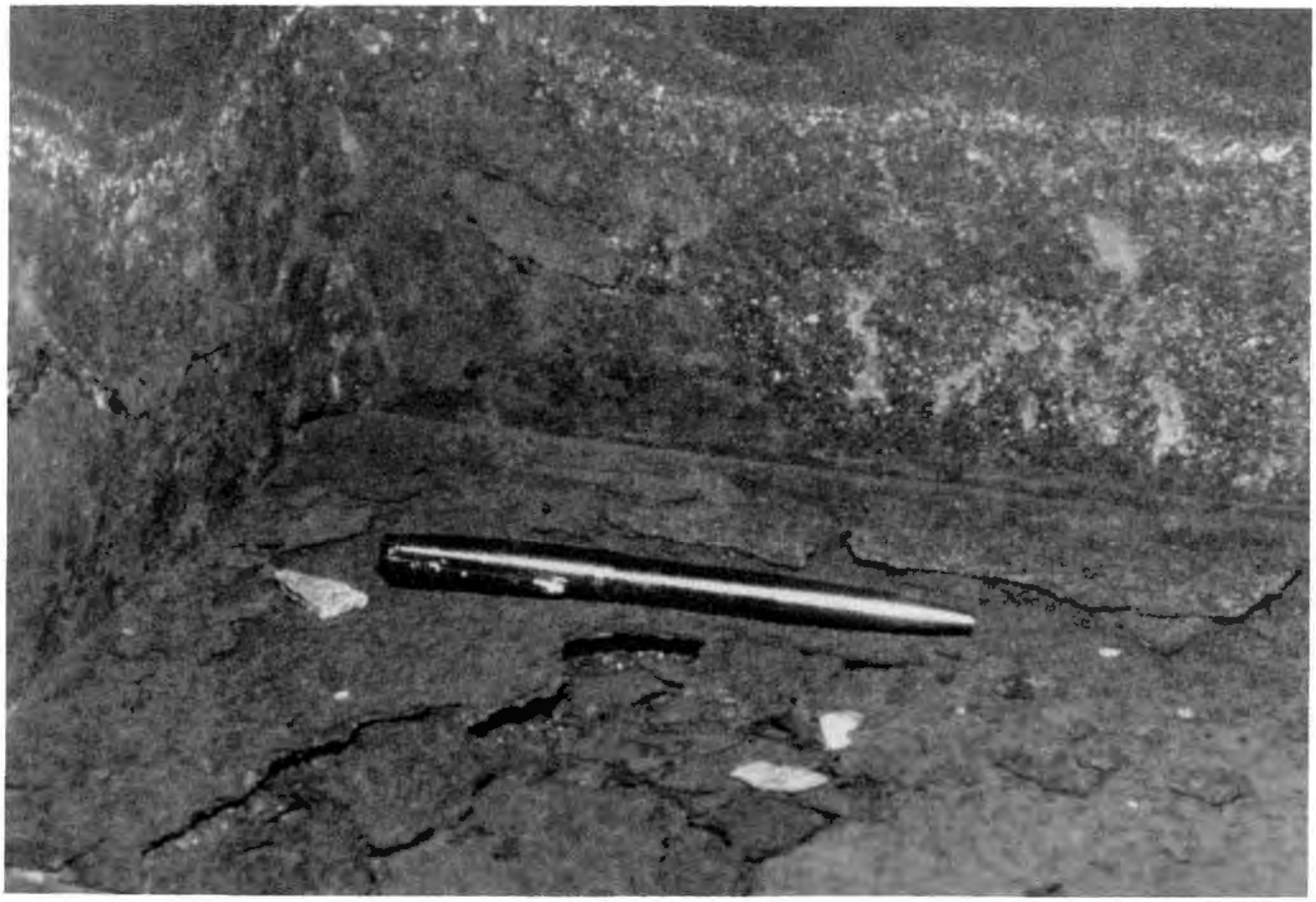
Maintenance Coating of Weathering Steel

Interim Report

FHWA-RD-91-087

March 1992



U.S.Department of Transportation
Federal Highway Administration

Research and Development
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, Virginia 22101-2296

FOREWORD

This report evaluates cleaning methods and maintenance coating systems for salt contaminated, pitted weathering steel bridges. In addition a swabbing method is described to determine the amount of residual salts remaining on the steel surface after preparation for painting.

The relative performance of maintenance coating systems were compared by exposure to accelerated testing regimens. Based upon these results maintenance materials and methods are identified for the protection of corroded weathering steel highway structures.

for Thomas J. Pasko, Jr., P.E.
Director, Office of Engineering and Highway
Operations Research and Development

NOTICE

Technical Report Documentation Page

1. Report No. FHWA-RD-91-087

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle

MAINTENANCE COATING OF WEATHERING STEEL
Interim Report

5. Report Date March 1992

6. Performing Organization Code

7. Author(s) B. R. Appleman, R. E. F. Weaver

8. Performing Organization Report No. SSPC Report 91-04

9. Performing Organization Name and Address

Steel Structures Painting Council
4400 Fifth Avenue
Pittsburgh PA 15213

10. Work Unit No. (TRAIS) 3E4c0112

11. Contract or Grant No. DTFH61-84-C-00063

12. Sponsoring Agency Name and Address

Office of Engineering and Highway Operations R&D
Federal Highway Administration
6300 Georgetown Pike
McLean, Virginia 22101-2296

13. Type of Report and Period Covered

Interim Report
October 1984-June 1990

14. Sponsoring Agency Code HCP-32

15. Supplementary Notes

FHWA Contracting Officers' Technical Representative: John Peart, HNR-30
Cooperating DOTs: IL, LA, MD, MI, NC, WI, WV. Others: Ontario Ministry of Transportation, NJ Turnpike, Garden State (NJ) Authority, AISI, NL Industries, University of Maryland.

16. Abstract

This report presents findings of a survey and laboratory evaluation of materials and techniques for cleaning and painting chloride-contaminated weathering steel bridges.

Laboratory techniques suitable for field usage were developed for assessing the conductivity and chloride level of prepared surfaces. The following cleaning techniques were evaluated for their effectiveness in removing chloride from corroded and pitted plates: air abrasive wet blasting, dry blasting (including alternative abrasives), dry blast and rinse sequences, pressurized water jetting, power tool cleaning, hand tool cleaning, and chemical strippers.

Eight coating systems, including organic and inorganic zinc, high-solids epoxies, thermal spray zinc, oil/alkyd, and petroleum wax were selected for laboratory evaluations. They were applied over laboratory and bridge specimens of weathering steel having various levels of chloride contamination using four preparation techniques: wet and dry blasting, power tool and hand tool cleaning. The coatings were exposed to salt spray, immersion in deionized water, and a composite test incorporating ultraviolet radiation, condensation, and freeze-thaw conditions. Based on these tests, and other considerations, the four surface preparation techniques and the following eight systems were selected for multisite 5-year bridge and test fence evaluation: epoxy zinc-rich, urethane zinc-rich, epoxy mastic, thermal spray zinc, three inorganic zincs (conventional and low-VOC ethyl silicate, and water-borne alkali silicate) and oil-alkyd control.

Preliminary guidelines were developed for weathering steel maintenance options of no painting, painting corroded areas only, and painting entire structure. The results of the field evaluations and updated guidelines for maintenance will be presented in a report expected to be issued in 1992. The present report also includes a summary of the researchers' bridge inspections and of previous bridge-related studies on corrosion and pitting, and cleaning and painting.

Cover Photo: Deterioration of uncoated weathering steel bridge in a salt environment.

17. Key Words

Weathering steel, maintenance painting, coatings, corrosion, guidelines, chloride contamination, accelerated testing

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 129

22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km

AREA

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

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft³	cubic feet	0.028	metres cubed	m³
yd³	cubic yards	0.765	metres cubed	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	Mg

TEMPERATURE (exact)

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

APPROXIMATE CONVERSIONS FROM SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
mm²	millimetres squared	0.0016	square inches	in²
m²	metres squared	10.764	square feet	ft²
ha	hectares	2.47	acres	ac
km²	kilometres squared	0.386	square miles	mi²

VOLUME

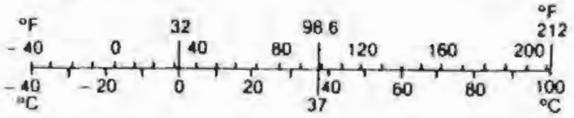
Symbol	When You Know	Multiply By	To Find	Symbol
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m³	metres cubed	35.315	cubic feet	ft³
m³	metres cubed	1.308	cubic yards	yd³

MASS

Symbol	When You Know	Multiply By	To Find	Symbol
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	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



* SI is the symbol for the International System of Measurement

(Revised April 1989)

MAINTENANCE COATING OF WEATHERING STEEL

TABLE OF CONTENTS

PAGE

TABLE OF CONTENTS (continued)

PAGE

LIST OF FIGURES

LIST OF TABLES

Page

LIST OF TABLES (continued)

I. INTRODUCTION

A. NEED FOR STUDY

Weathering steel, introduced in the 1960's, is high strength steel containing low amounts of chromium and other alloys, which offers improved corrosion resistance compared to carbon steel. It was generally erected without painting. In recent years, however, it has been recognized that in areas of high humidity and condensation, and where chlorides can accumulate, severe corrosion, scaling, and pitting of weathering steel can occur. Bridges in these environments require corrosion protection by painting to avoid potential metal loss.

Painting of new uncontaminated weathering steel is generally not considered a problem. Test fence and laboratory data developed by the paint industry have indicated that conventional coating systems such as oil alkyds and epoxies will perform comparably on weathering steel and on carbon steel if the degree of surface preparation is equivalent.

The major problem faced by highway departments and other owners of weathering steel structures is protecting weathering steel that has corroded in the presence of chlorides and other contaminants. Conventional cleaning techniques such as dry abrasive blasting do not remove the chlorides, which apparently penetrate the bases of pits in the steel. The performance of standard highway coatings such as oil alkyd, epoxies, and zinc-rich systems over chloride contaminated steel has not been satisfactory.

B. OBJECTIVE AND APPROACH

The principal objective of this program is to establish techniques, procedures, and guidelines for maintenance cleaning and coating of bridges constructed of weathering steel.

The first step is to review the existing literature to determine the extent and nature of the problem and to identify the chemical and physical processes and factors associated with this phenomenon.

Because of the critical importance of the surface condition to coating durability, a major effort is directed at the surface cleanliness of the steel. In particular, the work will consider the role of chlorides in accelerating the metallic corrosion and the paint degradation. By establishing a standard laboratory technique for measuring the amount of soluble salts on a surface, the accuracy and precision of any field technique can be determined.

Surface preparation methods to be considered include dry abrasive blasting, and various forms of wet and water blasting, along with other special techniques such as chemical or heat treatment of the surface. Each method is to be evaluated for its effectiveness in removing chloride as well as its practicality and suitability as a field cleaning technique. Although it would be desirable to remove all, or essentially all, of the chloride from the surface, this may not be economically feasible for most structures. What is of principal interest is how the chloride remaining on the surface affects the adhesion and durability of the coating system.

The next step is, therefore, to evaluate the performance of candidate coating systems applied over surfaces containing varying levels of chloride. Coatings are to be selected on the basis of commercial availability, demonstration of performance capability under adverse circumstances, and practicality for field application.

Substrates to be used for this testing will include actual specimens cut from corroded highway bridges to provide representative surface conditions.

The testing and evaluation of coatings will be conducted in two phases. In the first (or screening phase) coatings will be examined in laboratory accelerated aging tests. These tests are suitable for identifying in a relatively short time period particularly poor coatings. Such coatings can then be eliminated prior to the more costly and time consuming field exposures. The screening tests also provide information on the relative severity of the various substrates and on the type of failure which occurs in the candidate coating systems.

The ultimate test of the coating systems durability and suitability are the field exposure tests. These are conducted at aggressive highway bridge sites and offer the following major advantages.

- The substrates include pieces of angle and plate cut from highway bridge steel. Thus coating will be tested on angles and tees rather than on flat plates. Also the specimens will contain built up corrosion products and embedded chloride exactly as they occur on the bridges.

- The test specimens are exposed at some of the most corrosive areas of the bridges; thus the coating systems are exposed and evaluated at the precise environments where they are required to protect against corrosion.

- The test specimens consist of small individual angles and plates. This feature allows all the specimens to be coated under controlled and uniform circumstances, thus eliminating the application itself as a variable. In addition, because the specimens are small and numerous, a statistical design can be applied to the placement of the specimens and through the use of replicates.

The coating systems are to be monitored and evaluated up to 5 years. This permits the observation and recording of surface and coating damages that may take some time to develop. It also allows relatively reliable estimates of the coating effectiveness and lifetime.

Based on all the above results, a set of guidelines will be prepared on how to maintain and protect weathering steel bridges. The guide would provide the following type of recommendations:

- Techniques for evaluating the severity of the exposure and the extent of corrosion and surface contamination.

- Suitable techniques for preparing the surface and determining the degree of cleanliness.

- Suitable coating systems for various types of structures and bridge sections.

- General information about which structures or portions of structures require protective coatings.

II. REVIEW OF PREVIOUS AND ONGOING WORK

The Michigan moratorium on weathering steel construction in 1980 focused major attention on the proper use and protection of weathering steel bridges. Since then, a number of studies and surveys have been made to address:

- Corrosion measurements and factors that influence corrosion.
- Corrosion protection by coatings and surface treatment.

The following sections review the major findings and conclusions of these studies, all of which are listed in the references.

A. STUDIES ON WEATHERING STEEL CORROSION

1. Michigan DOT (1980)

In the late 1970's, Michigan DOT personnel observed large amounts of exfoliation (i. e., scaling) of weathering steel in the vicinity of joints in bridges in excess of 10 years old.(1,2) The worst areas were those where deicing salts had penetrated leaking deck joints, where rust scales 1/2- to 3/4-in (13- to 19-mm) thick were developed. Corrosion was also taking place in urban bridges exposed to traffic spray, which included deicing salts.

According to Michigan DOT officials:

> While the attack from leakage is more immediately apparent, and the area affected is a small percentage of the total steel surface, the attack in the long run is concentrated and severe, and may proceed for long distances along the bottom flange, both up and down grade from the source. Spray, on the other hand, has a less immediate effect, but covers nearly all of the steel surface. In either case, the salt causes continuing corrosion of the steel, preventing the formation of a protective rust layer, and makes the weathering steel perform much the same as ordinary structural steel. Recent results show that, in some cases, the long term effects of spray can be approximately equal in severity to the effects of leakage, while covering a far greater proportion of the steel.(1,2)

For most structures, the corrosion and pitting were not readily evident for the first 6 to 7 years; detailed examinations, however, revealed that section loss had occurred on these younger structures also. The DOT also noted other areas of concern, including the following:

- Crevice corrosion -- The rate of attack in crevice corrosion was many times greater than on exposed surfaces.

- Pitting -- This was felt to result in a possible reduction in fatigue strength.

- Debris -- The accumulation of corrosion products and other debris creates an environment in which weathering steel cannot dry out, a step needed to form the tight patina.

- Capillarity -- "Wicking or capillarity of the rust coating draws salt solution to many areas of the structure that would otherwise not be expected to be contaminated." Deicing salts may be drawn 8 in (20 cm) above the web to the flange and for considerable distances uphill from a leaky joint or crack.

- Mill scale - there is evidence that mill scale causes substantially more pitting than a blast cleaned surface.

Based on these findings, the Michigan DOT issued moratoria in 1979 and 1980 on further construction of weathering steel bridges and initiated a number of research projects to more thoroughly examine the debris and prevalence of pitting and corrosion and to identify approaches (e.g., cleaning and coating) to mitigate the corrosion.

2. American Iron and Steel Institute

The Michigan reports quickly gained the attention of the steel, bridge, and corrosion/coating industries, which were concerned about the condition and possible remedial actions for other bridges and the future of weathering steels in bridge construction.

Accordingly, the American Iron and Steel Institute (AISI) organized a task group of steel industry and highway agency representatives to evaluate and analyze the performance of weathering steel bridges nationally.(3) The task group inspected 49 bridges to determine the condition of the oxide (tightness, color, texture), location of corrosion and pitting, presence and type of scaling, condition of joints, fasteners, welds, and connections, type and condition of expansion joints, age of bridge, construction type, environment (industrial, urban, rural), use of deicing salt, precipitation, vertical clearance, average daily traffic. The AISI task group reported as follows:

- 30 percent of the bridges showed good performance in all areas.
- 58 percent showed good overall performance with moderate corrosion in some areas.
- 12 percent showed good overall performance with heavy corrosion in some areas.

