless steels are used.(8) Furthermore, the suction holes in the rolls should remain unblocked and the applied load on the rolls should not exceed the design load. Regular inspection for cracking may prevent catastrophic failure and process outages.

Dry-End Operations

Following the pressing of the wet-end operations, the continuous sheet is compressed by steam-heated rollers to allow the fibers to begin bonding together. Coatings are then applied to add to the surface appearance before the sheet is spooled for storage.(7)

Corrosion problems within the paper machines include chloride pitting and crevice corrosion, thiosulfate pitting, and microbiological attack. A minimum of Type 304 stainless steel should be used.(8)

Determining Corrosion Cost for the Pulping Industry

In 1998, Singbeil(15-16) estimated the total corrosion cost for the pulping industry using cost data collected by Davy and Mueller in the period 1968 to 1971 and presented in 1974.(17) The (old) cost data were combined with the 1998 production volumes, paper prices, and production statistics from the Lockwood-Post's Directory.(1)

Table 2 shows Singbeil's results as calculated from the amount of various types of pulp produced in the United States, Canada, and the world, along with the corresponding costs. Singbeil's calculations do not include downtime as a result of corrosion-related problems. The data shown are presented in metric tons and 1998 U.S. dollars as calculated using an implicit price index of the gross domestic product (GDP) for Canada to correct for inflation. The comparison is made under the assumption of similar corrosion issues in 1975 versus 1998, while in fact, the process of paper-making has changed significantly. Today's corrosion issues are different from 1975 because of changed water and chemical usage.

Table 2. Estimated annual corrosion cost (1998 dollars) for the U.S., Canadian, and world pulping industry in 1975 and 1996, based on calculations by Singbeil,(15) using 1974 data from Davy and Mueller(17) and the *1998 Fact & Price Book.*(18)

UNITED STATES		**ESTIMATED CORROSION COST**		**1975 DATA**		**1996 DATA**	
		Per Short Ton*	**Per Metric Ton****	**Production*****	**Corrosion Cost**	**Production*****	**Corrosion Cost**
		1975 CAN$	**1998 U.S.$**	**Metric Tons x 1,000**	**1998 US$ x million**	**Metric Tons x 1,000**	**1998 US$ x million**
Mechanical		$1.45	$4.67	4,004	$18.7	5,372	$25.1
Semi-Chemical		$1.83	$5.89	3,103	$18.3	3,500	$20.6
Sulphate (Kraft)	Bleached	$5.08	$16.36	12,819	$209.7	28,751	$470.3
	Unbleached	$3.20	$10.31	13,814	$142.4	19,439	$200.3
Sulfite	Bleached	$3.71	$11.95	1,587	$19.0	1,172	$14.0
	Unbleached	$1.83	$5.89	332	$2.0	-	-
Other Pulp		$2.65	$8.53	1,241	$10.6	-	-
Market****		$3.20	$10.31	3,940	$40.6	7,584	$78.2
Total Corrosion Cost			**TOTAL**	**40,840**	**$461.2**	**65,818**	**$808.5**

WORLD		**ESTIMATED CORROSION COST**		**1975 DATA**		**1996 DATA**	
		Per Short Ton*	**Per Metric Ton****	**Production*****	**Corrosion Cost**	**Production*****	**Corrosion Cost**
		1975 CAN$	**1998 US$**	**Metric Tons x 1,000**	**1998 US$ x million**	**Metric Tons x 1,000**	**1998 US$ x million**
Mechanical		$1.45	$4.67	6,007	$28.0	10,973	$51.2
Semi-Chemical		$1.83	$5.89	233	$1.4	381	$2.2
Sulphate (Kraft)	Bleached	$5.08	$16.36	5,082	$83.1	10,798	$176.6
	Unbleached	$3.20	$10.31	1,315	$13.6	1,435	$14.8
Sulfite	Bleached	$3.71	$11.95	515	$6.2	331	$4.0
	Unbleached	$1.83	$5.89	1,443	$8.5	435	$2.6
Other Pulp		$2.65	$8.53	226	$1.9	-	-
Market****		$3.20	$10.31	4,888	$50.4	9,676	$99.7
Total Corrosion Cost			**TOTAL**	**19,709**	**$193.1**	**34,029**	**$351.2**

Table 2. Estimated annual corrosion cost (1998 dollars) for the U.S., Canadian, and world pulping industry in 1975 and 1996, based on calculations by Singbeil,(15) using 1974 data from Davy and Mueller(17) and the *1998 Fact & Price Book*(18) (continued).

CANADA		**ESTIMATED CORROSION COST**		**1975 DATA**		**1996 DATA**	
		Per Short Ton*	**Per Metric Ton****	**Production*****	**Corrosion Cost**	**Production*****	**Corrosion Cost**
		1975 CAN$	**1998 US$**	**Metric Tons x 1,000**	**1998 US$ x million**	**Metric Tons x 1,000**	**1998 US$ x million**
Mechanical		$1.45	$4.67	22,752	$106.2	34,420	$160.7
Semi-Chemical		$1.83	$5.89	5,651	$33.3	5,727	$33.8
Sulphate (Kraft)	Bleached	$5.08	$16.36	25,534	$417.7	73,966	$1,210.0
	Unbleached	$3.20	$10.31	21,149	$217.9	31,768	$327.4
Sulfite	Bleached	$3.71	$11.95	4,279	$51.1	3,550	$42.4
	Unbleached	$1.83	$5.89	3,386	$20.0	1,158	$6.8
Other Pulp		$2.65	$8.53	4,815	$41.1	12,227	$104.3
Market****		$3.20	$10.31	20,069	$206.8	37,895	$390.5
Total Corrosion Cost			**TOTAL**	**107,635**	**$1,094.2**	**200,711**	**$2,276.0**

* Davy and Mueller, "Pulp and Paper Industry Worldwide Corrosion Costs," *Pulp and Paper Industry Corrosion Problems, Vol. 1*, NACE, Houston, TX, 1974.

** Extrapolated using implicit price index of 4.234 GDP for Canada 1969–1998, assume $0.69 US$/CAN$; 1 short ton = 0.9072 metric ton.

*** Pulp production data for 1975 and 1996 extracted from *International Fact & Price Book 1998*, PPI, Belgium.

**** Market pulp defined as pulp of any grade produced for export – not destined immediately for paper or board production. It is excluded from other totals.

The 1975 survey by Davy and Mueller used data from 1968 to 1971 to estimate the cost of corrosion in 1975 Canadian dollars (CAN$) of the pulp and paper industry to be between CAN$1.60 per metric ton (CAN$1.45 per short ton) for mechanical pulp production and CAN$ 5.09 per metric ton (CAN$5.08 per short ton) for fully bleached Kraft pulp production. Singbeil(15) extrapolated this data using an implicit price index GDP of 4.234 for Canada as a measure of inflation. The estimated cost of corrosion in 1998 U.S. dollars (US$) for different kinds of pulp ranged from US$4.67 per metric ton (US$4.24 per short ton) for mechanical pulp to US$16.36 per metric ton (US$14.84 per short ton) for fully bleached Kraft pulp. The table shows that the annual estimated cost of corrosion for the pulping industry in the United States is $808.5 million

Determining Corrosion Cost as a Percentage of Maintenance

For the current research project, Singbeil(16) was asked which areas of the pulp and paper-making processes experience the highest corrosion rates. In addition, Singbeil was asked to estimate the annual cost of materials aging, including corrosion, repairs, replacement materials, preventive maintenance, and periodic inspection as a percentage of the total annual maintenance budgets. Dividing the pulp and paper industry into three major product areas, the estimates were 40 to 60 percent of the maintenance budget for the production of bleached market pulp, 35 to 50 percent of the maintenance budget for fine papers, and 25 to 30 percent of the maintenance budget for paperboard. The remaining portions of the maintenance budgets were attributed to regular wear and tear of the equipment.

These percentages can be used only as rough estimates because the severity of corrosion is dependent on the age, condition, and materials of the mill. Today's older pulp and paper mills still contain significant amounts of carbon steel. New mills are being constructed with greater amounts of stainless steel and corrosion-resistant materials. As a result, it is expected that less maintenance will be required in the future in order to overcome corrosion-related problems.

In a 1995 study published by Pulp & Paper International and the Maintenance Association of the Paper Industry (MAPI),(19) it was estimated that maintenance costs in the pulp & paper industry range from $28.70 per metric ton ($26.04 per short ton) to $143.65 per metric ton ($130.32 per short ton). The total cost of corrosion can be calculated by multiplying these values by the 1998 production statistics for fine papers, bleached market pulp, and paperboard, as reported in the Lockwood-Post's Directory(1) and the estimated corrosion costs as a percentage of the total maintenance costs (see table 3).

Table 3. Total annual corrosion costs for wood pulp, paper, and paperboard production as determined from 1998 production data,(1) total maintenance costs,(19) and estimates of percent corrosion costs in the total maintenance costs.(16)

PAPER PRODUCT TYPE	1998 PRODUCTION(1)		TOTAL MAINTENANCE COST(19)		CORROSION COST IN MAINTENANCE(16)		TOTAL	
	Short Tons	Metric Tons	$ / Short Ton*		%		$ x million	
	x 1,000		Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
Wood Pulp	64,183	58,226	$26.04	$130.32	40	60	$1,003	$5,019
Paper	44,777	40,621	$26.04	$130.32	35	50	$583	$2,918
Paperboard	49,719	45,132	$26.04	$130.32	25	30	$389	$1,945
TOTAL							**$1,974**	**$9,881**
TOTAL 1998 SALES = $164.9 BILLION					**FRACTION**		**1.20%**	**5.99%**
AVERAGE: $5.928 BILLION								

*$26.04 / short ton = $28.70 / metric ton; $130.32 / short ton = $143.65 / metric ton.

The table shows that the total annual corrosion costs for the pulp, paper, and paperboard industry, as determined as a fraction of the maintenance cost, ranges from $1.97 billion to $9.88 billion (average: $5.928 billion). These estimates are 1.20 percent and 5.99 percent, respectively, of the total 1998 sales of $164.9 billion for the entire U.S. pulp and paper industry, as reported in the Lockwood-Post's Directory.(1) In comparison, Singbeil calculated the cost of corrosion in the pulping industry at only $808.5 million (see table 2).

CORROSION CONTROL METHODS

Corrosion control methods in the pulp and paper industry include equipment design, process design, and the use of corrosion inhibitors. Using any of these techniques reduces or eliminates corrosion within a system.

Equipment Design

Pulp and paper equipment design consists of proper material selection in conjunction with the process chemicals and the prevention of stagnant process fluids in the equipment.

Low-alloy carbon steel would be the material of choice if corrosion were not a problem; however, for many processes, stainless steel and even nickel-base and titanium alloys are required for better performance in corrosive environments. Current U.S. pulp and paper mills are constructed of about one-third carbon steel and two-thirds stainless steel.(12) Within the group of stainless steels, there are several alloy grades. Their relative cost is dependent on the concentration of the major alloying elements (Cr, Ni, Mo, etc.), the volume produced, and the form in which it is supplied (tube, pipe, plate, or block). In general, stainless steels are 10 percent to 20 percent more expensive than low-alloy carbon steels.

Stagnant and slow-flowing process fluids in pulping equipment can occur in crevices and water traps. Fluid stagnation often leads to an increase in concentration of the chemicals and the local creation of a severe environment in which pitting and crevice corrosion may occur. By designing drain holes and easy access to the equipment, stagnant solution can be removed. Slow-flowing fluids containing a solid fraction of pulp may deposit a layer of pulp on the bottom of piping and reservoirs. Under-deposit corrosion mechanisms, such as crevice corrosion and pitting, may occur. If equipment is designed with sufficiently fast and/or turbulent flow, deposit formation can be controlled. In addition, regularly scheduled cleaning and proper equipment maintenance can prevent the buildup of pulp and decrease the amount of stagnant solutions.

Process Design and Corrosion Inhibitors

Corrosion rates in mill equipment also depend on the chemical composition within each section of the process. The chemical composition varies from mill to mill depending on the processes involved, the closure of the mill's systems, the desired paper grade, the speed of the process, and the amount of pulp or paper being produced.

In general, the corrosivity of an environment will increase when the temperature is increased, when the pH is reduced, when the dissolved solids content increases, and when the chloride and sulfur compound concentrations are increased. Therefore, by monitoring the process and maintaining the proper temperature, pH, dissolved solids content, and chloride and sulfur compound concentrations, the amount of corrosion can be controlled.

In some processes, corrosion inhibitors can be added to the process to mitigate corrosion. Continued measurements of the process chemistry should be made to ensure that the correct dosage of the added corrosion inhibitor is maintained.

Preventive strategies for corrosion control in the pulp and paper industry include the verification of average corrosion rates, using weight loss coupons, regular inspection, and preventive maintenance. Preventive strategies are considered during the design and construction phases when new equipment is made, or when existing equipment is refurbished or repaired. Corrosion prevention techniques focus on minimizing the initiation of corrosion altogether, while corrosion control techniques are used to minimize the propagation of ongoing corrosion.

Weight Loss Coupons

Weight loss coupons are commonly used as a means to measure the average corrosion rate in a process or in the atmosphere of a pulp or paper plant. This technique is relatively cheap and easy to use, because all it requires are some pieces of metal that are weighed, exposed for a period of time, and weighed again. Using the difference between the weight of the coupon before and after the test, the average corrosion rate can be calculated. An advantage of this technique is that several coupons of different materials can be exposed simultaneously.

By performing weight loss tests, engineers can estimate the corrosiveness of an environment over a period of time. If the corrosion rate is determined to be too high, preventive measures can be taken to prolong the remaining life of the equipment. The preventive actions can include the addition of a corrosion inhibitor, a change in the process, an application of anti-corrosion coatings, or the addition of a cathodic protection system.

Inspection and Preventive Maintenance

An additional method to monitor the corrosion rate is through regular visual inspection of all parts of the equipment that are exposed to corrosive environments. These inspections use nondestructive examination (NDE) to reveal corrosion pits, crevice corrosion, or wall thinning before they will affect or stop the production process or degrade the paper to below its product quality specifications.

Regular inspection is performed as part of the maintenance program in plants. The results of the inspections are used to plan equipment repairs during scheduled shutdowns and to take action to maintain optimum production quality and quantity.

CORROSION MANAGEMENT

In dealing with corrosion issues, several philosophies have been developed to determine the most cost-effective solutions to continue production in order to maximize profit. These philosophies include a "do nothing" approach, a "do everything" approach, and a "do what it takes" approach.

By doing nothing to prevent corrosion problems, machinery is essentially used until it fails. As a result, the failed equipment must be completely replaced, causing high capital costs, loss of production due to downtime, lower quality products, and even catastrophic failure in the worst case scenario. The "do nothing" approach, which is often found within the pulp and paper industry, is not a cost-effective solution in the long run. For example, in the case of a northeastern paper mill's bleach plant that produced 1,322 metric tons (1,200 short tons) per day, the cost of a complete shutdown was estimated to be $240,000 / operating day using the industry standard of a $220 contribution / metric ton ($200 contribution / short ton).(20)

The "do everything" approach is to prevent corrosion as much as possible. This includes monitoring corrosion and using protective techniques such as cathodic protection, inhibitors, and protective coatings. This philosophy is also not very cost-effective due to the high investment costs involved.

In many mills, corrosion management is concentrated around the maintenance groups. Maintenance engineers deal with all outages, replacements, inspections of the equipment, and corrosion as an integrated part of their work. The objective of their work is to ensure that production runs continuously 24 hours per day, 7 days per week. Their primary concerns are safety, equipment integrity, and product purity. Examples of corrosion affecting production are corrosion products polluting the paper and corrosion of rolls scarring the sheets of paper. Corrosion of components may result in fractures or leaks in the machines, causing production loss and safety hazards. Critical equipment such as pressure vessels, boilers, and tanks are usually inspected using nondestructive examination (NDE) to determine repair and replacement schedules.

Some larger mills employ one or more in-house corrosion specialists or metallurgists to deal with corrosion problems. In addition, they contract out to obtain the assistance of consultants that specialize in corrosion in the pulp and paper industry. In recent years, material properties expertise has become the responsibility of the equipment suppliers so that the individual mills can rely on the specified equipment design life.(19) Finally, organizations such as the Technical Association of the Pulp and Paper Industry (TAPPI) and the National Association of Corrosion Engineers (NACE) offer assistance to overcome issues common to the pulp and paper industry.

CHANGES FROM 1975 TO 2000

Over the past 25 years, processes and the thought put into those processes have changed dramatically. Today's digital world has had a tremendous effect on the required production of the pulp and paper industry. In addition, recycling and environmental issues have forced the pulp and paper industry to change their processes. Finally, the competition within the pulp and paper industry has changed the way companies solve their maintenance issues.

The Digital World

The increased use of computers, the internet, electronic documents, and data storage has two seemingly opposing effects. The fact that data are transmitted in electronic format reduces the amount of paper used for printing reports or letters. On the other hand, the increased use of computers and the easily accessible "print" button, while printing paper is relatively inexpensive, increases the need for greater amounts of products from the pulp and paper industry.

A second phenomenon that has increased the use of paper over the last 25 years is the dramatic increase in commercial mailings. These everyday letters and brochures, which are delivered to almost every residence and business and offer various services and products, are commonly called "junk mail." This term shows the low value that people attribute to these paper products, while their use is widespread.

Recycling and Environmental Issues

The use of chemicals and the use of large amounts of water in paper production are under increased scrutiny in recent years. Due to this scrutiny, closed-loop system processes are more frequent. Closed-loop system processes lead to an increase in corrosion-related problems because of increased temperatures and larger concentrations of chemicals present in the closed-loop process streams. At the same time, recent developments in bleaching processes using ozone, oxygen, and peroxide have reduced the amount and concentration of chlorine products used. These changes actually tend to decrease the corrosivity of the process streams in the bleaching operation, thereby, allowing lower grades of stainless steel to be used.

Older mills have been converted for new processes. For example, due to the use of different chemicals in modern pulping processes, a variety of corrosion problems are observed that were not observed before. Chlorine-free bleaching processes are being developed to minimize dioxins based on chemicals such as O_2, O_3, ClO, H_2O_2, and peracetic acid.

Recovered Paper

Another topic of importance to the paper and pulp industry is recycling. With the development of de-inking technologies, 45 percent of all paper used by Americans was recovered in 1998.(21) According to the EPA,(7) the American Forest and Paper Association (AF&PA) has set a goal of 50 percent recycling by its members in 2000. Despite these percentages, the U.S. utilization of secondary fibers, which are taken from recycled paper, is only approximately 30 percent of the total fibers used for the production of paper. In comparison, resource-deficient countries, such as Japan, approximate 50 percent secondary fiber usage of the total fibers used for the production of paper. As decontamination technology progresses, secondary fibers will play an increasing role in the supply of paper.

Competition Issues

The competition within the pulp and paper industry has required mills to produce more product than ever before at a faster rate at less cost. In order to keep an advantage over other operating mills, secrecy and lack of information have become issues.

Maintenance's role in the pulp and paper industry has also changed.(19) The monitoring of corrosion rates, the implementation of preventive measures, and the adjustment of the production processes to minimize the severity of corrosion are actively being pursued.

CASE STUDY FOR THE PULP AND PAPER INDUSTRY

Metsä-Rauma Pulp Mill – Totally Chlorine-Free Production

The objective of this case study is to show that changes in production methods affect the optimum material selection for production equipment and change corrosion issues. In new construction, such as the Metsä-Rauma pulp mill in Finland, the best corrosion design can be implemented. However, existing plants must be modified to accommodate changing corrosion conditions.

One example of different materials of construction is the replacement of carbon steel with stainless steel, which has been occurring in the United States over the last two decades. Because of the high cost to replace equipment and because of the fact that current carbon steel equipment may still operate for a longer time before reaching its useful life, mills continue to operate with corroding equipment as long as possible. In many cases, it is more economical to maintain and operate aging mills than to pay for the cost of an entirely new mill with the most modern anti-corrosion design.

In March 1996, a 570,000-metric ton/year (628,000-short ton/year) capacity, single-line, softwood pulp mill was opened in Metsä-Rauma, Finland. The Metsä-Rauma facility produces bleached softwood Kraft pulp that is manufactured totally chlorine-free (TCF) by using only oxygen, ozone, and hydrogen peroxide. According to Pulp and Paper International, the capital costs invested in the mill were approximately $550 million, the construction time was 22 months, and the mill has 180 employees. Metsä-Rauma was built adjacent to the UPM-Kimono paper mill, which helped to reduce the overall cost of the mill by sharing resources and equipment.

The Metsä-Rauma pulp mill is the first TCF pulp mill in the world. This is a different type of mill than the previously used elemental chlorine-free (ECF) pulp mill. The capital cost of the TCF Metsä-Rauma mill was approximately $17 million less than the construction of a similar ECF mill would have been because the absence of chlorine dioxide allowed for a simpler design of the bleaching plant and a smaller volume reactor. Stainless steels were used for construction of the TCF bleaching plant instead of the glass fiber-reinforced plastic or titanium that had been used in ECF mills.(22) In fact, the facility is one of a kind as it is made entirely of stainless steel.(12)

With the mill's aim of gradually closing the bleaching water cycles, the water consumption and effluent discharges are less than one-third of those in modern conventional mills. Metsä-Rauma's water consumption of 16.5 m^3/metric ton (15 m^3/short ton) of pulp includes 11 m^3/metric ton (10 m^3/short ton) for cooling water.(22) By using the proper grades of stainless steel for each process, the maintenance costs associated with equipment made from carbon steel will be significantly reduced. For comparison, it is estimated that a new state-of-the-art integrated mill (pulp and paper together) would cost approximately $1 billion.(3)

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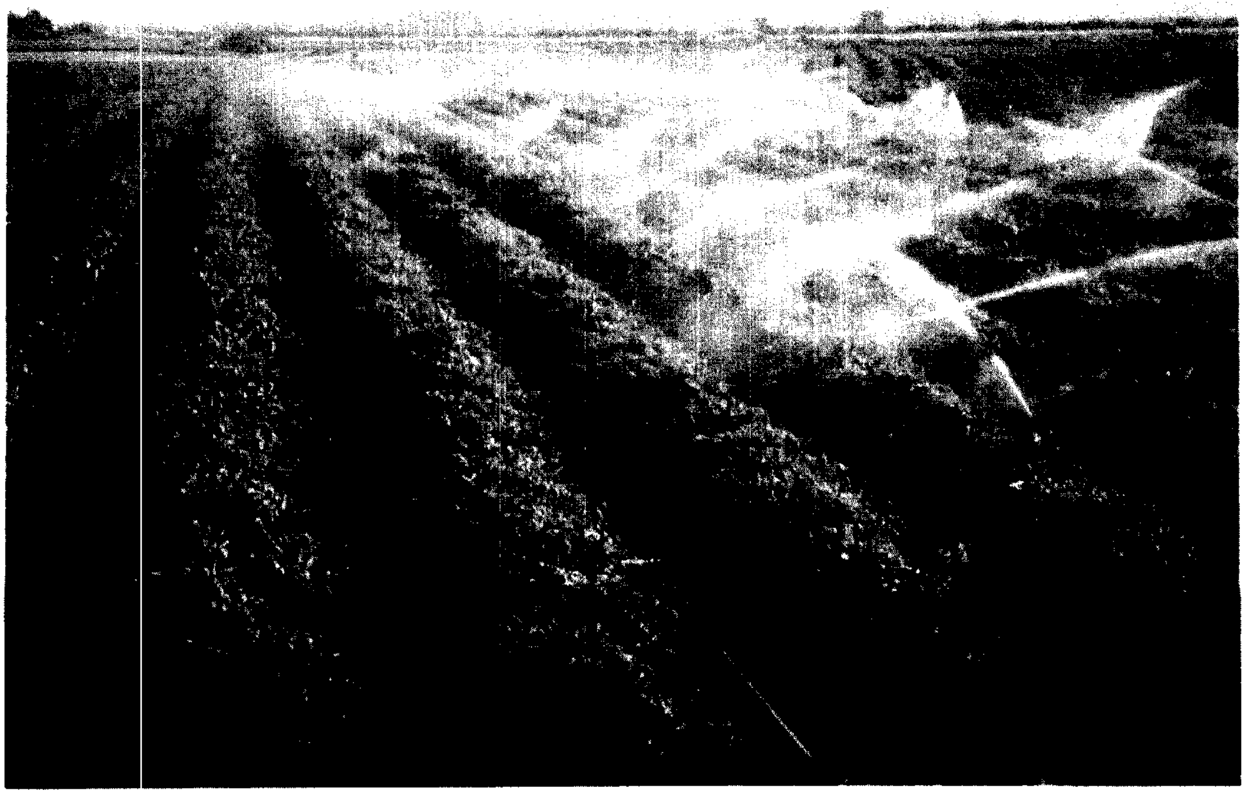
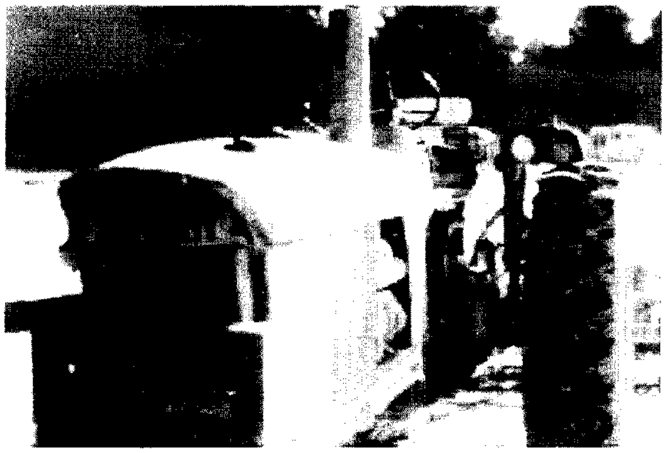
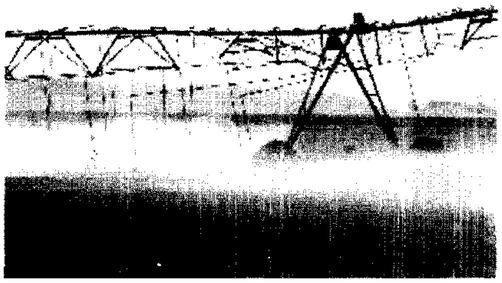
APPENDIX X

AGRICULTURAL PRODUCTION

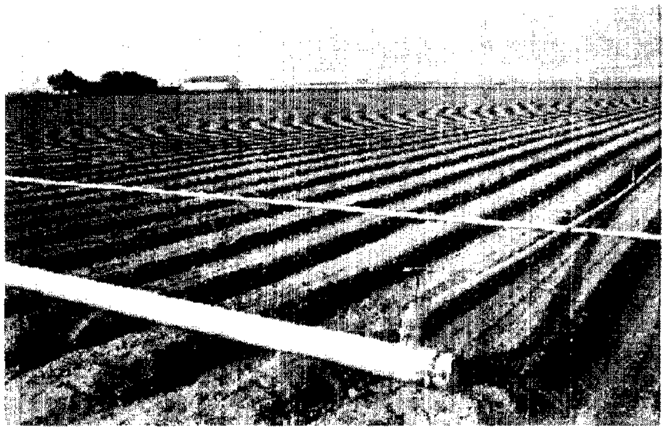




Corroded tractor



Irrigation systems



Produce harvesting

Barn with two tanks and combine

APPENDIX X

AGRICULTURAL PRODUCTION

IVELISSE TUBENS[1] AND MICHIEL P.H. BRONGERS[1]

SUMMARY

Based on the 1997 Census, the total value of farm machinery and equipment is approximately $15 billion per year. The two main reasons for replacing machinery or equipment include upgrading old equipment and substitution because of wear and tear. Failure due to corrosion damage would be grouped in this category; however, national data on the types of failures occurring in farm equipment were not found. Discussions with people in this industrial sector resulted in an estimate of corrosion costs in the range of 5 percent to 10 percent of the value of all new equipment. This means that the total cost of corrosion in the agricultural production industry is in the range of $748 million to $1.498 billion per year, with an average of $1.123 billion per year.

Corrosion control and prevention can be accomplished by keeping equipment clean and dry after each use, applying corrosion-resistant materials or materials with a corrosion allowance, applying external coatings (paints) or internal lining systems, or using cathodic protection. Strategies for maintaining and optimizing inspection programs for agricultural equipment (i.e., minimizing safety concerns for fertilizer tanks) with a high corrosion risk need to be developed. Development of new and improved inspection techniques is required to ensure the integrity of agricultural equipment.

