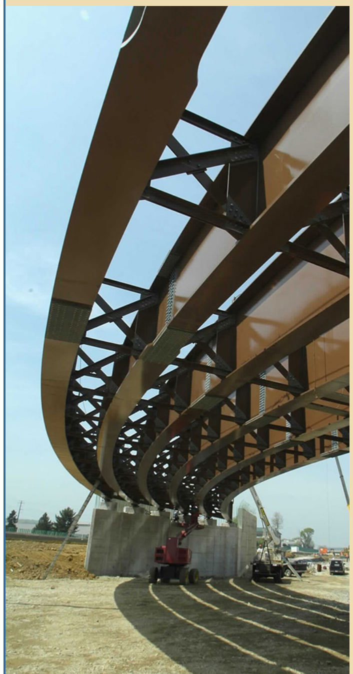

U.S. Department of Transportation
Federal Highway Administration

Steel Bridge Design Handbook

Corrosion Protection of Steel Bridges

Publication No. FHWA-IF-12-052 - Vol. 19

November 2012

Steel Bridge Design Handbook: Corrosion Protection of Steel Bridges

Publication No. FHWA-IF-12-052 - Vol. 19

November 2012

Technical Report Documentation Page

1. Report No. FHWA-IF-12-052 - Vol. 19	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Steel Bridge Design Handbook: Corrosion Protection of Steel Bridges		5. Report Date November 2012
		6. Performing Organization Code
7. Author(s) Robert Kogler (Rampart, LLC)		8. Performing Organization Report No.
9. Performing Organization Name and Address HDR Engineering, Inc. 11 Stanwix Street Suite 800 Pittsburgh, PA 15222		10. Work Unit No.
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address Office of Bridge Technology Federal Highway Administration 1200 New Jersey Avenue, SE Washington, D.C. 20590		13. Type of Report and Period Covered Technical Report March 2011 – November 2012
		14. Sponsoring Agency Code

15. Supplementary Notes
This module was edited in 2012 by HDR Engineering, Inc., to be current with the AASHTO LRFD Bridge Design Specifications, 5th Edition with 2010 Interims.

16. Abstract
Corrosion is a serious threat to the long-term function and integrity of a steel bridge. Structural steel will corrode if left unprotected or inadequately protected from the natural environment. This corrosion can take the form of general uniform thickness loss or concentrated pitting depending on exposure to the environment and the steel design detail in question. Bridge designers should view corrosion as a long term threat to the integrity of the bridge structure, and is a critical consideration that must be addressed in a rational manner during the design process.

While there are several proven strategies for corrosion protection of steel bridges, there is no universal solution. The proper system must be chosen to accommodate cost, fabrication and productivity, and long term performance and maintenance. Additionally, each corrosion protection system must be selected based on the anticipated exposure of the structure to corrosive elements over its lifetime. This module highlights the most common issues confronting bridge designers regarding corrosion protection and provides guidance in this area.

17. Key Words Steel Bridge, Corrosion, Corrosion Protection, Steel Coatings, Galvanization, Metalized, Weathering Steel	18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No of Pages	22. Price

Steel Bridge Design Handbook: Corrosion Protection of Steel Bridges

Table of Contents

List of Figures

List of Tables

FOREWORD

It took an act of Congress to provide funding for the development of this comprehensive handbook in steel bridge design. This handbook covers a full range of topics and design examples to provide bridge engineers with the information needed to make knowledgeable decisions regarding the selection, design, fabrication, and construction of steel bridges. The handbook is based on the Fifth Edition, including the 2010 Interims, of the AASHTO LRFD Bridge Design Specifications. The hard work of the National Steel Bridge Alliance (NSBA) and prime consultant, HDR Engineering and their sub-consultants in producing this handbook is gratefully acknowledged. This is the culmination of seven years of effort beginning in 2005.

The new *Steel Bridge Design Handbook* is divided into several topics and design examples as follows:

- Bridge Steels and Their Properties
- Bridge Fabrication
- Steel Bridge Shop Drawings
- Structural Behavior
- Selecting the Right Bridge Type
- Stringer Bridges
- Loads and Combinations
- Structural Analysis
- Redundancy
- Limit States
- Design for Constructibility
- Design for Fatigue
- Bracing System Design
- Splice Design
- Bearings
- Substructure Design
- Deck Design
- Load Rating
- Corrosion Protection of Bridges
- Design Example: Three-span Continuous Straight I-Girder Bridge
- Design Example: Two-span Continuous Straight I-Girder Bridge
- Design Example: Two-span Continuous Straight Wide-Flange Beam Bridge
- Design Example: Three-span Continuous Straight Tub-Girder Bridge
- Design Example: Three-span Continuous Curved I-Girder Beam Bridge
- Design Example: Three-span Continuous Curved Tub-Girder Bridge

These topics and design examples are published separately for ease of use, and available for free download at the NSBA and FHWA websites: http://www.steelbridges.org, and http://www.fhwa.dot.gov/bridge, respectively.

The contributions and constructive review comments during the preparation of the handbook from many engineering processionals are very much appreciated. The readers are encouraged to submit ideas and suggestions for enhancements of future edition of the handbook to Myint Lwin at the following address: Federal Highway Administration, 1200 New Jersey Avenue, S.E., Washington, DC 20590.

Myint Lwin

M. Myint Lwin, Director
Office of Bridge Technology

1.0 INTRODUCTION AND BACKGROUND

Corrosion is a serious threat to the long-term function and integrity of a steel bridge. Structural steel will corrode if left unprotected or inadequately protected from the natural environment. This corrosion can take the form of general uniform thickness loss or concentrated pitting depending on exposure to the environment and the steel design detail in question. The designer should view corrosion as a long term threat to the integrity of the bridge structure – a critical design consideration that must be addressed in a rational manner during the design process.

Corrosion is a time-based process that generally takes several years to develop deterioration significant enough to cause concern. For this reason, corrosion is often considered an ownership or maintenance issue. While this may be true in practical terms, corrosion is most appropriately addressed by specification of a proper corrosion protection system during the design phase. It has been shown that corrosion played a significant role in the catastrophic collapse of both the Silver Bridge (Point Pleasant, WV) in 1967 and the Mianus River Bridge (Connecticut) in 1983 (1) (2). Therefore, corrosion is not an issue to be taken lightly by the designer.

Figure 1 Photograph of a connection severed due to corrosion.

It is important to place the issue of corrosion in perspective. Corrosion is a concern beyond steel bridges alone. Because reinforced concrete and prestressed concrete bridges also employ steel components in their designs, these bridges are also susceptible to the effects of corrosion. It can be reasonably argued that although steel bridges tend to show the outward effects of corrosion more readily than concrete structures, steel bridges are inherently easier to inspect and maintain than concrete bridges.

Figure 2 Photographs of corrosion of prestressing strands on underside of two prestressed concrete bridges.

While there are several proven strategies for corrosion protection of steel bridges, there is no universal solution. The proper system must be chosen to accommodate cost, fabrication and productivity, long term performance and maintenance. Additionally, each corrosion protection system must be selected based on the anticipated exposure of the structure to corrosive elements over its lifetime. This module highlights the most common issues confronting the steel bridge designer regarding corrosion protection and provides some guidance in this area.

2.0 KEY ISSUES

There are four key issues to consider in the design of a bridge corrosion protection system: Environment, Materials of Construction, Design Detailing, and Cost.

2.1 Environment

The local environment of a structure substantially influences the rate of corrosion of exposed steel and the deterioration of the protective coating. Traditionally, corrosion engineers have classified the general (macro) environment surrounding a structure as mild (rural), industrial, moderate, or severe (marine). These general classifications are of some limited use to the bridge designer as a starting point for determining the appropriate level of corrosion protection required for the structure. The designer should begin by assessing the surrounding environment for the subject bridge with specific focus on the potential for salts or deleterious chemicals to contact and remain on the steel surfaces and for excessive amounts of moisture to remain on steel surfaces. For highway bridges the following types of environments are distinguished (3):

- Mild (Rural): Little to no exposure to natural airborne and applied deicing salts. Low pollution in the form of sulfur dioxide, low relative humidity, absence of chemical fumes, usually an interior (inland) location.