The report concluded that "a majority of weathering steel bridges are performing satisfactorily. There are notable exceptions in Michigan, where local environmental conditions include exceptionally heavy use of deicing salts and design details such as pin/hanger connections for cantilevered/suspended spans."

The AISI task group agreed that the Michigan bridges inspected were indeed suffering from advanced corrosion and had not developed the protective oxide needed by weathering steel for corrosion protection. As shown above, this was at least partially attributed to the heavy use of deicing salt in Michigan and the cantilevered construction. Another factor which was cited was the depressed roadway ("tunnel") effect. In the original 1979 moratorium, Michigan had specifically restricted construction of bridges with low under clearances (less than 20 ft [6.1m]) and vertical retaining walls. However, in the 1980 analysis, Michigan indicated that any grade separation over truck lanes of a freeway would produce sufficient salt spray and resulting corrosion and that "tunnel-like" conditions were not necessary for accelerated corrosion to take place. Thus, the AISI and Michigan DOT came to differing conclusions about the conditions under which accelerated corrosion would occur.

3. Ontario Ministry of Transportation

Ontario, like Michigan, had gone largely to weathering steel bridges in the late 1960's and 1970's. Following the problems cited by Michigan, D. Manning of the Ministry initiated a detailed inspection of 61 of the 103 weathering steel bridges on the provincial highway system.(4) The inspection consisted of a visual survey of each structure, with defects or unusual features recorded and photographed. The inspection included the interiors of several box beam structures.

Manning concluded that the vast portion of the steelwork was in good condition, with localized areas of accelerated corrosion present on most structures. The areas identified as being most vulnerable to corrosion were as follows:

- Steel components in the vicinity of leaking expansion joints.
- Top of the bottom flange of I-sections.
- The interior of any box section where moisture is present.

Manning proposed a number of design changes (including avoidance of ledges and horizontal surfaces, better drainage and ventilation for box girders, ensuring access to inspection hatches, and identifying preferred weld details). He also recommended that the Ministry measure corrosion rates under sheltered conditions and that the steelwork be blast cleaned prior to exposure and that debris be removed from boxes before bridge is accepted. He also provided a number of recommendations for existing bridges, including removing corrosion products by power tool cleaning, removing debris from corrosion prone areas, sealing access to moisture in enclosed areas, and retrofitting with vents.

4. NCHRP Study

In 1982, the National Cooperative Highway Research Program (NCHRP) initiated a study to address the questions raised by the previously mentioned studies.(5) The objectives of NCHRP Project 10-22, "The Performance of Weathering Steel in Bridges" were to:

- Assemble a systematic body of information on the performance of weathering steel.

- Document and evaluate the current state of practice.

The report was based on a review of the literature, a survey of practice of highway agencies and other organizations and contact with knowledgeable individuals. Among the topics addressed in this report are field performance of weathering steel, corrosion mechanisms, the influence upon corrosion of different types of environments and conditions, and performance of painted weathering steel. A few of the highlights are described below.

- Performance of Weathering Steel Bridges

The authors present results of a survey indicating the number of weathering steel bridges in the U.S. and the intended future use by the individual States. They also describe the experiences of Michigan and the AISI inspections described above. In addition, they identify experiences in several other States where there has been excessive corrosion of weathering steel bridges.

A key finding is that bridge steel subjected to extended wet periods could develop severe corrosion and pitting even in the absence of deicing salts. One important example was bridges in Alaska, which had been exposed to humid environment from high annual rainfall, wind driven rain, fog, mists and fresh water leaking through the deck. Under these conditions the weathering steel corroded at a rate comparable to that of unpainted carbon steel in an essentially chloride free environment. Severe corrosion was also documented on some bridges in California, which also were subjected to high condensation and humidity but with no significant presence of chloride or sulfate. Several bridges in Ohio, which were subject to a high condensation, also exhibited severe rust flaking and corrosion in certain moisture prone areas, again under conditions of very low chloride.

There are also several examples cited of bridges in Texas, Iowa, and Louisiana where the accelerated corrosion was attributable to chlorides and which in several cases required that the bridges be painted.

The authors also cite experiences in France and East and West Germany, all of which restrict the use of weathering steel to very specific locations where exposure to moisture and chloride will be minimal. There are also some examples cited of some unpainted weathering steel bridges in Japan. In that country, weathering steels were specified because of their welding properties rather than weathering characteristics, and the standard practice is to paint weathering steel.

- Corrosion Mechanisms

The authors first reviewed the basic corrosion mechanism of carbon steel, and showed how pollutants such as SO_2 can accelerate the corrosion rate. Using a two-layer model, the authors explain the difference between carbon steel and weathering steel corrosion. For the latter, the presence of the alloying elements (chromium and copper) results in a more stable, amorphous form of the iron oxide in the inner layer, which also becomes enriched in these alloying elements. Also presented in this section are the results of studies showing the influence of the varying levels of these alloys on the corrosion rate of different types of weathering steel.

The stable, amorphous form of the oxide will not occur if the steel remains wet for long periods of time. The deleterious effect of chlorides and other anions are explained as follows: chloride changes the potential of steel, increasing its tendency to corrode by creating a more active, anodic surface. Chlorides also tend to produce crystalline oxides rather than the protective amorphous oxides. Furthermore, chlorides reduce the threshold humidity for condensation: in the presence of chloride, water condenses at a lower relative humidity and the scale thus remains wet for a longer period of time.

- Laboratory and Field Corrosion Data

In two chapters, the authors present voluminous data on various experimental evaluations of the extent of corrosion in various environments and configurations. The results are presented in mils (or microns) of penetration as a function of time. The data encompass various grades of steel, including carbon steel, copper steel, A-588 weathering steel (Grades A and B) and A-242 weathering steel. Factors that influence the corrosion environment include the following: deicing salts, other pollutants, time of wetness, acidity of environment. Other factors considered are sheltering, orientation (direction), angle of exposure, and effect of crevices, galvanic corrosion, and pitting.

The authors caution against general statements such as found in some standards and literature comparing corrosion rates of weathering steel to carbon or copper steel. The relative rates are influenced by whether one is looking at the average penetration over a period of time or the corrosion rate obtained after the oxide has stabilized (if this can be demonstrated to have occurred). The data presented in this chapter show numerous instances where weathering steel corrodes at rates equal to or greater than that of carbon steel.

- Additional Discussion

Other areas addressed in this report which are beyond the scope of this present study are as follows:

- Strengthening mechanisms and toughness.
- Weathering fatigue.
- Fatigue design.
- Structural details.
- Connections.

The authors' discussion on painting of weathering steel is presented in the next section of this report.

The main conclusion of the NCHRP report is as follows:

> The majority of weathering steel bridges are in good condition, although there are local areas of accelerated attack in many structures. Weathering steels can still be utilized if designs are improved, vulnerable areas painted, and chloride contamination avoided.

Several areas of additional needed research are also presented. Although the conclusions in this report are similar to the AISI, the authors have placed much greater emphasis on the corroded and pitted areas and demonstrated that these are typical of highway steel environments and can be expected to occur in many instances.

5. Michigan DOT (1985)

Following the severe problems discovered in the late 1970's, Michigan DOT initiated a major study to determine the extent and magnitude of corrosion and pitting and to identify remedial approaches.(6) Fifty bridges were selected, having a range of locations (rural, urban), and ages (up to 16 years). On each bridge, extensive metal thickness readings were taken. It was of interest to compare corrosion rates on different portions of the bridge (e.g., leaking joints, splash areas, connections, and nonchloride attacked areas) as well as different bridges. The researchers developed a technique involving sanding to expose bare metal and taking multiple readings using an ultrasonic thickness gauge. To assure statistical significance, over 300 complete beam sections were measured. The data are presented in the form of plots of penetration from nominal (measured thickness minus nominal thickness) over exposure time (to 16 years). For most bridges, readings were taken once, but by combining data from similar bridge environments and components of different ages, a multiyear plot was derived. As expected, the 95-percent confidence bands diverge over time. The average corrosion rates ranged from a low of 0.2 mils (5 microns) per year for unsalted, boldly exposed areas to 5 mils (125 microns) per year for salt-contaminated areas (localized pitting of 16 mils (400 microns) per year was reported for the worst exposures). A significant conclusion is that these rates are sufficient to cause perforation of bridge members during their service lives. The authors conclude that for most environments in Michigan, painting will be required on weathering steel bridges. Structures exposed to significant amounts of salt should be painted within 15 to 20 years of erection. For less severe environments, painting may be desirable to limit the gradual erosion of a structure's original safety factor and to reduce the likelihood of corrosion fatigue damage. Additional research is suggested to examine how corrosion rates may change over time.

6. Louisiana State University

A detailed investigation of weathering steel corrosion was also undertaken by a research group at Louisiana State University .(7) The work was sponsored by the Louisiana DOTD. Initial work consisted of sampling and examining rust scales from weathering steel bridges in Louisiana and three other States. The group characterized rust according to the appearance (size of grain and color), extent of water retention, and chloride content. Appreciable quantities of sulfur were measured in all samples, with several showing especially high levels. Other elements detected were calcium and silicon. A second phase of the project involved evaluating laboratory exposure regimens to simulate corrosion and pitting of weathering steel. Corrosion tests included salt fog, simulated open and sheltered environments, continuous salt water immersion and rapid (30 minute) wet/dry cycles. The authors found that the same type of rust occurred in the wet/dry artificial test as that formed in the field. The report presents a detailed review of earlier studies of pitting and corrosion and examines various reaction sequences in light of the experimental results. In each case the initial rust in atmospheric conditions is amorphous.

The development of long-term corrosion resistance depends on the stabilization and limitation of growth of the amorphous layers. Under conditions of chlorides, sheltering, and extended wetness, the amorphous phase is transferred into various crystalline forms, which are less protective and lead to formation of rust scale (ferric hydroxide). The authors proposed specific mechanisms of corrosion of weathering steel, based on wet/dry cycles, continuous immersion, presence of chloride, and pH. The techniques used to identify the structure, morphology, and growth characteristics of the rust included scanning electron microscopy, energy dispersive spectroscopy, X-ray diffraction, infrared spectroscopy, atomic absorption, optical microscopy, and selective ion-electrode.

A third phase of the work, which was done in conjunction with Louisiana DOTD, was an evaluation of rust stabilizing treatments, including phosphoric, benzoic, and tannic acids. This part of the work is discussed in a separate section of this chapter.

B. STUDIES ON PAINTING OF WEATHERING STEEL

Historically, the major benefit claimed from weathering steels is that they do not require painting. Even 30 years ago, however, there were a number of coatings and steel researchers who recognized that there might be circumstances under which it might be advantageous to paint weathering steel. Some examples of those circumstances are as follows:

- High strength, low alloy steels provide some structural benefits not related to their weathering properties. The improved weathering properties would not necessarily preclude the need for corrosion protection in particular environments. The major corrosion control technique for bridge steel is painting.

- Because of the tighter oxide that can develop on weathering steels, this substrate may provide a better surface for application of coatings, and result in longer paint lifetime. Because corrosion protection and maintenance painting can be such a major portion of the long-term cost of a structure, improved painting life may be a valid reason for selecting a weathering steel.

- For weathering steel bridges which have a majority of the steel in a boldly exposed condition, it may be possible to defer painting of these areas for up to 20 years; thus, by selecting a weathering steel, the initial or shop painting of the steel could be deferred. Of course, it would still be necessary to paint or otherwise protect the areas of a bridge subject to continuous moisture or chloride penetration.

There are several important questions that must be answered regarding the painting of weathering steel:

- How well do the various coatings systems perform over new weathering steel compared to carbon steel?
- How can effective corrosion protection be obtained for weathering steel which has become contaminated with chlorides and other pollutants?

The remaining chapters of this report deal with the various requirements for assessing steel surfaces and cleaning and painting varying types of weathering steel. In this section, we will review previous laboratory and field evaluation studies on painting of weathering steel.

1. Field Studies

a. Copson and Larrabee(8)

This was the first set of data which indicated superior performance of coatings applied to weathering steel compared to carbon steel. Three 1-mil (25 microns) oil-alkyd coatings lasted twice as long on high strength low alloy (HSLA) steel as on copper or carbon steel in industrial, marine, and semi-rural environments after 8 years. The authors found similar results for coatings applied to railroad hopper cars and the outer plates of a railroad bridge.

b. Schmitt and Mathay(9)

In this experiment, a vinyl coating system was applied to blast-cleaned A-588, A-242, and carbon steels, and exposed for 2 years at seven industrial plants. Again, the coatings applied over the A-588 and A-242 steels had less undercutting at the scribe after 1 year at all the plants, and were also rated higher at petrochemical plants after 2 years (all coatings at sulfur and chloralkali plants having failed at that time).

c. Wonders (from Albrecht)(5)

This study evaluated the relative performance of different coatings systems applied over carbon and weathering steels. After 1 year on exterior racks, the author reports that the inorganic and organic zinc-rich coatings gave better performance than the alkyd, epoxy, and vinyl systems. No conclusions were reported regarding the relative performance of carbon and weathering steel.

d. Coburn (10)

The author reports on a series of studies comparing carbon and weathering steel and a variety of coatings systems. Results of a 1-year exposure at two coke plants was that coatings performed better over weathering steel than over carbon steel. The best coatings were organic and inorganic zinc, which were superior to oil alkyd and vinyls, with epoxy being the worst. A 15-year exposure at the 80-ft (25-m) lot at Kure Beach, North Carolina, also showed a clear superiority of weathering steel to carbon steel. Of the coatings tested, alkyds came out best, with intermediate performance given by vinyl and chlorinated rubbers, with epoxy and urethane being the worst. In this study, separate ratings were obtained for faces and edges, with the latter giving much earlier failure (as expected). Another series, also done at Kure Beach after 15 years, evaluated wire brushing versus white metal blasting on 12-ft by 1-ft (3.7- by 0.3-m) sheet steel of carbon and weathering steel. Again, the weathering steel gave superior results, as did the white metal blasting.

e. Storad (11)

In this study, unspecified coatings were applied to A-36 and HSLA steels prepared by commercial blast cleaning and wire brushing. After 11 years exposure at a chloralkali plant, the author reports the weathering steel gave better performance than the carbon steel.

f. Overseas Studies

The following three studies give data which do not support the superiority of coated weathering steel over coated carbon steel.

Nakayama (Japan) applied a coating system to carbon steel and two weathering steels for a 4-year outdoor test.(12) After 1 year, the weathering steel panels showed less corrosion, but after four years there was no significant difference between the carbon and weathering steels.

Van Eijnsberger (Netherlands) applied one-coat and two-coat epoxies to blast cleaned carbon and weathering steel.(13) After 3years in a marine industrial site, he reported no significant differences between carbon steel and weathering steel in their ability to resist undercutting at the scribe.

Kurska, *et al.* applied a coating to carbon and low alloy steel which had been pre-weathered for three months and then blast cleaned and degreased.(14) No difference was noted between the steels in salt fog and 12-month outdoor weathering studies.

g. SSPC/NL Study

A major exposure study was initiated in 1960 by several industry groups, including the SSPC, the Federation of Societies for Coatings Technology (FSCT), Inco Labs, NL Industries, and others. The steels included carbon steel and seven kinds of weathering steel. Twelve-inch (30.5 cm) angles were cleaned by three methods (white metal, commercial blast, and wire brushing), and the coatings included six oil alkyds specification paints, primarily those used on bridges. The angles were exposed at the 800-ft (250-m) lot at Kure Beach, at industrial sites in Hightstown and Perth Amboy NJ, and at a rural marine site in Long Island NY. The study has never been formally reported on, but an update of results was presented at an FSCT meeting in 1981.(15, 16) It was reported that all seven coated low alloy steels had outperformed the coated carbon steels.