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[1] CC Technologies Laboratories, Inc., Dublin, Ohio.

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SECTOR DESCRIPTION

According to the 1998 Economic Census, "agricultural operations" is defined as producing livestock, poultry, or other animal specialties and their products, and producing crops, including fruits and greenhouse or nursery products. According to the U.S. Department of Agriculture (USDA) National Agricultural Statistics Service (NASS), there are 1,911,859 farms in the United States.(1) The eight major U.S. field crops include corn, sorghum, barley, oats, wheat, rice, upland cotton, and soybeans. The major livestock are poultry, cattle, hogs, and sheep.

Figure 1 illustrates the 1997 farm production expenditures by percentage in the United States. The percentage of total expenditures spent on chemicals, fertilizer, and seeds, and supplies, repair, and construction are 14.6 percent and 10.2 percent, respectively. In 1997, approximately $11 billion was spent on fertilizer (see figure 2). There was an increase in fertilizer expenditures of 27 percent in the period from 1992 to 1997. The consumption of fertilizer has increased, causing more corrosion problems in fertilizer tanks and farming equipment. According to agricultural industry experts, chemicals and fertilizer are one of the major causes of corrosion in the agricultural industry;(2-3) therefore, it can be inferred that corrosion costs are mainly due to chemical usage on agricultural equipment.

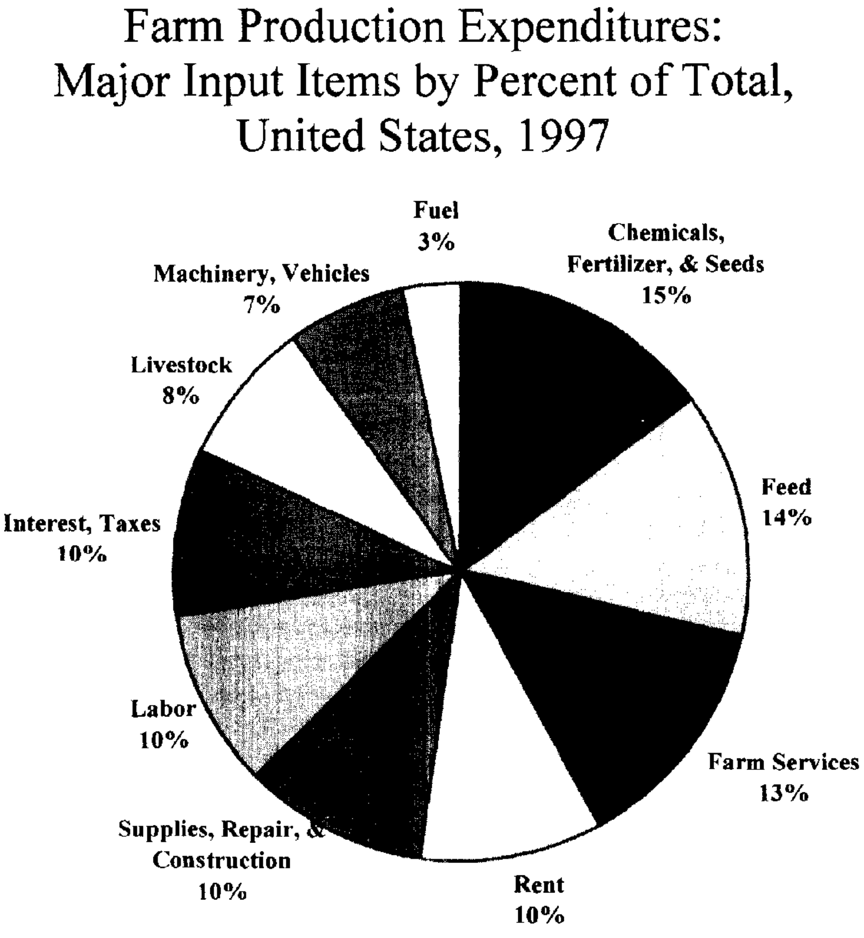

Figure 1. Illustration of 1997 major input items and expenditures in farm production in the United States, according to the USDA National Agricultural Statistics Service.(4)

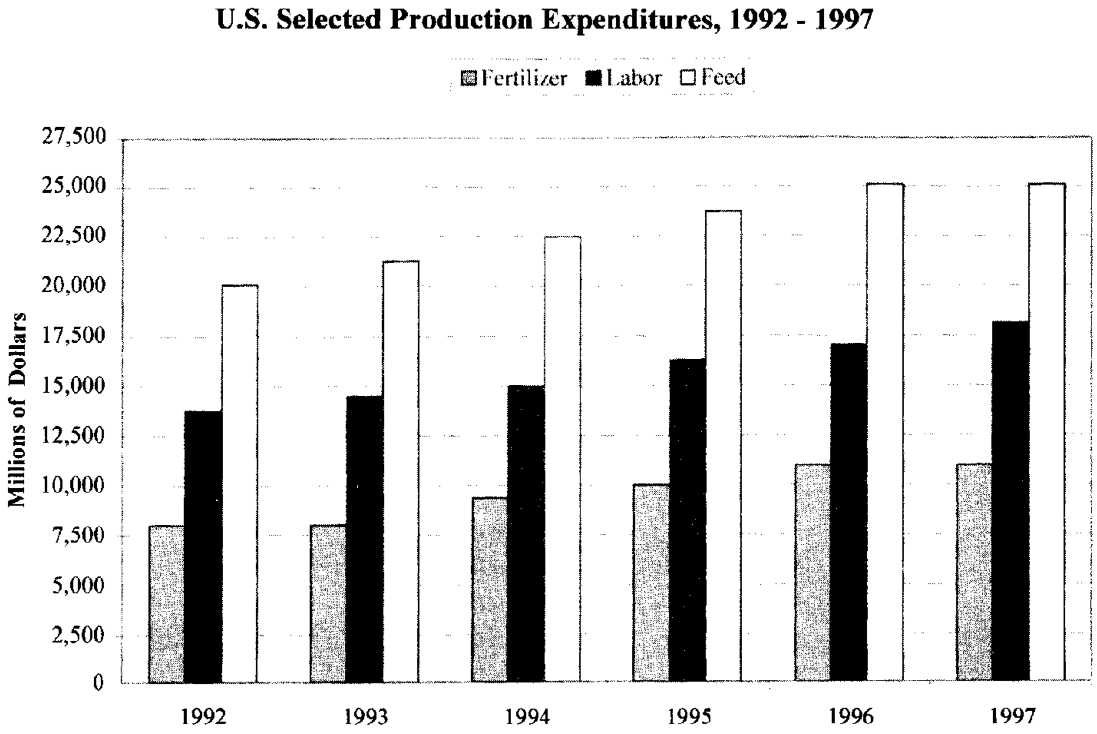
U.S. Selected Production Expenditures, 1992 - 1997

Figure 2. U.S. farm production expenditures for fertilizer, labor, and feed from 1992 to 1997, according to the USDA National Agricultural Statistics Service.(4)

AREAS OF MAJOR IMPACT

Agricultural Fertilizers

Corrosion problems occur in plumbing systems of agricultural sprayers when proper maintenance is ignored. Corrosion of sprayer components can be prevented by utilizing rubber components (i.e., gaskets, diaphragms, hoses, etc.) or by using motor oil in the final flushing of the sprayer.(5) An alternative to using motor oil is to use automotive antifreeze with a rust inhibitor. Furthermore, as many components as possible that are in contact with the spray solutions should be made of chemically resistant materials such as ethylene vinyl acetate (EVA) and ethylene propylene dione monomer (EPDM).

The major fertilizer used in agricultural is urea ammonia nitrate (UAN). Chemicals such as anhydrous ammonia, used in farming fertilizers, are very aggressive. Inserve is an inhibitor added to anhydrous ammonia, which inhibits the biological conversion of ammonia to nitrate.(2) Nitrate, when formed, could be corrosive.

Fertilizer Tanks

Fertilizer tanks are generally fabricated from ASTM A36 carbon steel. The tanks are welded externally and internally to prevent crevices and to provide maximum resistance to corrosion. However, they are susceptible to pitting and erosion-corrosion in the acetic solutions used in fertilizers.

Milking Process Systems

Moisture content, sanitizing chemicals, and animal respiration in milking parlors causes problems on milking parlor ceilings. In order to prevent corrosion, ceilings are constructed from painted carbon steel. Replacement of a parlor ceiling costs approximately $5,000 to $10,000.(6)

Milking processing units are constructed from stainless steel and contain rubber-lined inflations in which the milk is collected. Corrosion problems occur due to hot water cycles and wash water used to clean the equipment. Replacement of a milking processing unit can cost approximately $5,000 to $10,000.(7)

Agricultural Fumigants

Agricultural fumigants, such as methyl bromide and phosphine, are used to disinfect food-processing facilities. They are used to control insects, nematodes, weeds, and pathogens in more than 100 crops, in forest and ornamental nurseries, and in wood products. They are primarily used in soil fumigation, post-harvesting protection, and quarantine treatment.

The use of phosphine as an alternative to methyl bromide has been a controversial issue. In 1999, the Agricultural Research Service (ARS) had a research budget of $14.4 million for seeking alternatives to methyl bromide.(7) Alternative chemicals such as phosphine have been proposed; however, phosphine in combination with carbon dioxide, heat, and humidity is corrosive to copper and electronic and electrical equipment in food-processing facilities. The corrosion kinetics of phosphine and copper are not well understood. Predictive models of potential damage will permit the development of preventive strategies that will allow continued fumigation with phosphine, but will prevent or mitigate corrosion damage to copper and other electrical conductors.

Electrical Systems in Agricultural Buildings

Agricultural buildings that house livestock require special care in selecting wiring materials, wiring methods, and electrical equipment because of corrosive dust, gases, and moisture. Corrosion of metallic conduit, boxes, and fixtures frequently leads to electrical system failure. Boxes and fixtures made of a non-metallic material or corrosion-resistant stainless steel, i.e., non-magnetic, are recommended for all agricultural buildings and are required in any buildings that house livestock or contain corrosive dust. Accelerated corrosion due to condensation occurs on electrical panels that have not been properly designed.

Agricultural Vehicles

According to the 1997 Economic Census Vehicle Inventory and Use Survey (VIUS),(8) 15 percent of all trucks (3.4 million of the total 72.8 million trucks) have their primary use as agricultural vehicles. The survey further noted that the specified primary products are farm products for 1.25 million trucks, live animals for 0.52 million trucks, and animal feed for 0.43 million trucks.

COST OF CORROSION

Determining the cost of corrosion in the agricultural production industry is not an easy task. Economic data for this industry generally include national dollar-amount values of sold products, such as vegetables or meat, but the information is that most farms are owned and operated by individual farmers and their families. Although information on the causes of equipment failure may be known for each farm, no national organization was identified to collect this information and make the information available to the general public. The result is that each farmer is faced with solving his own corrosion problems without having a resource to help in the selection of a corrosion control method that would be the best economical solution.

One method to estimate the national cost of corrosion uses the total annual value of new farm machinery and equipment. According to the 1997 Economic Census *Farm Machinery and Equipment Manufacturing* report,(9) the value of product shipments totaled $14.97 billion. This includes farm-type two-wheel and four-wheel drive tractors with or without attachments; farm dairy equipment; planting, seeding, and fertilizing machinery; harvesting machinery; haying machinery; parts for farm machinery; farm plows, harrows, rollers, pulverizers, cultivators, and weeders; commercial turf and grounds care equipment; and other farm machinery and equipment. Table 1 summarizes the 1997 shipment value for each of these categories.

Table 1. Summary of 1997 shipment values of farm machinery and equipment, according to the 1997 Census.

PRODUCT CLASS	1997 SHIPMENTS VALUE	ASSUMED CORROSION COST	
	($ x million)	5%	10%
Farm-type 2- and 4-wheel drive tractors	3,857	193	386
Diary equipment, sprayers, dusters, elevators, and blowers	745	37	75
Planting, seeding, and fertilizing machinery	1,080	54	108
Harvesting machinery	2,970	149	297
Haying machinery	664	33	66
Parts for farm machinery (sold separately)	1,425	71	143
Plows, harrows, rollers, pulverizers, cultivators, and weeders	609	30	61
Other farm machinery and equipment	1,837	92	184
Commercial turf and grounds care equipment	1,340	67	134
Farm machinery and equipment (not specified by kind)	439	22	44
TOTAL	**$14,966**	**748**	**1,498**
	AVERAGE: $1.123 billion per year		

To analyze the total shipment value further, the reasons for buying a new piece of machinery or equipment must be determined. The two main reasons for replacing machinery or equipment include upgrading old equipment and substitution because of wear and tear. Failure because of corrosion damage would be grouped in this last category. In discussions with people involved in agricultural research and manufacturing, it became evident that no actual survey data with percentages on the types of "wear and tear" are available; therefore, an assumption as to this percentage was made as being in the range of 5 to 10 percent of the total value of new equipment and machinery shipments, with a 7.5 percent average. These percentages were included in table 1 so that an estimate of the cost of corrosion in the agricultural production industry could be determined. Although opinions on the accuracy of these assumed that percentages may vary, the authors of this sector analysis agreed that the estimate of the corrosion cost in the range of $0.75 to $1.5 billion per year is probably in the right order of magnitude. The average of this cost range is $1.1 billion per year.

CORROSION CONTROL METHODS

Corrosion control and prevention can be done by keeping equipment clean and dry after each use, by applying corrosion-resistant materials or materials with a corrosion allowance, by applying external coatings (paints) or internal lining systems, or by using cathodic protection.

Agricultural production occurs by working or using farmland; therefore, equipment used to work the fields is exposed to the climate and weather of that area of the country. Water from rain or wet products may collect in the corners or ridges of the equipment and may cause corrosion. Also, at locations where mud can build up, or where waste from the vegetables, cattle, or feed can stay behind, corrosion may occur.

Another location of corrosion concern are fuel and fertilizer storage tanks on farms. The sector description on hazardous materials storage (Appendix G) describes the problems associated with aboveground storage tanks (ASTs) and underground storage tanks (USTs) in more detail. In this sector description, it will only be mentioned that corrosion of tank bottoms, walls, roofs, and roof structures can pose a danger to their structural integrity. Corrosion may cause leaks that result in loss of product or pollution of the soil and water around a tank. Of course, fuel leaks and soil pollution should be prevented, especially in a farm environment, where production depends on good soil quality.

Keeping Equipment Clean / Dry

An obvious method of corrosion control is to keep equipment and machinery clean and dry after each use. Prevention of corrosion under deposits such as mud or product waste can prolong the life of machinery. Also, the exposure to bacteria, fertilizers, cleaning compounds, and sanitizing solutions should be minimized. In addition, the removal of mud will decrease the wear and possible erosion-corrosion on engines and moving components, because there is less sand between the moving parts.

Material Selection

Corrosion-resistant materials can be selected for farming equipment and machinery, but the added cost of high-alloy components is often restrictive. Where possible, painted carbon steel is the primary material of choice for most machinery and equipment, because of its low cost and relative ease of maintenance. Nickel alloys are used for augers, which provide resistance to corrosion, abrasion, and wear. Stainless steel fittings are used in equipment exposed to corrosive fertilizers, or in milking equipment. Fiber-reinforced polymer storage tanks can be used for water storage or to store relatively small quantities of chemical products used for farming.

External Coatings / Paints

Painting the exposed external surfaces of equipment provides corrosion protection and improved appearance. Selection of the coating type depends on the use of the equipment. External coatings must be able to withstand the effects of abrasion, weather, and ultraviolet light. Surface preparation and application of paint is an easy method to prevent or slow down the effects of corrosion. Farmers can do this work themselves, repairing aging equipment on an as-needed basis.

For underground structures, such as USTs, corrosion control of the external surfaces can be achieved with a combination of cathodic protection and a dielectric coating. However, an external coating must be applied when the tank is new. A buried tank cannot be retrofitted with an external coating unless it is removed from the ground.

Internal Linings

Internal corrosion protection, where required due to contamination or corrosive products in storage tanks, is commonly maintained with an internal liner, sometimes in combination with galvanic cathodic protection. Internal coatings are specified in order to prevent internal corrosion and to prolong the operation life of tanks. A specific example of internal linings is their application on mild steel fertilizer tanks. They are used primarily for corrosion protection from both fumes and condensation in the vapor space and immersion exposure to the stored liquid chemicals.

Cathodic Protection

Aboveground tanks that are subject to a stored liquid and that can have a contaminated water layer should be internally coated and cathodically protected on the bottom and partially along the wall. The external bottom corrosion of site-fabricated tanks (most tanks greater than 4 m in diameter) can be controlled with a combination of select sand/concrete foundation pads, impervious liners, and cathodic protection (CP).

The design of CP for new or existing ASTs and USTs includes consideration of the proximity to other metallic structures and existing CP systems, the type of grounding, the estimated remaining life of the tank, the type and temperature of the stored product, the amount of product stored, the cycling rates, the method of tank bottom plate construction, the type of tank foundation, the type of secondary containment, if any, and the back-fill soil characteristics. There are two types of CP: (1) sacrificial anode CP, by zinc or magnesium ribbon or ingot anodes, and (2) impressed-current CP, using perimeter, deep-buried, angle-drilled anodes or vertical, loop, or string under-tank anodes.

CORROSION MANAGEMENT

The U.S. Environmental Protection Agency reports that an independent on-farm assessment program is currently being developed. The on-site assessment will include a detailed review of all production operations and waste management practices of a facility and a thorough inspection of all facilities. Some practices and conditions assessed will include the condition of water recycle lines and pumps; condition and design of flush equipment and manure piping; construction materials and age of structure; and condition and maintenance of piping, check valves, and other transfer equipment.(10)

The American Petroleum Institute (API) performs annual inspections on fertilizer tanks. The inspectors visually inspect corrosion conditions, coating conditions, and welds. Before an inspection, the tank must be cleaned in order to remove hazardous gases or chemicals. A basic API inspection for a standard tank can cost approximately $3,000 to $5,000.(3)

The National Electrical Code (NEC) provides minimum standards and recommended practices to ensure safety and reduce the risk of electrical system failure. The code provides proper installation procedures and equipment materials required for corrosion prevention and safety. Corrosion must be minimized in agricultural buildings because it may lead to electrical failures.

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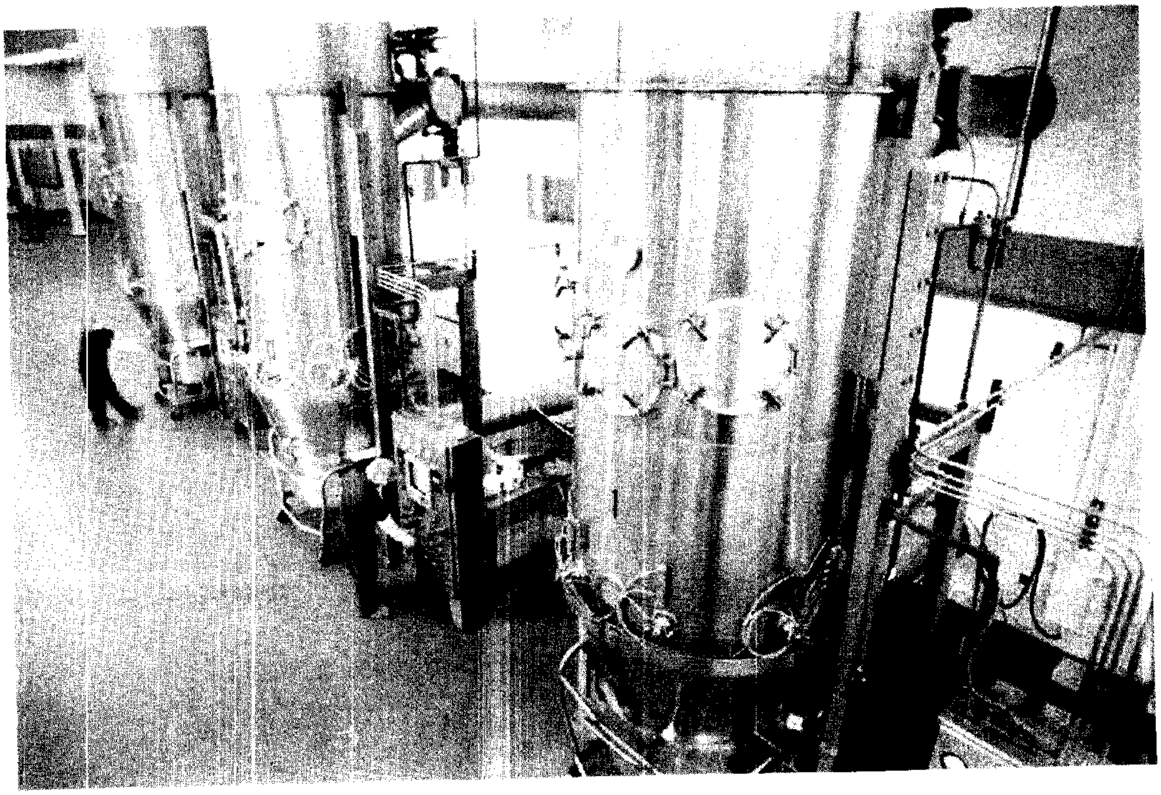
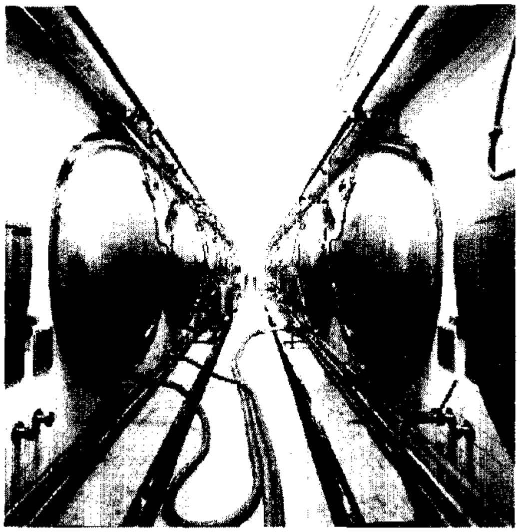
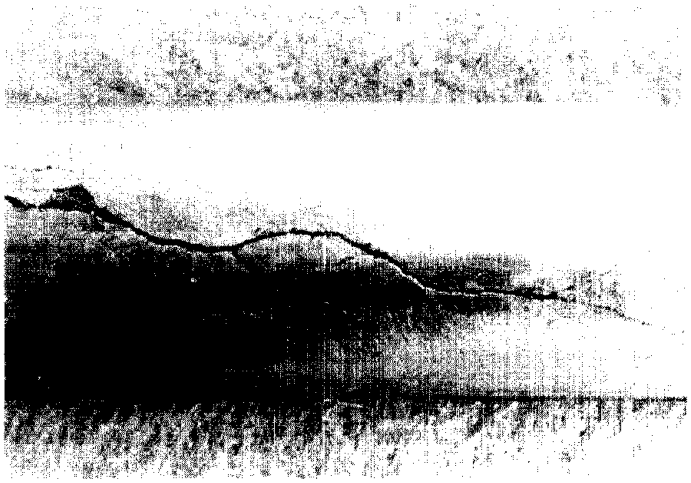
APPENDIX Y

FOOD PROCESSING

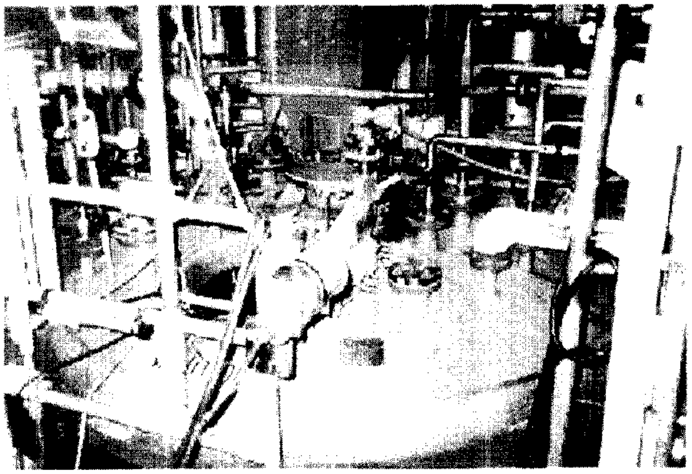



Stainless steel tanks for beer storage


Stress-induced cracking


Cracked weld in stainless steel


Copper vessels for chocolate manufacturing


Reactor vessel

APPENDIX Y

FOOD PROCESSING

IVELISSE TUBENS[1] AND MICHIEL P.H. BRONGERS[1]

SUMMARY

Product quality, health, and sanitation issues are major concerns in the food-processing industry. The industry cannot tolerate corrosion deposits in the manufactured product. The industry, therefore, needs to account for corrosion control before production starts. Stainless steel consumption and cost in food processing is attributed to corrosion control and prevention. The total estimated stainless steel cost for the food-processing industry is $1.8 billion per year. This cost includes stainless steel utilized in beverage production, food machinery, cutlery and utensils, commercial and restaurant equipment, and appliances. The annual cost of aluminum cans is $250 million and the annual cost for corrosion inhibitors in the food-processing industry is approximately $50 million. Therefore, the total estimated cost of corrosion in this sector is $2.1 billion per year.

Maintenance management systems are implemented in food-processing plants to monitor machine production histories, downtime, and reliability to prioritize equipment and maintenance problems. Reliability-based maintenance (RBM) teams are used in conjunction with maintenance management systems to predict maintenance needs and conduct root-cause analyses of food-processing equipment failures. Strategic maintenance programs are part of the plant's overall vision of the future, which aims at boosting production efficiency.

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[1] CC Technologies Laboratories, Inc., Dublin, Ohio.

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SECTOR DESCRIPTION

The food-processing industries are among the largest manufacturing sectors in the U.S. economy, accounting for approximately 14 percent of the total U.S. manufacturing output. From 1972 to 1987, the number of food-processing facilities has declined from 28,193 to 20,583 (a 27 percent decrease). Since 1992, the number of facilities has increased again to 20,792 (a 1 percent increase).(1) According to composite statistics, sales for public food-processing companies were $265.5 billion in 1999. Sales are projected to increase to $315 billion in 2001.

In the 2000 manufacturing survey conducted by *Food Engineering*, food-manufacturing professionals in top management, production management, engineering, quality control, packaging, and purchasing across every segment of the industry were interviewed on the improvements needed in food-processing facilities. The results show that improvements on equipment (17.9 percent of the total respondents) and maintenance systems (65.4 percent of the total respondents) need more attention.(2) According to 24 percent of the total respondents, the results show that 25 percent or more of the budget is allotted for purchasing production, packaging, or process control equipment. Improvements on equipment include selection of corrosion-resistant materials with surface finishes and replacement of parts or components. Improvements on maintenance systems require implementing a schedule program where food-processing systems are routinely checked for failing parts due to corrosion or mechanical problems.

The number of U.S. food plant construction projects in 1999 was 753, compared with 327 construction projects in 1994. Table 1 shows a summary of the total number of projects, renovations and expansions, and new plants from 1994 to 1999. In 1999, 68 percent of the total construction projects consisted of plant expansions or renovations.(2) Renovations and expansions can include an increase in installation of improved equipment for optimal process operation and new processes.

Table 1. U.S. food plant construction projects from 1994 to 1999.(2)

YEAR	TOTAL NUMBER OF PROJECTS	RENOVATIONS/ EXPANSIONS	NEW PLANTS
1994	329	188	141
1995	406	250	156
1996	485	286	199
1997	756	484	272
1998	867	557	310
1999	753	512	241

DESCRIPTION OF FOOD-PROCESSING COMMODITIES

In the food-processing industry, product quality is the key issue. Corrosion products are not acceptable in the food product due to health reasons; therefore, almost all production equipment is fabricated from corrosion-resistant material. The New Mexico Environmental Improvement Board defines a corrosion-resistant material as "a material that maintains its original surface characteristics under the prolonged influence of the food, cleaning compounds, and sanitizing solutions that may contact it."(3) Food-processing equipment includes stoves, ranges, hoods, meat blocks, tables, counters, refrigerators, sinks, dishwashing machines, and steam tables.

The processed-foods sector is much larger than the farm sector in both total value of production and international trade. Distinctions are made between agricultural products and processed foods at both the producer and the consumer levels. Agricultural production is based on abundant fertile land and favorable farm structure; however, the food-processing industry emphasizes technology and convenience for consumers.