- Industrial: High sulfur dioxide or other potentially corrosive airborne pollutants, moderate or high humidity. This classification has become less important in recent years as long-term corrosion data shows the corrosive effects of airborne pollutants has diminished with the implementation of clean stack gas regulations. This atmospheric classification is still a consideration directly downwind of known corrosive process stream contaminants.

- Moderate: Some (occasional) exposure to airborne salts or deicing salt runoff.

- Severe (Marine): High salt content from proximity to seacoast or from deicing salt, high humidity and moisture.

The above definitions are, by necessity, generic. Many bridges will not fall distinctly into any of the categories. Some bridges may have intermediate climates with moderate sulfur dioxide and moderate humidity, while others may suffer from high humidity, high sulfur dioxide, and salt. Frequently there is a large variation in the environment even within a very small geographic area due to local effects. Salt and moisture levels may vary substantially from one end of a structure to the other. The direction of sun and wind and the degree of sheltering strongly influence the highly critical time of wetness of structural members. Steel that is never exposed to sunlight may have a much higher time of wetness than unsheltered members. It does not appear that there is a specific “critical” or “threshold” acceptable time of wetness. Rather, a higher time of wetness combined with higher levels of contamination in the moisture and on the steel surface leads to higher corrosion rates (4). Also, since a true wet-dry cycle is necessary for the proper formation of protective corrosion films on weathering steel, details that remain almost constantly wet will not be able to form this protective film and will continue to corrode during their lifetime.

For the purposes of steel bridge design, the most important designation is the breakpoint between a moderate and a severe environment. For mild environments, corrosion is a less critical issue and there are many options available for the designer. For severe or marine environments, the choices are limited to highly durable options due to the high corrosivity of the site. It is the large number of sites that fall into the moderate designation where under- and overdesign of the corrosion protection system most frequently occur.

Significant historical data exist that show airborne salt levels fall off dramatically as the location moves away from the shoreline. This effect shows that in some locations the "marine" characteristic of a coastal environment can abate even within a few hundred meters from the shore (5). However, in other locations, although the gross corrosion rate does diminish inland, the corrosivity remains relatively high several miles from the coast. In addition, it has been shown that storms can carry airborne salts miles inland on a frequent basis. These data and the experiences taken from past bridge performance indicate that the corrosivity of a specific location is highly site-specific, depending on proximity to the ocean, but also on wind patterns, storm frequency, and height above the water. Therefore, there is not a specific detailed map defining the boundary between moderate and severe corrosion sites. If a structure is to be located over or within several miles of natural salt water, the designer should investigate the potential corrosivity in detail prior to choosing a suitable protection system and err on the side of conservatism.

Table 1 shows section loss data developed in a comprehensive study conducted by the American Society for Testing and Materials (ASTM) in the 1960's (6). The data show the rapid general falloff in corrosion rates of carbon steel in moving from a marine to an industrial to a rural site. The data also show that there is a wide variation in corrosion rates within each macro-environment depending on such variables as distance from the shoreline, height above ground level, and others. It is also important to note that these are corrosion rates for 1960s-era carbon steel under ambient conditions with no direct exposure to deicing salts. Direct, frequent contact between bare steel and deicing salts will produce corrosion rates closer to those listed for a marine environment.

Table 1 Corrosion Rates for Carbon Steel at Various Locations

Location	Environment (macro)	Section loss (µm) 1 yr	Section loss (µm) 2 yr
Phoenix. AZ	rural	6.6	9.2
Vancouver, B.C.	rural-marine	17.3	26.7
Detroit, MI	industrial	23	28.9
Potter County, PA	rural	21.8	41.1
State College, PA	rural	25.1	45.9
Durham, N.H.	rural	35.4	54.7
Middletown, OH	semi-industrial	36.2	57.6
Pittsburgh, PA	industrial	42.8	61.3
Bethlehem, PA	industrial	55.1	75.3
Newark, NJ	industrial	72.4	102
Bayonne, NJ	industrial	127	155
East Chicago, IN	industrial	111	169
Cape Kennedy, FL 0.8 km from coast	marine	41.1	173
Brazos River, TX	industrial-marine	107	187
Cape Kennedy, FL 54m from coast, 18 m elevation	marine	61.3	263
Kure Beach, NC 240 m from the coast	marine	85.1	292
Cape Kennedy, FL 54m from coast, 9 m elevation	marine	70.8	330
Daytona Beach, FL	marine	209	592
Cape Kennedy, FL 54 m from coast, ground level	marine	191	884
Point Reyes, CA	marine	315	1004
Kure Beach, NC 24 m from the coast	marine	712	1070
Cape Kennedy, FL beach	marine	1057	

Away from the coast, the question of designation between moderate and severe becomes one of frequency of deicing salt application and the realistic ability for keeping the deicing salt runoff from contacting the steel superstructure. Again, there are areas of the country where deicing applications are frequent and heavy. In these (mostly northern) areas the default position must be a high durability corrosion protection system, unless the designer can painstakingly detail the particular bridge to avoid all potential contact between regular salt containing runoff and splash and the structural steel(7, 8, and 9). There is also a large portion of the country where deicing salts are never used. It is the area in the middle latitudes of the country where deicing salts are applied inconsistently or infrequently and where the question of adequate long-term corrosion protection must be addressed in a rational, site-specific manner.

Identifying the corrosion environment is important because the suitability of weathering grade steels and the durability of protective coatings are directly affected by their exposure environment. Thus, in some locales, there may be several corrosion protection options appropriate for the exposure; whereas in more severe locations; however, only a maximally durable coating system would be acceptable.

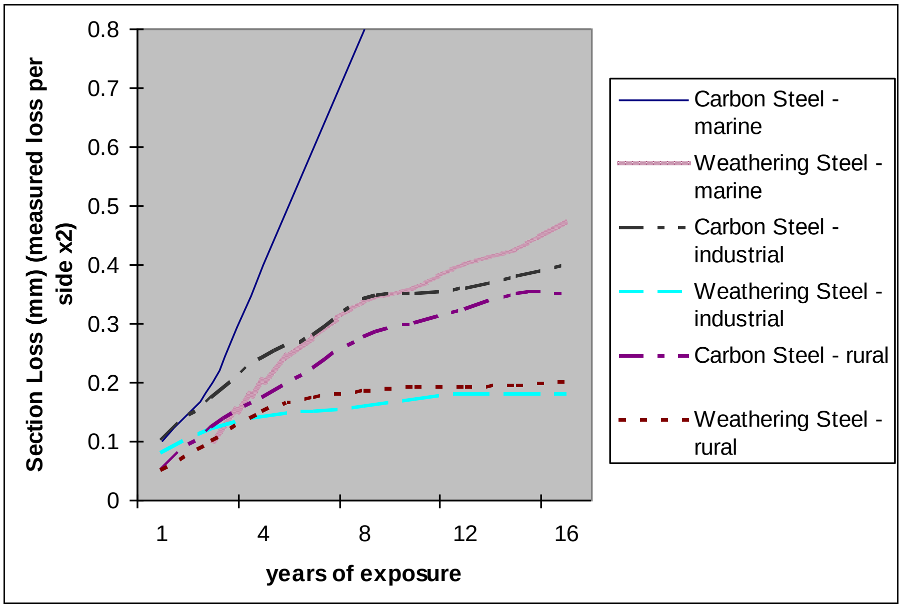

Figure 3 Graph showing corrosion rates for carbon and weathering steel in various environments.