2. Laboratory Studies

a. Gallagher and Wonders(17)

This study evaluated several zinc-rich coatings applied over both new and contaminated A-588 steel, with two varieties of blast cleaning. The panels were exposed for 90 days in a Cleveland Condensing Cabinet. The authors found that zinc-rich coatings give excellent performance over weathering steel, and recommended use of a dry blast plus inhibitive rinse for chloride-contaminated surfaces.

b. Raska -Texas Highway Dept.(18)

Based on problems with cleaning and painting of weathering steel bridges in a marine atmosphere, the Texas Department of Highways and Public Transportation initiated a field exposure study. Six-by-twelve inch (15- by 30-cm) A-588 panels were weathered for 6 months at a bridge site in Port Isabelle in southern Texas. The weathered panels were then cleaned with a variety of techniques including: near white metal blast (SSPC-SP 10); brush blasting followed by water blasting followed by near white metal blasting; water blasting followed by near white metal blasting; and brush off blasting followed by low pressure water flushing, followed by near white metal blasting. In addition, for each of these techniques, a separate set of panels was allowed to flash rust before painting. A total of nine coating systems were applied, including the Texas standard system (oil modified urethane, urethane zinc-rich with vinyl toluene acrylic topcoat). Other primers included chlorinated rubber alkyd, epoxy, oil base, two-pack inorganic zinc, single pack inorganic zinc, moisture cured urethane zinc, and epoxy zinc-rich, with all but the moisture cured urethane zinc topcoated with the State standard. Coatings were exposed at the bridge test site (marine exposure) for 2 years. Raska reports that the inorganic zinc, organic zinc, and an oil base were best over the SP-10 surfaces, with the organic epoxy, conventional epoxy, and the oil modified urethane zinc-rich best over the flash rusted surfaces. Overall the epoxy zinc-rich was considered best and was selected for a full painting of the bridge. The recommended surface preparation was to brush blast all rusty areas to remove all scaly rust, flush all surfaces with fresh water at low pressure, and blast clean to SSPC-SP 10. The author also noted that cleaning A-588 is more difficult than cleaning A-36 steel.

c. Tinklenberg(19)

Tinklenberg of Michigan DOT has conducted several salt spray laboratory evaluations of various types of steels, surface preparations, and coatings. One early study evaluated five generic types of coatings over A-36 and A-588 millscale panels. The ranking of coatings from best to worst was organic zinc/epoxy, inorganic zinc/vinyl, urethane/epoxy, multicoat lead free alkyd, and aluminum epoxy mastic.

A second study examined a variety of weathering steels including panels exposed outdoors at rural site, panels exposed in salt spray cabinet, and panels cut from chloride corroded and pitted hanger plates. The author reported that the contamination on the A-588 resulted in a decrease in coating life. In this study also, the zinc-rich coatings gave the best performance.

In both of these studies, Tinklenberg found that coatings applied to A-588 gave about equal performance to those applied to A-36 in salt spray cabinets.

A third study was designed to evaluate different cleaning methods, including blast cleaning with wash cycles, and different degrees of blast cleaning. The author reported that the wash cycle had little effect on the coating performance but that the degree of cleaning was significant (i.e., brush off and commercial blast were inferior to near white metal blast). The organic zinc/epoxy, with or without a urethane topcoat, gave the best performance, with chlorinated rubber and lead-free alkyds the worst. Intermediate were inorganic zinc/epoxy, moisture-cured urethane/epoxy, and epoxy/urethane.

d. O'Leary et al., West Virginia DOH(20)

Also based on concerns over possible need for protecting weathering steel bridges, West Virginia DOH conducted a combination laboratory and field evaluation. The substrates were A-588 and A-36 composite panels (i.e., KTA panels). The A-588 were exposed for 14 days in a salt spray cabinet, then blast cleaned to SSPC-SP 10. The panels were coated with 32 systems, including coal tar pitches, rust preventative compounds, epoxy urethanes, one-and two-component inorganic zinc systems, organic zinc systems, zinc chromate and zinc phosphate alkyd, all-urethane systems, and high-build epoxy. The coated panels were scribed and first exposed in salt spray for 500 hours. Coatings giving satisfactory performance (21 of the 32 selected initially) were then placed on a test fence at a severe industrial site for 20 to 40 months. Twelve of the coating systems showed excellent ratings after 20 or more months. These included the following:

- One-component organic zinc/epoxy/urethane.
- Three-coat polyurethane.
- Zinc chromate alkyd/rust preventative (composition unknown).
- One- and two-component inorganic zinc/vinyl high-build/vinyl.
- One-component epoxy ester zinc-rich/polyester epoxy (2 coats of topcoat).
- Epoxy zinc chromate (2 coats)/urethane.
- Two-coat epoxy system.
- One- and two-component organic zinc/epoxy.
- Urethane/epoxy.

A second set of coatings was applied to A-588 steel which was blast cleaned to SSPC-SP 10 and placed under an expansion dam on a bridge for 12 months. Although about half the panels were missing, eight of the systems received a 10 rating after 12 months' exposure on the same bridge site. These included mostly zinc-rich systems, along with a one-coat inhibitive chlorinated rubber, an epoxy urethane, and a urethane epoxy.

C. SURFACE TREATMENTS

Surface treatments have been applied to stabilize the oxide products and to form a corrosion resistant surface layer on weathering steel. These treatments are applied to ensure the formation of the stable layer in locations where required conditions or patina formation (i.e., open, bold exposure to rain and drying) are not attained. Examples include humid, sheltered and chloride laden areas. These treatments are also claimed to reduce the staining caused by scaling in the early stages of weathering steel corrosion. Two such treatments are discussed, a commercial one developed in Japan and an experimental one developed by Louisiana State University.

1. Phosphate/Acrylic

The Japanese treatment, known as "weather coat" was developed in the mid-1960's by the Nippon Steel Company for use in Japan's high temperature and high humidity environments. It is a two-coat system; the first coat consists of zinc-oxide/zinc-phosphate complex which is spray-applied or in which the steel components are dipped at 120 °F (50 °C), following pickling or blast cleaning.(21,22) The phosphate complex is claimed to accelerate the formation of a stable amorphous iron oxide layer. The second coat (called Prepalene) is an acrylic resin solution which is spray applied after the primer has dried. It is a water permeable coating designed to prevent loss of the oxide layer during the rust stabilization process. The developers have presented data to show reductions in the weight loss compared to untreated weathering steel. This process often requires multiple applications of the chemical treatments in the shop in addition to field repairs. According to Albrecht, the process adds 10 to 20 percent to the cost and there are insufficient data on the long-term effectiveness of the treatment.

2. Phosphoric, Benzoic, and Tannic Acids

Louisiana State University evaluated a variety of surface modifications and treatments as part of their extensive investigation of weathering steel corrosion.(7) The authors had identified several studies reporting the benefits of tannic, phosphoric, and benzoic acid in forming stabilized forms of oxide. The following treatments were selected for laboratory and field evaluation:

- Abrasive blasting.
- Abrasive blasting followed by 25 percent phosphoric acid or 25 percent phosphoric and benzoic acid.
- Acid pickling.
- Acid pickling plus 10 percent tannic acid.
- Acid pickling plus 10 percent tannic acid followed by 25 percent phosphoric acid or 25 percent phosphoric-benzoic acid.

The surface treatments were applied to three types of weathering steel and carbon steel on test plates and bridge beams. The panels were exposed in simulated laboratory tests (including wet-dry cycles with chloride and sulfate additions, salt spray, and continuous immersion), and on bridge racks and beams. The bridge beams included both exterior and interior sections at several exposure environments. The authors evaluated the amount of metal loss and examined the depth and extent of pitting. Metal loss ranged from about 1 mil (25 microns) per year in rural environments to 3 to 5 mils (75 to 125 microns) per year in sheltered environments and salt exposed areas. The data are not very precise because they were measured only over a 2-year period. No pitting was observed on the exterior beams, but in the interior (sheltered) areas and partially enclosed boxes, pitting of 10 to 30 mils (250 to 750 microns) was recorded.

The 25 percent phosphoric acid and 25 percent phosphoric-benzoic acid were reported to result in about a 1/3-reduction in the corrosion loss after 12 months. Similar results were obtained in the laboratory studies. The tannic acid by itself had a beneficial effect in areas of extended wetness. The authors concluded that surface modification treatments are a viable alternative to painting. Specific recommendations were as follows: sheltered areas should be treated after about 1 to 2 years of exposure by wet blasting followed by 25 percent phosphoric acid spray. The treatment should be repeated after 1 year in moderate environments, and at intervals of 6, 12, and 24 months for coastal environments. Treatment should also to be repeated every 10 years. The boxed areas are recommended to be treated with 10 percent tannic acid and 25 percent phosphoric acid at various intervals. For coastal bridges only, the exterior (exposed) areas are also recommended for treatment.

These recommendations are based on very limited field trials. They do not address the questions of long-term corrosion protection, application cost, and logistics and disposal costs of these acid treatments.

D. OTHER STUDIES OF WEATHERING STEEL

1. Bridge Case Histories

Over the last 20 years or so, a number of weathering steel bridges have been painted; these include structures painted during or immediately after erection and those painted after weathering for several years. Albrecht and Naeemi have listed 10 or 12 bridges painted in the 1960's and '70's.(5) An updated version of their table is presented in appendix B. In addition, in the last 10 years, Michigan DOT has painted approximately 15 or 20 bridges, almost all of them using the Michigan DOT standard system of epoxy zinc-rich primer, epoxy intermediate and urethane topcoat. Michigan DOT has established a qualified product list based on a battery of laboratory tests. This QPL is updated every year or two as new products are submitted and as the state gains experience with different manufacturers' systems.

2. Weathering Steel Forum

In July 1988 the Federal Highway Administration with cooperation from the American Iron & Steel Institute held a 2-day "Weathering Steel Forum." The Forum addressed two major questions regarding weathering steel: the effect of corrosion on fatigue life and the problems and considerations for maintenance. The FHWA has issued a proceedings book on the presentations and discussions during the conference.(23) During the opening general session, there were general presentations on corrosion and use of weathering steel by New Jersey Turnpike, Michigan DOT, Louisiana DOTD, and steel industry and SSPC representatives. During the special session on maintenance, additional information was presented from both New Jersey Turnpike and Michigan DOT on the specific corrosion problems and the remedial measures being taken. Michigan DOT reported a major program to conduct painting on all weathering steel bridges with emphasis on those approaching 15 to 20 years of age. A New Jersey Turnpike representative noted that the New Jersey Turnpike approach to maintaining weathering steel bridges included construction of dams and drains to eliminate salt water runoff. In some cases, bridges that were 20 years old were being replaced because of the inability to effectively prevent chloride from penetrating the joints and accelerating the corrosion.

3. SSPC Field Inspections

During the early stages of this project, SSPC personnel visited a number of highway bridges to observe firsthand the environments, configuration, and extent of corrosion. A list of the field visits is given in table 1. A thorough description of the observations and comments on these inspections is given in appendix B.

Table 1. Field visits.[1]

DATE	LOCATION/CONTACT	NO. OF BRIDGES	DESCRIPTION	SAMPLES/ TESTS
11/84	Detroit, MI/Gary Tinklenberg, MI DOT	11	Detailed inspection tour hosted by MI DOT, including snooper and boat	rust scale
11/84	New Orleans, LA/Kirt Clement, LA DOTD	2	Lulling -- inside towers, piers, Duluth Canal -- over piers	rust scale
12/84	West Virginia/John O'Leary, WV DOH	1	New River Gorge -- catwalk, piers	rust scale
2/85	New Jersey Turnpike/none	3	Overpasses, abutmentsfrom roadway only	rust scale
3/85	North Carolina/William Medford, NC DOT	3	Overpasses from roadway only	rust scale
5/85	Hightstown, NJ/Doug Nash, NL Chemicals	0	NL Test fence 20 years data	rusted angles
8/85	Ontario, Canada/David Manning, Ontario Ministry of Transportation	3	River crossing, box girders, inspection covers	rust scales, conductivity readings
10/85	Garden State Parkway, NJ/Pat De Rosa	1	Raritan Bridge, painted A-588	conductivity
10/85	NJ Turnpike/Howard Bymes	1	Oakmont viaduct, panted A-588	conductivity
10/85	Universtiy of Maryland/Pedro Albrecht	0	Test beams	conductivity

[1] Details in appendix B.

III. EVALUATION OF CLEANING METHODS

A major objective of this project was to evaluate the effectiveness of various cleaning methods in removing corrosion products, millscale, and chemical contamination from weathered and contaminated A-588 steel. This also required a procedure to determine the effectiveness of various methods. The ultimate aim is to establish a practical procedure for preparing steel to be coated and protected from corrosion and pitting.

In order to achieve these aims, it was first necessary to obtain representative specimens of weathering steel; then to apply various cleaning techniques; and finally to measure their effectiveness in removing the surface debris.

Accordingly, a detailed plan was developed which included the following steps.

- *Develop techniques for accelerating the corrosion and pitting of A-588 steel.* It was not considered practical to utilize actual field (bridge) specimen because these were not as readily available as required and they would not be sufficiently uniform for the type of studies planned.
- *Develop techniques for assessing surface.* Techniques would be required for the laboratory (i.e., highly accurate and precise techniques suitable for reference measurements) and field techniques (to assess a bridge surface in situ to determine the level of contamination both prior to and after cleaning). It would be necessary to evaluate the surface morphology (e.g., pits, scaling, corrosion products) and the amount of chlorides and other possible soluble salt contaminants.
- *Select and evaluate candidate cleaning methods.* Various methods included dry and wet cleaning, alternate abrasives, chemicals, power tools and others. Each method would be evaluated using the methods developed previously.

A. DEVELOP TECHNIQUES FOR ACCELERATING CORROSION AND PITTING

The goal of this subtask was to simulate in a laboratory the corrosion and pitting that occurred on A-588 bridges subjected to leakage and spray of deicing salts. Bridge specimens were used in judging the laboratory simulation tests. In this activity, the SSPC was greatly assisted by the AISI and several cooperating highway departments. The States agreed to remove noncritical members (e.g., stiffeners, T-beams, hatch cover plates). The AISI members furnished replacement pieces where necessary and the AISI paid for shipping the steel to Pittsburgh. In addition, several States furnished special laboratory exposed specimens used in their own research programs. A list of the specimens received is given in table 2. (Note: these specimens were also utilized in the laboratory and field evaluation of coating system performance, described later in this report.)

The following laboratory techniques were examined:

- Exposure in salt spray cabinet (continuous exposure to 5 percent salt water mist at 35 °C).
- Intermittent exposure to salt spray (specimens removed from cabinet or cabinet exposed to ambient and specimens allowed to dry). This is considered more

Table 2. A-588 bridge steel received.

1. Michigan DOT

   a. 1 channel, 60 in (1.5 m) long,18 in (46 cm) wide, 1/2 in (1.3 cm) thick, with 3-3/4 in (10 cm) flange
   b. 1 channel, 38 in (97 cm) long, 25 in (64 cm) wide, 3/8 in (1 cm) thick, with 3 in (7.6 cm) flange
   c. T-panels
      3 ea. 3- by 5- by 7/16 in (97- by 64- by 1.1 cm) panels from badly pitted 4- by 4 ft (1.2- by 1.2 m) angle
      1 ea. 3- by 5- by 1/2 in (7.6- by 13- by 1.3 cm) panel from I-75 at 8-Mile Road
      1 ea. 3-in by 5-in by 5/8 in (7.6- by 13- by 1.6 cm) panel from hanger plate of Grand Blvd. Bridge, Detroit

2. New Jersey Turnpike

   a. 1 beam, approximately 10 ft by 4-1/2 in by 16 in (3.1 m by 11 cm by 41 cm)
   b. 2 inspection cover plates, each 24- by 39 in (61- by 99 cm)

3. Louisiana DOTD

   1. T-beam, 8 in by 10 ft by 1/ 2 in by 16 ft-8 in (20 cm by 3.1 m by 5.1 m)

4. University of Maryland

   5 welded beams, 15-ft-6 in by 14 in by 3/8 in with 6-3/4 in flange. (4.7 m by 36 cm by 0.95 cm with 17 cm flange)

   (Three beams had received regular salt spray three times per week during the winter months; the other two beams were not sprayed.)

5. Ontario Ministry of Transportation

   a. 12 stiffeners 98 in (2.5 m) long, 3- by 3 in (7.6- by 7.6 cm) angle, 5/16 in (0.79 cm) thick
      14 pieces 54 in (1.4 m) long, 3- by 3-in (7.6- by 7.6 cm) angle, 5/16 in (0.79 cm) thick
   b. 10 inspection hatch cover plates approx. 22-in by 26-in by 1/2 in (66- by 66- by 1.3 cm)

6. Wisconsin DOT

   1 T-beam, 10 ft by 5-1/4-in (3.1 m by 13 cm) (flange); by 3-1/4-in (8.3 cm) (web); T-section 3/16-in (0.48 cm) thick

7. West Virginia DOH

   7 inspection hatch cover plates 3- by 3-ft (91- by 91 cm)

8. Illinois DOT

   1 beam, 5-ft by 12-in by 8-in flange (1.5 m by 30 cm by 20 cm flange)

representative of bridge conditions in which the exposure to deicing salt is also intermittent.