U.S. processed-foods commodities include processed seafood, fresh meat products, frozen specialties, bottled/canned soft drinks and carbonated waters, frozen bakery products, prepared flour mixes and dough, distilled and blended liquors, macaroni and noodles, and ice cream and frozen desserts. The largest food-processing industry groups are meat products and grain mill products.

AREAS OF MAJOR CORROSION IMPACT

The corrosion environment in the food and beverage industry involves moderately to highly concentrated chlorides, often mixed with significant concentrations of organic acids. The water side of the processing equipment can range from steam heating to brine cooling. Purity and sanitation standards require excellent corrosion resistance to pitting and crevice corrosion. Sulfiting agents producing sulfur dioxide when used to treat foods include sodium sulfite, sodium bisulfite, potassium bisulfite, sodium metabisulfite, and potassium metabisulfite. All are generally corrosive to food-processing equipment.

Underdeposit Corrosion

Underdeposit corrosion is likely to occur in cooling systems where scales or foulants exist. The presence of general fouling and scales can cause the formation of a differential cell, which begins the process of corrosion. Due to the difference in oxygen concentration at the metal surface beneath the deposit and the oxygen concentration in the water, a differential cell forms, resulting in the corrosion reaction.

The food-processing industry uses water for washing, transporting, blanching, cooking, cooling, and cleaning. In particular, heating and cooling processes require large amounts of water. Underdeposit corrosion is caused by using water in boilers, rotary cookers, and hydrostatic sterilizers.

Aluminum alloys are susceptible to underdeposit corrosion. Stainless steels are also susceptible to underdeposit corrosion, as well as deep pitting. Anodic, cathodic, and filming inhibitors are used to mitigate corrosion.(4)

Biocides such as chlorine dioxide and bromine compounds (oxidizers) are used for sterilization; however, these chemicals can interfere with the performance of the inhibition system. In order to prevent corrosion, the concentration of biocides into the water stream must be controlled.

Galvanic Corrosion

Galvanic corrosion is an accelerated attack between two dissimilar metals that are coupled in electrical contact and exposed to an electrolyte. For example, in hydrostatic sterilizers, the flight bars are made from aluminum or stainless steel, the transport chain is made from carbon steel, and both are exposed to hot water and steam.(4) The less noble metal of the couple is susceptible to galvanic corrosion. In the case of aluminum and carbon steel, the aluminum is less noble and, therefore, will corrode. Replacement of chains and flight bars can cost up to $250,000 in a typical commercial sterilizer.

Stress Corrosion Cracking

Stress corrosion cracking (SCC) in types AISI 304 and AISI 316 stainless steel piping and tanks is a problem in water lines in brewery applications.(5) A common form of stress corrosion cracking occurs at temperatures higher than ambient in the presence of chlorides. Duplex stainless steels and alloys containing molybdenum alloys are used as alternatives that are more resistant to stress corrosion cracking. Cracking may occur from the process or from the outside, for example under insulation. Reducing the amount of oxygen ingress and lowering the process temperature minimizes the possibility of stress corrosion cracking.

CORROSION CONTROL METHODS

Corrosion-Resistant Materials in the Fabrication of Food-Processing Equipment

A variety of materials are being used for food processing, depending on the type of food and the processing conditions, such as temperature and pH values Stainless steels and aluminum alloys are the primary materials used in food processing. Plastics and other metals may be used; however, lead- and cadmium-plated materials may impart toxic substances into foods.(6) Food contact surfaces must be smooth, non-adsorbent, non-leaching, and insoluble in the food.

Stainless Steels

Stainless steel is very resistant to corrosion in food-processing environments. Although stainless steel is generally resistant to corrosion, it is not immune in a chloride-containing environment. Corrosion is a problem in stainless steels when exposed to chlorine, commonly used to sanitize equipment, and hydrochloric acid, used in some cleaning agents and processing liquids. Corrosion products should be removed immediately because they impede proper cleaning of surfaces.

Table 2 shows the total stainless steel consumption used to manufacture food equipment and machinery and the estimated cost for stainless steel. The stainless steel consumption in the food-processing industry is approximately 15.3 percent (370,000 tons) of the overall stainless steel market of 2.4 million tons per year.(7)

The price per pound of each stainless steel increases with more complex geometry. The price per pound for 2,000 lb of type 316 stainless steel was used to determine the estimated cost for stainless steel in the food-processing industry. The price per ton for each type was the following: (1) sheet and strip = $2,620 per ton ($1.31 per lb), (2) plate = $2,500 per ton ($1.25 per lb), (3) bar = $10,820 per ton ($5.41 per lb), and (4) pipe and tube = $22,300 per ton ($11.15 per lb).(8-10) The estimated total cost of stainless steel for the food-processing industry was determined to be approximately $1.8 billion, which is only a portion of the total cost for the food-processing industry.

Table 2. Annual tonnage and cost of stainless steel specified by final form in the United States, as reported by the Specialty Steel Industry of North America in 1998. (See references 7 through 10.)

FOOD EQUIPMENT	SHEET & STRIP		PLATE		BAR		PIPE & TUBE		TOTAL COST
	$2,620 / ton		$2,500 / ton		$10,820 / ton		$22,300 / ton		
	tons	$ x million	tons	$ x million	tons	$ x million	tons	$ x million	$ x million
General	8,854	23.2	2,528	6.3	3,198	34.6	4,490	100.1	164.2
Beverage	6,566	17.2	64	0.2	10	0.1	-	-	17.5
Food Machinery	139,618	365.8	25,157	62.9	21,974	237.8	18,490	412.3	1,078.8
Food Service Machinery	43,614	114.3	5,940	14.9	3,215	34.8	4,093	91.3	255.2
Cutlery/Utensil	38,102	99.8	-	-	6,887	74.5	-	-	174.3
Commercial/Restaurant Equipment	15,269	40.0	60	0.2	-	-	-	-	40.2
Appliances	21,974	57.6	37	0.1	-	-	-	-	57.7
TOTAL TONNAGE	273,997		33,786		35,284		27,073		370,140
TOTAL COST		$717.9		$84.5		$381.8		$603.7	$1,787.8

1 ton = 2,000 lb = 904 kg

Aluminum

Aluminum is also often used in processing equipment and is much less expensive than stainless steel; however, it is not as strong or as durable. Aluminum alloys are commonly used in the processing, handling, and packaging of foods and beverages. Approximately a quarter of all aluminum goes into packaging. In addition to high corrosion resistance, many of these applications depend on the nontoxic nature of aluminum and its salts, as well as freedom from catalytic effects that cause product discoloration.(11)

Aluminum cans contain internal and external coatings, primarily for decoration and protection of product taste. Oxygen is also removed before the can is filled with the product. This prevents the can from oxidizing and from the potential risk of toxicity.

Its shiny appearance, the relatively low weight per volume, and favorable mechanical properties, such as material strength and ease of forming and handling, are some of the many reasons for using aluminum for food packaging. In addition, aluminum has superior corrosion resistance over coated carbon steel because it forms a naturally protective oxide on its surface, which effectively prevents further atmospheric corrosion from occurring. Also, aluminum is lighter than, for example, stainless steel; therefore, aluminum is the preferred material used in beverage cans. In 1996, 99 billion aluminum cans were produced and 63.5 percent of these cans were recycled.(12) In comparison, the U.S. steel industry remelted nearly 19 billion steel cans in 1996, which is 58 percent of the total 33 billion steel cans produced. If 0.45 kg (1 lb) of aluminum cans yields 29.51 cans, approximately 1.54 billion kg (3.4 billion lb) of aluminum were consumed.(13) Assuming that the price of 1 kg of aluminum is $1.62 ($0.73 per lb),(14) the total cost of aluminum consumption for 99 billion cans is $2.5 billion. If it is assumed that 10 percent of the aluminum consumption is due to corrosion, then the direct corrosion cost can be estimated at $250 million per year.

Corrosion Inhibitors

Inhibitor technology has been introduced for harsh environments encountered in equipment such as rotary cookers and hydrostatic sterilizers. They are exposed to hot water, steam, and cooling water. A single approach to treating these systems will not provide adequate protection. Combinations of anodic, cathodic, and filming inhibitors are selected for corrosion prevention, depending on the water composition and equipment material.

The cost of inhibitor consumption depends on the water quality and quantity, the size of the equipment, and the operation time. A food-processing industry expert provided a cost estimate for a food plant operating nine rotary cookers and five hydrostatic sterilizers. The plant treats the potable water and hot water system for corrosion protection. Based on the annual cost divided by the annual water usage, the scale/corrosion protection cost would average about $2.50 to $3.00 per 3,785 L (1,000 gal) of water used in the plant for these systems.(4) Therefore, the annual corrosion cost associated with inhibitor use of this plant is between $2,500 and $3,000. Extrapolation of this cost to the approximately 20,000 food plants currently in operation results in a total inhibitor cost ranging from $50 million to $60 million per year.

Coatings

Coatings used in food-processing plants must withstand high-pressure cleaning and microbial attack. Microbial attack is a major maintenance problem in breweries and beverage bottling plants. Antimicrobial additives are used in order to control bacterial activity and growth. Urethane coatings instead of epoxy coatings are preferred in the food-processing industry because they are resistant to cleaning compounds.(15)

Calculating the Cost of Corrosion

In summary, the total estimated stainless steel cost for the food-processing industry is $1.8 billion per year. The annual cost for aluminum cans is $250 million per year, and the annual cost for corrosion inhibitors in the food-processing industry is approximately $50 million per year. Therefore, the total estimated cost of corrosion is $2.1 billion per year.

CORROSION MANAGEMENT

Maintenance management systems are implemented in food-processing plants to monitor machine production histories, downtime, and reliability to prioritize equipment and maintenance problems. Reliability-based maintenance (RBM) teams are used to predict maintenance needs and to analyze the root cause of food-processing equipment failures. Strategic maintenance programs are part of the plant's overall vision of the future, which aims at boosting production efficiency.

CHANGES FROM 1975 TO 2000

To meet consumer needs, food-processing companies are expanding and renovating their facilities in order to improve operating efficiency. Food manufacturing has undergone technological changes, including aseptic processing and microwaveable processing. Thus, there is a great demand for technology and machinery to meet consumer demand.

Food manufacturers' continuous efforts to boost income and market share through acquisitions, overseas growth, cost controls, and new-product development have resulted in prosperous economic times. Many companies are restructuring to consolidate operations after acquisitions. According to the Food Institute, food manufacturing mergers and acquisitions reached a record 288 in 1999, continuing an upward trend throughout the decade.

The brewery industry has realized that it is more cost-effective to select corrosion-resistant materials than to use coatings and cathodic protection on the processing equipment. In the 1980's, cathodic protection was used on pasteurizers made from mild steel;(5) however, modern pasteurizers are protected from corrosion by selecting AISI 304 stainless steel instead of using cathodic protection. Inhibitors are used to eliminate underdeposit. Coatings are avoided due to concern about product contamination.

The food-processing business focuses on product quality and mass production. Food-processing equipment is designed for low failure rates and long life expectancy; therefore, equipment replacement rates and costs are kept to a minimum.

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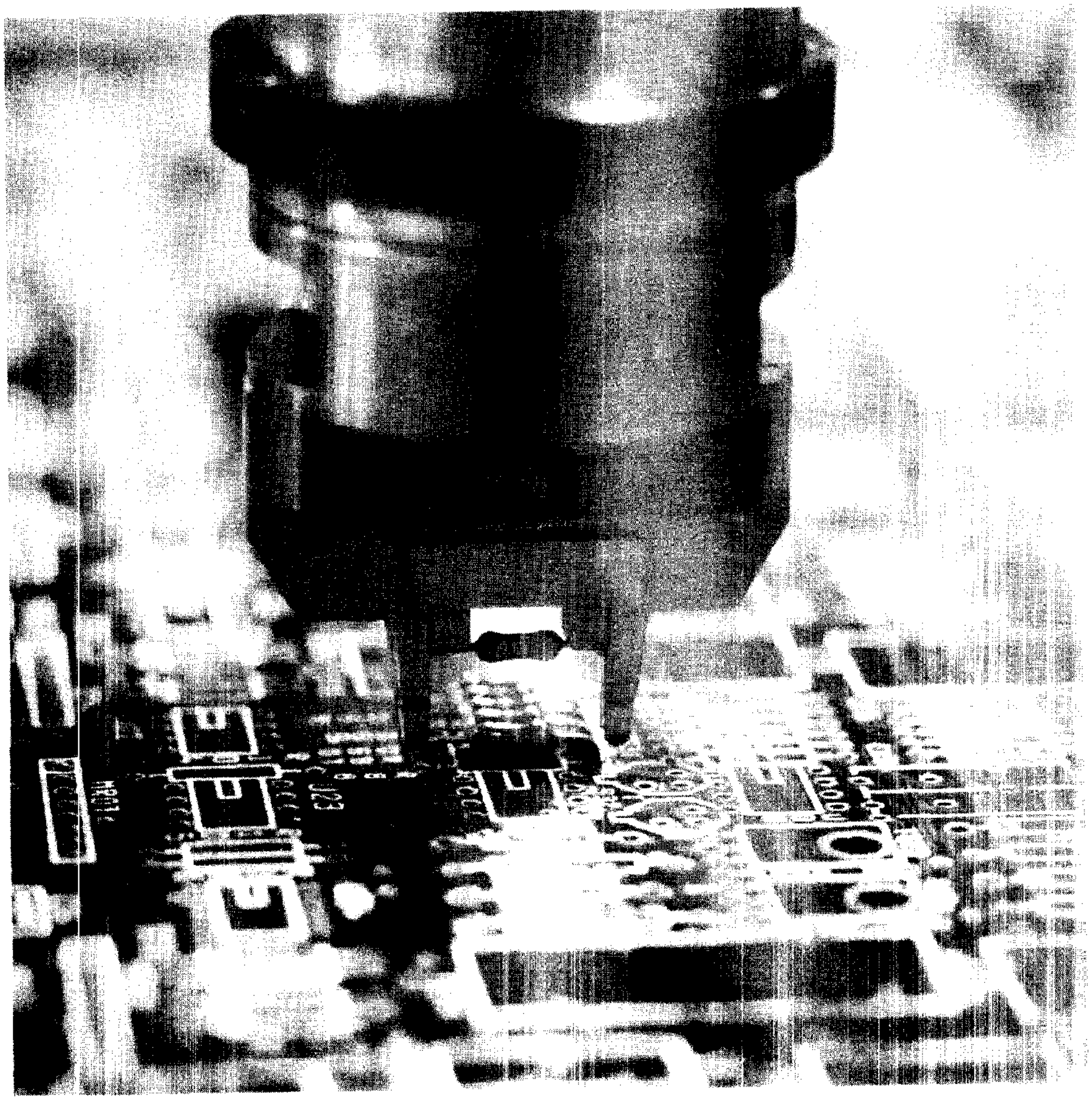
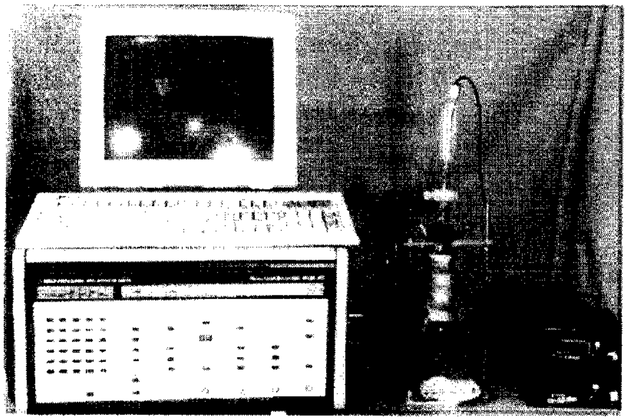
APPENDIX Z

ELECTRONICS





Instrumentation

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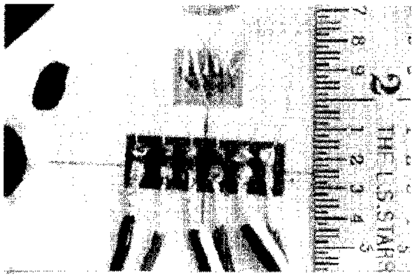

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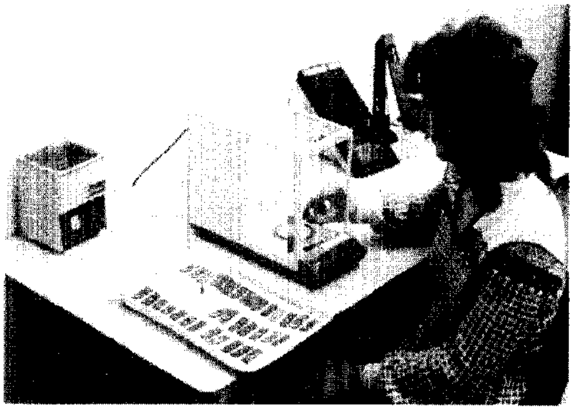
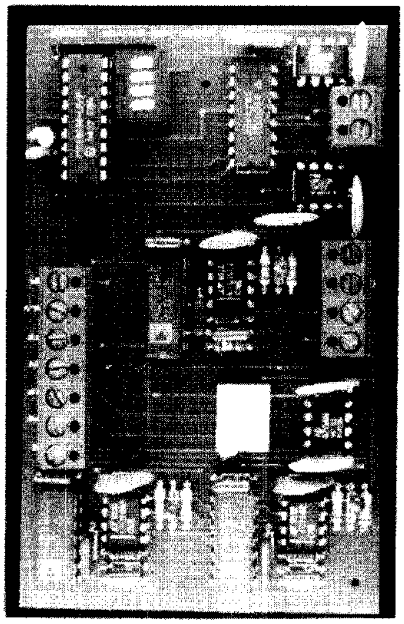


Laboratory equipment

Office electronics



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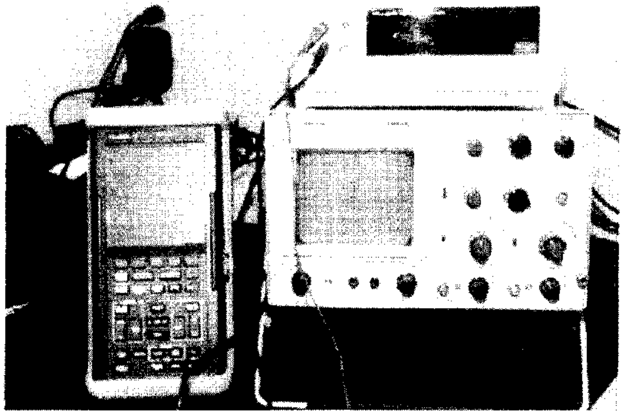

Electronic testing equipment

ELECTRONICS

MARK YUNOVICH[1]

SUMMARY

Corrosion in electronic components manifests itself in several ways. Computers, integrated circuits, and microchips are now an integral part of all technology-intensive industry products, ranging from aerospace and automotive to medical equipment and consumer products, and are therefore exposed to a variety of environmental conditions. Corrosion in electronic components is insidious and cannot be readily detected; therefore, when corrosion failure occurs, it is often dismissed as just a failure and the part or component is replaced.

Because of the difficulty in detecting and identifying corrosion failures, the cost of corrosion is difficult to determine. Arguably, in many instances, particularly in the case of consumer electronics, such devices would become technologically obsolete long before corrosion-induced failures. In addition, while corrosion-related user costs due to irretrievably lost data could be staggering, as the electronic information and data exchange become more intensive, most sensitive information is frequently backed up. Capital-intensive industries with significant investments in durable equipment with a considerable number of electronic components, such as the defense industry and the airline industry, tend to keep the equipment for longer periods of time, so that corrosion is likely to become an issue. Although the cost of corrosion in the electronics sector could not be estimated, it has been suggested that a significant part of all electric component failures may be caused by corrosion.

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[1] CC Technologies Laboratories, Inc., Dublin, Ohio.

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SECTOR DESCRIPTION

Corrosion of electronic components manifests itself in several ways. Computers, integrated circuits, microchips, etc. are now an integral part of all technology-intensive industry products, ranging from aerospace and automotive to medical equipment and consumer products, and are therefore exposed to a variety of environmental conditions.

As electronics become more and more ubiquitous and the devices more robust, concern over the operating environment seems to lessen, particularly in the personal computer (PC) market. Desktop computers can now be found in most homes and the vast majority of businesses. Availability of sub-$1,000 computers has effectively made them a commodity. In 1989, an estimated 21 million PCs were sold worldwide, approximately 9 million of them in the United States. In 1998, worldwide PC sales totaled almost 93 million and U.S. sales approximately 36 million. In 1990, almost 15 percent of U.S. households owned a computer. In 1999, nearly 50 percent of U.S. households owned a computer.(1) Personal use accounts for only approximately 30 percent of PC sales, while businesses, the government, and schools represent the rest.

The trend toward miniaturization of technology has led to the development of small personal electronic devices, such as pagers, cellular phones, and palm-sized personal organizers and computers. The PalmPilot was released in 1996 and by mid-1999, three million units had been sold.(2)

In 1999, more than 98 percent of 101 million American households had a television set. VCRs could be found in 80 percent of those households, and more than 94 percent of the households had telephones.(3) Most of the other household appliances, from toasters to washers, are controlled by electronic modules. In addition, there were 4,782 AM radio stations, 5,745 FM radio stations, and 1,599 television stations. The majority of the 200 million automobiles currently in use also have electronic components. Some of the statistics on consumer electronics are summarized in table 1.

Table 1. Household/consumer electronics statistics.

Cable TV households	1998	74,550,000
Total TV households	Jan. 1999	99,400,000
TV households with two or more sets	Jan. 1999	74%
TV households with VCRs	1997	74%
Households with video game consoles	1995	40%
Internet users per 1,000 people	1998	283

The short span needed for market penetration for some of the modern devices, along with the ownership data, is shown in figure 1.(4) Note the short span needed for cellular phones to become a common device, compared to that of an ordinary telephone.

According to some publications, America Online's system "conveys 760 million" email messages per day, twice as many as the letters handled by the U.S. Postal Service.(5)

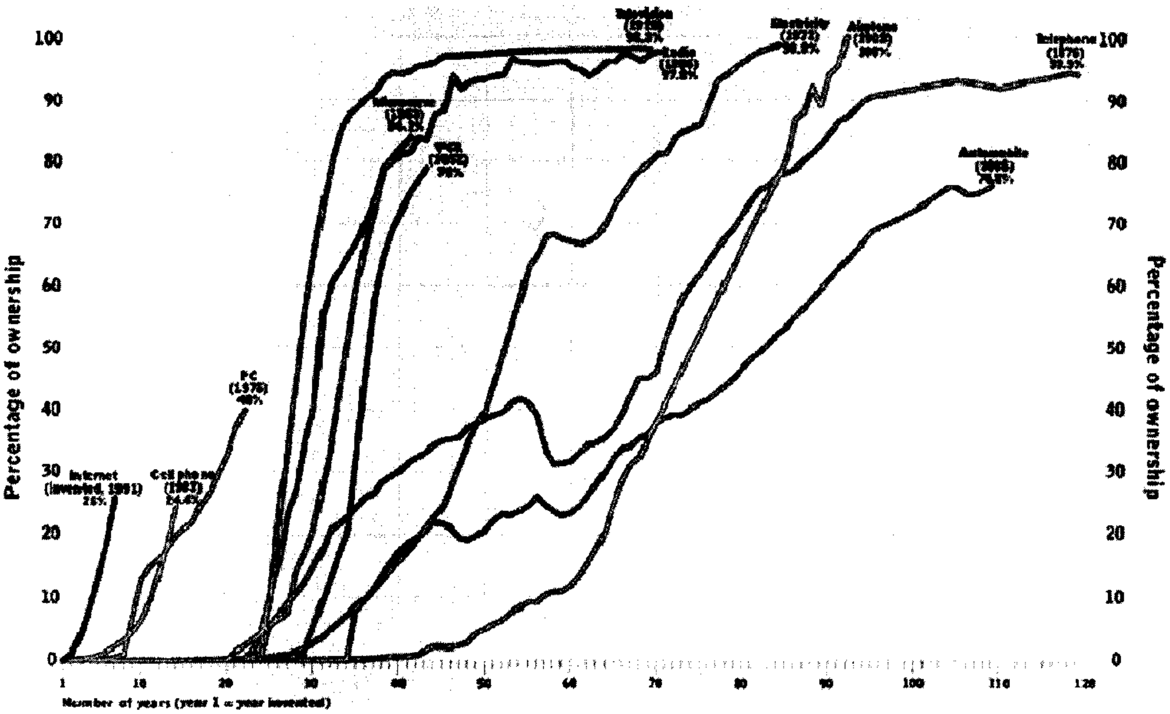

Figure 1. "Time-to-ownership" for some electronic devices.

The value of automotive electronic components manufactured in 1997 was estimated at $1.4 billion.(6) According to the U.S. Census Bureau,(7) during 1999, the total value of shipments for consumer electronics (excluding computers) was $8.2 billion, an increase of 4.6 percent from the 1998 value of $7.8 billion. Automotive audio equipment increased 15.7 percent from $941.5 million in 1998 to $1.1 billion in 1999. Shipments of television receivers increased 9.6 percent from $3.9 billion in 1998 to $4.3 billion in 1999. All other consumer audio and video equipment shipments decreased 16.7 percent in 1999 from $827.2 million in 1998 to $689 million in 1999. Loudspeakers, microphones, kits, and public address systems decreased 1.3 percent from $2.1 billion shipped in 1998.

The U.S. Census Bureau reported the 1997 value of shipments in the Manufacturing – Industry Series.(1) Table 2 shows a summary of the value of shipments for various industries that manufacture electronics. This table is not all-encompassing, and components that are manufactured in one industry are used in another. If the shipment values for the electronics manufacturing industries listed on this table are summed, a total value of $335.8 billion per year can be estimated. The table shows that the manufacturing of semiconductors and related devices, and the manufacturing of computers are the largest industries. Broadcasting equipment, including radio, television, and wireless communications equipment, and telephone apparatus manufacturing have significant shipments as well.

Table 2. Industry statistics for electronics manufacturing industry in 1997, according to the U.S. Census Bureau.[8]

ELECTRONICS MANUFACTURING INDUSTRIES	1997 TOTAL VALUE OF SHIPMENTS	
	$ x billion	**%**
Semiconductor and Related Device Manufacturing	78.0	23.2
Electronic Computer Manufacturing	65.9	19.6
Radio and Television Broadcasting and Wireless Communications Equipment Manufacturing	39.5	11.8
Telephone Apparatus Manufacturing	37.8	11.3
Other Computer Peripheral Equipment Manufacturing	26.9	8.0
Printed Circuit Assembly (Electronic Assembly Manufacturing)	25.6	7.6
Computer Storage Device Manufacturing	13.3	4.0
Other Electronic Component Manufacturing	10.4	3.1
Bare Printed Circuit Board Manufacturing	9.6	2.9
Audio and Video Equipment Manufacturing	8.2	2.4
Electronic Connector Manufacturing	5.7	1.7
Other Communications Equipment Manufacturing	4.2	1.3
Electron Tube Manufacturing	3.8	1.1
Electronic Capacitor Manufacturing	2.5	0.7
Electronic Coil, Transformer, and Other Inductor Manufacturing	1.6	0.5
Computer Terminal Manufacturing	1.5	0.4
Electronic Resistor Manufacturing	1.3	0.4
TOTAL	**$335.8**	**100.0%**

CAUSES OF CORROSION

The most common electronic components include integrated circuits (IC), printed circuit (PC) boards, and connectors and contacts. Traditional materials used for IC conductors are aluminum-based alloys, often alloyed with silicon and copper. Major metallic components in PC boards, such as conductors and connectors, are typically made of copper where soldering is done with lead-tin alloys. Contacts are commonly manufactured from copper covered with electroplated nickel or gold for improved corrosion resistance.

As electronic devices become more and more common, they become increasingly exposed to much harsher conditions than the air-conditioned rooms used to house early computers. Although the microchip in an automobile, for example, is not directly subjected to the same hazards as the car body, given the dimensions of the former (silicon-based integrated circuit elements are spaced less than 0.2 microns), the tolerance for corrosion loss is much smaller (on the order of picograms (10^{-12}g)). Minimum line width in the state-of-the-art PC boards in 1997 was less than 100 microns. On hybrid integrated circuits (HICs), line spacings may be less than 5 microns.[9]

Submicron dimensions of electronic circuits, high-voltage gradients, and an extremely high sensitivity to corrosion or corrosion products present a unique set of corrosion-related issues. The documented reasons for failures are discussed in greater detail below.