Figure 3 above was constructed as a composite from long term corrosion exposure data available in the literature (10). The values used are averages from various exposure programs under a variety of conditions and do not represent worst case estimates for the particular cited macro-environment. However, these curves do show the relative corrosivity differences between different general classifications of macro-environment as well as the relative benefit to corrosion protection of the weathering grade steels in each of the environments. Clearly the figure shows that marine environments produce corrosion rates which are unacceptably high. In addition to the highest measured rates, data for marine environments show the most scatter. The designer must exercise caution and conservatism when citing anticipated corrosion performance from single marine exposure data points as individual data points can be either low or high.

Figure 3 also illustrates a key performance property of weathering steel. The initial (years 1 and 2) corrosion rates for weathering steels are lower, but similar to that of carbon steel; however, weathering steel corrosion rates tend to flatten out over time, yielding long-term rates which are much more acceptable than those for plain carbon steel. The flattening of the corrosion curve determines the acceptability of a particular environment for bare weathering steel. As is evident in the marine curves, the rate for weathering steel reduces over time but does not fully flatten out. This behavior will lead to long-term section loss that will continue over time and eventually become a maintenance or performance issue. For the other environments, the curves flatten out to an ambient corrosion rate that is negligible.

The key variables for defining the corrosivity of a particular bridge site are as follows:

Time of Wetness – The cumulative amount of time the steel surfaces will stay wet. This is affected by proximity to water sources, ambient humidity, local rainfall, etc.

Salt – Airborne salt from natural sources that can settle on steel surfaces as well as salt from deicer runoff.

Other contaminants – Airborne pollutants and runoff or debris from traffic can increase corrosion rates.

Temperature – Corrosion rates tend to increase with increasing ambient temperature.

Wind Direction – Local wind conditions have a significant impact on salt and contaminant distribution from ambient sources.

Anticipated Traffic Loading – High traffic loading on or under a structure tends to increase deicer application rates and increase airborne levels of deicing salts.

The general environment of a structure can be determined from the macro-environment: the geography (proximity of seacoast, industry, cities) and climate (acidity and quantity of rainfall, relative humidity and pollution levels). However, the decision regarding an appropriate corrosion protection system also requires an examination of micro-environments anticipated for the bridge in question. Specifically, the designer has to anticipate the long term impact of the combination of environmental factors and the influence of specific structural configurations on the concentration of corrosive elements on the steel surfaces. The designer should minimize the areas on the structure that will have a high time of wetness and areas that will frequently be exposed to salt (7) (8) (9).

Figure 4 Photograph showing heavy corrosion of bottom flange and web due to collection of constantly wet debris.

Time of wetness can become an issue for areas of the structure that trap or retain water or debris. These areas include horizontal plates or elements or configurations that form a pocket at the junction of two or more members. Such configurations should be avoided if possible; or, if necessary, drainage paths should be provided. It should be noted that weep holes (drainage holes at low points) and drip bars (small bars that allow water to channel off and drip away from structures at high points) are good practice where the detail itself cannot be modified to eliminate the potential for trapping and carrying unintended drain water; however, these elements are not always reliable over the long term, as weep holes can clog and drip bars are only effective for low drainage flow (e.g., condensation) situations. In addition, designers should recognize that traditionally, deck drainage systems have shown a limited effectiveness due to being undersized and inefficient in moving stormwater from decks. Therefore, it should be assumed that steel below the deck will not be kept dry by such systems. Debris buildup can also occur from nesting birds. If possible, access to the interior of box beams should be screened to keep birds from nesting inside them.

Figure 5 Photograph showing debris accumulation at a connection point.

Another significant design consideration is the effect of saltwater splash onto steel or painted steel surfaces. This effect is particularly critical for bridges spanning salt water and for grade separations that have significant truck traffic passing underneath. Truck traffic at highway speeds creates a significant water (and salt, if applied) plume to a height well above traffic. There has been insufficient research to strictly define a typical plume height for salt above a highway roadbed, so there is no specific limitation in this regard. However, grade separations with only a few feet of clearance above treated roads are exposed to significant airborne salt throughout the winter. For heavily salted roads with heavy traffic, this effect can dramatically increase the local corrosivity of the steel areas directly above and to the side of traffic. For example, a weathering steel bridge showing an ambient corrosion rate of less than 1 mil per year (0.0254 mm per year) can show a corrosion rate of four times that on bottom flanges just above truck travel lanes (11). Deicing salt application history for the intended location of the new bridge is another key piece of information for the bridge designer in selecting a corrosion protection strategy. Exact local salt usage data is generally difficult to obtain with any reliability, as it is not kept consistently and relies on local maintenance records. However, analyzing factors such as typical local snowfall, traffic levels, and proximity to metropolitan areas can yield a reasonable qualitative estimate of road salting frequency. Over the past two decades, with the aggressive philosophies adopted by most transportation departments regarding bare, safe driving pavement during winter freezing events, the frequency of salt application to roadways has gone up dramatically. This increased use of deicing chemicals has placed an increased burden on the corrosion protection systems for all bridges in these environments. The designer should be cognizant of the fact that although there are isolated experimental uses of alternative, non-corrosive deicing agents, these technologies are far from establishing any significant market share. The designer should assume with some conservatism that the effects of corrosive highway deicers will continue well into the future. For this reason, the designer should assume that the steel will become contaminated with salt in areas that receive frequent applications of deicers. This assumption will drive the structure into a moderate to severe corrosion classification. The designer may then choose to use a less durable corrosion protection system, but only after ensuring appropriate detailing to keep the salt off of the steel. These local areas and details must be protected with a high performance coating system. This philosophy drives the current requirement (FHWA Technical Advisory T5140.22 "Uncoating Weathering Steel in Structures") to paint the ends of weathering steel beams a length of 1.5 times the web depth to protect the steel directly beneath expansion joints. This same philosophy should be applied to other steel members expected to lay in the drainage path or splash areas of the bridge.

2.2 Materials of Construction

2.2.1 Coatings for Blasted Steel

For several decades, the predominant protective coating system used for bridge steel was several coats of lead-containing alkyd paint. This system was inexpensive, easy to apply, and provided reasonable corrosion protection as long as periodic maintenance painting was performed. This system was generally applied directly over intact millscale with little-to-no surface preparation (12). In the 1970's, the advantages of abrasive blasting to remove millscale and provide a clean surface for paint application became well known. Since this time, full-scale surface cleaning by abrasive blasting has become standard practice. The benefits of this surface preparation to the performance of coatings are unquestioned today (13). The use of sophisticated surface preparation opened the door for the use of truly high performance coatings – primarily multicoat systems using a zinc-rich primer as the main corrosion protection component. Today (2006) it is standard practice in the steel fabrication shop to completely abrasive-blast all structural steel. For weathering grade steels that do not receive paint, this practice removes millscale – which can promote corrosion of the base steel – and allows uniform initial formation of an adherent protective corrosion patina. For steel to be painted, shop preparation is generally specified as an SSPC SP-10 Near White metal blast with additional specification of a surface profile depth (generally 2 to 4 mils) compatible with the particular primer being used – most frequently a zinc-rich primer.

Over the past three decades, advances in paint chemistry and environmental regulations have driven various formulation changes in paints. These changes have brought to market coatings that continue to perform better than their predecessors. At the same time, performance across the spectrum of bridge paints has much greater variation (13). In other words, it is more important than ever to specify an appropriate coating system that is known (through testing and validation) to perform well. Specification of coatings by generic type or using an "or equal" approach can lead to disappointing performance results.

Figure 6 Photograph that shows the testing of various generically similar paint systems with wide variations in performance.

The majority of state highway departments currently specify the use of some type of zinc-rich primer based coating system. For new steel, although the use of full shop application for all coats is increasing, the predominant approach is to blast and prime in the shop and apply topcoats following erection of the structure. In this scenario, ethyl silicate inorganic zinc is the primer of choice. A 1996 survey by the Transportation Research Board found that 42 of 54 bridge agencies specify zinc-rich primers for new construction (14).