- Exposure to cyclic noncondensing humidity. (Specimens first received a small dose of salt, then were placed in a chamber with close to 100 percent relative humidity, but where condensation on the surface did not occur. Periodically the chamber was opened to ambient, lowering the humidity). This simulates the condition in which the surface becomes covered with salt, which remains on the surface during periods of rain and high and low humidity.
- Intermittent salt water immersion (specimens exposed in KTA-Tator test chamber known as "Envirotest," which consists of a salt water immersion period, a dry-out period at ambient and a heating period).
- Exposure to cyclic condensing humidity (specimens placed in commercial "UV-CON" weathering cabinet, which alternates exposure to 100 percent RH water vapor that condenses on the surface and elevated temperature dryout period; prior to exposure in UV-CON, specimens were placed in salt spray chamber to receive salt contamination.)
- Intermittent tap water immersion (specimens placed in immersion tank which was alternately filled with tap water and emptied to allow specimens to dry; specimens also pre-exposed in salt spray). Note: this technique and the one using the UV-CON were not examined until the latter part of the project.

In addition to these laboratory exposures, specimens were also placed in accelerated outdoor exposure environments as follows:

- Periodic salt spray in industrial environment (specimens placed in rack on roof of Mellon Institute in Pittsburgh and sprayed with salt water mist several times per week)
- Covered exposure in severe marine environment (specimens placed at 80-ft (25-m) lot in Kure Beach, NC; specimens exposed horizontally and covered to retard runoff of salt water)
- Periodic salt water wash in marine environment (specimens placed on rack at Miami Marine Research station and cascaded with sea water for 15 minutes every 6 hours).

Table 3 summarizes types and locations of tests, numbers of panels, time exposed, and original condition of the test panels. Representative specimens from each of these categories were blast cleaned to allow examination of the surface for pitting and corrosion. These were compared with sections of bridge beams obtained from Michigan and New Jersey. The Michigan specimens ranged from slightly to severely pitted. Some of the New Jersey specimens showed severe corrosion and apparent metal loss, but there was relatively minor pitting.

None of the accelerated specimens had pits which were as deep as the ones from Michigan, nor did any of the artificially created pits show any billowing out at the bottom. The specimens

Table 3. Panels exposed in accelerated corrosion environments.

	Carbon Steel		Weathering Steel	
	Blast Cleaned	Millscale	Blast Cleaned	Millscale
Envirotest				
2 weeks	2	4	4	4
4 weeks	2	2	4	4
Non-Condensing Humidity				
3 weeks	2	2	6	6
6 weeks	7	7	12	12
Miami Marine				
1 month	1	1	4	4
2 months	1	1	4	4
3 months	1	1	4	4
Kure Beach				
2 months	1	1	4	4
4 months	1	1	4	4
6 months	1	1	4	4
Mellon Roof				
2 months	1	1	1	1
Continuing	2	2	11	11
Salt Fog Cycled				
7 weeks	1	1	0	3
Various Times	4	4	9	9
Salt Fog Continuous				
7 weeks	1	1	0	3
Various Times	4	5	8	9

NOTES:

KTA-Envirotest -- continuous cycle of 2 hours immersion in 5% salt solution, followed by 2 hours of drying with heat lamps and UV light.

KTA Non-Condensing Humidity -- before being placed in the cabinet the panels are wetted with a known concentration/known amount of NaCl solution.

Miami Marine Research -- panels were sprayed with sea water for 15 minutes every 6 hours.

Kure Beach - 25 meter (80 ft) lot -- a cover protects panels from washing effect of rain.

Mellon Institute Roof -- panels are sprayed until wet once a day with 5% NaCl solution.

Salt Fog Cycled - panels were removed once or twice a day for several hours each time.

Salt Fog Continuous - as per ASTM B117.

from the salt spray testing, both continuous and intermittent, had the deepest pits of the artificially weathered specimens. These ranged from 2-1/2 to 3 mils (63 to 75 microns), compared to the deepest Michigan specimen pits of almost 4 mils (100 microns). The salt spray specimen pits were also generally broader and more evenly dispersed than the Michigan specimen pits.

The specimens weathered in the KTA Envirotest also exhibited marked pitting, but shallower than the salt spray pitting. The specimens which had been immersed with millscale showed more pitting than those which had been blast cleaned prior to immersion in this test. This agrees with the findings of Michigan DOT.

The specimens which had been exposed at Miami Beach to a combination of atmospheric exposure and seawater spray showed some pitting in areas which had been covered with plastic. However, the pits were generally less than 1 mil (25 microns). The longest specimens were exposed for the 3 months. The specimens that were exposed on the Mellon Institute roof with daily salt spray showed corrosion but very little pitting. The same is true for the salt contaminated panels which had been exposed to high relative humidity.

Although the artificially corroded specimens did not simulate the type of pitting obtained in the Michigan environment, they were considered suitable for use as a screening test for evaluating surface cleaning methods.

On the basis of these data, intermittent salt spray was selected as the most practical technique for producing pitting and corrosion on weathering steel. The standard procedure was as follows:

- 7 am: Salt spray cabinet turned on for 3 hours.
- 10 am: Salt spray cabinet turned off and opened to ambient for 4 hours.
- 2 pm: Salt spray on for 3 hours.
- 5 pm : Salt spray off overnight.

The panels were therefore exposed to salt spray about 6 hours per day or 3 hours per cycle. The dry time was a minimum of 4 hours which typically resulted in a complete drying of all surfaces. The duration of the cyclic salt spray was measured in cycles; 100 cycles was sufficient to achieve a fair amount of broad pitting and thorough chloride contamination of the corrosion products.

A refinement of the test, which was developed later in the project, used a combination of salt spray and frequent intermittent immersion. After evaluating numerous alternatives the optimum procedure for rapidly simulating A-588 pitting was as follows. Blast clean mill-scale bearing A-588 panels to between brush-off (SSPC-SP 7) and commercial (SSPC-SP 6). Expose specimens in salt spray continuously for 7 days. Then place in special tank which immerses specimens in tap water for 5 minutes every hour for 10 days (about 240 cycles).

The pits obtained in this weathering procedure were very similar to those observed on the specimens from the Michigan and Wisconsin bridges.

B. DEVELOP TECHNIQUES FOR ASSESSING SURFACES

The above techniques produced specimens with heavy rust and scale layers having substantial chloride contamination. Analysis of the rust scales showed moderate to high levels of chloride. Preliminary examination of blast specimens indicated the presence of substantial soluble chloride remaining on the surface after blast cleaning.

Earlier work had shown that the presence of chloride levels of several ten thousandths of an ounce per ft^2 (tens of micrograms per cm^2) are potentially detrimental to performance of protective coatings. However, determining the residual chloride on a rough surface is not trivial. The chloride may be deeply embedded in the pits and the residual oxide, and dispersed into the contours of the profile.

Laboratory Extraction Procedure

Accordingly, it was determined to establish a laboratory technique which would remove essentially 100 percent of the water extractable chloride as well as other water solubles. Following some evaluations with variables such as water temperature, extraction vessels and configurations, and extraction times, we settled on a method in which the entire test specimens were immersed in boiling deionized water for about 30 minutes. The details of the extraction procedure are given in appendix A.

Because the technique requires total immersion, the specimen size is limited; however this was not a major problem as the typical laboratory specimen was 4- by 6-in (10- by 15-cm). Field specimens to be analyzed were cut into appropriate size. It is also important to clean all sides and edges of the panels prior to boiling to avoid depositing chloride-containing rust into the water.

This procedure was established as a laboratory reference procedure against which other procedures, such as swabbing, could be compared.

The major quantities of interest were the amounts of chloride in the extract and the total amount of water soluble material. The chloride ion was measured by selective ion electrode and the total water soluble by conductivity. Other techniques evaluated were Quantab strips (for chloride) and EM Quant (for soluble ferrous ion). The selective ion electrode and the conductivity were determined to be the most accurate and efficient for laboratory analyses. The development of field assessment procedures is discussed later in this report.

Comparing Chloride Concentration vs. Conductivity

A direct linear correlation was established between the chloride concentration (in ppm) and the conductivity (in µg/cm) of a standard potassium chloride solution. Thus if it is known that only chlorides are present in solution, the chloride concentration can be determined from the conductivity (see appendix A). For one set of samples, which were corroded for a short time in a salt spray chamber, we obtained good correlation between chloride concentrations computed from selective ion and conductivity (see appendix A). However, in another set of experiments, the total quantity of dissolved solids was about three to four times the amount of chloride. These experiments also demonstrated that Quantab strips give relatively accurate results for chloride levels of about 12 ppm or higher. For lower concentration the Quantabs are not sensitive enough. For extractions using 30 cc of solution, this concentration corresponds to a threshold sensitivity of about 1.3×10^{-4} oz/ft^2 (4 $\mu g/cm^2$).

For most of the subsequent surface analyses, the primary technique used was conductivity. This technique is easy and reliable and can be used readily in both lab and field applications.

Field Extraction Procedure

A field extraction procedure was developed based on swabbing the surface and collecting and analyzing the rinsings. This procedure is primarily intended to be used over surfaces cleaned from rust and scale, although it can be used on intact rust or paint. A defined area of the cleaned surface is marked off and swabbed with cotton or glass wool, soaked in deionized water, the swabs are carefully squeezed and collected in a beaker or bottle. The detailed procedure is given in appendix A.

The liquid extract can be analyzed in the field or retained for subsequent laboratory analysis. Most of the same techniques used in the laboratory can be used in the field. The most suitable field analysis technique is conductivity, which can be run quickly and accurately. The selective ion electrode analysis is available in a portable unit, but it is not especially rugged and is not easy to perform on bridges. The Quantabs are suitable for field analysis, but the test is slightly more time consuming and tedious than conductivity.

A set of A-588 panels was precorroded and evaluated to determine the optimum number of extractions and the approximate precision of the extraction procedure. Seven 4- by 6-in (10- by 15-cm) plates were exposed to 100 cycles of intermittent salt spray. Each was extracted 3 successive times using a standard procedure and the solution analyzed for chloride ion and conductivity. The average amounts extracted for the three extractions are shown in table 4.

Table 4. Extraction efficiency and precision.

	ISE Analysis (a)			Conductivity	
	PPM Cl- (Mean)	PPM Cl- (Coeff)	Equivalent Conductivity (b) µS	µS (Mean) (d)	µS (Coeff) (c)
Extract No. 1	10.76 (e)	0.28	47.1	147.1 (e)	0.2
Extract No. 2	5.04	0.34	24.7	70.3	0.44
Extract No. 3	4.4	0.53	22.2	120.9	0.21
No. 1 + No. 2	15.8	0.21	66.8	217.4	0.19
No. 1 + No. 2 + No. 3	20.63	0.2	85.7	338.3	0.19

(a) Ion selective electrode method.
(b) Conductivity calculated from chloride using equation:
conductivity (µS) = 5.0258 + 3.9118 ppm (Cl-).
(c) Coefficient of variation: standard deviation divided by mean.
(d) Units are micro-siemens (micromho/cm).
(e) Average of 7 specimens.

These results show that the third swabbing still extracted a significant amount of material from the surface. These data are consistent with previous data that swabbing only extracts a fraction of the total water soluble material on the surface. Based partially on these data, we decided to include two swabbings in the field procedure. The sum of two swabbings would be expected to yield a higher overall precision (based on the correlation coefficient).

The results also show that substantial quantities of soluble salts other than chloride were extracted. The chlorides account for about 25 to 30 percent of the conductivity. Other species believed to contribute to the conductivity include carbonates, however no specific investigation was conducted to identify or quantify these other soluble salts.

C. SELECT AND EVALUATE CANDIDATE CLEANING METHODS

The main criterion for selecting a surface preparation method is its effectiveness in removing corrosion products and soluble salts from the surface in preparation for painting. Other criteria that were considered were cleaning rate, utility/power requirements, consumption rate of abrasives, water, or other consumable materials, practicality and maneuverability of unit, safety and reliability, and availability of equipment and materials. The techniques evaluated are listed in table 5.

The evaluations could not all be accomplished in one experiment because of the need to use specialty equipment and treatment. In addition, it was not possible to prepare all the specimens in a single run of the salt spray cabinet. In order to make comparisons more meaningful, all comparisons referred to a standard method of dry blasting for the various cleaning methods. The table also includes the standard deviations of these readings, which were derived from the boiling water extraction and analyzed by conductivity meter (see appendix A). A brief review of the method and the results of the experiment is given below.

- Dry Blasting: Panels cleaned at Clemco had relatively high levels of soluble salt remaining on the surface (approximately 100 micrograms per cm^2). There were no noticeable differences from the results for medium or fine abrasives. The specimens cleaned at Conomos and KTA-Tator facilities showed lower levels of soluble salts. This may result from a difference in the initial condition of the steel (i.e., corroded in different salt spray runs).

- Air Abrasive Wet Blast: At Clemco, the same unit was used for wet and dry blasting to minimize the influence of equipment variations. The results indicate that this technique produces a surface that is about 50 percent cleaner than dry blasting. There was also little effect of abrasive size.

- Pressurized Water Jetting (10,000 psi, 70 MPa): This technique can be used with or without abrasives. With abrasives injection, the results were comparable to those obtained with air abrasive wet blasting, i.e., 50 percent as much soluble salt as dry blast. Without the abrasives, this technique proved incapable of removing the tight rust layers, and consequently left a large amount of soluble salt.

- Dry Blast Plus Water Wash: This technique was overall superior to dry blast, but inferior to the other wet methods of cleaning. The medium sand produced a cleaner surface than fine sand.

- Dry Blast Plus Steam Cleaning: Steam cleaning at a pressure of 7 psig (48 Pa) removed approximately half the soluble salts remaining after dry blasting and is thus also equivalent to the air wet blast and pressurized water jetting with abrasive.

- Dry Blast Plus Flame Cleaning: Flame cleaning was included because of the hypothesis that the high temperatures could cause ferric chloride ($FeCl_3$) to

Table 5. Surface preparation methods evaluated.

Set	Cleaning Method	Abrasives	Operator	Soluble Salt µg/cm2	Standard Deviation	% of Control
1	dry blast	medium sand	Clemco	109	3	100
2	dry blast	fine sand	Clemco	100	7	92
3	dry + water wash	medium sand	Clemco	68	5	
4	dry + water wash	fine sand	Clemco	96	8	88
5	air abr. wet blast	med sand	Clemco	47	2	43
6	air abr. wet blast	fine sand	Clemco	55	4	50
7	hi-pressure water jet	medium sand	Clemco	45	9	41
8	hi-pressure water jet	fine sand	Clemco	46	5	42
9	hi-pressure water jet	none	Clemco	174	10	160
10	dry blast	medium sand	Conomos	47	7	100
11	dry + steam clean	medium sand	Con/SSPC	23	6	49
12	dry + flame clean	medium sand	Con/SSPC	55	6	117
14	chem. stripper (Pentek 60)	none	SSPC			
15	roto-peen + water wash	none	SSPC	134	30	285
16	Clean-N-Strip disc	none	SSPC			
17	overblast (repeated)	medium sand	Conomos	30	6	64
18	dry blast	staurolite	Conomos	31	5	66
19	dry blast (SP 7)/water/ dry	medium sand	Conomos	30	6	64
20	dry blast (SP 6)/water/ dry	medium sand	Conomos	21	4	45
21	ultra water jet (35 KSI)	none	Admac	14		?

volatilize, and thereby become dislodged from the pits. As shown, this treatment had no noticeable effect on the amount of soluble salts.

- Chemical Stripper: A chemical stripper, Pentek 603, is designed to penetrate and dissolve rust, and after hardening, to strip rust from the surface. The soluble salt levels remaining after one and two applications of the stripper, respectively, were 5.7 and 1.0×10^{-3} oz/ft ^{2} (174 and 32 μg/cm ^{2}).

- Dry Blast Plus Chemical Stripper: Pentek 603 had essentially no effect when applied to a surface that had been previously blast cleaned.

- Roto-Peen Plus Water Wash: Roto-Peen is an important new power tool which allows cleaning of rusted or painted surfaces to bare metal. However, the tool cannot reach the bases of deep pits. The results indicate that even when water washing, there is about three times more soluble salt remaining on the surface than is found after dry abrasive blasting.

- Non-Woven Abrasive Discs: Another newly developed power tool consists of non-loading woven abrasive discs. These can be used in conjunction with rotary peening (to reduce excess profile and rough peaks) or by themselves to remove tight rust and paint. They can provide a profile of about 1 mil (25 microns). They are described in SSPC-SP 11.