Environmental Contamination (Airborne Contaminants)

One of the most common reasons for electronic failure is environmental contaminants and conditions. The list of contaminants includes fine and coarse particles of such species as chlorides, sulfates, sodium, ammonium, potassium, magnesium, and calcium. The single most important environmental condition affecting the impact of particulate matter and gases (such as sulfur dioxide and nitrogen oxides) is relative humidity. Coarse particles (2.5 to 15 microns) are typically formed as a result of human activity(10) or originate from soil. Fine particles (0.1 to 2.5 microns) come from the combustion of fossil fuels and, at times, from volcanic and geological activity.

In electronic devices, coarse particles may cause malfunctions by interrupting electrical contact between mating pairs of contacts on connectors or relays. They typically require higher relative humidity conditions than the fine particles.

According to the ISA – Instrument Systems and Automation Society standard, there are four classes of industrial atmospheres with respect to copper reactivity. The summary is presented in table 3.

Table 3. Classification of industrial atmospheres' corrosivity to copper.(11)

CLASS	DESCRIPTION	EXPECTED TIME-TO-FAILURE
G1 (mild)	Corrosion is not a factor (less than 300 angstroms per month)	No corrosion-related failures
G2 (moderate)	Corrosion is measurable (less than 1,000 angstroms per month)	Failure within 3-4 years
G3 (harsh)	High probability of corrosion (less than 2,000 angstroms per month)	Failure within 1-2 years
G4 (severe)	Considerable corrosion (less than 3,000 angstroms per month)	Failure within 1 year

Another classification of the corrosivity of the environment is based on the levels of relative humidity and contaminants.

FORMS OF CORROSION

Anodic Corrosion

Given the spacing between components of the ICs, when a voltage is applied to a device, voltaic gradients on the order of 10^5 to 10^6 V/cm can exist across surfaces, accelerating electrochemical corrosion reactions and ionic migration. In ICs, positively biased aluminum metallizations are susceptible to corrosion. Combination of the electric fields, the atmospheric moisture, and the contamination by halides leads to corrosion attack on aluminum. Gold and copper metallizations are also subject to corrosion under these conditions.

Cathodic Corrosion

Negatively biased aluminum metallizations, as with those with the positive bias, can also corrode in the presence of moisture due to high (basic) pH produced by the cathodic reaction of water reduction. High pH leads to dissolution of the passive surface layer of oxides and aluminum substrate with the corresponding increases in conductor resistance (up to an open circuit).

Electrolytic Metal Migration

Detected early on in electromechanical switches, this problem occurs in relation to the silver-containing compounds. In the presence of moisture and an electric field, silver ions migrate to a cathodically (negatively) charged surface and plate out, forming dendrites. The dendrites grow and eventually bridge the gap between the contacts, causing an electric short and an arc. Even a small volume of dissolved metal can result in formation of a relatively large dendrite. Under certain humidity and voltage gradient conditions, a 30-day exposure becomes equivalent to 4 years of service in a typical office environment.(10) Other materials susceptible to the metal migration include gold, tin, lead, palladium, and copper.

Pore-Creep in Electrical Contacts and Metallic Joints

To prevent tarnishing of connectors and contacts, a noble metal (e.g., gold) is plated on the contact surface. Since the coverage is never complete, the substrate material can corrode at the imperfections. If the substrate is copper or silver, and it is exposed to a sulfur- or chloride-containing environment, corrosion products can creep out from the pores and over the gold plating, forming a layer with high contact resistance.

Fretting Corrosion of Separable Connectors With Tin Finishes

Fretting corrosion in electronic components is manifested as the continuous formation and flaking of tin oxide from a mated surface on tin-containing contacts. As the components start to utilize more and more tin (rather than gold, to cut the costs), the problem becomes more frequent. The only solution for this hard-to-diagnose, and often intermittent, problem is to replace the faulty part.

Galvanic Corrosion

Galvanic corrosion occurs when two dissimilar metals, such as aluminum and gold, are coupled together, as is commonly done for packaged (plastic encapsulated) integrated circuits. The polymers used for packaging are porous and the gaskets around hermetic covers (such as ceramic or metal) sometimes leak; therefore, in humid environments, moisture can permeate to the IC bond pad, creating conditions conducive to galvanic corrosion. Electronic devices tend to dissipate considerable heat during operation, which leads to reduced relative humidity. During power-down or storage periods, the relative humidity rises, which presents more danger.(12)

Processing-Related Corrosion of Integrated Circuits

IC circuits are exposed to a number of aggressive media used in reactive ion etching (RIE) or wet etching for patterning of aluminum lines, which can lead to corrosive residues. RIE of aluminum metallizations utilizes a combination of aggressive chlorine-containing gases. If removed untreated from the etcher, patterned structures are covered with aluminum chloride residue, which is hydroscopic and forms hydrochloric acid in the presence of moisture.(12)

Micropitting on Aluminum on IC During Processing

Aluminum metallizations, alloyed with copper, can form intermetallic compounds (such as Al_2Cu) along the grain boundaries, which act as cathodic sites relative to the aluminum adjacent to the grain boundaries. This leads to dissolution of an aluminum matrix in the form of micropitting during the rinsing step after chemical etching.

Corrosion of Aluminum by Chlorinated/Halogenated Solvents

Both liquid and vapor-phase halogenated solvents used for production of ICs and PCs readily corrode aluminum-containing components. Water contamination of the solvents increases the time-to-corrosion on the one hand; however, on the other hand, it increases the subsequent corrosion rate. Dilution of the stabilized solvents with aromatic or alcohol solvents leads to the breakdown of the halogenated solvent and the formation of chloride ions, which corrode aluminum and aluminum-copper alloys.

Solder Corrosion

Lead-tin solder alloy's resistance to corrosion in aqueous and gaseous environments is a function of the alloy composition. It improves significantly when the tin content increases above two weight percent. Lead forms unstable oxides, which easily react with chlorides, borates, and sulfates.(12)

Corrosion of Magnetic and Magneto-Optic Devices

Besides electronic circuits, corrosion-related failures can occur in advanced magnetic and magneto-optic storage devices, where thin-film metal discs, thin-film inductive heads, and magneto-optic layers are affected. Corrosion takes place in sites where the deposited carbon overcoat is lacking due to intentional roughening of the disc and where the magnetic cobalt-based layer and nickel-phosphorus substrate become exposed. Given the potential differences between the noble (positive) carbon and the metal substrate, a galvanic couple may form, leading to rapid galvanic-induced dissolution of the magnetic material.(12)

Magneto-optic devices utilize extremely reactive alloys for the recording media (due to high terbium content). Exposure of magneto-optic films to aqueous solutions or high-humidity conditions results in a localized attack (pitting), even during storage in ambient office conditions.(12)

While attempts have been made to mitigate corrosion of electronics by encapsulating the components in plastics, polymers are permeable to moisture. Hermetically sealed ceramic packaging is more successful; however, care must be exercised to prevent moisture and other contaminants from being sealed in. One common approach for mitigating corrosion of circuits housed inside a relatively large-size chassis includes the use of volatile inhibiting compounds (requires periodic replacement of the carrier).

CORROSION COSTS

The cost of corrosion is very difficult to determine. Arguably, in many instances, particularly in the case of consumer electronics, the devices would become technologically obsolete long before corrosion-induced failures occur. Also, while corrosion-related user costs (due to irretrievably lost data) could be staggering, as electronic information and data exchange become more and more intensive, most sensitive information is frequently backed up.

Capital-intensive industries with significant investments in durable equipment with a considerable number of electronic components (e.g., defense, airline, etc.) tend to keep the equipment for longer periods of time (tens of years), such that corrosion is likely to become an issue. There is even an opinion that the vast majority, if not all, of the electronic component failures are caused by corrosion. (13)

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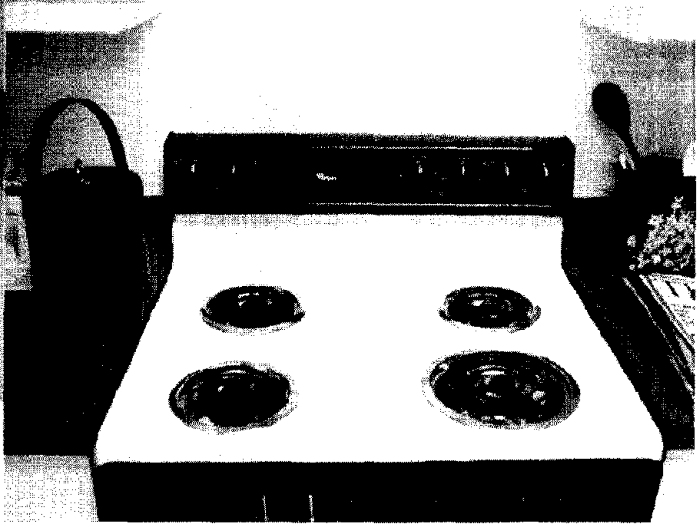
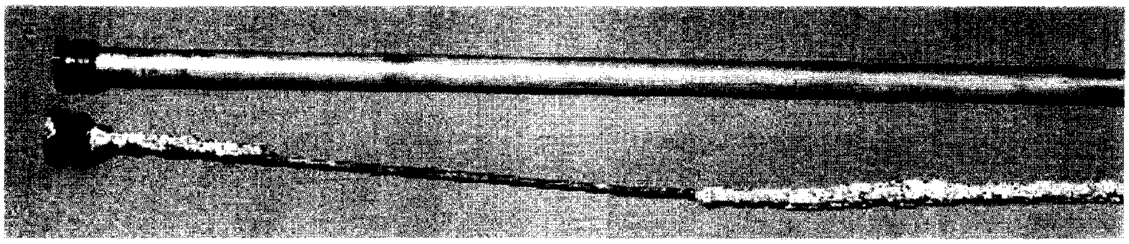
APPENDIX AA

HOME APPLIANCES

Refrigerator and water cooler



Stove



Comparison of a new anode and a spent anode

APPENDIX AA

HOME APPLIANCES

MICHIEL P.H. BRONGERS[1] AND IVELISSE TUBENS[1]

SUMMARY

The appliance industry is one of the largest consumer product industries. For practical purposes, two categories of appliances are distinguished: "Major Home Appliances" and "Comfort Conditioning Appliances." In 1999, 70.7 million major home appliances and 49.5 million comfort conditioning appliances were sold in the United States, for a total of 120.2 million appliances.

The average consumer buying an appliance is only marginally interested in corrosion issues; therefore, during the useful life of the appliance, no corrosion management is done by consumers. For example, very few people realize that there is an anode in every water heater, and that this sacrificial bar of metal should be checked and, if necessary, replaced with a new one to prevent water heater failure due to internal corrosion. The life expectancy of appliances is determined from past experience and sales data. Improved corrosion design for appliances can increase their life expectancy; however, if improved corrosion protection would mean the use of more expensive components for the appliances, then consumers may not be interested.

A corrosion cost calculation was made for the sacrificial anodes in the 104 million water heaters in the United States. The benefits of anode maintenance are longer tank life, less rust build-up, and savings on costly changeovers. The increased life expectancy from anode maintenance can save consumers money. However, a cost-benefit analysis may show that the cost of replacing anodes could exceed the benefits of increased life expectancy and postponing water heater replacement. The annual cost of replacing water heaters was estimated at $460 million per year, the cost of anode replacement was estimated at $780 million per year, and the cost benefit of a hypothetical design improvement that would increase the life expectancy of water heaters by 1 year was estimated at $778 million per year.

A corrosion cost calculation was also made for the annual coating costs of the 120.2 million newly purchased major appliances in the United States. Based on an estimated installed cost for coatings of $2 per appliance, the total cost is approximately $240 million per year. The cost of $2 is a marginal value in the average cost of appliances. Therefore, this cost is probably worth spending because of the more appealing appearance of non-corroding appliances. On the other hand, the internal components of appliances, those that are not directly visible to consumers, should be protected from corrosion as well. For example, the above calculation does not consider the application of internal coatings, such as galvanizing steel, for longer life.

The assumptions made in the anode calculations and the coating calculations are only approximations, and no adjustment is provided for the use of corrosion-resistant materials in most appliances. It is recognized that the estimates are probably not very accurate, because of the large variety in appliances. Considering the significant costs of appliances to consumers, and the fact that the potential savings from longer life expectancies can be considerable, it is recommended that a broad study, including a full analysis of statistical data, be performed to research the potential cost-savings related to the increased life expectancies of appliances.

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In summary, the cost of corrosion in home appliances is very significant. The first cost is the purchase of replacement appliances because of premature failures due to corrosion. It is evident that water heater replacement is often attributed to corrosion. For water heaters alone, this cost was estimated at $460 million per year, using a low estimate of 5 percent of the replacement being corrosion-related. The cost of internal corrosion protection for all appliances includes the use of sacrificial anodes ($780 million per year), corrosion-resistant materials (no cost estimate), and internal coatings (no cost estimate). The cost of external corrosion protection using coatings was estimated at $260 million per year. Therefore, the estimated annual total cost of corrosion in home appliances is at least $460 million + $780 million + $260 million = $1.5 billion per year.

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SECTOR DESCRIPTION

This sector describes the U.S. home appliances industry and the estimated cost of corrosion for this industry. In this sector, the focus will be on those appliances that people have in their homes, and will not be on commercial appliances, such as those used in warehouses, office buildings, or restaurants. More information on commercial equipment used in manufacturing environments is given in the sectors titled "Chemical, Petrochemical, and Pharmaceutical Industries" (Appendix V); "Agricultural Production" (Appendix X); and "Food Processing" (Appendix Y) of this report.

Home appliances are an integral part of the American lifestyle, providing convenience and high-quality performance for cooking, washing, cleaning, heating, or cooling purposes. Appliances save time, sanitize, and contribute to safety and conservation in the course of any daily chores. The appliance industry is one of the largest consumer product industries.

Every year, *Appliance Magazine*(1) publishes an annual report on the number of appliance unit shipments in the United States. In this review, a distinction is made between "Major Home Appliances" and "Comfort Conditioning Appliances."

MAJOR HOME APPLIANCES

- Microwaves
- Ranges
- Refrigerators
- Water heaters
- Washers
- Dryers
- Dishwashers
- Food waste disposers
- Freezers
- Water softeners
- Trash compactors
- LP ranges and cooktops for RVs

COMFORT CONDITIONING APPLIANCES

- Fans
- Air conditioners
- Humidifiers
- Furnaces
- Portable heaters
- Heat pumps
- Dehumidifiers
- Room heaters
- Boilers

In the current sector description, both categories will be described, because both are equally important in maintaining a home and everyday comfort of living. In addition, the costs for both types of appliances are fully paid by their individual owners. Table 1 and table 2 show the trends of (new) appliance shipments over the last 25 years. In 1999, 70.7 million major home appliances and 49.5 million comfort conditioning appliances were sold in the United States, for a total of 120.2 million appliances.

Table 1 shows a summary of the number of new major home appliances shipped annually for the period 1975 to 1999. The table shows that microwaves, ranges, and refrigerators are the leading appliances in sales, followed by water heaters, washers, dryers, dishwashers, and food waste disposers. Smaller quantities are sold of freezers, water softeners, and trash compactors. The table also shows that the sales of microwaves have increased from 0.79 million in 1975 to 11.6 million in 1999. The growth in sales for the other appliances has been less dramatic, but the sales of almost every appliance have seen an increase of approximately 100 percent in the last 25 years. The sales of freezers and trash compactors have decreased.

Table 1. Statistical review of unit shipments of new major home appliances (excluding commercial appliances) in the United States for years in the period 1975 to 1999, as reported in annual reports of *Appliance Magazine.*(1-3)

APPLIANCE	1975	1980	1985	1990	1995	1999	CHANGE 1975-1999
	Quantity	Quantity	Quantity	Quantity	Quantity	Quantity	%
Microwaves	790,000	3,320,000	10,883,000	9,276,330	8,975,000	11,581,085	+1,366
Ranges	5,077,400	6,468,500	7,952,000	8,322,800	9,641,500	11,118,600	+119
Refrigerators	4,895,000	5,667,000	6,863,500	8,033,800	9,825,500	10,737,383	+119
Water heaters	4,828,510	5,269,284	6,981,214	7,132,585	8,370,330	9,214,858	+91
Washers	4,478,000	4,816,000	5,581,500	6,536,100	7,101,100	7,508,200	+68
Dryers	3,060,000	3,383,000	3,913,500	4,595,100	5,384,600	6,477,700	+112
Dishwashers	2,702,000	2,738,000	3,575,400	3,636,900	4,553,500	5,711,200	+111
Food waste disposers	2,080,000	2,962,000	4,105,000	4,137,200	4,518,900	5,369,400	+158
Freezers	2,736,000	2,062,000	1,235,800	1,296,000	1,690,500	1,987,200	-27
Water softeners	-	-	-	574,133	717,542	951,498	-
Trash compactors	233,000	235,000	177,200	185,000	98,400	114,700	-51
LP ranges and cooktops for RVs	-	123,896	-	-	-	-	-
TOTAL	**30,879,910**	**37,044,680**	**51,268,114**	**53,725,948**	**60,876,872**	**70,771,824**	**+129%**

Table 2 shows a summary of the number of new comfort conditioning appliances shipped annually, for the period 1975 to 1999. This table shows that air fans, air conditioners, and humidifiers are the leading appliances in sales, followed by furnaces, heaters, and heat pumps. Smaller quantities are sold of dehumidifiers, room heaters, and boilers. The table further shows that sales of humidifiers have increased from 1.0 million in 1975 to 9.8 million in 1999, and sales of room heaters have increased from 0.13 million in 1975 to 0.50 million in 1999. The growth in sales for the other appliances has been less dramatic, but sales of almost every appliance have seen an increase of approximately 100 percent in the last 25 years. The sales of portable heaters have decreased.

Table 2. Statistical review of unit shipments of new comfort conditioning appliances (excluding commercial appliances) in the United States for years in the period 1975 to 1999, as reported in annual reports of *Appliance Magazine.*[1-3]

Appliance	**1975**	**1980**	**1985**	**1990**	**1995**	**1999**	**Change 1975-1999**
	Quantity	**Quantity**	**Quantity**	**Quantity**	**Quantity**	**Quantity**	**%**
Fans	7,839,000	14,640,000	18,919,054	31,918,667	14,340,000	19,100,000	+144
Air conditioners	4,441,484	5,150,885	5,716,787	7,353,275	8,363,476	11,467,276	+158
Humidifiers	1,031,000	821,000	1,231,000	1,058,330	3,140,000	9,800,000	+851
Furnaces	1,994,166	1,948,430	2,564,090	2,537,856	2,917,694	3,419,024	+71
Portable heaters	2,990,000	4,569,000	6,684,000	6,155,900	3,138,000	2,700,000	-10
Heat pumps	-	442,829	820,623	808,655	1,024,885	1,293,395	-
Dehumidifiers	392,000	673,000	588,400	742,500	1,002,800	871,000	+122
Room heaters	125,130	282,300	282,969	317,775	575,940	503,131	+302
Boilers	187,021	344,972	295,982	316,073	338,003	349,943	+87
TOTAL	**18,999,801**	**28,872,416**	**37,102,905**	**51,209,031**	**34,840,798**	**49,503,769**	**+161%**

Replacement Rates and Life Expectancies

The life expectancy of appliances is determined from past experience and sales data. Table 3 shows a list published in the year 2000 by *Appliance Magazine*, showing life expectancies for each type of appliance, with a low, a high, and an average number of years before a first owner purchases a replacement for an appliance. This does not necessarily mean that the appliance is worn out. When a replacement is purchased, the old unit is either traded in, relegated to use elsewhere, given away, or discarded, thereby ending the first-owner life cycle. The estimates contained in the table represent the expert judgement of *Appliance Magazine* staff based on input obtained from many sources.

In addition to the life-cycle expectancy for each appliance category, the estimated number of units that will be eligible for replacement in 2001 are given in the table. These appliances may be replaced with the same type of product, an appliance of a different type, or not at all. To obtain these figures, the average life expectancy (in years) was taken and used to find the number of unit shipments made that many years prior to 2001. It is noted that these replacement numbers do not take into account the changes in life expectancy over the years.

Table 3. Life expectancy / replacement time of appliances, as reported in the 23rd annual portrait of the U.S. appliance industry.[4]

MAJOR HOME APPLIANCES (EXCLUDES COMMERCIAL APPLIANCES)

	Life Expectancy, years			**Units to be replaced in 2001**	**Units that were shipped in 1999**
	Low	**High**	**Average**		
Microwaves	5	10	8	8,132,300	11,581,085
Ranges, electric	13	20	16	3,227,700	7,016,939
Ranges, gas	15	23	19	1,367,400	3,136,200
Ranges, hoods	9	19	14	2,595,000	3,000,000
Refrigerators, compact	4	12	8	1,030,000	141,283
Refrigerators, standard	10	18	14	6,972,100	9,098,600
Water heaters, electric	6	21	14	3,396,395	4,281,199
Water heaters, gas	5	13	9	4,241,354	4,933,659
Washers	8	16	12	6,607,500	7,508,200
Dryers, electric	11	18	14	3,381,200	4,864,700
Dryers, gas	11	16	13	1,046,800	1,443,000
Dishwashers	9	16	12	3,668,400	5,711,200
Food waste disposers	10	15	13	4,232,600	5,369,400
Freezers	12	20	16	1,472,800	1,987,200
Water softeners*	-	-	-	-	951,498
Compactors	7	12	11	185,000	114,700
TOTAL				**51,556,549**	**71,138,863**

COMFORT CONDITIONING APPLIANCES

	Life Expectancy, years			**Units to be replaced in 2001**	**Units that were shipped in 1999**
	Low	**High**	**Average**		
Fans, ceiling	7	18	13	6,400,000	19,100,000
Air conditioners, room	7	16	12	5,091,100	6,113,600
Air conditioners, unitary	8	19	13	3,214,606	5,353,676
Humidifiers	6	13	10	612,000	9,800,000
Furnaces, electric	9	20	14	375,055	-
Furnaces, gas	11	23	17	2,049,335	3,293,646
Furnaces, oil	13	23	18	127,305	125,378
Portable heaters	8	13	11	5,542,900	2,700,000
Heat pumps	6	21	14	918,432	1,293,395
Dehumidifiers	9	13	11	742,500	871,000
Room heaters, vented gas	7	18	13	91,426	35,927
Room heaters, unvented gas	13	23	18	217,566	467,204
Boilers, gas*	-	-	-	-	200,893
Boilers, oil*	-	-	-	-	149,050
TOTAL				**25,382,225**	**49,503,769**

*No data available for the life expectancy of water softeners and boilers.

AREAS OF MAJOR CORROSION IMPACT

Corrosion Impact by Type of Corrosion

There are some common areas of significant corrosion impact for major home appliances and comfort conditioning appliances. The corrosion types include: internal corrosion from process water and external corrosion from wet locations.

Internal Corrosion

The most important reason for corrosion in appliances is the water that is being handled by the equipment. This type of corrosion affects the internal components of appliances and limits life expectancy. In the category of major home appliances, the following appliances are most susceptible to internal corrosion: refrigerators, water heaters, washers, dish washers, and water softeners. In the category of comfort conditioning appliances, the following appliances are most susceptible to internal corrosion: air conditioners, humidifiers, furnaces (especially those high-efficiency furnaces, because of condensate formation in the heat exchangers), dehumidifiers, and boilers.

Internal corrosion in appliances is a problem because it limits the useful life. This is a direct cost of corrosion. For example, a unitary air conditioner has an average life of 13 years, as mentioned in table 3. One of the reasons for this limited life expectancy is that condensate in the air conditioner corrodes the internal metal components. If the useful life would be longer, people would not be buying a new unit after 13 years, which would save a significant amount of money for consumers.

A quick estimate of the annual cost that could be saved if unitary air conditioners would have one more year of useful life can be made as follows: Table 3 shows that 3.2 million units are up for replacement in 2001. If improved corrosion resistance could make the average life of a unit 14 years instead of 13 years, then 1/14th of the replacement cost would not have been incurred. The estimated average unit cost is approximately $300. It is recognized that this number may be reasonable for window air conditioners while being too low for whole house air conditioners. If this estimate is used, then the hypothetical cost-savings due to improved corrosion design would be: 3.2 million x 1/14 x $300 = $68.5 million per year.

The above estimate is only an example, and it is only showing a calculation of one type of appliance. Also, it is not shown how much the annual cost would be to achieve the improved corrosion design. For a complete analysis, both costs and benefits should be considered, and for a national estimate, the results for all appliances should be combined.

External Corrosion

The second type of corrosion that affects the appliances is external corrosion. External corrosion can deteriorate the appearance of the surface of an appliance, but that generally does not limit the capability of an appliance to function properly. However, the value of appliances surely decreases when external corrosion occurs, because consumers do not find rusty appliances in their home appealing. In addition to corrosion of non-coated surfaces, corrosion can occur when coated or painted surfaces become chipped or nicked. Examples of wet environments around appliances are a furnace or a boiler in the humidity of a damp basement, an air conditioning unit standing in a yard or hanging from a window, being exposed to the rain and moisture (especially in coastal areas where salt is in the air), and kitchen equipment of which the exteriors are often cleaned with water or wet towels.

External corrosion of appliances is a problem because it deteriorates their appearance, and therefore affects their resale value. This cost is a direct cost of corrosion. The tables at the beginning of this sector description show the number of new appliances shipped in the United States. But, in many cases, people decide to upgrade appliances before the entire useful life has been consumed. Therefore, the resale value of second hand appliances is important, because the money received from a trade-in or resold appliance can pay for part of the cost of a new appliance.

Corrosion Impact by Type of Appliance

Corrosion issues vary with the type of appliance. Corrosion can build up and destroy parts of or the entire appliance. In the following text, the areas of major corrosion impact regarding the internal components of appliances are described for several appliances that can be significantly affected by corrosion. These appliances include: water heaters, boilers, high-efficiency furnaces, and air conditioners.

Water Heaters

The heating coils in water heaters are exposed to the water in the heater tank. Common water contaminants such as chlorides, fluorides, and sulfates can cause corrosion of the heating coils, the water heater connections, the tank wall, and the tank frame. The elevated temperature of the water in the heater is further likely to increase the rate at which internal corrosion occurs.

One method to control internal corrosion is the use of corrosion-resistant materials, such as stainless steels and other corrosion-resistant alloys (CRA) for the heat exchanger coils. Another method that is always applied in water heaters to control the internal corrosion is the application of sacrificial anodes. The condition of the water heater's sacrificial anode is critical for its corrosion protection. In sacrificial cathodic protection of water heaters, a magnesium rod is permanently inserted into the water and the rod serves as a sacrificial anode to protect the carbon steel parts.

Boilers

Boilers are heat exchangers constructed of carbon steel to produce hot water or steam by being heated with an oil or gas burner. The hot water or steam is transferred to radiators to provide heat. After releasing heat, the cool water or steam condensate is returned to the boiler for reheating.

A common problem in boilers is the occurrence of calcium oxide scale build-up on the heating elements. This is not a corrosion problem in itself, because it is caused by a chemical reaction in the water at higher temperatures. However, a scale deposit present on a metal surface may cause corrosion under the deposit. This type of under-deposit corrosion can be aggravated when corrosive elements such as sulfides and/or chlorides are present in the water. While scale deposits reduce the thermal conductivity of the steel, and thereby increase energy costs, corrosion of the heating element can lead to a catastrophic tubing failure, which requires costly repairs.

High-Efficiency Furnaces

Corrosion can occur in furnaces when condensation occurs, which can corrode the internal metal surfaces. Condensation is a problem in high-efficiency furnaces, because operating at greater efficiencies means that the appliance must operate in a condensing mode. Currently, these types of furnaces are designed with a maximum annual flue utilization efficiency (AFUE) of 90 percent, compared to the standard minimum efficiency of 78 percent. To operate a high-efficiency furnace, the flue gas must be cooled to a temperature below the dew point, by which the combustion-generated moisture is condensed in the heat exchanger, and the latent heat of vaporization is recovered for utilization.