An additional motivation for using inorganic zinc primers in the shop is the requirement for slip and creep resistance of the coating system used between steel plates at a bolted connection. This requirement reflects the concern that using a full three-coat system on each side of adjacent bolted surfaces would place perhaps 20 mils of paint between the bolted plates. This thickness of paint may slip and creep over time causing the connection to become loose (15). Since the inorganic zinc provides the primary corrosion protection of the paint system, and because of its inherent hardness, a single coat of inorganic zinc is usually applied in these splice plate areas. Testing of these primers confirms the acceptability of individual paint formulations.

Initial applications of zinc-rich coating systems to bridges beginning in the 1970's used vinyl topcoats. With recent regulations limiting the amount of solvent in coatings, vinyls have been replaced in the industrial coatings marketplace. The predominant topcoating system used now (2006) for zinc-rich primers consists of an epoxy midcoat with a polyurethane topcoat. This three-coat approach to bridge painting is accepted practice over much of the nation. In this approach, the zinc-rich primer provides the primary corrosion protection for the steel. The epoxy midcoat provides an excellent moisture barrier and adds physical protection to the zinc primer. The polyurethane topcoat forms a weatherable additional moisture barrier with long-term color and gloss retention and resistance to gradual erosion (chalking) caused by exposure to sunlight.

Other agencies use systems that substitute waterborne acrylic for the obsolete vinyl topcoat. A few states use a multicoat, all waterborne acrylic system for bridges that do not have heavy salt exposure.

Most agencies maintain their own unique set of qualification factors for proprietary coatings. These systems employ standard accelerated “torture tests” which attempt to mimic years of harsh exposure over the period of a few thousand hours in a test cabinet. Recently, the bridge community has established a cooperative testing program for bridge paint performance. This program, the National Transportation Product Evaluation Program (NTPEP), is maintained by the American Association of State Highway and Transportation Officials (AASHTO) and provides the first national level clearinghouse for bridge paint performance data (16). This program will bring a greater level of consistency and performance to bridge paint coatings. The designer should consider this a unique, unbiased resource for paint material selection.

Quality of application is a key factor in the success or failure of any paint system. The AASHTO/NSBA Steel Bridge Collaboration has produced a guide specification for shop painting steel structures (17). This document represents a good collection of detailed language and specification references for achieving quality. Good Painting Practice, Volume 1, published by SSPC, the Society for Protective Coatings, also provides an excellent reference for the detailed issues involved in painting bridges and other industrial steel structures.

In the future, there is great potential for paint performance to improve in many areas. The aforementioned national testing program has opened the opportunities for bridge owners and specifiers to reexamine many of the entrenched practices of a three-coat paint specification. Efforts are underway to develop coatings that can match the performance of multicoat systems with a single, fast-drying coat of paint. Success on this front would remove a significant production bottleneck from the steel fabrication shop – allowing time for paint to dry before handling – and also potentially save significant cost.

In addition, specifiers have given little weight to the long-term aesthetic performance of bridge paint systems. Properties such as color and gloss retention can now be more easily analyzed for specific paint formulations. As the aesthetics of bridges become more important to engineers and community groups alike, the robust performance characteristics of modern industrial coating systems will become more important to bridge construction and rehabilitation efforts.

2.2.2 Metalizing

A small but growing number of bridges and bridge components have been metalized for corrosion protection. Metalizing is a process in which modified gas or electric arc welding equipment is coupled with compressed air to melt and project zinc or aluminum alloy wire onto a steel surface. Correctly applied, metalized coatings show outstanding corrosion protection quality. The metalizing industry highly recommend at least a sealer and often a sealer and finish coat over metalizing (18). Several factors have held the proliferation of metalizing in check in the bridge market. The concerns of owners and fabricators include cost, productivity, and the learning curve of the industry with regard to the nuances of the metalizing process. Metalizing requires at least an SSPC SP-10 abrasive blast cleaning and application of 8 to 12 mils of thermal sprayed metal (either zinc or zinc/ aluminum alloy). This system has demonstrated durability in marine environ-ments, and recent improvements in the productivity of application equipment may make metalizing more attractive for both shop and field applications (19) (20).

2.2.3 Galvanizing

Bridge components have been hot-dip galvanized for many years. This process places the entire steel component into a molten kettle of molten zinc. The zinc coats the steel with the heat of the process causing the formation of several metallurgical transition layers between the steel and zinc. This process results in a corrosion-resistant, adherent coating on the steel. Corrosion resistance of galvanized steel is dependent upon the thickness of the applied zinc and the self corrosion rate of zinc in the given exposure environment. Historically, galvanized surfaces have been troublesome to paint, limiting color choice to the gray spangled and mottled appearance of the galvanizing. However, in recent years the galvanizing industry educated many owners on the specific procedures necessary for successful painting, and topcoated galvanized steel is now commonplace.

For steel bridges, the two primary limitations for galvanizing have been transportation costs and galvanizing kettle size and availability. Since the structural element must be fully immersed in the kettle, large beams are a challenge. There are now several kettles in North America between 50 and 80 feet in length (21).

2.2.4 Weathering Steel

Weathering steel is an important option for the bridge designer. The availability of high performance steel (HPS) grades 70 and 100 has broadened its applicability. These steels are designed as weathering grade steels and have corrosion resistance essentially equal to that of ASTM 588 weathering steel.

The FHWA Technical Advisory T5140.22 “Uncoated Weathering Steel in Structures” (22) provides guidance to the states for development of their own policies regarding the use of weathering steel. This document contains a digest of the primary benefits and concerns regarding weathering steel and provides specific guidance on its appropriate use. Written in 1989, the document is undergoing a review and rewrite; however, the majority of its content remains useful as a starting point.

Weathering grade steels have been available for several decades. They have been produced in various proprietary chemistries; but essentially small amounts of copper, chromium, nickel and silicon are added to carbon steel to achieve an alloy with enhanced weathering properties. These steels will form a rust patina when exposed to the environment providing a barrier between the bare steel and the corrosive elements of the environment. When properly detailed and exposed to environments that include cyclic wet/dry exposures and do not introduce significant amounts of corrosive contaminants to the steel surface, this tightly adherent patina provides a weathering steel structure with its own protective coating that slows the self-corrosion rate of the steel to a very low rate.

Although highway bridges were not the first industrial application of weathering grade steels, they have been the primary market for the material since the first weathering steel bridges were built in the mid 1960’s. Since then over 4,000 weathering steel bridges have been placed in service on the national highway system (10). After some corrosion problems were experienced by various states, resulting from improper detailing and overextension of the technology to a few highly corrosive applications, several agencies discontinued the use of weathering steel. However, increased understanding of the benefits and limitations of weathering steel, coupled with the introduction of weathering grade high performance steels, and the economic and productivity concerns of painting, has created a revived market for weathering steel in the construction of new bridges.

The primary benefit of weathering steel is the promise of long-term corrosion protection without the need for either initial or maintenance painting. The steel industry has made the point that weathering steel, when properly applied, results in a structure that provides first cost and life cycle cost savings. A recent FHWA-sponsored study indicates the median cost of shop coating is 7% (primer) and 11% (three coats) of the cost of the fabricated girder (23). With the subsequent recent dramatic movements in steel prices, it is difficult to define the premium paid for weathering grade versus carbon steel, but historically, this premium has been around 4%. So it seems on the surface that from a first cost basis, weathering steel is an obvious choice. However, due to the assumption that all bridge expansion joints will eventually leak, current guidelines require weathering steel bridge elements to be painted at non-integral beam ends to a length of 1.5 times the girder depth. In addition, weathering steel girders are shop blasted to remove millscale so that the initial protective oxide layer is uniform. These requirements offset some of the potential cost savings associated with weathering steel versus painted steel.