- Overblast: This technique consists of repeated dry blast cleanings using medium abrasive. There was no improvement in the level of soluble salts, indicating that some water is required to remove soluble salts.

- Ultra-High Pressure Water Jetting (35,000 psi, 240 MPa): In the limited trials of this technique, it was unable to completely remove most of the rust scale and hence could not produce a commercial blast surface (SSPC-SP 6). The technique was effective in removing soluble salts from the surface, although it is likely that salts remain embedded in the residual rust.

In a separate SSPC experiment, several of the cleaning methods were also evaluated on cut-up pieces of bridge steel obtained from New Jersey Turnpike, along with a set exposed in SSPC salt spray. The NJ Turnpike results corroborate the findings regarding the lack of improvement by staurolite and the dry/wet/dry procedure. The overblast technique had a more pronounced effect on the New Jersey Turnpike steel.

Selection of Techniques for Coating Evaluation

The previous results indicated that wet methods of blast cleaning produced surfaces with the lowest levels of soluble salts. From previous work by SSPC and other studies, it was determined that air/abrasive wet blast is a more productive and efficient technique than pressurized water jetting with abrasive injection. The rinsing or low-pressure spray following dry blast was found to be less consistent, and in addition, required a two-step process. The pressurized water jetting, even at ultra-high pressures, proved ineffective in removing the tight rust and millscale from the A-588 panels.

Dry blasting was selected as a control technique against which wet blasting and other procedures could be compared. The abrasive size had little influence on the resulting soluble salt levels, thus the medium abrasive was selected for the evaluations of coatings.

Power tool cleaning to bare metal was also selected for the coating evaluation studies because it may provide an alternative to blast cleaning where relatively small areas are contaminated by chlorides (e.g., near expansion joints). Tools used were rotary peening flaps and non-woven discs. The power tool cleaning would be followed by a low-pressure water rinse.

The fourth cleaning method selected was hand tool cleaning using chipping hammers and wire brushes. This represents a situation in which minimal or no cleaning is performed in certain areas of the structure. For example, this could include areas determined to have low levels of soluble salts on the surface and not meriting the cost of the superior cleaning methods.

Surface Pretreatment Methods for Coating Evaluation Studies

The following types of steel were selected to be included in the coating evaluation laboratory trials:

- A-588 as received from mill with intact millscale (essentially chloride free).

- Laboratory corroded and pitted A-588 steel (high-chloride): These were specimens that were exposed to 100 cycles in the SSPC intermittent salt spray test.

- Laboratory corroded A-588 steel (low-chloride): Specimens exposed to 10 cycles of intermittent salt spray.

- Field-corroded and pitted A-588 (high chloride level): These were specimens obtained from Michigan DOT and Ontario Ministry of Transportation, which were measured to have high levels of soluble salts.

- Field-corroded A-441 steel (low chloride level): These were specimens obtained from New Jersey Turnpike bridge beams. (Note: A-441 is an alternative low-alloy steel.)

The pretreatment and cleaning of these specimens are described in the chapter on laboratory evaluation of coatings.

IV. LABORATORY EVALUATION OF COATINGS

The only proven valid test for bridge coatings is exposure on outdoor sites representative of the bridge conditions. In this project, such an evaluation is planned to be run for a 5-year period, as part of task C. Prior, however, to field evaluations, it is useful to conduct laboratory evaluation tests to identify coatings suitable for the subsequent field evaluations. A major purpose of the laboratory testing is to screen coating systems, by eliminating those which are less likely to provide long-term durability properties or which do not exhibit acceptable application properties.

The laboratory evaluations include three major phases: design, testing and analysis.

A. DESIGN OF LABORATORY EVALUATIONS

The steps required in this phase include the following:

- Select coatings.
- Select surface treatments and substrates.
- Select laboratory tests.
- Select evaluation techniques and criteria.
- Develop experimental matrix.

1. Select Coatings

Coating selection is based on input from State and Federal highway officials, manufacturers and consultants, literature review, and results of previous evaluations on related types of structures.

The criteria established were as follows:

- Successful case histories on bridges or similar structures.
- Ability to protect chloride-contaminated surfaces.
- Product commercially available.
- Previous use on carbon steel structures.
- Could be applied with standard application equipment.
- Did not contain any lead, chromate, or other hazardous materials.

The coatings selected were as follows:

System #1: Oil alkyd, lead silico-chromate (Federal Spec. TT-P-615), two-coat system (5 to 6 mils [125 to 150 microns]).

This system was selected as a control. It has been extensively used by highway departments, SSPC, and other agencies. It has provided excellent protection on blast cleaned steel and is regarded as one of the better coatings for hand cleaned steel.

System #2: Inorganic zinc-rich primer (two-package ethyl silicate) with standard vinyl topcoat (SSPC-Paint 9) (4 to 5 mils [100 to 125 microns])

This system is the most widely-used system among highway departments for new steel bridges (i.e., shop-applied). Inorganic zinc has a successful history in marine environments, having been used in offshore applications. It is claimed that the inorganic zinc is tolerant of chlorides, because of possible reaction of zinc with chlorides, and the nature of the film (i.e., porous film does not promote osmotic blistering). Results of this test show some experimental evidence that inorganic zinc does protect chloride-contaminated carbon steel.

System #3: Epoxy-polyamide zinc-rich primer with high-build epoxy topcoat (6 to 8 mils [150 to 200 microns])

This is a system recommended by the Michigan DOT based on extensive laboratory tests and some field experience. It is claimed to be more tolerant than inorganic zinc of field surface preparation and application deficiencies. It was also identified by the Texas DOT as the most suitable coating for A-588 steel. Because of its strong history, two separate systems were selected from two manufacturers to gain some information on the variability in performance within this generic class.

System #4: High-solids epoxy polyamide mastic with epoxy topcoat (6 to 8 mils [150 to 200 microns])

This system was developed in the early 1970's for use over less-than-ideal surfaces (e.g., rusted). In the last few years, a number of highway systems have evaluated and adopted this type of system. This particular product showed excellent performance in a recent SSPC evaluation of coatings for rusted A-588 weathering steel joints.

System #5: Single component moisture-cured urethane (aluminum and zinc-filled) plus high-build epoxy topcoat (5 to 7 mils [125 to 175 microns])

This system is also promoted as tolerant of rust. The system has been used on an experimental basis on Allegheny County PA bridges and on some large industrial structures.

System #6: Single component moisture-cured zinc-rich urethane with two-component aliphatic urethane topcoat (5 to 6 mils [125 to 150 microns])

This is a variation of system #5, with zinc as the main active pigment in a urethane binder. Manufacturer presented excellent data on laboratory and test fence evaluations.

System #7: Petroleum wax with calcium sulfonate inhibitor (two-coat system) (4 to 6 mils [100 to 150 microns])

This system was also promoted as applicable to rust and other surface contamination. The system has performed extremely well in the SSPC laboratory evaluation of rusted and contaminated weathering steel joints.

System #8: Thermal spray zinc (6 to 10 mils [150 to 250 microns])

This system was selected because of its potential for extremely long-term corrosion protection. It has been used recently on some State and county bridges with early indications of success.

2. Select Surface Preparation and Substrates

Surface Preparations

Surface preparations were selected based on their suitability for field use and their capability of removing chlorides from the surface. As discussed in chapter IV, the four preparations are as follows:

- Dry abrasive blasting with medium sand (30 mesh).
- Wet abrasive blasting with medium sand.
- Power tool cleaning, using roto-peen flaps and nonwoven abrasive discs (as described in SSPC-SP 11).
- Hand tool cleaning (control technique)

Substrates

It is important that the steel substrate selected be representative of the bridge steel to be protected. As discussed in chapter IV, we obtained and examined a variety of bridge specimens for use in this project. In addition, considerable effort was expended on laboratory techniques to simulate these types of steel. The steel substrates selected were as follows:

- Millscale-Bearing A-588 Steel

This represents steel as received from the mill which would be utilized for new A-588 bridges. Because of the problems identified with aged weathering steel bridges in certain environments and configurations, it is quite possible that some agencies elect to paint their A-588 bridges while in the fabricating shop or shortly after erection.

- High-Chloride Field Steel

These specimens, obtained from the Michigan DOT and the Ontario Ministry of Transportation, contained relatively high levels of chloride even after blast cleaning (over 3 x 10^{-3} oz/ft^2 [100 $\mu g/cm^2$]). This indicated that the chloride had penetrated the corrosion layers. Although primarily intended for field exposures (task D), there was an adequate supply to allow a small branch test with these substrates.

- Low-Chloride Field Steel

These were specimens from New Jersey Turnpike which were measured to have relatively low levels of chloride remaining after blasting (approximately 6.5 to 13 x 10^{-4} ft^2 [20 to 40 $\mu g/cm^2$]). They were selected to represent portions of bridges not subject to leaky joints, but where there was some salt in the environment.

- High-Chloride Laboratory Steel

These were specimens exposed to 100 cycles in the salt spray cabinet. This technique was determined in task B (chapter IV) to give panels fairly representative of field-contaminated specimens.

- Low-Chloride Laboratory Steel

These are similar to the preceding substrate, but were exposed for fewer cycles (approximately 10) and had correspondingly lower levels of chloride remaining in the oxide layers and the profile.

3. Select Laboratory Tests

Although laboratory accelerated tests are not suitable for predicting or correlating field performance, they may be suitable for identifying major deficiencies in coating systems. The approach was to select a battery of tests which provided a range of acceleration factors with conditions that might be experienced in the field. The types of exposure conditions incorporated into the program were as follows: salt spray, water immersion, moisture condensation, ultraviolet radiation, and freeze-thaw conditions. To represent these conditions, the following three exposure tests were selected.

- Salt Spray Test (ASTM B117): This test was selected because it has become a standard accelerated test in virtually all protective coating evaluation programs. Although it has not generally been found to be a useful predictor of field performance, it does provide a benchmark against which other test procedures can be evaluated. The salt spray would be expected to provide some indication of a coating's ability to resist attack by chloride, although there are certainly other factors that affect the coating's performance in the salt spray cabinet.

- Immersion in Deionized Water: This test is widely used for marine coatings which will experience immersion or immersion-like conditions. There are certain bridge components (e.g., bottom flanges and other horizontal surfaces) which may be immersed for certain time periods. Deionized water was selected because it provides a higher osmotic pressure and therefore more of an acceleration factor to promote blistering due to soluble salts (i.e., chlorides) on the surface. The test was run at 149 °F (65 °C).

- Composite Test: Ultraviolet Radiation/Condensation/Freeze-Thaw Conditions - This composite test subjects coatings to several significant environmental conditions. The UV and condensation portion, described by ASTM G53, was run in an Atlas Instruments UV-Con Chamber. Periodically, the panels were removed from the UV-Con chamber and placed in a freezer overnight; this subjected the coatings to a hot-cold stress and also to a mechanical stress produced by formation of ice from any trapped water. The actual cycle used was as follows:

- Ultraviolet: 2 hours at 158 °F (70 °C).
- Condensation Cycle: 2 hours at 104 °F (40 °C).
- Two times per week the specimens were removed to freezer at -4 °F (-20 °C), left there overnight, then reintroduced to the UV-Con chamber.

4. Design Test Matrix

The parameters included the following:

9 coatings (primer/topcoat combination)
5 substrates
4 surface preparation methods
3 exposure tests
3 replicates (necessary in order to provide adequate precision)

The full factorial results in 1,620 panels (9 x 5 x 4 x 3 x 3), which was beyond the scope of this test program. The scope was reduced by assigning the following branch tests:

- Branch A

This was a major test to evaluate coatings over blast-cleaned steel. It included six coatings which were applied over high- and low-chloride substrates cleaned by wet and dry blasting. The steel (new stock from the mill) was sheared into test panels by a fabricator. Dry blast over mill scale was used as a control substrate-surface preparation. This branch included all three accelerated tests.

- Branch B

The objective was to evaluate coatings over non-blast cleaned steel. It included the four coatings designed for rusty steel. Substrates included high- and low-chloride specimens and preparation was by hand tool cleaning and power tool cleaning. These systems were exposed in salt spray and the composite UV-condensation/freeze-thaw test.

- Branch C

This branch was designed to compare the performance of coatings over laboratory contaminated steel versus coatings over field-contaminated steel. Mill scale steel was used as a control substrate. Three surface preparation methods were used, with salt spray selected as the exposure test.

- Branch D

This branch evaluated thermal spray zinc coatings versus an organic zinc system. It was necessary to prepare the thermal spray at a separate facility. The zinc was applied by wire spray to a dry film thickness of 6 to 10 mils (150 to 250 microns). Branch D is a condensed version of branch A. A summary of the laboratory test plans is given in table 6.

B. CONDUCT LABORATORY EVALUATIONS

A large batch of new mill-scale-bearing-A-588 steel was cut into 4- by 6- by 1/8-in (100- by 150- by 3.2-mm) panels and pre-corroded as described previously. The bridge specimens were likewise cut into 4- by 6-inch panels in order to conform to the requirements of the accelerated test equipment. The specimens were all stamped with a unique identification number. The panels which were to be dry or wet blasted were shipped to a Clemco facility in Memphis, TN, which was better set up to blast clean large numbers of panels. In order to obtain a better comparison of the influence of water on performance, the wet and dry blasting were done with the same unit, but with water turned off for dry blasting. An SSPC representative was present during all the blast cleaning operations to oversee the preparation and make sure that panels were properly labelled and packaged to prevent contamination or prolonged exposure to the atmosphere. The power tool cleaning and hand tool cleaning preparations were done in the SSPC laboratory. The applications of the coatings (with the exception of the thermal spray zinc) were also performed in the SSPC laboratory. SSPC has developed standard procedures for applying experimental and other paints to large numbers of test panels. These included hand-dipping of edges to prevent edge corrosion. The dry film thicknesses are measured at five locations after each layer of paint is applied. Panels with excessively high or low film thicknesses or nonuniform film thicknesses are

Table 6. Final plan for laboratory evaluation of coatings.

Laboratory Test Methods

1. Salt Spray (ASTM B-117)
2. Immersion (deionized water), ambient temperature (to 70 ± 5 °F)(21 ± 3 °C)
3. UV Condensation (ASTM G-53)/Freeze-Thaw (ASTM D-2246)

Coating Systems

1. Oil/alkyd, Federal Spec. TT-P-615, lead silico-chromate, two-coat system.
2. Inorganic zinc-rich primer, two-package ethyl silicate, plus vinyl topcoat.
3. Epoxy polyamide zinc-rich system with high-build epoxy polyamide topcoat (two different systems).
4. High-solids epoxy polyamide mastic with epoxy polyamide topcoat.
5. Moisure-cured urethanes containing aluminum and zinc with high-build epoxy topcoat.
6. Zinc-rich urethane with urethane topcoat.
7. Petroleum wax-type coating (two-coat system).
8. Thermal spray zinc.

Surface Preparation

1. Dry blasting (medium abrasive) to near-white metal.
2. Air abrasive wet blasting (medium abrasive) to near-white metal.
3. Hand tool cleaning (wire brushing) to SSPC-SP 2.
4. Power tool cleaning (roto-peen) to remove most rust.

Types of Substrates (all weathering steel)

1. Laboratory specimen corroded in salt spray (low chloride).
2. Laboratory specimen corroded in salt spray (high chloride).
3. Field specimens from Michigan or Ontario (high chloride).
4. Field specimens from New Jersey (low chloride).
5. New millscale-bearing steel.

Testing Plan

Branch A - Blast Cleaned Surfaces.
Six coatings (nos. 2, 3A, 3B, 4, 5, 6 above).

Table 6. Final plan for laboratory evaluation of coatings (continued).

Three surfaces

- Dry blast of high-chloride lab specimens.
- Air abrasive wet blast of high-chloride lab specimens.
- Dry blast of new mill scale steel.

Three lab tests: salt spray, UV-condensation/freeze-thaw, and immersion
Two replicates per panel
Total panels needed 6 x 3 x 3 x 2 = 108

Branch B - Non-Blast Cleaned Surfaces
Four coatings (nos. 1, 4, 6, and 7)
Two initial surfaces (high-chloride and low-chloride laboratory specimens)
Two surface preparations (hand tool clean and power tool clean).
Two tests (salt spray and W condensation-freeze/thaw
Three replicates per system
Total panels: 4 x 2 x 2 x 2 x 3 = 96

Branch C - Field Steel as Substrate
Three coatings-(l, 3A, 4)
Four substrates (high chloride filed specimen, low-chloride field specimen, high-chloride lab specimen, new millscale specimen)
Three surface prepQrations (dry blast clean, wet blast clean and power tool clean)
One test (salt spray)
Three replicates
Total panels: 3 x 4 x 3 x 3 = 108

Branch D - Evaluation of Thermal Spray Zinc
Two coatings (3B and 8)
Two surfaces (dry blast and wet blast of high-chloride lab specimens)
Two tests (salt spray and UV Condensation/freeze-thaw)
Three replicates
Total panels: 2 x 2 x 2 x 3 = 18

Total test panels to be included - approximately 320 discarded. Following an appropriate period of cure (usually 2 weeks), the panels are placed in testing chambers. The specimens were examined at regular intervals for rusting, blistering, and other film defects.