Research in the mid-1980s on corrosion of materials used in condensing heat exchangers in furnaces indicated that the greatest probability of corrosion occurs when the appliance goes through the transition from wet to dry conditions. This is because the acidity of the condensate increases as the water evaporates. The flue gas generated is a mildly acidic liquid that is corrosive to alloys such as Type 304 and Type 316 stainless steel commonly used in heat exchanger furnaces. The corrosivity of the condensate can increase due to common airborne contaminants, particularly chlorine-containing compounds, present in indoor environments and carried into the burner by the combustion process. Research on corrosion-resistant materials for condensing heat exchangers, such as by

Battelle[5-6] and the American Gas Association (AGA) Laboratories for the Gas Research Institute (GRI),[7-8] resulted in recommendations for condensing heat exchanger design. These recommendations included design recommendations on how to minimize condensation in non-condensing regions of heat exchangers, how to reduce the corrosiveness of flue-gas condensate, and a list of materials that are corrosion-resistant to flue-gas condensate.

The application of non-metallic materials for full condensing types of appliances is an alternate option to steel. For example, polyvinyl chloride (PVC) is preferable in the vicinity where the exit flue gas would be in the temperature envelope in which stress corrosion cracking of stainless steels is a problem. However, the application of some plastics is difficult at temperatures higher than ambient, because they become increasingly soft.

Air Conditioners

Aluminum and copper are materials used for the internal components of air conditioners. Coils and cooling fins are made from aluminum and piping is usually made of copper. Aluminum is susceptible to galvanic corrosion when it is in contact with copper components. Galvanic corrosion can occur when two dissimilar metals are in electrical contact in an electrolyte (in this case, water).

Piping or plumbing systems made from copper alloys are susceptible to erosion-corrosion in unfavorable fluid flow conditions. Erosion-corrosion can occur when erosive action of the flowing stream removes the protective copper oxide film from the metal surface, thereby exposing non-passivated bare metal to the corrosive environment.[9]

CORROSION CONTROL METHODS

There are three basic corrosion control methods that are used to protect or mitigate corrosion in home appliances: corrosion control by sacrificial anodes, the use of corrosion-resistant materials, and corrosion control by coatings and paint. The following text describes each of these basic methods, using some practical examples and showing some basic cost calculations.

Corrosion Control by Sacrificial Anodes

Most people do not realize that by checking and changing a deteriorating anode, the life of a hot water heater can be extended considerably. It has been stated that the direct cost of not having to replace broken water heaters can result in savings for individuals and businesses of as much as 70 percent – both in time and money.[10] In addition, checking and, if necessary, replacing the (one or two) anode(s) of a water heater provides protection from sudden floods, which can result in indirect costs for clean-up and damages. The indirect cost can potentially be much larger than the costs related to installing a new tank, or of retrofitting an old one. The life expectancy of sacrificial anodes depends on the local water conditions, and can range from 2 to 3 years to more than 10 years.

The key benefits of proper anode maintenance are:

- Tank lasts longer.
- Less rust build-up.
- Save on costly changeovers.

Calculating the Cost of Corrosion Protection by Sacrificial Anodes

Every water heater has one or more sacrificial anodes to protect the internal components from corrosion. There are two types of possible corrosion costs related to anodes: the cost of replacing the entire water heater because it failed due to corrosion, and the cost of replacing the anode(s) only, which includes the cost of materials and labor. Alternatively, one could consider an improved design with a longer anode life that could possibly increase the life expectancy of water boilers. In the following paragraphs, these three methods of estimating corrosion costs are applied. It is noted that the assumptions made in these calculations are only partial approximations (for one type of appliance), and that should be performed to get national estimates for all appliances.

Cost of Replacing Water Heaters

As shown in table 3,(4) the total number of new water heaters shipped in 1999 was 9,214,858 heaters, distributed over 4,281,199 electric water heaters and 4,933,659 gas water heaters. The average life expectancy is 14 years for electric water heaters and 9 years for gas water heaters. According to *Consumer Reports Online*,(11) the range of installed costs for new water heaters is $800 to $1,200 (average $1,000). If this average $1,000 value is multiplied by the total number (9,214,858) of new water heaters in 1999, it is estimated that a total of $9.2 billion was spent in the United States on replacement of water heaters.

The *Appliance Magazine* report(4) does not specify the reasons for appliance replacement, but it may be assumed that some portion is due to modernization, while another portion is due to substitution because of wear and tear. Corrosion failure would be ranked in the wear-and-tear category. If it is assumed (no other data available for this calculation) that 5 percent of the annual replacement of water boilers is due to corrosion failure, then the cost of corrosion in 1999 would be $9.2 billion x 5 percent = $460 million per year.

Cost of Anode Replacement

Using the numbers in table 3,(4) an approximation of the total number of current water heaters can be made by multiplying the number of unit shipments by the average life expectancy of the appliance. This calculation results in estimates of approximately 4,281,199 heaters per year year x 14 years = 59,936,786 electric water heaters, and 4,933,659 heaters per year x 9 years = 44,402,931 gas water heaters. Adding these two numbers results in a total of 59,936,786 + 44,402,931 = 104.3 million water heaters in use.

Statistical data were not found on the number of water heaters that are serviced with a replacement anode each year. Therefore, to complete this calculation, an assumption was made that, on average, 5 percent of all water heaters would have their anodes replaced each year. In other words, it was assumed that 1 out of 20 water heaters gets its anode replaced each year. The other estimate required for the calculation is made as a total cost of $150 per anode replacement for materials ($80 per anode) and labor ($70 for one hour). The total annual cost of anode replacement then becomes: 104 million anodes in water heaters x 5 percent replaced per year x $150 per replacement = $780 million per year.

Cost-Savings of Increased Life Expectancy

In an earlier calculation, the assumption was made that the corrosion life could be extended by 1 year by improved corrosion design. If this were true, the average life expectancy of electric water heaters would increase from 14 years to 15 years, and the average life expectancy of gas water heaters would increase from 9 to 10 years. Under these assumptions, the hypothetical cost-savings because of improved corrosion design for electric water heaters would be 4.28 million x 1/15 x $1,000 = $285 million per year, and for gas water heaters it would be 4.93 million x 1/10 x $1,000 = $493 million per year. The total cost-savings would be $285 million + $493 million = $778 million per year.

Summary of Costs Related to Sacrificial Anodic Protection

In the above paragraphs, the cost of replacing water heaters was estimated at $460 million per year, the cost of anode replacement was estimated at $780 million per year, and the cost of increased life expectancy of water heaters was estimated at $778 million per year. The magnitude of the dollar values is similar.

The benefits of anode maintenance are longer tank life, less rust build-up, and savings on costly changeovers. However, a cost-benefit analysis may show that the cost of replacing anodes could exceed the cost of the increased life expectancy or the cost of water heater replacement. In addition, it was not shown that increased life expectancy without increased cost would be technically feasible. Also, it is not known how much life is actually gained by the replacement of water heater anodes, because the appliance may fail because of another reason, such as a heating element failure. As noted earlier, the assumptions made in these calculations are only approximations, and therefore it is recommended that a full analysis of statistical data be performed to get an insight into the nationally incurred costs of the corrosion issues related to sacrificial anodes in water heaters.

Corrosion Control by Corrosion-Resistant Materials

If possible, one would like to manufacture all appliances of unpainted carbon steel, because of its high strength and relatively low cost. However, in reality, corrosion-resistant materials must be used to prevent corrosion from occurring. Common materials used for this purpose are plastics, galvanized steel, stainless steel, aluminum, and copper-nickel alloys.

Plastics are used because they are corrosion-resistant and they prolong the product life and the durability in the hostile environments where major appliances must operate. It has been reported(12) that the use of plastics can increase durability and equipment life by 30 to 40 percent.

Galvanized steel is carbon steel with a zinc coating, that protects the cold-rolled steel from corrosion in aqueous and high-temperature environments. Galvanized steel is used in laundry appliances because it provides detergent resistance. The cost for processing steel into galvanized parts is dependant upon the facility, but generally ranges from $50 to $100 per metric ton of zinc.

Stainless steels are commonly used to design high-efficiency furnace components (heat exchangers). According to the Specialty Steel Industry of North America, the total stainless steel usage for heating and air conditioning equipment is 81.0 million kg (89 thousand tons). The annual (1998) consumption of stainless steel for the appliance industry was estimated at $315 million per year.(13) Assuming that the reason for using stainless steel is to control corrosion, the estimate can be attributed entirely to corrosion.

Aluminum is often used for control panels of appliances. The thin aluminum oxide film that forms instantaneously on aluminum when exposed to air serves as protection against corrosion. Surface treatments such as anodizing and cladding help to further improve corrosion resistance.

Copper-nickel alloys are typically used in tubing and coils of heater and air conditioning systems because of their high thermal conductivity in heating and cooling applications. Copper-nickel alloys (e.g., 70/30 Cu/Ni and 90/10 Cu/Ni) have acceptable erosion-corrosion resistance in water compared to pure copper.

Corrosion Control by Coatings and Paint

Liquid coatings (paints), powder coatings, and porcelain enamel coatings are used in the appliance industry. Pretreatments that influence the appliance performance level are used for surface cleaning and adhesion purposes of coatings. Pretreatment systems include iron phosphate and zinc phosphate. The cost of iron and zinc phosphate pretreatments depends on the following factors: (1) continuous or intermittent manufacturing, (2) the geometry of the part, and (3) control of chemical processing.

Liquid coatings are used for refrigerators since they are corrosion-resistant and have a relatively low cost. For refrigerator coils, the thickness of the coating is on the order of 0.05 mm to 0.10 mm (0.002 to 0.004 in). In clothes washers and dryers, a primer coating is applied to galvanized steel. The average cost of liquid coating(14) is estimated as $1.32 to $1.50 per kg ($0.60 to $0.68 per lb). If the cost of primer and topcoat are both considered, the total cost is estimated as $2.64 to $2.99 per kg ($1.20 to $1.36 per lb).

Powder coatings are organic coatings that are used primarily on boiler and furnace steel sheets. They are applied by depositing a mist of powder on the product in an electrostatic field, followed by a baking process. Powder coatings are becoming more widely recognized because of their benefits with regard to environmental issues and quality of coating, coating requirement, and cost. Powder coatings are applied as single coatings, and have an estimated price of $2.20 to $3.30 per kg ($1.00 to $1.50 per lb). When the recovered material is captured and reused, this price is reduced by 60 percent; therefore, the cost is reduced to $1.32 to $1.98 per kg ($0.60 to $0.90 per lb).

Porcelain enamel is mainly used in high-level performance appliances. They are more scratch-resistant and heat-resistant than the thinner liquid and powder coatings; however, porcelain enamel is porous. Holidays are sometimes found in the porcelain (glass). Magnesium, zinc, and aluminum anode rods are used in combination with porcelain enamel coatings in water heating systems to act as a sacrificial anode. Enamel coatings are applied as thick films, ranging between 0.10 to 0.15 mm (0.004 to 0.006 in). The estimated cost is $2.20 to $3.30 per kg ($1.00 to 1.50 per lb). In the application, the material costs are estimated to cost 50 percent less than those used for organic coatings; however, the process of applying porcelain enamel to metal substrate is costly.

Calculating the Cost of Coatings on Appliances

The above analysis showed some estimated costs for three types of coatings. These costs only include the ingredient materials, not the application cost. In summary, the estimated material costs were:

Liquid coatings:	$2.64 to $2.99 per kg
Powder coatings:	$1.32 to $1.98 per kg
Enamel coatings:	$2.20 to $3.30 per kg

To calculate a national estimate of coating costs, an average coating cost per appliance must be assumed, and for the following calculation, this average is estimated at $2 per appliance. Table 1 and table 2(1-3) summarized that in 1999, the total number of major home appliance and comfort conditioning appliance unit shipments was 70,771,824 + 49,503,769 = 120,275,593. Applying a coating to all these new appliances is therefore estimated to cost a total of 120,275,593 x $2 = $240 million per year.

CORROSION MANAGEMENT

The average consumer buying an appliance is only marginally interested in corrosion issues. If an appliance looks acceptable in appearance in a store, it is automatically assumed that it will maintain that appearance over the life of the appliance. Therefore, during the useful life of the appliance, no corrosion management is done by consumers. For example, very few people realize that there is an anode in every water heater, and that this sacrificial bar of metal should be checked and, if necessary, replaced with a new one to prevent water heater failure due to internal corrosion. The life expectancy of appliances is determined from past experience and sales data. Improved corrosion design for appliances can increase their life expectancy; however, if improved corrosion protection would mean the use of more expensive components for the appliances, then consumers may not be interested.

CHANGES FROM 1975 TO 2000

Statistics of the last 25 years (1975 - 1999) show that the number of new appliances has consistently exceeded the number of replacement appliances purchased. The average life expectancy of appliances has probably increased in the same period because of improved use of anodes, corrosion-resistant materials, and paints and coatings. A portion of this increase has been due to the increased standard of living, while another portion can be attributed to the growth of the population from 1975 to 2000.

Replacement and limited useful life is preferred by manufacturers of appliances. The calculations in this sector description show that the non-optimal performance of appliances comes at a significant cost to consumers. Although the consequences of an appliance undergoing corrosion or failing are not catastrophic, the costs to replace appliances are considerable. Statistics show that, on average, every American buys one appliance every 2 years and 3 months (270 million citizens / 120.2 million appliances per year).

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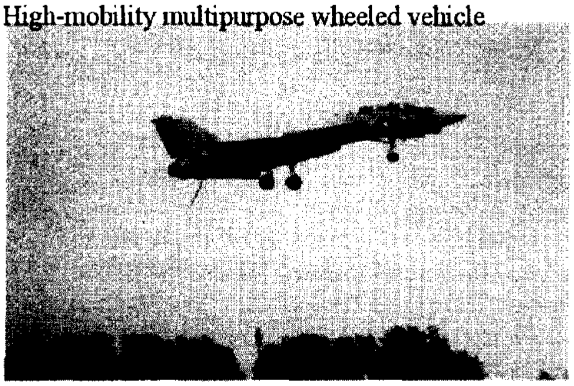
APPENDIX BB

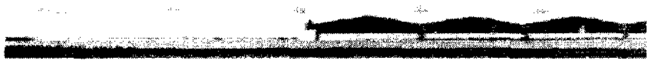
DEFENSE

High-mobility multipurpose wheeled vehicle



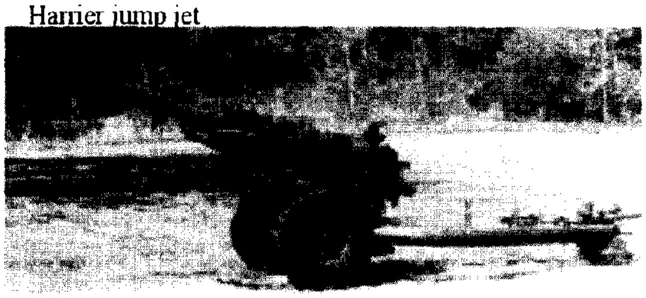
F-18 Fighter Jet

Towed howitzer

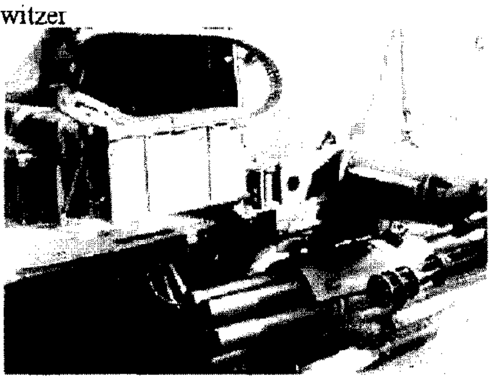


KC-135 tanker

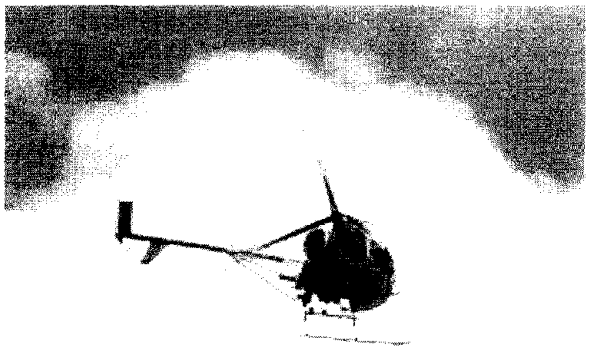
Harrier jump jet



Towed howitzer



Rocket launcher on helicopter



Helicopter

DEFENSE

GERHARDUS H. KOCH, PH.D.[1]

SUMMARY AND ANALYSIS OF RESULTS

Corrosion Control and Prevention

The ability of the U.S. Department of Defense (DOD) to respond rapidly to national security and foreign commitments can be adversely affected by corrosion. Corrosion of military equipment and facilities has been, for many years, a significant and ongoing problem. The effects of corrosion are becoming more prominent as the acquisition of new equipment is slowing down and the services of aging systems and equipment are increasingly relied upon. The data provided by the military services indicate that corrosion is the number one cost driver in life-cycle costs. The total annual cost of corrosion incurred by the military services (Army, Air Force, Navy, and Marine Corps) for both systems and infrastructure was estimated at $20 billion.

A considerable portion of the cost of corrosion to the Army is attributed to ground vehicles, including tank systems, fighting vehicle systems, fire support systems, high-mobility multipurpose wheeled vehicles (HMMWV), and light armored vehicles. Other systems that are affected by corrosion include firing platforms and helicopters. Many of the Army systems are well beyond their design service lives and because of the generally aggressive operating environments, corrosion is becoming increasingly severe and costly. While often replacement of the aging systems is not budgeted for, insufficient use is being made of existing technology to maintain these systems in a cost-effective way. Even with the procurement of new weapons systems, the use of corrosion-resistant materials and design are often neglected. For example, when the HMMWV was procured, corrosion was completely ignored in the design and manufacturing of the vehicle. Without corrosion design and the incorporation of corrosion-resistant material, the acquisition cost of the vehicle could be reduced. However, costly corrosion problems were experienced on the vehicles only a few months after delivery. Similar problems were found with the acquisition of other systems, such as the medium tactical vehicles (MTV).

In recent years, the Air Force has experienced considerable corrosion problems. As with the commercial aircraft industry, corrosion on the airframe has, in the past, not been considered to have an impact on the structural integrity; therefore, a “find it and fix it” approach has long been the preferred way to deal with corrosion in aircraft. With no significant funding available for new systems acquisition, the Air Force is forced to extend the operational life of many of the aircraft far beyond their design service lives. For example, the KC-135, which is the backbone of the Air Force tanker fleet, and which was built between 1955 and 1963, will have to serve until the year 2040. This aircraft, which was built with 1950s corrosion control technology (none), was never meant to serve this long, and hence, severe corrosion has been experienced. The results of all the corrosion problems with the KC-135 have led to a significant increase in depot maintenance over the past 10 years. Mainly as a result of corrosion, the depot overhaul flow days have increased from less than 100 days in 1990 to approximately 350 days in 2000.

Because of their missions, the Navy and Marine Corps have always operated in aggressive corrosive environments. The Navy operates the fleet as well as naval aircraft, and harbor and dock facilities. The fleet consists of various types of surface ships and submarines, which are continuously exposed to marine environments. The primary defense against corrosion is the diligent use of protective coatings. In addition to coatings, cathodic protection systems are used for corrosion protection of the underwater hull. In recent years, more durable and longer lasting paint systems have been introduced to replace what used to be very labor-intensive paint systems.

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[1] CC Technologies Laboratories, Inc., Dublin, Ohio.

Navy aircraft systems require constant maintenance due to operation in predominantly marine environments. As in the Air Force, many aircraft systems are operating beyond their design service lives, which leads to an increasing cost of corrosion maintenance.

Opportunities for Improvement and Barriers to Progress

The aging of military systems poses a unique challenge for maintenance and corrosion engineers in all four Services. The most serious problem facing the military is aging equipment, with no immediate promise of replacement; therefore, there is a need to develop corrosion maintenance programs that can carry the various aging systems well into the 21st century. Such a program requires cooperation between all the services and the commitment of systems management and maintenance personnel to succeed. Developing an optimum approach to inspection, monitoring, and maintenance is necessary to maintain the readiness of the nation's military systems in a cost-effective manner until replacement by new systems is possible. Awareness of the corrosion problems and knowledge about state-of-the-art corrosion control techniques will be essential in developing and carrying out a successful corrosion control and maintenance program.

Although each of the services is trying to deal with its own aging systems problem, it is of the utmost importance that a cooperative corrosion/integrity program is implemented. For example, while the Navy has been dealing with corrosion on its aircraft on a daily basis, the Air Force has, until recently, ignored corrosion unless it becomes clearly visible. Although the Air Force currently has a well-developed program in place to monitor and control fatigue cracking [i.e., Air Force Structural Integrity Program (ASIP)], corrosion was not considered to be a structural threat and was therefore essentially treated on a "find it and fix it" basis, but only when it was clearly visible.

When new systems are procured, the design service lives, as determined by corrosion, have often taken a backseat to immediate performance and quantity of procurement.

Recommendations and Implementation Strategy

In order to preserve the aging military assets, a DOD corrosion control and maintenance program must be developed and implemented for all of the services. An important component of such a program is the increase in awareness and recognition by all military personnel from systems management to procurement and maintenance personnel that corrosion is an important factor in the life of any military system. Courses and training will be needed to develop the knowledge to deal with corrosion. Funding needs to be made available to develop predictive corrosion models and new inspection and monitoring techniques, which will enable systems management to maintain their systems in a cost-effective manner.

Life-cycle costing must be considered when new systems are procured. This will allow acquisition of systems with the best available corrosion protection.

Summary of Issues

Increase consciousness of corrosion costs and potential savings.	Both personnel responsible for the procurement of new systems and those responsible for maintaining existing systems must be aware of the effects of corrosion, as well as the corrosion control techniques and methods that are available to cost-effectively mitigate these effects.
Change perception that nothing can be done about corrosion.	Although corrosion is a well-known phenomenon in the military, state-of-the-art mitigation techniques are generally not used.
Advance design practices for better corrosion management.	When new systems are procured, performance and quantity are emphasized at the expense of corrosion control.
Change technical practices to realize corrosion cost-savings.	The key is to incorporate state-of-the-art inspection monitoring and other corrosion control techniques into a corrosion management system.
Change policies and management practices to realize corrosion cost-savings	Systems management must appreciate the importance of corrosion and understand its impact on total life maintenance costs. Cooperation between the services to manage the military's new and aging assets is a necessity. The "find it and fix it" mentality to corrosion maintenance should be changed.
Advance life prediction and performance assessment methods.	The development of corrosion life prediction and performance models is critical to cost-effective asset management. Effective predictive models are currently not available.
Advance technology (research, development, and implementation).	Technological advances that are needed include a better understanding of the corrosion process and improved inspection and monitoring techniques.
Improve education and training for corrosion control.	Education and training of engineering personnel and technicians are necessary if a cost-effective corrosion control and maintenance program is to be implemented.

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SECTOR DESCRIPTION

The ability of the U.S. Department of Defense (DOD) to respond rapidly to national security and foreign policy commitments can be adversely affected by equipment-related factors. Using available resources, minimization of downtime and maximization of battle readiness must be accomplished through the useful operational life of the equipment. If this is done effectively, equipment can be deployed in a timely and responsive manner and maintained in the field with a minimum of downtime.

Corrosion of military equipment and facilities has been a significant and on-going problem. Large yearly costs are incurred to protect these assets from corrosion, affecting procurement, maintenance, and operations. The effect of corrosion on various systems is a problem that is becoming more prominent as the acquisition of new equipment slows and more reliance is placed on modifications and upgrades to extend the life of the current systems. As the intention to operate the aging fleets of aircraft, ships, land combat vehicles, and submarines continues into the 21st century, the potentially detrimental effects of corrosion on the cost of ownership, safety, and readiness must be fully appreciated. The effects of corrosion of the DOD equipment will continue to get worse unless and until new technologies can be utilized to reduce the cost of ownership. Within the DOD, the annual costs are very difficult to ascertain; however, from available data obtained from the individual services (Army, Air Force, Navy, and Marine Corps), it can be estimated that the total annual cost of corrosion to the DOD is approximately $20 billion for systems and infrastructure.(1)

Available data from the services indicate that corrosion in DOD weapons systems is the number one cost driver in life cycle-costs.(2) While the individual services have attempted to quantify the cost of corrosion, neither the mechanisms nor the methodologies exist to accurately quantify what appears to be an enormous problem. Moreover, analysis of field data reveals instances where questionable materials selection early in the acquisition process has led to enormous unanticipated increases in life-cycle costs due to corrosion.(3) Finally, with ongoing force reduction and a reduction in budgets, serious consideration must be given to the selection of advanced materials, processes, and designs that will require less manpower for corrosion inspection and maintenance. The following sections provide specific information on the corrosion costs incurred by the Army, the Air Force, the Navy, and the Marine Corp. It should be noted that the corrosion costs of selected components in these services do not add up to the $20 billion that was referenced above. They only serve as examples of how corrosion can significantly affect the equipment and facilities of the armed services.

Army

The Army, which is a major branch of the armed forces, owns and operates a range of facilities and equipment. These include buildings, vehicles and trucks, aircraft and helicopters, missiles, and weapons storage facilities. Corrosion creates a significant burden for the Army, affecting the Army's readiness, equipment reliability, troop morale, and, in particular, the cost of maintenance of the weapons systems.

Vehicles

A considerable portion of the corrosion cost ($2 billion) is attributed to Army ground vehicles. The major types of vehicles operated by the Army are listed below:

- Abraham Tank Systems – M1 Abrams
- Bradley Fighting Vehicle Systems
  - M2 Infantry Fighting Vehicles (IFV)
  - M3 Cavalry Fighting Vehicles (CFV)
  - Multiple-Launch Rocket Systems (MLRS)
  - Command and Control Vehicles (C2V)

- Bradley Carrier Systems
- Bradley Fire Support Vehicles
    - Medium Tactical Vehicles
    - 2½-Ton Cargo Trucks
    - 5-Ton Cargo Trucks
- High-Mobility Multipurpose Wheeled Vehicles (HMMWV)
- Light Armored Vehicles

Generally, little attention is given to corrosion and corrosion control of Army vehicles. In fact, corrosion on these vehicles is allowed to occur until it affects their load-carrying capacity. Moreover, little has been done to incorporate corrosion protection and control in the design and manufacturing of Army vehicles. For example, none of the medium tactical vehicles has galvanized steel in the body. The high-mobility multipurpose wheeled vehicle (HMMWV) (see figure 1) is known to have several corrosion control shortcomings that result in very high corrosion maintenance costs.(2,4) In designing the HMMWV, several corrosion control features that are now common in commercial vehicles have not been applied.(2) One of the most glaring faults with the HMMWV is that the frame is built of ordinary 1010 steel and that no galvanizing or other corrosion protection is applied. A further problem with the frame is that holes are drilled into the sides of the frame with no drain holes in the bottom. This allows water and dirt to enter and stand inside the frame. Other problems include the use of 1010 carbon steel for components such as fasteners, handles, and brackets, as well as the use of dissimilar metal couples, such as aluminum frames bolted to the steel frames. These and other omissions of corrosion control have led to costly maintenance and repair. During an Inspector General's Audit, various areas prone to corrosion were identified(4) (refer to Case Study 1). The significant shortcomings identified by this audit included:

- use of 1010 carbon steel without galvanizing or any protective coating,
- presence of many galvanic couples and the use of more than 2,800 rivets that may act as possible locations for corrosion,
- use of painting procedures that are not state-of-the-art, and
- use of paint that provides little corrosion protection, such as the chemical agent-resistant coatings that deteriorate rapidly in the presence of a corrosive environment.

According to the Inspector General's report, the overall corrosion-related issues associated with the HMMWV and other vehicles cost the Army an estimated $2 billion to $2.5 billion per year.(4) The report points out that corrosion not only affects the cost of vehicle ownership, but also readiness and the overall life of the vehicle. Although there are no cost figures available, the Inspector General estimated that vehicles requiring corrosion repairs were out of service between 2 and 12 months. Furthermore, the threshold for replacement of wheeled vehicles is 65 percent of the acquisition cost of the vehicle. The Inspector General found several examples where the corrosion damage was actually greater than 65 percent of the replacement cost, resulting in vehicles as new as 5 years old being scrapped to be replaced by new vehicles. A more detailed description of corrosion issues with the HMMWV is provided as a case study.