Extensive data exist regarding the corrosion performance of weathering steels. Most of these data are taken from studies with small, thin test panels exposed to the general environment in various locations around the world. Caution should be exercised when scaling this data up to judge the potential for corrosion of a large, complex structure. In addition, there is a growing body of data taken directly from the performance of bridge structures. The following highlights conclusions taken from the pertinent data:

- Weathering steel requires some amount of moisture and a wet/dry weathering cycle over a period of time to develop a tightly adherent, protective oxide layer. However, excessive moisture or the presence of salt will disrupt this process and result in a structure that corrodes at an unacceptable (much higher) rate (5) (24) (7).

- Weathering steel, like all steels, will corrode at varying rates from structure to structure and element to element. Corrosion is a complex phenomenon relying upon the macro- and micro- environments, the temperature, specific concentration of contaminants, and the specific surface structure of the individual piece of steel. Engineers should expect corrosion rates to occur over a broad range, even in similar situations. For this reason, it is improper to look only at average rates of corrosion. Credence must also be given to data from the higher end of the range – the extreme value of the data- for this is where the potential first, failure lies.

- Improperly located and/or detailed weathering steel structures have shown average corrosion rates of up to 0.004 inches (4 mils) per year per exposed side. Since weathering steel tends to exhibit local pitting as it corrodes, the depth of pits can be much deeper (10) (9) (4).

- Nearly all of the reported failures of weathering steel on bridges have occurred in applications where the steel is wet for a significant portion of time or the steel is exposed to salt from the ocean or deicing operations.

Properly functioning weathering steel will corrode at a steady-state rate less than 0.3 mils per year (7.5 microns per year). Corrosion in excess of this rate indicates that weathering steel should not be used bare at that location (5) (25).

2.3 Design Detailing

The most important considerations in designing for corrosion protection of a steel bridge are preventing water ponding, diverting the flow of runoff water to prevent it from impinging on the steel structure, preventing the accumulation of debris that traps salt and moisture, and preventing natural salt or applied deicing salt from contacting the steel surface (7).

Steel bridge designs continue to evolve so that there are many different types currently in service. Steel bridges can be simple, rolled beam or plate girder construction with all of the steel located below the level of the roadway deck. They can be constructed of a combination of steel trusses located below and above the deck. They can have unique, challenging components such as main cables and suspender cables on a suspension or cable-stayed bridges, or they can be highly complex with moving parts such as a bascule or liftspan bridge. From the perspective of corrosion protection and coatings, the following variables are considered important in that they may impact coating materials or methods chosen:

Complexity – Bridges with high levels of surface complexity are more difficult and expensive to clean and paint. Complex details include box beams, riveted construction, lacing bars, and tight clearances between members.

Height and access – Rigging for access to steel surfaces is often an important factor in the cost and schedule of a bridge coating project. By their very function, bridges cross difficult-to-access areas. Often, access to a structure is also heavily impacted by local traffic patterns. Sometimes viaducts and overpasses may be accessed from below. Arch, truss, suspension and bridges over water, however, require at least some closure of the bridge deck for access and equipment placement. Also, bridge painting operations must be contained and ventilated to trap, collect, and dispose of blasting waste and paint overspray.

Large and unique structures – Cable-stayed and suspension bridges have unusual features which require a separate approach when performing maintenance painting. There may be a requirement for separate specifications and contracts for painting of tower, cables, anchorage areas, fixed approach spans and suspended truss spans. In addition, moveable bridges have obvious special requirements associated with moving mechanical parts. These unique features require protective coatings with added flexibility and compatibility with specific lubricants.

Utilities – Many bridges serve as a piggyback for local utility crossings. Live utilities attached to bridge steel can impact the maintenance-painting operation. Utilities must be protected during painting operations, and their physical presence may obstruct maintenance painting of underlying structural steel.

Rail sharing – Some bridges share their capacity between automotive traffic and rail traffic. This presents the unique challenge of operating with deference to the rail schedule for access. The proximity of high voltage third rails can also restrict the use of certain surface preparation methods, particularly the various surface preparation methods using high pressure water to clean.

Since many bridges cross a body of water, there is an inherent source of local moisture to promote corrosion and coating deterioration. This is especially true if salt or brackish water is crossed by the bridge. For highway bridges, the other primary source of corrosivity is the large quantity of deicing salt spread on the roadway during the winter months. This is a factor only in areas that experience freezing temperatures and frequent winter storms. Where salt is applied, it tends to drain from the bridge deck, through expansion joints and other designed-drainage areas onto the painted structural steel below, collecting onto horizontal surfaces and continuing to damage the coated steel for several months or years after application.

There are several areas on each structure that should be examined separately from the standpoint of localized corrosivity. These include:

Drainage areas – various areas of the steel structure below the roadway surface will see the majority of drainage and runoff from the deck above. These areas will have a higher time of wetness than the rest of the steel structure. They will also receive an increased level of dirt and debris from the roadway. This is critical in areas that receive significant amounts of deicing salt. These areas will often have a much higher corrosion rate relative to the rest of the bridge.

Figure 7 Photograph showing the corroded off end of a deck drain downspout. This drainage was undersized and designed with sharp angles in the down spouting. It eventually corroded out and subsequently sprays salt laden deck drainage directly onto structural steel.

Figure 8 Photograph of a girder end on a bearing below a leaking deck joint. Horizontal flange and vertical stiffeners create an excellent trap for debris and moisture.

Designed, directed drainage is often inadequate and deck-mounted expansion joints often leak as well.

Splash zones - Splash zones exist in the lower parts of bridges over any body of water and also in areas that receive significant splash and spray from traffic. These areas include the lower parts of towers and pilings; parapets, curbs, and guardrails; and lower portions of overhead truss structures and overpasses.

Fascia beams and other outboard members – Salt and moisture carried by prevailing coastal winds and increased ultraviolet exposure (sunlight) can accelerate corrosion and paint failure in these areas.

Bottom flanges – Coatings on the lower portions of flanged structures break down early due to higher times of wetness for these parts relative to the rest of the bridge. The higher time of wetness is caused by preferential condensation on the lower portions of a steel element.

Deck Joints - Eliminate or minimize the number of deck joints. Use of integral abutments rather than expansion joints at the ends of spans can significantly reduce the maintenance needs of a bridge. In cases where joints must be employed, minimize the number of joints by employing continuous spans, and use closed or sealed joints as opposed to open joints with troughs. Experience shows that troughs tend to fail or become clogged with debris over time, limiting their effectiveness. Consider use of sealed modular joints in place of multiple single compression seal joints (26).

Figure 9 Photographs showing steel directly beneath transverse and longitudinal expansion joints that have leaked corrosive runoff from the deck.

Clearance - Vertical and lateral clearance is required on a macro scale to prevent the splash and spray of traffic from increasing local corrosion rates in these areas of the structure. For specific details, clearance must be provided to allow for cleaning and coating of steel in a maintenance scenario.

Unique details – Coatings for suspender cables are required that demonstrate excellent long-term performance and flexibility under corrosive and high sunlight exposure. Success has been found with certain unique formulations of waterborne acrylic as well as calcium-sulfonate-modified alkyd coatings with slow-dry properties.

Gratings, bearings, and curbs – These elements are difficult and inefficient to paint in the traditional manner. They are often galvanized, metalized or fabricated from inherently corrosion resistant alloys.

2.3.1 Detailing

- Water/debris traps should be avoided at all costs. These areas are the traditional breeding ground for rapid corrosion of structural steel.

- Inaccessible details that do not allow for inspection and maintenance are poor design practice and must be avoided.

- Edges tend to show coating breakdown well before the general flat surfaces of steel in corrosive atmospheres. This is the reason that good painting practice includes hand striping of coatings on edges and complex surfaces prior to application over larger flat surfaces.

- Built-up members and back-to-back members should be avoided since they are impossible to maintain and generally only receive an initial coat of primer for protection. Where built-up members are unavoidable, durable caulking systems can be used to add protection from water seepage into the faying surface.

- Drains and scuppers have traditionally been undersized and receive little attention in maintenance. Most frequently, these systems have a useful life of only the first few years. They should be minimized or carefully designed to remain clear of debris and have adequate capacity. Drainage pipes should have a steep slope and no sharp bends to minimize debris build-up.