The rust is measured in accordance with modified ASTM D610/SSPC-Vis 2, in which the amount of rust present is visually compared to a photographic standard. The ratings range from 10 (perfect) to 0 (totally rusted) in a roughly logarithmic scale related to the percentage of the surface containing rust. The SSPC, along with other groups, has adopted the rating of 7 as representing failure, thus an important parameter is the number of hours until the panel has reached a 7 rating.

The blistering is evaluated in accordance with a modified version of ASTM D714. In this case both the size and frequency of blisters is estimated against a series of photographic standards. The smallest blisters are assigned a numerical rating of 8 and the largest a rating of 0 or 2. Frequency ranges from VF (very few) to D (dense). The SSPC failure criterion for blistering is 8 and MD (blistering of size 8 and frequency of medium dense). Blister ratings considered as failed include 8D, 8MD, 6D, 6 MD, 6M, 4D, 4MD, 4M, 4F, 2D, 2MD, 2M, 2F, 2VF.

The rating schedules were approximately as follows:

- Salt spray: 24, 48, 72, 144, 216, 360, 408, 960, 1512 hours.
- Immersion: 48, 500, 1000, 1500, 2000, 2500 hours.
- UV-CON/FT: 48, 100, 200, 500, 1000 hours.

The final ratings for the laboratory tests are given in tables 7, 8, and 9 for branches A, B, and C respectively. Panel ID's and individual panel ratings over time are given in appendix C.

C. ANALYSIS OF BRANCH TESTS

- Branch A

The salt spray data from table 7 show that in the salt spray test there were four failures on wet blasted surfaces, two on dry blasted, and zero on the blast cleaned mill scale substrate (control). In the immersion tests, however, the dry blast had five failures versus one for the wet blast and one for the control. Possibly the wet blast was able to reduce the amount of soluble salts on the surface, thereby reducing the tendency to blistering. The differences in performance between these two surface preparation techniques over a high-chloride surface was not great, but both were definitely inferior to an essentially chloride-free substrate (i.e., blast cleaned mill scale). The coatings also showed different behaviors in the two tests. Systems 2, 3A and 3B all had several failures by rusting in the salt spray, but collectively had only one panel which was not perfect in the immersion testing. Conversely, coatings 4 and 6, which showed no failures in salt spray, each had three panels failing out of 6 in the immersion test. Only coating 5 had no failures in either test. In the UV-Con/freeze-thaw test, virtually all the panels showed perfect 10 ratings for both rust and blistering throughout the experiment; thus this is not a very severe test for these high-technology coatings applied to a blast cleaned substrate. A summary of the results for branch A is presented in table 10.

Table 7. Branch A -- laboratory evaluation of coatings, final ratings.[1]

I. Salt Spray: Rust rating[3]

	High Chloride/Dry Blast				High Chloride/Wet Blas				Mill Scale/Dry Blast				
Coating[2]	Rating	Hours to Failure	Rating	Hours to Failure	Rating	Hours to Failure	Rating	Hours to Failure	Rating	Hours to Failure	Rating	Hours to Failure	No. Failures
2	7[4]	1000	7[4]	1000	9+		9		9+		10		2
3A	9		8		7	1000	7	1000	9		8		2
3B	8		8		7	1000	7	1000	9		8-		2
4	9+		9		8		8		8+		+		0
5	9		10		9		10		10		10		0
6	10-		10-		10-		10		10		10		0
No. of Failures		2				4				0			6

II. Salt Spray: Blister Rating[5]

2	6MD	1000	6MD	1000	6M	1000	6M	1000	6M	1000	6M	1000	6
3A	10		10		10		10		10		10		0
3B	10		10		10		10		10		10		0
4	9D	1500	9D	1500	8F		6VF		10		8F		2
5	10		10		10		10		10		10		0
6	6MD	200	6MD	200	8F		8M	1500	8M	1000	8M	1000	5
No. of Failures		6				4				4			13

III. Immersion:[6] Blister Ratings[5]

2	10[4]		10[4]		10		10		10		10		0
3A	4VF	450	10		10		10		10		10		0
3B	10		10		10		10		10		10		0
4	6D	450	6D	450	F		8F		10		8D	1500	3
5	10		10		8F		10		10		10		0
6	6M	450	6MD	450	8M	1100	6F	1100	10		8M	200	5
No. of Failures		4				2				2			8

IV. Ultraviolet-Condensation/Freeze-Thaw Exposures

Note: No failures occurred by rust or blister in this test.

---

[1] Salt spray ran for 1512 hours, immersion for 2462 hours.

[2] See Table 6 for details.

[3] Rust rated per ASTM D610/SSPC-Vis 2. Rating of 7 or less considered failure. Numbers in parentheses are hours until failure.

[4] Two numbers represent replicate panels.

[5] Blistering rated according to ASTM D714. Rating of 8M, 6F or worse considered a failure.

[6] No failures occurred by rust in immersion test.

Table 8. Branch B -- Laboratory evaluation of coatings, final ratings.

I. Salt Spray: Rust Ratings[3]

		Power Tool Replicates						Hand Tool Replicates						No. Failures	
Coating[2]	Substrate[2]	First		Second		Third		First		Second		Third			
1	High Cl-	0	[360]	0	[360]	0	[960][4]	0	[360]	0	[144]	0	[216]	6	[360]
	Low Cl-	6	[960]	6	[960]	4	[960]	0	[960]	0	[960]	0	[960]	6	[960]
4	High Cl-	9		9		9		8+		9		9		0	
	Low Cl-	10		9-		9		9		7	[1512]	8		1	
6	High Cl-	8		8		9		7	[144]	7	[[144]	7	[1512]	3	
	Low Cl-	10		2-		10-		10		9+		10		0	
7	High Cl-	0	[144]	0	[144]	0	[216]	0	[144]	-	[144]	0	[216]	6	[144][5]
	Low Cl-	0	[360]	0	[408]	0	[960]	0	[360]	0	[360]	0	[216]	6	[360]

No. of Failures	High Cl-	6 [216]	9 [144]	15 [144]
	Low Cl-	6 [960]	7 [960]	13 [960]
		12 [360]	16 [216]	28 [360]

II. Salt Spray: Blister Ratings[6]

		Power Tool Replicates						Hand Tool Replicates						Average Failure Time	
Coating[2]	Substrate[2]	First		Second		Third		First		Second		Third		Power Tool	Hand Tool
1	High Cl	0	[48]	0	[144]	0	[48]	0	[48]	0	[48]	0	[48]	80	40
	Low Cl-	4D	[960]	6D	[960]	6D	[960]	0	48	0	24	0	[48]	960	40
4	High Cl-	4D	[216	4D	[216]	4D	6	3D	[144]	3D	[144]	3D	[144]	216	144
	Low Cl-	8D	512	8D	1512	8D	[1512]	6D	[216]	6D	[216]	6D	[144]	1512	192
6	High Cl-	4MD	[144]	3MD	[216]	3MD	[144]	4D	[[72]	6D	[72]	6D	72	168	72
	Low Cl-	6MD	[360]	8M	[960]	6MD	[144]	8D	[144]	6MD	[216]	6MD	[144]	488	168
7	NOTE: Blister ratings could not be taken because of damage to soft coating.														

Average Failure Time	High Cl-	155 hours	88 hours
	Low Cl-	987 hours	133 hours

[1] Salt spray run for 1512 hours. UV-Con/Freeze-Thaw for 1128 hours. See text for specific cycle.
[2] See table 5 and appendix C for details.
[3] Rust rated according to ASTM D610/SSPC-Vis 2. Rating of 7 or less considered to be failure.
[4] Unbracketed numbers are average final rust ratings of three replicate panels.
Numbers in brackets are the number of hours until one panel failed (i.e., reached rust rating of 7).
[5] Median time to failure of failed panels
[6] Blistering rated according to ASTM D-714. Rating of 8M, 6F or worse considered a failure.
[7] Third replicate was exposed in a separate run of the UV-Con/Freeze-Thaw test. For coating 7, the third replicate was omitted.
[8] Estimated.

Table 8. Branch B -- Laboratory evaluation of coatings, final ratings (continued).

III. UV-Con/Freeze-Thaw : Rust Rating

		Power Tool Replicates						Hand Tool Replicates						
Coating	Substrate	First		Second		Third		First		Second		Third		No. Failures
1	High Cl-	10		10		8		7	[1100]	7	[1100]	2	[750]	3
	Low Cl-	10		10		10		10		10		10		0
4	High Cl-	10		20		20		8+		8		7	[750]	1
	Low Cl-	10		10		10		10		10		10		0
6	High Cl-	9		9		8		8		7	[1100]	7	[300]	2
	Low Cl-	10		9		10		9		9		8		0
7	High Cl-	6	[700] [8]	8		•• [7]		4	[200]	6	[600] [8]	•• [7]	3	
	Low Cl	10		10		88		6		8	[700]	••	1	

No. of Failures	High Cl-	1	8	9
	Low Cl-	0	1	1
TOTAL		1	9	10

IV. UV-Con/Freeze-Thaw: Blister Rating

		Power Tool Replicates						Hand Tool Replicates						
Coating (b)	Substrate (b)	First		Second		Third		First		Second		Third		No. Failures
1	High Cl-	10		10		6F	[1100]	2M	[500] [8]	6M	[700]	2D	[300]	4
	Low Cl-	10		10		10		10		10		6MD	[1100]	1
4	High Cl-	10		10		10		4VF	[500] [8]	4VF	[500]	4M	[200]	3
	Low Cl-	10		10		8F		10		10		10		0
6	High Cl-	6VF	[700] [8]	6M	[700] [8]	4M	[500]	2MD	[500]	4MD	[500]	4MD	[500]	5
	Low Cl-	10		10		8F		2F	[500]	6F	[500]	4M	[750]	3
7	High Cl-	8M		10		•• [7]		4F	[500] [8]	6MD	[700]	•• [7]		3
	Low Cl-	10		10		••		8M		10		••		1

No. of Failures	High Cl-	4	11	15
	Low Cl-	0	5	5
	TOTALS	4	16	20

Table 9. Branch C -- laboratory evaluation of coatings , final ratings.[1]

I. Salt Spray: Rust Rating[3]

		Dry Blast Replicates						Wet Blast Replicates						Power Tool Cleaning Replicates						
Coating[2]	Substrate[2]	First		Second		Third		First		Second		Third		First		Second		Third		No. Failures
1	High Cl- Lab	0	[800]	0	[800]	6	[1100]	0	[800]	2	[800]	4	[1100]	0	[800]	0	[800]	2	[450]	9
	High Cl- Field	4	[800]	0	[250]	4	[750]	4	[800]	2	[800]	4	[750]	0	[800]	0	[250]	0	[450]	9
	Low Cl- Field	4	[800]	2	[800]	6	[2200]	4	[800]	4	[800]	6	[1100]	6	[800]	6	[800]	6	[1100]	9
	Mill Scale	4	[800	6	[800]	4	[750]	7	[800]	7	[1200	8		7	[1200]	7	[1200]	8		7
3A	High Cl - Lab	9		8[7]		8		8		8		8		7	[800]	7	[800]	7	[1100]	3
	High Cl- Field	9		9[7]		9		9-		9		10		7	[800]	7	[800]	8		2
	Low Cl- Field	10		10[7]		9		9[7]		8		8		9[7]		9		8		0
	Mill Scale	9		10[7]		9		9		8		8[7]		9		9[7]		9		0
4	High Cl- Lab	9		9		9		9		9		9		9		9		9		0
	High Cl- Field	10		10		10		10		9		10		9		10		10-		0
	Low Cl- Field	10		10		10		9		9		9		10		10		10		0
	Mill Scale	10		10		10		10		10		10		10		10		10		0
No. of Failures	High Cl- Lab			3						3						6				12
	High Cl- Field			3						3						5				11
	Low Cl- Field			3						2						3				9
	Mill Scale			3						11						2				7
TOTAL				12												16				

[1] Salt spray data given after 1100 to 1200 hours, about 2/3 of panels were exposed for an additional 1000 hours.

[2] See table 5 for details.

[3] Rust rated according to ASTM D610/SSPC-Vis 2. Rating of 7 or less considered to be failure.

[4] Blistering rated according to ASTM B714. Rating of 8M, 6F or worse considered to be failure.

[5] R indicates panel was removed prior to termination because of complete failure.

[6] Estimate.

[7] Panels which failed after 2300 hours.

Table 9. Branch C – laboratory evaluation of coatings, final ratings (contined).

II. Salt Spray -- Blister Rating[4]		Dry Blast Replicates						Wet Blast Replicates						Power Tool Cleaning Replicates						
Coating[2]	Substrate[2]	First		Second		Third		First		Second		Third		First		Second		Third		No. of Failures
1	High Cl- Lab	R	[250]	R[5]	[250]	2D	[750]	R	[500][6]	R	[500][6]	4D	[750]	R	[100]	R	[100]	4D	[450]	9
	High Cl- Field	6D	[500][6]	R	750	6MD	[1100]	4D	[800]	4D	[800]	4D	[750]	R	[250]	R	[100]	R	[70]	9
	Low Cl- Field	6D	[500][6]	6D	[500]	4MD	[750]	2D	[500][6]	2D	[500][6]	2D	[750]	4MD	[750][6]	6D	[750]	6MD	[750]	9
	Mill Scale	6D	[250]	6D	[500]	2MD	[750]	1D	[500][6]	1D	[500][6]	2MD	[750]	2MD	[500]	1MD	[500]	2MD	[750]	9
3A	High Cl- Lab	10		10		10		10		10		10		10		10		10		0
	High Cl- Field	10		10		10		10		10		10		4F	[1200]	10		10		1
	Low Cl- Field	10		10		10		10		10		10		10		10		10		0
	Mill Scale	10		10		10		10		10		10		10		10		10		1
4	High Cl- Lab	6D	[250]	6D	[250]	6MD	[750]	8VF		10		8F		4D	[250]	2D	[250]	4MD	[250][6]	6
	High Cl- Field	10		10		8M	[450]	6VF		8F		6VF		6D	[250]	8D	[250]	8MD	[450]	4
	Low Cl- Field	10		10		10		10		10		10		8MD	[1250]	8MD	[1250]	10		2
	Mill Scale	6VF		10		8F		10		10		10		10		10		10		0
No. of Failures	High Cl- Lab					6						3						6		15
						4						3						7		14
						3						3						5		11
						3						3						3		9
TOTAL						16						12						21		49

[1] Salt spray data given after 1100 to 1200 hours, about 2/3 of panels were exposed for an additional 1000 hours.

[2] See table 5 for details.

[3] Rust rated according to ASTM D610/SSPC-Vis 2. Rating of 7 or less considered to be failure.

[4] Blistering rated according to ASTM B714. Rating of 6M, 6F or worse considered to be failure.

[5] R indicates panel was removed prior to termination because of complete failure.

[6] Estimate.

[7] Panels which failed after 2300 hours.

- Branch B

In this test, it is possible to make the following comparisons: power tool vs. hand tool, high-chloride vs. low-chloride, and comparison of the four coatings. In table 8, the final ratings are presented for the evaluations in salt spray and UV-Con/freeze-thaw. For coatings which failed (ratings of 7 or less), the time to failure is given in parentheses. This provides another parameter to compare coatings which have failed. In both these tests (salt spray and UV-Con) there were significantly more failures by rusting and blistering than in branch A even for the two coatings (4 and 6) which were included in both branches. This was attributed to the use of power and hand tool cleaning. In the salt spray test, the power tool cleaning had slightly fewer failures than hand tool cleaning (12 vs. 16) and higher median time-to-failure (360 hours vs. 216 hours). The number of failures of the high-chloride substrates was only slightly more than the low-chloride substrates (15 vs. 13), but comparison of the median failure time (144 for high-chloride, 960 hours for low-chloride) indicates that there is a substantial effect from the level of chloride. In the salt spray tests, all the panels of coatings 1 and 7 exhibited complete failure during the tests. The median failure time of coating 1 was approximately three times that of coating 7 (the petroleum wax system). Of the two better-performing coatings, coating 4 had only one failure vs. three for coating 6. These two coatings were approximately equal in the evaluations of branch A over blast cleaned steel in both salt spray and immersion.