A 1999 report by the U.S. General Accounting Office (GAO) reported that the Army plans to purchase, from 1991 through 2022 (a 32-year period), 85,488 medium tactical vehicles (MTVs) at a projected cumulative cost of $15.7 billion (85,488 x $200,000) to replace its aging medium truck fleet.(5) The report stated that the first 4,955 MTVs that were produced did not meet the MTV's corrosion protection requirements. The contract with the supplier specified that the trucks were to be designed to prevent corrosion from perforating or causing other damage requiring repair or replacement of parts during the initial 10 years of service. Corrosion was found on the cabs of trucks in less than 3 years. Rather than making the contractor replace all 4,955 truck cabs at a cost of $31 million, the Army accepted the contractor's proposal to repair the corrosion damage and to provide a 10-year warranty, not to exceed $10 million, against any future corrosion.

Figure 1. High-mobility multipurpose wheeled vehicle.

The Army also subjected one of the 4,955 trucks to contract-specified corrosion tests. It failed with corrosion being detected in 60 areas. Subsequently, the Army and the contractor agreed on modified production procedures for the next 2,491 produced trucks in order to address the corrosion problem. The contract's final 3,751 trucks were produced with galvanized steel cabs. The Army agreed to pay up to $7 million additional funding for these cabs and other corrosion improvements.

Firing Platforms

Other significant contributors to corrosion costs in the Army are the howitzer firing platforms.(3) The M119 is a 105-mm towed howitzer of British design (see figure 2). Procurement of the M119 started in the late 1980s and was completed in 1996, with a total of approximately 500. In early 1997, severe corrosion was detected on the platform. An investigation by the Army indicated several deficiencies that lead to severe corrosion, including various dissimilar metal contacts resulting in galvanic corrosion and areas on the platform where water could collect. The design of the howitzer platform was such that it needed to be replaced at a cost of $18,000 each; therefore, the total cost to remedy the corrosion problem is estimated to be approximately $9 million.

Figure 2. M119 105-mm towed howitzer.

A second howitzer corrosion problem is experienced with the towed M198 howitzer of which 1,800 are in service (see figure 3). In order to maintain system readiness, an annual expenditure of $5,300 for parts replacement is required for each M198. The total annual maintenance cost for just corrosion-related parts replacement is estimated at $10 million (1,800 x $5,300). Figure 4 shows an attempt to avoid corrosion in an M198 howitzer frame by drilling a drain hole; however, by not having the drain hole at the lowest point, water can still collect inside the frame.

Figure 3. M198 towed howitzer.

Figure 4. Drainhole in M198 towed howitzer.

Helicopters

The Army operates several helicopters for several different duties, with many of the helicopters dating back to the Vietnam era:

UH-1	Huey	personnel ferrying helicopter (900)
UH-60	Blackhawk	personnel ferrying helicopter

CH-47	Chinook	heavy-cargo lifting helicopter (431)
AH-1	Cobra	gunship (379)
AH-64	Apache	attack helicopter (743)
OH-58	Kiowa	reconnaissance helicopter
RAH-66	Comanche	reconnaissance, light attack, and air combat helicopter (1,213 starting deployment in 2008)
MH-6	Little Bird	light assault

In February 2000, the Army released a report indicating that 40 percent of its helicopter fleet is not combat-ready.(6) In addition, these problems are experienced particularly with aging equipment such as the Vietnam War-era Hueys and Cobras, which are assigned mostly to the National Guard and the Army Reserve Units. In addition, newer helicopters, such as the Apaches and Chinooks, also suffer from combat-readiness problems. Approximately 8 to 22 percent of overhaul and repair costs are due to corrosion. In fact, it was estimated that in 1998, approximately $4 billion was spent on corrosion control of helicopters alone.(3)

Air Force

As the fleet of military aircraft and support equipment ages, the damage caused by corrosion becomes of increasing concern. The aircraft spend a longer time in depots for maintenance and repair, which leads to a decrease in readiness and an increase in the cost to maintain the aircraft. Moreover, a possible loss of integrity of the structure is possible if the corrosion goes undetected and becomes severe.

Recently, a study was completed for the Air Force Corrosion Program Office to determine the annual cost of direct corrosion maintenance to the Air Force.(7) The Air Force study examined the cost for fiscal year 1996 and examined costs for all Air Force systems and equipment, including all aircraft, aircraft subsystems, ground systems, vehicles, missiles, munitions, ground support equipment, and space equipment. Corrosion maintenance was defined as a comprehensive inspection for corrosion, all repair maintenance due to corrosion, washing sealant application and removal, and all coating application and removal. Intangible or indirect costs, such as aircraft downtime; the impact on mission performance ability or readiness that results from downtime; and the depreciation effects that result from corrosion maintenance, such as repeated grind-outs of skin and structure, were not addressed in the study. Other intangible or indirect costs that were not addressed include the costs of building corrosion control facilities; the cost of building and maintaining formal corrosion maintenance schools for training of maintenance technicians; and the cost to produce, distribute, and install specialized corrosion control equipment in corrosion control shops.

The total cost of direct corrosion maintenance to the Air Force for fiscal year 1997 was estimated at approximately $800 million.(7) The elements that make up this total cost are summarized in table 1. The table clearly indicates that the majority of the cost can be attributed to aircraft repair and paint. There were also significant expenditures in washing and vehicle maintenance. In addition to the total cost findings, it was found that maintenance in the depot accounted for 80 percent of the total cost of corrosion maintenance. Moreover, it was found that while the total number of aircraft in the fleet has decreased by about 20 percent, the costs have only declined 10 percent, and that maintenance directly attributed to aircraft has actually increased.

The study further compared the 1997 fleet costs with the 1990 fleet costs (see table 2).(7) Changes in the overall corrosion maintenance costs and the contribution of different weapons systems were examined, as well as changes in the per plane costs within the specific weapons systems.

Table 1. Elements of total corrosion maintenance cost to the Air Force.[7]

TOTAL MAINTENANCE COST, FISCAL YEAR 1997	
Repair	$572,352,704
Wash	28,443,783
Paint	145,951,530
Vehicles	23,291,759
Munitions	6,247,341
Other	18,540,036
TOTAL	**$794,827,153**

Table 2. Corrosion maintenance cost for individual military aircraft in 1990 and 1997.[7]

AIRCRAFT	1990 FLEET COSTS (1997 $)	NUMBER OF AIRCRAFT	CORROSION COST (%)	1997 FLEET COSTS (1997 $)	NUMBER OF AIRCRAFT	TOTAL CORROSION COST (%)	CHANGE IN NUMBER OF AIRCRAFT
A-10	25,611,157	524	4.25	4,326,700	375	0.69	-149
B-1	1,267,086	76	0.21	7,326,979	95	1.17	19
B-52	95,751,947	228	15.90	39,545,321	94	6.29	-134
C-130	137,963,143	694	22.91	50,351,736	694	8.01	0
KC-135	113,554,678	644	18.86	205,561,487	602	32.72	-42
C-141	68,621,286	231	11.40	102,584,893	220	16.33	-11
C-5	17,019,858	126	2.83	104,595,003	126	16.65	0
CLS	3,286,630	180	0.55	6,301,275	321	1.00	141
E-3	3,698,062	32	0.61	19,851,017	32	3.16	0
F-111	41,778,986	245	6.94	7,749,299	37	1.23	-208
F-15	23,325,398	749	3.87	29,194,683	737	4.65	-12
F-16	17,010,711	1,260	2.83	15,728,095	1,513	2.50	253
Helos	4,854,452	179	0.81	2,511,531	215	0.40	36
C-10	666,302	52	0.11	7,439,773	59	1.18	7
T-37	2,278,434	527	0.38	1,326,593	420	0.21	-107
T-38	13,105,291	812	2.18	23,894,508	451	3.80	-361
A-7	1,600,922	214	0.27				-214
A-37	345,047	58	0.06				-58
F-4	26,867,597	746	4.46				-746
F-5	72,943	7	0.01				-7
OV-10	3,438,883	54	0.57				-54
TOTAL	**$602,118,813**	**7,638**	**100.01%**	**$628,288,893**	**5,991**	**99.99%**	**-1,647**

One of the most significant results was the effect of aging on weapon systems costs. Each of the oldest fleets of aircraft is a high-dollar driver where the difference in costs between these fleets is primarily a reflection of the difference in size and difference in age. Together, these fleets consume more than half of the total corrosion maintenance costs expended by the Air Force. It is anticipated that these corrosion maintenance costs will increase due to continued aging of the fleet. For example, the KC-135 fleet (see figure 5), which was built between 1955 and 1963, is, despite its age, the backbone of the Air Force's tanker fleet. The KC-135 was never meant to handle its mission for this long and was therefore not constructed with corrosion prevention as a primary concern. Moreover, since no funds are available for replacement tankers, it was decided to operate the fleet until the year 2040. Without extensive corrosion maintenance, structural degradation due to corrosion will limit the KC-135 life to less than the year 2040. Because of the decision to extend the service life of the KC-135 well beyond its corrosion design life, corrosion maintenance expenditures have increased from an average of $176,327 per aircraft in 1990 to $341,464 per aircraft in 1997, which is a 94 percent increase. Cost forecasts by the Air Force predict that during the first decade of 2000, the cost of airframe depot maintenance will increase by a factor of two to three. After this period, the costs are expected to level off if all critical components that are subject to corrosion damage are repaired or replaced. Case Study 2 will discuss the KC-135 in more detail.

Figure 5. KC-135 tanker aircraft.

Other significant observations reported in the Air Force Cost of Corrosion study are:

1. The A-10, C-130, and F-16 fleets experienced a reduction in the cost of corrosion maintenance greater than the reduction in fleet size. The decrease in A-10 costs is a strong indicator that corrosion problems with this particular aircraft have been largely resolved. Repeat maintenance has not been required in the areas that received extensive corrosion treatment.

2. The decrease in C-130 corrosion maintenance costs reflects the completion of a significant wing modification on the C-130E fleet and the continued delivery of C-130H models that are built with much more effective corrosion prevention technology than the A, B, and early E models they replaced.

3. The decrease in F-16 costs appears to be a reflection of a significant increase in the fleet size, which results in a younger fleet.

4. Increases are noted in the cost of corrosion maintenance for both the B-1 and E-3 fleets. During the earlier (1990) study, there were no depot corrosion costs reported and, since that time, programmed depot maintenance (PDM) programs have started up. Both aircraft have larger than average percentages going through PDM.

5. The F-111 PDM reduced dramatically because of a projected phase-out of the fleet.

6. The T-38 Queen Bee flow is basically unchanged despite a significant reduction in fleet size. Corrosion maintenance remains a significant part of the T-38 workload.

Navy

The Navy is divided into several components, including ships, submarines, aircraft weapons, and facilities (buildings, piers, docks, and harbor structures). An internal Navy study conducted in 1993 estimated the total cost of corrosion for all naval systems at $2 billion per year.(8)

Ships

The Navy fleet consists of various surface ship battle forces, including 11 aircraft carriers, 106 surface combatants (i.e., cruisers, destroyers, and frigates), 39 amphibious warfare ships, 34 combat logistics ships, and 31 support/mine warfare ships (total of 221 ships). The surface ships are subject to extremely aggressive environments. An extensive corrosion control program is required to maintain the fleet during dry-dock cycles. The primary defense against corrosion is the diligent use of protective coatings. In addition to coating, cathodic protection is used for protection of the underwater hull. The cost to maintain the cathodic protection systems is low compared to the cost of maintaining the various protective coatings.(9) Figure 6 shows a photograph of a destroyer, indicating the different shipboard coatings that are currently in use. The traditional coatings indicated in the figure have a design life of 10 to 15 years, after which the ship has to be in dry dock to completely remove the "old" coatings and apply a "new" coat.

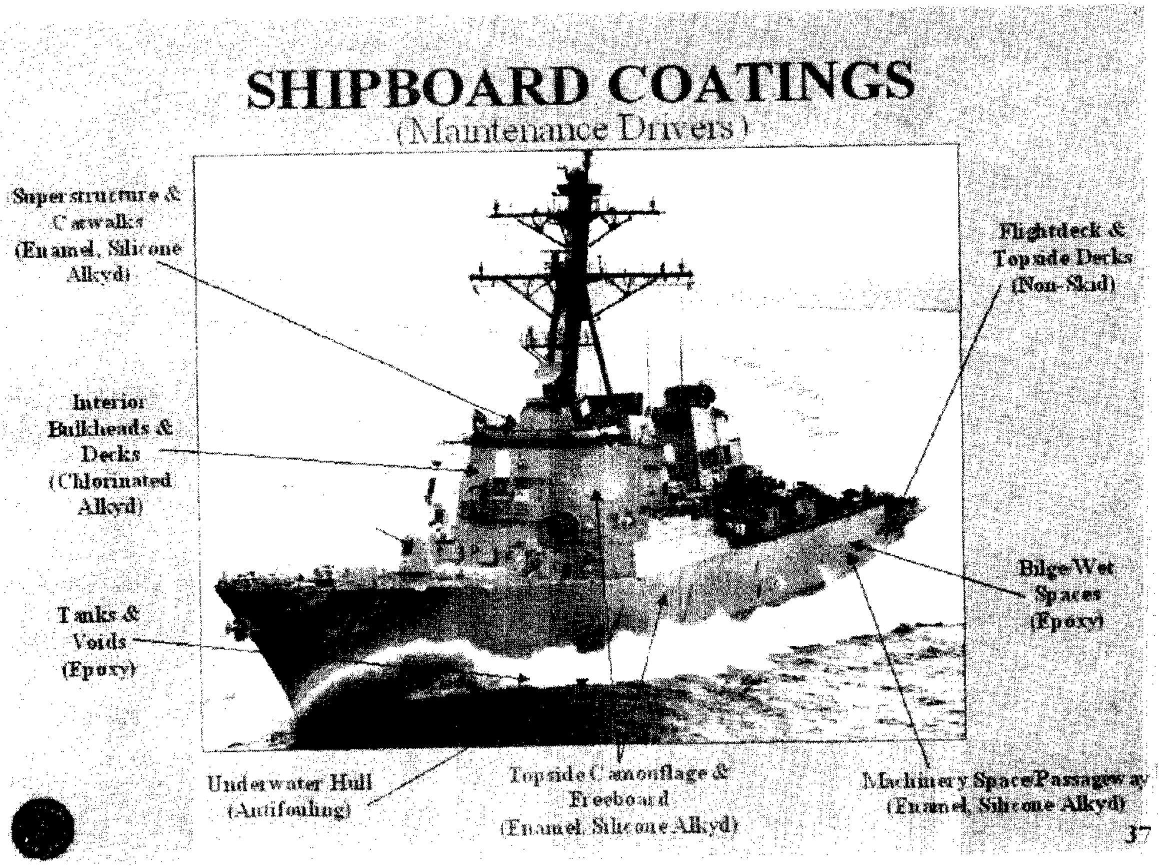

Figure 6. Destroyer with different shipboard coatings currently in use.(9)

Between the major maintenance cycles, there is an annual maintenance demand for continuous coating maintenance. Table 3 shows the breakdown in man-years per ship for the different painting activities.

Table 3. Annual maintenance demand on sailors for coating maintenance of Navy surface ships.(9)

MAINTENANCE ACTIVITIES	MAN-YEARS PER SHIP
Topside & Freeboard (Enamel, Silicone Alkyd)	9.0
Flight Decks & Topside Decks (Non-Skid)	4.0
Bilges/Wet Space Corrosion	4.5
Machinery Space/Passageways (Enamel, Silicone Alkyd)	2.25
Interior Bulkheads & Decks (Chlorinated Alkyd)	3.0
Superstructure, Catwalks, Mixing/Fan Room Corrosion (Epoxy)	3.25
TOTAL	**26.00**

Assuming that the cost of a man-year is $150,000, the average corrosion-related maintenance cost between dry-dock cycles can be estimated at $3.9 million per ship per year. When it is estimated that a total of 6,500 man-years are expended on the preservation of all surface ships in 1 year,(9) the total annual cost for corrosion-related maintenance between dry-dock cycles can be estimated at $975 million (6,500 man-years for all ships x $150,000 / man-year).

Submarines

The Navy operates 18 fleet ballistic missile submarines and 56 nuclear attack submarines. Because of the secretive nature of submarines, no information on corrosion maintenance could be obtained.

Aircraft

Corrosion has a significant impact on the life-cycle costs of naval aircraft. The Navy has three levels of aircraft maintenance, including organizational, intermediate, and depot maintenance. The organizational maintenance is performed on individual equipment and includes inspection, servicing, lubrication, adjustments, and replacement of parts, assemblies, and subassemblies. The intermediate maintenance is conducted on parts after removal from equipment and includes calibration, repair, or replacement of damaged or unserviceable parts and components or assemblies. Finally, depot maintenance involves major overhaul or complete rebuild of parts, assemblies, sub-assemblies, and end items, including the manufacture of parts, modifications, testing, and reclamation as required. A current estimate for corrosion maintenance costs is $200,000 per Navy aircraft per year,(8) which is approximately twice as much as the corrosion costs for Air Force aircraft ($100,000 per year) operating under less corrosive conditions. Note that the average corrosion maintenance cost for Naval aircraft is higher than the average cost for Air Force aircraft, which is reasonable considering the more severe environment in which Naval aircraft operate. With a total number of 4,000 naval aircraft, the annual corrosion cost can be estimated at $800 million.

One of the major tools to prevent corrosion on Navy aircraft is painting. In 1997, the Office of the Inspector General issued a report on the effectiveness of the Navy Aircraft Corrosion Prevention and Control Program at the organizational level.(10) The study focused on nineteen F-18 squadrons and seven F-14 squadrons. It was concluded that during the review period, from August 1, 1995 through August 1, 1996, 341 percent more paint than necessary was used for the prevention and control of corrosion damage of the F-18 aircraft and that the F-14 squadrons were painting large sections of their aircraft every 56 days. The report suggested that the Navy could reduce the organizational maintenance cost by $1.7 million over the next 6 years for the above-mentioned aircraft by limiting aircraft painting to touch-up painting only.

Facilities

All services own and operate extensive facilities, such as air and naval bases. The Air Force operates and maintains a 217 air bases (181 in the United States and 36 abroad) and the Navy operates 17 U.S. naval ports and 6 foreign ports. In addition, the Navy operates 20 Naval air stations and 4 submarine stations in the United States. In addition, the Army and the Marines operate numerous facilities for their troops, personnel, and equipment.

Many of the above facilities operate as ports or communities, respectively, with gas and electrical supply, drinking water, and sewer systems, and deal with corrosion issues similar to those discussed elsewhere in this report. Information on corrosion-related costs for these defense assets was not available; however, based on other studies described in this report, it is reasonable to assume that these costs are on the order of several billion dollars annually.

CASE STUDIES

Case Study 1. Army: High-Mobility Multipurpose Wheeled Vehicle

Introduction

Years of research and improvement by automobile manufacturers have led to the highly corrosion-resistant automobiles that most Americans drive today. Unfortunately, the lessons learned over the past 30 years are not always applied to new designs. A recent example of how poor design and material selection can lead to extensive corrosion problems is the Army's high-mobility multipurpose wheeled vehicle (HMMWV).(4)

The HMMWV is a light tactical vehicle procured by the Army and also used by the Marine Corps. The HMMWV is essentially a light truck that was designed for nearly any type of terrain or environment. While many modifications and variants are available, including heavily armored versions, the base structure and drivetrain of the HMMWV is very similar to many commercial vehicles. In fact, a civilian version of the vehicle with a more luxurious interior and non-camouflage paint is sold as the AM General Hummer.

The HMMWV first received attention during the Gulf War in the early 1990s. Since the Gulf War, the HMMWV has nearly become a symbol of the American Army during their missions to Bosnia, Somalia, Haiti, and Serbia. Unfortunately, along with all of the operational success, the Army and Marines began to notice that their HMMWVs were beginning to have severe corrosion problems after only a few years in operation. The Office of the Inspector General for the U.S. Department of Defense performed an evaluation on the corrosion prevention systems used on the HMMWV and published their findings in a 1993 report.(4)

Corrosion Control Shortcomings of the HMMWV

Government contracts on equipment such the HMMWV are written to emphasize performance specifications rather than design specifications. Performance specifications state that a piece of equipment must perform at a particular level for a given time frame. For example, the corrosion control specification on the 1989 contract for the HMMWV requires that:

> *The vehicle shall be capable of operating for a total service life of fifteen (15) years, which can include varying or extended periods in a corrosive environment involving high humidity, salt spray, road deicing agents, gravel impingement, and atmospheric contamination. During the 15-year service life, there shall be no corrosion past Stage One.*

> *Such a capability shall be achieved by a combination of design features (as found in, but not limited to, the* TACOM Design Guidelines for Prevention of Corrosion in Combat and Tactical Vehicles*), materials section (i.e., composites), production techniques, process controls, inspection, and documentation. No action beyond normal washing, periodic inspection, and repair of damaged areas shall be necessary to keep the corrosion prevention in effect.*

The advantage of using a broadly defined performance-based contractual specification is that making requirements too specific restricts the products and materials that can be used, and does not allow for new ideas and technologies. The Army does have a policy, however, indicating that state-of-the-art corrosion technology is to be used on the original equipment design, manufacturing, maintenance, supply, and storage for all Army systems and equipment. The design and manufacture of the HMMWV, however, fell short of this requirement for state-of-the-art corrosion technology with no overall corrosion protection and a lack of attention to corrosion control in the design of the vehicle.

An analysis of the corrosion control deficiencies of the HMMWV, presented in a 1995 report by Metals Information Analysis, indicated that the corrosion problems with the HMMWV are a result of design mistakes that had been eliminated in commercial vehicles years before the design of the HMMWV. One of the most glaring faults was in the design and construction of the steel frame. The frame was built out of ordinary 1010 steel and no galvanizing or other corrosion protection was applied to the steel to ensure its corrosion performance. Another problem with the frame was that holes were drilled into the sides of the frame members; however, no holes were drilled in the bottom of the frame to allow for drainage. This allowed water to enter the frame and stagnate on the interior of the frame, causing the frame to corrode from the inside out. The lack of drainage on a vehicle designed to be able to go through water up to 1.5 m (60 in) deep reveals the lack of thought that was initially put forth in the corrosion prevention during the design stage.

A problem throughout the vehicle is that 1010 carbon steel is used for many of the components, such as fasteners, handles, and brackets, as well as the frame. These parts have corroded on almost every HMMWV in service, leading to extensive repairs and maintenance. During the Inspector General's Audit, an examination was performed on 275 vehicles, showing multiple areas of corrosion. The results of this survey are presented in table 4, summarizing the major vehicle parts that the auditors inspected and found to be corroded. Most of these corrosion problems could have been eliminated using galvanizing and high-quality coatings. Other problems could have been avoided using polymers and other alternate materials. Care must be taken, however, in selecting these materials. For example, the hood of the HMMWV is made out of a type of polymer called sheet molding compound. The hoods have not had any corrosion problems, but they have often cracked (due to soldiers jumping on them while performing their duties) because of the poor elastic properties of the polymer.

Several different metals were used on the HMMWV, leading to dissimilar or galvanic corrosion. Much of the body of the HMMWV is made out of aircraft grades of aluminum, while the frame and doors are made of 1010 carbon steel. The entire vehicle is secured with more than 2,800 rivets and while this design affords the HMMWV a high strength-to-weight ratio, each of the rivets is a preferential site for corrosion.

A particular weakness of the HMMWV, compared to standard commercial vehicles, are the coating systems used. Most commercial vehicles use a multi-step coating process to both protect the galvanized steel and to enhance the appearance of the vehicle. One of the most important parts of the coating application process is electrodeposition or E-coating technology. In electrodeposition, the part to be coated is immersed in the coating material while an electrical current is applied to the part. The advantage of using an electrodeposited primer is that the manufacturer can be assured of complete coverage of the surface, including otherwise inaccessible areas. On the HMMWV, E-coating technology was not used for coating application; rather, the coating was applied using the older technology of spraying.

Table 4. Number and percentage of corrosion-affected parts found during the Inspector General's investigation.(5)

VEHICLE PARTS	NUMBER OF VEHICLES AFFECTED (275 POSSIBLE)	PERCENTAGE OF VEHICLES AFFECTED
Engine Compartment		
- Heads	49	18
- Injectors	53	19
- Engine Mounts	78	28
- Valve Covers	87	32
- Radiator Assembly	131	48
Suspension and Steering		
- Idler Arms	48	17
- Control Arms	78	28
- Rie Rods	124	45
- Axle Housings	161	59
- Springs	205	75
Body		
- Fenders	72	26
- Bumpers	105	38
- Doorframes	115	42
- Beds	120	44
- Tie-Downs/Lift Points	209	76
Underbody		
- Metal Brake Lines	35	13
- Air Tanks	40	15
- Driveshafts	105	38
- Fuel Lines	106	39
- Universal Joints	135	49
Other		
- Welded Seams	73	27
- Fuel Tank Assemblies	135	49
- Nuts, Bolts, and Fasteners	177	64
- Frame	187	68

The corrosion protection of the HMMWV was to be provided exclusively by the military coating specification Mil-C-46164 and the Chemical Agent-Resistant Coating (CARC). The CARC paint system consists of a surface cleaning, epoxy primer, epoxy interior topcoat, and a polyurethane exterior topcoat. The purpose of this coating was to provide resistance to chemical penetration of the coating and to aid in decontamination of the vehicle in case of chemical attack. Other benefits of the coating were to provide corrosion protection as well as to provide camouflage protection, as the CARC paint was available in different camouflage colors. Unfortunately, as shown in table 5, the CARC coating has deteriorated much more quickly than was expected. There are several reasons for this failure, the most important being the physical properties of the CARC paint. The CARC paint hardens after application to an extremely inelastic material. The metals to which the paint was applied were much more elastic and also expanded and contracted more rapidly due to environmental conditions. The result is that the CARC paint is easily disbonded from the metal and often falls off; therefore, the protection that it would give is lost.

Table 5. Number and percentage of inspected HMMWVs found with deteriorated CARC paint in different locations with different services.[5]

OWNER	LOCATION	NUMBER OF HMMWV INSPECTED	NUMBER OF INSPECTED HMMWV WITH DETERIORATED COATING	
			Number	Percent
Army	Fort Bragg	17	4	24
Army	Fort Still	13	9	69
Army	Fort Knox	9	3	33
Army	Fort Drum	11	11	100
Marine Corp	MCLB – Atlantic	2	2	100
Marine Corp	Camp Lejeune	40	30	75
WI Nat'l Guard	Various	29	13	45

Another weakness of the CARC paint is that it is a relatively difficult coating to apply. Under ideal factory conditions, the necessary thickness levels are not too difficult to achieve; however, field repair of the coating has been difficult. The coating is difficult to apply in the field because the coating thickness must be correct. If the coating is too thick, the coating will fall off; if the coating is too thin, the coating is ineffective. Moreover, CARC paint for field application contains a high level of volatile organic compound (VOC). Strict environmental regulations now allow only 0.9 L (1 quart) per day per area to be used to reduce the level of VOC emissions. Thus, reapplication and touch-up are severely restricted.

Cost of Corrosion

The Inspector General's report contained the following recommendations with respect to corrosion problems on the HMMWV:

1. Incorporate state-of-the-art corrosion prevention technology for all future acquisitions and extended service programs for wheeled vehicle systems. Design specifications should be used in contractual documents.

2. Prepare life-cycle cost estimates that show the cost of corrosion-related maintenance and repair cost alternatives applicable to all future wheeled vehicle systems acquisitions and extended service programs.

The use of state-of-the-art corrosion prevention technology should be evaluated in terms of life-cycle costs associated with a system such as the HMMWV. There have been several attempts to assess the cost of corrosion on wheeled tactical vehicles. The Inspector General's report claimed that overall corrosion-related issues cost the Army an estimated $2 billion to $2.5 billion per year. During their study of several HMMWVs, the Inspector General found some significant corrosion costs in repairing the vehicles. One vehicle had only 89.5 km (55.6 mi) on the odometer; yet, it was estimated that it would cost $3,109 to repair the corrosion damage to the floor pans, transmission cooling line, cargo bed, body and frame bolts, rocker panels, fly wheel, tie rods, A-frame assembly, and other miscellaneous parts. A second vehicle, returned from operational service, had an estimated repair cost of $18,019, which is more than half of the $36,000 initial unit procurement cost.