- Box or tubular members should be fabricated airtight and, thus, watertight, if possible. If not possible, then provisions for airflow and drainage must be made in these members.

- Experience indicates that welded box girders cannot be made watertight for the long term. These structural elements should be provided with drainage holes at low points and hatches for access and inspection. It is often common to paint the inside of boxes with white topcoats to facilitate inspection and to provide corrosion protection, since box interiors are not readily available for maintenance.

Avoid direct contact between dissimilar metals. In this scenario, the more electro-chemically active metal will sacrifice (corrode) to protect the more noble metal (27). Direct contact between steel and aluminum, steel and stainless steel, steel and bronze, etc., in a wet environment, will cause accelerated corrosion of one of the two metals.

Figure 10 Photograph showing the area under an open grid deck, which is acting as one large leaking joint.

2.4 Cost

Significant analysis has been made regarding life cycle corrosion control strategies for existing steel bridges (28 and 29). These analyses researched the highly variable cost factors associated with field coating removal and application for bridges. In addition, the variability in performance of maintenance coating systems based on surface preparation, coating material formulation, and specific environmental exposure has been documented (13). Through this research, well-founded approaches to life cycle cost analysis have been formulated, and useful tools for comparing the many possible scenarios associated with bridge maintenance painting have been developed.

Similar analysis has been accomplished for new steel structures. The following is an effort to apply the tools and concepts recently used for maintenance painting scenarios to analyze corrosion control options for new steel.

Alternative bridge corrosion protection costs may be compared by determining an equivalent cost for each of several maintenance scenarios, considering the cost of each scenario over the entire life cycle of the structure, and using simple financial principles that consider the time value of the cash flows representing each scenario. This type of analysis results in the long-term financial advantages or disadvantages of maintenance options with various initial costs.

From the perspective of corrosion control design, life-cycle cost is defined as follows:

> The total cost of corrosion protection for a structure in present-day dollars. This cost includes fabrication, construction, corrosion control system installation, and corrosion control system maintenance for the defined lifetime of the structure.

Determining life-cycle cost requires knowledge of the material cost, the shop surface preparation and coating application costs, the expected useful life of the corrosion control system, the maintenance costs for each particular scenario, and the estimated service life of the structure. By considering the entire maintenance life of a structure, the life-cycle cost impact of selecting a particular corrosion protection strategy can be determined.

A comparative cost analysis must consider various options for initial and maintenance corrosion control systems. For simplicity, three fabrication options will be illustrated herein. The first option is A709 grade 50 steel with a shop-applied zinc-rich primer and two topcoats applied after erection in the field. The second option is fabrication from A709 grade 50 steel with shop surface preparation and application of thermal sprayed zinc (metalizing). The third option is fabrication from A709 grade 50W weathering steel. For maintenance, the analysis will consider several options (each potentially optimum) based on the specific environment of the bridge. All costs presented are in terms of 2006 dollars.

2.4.1 Fabrication Costs

Since current cost data for maintenance painting options are in the units of dollars per square foot of surface area, it would be most convenient to develop generic or “typical” fabrication costs in the same units. This is difficult since steel costs reflect commodity pricing trends which fluctuate on many variables. Also, these prices are available per pound or per ton of steel. Conversion to area-based costs are dependent on design specifics. The literature cites various conversion factors in the range of 100 to 200 square feet per ton. Assuming delivered steel costs are in the range of $1.00 per lb. ($2,000 per ton) and using 150 square feet per ton yields a steel cost of $13.33 per square foot. Weathering steel (A709 grade 50W) is currently delivered at a premium of about $0.04 per pound or 4% over conventional grade 50. This premium yields a cost for A709 grade 50W of $13.86 per square foot (a premium of $0.53 per square foot over conventional grade 50 steel) (30).

Cost for shop application of primers are difficult to break out due to the unique design of each bridge and the unique setup of each fabrication shop. A reasonable estimate is approximately 7% (blast and prime) (23). This yields an assumed delivered cost of $14.26 per square foot (a premium of $0.93 over uncoated grade 50). Various bridge owner agencies have their own estimates for a full 3-coat paint system application for new steel; however, for consistency, this analysis will use the same model used for maintenance painting cost analysis. Using this model to approximate the cost of field application of topcoats to newly erected steel yields an estimated cost of $1.61 per square foot.

2.4.2 Maintenance Painting Costs

The past several years have introduced significant changes in the methods of bridge maintenance painting operations. The most significant changes have been in response to dramatic increases in environmental and worker protection regulations. 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. These regulations are relatively new, and states are at various stages of the engineering learning curve in terms of striking an efficient balance between prudent engineering maintenance decisions and fiscal realities. This has caused a large diversity in operational practices and their cost.

2.4.3 Cost of the Coating System

At present, costs of total paint removal and repainting jobs can range from $4.00 per square foot to as much as $20.00 per square foot (14). Some of this range can be explained by factors that make each bridge maintenance job unique (e.g., access for high structures or structures over water, condition of bridge deterioration, unusual traffic control, etc.). Most “typical” blast and repaint jobs are between $7 and $10 per square foot. The alternative approach to bridge maintenance painting involves using a water wash, minimal removal of existing paint and rust with power tools, and application of a maintenance coating system. This method is commonly referred to as “overcoating” and costs between $1.50 and $5 per square foot. Techniques employing a mixture of pressurized water and abrasive have also become popular. These techniques provide surface preparation quality and productivity advantages over tool cleaning while not requiring the containment (and associated cost) of dry blasting. These techniques range in cost between $3.00 and $6.00 per square foot.

Table 2 shows the significant initial cost savings achieved by specifying overcoating rather than full abrasive blasting. As expected, the theoretical cost for the abrasive+water option falls in between the overcoating and blasting options. Relating these cost numbers in a meaningful way requires reliable information regarding the expected performance of each option.

Table 2 Estimated Maintenance Painting Costs

Method	Total Job Cost	Cost of Labor	Cost of Materials	Total Cost per sq. foot
Abrasive Blast plus 3-coat paint system	$197,988	$44,844 (23%)	$23,849 (12%)	$6.60
Hand Power tool clean (5% deterioration) with spot prime and 2 full overcoats	$60,727	$27,876 (46%)	$8,567 (14%)	$2.02
Spot & Sweep with abrasive-injected water blasting (5% deterioration) plus spot prime and 2 full overcoats	$111,112	$38,784 (35%)	$13,305 (12%)	$3.70

2.4.4 Life of Coatings

The second essential question to be answered before performing a life-cycle analysis is how long a coating system will perform in the given environment. Research and in-service documented experience has generated a significant amount of performance data on various coating systems. Of particular interest is the difference in coating system life expectancy between high-performance coatings (e.g., zinc-rich or metalizing) applied over steel prepared to SSPC SP-10 (near white metal abrasive blasted surface) and typical "maintenance" coatings (e.g., epoxy, alkyd, or moisture-cured urethane) applied over existing bridge paint prepared to SSPC SP-3 (power tool-cleaned surface with adherent old paint and rust remaining). These are the two most probable painting options facing bridge coating specifiers.

For 3-coat, zinc-rich primer paint systems (e.g., ethyl silicate inorganic zinc) data suggest marine environment performance of 15-20 years and performance of 25 years in less aggressive, salt containing environments. This data has been confirmed by inspection of coatings applied to bridges in Iowa, West Virginia, Louisiana and other states where zinc-rich systems applied in the mid-to-late 1970's are now beginning to require some maintenance painting. For metalized systems (zinc and zinc/aluminum alloy), the data in the literature suggest service life expectancies of at least 20-25 years in marine and salt-rich environments and up to 40+ years in less severe salt-containing environments (13).