In the UV-Con/freeze-thaw test of branch B, power tool cleaning provided substantial improvement over hand tool cleaning (one failure vs. nine failures). Similarly, the low-chloride substrates gave substantially better performance than the high-chloride substrates (again, one failure vs. nine failures). Coatings 1 and 7 showed the most failures (3 each). However, the differential between coatings 1 and 7 and coatings 4 and 6 was much less than in the salt spray test. Apparently the hand tool cleaning is entirely inadequate to prevent corrosion of the underlying substrate, which is presumably aided by an osmotic force related to the chlorides remaining on the surface. This test provides a very dramatic indication of the importance of removing or reducing the amount of chloride on the surface prior to applying a coating.

- Branch C

This branch is designed to compare results over different sources and levels of chloride content as well as between dry blast, wet blast, and power tool cleaning methods. Because of the large difference in performance among the three coatings, each will be discussed separately. (See table 9.)

For coating system 1 (two-coat oil alkyd) all the chloride-containing substrates (high-chloride lab [HCL], high-chloride field [HCF], and low-chloride field [LCF]) failed in both rust and blister salt fog ratings for all three preparations. The average time to failure by rust was highest in LCF and lowest in HCF. There was a small difference among the three surface preparation methods, with power tool cleaning showing three early failures (less than 500 hours), dry blast showing one early failure, and wet blast none.

For coating system 3A (epoxy zinc-rich with epoxy topcoat) salt spray rust failures were observed for HCL and HCF power-tool cleaned panels, but not for low-chloride lab (LCL) blast cleaned or mill scale panels. The only panel which failed by blistering was also one of the ones that was power tool cleaned. The above data are for 1100 to 1200 hours. At 2300 hours there were some additional failures noted for all substrates and cleaning methods.

For coating system 4 (high-solids epoxy mastic with epoxy topcoat), there were no rust failures at 1100 hours in salt spray, although several power tool cleaned specimens failed at 2300 hours. Interestingly, there were substantial failures by blistering for all the chloride-contaminated substrates in the order HCL (most), HCF, LCF. Of the 12 failures, 8 occurred on power tool cleaned substrates and 4 were over dry blast cleaned. For wet blasted substrates, there was a noticeable amount of blistering, but none that were judged to be failures.

Excluding coating system 1, the number of failures for the four substrates (including both blistering and rust) were as follows: HCL: 9 failures; HCF: 6 failures; LCL: 2 failures; and mill scale: 0 failures. For the cleaning methods the results were: dry blast cleaning: 4 failures; wet blast cleaning: 0 failures, and power tool cleaning: 13 failures.

- Branch D

Neither of the two coatings (thermal spray zinc or organic zinc-rich) showed any failures in either the salt spray or the UV-Con/freeze-thaw test. It is not clear why coating 3B exhibited better performance in this test than in the similar test in branch A, in which there were a couple of 7 ratings in the salt spray. The difference may be due to the variability in the salt spray or to the coating film thickness or other application variables. The conclusions from these and the other branch tests are discussed below and summarized in table 10.

Comparison of Coatings

Coating system 1 (two-coat oil alkyd, lead, TT-P-615 standard) was significantly inferior to the high-technology coatings in the salt spray tests in branch B (hand and power tool cleaned). In the composite UV-Con/Freeze-Thaw tests in branch B, the coatings all exhibited some blistering, with none of the four particularly effective. Overall, in the composite test, system 6 (zinc-filled urethane) had the worst rating based on blistering failures. Coating 7 gave very poor rust resistance. Blistering was difficult to rate because of the damages which could not be readily distinguished from blisters. Overall, coating 7 (petroleum wax) was the poorest performing coating.

Among the high technology coatings (i.e., Systems 2, 3A, 3B, 4, 5, and 6), the organic zinc-riches (Systems 3A and 3B) overall gave the best blister resistance, while system 6 had the worst blister resistance. System 6 was also inferior to system 4 over hand cleaned steel (branch B) in all tests. Coating system 5 (zinc-aluminum moisture-cured urethane) had overall excellent properties over blast cleaned steel in both immersion and salt spray. The thermal spray metallic zinc coating gave essentially perfect ratings in the salt spray and UV-Con/Freeze-Thaw.

Comparison of Substrates

As expected, the surface producing the fewest failures was blast cleaned intact mill scale, which had not been exposed to a chloride environment. The low chloride specimens from both laboratory and field pre-exposures resulted in substantially fewer failures than the coatings applied to high-chloride surfaces. There was little difference in the results observed with the high-chloride specimens obtained from field sources (Michigan and Ontario bridges) and those obtained from a laboratory corrosion sequence. Thus, the laboratory prepared specimens are considered appropriate substrates for evaluating coatings over chloride-contaminated weathering steel.

Table 10. Summary of laboratory coating performance evaluations.[1]

Branch[2]	Test[3]	Parameter[4]	Substrate[5]	Surf. Prep.[6]	Coating Rankings[7]
A	Salt Spray	Rust	MS > HCL	DB > WB	(5, 6) ≥ 4 > (2,3A, 3B)
A	Salt Spray	Blister	MS > HC	WB > DB	(3A, 3B, 5) > 4 > (2, 6)
A	Immersion	Rust	No Failures	- - - - - - - - - -	- - - - - - - - - - - - -
A	Immersion	Blister	MS > HCL	WB > DB	(2, 3B) ≥ (3A, 5) > (4, 6)
A	UV-Con/F-T	Rust/Blister	No Failures	- - - - - - - - - -	- - - - - - - - - - - - -
B	Salt Spray	Rust	LCL > HCL	PT > HT	4 > 6 > 1 > 7
B	Salt Spray	Blister	LCL > HCL	PT > HT	4 > 6 ≥ 1
B	UV-Con/F-T	Rust	LCL >> HCL	PT >> HT	4 > 6 > l > 7
B	UV-Con/F-T	Blister	LCL >> HCL	PT >> HT	(1, 4, 7) > 6
C	Salt Spray	Rust	MS > LCF > HCF≥ HCL	(DB, WB) > P	4 > 3A >> 1
C	Salt Spray	Blister	(MS, LCF) > (HCL, HCF)	WB >DB > P	3A > 4 >> 1
D	Salt Spray	Rust/Blister	No Failures	- - - - - - - - -	- - - - - - - - - - - - - -
D	UV-Con/F-T	Rust/Blister	No Failures	- - - - - - - - -	- - - - - - - - - - - - - -

[1] Explanation of Symbols
X ≥ Y indicates that coating or treatment X was slightly better than Y.
X > Y indicates that X was significantly better than y.
X >> Y indicates that X was much better than Y.
Based on data from tables 6, 7, and 8

[2] Test Branches designed as follows
- A Blast cleaned steel, 6 coating systems
- B Non-blast cleaned steel, 4 coating systems
- C Field vs. lab corroded steel, 4 substrates, 3 coating systems
- D Thermal spray coating vs. organic zinc-rich coating

[3] See Appendix C for details.

[4] Rust rated according to ASTM D610/SSPC-Vis 2; Blistering rated according to ASTM D714.

[5] Key: MS (millscale), new A-588 steel
HCL (high-chloride laboratory) panels exposed to 100 cycles in salt spray cabinet prior to surface preparation.
HCF (high-chloride, field) specimens obtained from Michigan or Ontario, having high levels of chloride contamination
LCF (low-chloride, field) specimens from New Jersey Turnpike, low levels of chloride contamination.

[6] Key: DB - dry blast (medium abrasive), WB - wet abrasive blast,
PT - power tool cleaning using heavy duty roto-peen and non-woven discs,
HC - hand tool cleaning using wire brush

[7] System 1: lead oil alkyd (2-coat)
System 2: inorganic zinc/vinyl
Systems 3A & 3B: zinc-rich epoxy polyamide/high build epoxy
System 4: high solids epoxy mastic/acrylic epoxy
System 5: moisture-cured zinc-aluminum urethane/high-build epoxy
System 6: zinc-rich urethane/urethane
System 7: petroleum wax primer/topcoat
System 8: thermal spray zinc

Evaluation of Surface Preparations

Abrasive blast cleaning methods were clearly superior to power tool cleaning to bare metal. An even greater difference in performance based on failure times is noticed between power tool and hand tool cleaning. The data on failures for wet and dry blasting over chloride-contaminated surfaces are summarized in table 11. These data show that the two methods were approximately equivalent for rust failures in salt spray; however, the wet blast gave fewer failures by blistering in salt spray and immersion. There were no failures evident on any of the panels exposed in the UV-Con/Freeze-Thaw test.

D. DISCUSSION OF ACCELERATED TEST RESULTS

The following trends and conclusions were identified based upon the limited exposures, number of specimens, and the need to select a single formulation representing the generic coating types compared.

1. The oil alkyd, lead silico-chromate (Federal Specification TT-P-615) two-coat system control (system 1) performed poorly in all comparisons and exposures.

2. The thermal sprayed zinc (system B) performed excellently over blast cleaned surfaces.

3. Testing of system 5 (aluminum-zinc filled, moisture-cured polyurethane with a polyamide topcoat) was limited to abrasive blasted substrates, over which it performed excellently in salt spray and immersion testing.

4. System 6 was similar to system 5 except the metallic content was limited to zinc. System 6 exhibited very poor blister resistance over blast cleaned substrates. This system did not perform well over hand cleaned substrates.

5. Both inorganic zinc (system 2) and zinc-rich epoxy (systems 3A and 3B) performed extremely well over abrasive blasted substrates in immersion. In salt spray, each of the systems exhibited some rust failures on high-chloride substrates. In addition, the vinyl topcoat blistered over the inorganic zinc-rich primer. The vinyl-inorganic zinc intercoat blistering has been noted by other investigators and is often dependent upon the chemical character of the vinyl constituents.

6. All systems tested (systems 1, 4, 6, and 7) with power and hand tool cleaning performed poorly when evaluated for blistering in the salt spray and UV-Con freeze-thaw tests. System 4, the epoxy mastic, was superior to the others tested, exhibiting only one failure over hand tool cleaning due to rusting in the salt spray. Blistering problems were also experienced with system 4 in salt spray and water immersion over abrasive blasted surfaces.

7. Abrasive blast cleaning methods were clearly superior to power and hand tool cleaning. An analysis of the time to failure of power and hand tool cleaned surfaces showed that power tool cleaning is significantly better than hand tool cleaning.

8. Coating performance was similar over the laboratory prepared pitted panels and the field corroded specimens. Thus, corroded specimens prepared by the previous

Table 11. Comparison of wet and dry blasting of high-chloride substrates.

	No. of Failures[1]/ No. Exposed	
	Dry Blast	Wet Blast
Salt Spray - Rust		
Branch A	2/12	4/12
Branch B	2/12	0/12
Branch C	0/6	0/6
	4/30	4/30
Salt Spray - Blister		
Branch A	6/12	3/12
Branch C	4/12	0/12
Branch D	0/6	0/6
	10/30	3/30
Salt Spray - Total Failures (Rust or Blister)[2]		
Branch A	6/12	7/12
Branch C	6/12	0/12
Branch D	0/6	0/6
	12/30	7/30
Immersion - Rust		
Branch A	0/12	0/12
Immersion - Blister		
Branch A	4/12	2/12
Immersion - Total Failure	4/12	2/12
UV-Con/Freeze-Thaw Total Failures		
Branch A	0/12	0/12
Branch D	0/6	0/6
	0/18	0/18

[1] Includes coating systems 2, 3A, 3B, 4, 5, 6, and 8.

[2] Note that a panel that fails by both rust and blister criteria is counted as only one failure.

documented laboratory procedure are appropriate substrates for evaluating coatings over chloride-contaminated weathering steel.

E. DESIGN OF FIELD EVALUATION OF COATINGS

Based on the above, the following experimental design was developed for field evaluation trials of coating systems for chloride-contaminated weathering steel. The design elements discussed are substrate, surface preparation, coatings, and sites.

• Substrate

The main requirement is that the coating systems be tested over surfaces having contamination representative of bridges in chloride-affected zones. Thus, a major emphasis was on obtaining actual specimens of bridge steel, which had been exposed to such conditions. Because of the large number of test specimens required, and the inherent variability of rusting and pitting of field specimens, a supplementary source of chloride-contaminated steel was sought. Based on the accelerated lab data, it was considered acceptable to use steel which was corroded in the laboratory using cyclic salt spray. The test design also included weathering steel having lower amounts of chloride. This was necessary because information was needed on performance of coatings in areas of bridges which did not receive direct chloride leakage or splash. These areas may represent the majority of the surface area of the steel, including flange areas remote from joints and roadways and web sections. The large beam from the New Jersey Turnpike was considered ideal for this requirement. Control substrates were new mill scale-bearing A-588 and new mill scale bearing carbon steel. The former were selected to provide information on the relative merit of painting the steel when new, and the latter to investigate the relative performance of coatings on carbon and weathering steel.

• Surface Preparation

The laboratory accelerated data has shown wet blasting to be slightly superior to dry blasting in blister resistance. Field testing of both methods is needed to determine if these preliminary conclusions would be corroborated. Based on the data presented in chapter IV on the effectiveness of various techniques in removing chlorides, other techniques such as fine abrasives, ultra-high pressure water jetting, and combinations of blast and rinse cycles were not included. It was felt preferable to increase the number of panels and sites with fewer surface preparations to increase the precision and validity of the experiment.

Power tool cleaning to bare metal was included because it had shown substantial improvements over hand tool cleaning and could provide a possible alternative means of preparing surfaces when blasting is restricted. Finally, hand tool cleaning was selected as a low-performance control technique.

• Coatings

The coatings were selected based on the results from the laboratory tests, experience from other States and industry, and recommendations by the FHWA Contracting Officer's Technical Representative (COTR). In the laboratory testing, two-coat systems had been used in order to provide systems that would show failure in relatively short time intervals. For the field evaluations it was decided to use the full-protection systems recommended by the manufacturers, which generally included three coats: primer, intermediate, and topcoat. Because of the level of contamination of the surfaces, the severity of the exposure environment, and the 5-year exposure time, it was considered necessary to evaluate the systems having the greatest chance of providing long term durability and protection.

The following systems were selected:

1 Three-coat oil alkyd system (two coats of TT-P-615 [oil alkyd with basic lead silico-chromate] and alkyd topcoat)

Although it did not perform well in salt spray, this system is a standard which is extensively used by highway departments. In addition, despite the salt spray shortcomings, it has given very good field performance on carbon steel and also in some limited evaluations on field weathering steel.

2. Inorganic zinc (ethyl silicate)/vinyl high-build/vinyl topcoat

This system is also widely used and highly regarded among highway agencies. It was selected despite its relatively poor performance in the salt spray test.

3. Zinc-rich epoxy-polyamide/high-build epoxy/urethane

This system was among the best in the laboratory testing. It was also the system recommended for use on chloride-contaminated weathering steel by both Michigan and Texas DOTs (see chapter III).

4. Penetrating epoxy primer/high-solids epoxy mastic/urethane topcoat

This system had the highest overall ratings of the coatings tested over hand cleaned weathering steel. It had also shown good performance in other evaluations over hand cleaned weathering steel and carbon steel.

5. Zinc-filled moisture-cured urethane/high-build epoxy/urethane

This system had given best overall performance of the coatings tested in branch A (blast cleaned steel) in immersion, salt spray, and UV-Con/Freeze-Thaw.

6. Water-based inorganic zinc primer (two-package)/water-based acrylic topcoat (two-coat)

This system, though not tested in the laboratory phase, was added to the matrix for field evaluations at the request of the COTR. The rationale was that there was an urgent need for systems that would be volatile organic compound (VOC) compliant in addition to meeting the performance requirements. The system had met with success in some limited application and laboratory evaluations by a fabricator and a highway department.

7. Thermal spray zinc/sealer/topcoat

This system had given outstanding performance in salt spray testing. The metallic zinc coating is also a solventless system and therefore does not contribute to the VOC emissions.

8. Low-VOC ethyl silicate zinc-rich primer/low-VOC urethane

This system was designated as a low-VOC alternative (less than 3.5 lb/gal [420 g/l]) to the inorganic zinc vinyl system. This system was applied to a limited number of test specimens in field exposures at the request of the COTR.