The Inspector General found that the corrosion not only affected the cost of HMMWV ownership, but the operation readiness and overall life of the vehicles as well. The Inspector General was not able to calculate the precise impact on operational readiness, but it was estimated that vehicles requiring corrosion repairs were out of service between 2 to 12 months. The Inspector General did not calculate the cost of this downtime; however, other estimates suggest that if costs for downtime were considered, the cost of corrosion to the Army for wheeled vehicles would be higher than $2 billion. The Inspector General also calculated that extensive corrosion could shorten the life of the HMMWV, partly due to the low acquisition cost of the vehicle. The threshold for replacement is considered to be 65 percent of the cost of the vehicle. In fact, the Inspector General found several examples where the corrosion damage of existing vehicles was higher than 65 percent of the replacement cost. Vehicles as new as 5 years old were being scrapped for new vehicles.

Recommended Solutions

The Inspector General found that the lack of life-cycle cost analysis led to the corrosion problems with the HMMWV. If a life-cycle cost analysis were performed on the possible corrosion control alternatives, the analysis would have indicated that proper corrosion control measures would provide significant cost-savings in the long run. Unfortunately, this analysis was not performed and the use of these corrosion control technologies would have increased the procurement cost of the HMMWV. The Inspector General also found that individuals in acquisitions were rewarded for keeping the procurement cost low and that no reporting system was in place at Tank Automotive and Armaments Command (TAACOM) to estimate future repair needs.

The corrosion concerns were not addressed, even after the extent of the corrosion problems with the HMMWV was known. TAACOM's Science and Technology Office put together the TAACOM CPC Acquisition (dated September 16, 1993) document for a procurement package for HMMWVs. This document stated the following:

> Corrosion Control – *The vehicle shall be capable of operating for a desired 20-year service life with a 15-year minimum which can include varying or extended periods in corrosive environments involving one or more of the following: high humidity, salt spray, road deicing agents, gravel impingement, atmospheric contamination, and temperature extremes. There shall be no corrosion past Stage One, nor corrosion impairment of fit or function. Corrosion control shall be achieved by a combination of design features, materials selection (e.g., composites, galvanized steel, E-coat, coil coating), production techniques, process controls, inspection, and documentation. The minimum requirement is galvanizing of ferrous components in accordance with the attached Galvanizing Policy, appropriate pretreatment, and E-coat primer. Subsequent use of rust-proofing materials, such as Mil-C-46164, is not a substitute for any of these minimum requirements.*

During the negotiations of the resulting contract, this section was deleted in order to reduce the procurement cost. The vehicles delivered under this contract were protected with Mil-C-46164 rust-proofing only. The most recent HMMWVs have been protected by using the methods outlined in the above paragraph; however, most of the 130,000 HMMWVs owned by the Army and Marines have virtually no corrosion protection due to the lack of life-cycle cost analysis before procurement. If TACOM follows the recommendations of their science and technology office and if life-cycle costing is performed on all systems before acquisition, the overall cost of ownership of the HMMWVs and other systems should be significantly decreased.

Case Study 2. Air Force: KC-135 Stratotanker

The KC-135 Stratotanker is a strategic air refueling tanker built by the Boeing Company, which can also be used as a cargo carrier or troop transport. The first KC-135 entered the Air Force fleet in 1957 and the last one was delivered in 1965. Currently, about 550 of the 732 tankers built remain in service. As a result of a decreasing DOD budget, there have been insufficient funds available to procure KC-135 replacement aircraft. Due to insufficient funding, the current KC-135 fleet has been projected to remain in service until 2040. With the average KC-135 tankers being more than 40 years of age, they will be more than 80 years old in 2040 and will have been in service for more than four times their original design service life. Generally, the structural life of both commercial and military aircraft is based on flight hours and number of fatigue cycles. In general, the life of aircraft is fatigue-limited, and corrosion is never considered to be a life-limiting factor. The minimum KC-135 structural fatigue life-limited components are the fuselage and the upper wing skin at 66,000 to 70,000 hours, while the actual fleet hours are only 15,000. Since the KC-135 utilization averaged only 300 to 400 flight hours per aircraft per year, it appears that the fleet can easily remain in service until 2040.

However, severe corrosion has been experienced on the aluminum alloy components of the KC-135 aircraft. This corrosion is the result of low utilization, where the majority of the time is spent on the ground being exposed to the corrosive atmospheric environments. In the 1950s, the KC-135 was never designed and constructed with corrosion prevention as a primary concern. The original structural alloys were aluminum alloys 2024-T3 and -T4, and 7075-T6 and 7178-T6, which are all susceptible to corrosion and stress corrosion cracking. The original construction was without any sealant in the lap joints and fuselage skins that had spot-welded doublers attached to them. Finally, the upper wing skins, which are made of the highly corrosion-susceptible aluminum alloy 7178, were attached with high-strength steel fasteners, causing dissimilar metal corrosion in certain areas.

A particularly severe problem is corrosion of the fuselage lap joints, where the voluminous corrosion products at the contact or faying surfaces of the lap joint cause deformation of the skin.(11-12) Figure 7 shows a photograph and a schematic cross-section of this so-called pillowing phenomenon. Because of the resulting stress fatigue and stress corrosion, cracks can nucleate near the fastener holes, jeopardizing the structural integrity of the fuselage. Other corrosion problems on the KC-135 aircraft include dissimilar metal corrosion and lap joint corrosion on the 7178 upper wing skin, lap joint corrosion on the 7075-T6 fuselage crown section, and stress corrosion cracking of the 7075-T6 forged frame sections.

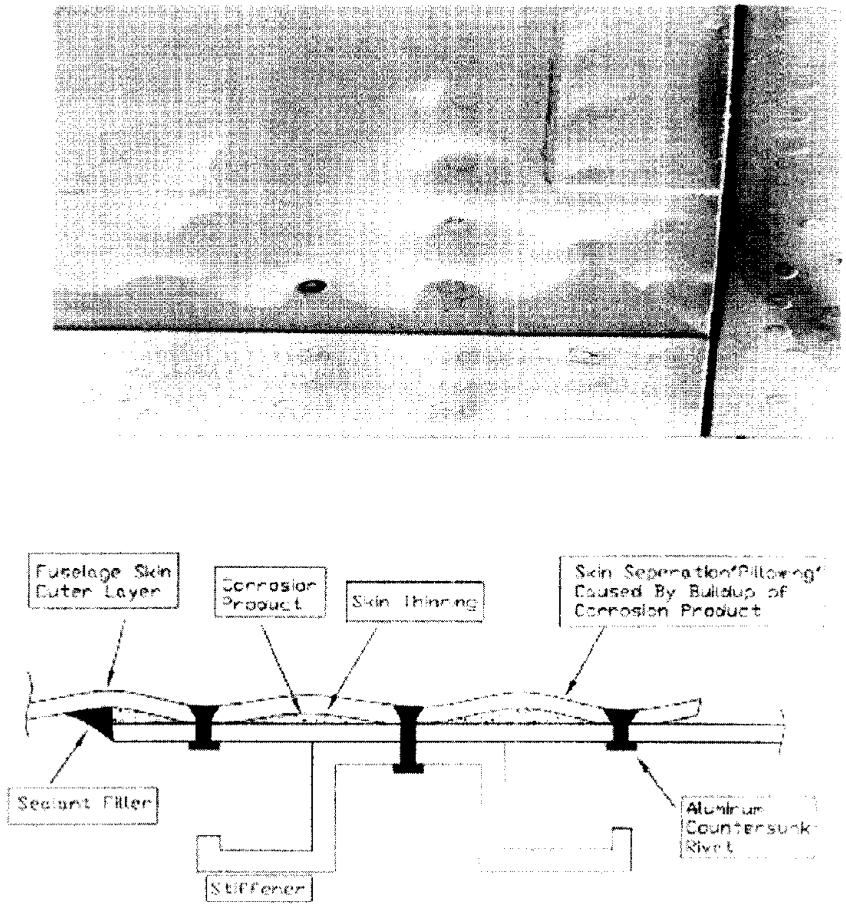

Figure 7. Photograph and schematic cross-section of the pillowing phenomenon resulting from lap joint corrosion.

As a result of all the corrosion problems of the KC-135, depot maintenance costs have increased significantly over the past 10 years. Figure 8 shows that the depot overhaul flows days have increased from less than 100 days in 1990 to approximately 350 in 2000.(13) The Air Force has expended considerable effort to develop methods to control the corrosion of the KC-135, ranging from characterizing the type and extent of the corrosion to developing new nondestructive inspection (NDI) techniques, to developing methods to slow down corrosion with corrosion preventative compounds (CPCs), to developing predictive models.

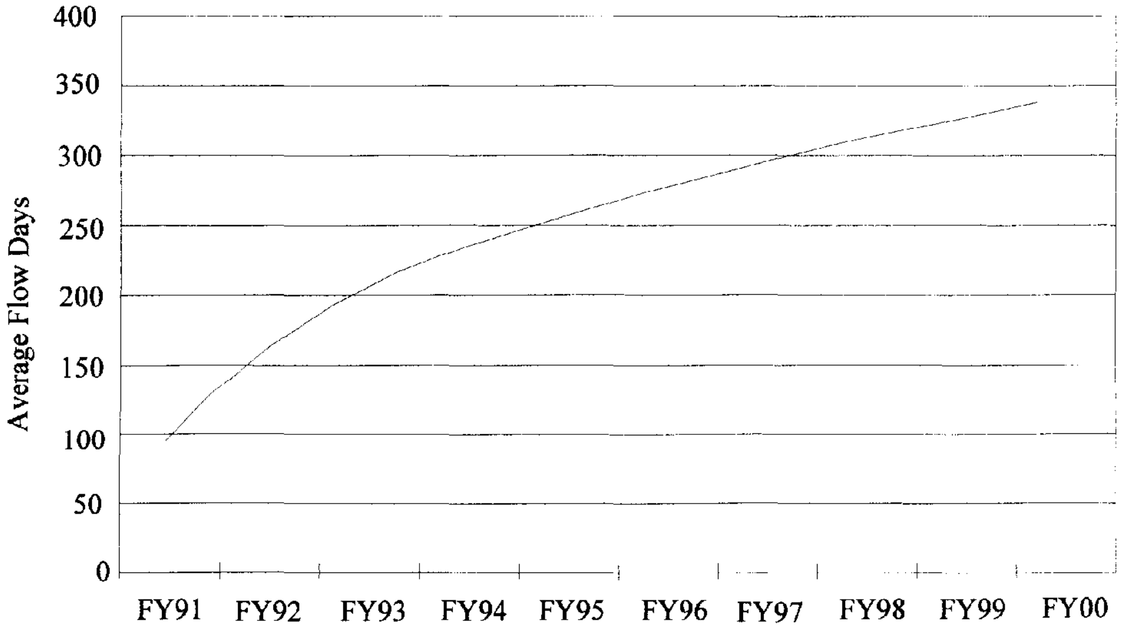

Figure 8. KC-135 periodic depot maintenance flow-day trend, for fiscal years 1991 through 1999.(13)

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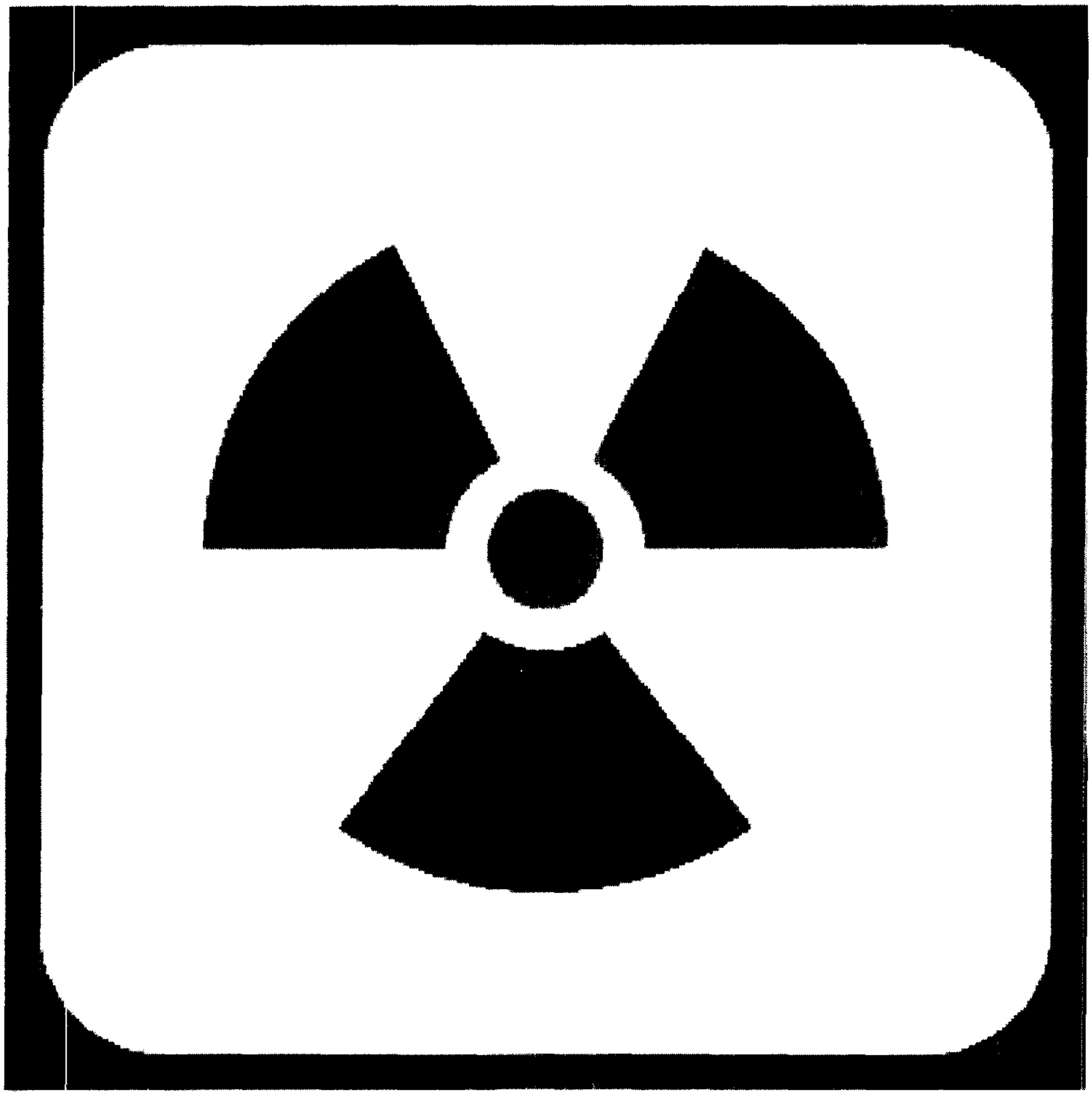
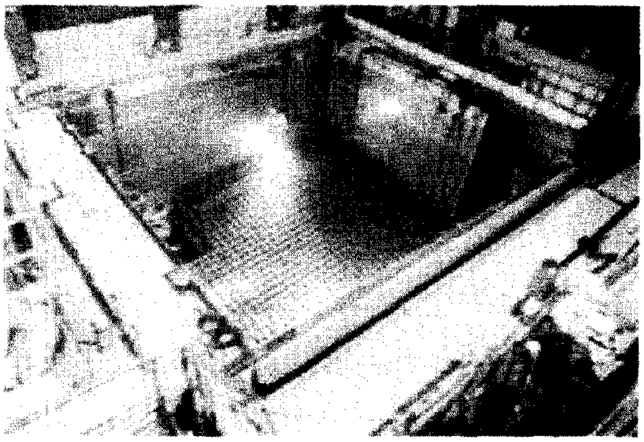
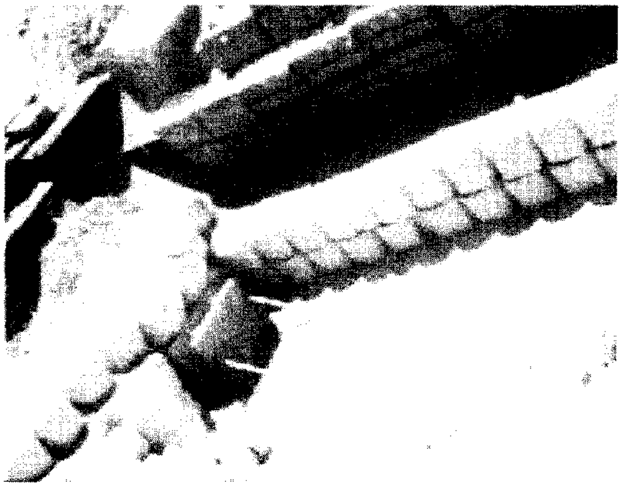
APPENDIX CC

NUCLEAR WASTE STORAGE




Yucca Mountain, Nevada


Wet storage


Underground dry storage

NUCLEAR WASTE STORAGE

MICHIEL P.H. BRONGERS[1]

SUMMARY

Nuclear wastes are generated from spent nuclear fuel, dismantled weapons, and products such as radio pharmaceuticals. The most important design item for the safe storage of nuclear waste is the effective shielding of radiation. Corrosion is a form of material degradation that may result when moisture or water comes into contact with the packaging materials. A corrosion failure may not result in a large release of nuclear waste and radiation; however, a leak would be considered potentially hazardous and, therefore, would not be acceptable.

In order to minimize the probability of nuclear exposure, special packaging is designed to meet the protection standards for temporary dry or wet storage, or for permanent underground storage. Currently, nuclear waste is stored at temporary locations, including water basins in nuclear power plants and at dry locations aboveground. Deep underground storage in Yucca Mountain, Nevada, has been proposed as a permanent storage solution for high-level nuclear waste from spent nuclear fuel.

The Office of Civilian Radioactive Waste Management of the U.S. Department of Energy (DOE) estimated that over the next 100 years, a total of $20.6 billion (1998 dollars) will be spent on development and evaluation, licensing, pre-emplacement construction, emplacement operations, monitoring, and closure and decommissioning of the permanent waste disposal site. It is noted that the 100-year estimates are for the time of construction, filling, and closing only. These estimates do not reflect the long-term processes of canister degradation beyond 100 or 10,000 years of storage. The current sector description includes a description of the aforementioned DOE report, but does not include data on the annual cost of corrosion related to the storage of nuclear waste.

The proposed design for the permanent waste disposal is for steel canisters containing the spent fuel to be stored within other steel canisters and buried horizontally in chambers 300 m below the earth's surface. Scientists designed the canisters to last at least 1,000 years and will depend on the mountain itself to provide a natural barrier to survive the minimum 10,000 years required by the government. If it is assumed that only part of the cost of waste packaging fabrication is spent on corrosion design and features that mitigate or prevent corrosion, then the average direct total cost of corrosion is less than $42.2 million per year ($4.98 billion per 118 years).

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[1] CC Technologies Laboratories, Inc., Dublin, Ohio.

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SECTOR DESCRIPTION

Nuclear wastes are generated from spent nuclear fuel from electric power plants, dismantled weapons, and products such as radio pharmaceuticals. The most important design item for the safe storage of nuclear waste is the effective shielding of radiation. In order to minimize the probability of nuclear exposure, special packaging is designed to meet the protection standards for temporary dry or wet storage, or for permanent underground storage. The most common materials of construction include steel and concrete. The wall thickness of the packaging is generally thick in comparison to the contained volume.

Corrosion is a form of material degradation that results when moisture or water comes into contact with the packaging materials. A corrosion failure may not result in a large release of nuclear waste and radiation; however, a leak would be considered potentially hazardous and, therefore, would not be acceptable. Currently, nuclear waste is stored at temporary locations, including water basins in nuclear power plants and at dry locations aboveground. Deep underground storage in Yucca Mountain, Nevada, has been proposed as a permanent storage solution.

When considering the total costs of nuclear storage, it is nearly impossible to distinguish the specific corrosion costs. Some corrosion-related costs that can be determined include the costs for nuclear waste packaging design and packaging fabrication, and the costs for remediation of temporary sites that are being used for longer periods than for which they were designed. This sector description highlights these topics.

The vast majority of nuclear shipments are very small in size [less than 0.45 kg (1 lb) per shipment] and total approximately 2.8 million shipments per year (average 7,656 shipments per day).(1) Spent fuel shipments (material only) typically weigh 0.5 to 1.0 metric ton for truck shipments and up to 10 metric tons for rail shipments. In addition, the protective lead shipping casks for containment of the spent fuel weigh many more additional tons. Corrosion is not an issue in the transportation of nuclear waste because of the stringent package requirements and the short duration of the transport; however, corrosion is an important issue in the design of the casks used for permanent storage. Figure 1 shows the volume of low-level waste received at U.S. disposal facilities in the 10-year period between 1985 and 1994.(2)

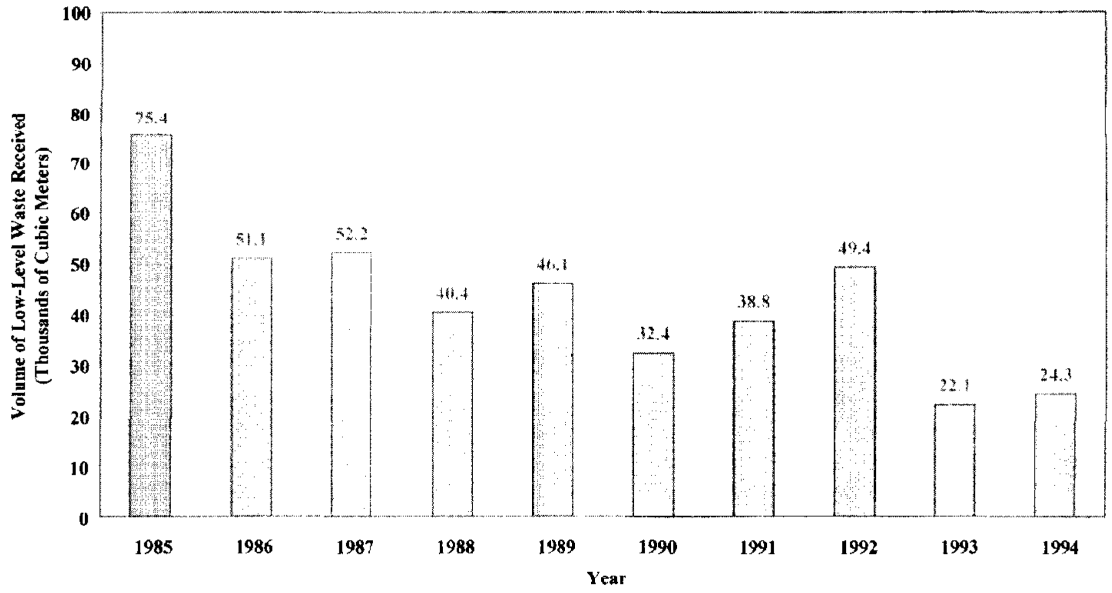

Figure 1. Volume of low-level waste received at U.S. disposal facilities between 1985 and 1994.(2)

Transition From Interim Storage to Permanent Storage

In 2000, interim storage facilities for nuclear waste were numerous. Interim nuclear storage is characterized by a number of older tanks that have a radioactive leak history and have a need for remedial action. Low-level waste (LLW) can be liquid or solid waste in containers. It is stored "dry", aboveground or relatively shallow underground (see figure 2). Currently, there are a total of 249.8 thousand m^3 of buried LLW and 105.9 thousand m^3 of stored aboveground LLW at U.S. Department of Energy (DOE) facilities.(3) The cost of dry storage is reported to be $1.2 million per cask.

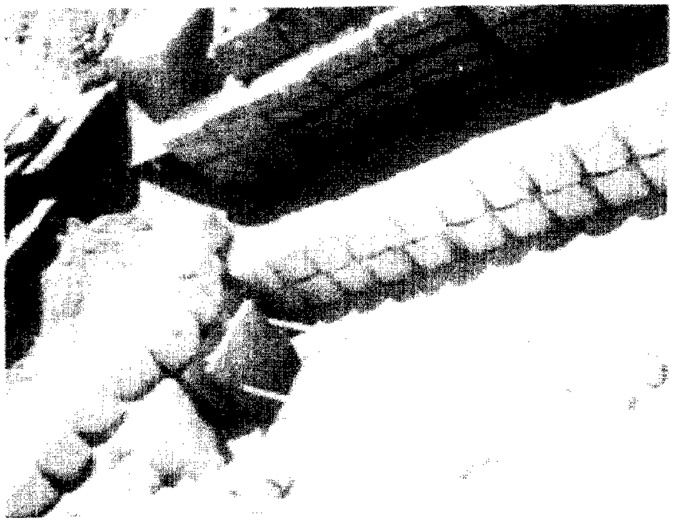

Figure 2. Example of shallow underground dry storage of low-level radioactive waste in Richland, Washington.(2)

High-level waste (HLW) from spent nuclear fuel from nuclear power plants is generally stored in water basins at the plants where it was used (see figure 3). Currently, approximately 30,000 metric tons of spent nuclear fuel is stored at commercial reactors.(3) Dry storage and wet basin storage are designed as temporary solutions. A long-term storage repository is currently under study and development; however, the research and design of a site as a permanent nuclear waste repository are not completed yet.

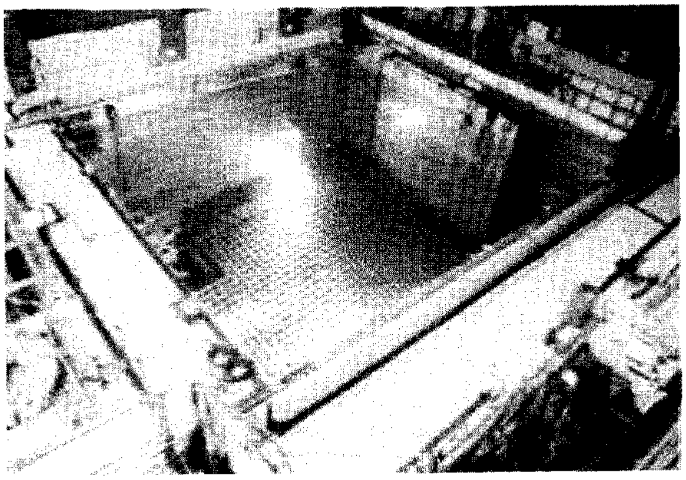

Figure 3. Example of wet storage (underwater) of high-level nuclear waste at the Diablo Canyon plant in California.(2)

As an example, the K West and the K East basins in Hanford, Washington, are two concrete basins that were built in 1951 to temporarily store nuclear fuel produced at DOE's Hanford site. Although the initial plan was to terminate the service within 20 years, the two basins continue to receive spent fuel from reactors. It has been reported that rods in open canisters have corroded in the basin, releasing isotopes into the basin water. Basin cleanup plans, waste removal, and groundwater contamination were subsequently reported. The cost of this work will be considerable.

Cask Design for Permanent Storage

In addition to the unavoidable material aging due to exposure to radiation from the radioactive contents, material aging due to corrosion is expected to be a concern in the long-term storage of nuclear waste. It has further been suggested that heat generation from radiation can drive the corrosion rate much higher. Several cask designs have been proposed, each with different materials of construction. The most common proposed materials include carbon steel, stainless steel, and concrete construction.

Today, nearly all nuclear waste generated is solid waste. As a result, this waste is relatively non-corrosive, which minimizes the risk for internal corrosion damage to storage and transportation tanks. There is, however, a significant amount of old liquid nuclear waste in storage, which can corrode the containers internally. In addition, the presence of water in the solid waste could potentially cause corrosion problems. External corrosion may occur as well, because the older liquid waste is stored in buried tanks and the tanks are therefore exposed to groundwater. The consequences of leaks are great from the perspective of remedial costs, damage to the environment, and a loss of public trust; therefore, long-term extrapolations must be made to ensure the structural integrity of the storage containers for centuries to come.

The potential for corrosion of permanent storage canisters has been and continues to be under investigation. In 1999, a literature review and a summary of plutonium oxide and metal storage packaging failures was published by Eller et al.(4) Metal oxidation in non-airtight packages with gas pressurization was identified as the most common mechanism of packaging failure. An example of a possible corrosion problem was further described in a study on hydrogen/oxygen recombination and generation of plutonium storage environments.(5) There are also publications available regarding the prediction of service life of steel in concrete used for the storage of low-level nuclear waste, for example, see the work by Andrade and Cruz.(6) The current sector description does not aim to be complete in describing all perceived corrosion issues. The above references are mentioned only as examples of past research.