Because of the diversity of materials used, and the wider variation in the quality of the surface preparation, performance of overcoating applications is more difficult to quantify. In testing sponsored by the Federal Highway Administration, various commercial overcoating products were evaluated on steel of varying initial cleanliness exposed to widely different environments. Under more corrosive conditions (e.g., marine, or near salt-laden drainage) even the best performers began to show significant failure after only 2 years of service; however, some of the better coatings performed quite well for several years under less severe exposure.

Sometimes this variation in performance can be seen on different areas of the same structure. Where overcoating techniques are used to repair areas of structures that have deteriorated, but have reasonably well-adhered existing paint and only minor surface rusting, successful performance of 7-10 years has been documented. However, in areas showing marginal to poor adhesion of the existing coating and significant rusting (e.g., measurable metal loss), overcoating applications carry much more risk and failures have occurred after less than three years of service. The subject cost analysis must assume that overcoating applications are only selected only for areas where there is a reasonable chance of longer-term success.

2.4.5 Corrosion Protection by Use of Weathering Steel

The use of weathering steel as the primary corrosion protection system for bridge steel has been the source of much debate over the past two decades. The literature cites a myriad of “successes” and “failures” of weathering steel in this role. What is known is that weathering steel provides significantly enhanced resistance to general corrosion rate (versus conventional grade 50 steel) in virtually all highway bridge environments. However, it is also clear that weathering steel suffers unacceptable rates of corrosion in areas where salt, debris, or moisture accumulate on steel surfaces. Many of the cited “failures” of weathering steel in the past have been attributed to design details which allowed these accumulations or to misapplication of weathering steel in locations that were inherently highly corrosive (e.g., marine environments). For the most part, the lessons learned have been applied to improve the success rate of weathering steel; however, many applications in northern areas still require application of coatings at beam ends and around drainage areas. These specifications may offset some of the intended cost savings associated with the selection of weathering steel.

For the purposes of this discussion, weathering steel is considered a viable corrosion protection system, but is not maintenance-free. It is reasonable to assume that some degree of maintenance coating or additional corrosion protection is necessary for weathering steel in salt-containing environments. The subject analysis examines three alternative maintenance scenarios with regard to weathering steel. There are obviously many other possible scenarios.

The development of user-friendly tools for assessing the relative cost impacts of various corrosion control options with respect to each individual maintenance decision is necessary for efficient analysis. An easy-to-use, spreadsheet-based bridge maintenance cost model has been developed by FHWA (13). This model uses traditional financial discounting techniques (i.e., total present value analysis) to obtain the equivalent uniform annual cost (EUAC) of various bridge maintenance options. It is designed to be useful to the bridge engineer with little specific training in coatings technology and cost estimating. Data must be input for expected coating system performance, installation cost, and expected remaining life of the structure. Using these inputs, the model calculates the EUAC for the specific parameters entered. Various corrosion control options can be compared by changing the listed variables to reflect different maintenance scenarios. For example, changing the input values for variables that effect production rates of the operation (e.g., surface preparation or application rates) or changing the estimated values for coating lifetime can have a significant effect on the output of the model.

2.4.6 Financial Considerations

A life-cycle analysis will result in $\$/ft^2$/year to represent the cost of a particular life cycle corrosion protection scenario. This term represents an "annualized" cost per square foot for various cash flows that represent various corrosion control scenarios available for designing and maintaining a particular structure (e.g., painted steel with maintenance vs. weathering steel with maintenance). The following formulas are derived from simple engineering economics and are used to determine the annualized cost per unit area ($\$/ft^2$/year):

$$FC = IC\,(l+e)^{np}$$

Where:

FC	=	future cash flow,
IC	=	initial cost,
e	=	escalation rate (inflation, assumed for this analysis as 1.9% for materials and 4% for labor), and
np	=	number of periods (years).

$$PV = FC/\,(1+I)^{np}$$

Where:

PV	=	present value
I	=	interest rate

$TPV = \Sigma PV$

Where:
TPV = total present value

$EUAC = TPV*((I*(1+I)^L)/((1+I)^L - 1))$

Where:
EUAC = equivalent uniform annual cost
L = expected lifetime of bridge.

2.4.7 Sample Analysis

This analysis uses the EUAC financial method and analyzes its effect on the life-cycle cost of several hypothetical corrosion control options. The single value used to quantify the cost of painting options is the total present value (TPV) of the cash flow for each option. The TPV is the amount of money necessary today to install and conduct maintenance for the design life of a structure, considering the cost of inflation and a money discount factor. In this analysis, options with the lowest TPV are favored.

This hypothetical analysis assumes a non-marine environment with winter application of deicing salts. The cost of raw steel is cancelled out in each comparison, so only the premium values for initial painting or metalizing and weathering steel are included in the analysis. Erection costs are assumed to be equal for each scenario. The cost and maintenance frequencies for this exercise are assumed and should not be considered reflective of current values or practices.

Table 3 Life Cycle Costing Scenarios

Scenarios	Costs
1-A709 grade 50 steel with shop-applied zinc primer and two field topcoats. Full removal and repaint every 20 years.	7% premium for shop applied primer; $1.61 /ft^2$ for 2 field topcoats, $6.60 /ft^2$ for each repainting
2-A709 grade 50W weathering steel, maintenance painting at selected areas beginning year 10.	4% premium for weathering steel, $3.70 /ft^2$ for maintenance painting
3- A709 grade 50W weathering steel, full blast and paint at year 15 and thereafter.	4% premium for weathering steel, $6.60 /ft^2$ for repaint
4-A709 grade 50 with shop primer, periodic maintenance, and full repaint at 30 years	7% premium for shop prime, $1.61 /ft^2$ for 2 field topcoats, $3.70 /ft^2$ for maintenance painting, $6.60 /ft^2$for full repaint
5-A709 grade 50 with shop applied metalized coating, maintenance painting at 30 years, repaint at 50 years and thereafter	15% premium for metalizing, $3.70 /ft^2$ for maintenance paint, $6.60 /ft^2$ for repaint
6- A709 grade 50W weathering steel, properly detailed with maintenance painting in corrosive areas every 20 years	4% premium for weathering steel, $3.70 /ft^2$ for maintenance painting

2.4.8 Results

Figure 11 presents the results of the EUAC analysis for each of the six scenarios outlined above. The figure shows the type of comparative result that is obtained with this analysis technique. It is important to note that the results of this analysis are heavily dependent upon the assumptions made for each scenario analyzed. For example, the chart shows that two of the three weathering steel scenarios (2 and 3) are slightly more costly than the two scenarios shown for painted steel (1 and 4). This is a direct result of the maintenance painting intervals assumed in these scenarios. While it is arguable that the maintenance painting schedules for the weathering steel scenarios (2 and 3) are aggressive for many environments, these results do demonstrate the fact that the life cycle cost of various cash flows is not intuitive based on initial cost comparisons.

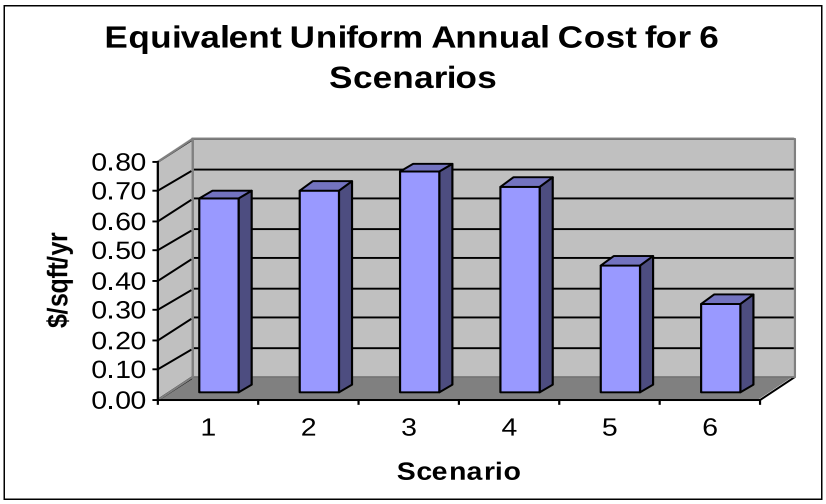

Figure 11 Equivalent Uniform Annual Cost Analysis for 6 Different Scenarios.

Hypothetical analysis also shows the third weathering steel scenario (#6) as being the lowest overall cost scenario. This particular scenario assumes the initial cost savings associated with weathering steel and proper design detailing and placement of the bridge in an appropriate environment such that only touch-up maintenance painting is required every 20 years. This can be a common scenario, but care must be taken to meet these detailing and application parameters in order to realize the potential cost savings associated with weathering steel. Misapplication or improper detailing will lead to scenarios closer to 2 or 3 requiring increased maintenance painting and associated increased cost.

Figure 11 also shows scenario 5 (metalizing) as having significant cost savings over the life of the structure when compared to the painting scenarios and two of the three weathering steel scenarios. This is due to two factors in the analysis. First, the relatively low assumed installation cost for shop metalizing when compared to shop priming and field topcoating. Second, the assumed durability (time to first maintenance) for the metalizing system has the largest effect on its low apparent cost.

Most important in the subject analysis is the method used to compare various specific options in great detail over the life of the structure. By changing variables in each scenario, the optimum scenario can easily change, but analysis shows quickly that corrosion durability has a large effect and is often much more important than differences in initial cost.

2.4.9 Risk

It must be emphasized that cost must be considered together with the risk associated with each corrosion protection option. The performance of all corrosion protection systems will vary with factors such as environmental exposure, design details, quality of coating application, and preventive maintenance. It is most often the unexpected, unplanned, and unbudgeted corrosion problem that becomes a severe cost item.

It is also important to consider the nature of the investment in long-term bridge maintenance. While life cycle cost analyses are useful tools for discriminating among various steel bridge maintenance options, the case should also be made for consideration of the most durable and feasible corrosion protection option, regardless of cost. This viewpoint is necessary at the design stage of a structure in order to put maintenance requirements into a competitive perspective with more traditional design drivers such as strength, capacity, and constructability. The traditional approach of considering corrosion control (often the determining factor in the long-term cost to maintain a structure) after the other fundamental design parameters have been decided will not serve the current aggressive lifecycle goals we are now placing on our bridges (e.g., rapid maintenance operations and a 75-year design life).

3.0 SUMMARY

Corrosion is a considerable threat to the integrity of highway bridges. The inherent corrosivity of many natural environments and the highly corrosive nature of deicing salts applied to highways over much of the U.S. create challenging conditions for the long-term maintenance-free function of a bridge. Designers, however, have many corrosion protection options at their disposal. Protective coatings, when properly applied, can provide many years of protection for very little initial cost. Weathering grade steels are available in strengths up to 100 ksi as well. These steels provide an excellent low-cost corrosion protection option, but the designer must be realistic about the potential environmental exposure both on a macro and micro level. Detailing the structure to eliminate joints (which will eventually leak) and areas that trap and maintain wet conditions is essential for all structures, painted and unpainted. Designers are encouraged to learn from past practices where corrosion protection was not considered a priority in the initial design stage. Past errors in judgment have underestimated the potential effects of moisture and salt and have led to significant costs for replacement of elements, and whole structures well before their functional obsolescence. This module presents an overview of important issues and considerations for the designer with regard to corrosion protection. Designers are directed toward the references used to develop this module for more robust guidance.

4.0 REFERENCES

1. "A Highway Accident Report – Collapse of U.S. 35 Highway Bridge," National Transportation Safety Board, 1971.

2. "A Highway Accident Report – Collapse of a Suspended Span of Rt 95 Highway Bridge Over the Mianus River, Greenwich, CT, June 28, 1983," National Transportation Safety Board, July 19, 1984.

3. "Painting Steel Bridges and Structures," Good Painting Practice, Volume I, Chapter 6.1; SSPC: The Society for Protective Coatings, 2002.

4. "Characterization of the Environment," Federal Highway Administration Research Report, FHWA-RD-00-030, August 2000.

5. Albrecht P., and Naeemi A., "Performance of Weathering Steel in Bridges," Transportation Research Board, National Cooperative Highway Research Program, Report 272, July 1984.

6. "Corrosiveness of Various Atmospheric Test Sites as Measured by Specimens of Steel and Zinc," Metal Corrosion in the Atmosphere, ASTM STP 435, American Society for Testing and Materials, 1968.

7. Albrecht P., Coburn S.K., Wattar F.M., Tinklenberg G., and Gallagher P., "Guidelines for the Use of Weathering Steel in Bridges," Transportation Research Board, National Cooperative Highway Research Program, Report 314, June 1989.

8. "Performance of Weathering Steel in Highway Bridges – A Third Phase Report," American Iron and Steel Institute, 1995.

9. McDad B., Laffrey D., Damman M., and Medlock R., "Performance of Weathering Steel in TxDOT Bridges," Texas Department of Transportation, May 2000.

10. Albrecht, P. and Hall, T.T., "Atmospheric Corrosion Resistance of Structural Steels," Journal of Materials in Civil Engineering, Vol 15, Issue 1, Jan/Feb 2003.

11. American Iron & Steel Institute Corrosion Advisory Group case studies.

12. Kogler, R., "Steel Bridge Lifecycle Corrosion Control Options," Transportation Research Board Annual Mtg 2002.

13. "Environmentally Acceptable Materials for the Corrosion Protection of Steel Bridges," Federal Highway Administration Report FHWA-RD-96-058, Jan 1997.

14. Appleman, B., "Lead-based Paint Removal for Steel Highway Bridges," National Cooperative Highway Research Program Synthesis 251, 1997.

15. “Specification for Structural Joints Using ASTM A325 or A490 Bolts, Appendix A, Class B,” Research Council on Structural Connections, June 23, 2003.

16. “Project Work Plan for the Evaluation of Structural Steel Coatings,” American Association of State Highway and Transportation Officials, National Transportation Product Evaluation Program, www.ntpep.org, June 2004.

17. “Standard Specifications for Highway Steel Bridge Coating Systems with Inorganic Zinc-rich Primer,” American Association of State Highway and Transportation Officials/National Steel Bridge Alliance Steel Bridge Collaboration, 2003.

18. “Specification for the Application of Thermal Spray Coatings (Metallizing) of Aluminum, Zinc, and Their Alloys and Composites for the Corrosion Protection of Steel,” SSPC-CS 23.00/AWS C 2.23M/NACE No.12, July 2003.

19. Ellor, J., Young, W., and Repp, J., “Thermal Sprayed Metal Coatings to Protect Sheet Piling: Final Report and Guide,” National Cooperative Highway Research Program report 528, 2004.

20. FHWA Bridge Coatings Technical Note – Metalizing, 1998.

21. American Galvanizers Association, www.galvanizeit.org

22. Federal Highway Administration Technical Advisory, UNCOATED WEATHERING STEEL IN STRUCTURES, T 5140.22, 1989.

23. Appleman, B. and Kline, E., “Analysis of Costs for Shop Painting of Bridges,” September, 2003, FHWA-RD-05-xxxx, unpublished.

24. “Performance of Weathering Steel in Highway Bridges – A First Phase Report,” American Iron and Steel Institute, August 1982.

25. “Corrosion of Metals and Alloys – Corrosivity of Atmospheres – guiding values for corrosivitiy categories.” International Standardization Organization Standard 9224 (1992).

26. Dexter, R., “Performance Testing of Modular Bridge Joint Systems,” National Cooperative Highway Research Program report 467, 2002.

27. Corrosion Engineering, Mars Fontana, 1986, pg 292.

28. Kogler, R., “Coating Material Selection for Optimum Steel Bridge Life Cycle Cost,” 16th Annual US/Japan Bridge Engineering Workshop, Oct 2000.

29. “Issues Impacting Bridge Painting: An Overview,” Federal Highway Administration research report FHWA-RD-94-098, August 1995.

30. Private correspondence with steel industry personnel