In a September 2000 meeting on key technical issues regarding container life, the U.S. Nuclear Regulatory Commission (NRC) and representatives of DOE discussed the ongoing research into the effects of corrosion processes on the lifetime of the containers.(7)

This meeting is mentioned here to illustrate the wide range of material issues that designers are facing. In nuclear waste containers, both corrosion from the inside and from the outside should be considered. The issues included, but were not limited to: general and localized corrosion of the waste package outer barrier; methods for corrosion rate measurements; documentation on materials such as Alloy 22 and titanium; the influence of silica deposition on the corrosion of metal surfaces; passive film stability, including that on welded and aged material; electrochemical potentials; microbiologically influenced corrosion (MIC); stress distribution due to laser peening and induction annealing; stress corrosion cracking (SCC) and its influence on rock fall impact strength; and deadload stressing and the effects of the fabrication sequence and of welding. This long list surely requires extensive research at considerable cost.

Effect of Location on Corrosion of Nuclear Storage Containers

The current plans for a permanent nuclear storage repository are to build it at a relatively dry site at a depth of several hundred meters below the surface. Scientists consider that the presence of water will eventually corrode the storage canisters. In the United States, the Yucca Mountain site (see figure 4) is reported to be a good location due to its low water content. The proposed design for waste disposal is for steel canisters containing the spent fuel to be stored within other steel canisters and buried horizontally in chambers 300 m below the earth's surface. Scientists designed the canisters to last at least 1,000 years and will depend on the mountain itself to provide a natural barrier to survive the minimum 10,000 years required by the government; however, there is no guarantee that canisters at Yucca Mountain will be free from water flow for 10,000 years.

Figure 4. View of the desert area surrounding Yucca Mountain, Nevada, which is the site of proposed permanent high-level waste storage.

Cost of Nuclear Waste Facility for Permanent Storage

In 1998, the Office of Civilian Radioactive Waste Management of the U.S. Department of Energy (DOE) published an analysis of the total life-cycle cost for the permanent disposal of radioactive waste in Yucca Mountain, Nevada.(8) This site is proposed for a high-level waste repository. The analysis was based on the most current plans, strategies, and policies. Since the estimates span over 100 years, the concept should be viewed as representative of the waste management system that will ultimately be developed. It is noted that the 100-year estimates are for the time of construction, filling, and closing only. These estimates do not reflect the long-term processes of canister degradation beyond 100 or 10,000 years of storage. Table 1 shows the total estimated repository costs by construction phase and by the average cost per year. Table 2 is similar to table 1; however, table 2 only reports the fabrication costs of the waste packages. If it is assumed that only part of the cost of waste packaging fabrication is spent on corrosion design and features that mitigate or prevent corrosion, then the average direct total cost of corrosion is less than $42.2 million per year ($4.98 billion per 118 years). This calculation excludes any costs of potential environmental clean-up if the permanent storage would leak radiation. It is also recognized that the majority of the costs are incurred in the period prior to 2041; therefore, the actual direct cost per year is higher for nuclear waste packaging fabrication for permanent storage.

Table 1. Total repository costs for radioactive waste in Yucca Mountain by construction phase (1998 dollars) as reported by the U.S. Department of Energy in 1998.(8)

CONSTRUCTION PHASE		NUMBER OF YEARS	HISTORICAL (1983-2002) ($ x million)	FUTURE COST WITHOUT CONTINGENCY (1999-2116) ($ x million)	CONTINGENCY COST ($ x million)	TOTAL (1999-2116) ($ x million)	AVERAGE COST PER YEAR ($ x million)
Development and Evaluation	1983-2002	20	4,910	990	no estimate	990	49.5
Licensing	2002-2005	4	0	670	90	760	190.0
Pre-Emplacement Construction	2005-2010	6	0	2,460	490	2,950	491.7
Emplacement Operations	2010-2041	32	0	13,580	2,310	15,890	496.6
Monitoring	2041-2110	70	0	2,590	630	3,220	46.0
Closure and Decommissioning	2110-2116	7	0	330	70	400	57.1
		TOTAL	**$4,910**	**$20,620**	**$3,590**	**$24,210**	

Table 2. Cost of nuclear waste packaging fabrication for permanent storage (1998 dollars), as reported by the U.S. Department of Energy.(8)

CONSTRUCTION PHASE		NUMBER OF YEARS	FUTURE COST WITHOUT CONTINGENCY (1999-2116) ($ x million)	CONTINGENCY COST ($ x million)	TOTAL (1999-2116) ($ x million)	AVERAGE COST PER YEAR ($ x million)
Development and Evaluation	1983-2002	20	0	0	0	0
Licensing	2002-2005	4	40	no estimate	40	10.0
Pre-Emplacement Construction	2005-2010	6	50	no estimate	50	8.3
Emplacement Operations	2010-2041	32	4,870	no estimate	4,870	152.2
Monitoring	2041-2110	70	20	no estimate	20	0.3
Closure and Decommissioning	2110-2116	7	no estimate	no estimate	no estimate	no estimate
		TOTAL	**$4,980**		**$4,980**	

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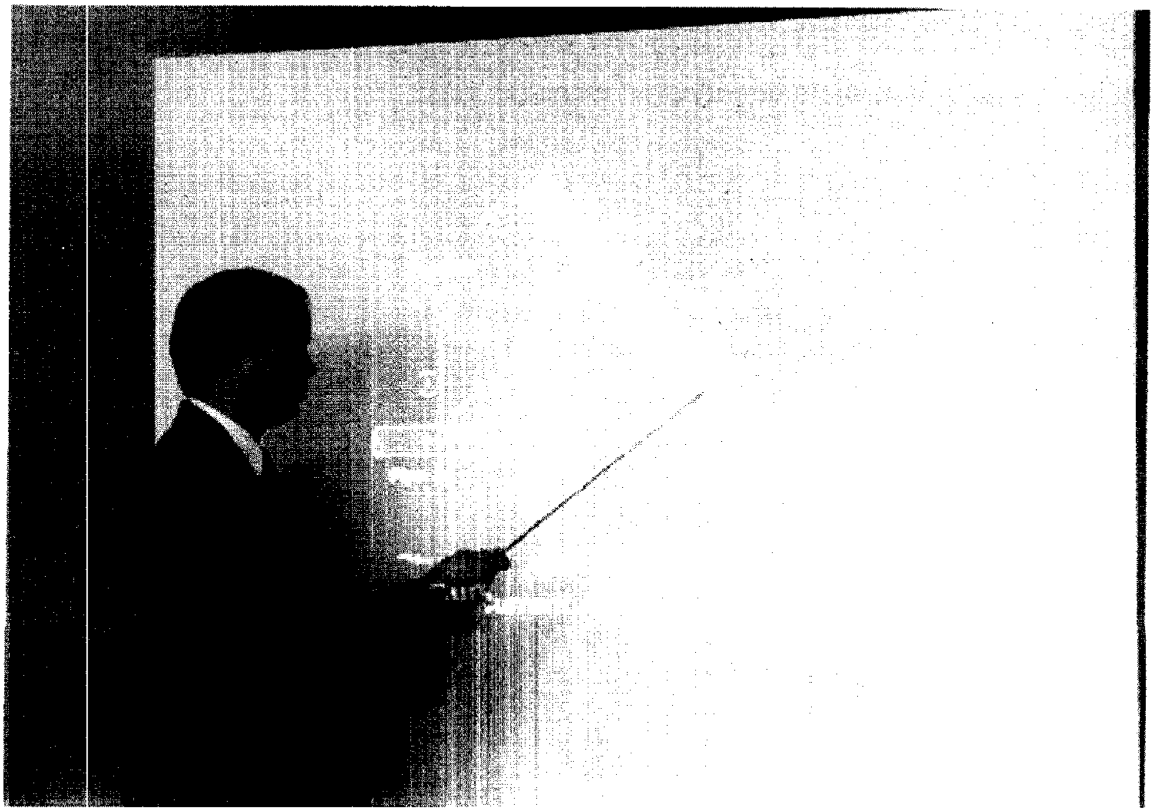
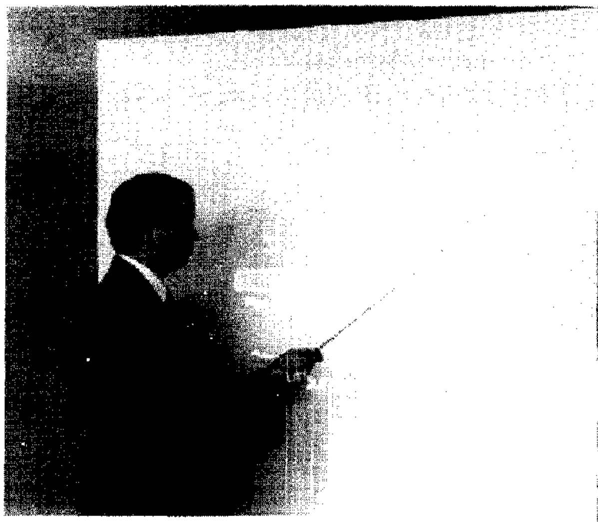
APPENDIX DD

PREVENTIVE STRATEGIES

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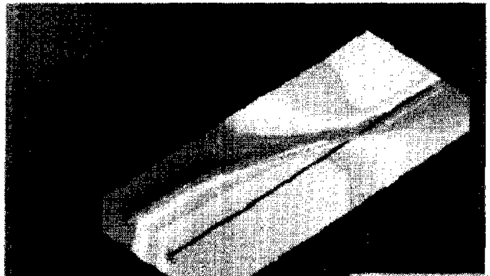
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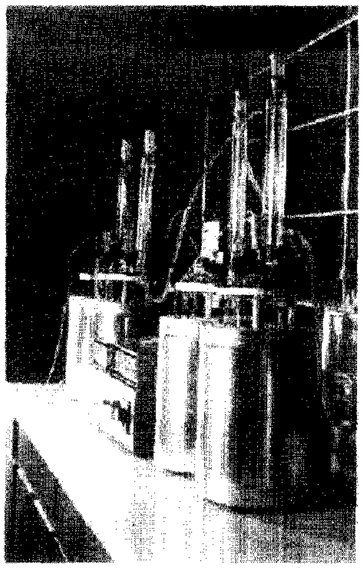
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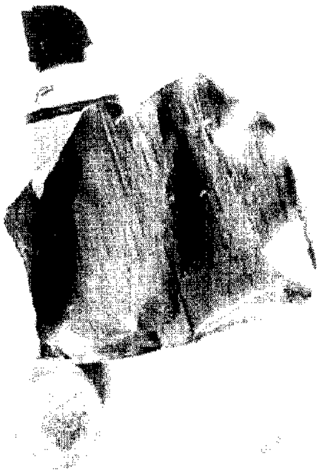
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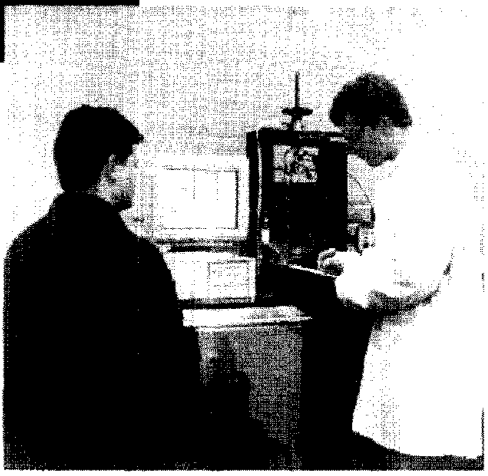
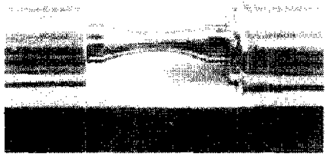
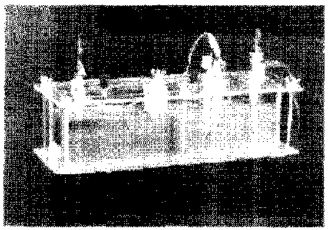

Hands-on training


Specimen for strength test


Corrosion test cell

PREVENTIVE STRATEGIES

JOE H. PAYER, PH.D.[1] AND RONALD LATANISION PH.D.[2]

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INTRODUCTION

The goal of preventive strategies is to use the opportunities to improve corrosion control in all economic sectors, resulting in increased integrity, durability, and savings. Benefits, approaches, and some specific recommendations are made for the following opportunities for improved corrosion practices:

Preventive strategies in non-technical areas:

1. Increase Awareness of the Considerable Corrosion Costs and Potential Savings.
2. Change the Misconception That Nothing Can Be Done About Corrosion.
3. Change Policies, Regulations, Standards, and Management Practices to Increase Corrosion Cost-Savings Through Sound Corrosion Management.
4. Improve Education and Training of Staff in Recognition of Corrosion Control.

Preventive strategies in technical areas:

5. Advance Design Practices for Better Corrosion Management.
6. Advance Life Prediction and Performance Assessment Methods.
7. Advance Corrosion Technology Through Research, Development, and Implementation.

PREVENTIVE STRATEGIES IN NON-TECHNICAL AREAS

Strategy 1. Increase Awareness of the Considerable Corrosion Costs and Potential Savings

Issue

A majority of studies regarding the costs of corrosion reveal that the costs of corrosion to the U.S. economy could be significantly reduced if available corrosion control technologies were implemented. Many corrosion problems go unresolved due to a lack of awareness from management and/or those responsible for operation, inspection, and maintenance of an engineering system. Today there is an even greater need for corrosion cost awareness given the rapid pace at which new engineering systems find their way into the marketplace.

Benefits

In addition to cost-savings, properly implemented corrosion prevention technologies can extend the life of engineering systems. The inefficiencies in corrosion management represented by poorly implemented corrosion control strategies can be substantially reduced with increased awareness.

Approach

An important issue is to find ways of engaging those who have a "need-to-know" regarding corrosion engineering, but are not necessarily trained in this field. Historically, short courses are one method for such interactions to occur. The emergence of such tools as distance learning and interactive software present another dimension to training. Similarly, the formation of a corrosion engineering analog of the historically important agricultural extension stations may serve this purpose well.

Recommendations

1. Prepare and disseminate case histories and technology briefs that document corrosion costs and demonstrate the benefits of sound corrosion control practices. In addition to engaging the engineering community, the challenge is to engage policy-makers as well as the general public. The latter should not be cast as warnings of impending problems, but rather as a deliberate attempt to express the reality regarding the lack of knowledge in corrosion control and costs. This has to be done at a level that stockholders and the public can understand and appreciate.

2. Inform the general public about corrosion costs and the nature of the opportunities for controlling corrosion, so that they will be able to make informed decisions themselves, where possible. The general public must also be alert to the potential possibilities of corrosion control and remind designers and maintenance managers about corrosion. Information on corrosion could encourage a change in public practice. For example, automobile coolants lose their corrosion inhibition characteristics after approximately 2 years of use. Car owners are likely to react to information that they would save themselves a great deal of trouble and money later by changing the coolant at regular intervals.

Strategy 2. Change the Misconception That Nothing Can Be Done About Corrosion

Issue

There is a widely held misconception that nothing can be done about corrosion. If progress is to be made, there not only has to be a greater awareness of opportunities for corrosion cost-savings, but there must also be a recognition that effective means are available to realize those savings. There are technical issues that require attainable advances in corrosion technology and more effective dissemination and implementation of available corrosion control technology. In addition, there are non-technical issues of perception, policy, and practices for improved corrosion control

Benefits

The benefits include direct and indirect corrosion cost-savings through more effective and widespread application of sound corrosion control. With a proper perception that opportunities for corrosion cost-savings exist, informed decisions can be made. Hence, viable options can be considered regarding corrosion-conscious designs and operating/maintenance practices to preserve and extend the life of structures.

Approach

As in the prior strategy, the approach is to find ways of engaging those who have a "need-to-know" regarding corrosion engineering. The programs are directed toward the education of several different constituencies, including policy-makers, operation and financial managers, technical and operating staff, and the general public. Multimedia delivery of educational pieces is recommended.

Recommendations

1. Prepare and disseminate case histories and technology briefs that document corrosion costs and demonstrate the benefits of sound corrosion control practices to policy-makers, management, and technical staff. In addition, well-documented cases supported by cost/benefit analyses demonstrate savings from proper corrosion control or excessive costs

from inadequate corrosion control. The implementation methodology, as well as the technology, should be documented.

2. Prepare and disseminate effective public awareness pieces to document successes in corrosion control, such as the advances in corrosion resistance of body panels in automobiles. The public must be convinced of the benefits of corrosion control. A great deal of planning is required in order to portray this information to the public via media sources. Past successes with improved nutrition, cancer prevention, and similar campaigns show that public education is possible, but not easy.

Strategy 3. Change Policies, Regulations, Standards, and Management Practices to Increase Corrosion Cost-Savings Through Sound Corrosion Management

Issue

There is a definite disparity in the application of effective corrosion control among industrial sectors and among entities within an industrial sector. When available corrosion control technology is not applied, opportunities for corrosion cost-savings will be missed. There is often a disparity between those who control corrosion costs and those who incur the costs. This can lead to a mentality of "build it cheaper and fix it later" and a disregard for life-cycle costs. The situation is further exacerbated when the builder is not made responsible for the "fix-it" costs.

Benefits

More effective corrosion control provides a safer and more reliable operation. The service life of structures and equipment is preserved and extended. These all result in significant cost-savings. Promoting sound technical practices along with corresponding management practices and policies will provide the driving force for implementing corrosion control procedures leading to cost-effective operations.

Approach

The approach is to identify the barriers that impede the application of sound corrosion control and stimulate more widespread use of effective corrosion control. The following criteria are suggested for the evaluation of current and proposed policies that can impact corrosion management.

1. Goal attainment - Does the policy achieve the goal?
2. Economic efficiency - Is the net benefit of the policy (benefit achieved by the policy minus the cost of implementing the policy) positive?
3. Equity - How does the policy affect income distribution?
4. Transparency - Do those involved understand the policy in terms of implementation and those who are affected by implementation?
5. Administrative simplicity - Is the policy feasible in terms of administration? Administrative work is examined for its cost complexity, elaboration, and/or level of confusion.

It should be noted that the development of governmental and industrial policies can benefit and encourage sound corrosion control management and implementation.

Recommendations

1. Compile and disseminate the state-of-the-art information through federal government agencies such as DOT, DOD, and DOE, as well as through the state and local governments.

These agencies regulate, finance, and provide information relevant to corrosion design and maintenance for structures in both the public and the private sector, and spend billions of dollars each year on structures that are subject to corrosion. With this type of action, these agencies will realize the savings and the improved services that result from designing for corrosion and managing it better.

2. Create accounts for maintenance and inspection that would ensure that corrosion maintenance and examinations were performed on time and effectively.

3. Change tax policies to eliminate bias against sound corrosion control practices. Current tax policies treat investment and maintenance costs differently. Investment costs are written off over a period of time, while maintenance expenditures are recognized as costs in the year that they are incurred.

   The intricacies of tax policies are rather complex; however, it is important to point out that the current tax policies bias decisions regarding corrosion control. Being able to expense maintenance expenditures while having to depreciate investment expenditures over many years wastes the nation's resources and at the same time imposes a significant inconvenience on the public due to premature corrosion-induced deterioration. The tax system needs to change in order to encourage more investment in improving the corrosion performance of structures and other capital items.

4. Critically review government regulations for their impact on corrosion costs. Myriad regulations at the federal, state, and local levels affect corrosion design and management. The regulations are intended to help the public; however, due to a lack of consideration of important factors regarding corrosion design and management, undesirable consequences may result. The impact of regulations on corrosion control practices and the costs of corrosion are often overlooked. With the added perspective of corrosion costs, the true cost/benefit balance of a regulation can be significantly changed.

   Regulations need to be reviewed and analyzed to uncover any and all implications for corrosion management. Those regulations that are outdated or skewed because they were formulated without considering their implications for corrosion need to be reconsidered. For example, the Environmental Protection Agency (EPA) has universally banned the use of chromates because of their threat to the environment and human health. However, chromates are also known to be among the most effective corrosion inhibitors. In fact, in some applications, there is no close alternative. Rather than an outright ban of these compounds (no-risk approach), the regulation should allow examination of specific cases using a benefit/risk framework. There are probably some applications where the use of chromates results in greater public benefits than its replacement. In these applications, the use can be controlled so that little or none of the compounds result in environmental discharge or human exposure.

5. For large federal programs, the regulations should be justified by cost/benefit analyses. For regulations relevant to materials and structures, the corrosion costs should be included in the cost/benefit analysis.

6. Many aspects of professional behavior are affected by voluntary standards, such as those by NACE, ASTM, and ISO. Corrosion design and management should be given greater attention in the development of voluntary standards. These standards often have a significant impact on regulations. For example, NACE developed a voluntary standard for cathodic protection of pipelines that was subsequently adopted by the Office of Pipeline Safety.

Strategy 4. Improve Education and Training of Staff in Recognition of Corrosion Control

Issue

Most engineering students have little or no exposure to corrosion science and engineering during their education. Despite broad recognition that engineering systems cannot be built without materials and that the performance of those systems are intimately associated with the chemical stability of the materials of construction in service environments, universities do not generally require materials science and engineering courses for their engineering students. In addition, courses on corrosion engineering are similarly not required for engineering majors. The same is true at the technical-staff level as well.

Benefits

A case could be made that, in terms of the technical literacy of an engineer (whether a chip designer or a bridge operator), materials are important and, therefore, belong as a course of study in every engineering discipline. The importance of corrosion science and engineering needs to be introduced as a corollary that affects the performance and the life of engineering systems of all kinds. Implementation of corrosion engineering into a core engineering curriculum would result in a greater awareness in engineering students of the benefits of corrosion engineering.

Approach

There is an opportunity in contemporary engineering schools to make the above case with particular reference to life prediction. Engineering systems of all kinds – from bridges, power stations, and other civil engineering structures to airframes and thin-film electronic and optical devices – are being asked to perform beyond their nominal design lives. The question of residual life is of increasing importance in our economy and political environment. Since materials corrosion (not just metallic corrosion) is a determinant in all such cases, a vigorous, well-planned campaign to engage engineering schools should be a top priority.

Recommendations

1. It is likely that the implementation stage would involve both initial correspondence and then follow-up visits with the leadership of a few targeted deans of engineering.

2. Develop and incorporate modules on corrosion prevention and control into engineering and management curricula. Knowledge regarding corrosion management, including designing for corrosion mitigation, should begin in the undergraduate curriculum and be part of the exam to become a certified professional engineer. Since there is typically no space in the undergraduate curriculum for additional required courses in corrosion, NACE (or other entities) needs to give increased attention to designing "modules" to be worked into the curriculum for awareness and treatment of corrosion. In addition to engineering knowledge, corrosion engineers need further training in engineering economics in order to be able to evaluate options for corrosion management designs, practices, and their consequences. Such training would allow corrosion engineers to advise decision-makers, both at the design phase and during operations and maintenance.

3. Incorporate a pilot program for the corrosion modules in a few specific universities. Efforts should be coordinated with the deans of engineering and the deans of business/management at these universities.

PREVENTIVE STRATEGIES IN TECHNICAL AREAS

Strategy 5. Advance Design Practices for Better Corrosion Management

Issue

Design practices often fail to even consider corrosion; therefore, avoidable corrosion costs are incurred. There are two facets of the problem. First, design engineers, generally mechanical, chemical, and electrical engineers, have an inadequate understanding of materials/environmental interactions and the various corrosion modes. Second, life-cycle costs or total ownership costs are often not considered in the design phase.

Benefits

Advance design practices increase reliability and safety, reduce costs, and conserve materials and energy.

Approach

Change the design paradigm. Make the currently "best practice" corrosion control technology available to the designers. Include corrosion performance in the design criteria, and promote life-cycle and total ownership cost analysis.

Recommendations

1. Provide designers with an understanding of corrosion performance and corrosion control methodologies. Develop and provide designers with effective databases and design tools for optimum corrosion management.

2. Educate current design engineers, corrosion engineers, and maintenance managers regarding the importance of and potential savings from proper corrosion management. A corrosion engineer needs to do more than offer the judgment that "corrosion management pays." The corrosion engineer must be prepared to demonstrate an attractive return on investment for designing for corrosion and corrosion management, as well as improving service and reliability. This requires knowledge of engineering economics that allows the corrosion engineer to perform economic calculations (such as a life-cycle cost analysis and a cost/benefit analysis). Corrosion engineers must be able to determine design and maintenance practices that reduce corrosion, as well as evaluate these practices to inform decision-makers.

Strategy 6. Advance Life Prediction and Performance Assessment Methods

Issue

At present, life prediction and performance assessment determinations are often uncertain because of the uncertainty of all variables that affect corrosion. Hence, the corrosion behavior can often not be adequately assessed or predicted with currently available tools. Inadequacies include the determination of the extent and severity of corrosion damage, the projections of the rates of corrosion, and the evaluation of the effects of alternative remedial actions.

Benefits

Life prediction and performance assessment methods can result in an increase in reliability and safety, a reduction in cost, and conservation of materials and energy. As a result, more efficient and effective life prediction and performance assessment analyses can be performed.

Approach

Technological advances in inspection methods and procedures are required to advance technology. In addition, accelerated test methods are required to test new materials in a short period of time. Improved understanding and modeling of corrosion processes are also required. Improved methods for monitoring service performance are required and experimental databases to support life prediction must be developed.

Recommendations

Carry out coordinated programs to address life prediction and performance assessment in high-priority areas, such as highway bridge structures, pipelines, and aircraft. Provide sufficient resources for technological advances and for transferring the technology and the methodology into practice.

Strategy 7. Advance Corrosion Technology Through Research, Development, and Implementation

Issue

Many of the industrial establishments that have been historically known for materials research in terms of the basic industries, including corrosion-resistant alloys, have abandoned their research and development programs. On the other hand, emerging industrial sectors, such as electronics, opto-electronics, biomaterials, and waste treatment, put high structural and environmental demands on materials of construction with low levels of corrosion tolerance. While this presents opportunities for proper corrosion management, the reality is that many of the emerging industries are populated by people who are unaware of the limits of materials in engineering service. Hence, there is a need to support the corrosion engineering research and development needs of the basic industries, to cultivate awareness through education and training, and to encourage a critical-mass research and development effort in certain emerging areas of technology.

Benefits

Some emerging technologies cannot be commercialized without success in solving corrosion engineering problems. For example, before supercritical water oxidation of chemical wastes can be implemented, corrosion issues with container materials need to be resolved. Another example where corrosion issues played a major role in the implementation of a new technology is the now-defunct work on magnetohydrodynamic (MHD) energy conversion. This initiative will permit implementation of useful and necessary advanced technologies that are otherwise restricted by unsolved corrosion problems.

Approach

The need for a critical mass effort, whether in terms of the basic industries or in terms of emerging technologies, suggests the value of the formation of industrial organizations that could serve to sponsor research and development work that no single company could afford to take on by themselves. Examples of such organizations are the Electric Power Research Institute (EPRI) serving the electrical utility industry, Gas Technology Institute (GTI) and Pipeline Research Council International (PRC*I*) serving the gas transmission industry, and the Material

Technology Institute (MTI) serving the chemical process industry. For highway structures, the National Cooperative Highway Research Program (NCHRP) performs research funded by the states in cooperation with the Federal Highway Administration (FHWA).

Recommendations

1. Other industries that could also benefit from "joint industry" programs include the automotive, aircraft, and electronics industries. Although it has been shown that improved design and maintenance practices have significantly reduced costs and disruptions due to corrosion, these industries would greatly benefit from joint industry programs to develop and implement new technologies. Specifically, significant benefits will be gained from a joint industry program to develop technologies for improved corrosion resistance of electrical and electronic equipment, which would benefit a broad range of industry sectors, notably the automotive and aircraft industries.

2. Corrosion research has, over the years, suffered from inadequate industry and government funding, especially given the cost and the inconvenience associated with corrosion of water mains, bridge structures, automobiles, airplanes, and pipelines. In contrast, physicists and biologists have captured the attention of the public and Congress by describing the dynamics of high-energy physics and biotechnology. While not as noteworthy to the popular press as some other technologies, corrosion research has much to contribute to delivering social services more efficiently and more reliably while lowering the costs of many of the products and services purchased by the public. It is therefore recommended that in addition to the above-recommended joint industry programs, more government funds should be made available for corrosion research. This report has shown that devoting more resources and more attention to corrosion research and practices results in a high return.