9. Coatings not included in field trials

The polar wax coating, which had done very poorly in salt spray and had poor application and handling properties, was deleted. In addition the second urethane system (system 6 in chapter 5) was excluded because it had the poorest performance of the coatings tested over blast cleaned steel (branch A). In the field evaluation trials, only one epoxy-zinc system was chosen, as opposed to the two tested in the laboratory phase.

- **Test Sites**

The test sites selected included three bridge locations in Michigan, Louisiana, and Pennsylvania, and two standard SSPC exposure locations, marine (Kure Beach, NC) and industrial (Neville Island, Pittsburgh, PA). The description of steel cutting and preparation and coating application and evaluation of performance will be presented in a subsequent report. The coatings for field site testing are listed in table 12.

Table 12. Coating systems for field evaluation.

Recommended System		Primer, Intermediate, and Topcoats	DFT (mils)	DFT (microns)
1 oil-alkyd	1	oil/alkyd, basic lead silico-chromate (TT-P-615, II)	1.5-2.5	38-64
	2	oil-alkyd	1.5-2.5	38-64
	3	alkyd (SSPC Paint 104)	1.5-2.5	38-64
			4.5 - 7.0	125-175
2 zinc/vinyl HB	1	ethyl silicate inorganic zinc (2-package)	2.0-4.0	50-100
	2	vinyl high build	2.0-4.0	50-100
	3	vinyl	1.0-2.0	13-25
			5.0-10.0	125-250
3 epoxy zinc/epoxy/ urethane	1	zinc-rich epoxy-polyamide (2-package)	2.0-4.0	50-100
	2	epoxy polyamide high build	4.0-6.0	100-150
	3	aliphatic urethane	1.5-2.5	38-64
			8.0-12.0	200-300
4 epoxy mastic/ urethane	1	penetrating epoxy primer (100% solids)	0.5-1.0	13-25
	2	epoxy polyamide high solids mastic	4.0-8.0	100-200
	3	epoxy polyamide high solids mastic	4.0-8.0	100-200
	4	aliphatic urethane	1.5-2.5	38-64
			10.0-18.0	250-450
5 urethane/epoxy/ urethane	1	moisture-cured zinc-filled urethane (1-package)	2.0-4.0	50-100
	2	epoxy polyamide high-build	2.5-4.0	64-100
	3	aliphatic urethane	1.5-2.5	38-64
			6.0-10.0	150-200
6 water-borne zinc/acrylic	1	water-borne alkali silicate inorganic zinc (self-cure)	3.0-5.0	75-125
	2	water-borne acrylic	2.5-3.5	64-89
	3	water-borne acrylic	2.5-3.5	64-89
			8.0-11.0	200-275
7 zinc flame spray	1	zinc flame spray	4.0-6.0	100-150
8 low-VOC zinc/ urethane	1	low-VOC (3.5 lb/gal [420 g/l) ethyl silicate inorganic	2.0-3.0	50-75
	2	low-VOC high-build aliphatic urethane	3.0-5.0	75-125
			5.0-8.0	125-200

V. INTERIM GUIDELINES

INTRODUCTION

These guidelines are intended to assist maintenance engineers in establishing and implementing procedures for corrosion protection and maintenance painting of weathering steel bridges. The emphasis is on structures with severe corrosion damage or chloride contamination, but also addressed is the need for preventative maintenance of weathering steel bridges. The guidelines address two principal questions:

- What type of remedial actions are recommended and under what conditions?
- What are the procedures and criteria for achieving these requirements?

A. SELECTING REMEDIAL ACTION (MAINTENANCE OPTIONS)

The primary goal of maintenance is to assure the structural integrity and safety of the bridge. A secondary objective is to provide a level of aesthetics because of the bridge's public nature and because of the need to retain the public confidence in bridges.

It is well documented that corrosion damage of carbon steel bridges has resulted in substantial structural deficiencies and loss of critical strength and even failure. Thus, for weathering steel bridges, it must also be assumed that unmitigated corrosion of joints and other critical areas can affect the structural integrity and safety.

Most maintenance programs require trade-offs between the optimal level of maintenance and the level which can be afforded and justified. Unfortunately, in many instance, the available funding is so low that the agency greatly increases the risk of catastrophic failure and utilizes a "bandaid" approach which often costs more in the long run than a properly planned and managed maintenance program.

The maintenance engineer has four basic choices of action regarding protection of weathering steel bridges:

- None: A "no action" decision may assume that no structural deficiencies will become manifest within the 2-year period. The decision may be based on a thorough analysis that the structure does not need maintenance or it may signify that other structures are in much greater need of immediate action.
- Protect Corroded or Damaged Areas Only (preventative maintenance): This decision is based on the assumption that certain areas of the structure (primarily around deck joints) are in much worse condition than the other areas of the structure which are not subject to leakage of deicing salts. Selecting this option requires the ability to define the special areas requiring protection.
- Protect Entire Structure: In this case, the weathering steel bridge is treated much like a carbon steel bridge, although there may be a need to use special techniques or materials for the most corrosion-prone areas on the structure.
- Preventative Maintenance (non-painting): This option includes measures to limit the exposure to deicing salts (e.g., by drains, scuppers, or better-sealing materials),

or to treat the surface to prevent the corrosive action of the salts (e.g., periodic washing or special chemical treatments).

Types and Sources of Data

The decision should be based on maximum available data. The major sources of data include the following:

- Biennial Bridge Inspection: Safety inspections are conducted every 2 years on essentially all weathering steel bridges. Inspectors record instances of broken bolts, damaged members, and excessive corrosion and scaling. However, there is substantial confusion and lack of agreement on what the acceptable levels of corrosion scale or surface roughnesses are. In some cases, it may be necessary to remove corrosion scale by blast cleaning or power tool cleaning to determine section loss or pitting. This is not part of a routine bridge inspection. Some suggested criteria for judging the severity of corrosion are given.

- Bridge Data: Relevant information that is readily available is as follows: age of bridge; level of salt usage (both under and over the bridge); type of construction (e.g., rolled beam, box girder, plate girder, truss); configuration (e.g., stiffeners, angles, types and number of joints); traffic type (e.g., trucks) and volume; accessibility for rigging; size and gauge of steel; exposure environment (e.g., rainfall, humidity, pollution, winds, temperature). These factors affect the degree of exposure of the bridge to corrosive agents, and the likelihood that chlorides and moisture will result in accelerated corrosion. For example, the Michigan DOT has shown that certain pin and hanger connections and sheltered areas of a bridge (i.e., "tunnel effect") can greatly accelerate the corrosion and pitting.

- Special Corrosion Inspection: This is a nonroutine inspection to examine the joints and other components for pitting, loss of section, or chloride penetration. It often requires special equipment to dismantle assemblies (e.g., pin and hanger connection) or to abrasive blast clean salt-exposed areas to examine pitting and metal loss. Dismantling joints is normally required only when there is suspicion of reduction in structural strength. However, examination of pitting and chloride contamination can yield valuable information on the type of cleaning and painting needed.

Analyzing Available Data

The maintenance decision depends on the agency's philosophy of maintenance and its perception of the risks from chloride corrosion, as well as the various factors enumerated above. One major, controversial question is the ultimate corrosion rate of unprotected weathering steel and its effect on fatigue life. The original literature from the steel industry indicated that the initially high levels would flatten out to a rate on the order of 1/4 that of carbon steel. Recent studies by the Michigan DOT and the University of Maryland indicated that, under conditions of chloride or moisture, the rates do not level off and may occur at one mil per year or greater for extended time periods. One recommendation is for agencies with structures suspected of high corrosion rates to institute regular monitoring of section thicknesses and its effect on fatigue life.

Following are some factors that favor the various maintenance options.

No Maintenance Option (includes deferring maintenance painting)

- No chloride deicing salt used.
- Non-leaking joints, jointless bridge, or very light traffic.
- Dry climate in rural area.
- Open structure, with minimum of angles and joints (e.g., box girders at 20 ft (6.1 m) or more above roadway).
- Inspection indicates very little corrosion (e.g., intact mill scale), or very light, small-grained scale on top flange and other locations.
- Long- term maintenance program includes future painting plans.

Paint Corroded Areas Only

- Evidence of severe localized corrosion, including heavy salt deposits noted near leaky joints.
- Little or no salt spray from below (e.g., no truck traffic, light overall traffic, or non-highway [e.g. river] crossing).

  NOTE: In the presence of extensive truck spray, it may be more prudent to paint the entire structure rather than the corroded areas only because of the difficulty of isolating the corroded areas (see next option).
- Scale continues to develop in localized areas even after 5 or more years.
- Configuration presents areas that tend to collect moisture and debris, and which are not readily cleaned by rain.

Paint Entire Structure

- Corrosion and scale evident in many parts of structure (e.g., evidence of salt running along the entire bottom flange, or salt spray from trucks on bottom of bottom flange).
- Humid or salt-laden environment (e.g., near marsh, bay, or coastal areas).
- Aesthetics important (e.g., desirable to have uniform appearance of the entire bridge).
- Difficult to isolate corrosion-prone areas.
- Rigging and mobility cost very high so that it would not be much more expensive to paint entire bridge.
- Corrosion data indicate that eventually entire structure will require painting.

Preventative Maintenance (non-painting)

- Drains, Scuppers, Dams: This option favored when such improvements can achieve major reductions in accumulation or distribution of chlorides into joints or along flanges. This evidence may be based on results from other agencies or other structures.

- Surface Chemical Treatment: Examples include benzoic acid, phosphoric acid, and tannic acid. This would be favored if results from the Louisiana State study indicate that this is a cost-effective procedure. To date, this has not been demonstrated.

- Periodic Washing with Water: This would be favored by conclusive evidence that such a procedure is effective in reducing the corrosion rate. Results of SSPC study, however, indicate that low pressure water jetting cannot remove chlorides embedded in the steel, thus this approach would require very frequent washings, perhaps after each salt application. To date, no good evidence has been presented on the value of such a preventative maintenance system.

Discussion

Many of the above factors are subjective and cannot be precisely measured or defined. Consequently there is a variety of practices and opinions by different State agencies and other interested parties.

B. OPTION 1: PROTECTIVE COATINGS ON CORRODED AREAS ONLY

The most susceptible areas of a structure are the areas beneath open joints where leakage can occur. It should be assumed that eventually all joints will leak, so the treatment should be applied to all the joints. In addition, there is an area around the joints which should also be protected because of the tendency of the running water to carry salt to these areas. This ranges from about 6 to 10 ft (2 to 3 m) on either side of the joints, and generally includes the entire web and flange area. As with any protective coating system, it is necessary to consider the following components of the system: surface preparation, application techniques, coating materials, film thickness and quality control.

1. Surface Preparation

- Cleaning Methods: The results of SSPC and other investigations indicate that abrasive blasting is mandatory for cleaning corroded weathering steel. Power tool cleaning to bare metal (SSPC-SP 11), while capable of removing most rust and millscale, leaves an unacceptably high level of chloride and other corrosion products in the pits, which, in laboratory testing, resulted in a substantially reduced lifetime for the major coating types recommended. The major choice is between wet abrasive blasting and dry abrasive blasting. Although the laboratory results were inconclusive, it was felt that a thorough wet abrasive blasting to achieve an SSPC-SP 10 would be most effective in reducing the amount of chloride on the surface. The SSPC results also indicate that medium sand (e.g., 20/40 mesh) is optimal, although the Michigan DOT favors a finer abrasive (e.g., staurolite). One approach in wet blasting is to use the minimum amount of water (for dust control) during the early stages but to conduct a final cleaning with larger volumes of water or pure water at about 200 psi (1400 KPa) to remove the soluble salts. Alternate cleaning techniques such as dry blasting followed by pressurized rinse (e.g., 200 psi [1400 KPa]), dry blasting followed by steam cleaning, or pressurized water jetting with abrasive injection may give equivalently clean results, but at much slower and less productive rates than wet abrasive blasting.

- Production Rates: Wet abrasive blasting is usually slower than dry blasting, possibly 75-90 percent of the production rate at best. The difficulty in removing the wet sand may further reduce the productivity. Blast cleaning of weathering steel requires more energy than for comparable carbon steel. Various estimates are 20 to 40 percent additional effort required (e.g., additional time and abrasive). This is attributed to the tightly adherent corrosion scale on the weathering steel which covers 100 percent of the surface, whereas for carbon steel typically only relatively small portions are badly corroded and pitted.

- Pressure: It is essential that contractor be required to use the proper pressure (90 psi [630 kPa] minimum, 110 to 115 psi [760 to 790 kPa] preferred) to give higher cleaning rates.

- Abrasives: A hard, angular abrasive is recommended, with Mohs hardness of 6 minimum, conforming to the SSPC abrasive specification. The preferred size is 90 percent between 20 and 40 mesh. Examples include copper slag and low-dusting silica abrasives. An alternative is a 40/60 mesh staurolite.

- Inhibitors: Because of questions about the effect on paint lifetime, it is recommended that no inhibitor be used. A small amount of light flash rusting (golden color) is not considered highly detrimental. On the other hand, if a dark blackish or bluish corrosion product appears, this is probably evidence that there is substantial soluble salt remaining on the surface, and that additional cleaning may be required. (See discussion on soluble salts.)

- Assessing Surface Cleanliness: Prior to painting, the surface should be evaluated for visual and chemical cleanliness as follows:

    1. Visual Cleanliness: No rust, millscale, or other foreign matter is permitted as stated in SSPC-SP 10. SSPC-Vis 1 should be used to assist in judging the cleanliness. The Michigan DOT recommends holding the visual standard at a slight distance (12 in or 30 cm) from the surface to get the most accurate comparison.

    2. Chemical Cleanliness: If soluble salts are suspect, the area should be evaluated using SSPC or other field techniques for detecting soluble salts. The recommended parameter to measure is conductivity following swabbing of the surface with deionized water. If the specific conductivity (conductivity x volume/area swabbed is 16 siemens.in (40 siemens.cm), the surface should be re-cleaned. If the specific conductivity is less than 4 siemens.in (10 siemens.cm), the surface is considered clean. Conductivities between 4 and 16 siemens.in (10 and 40 siemens.cm) indicate the surface is marginal. NOTE: Additional investigations by the FHWA and the National Shipbuilding Research Program (NSRP) are developing more precise threshold limits for the acceptability of soluble salts.

2. Application

- Application Methods: The preferred method is conventional air spray because it allows greater control of the amount of paint applied. However, the selection should ultimately be based on the manufacturer's recommendations. Brushing may require special inspection to ensure that the proper film thickness is achieved.

- Quantity of Paint: Because weathering steel is considerably rougher than carbon steel, it requires a substantially higher volume of primer; estimates range from 30 to 50 percent. The contractor should be made aware of this factor in bid negotiations.

- Dry Film Thickness: For the primer, a 3-mil (75 micron) minimum DFT is recommended. The thickness gauge should be calibrated on bare weathering steel in accordance with SSPC-PA 2.

3. Coating Materials

- Primers: Based on results by the Michigan DOT and the Texas DOT, the preferred system is an epoxy polyamide zinc-rich primer. Alternative primers include the following:
    - Inorganic ethyl silicate zinc-rich (two-package).
    - Zinc-filled moisture-cured urethane.
    - High solids epoxy mastic.

- Intermediate and Topcoats: The recommended intermediate coat is a high-build epoxy polyamide, procured from the same manufacturer as that of the primer. For fascia girders or where added protection is needed, a two-package aliphatic urethane may also be added as a topcoat.

- Sources of Coatings

    - Epoxy zinc-rich primers: can be selected from the Michigan DOT or Louisiana DOTD Qualified Product Lists. Inorganic zinc systems can be selected based on the Florida DOT QPL or NASA QPL.

    - Epoxy Mastics: Specifications are available from South Carolina or Connecticut, or from the Pennsylvania DOT QPL.

    - Zinc-Rich Urethane: One source is the Allegheny County, Pennsylvania, Engineering Department Bridge Painting Specification.

C. OPTION 2: FULL REPAINT

In some cases it will be possible to distinguish between the corroded and the noncorroded areas. The former will often consist of the joints and areas such as those along the top of the bottom flange where water runoff is present or the bottom of the bottom flange which is subjected to salt spray from trucks.

1. Corroded Sections: These should be painted as described in the previous section.

2. Non-Corroded Sections

- Surface Preparation: The preferred methods are dry blasting and wet abrasive blasting. From a performance standpoint, *Power Tool Cleaning To Bare Metal* (SSPC-SP 11) is acceptable; however, it is often too slow for general use. Pressurized water jetting without abrasive is also an acceptable technique for non-corroded areas which will be coated with the same systems noted below for hand tool cleaning. Hand tool cleaning can be an acceptable preparation method under the following circumstances: only noncorroded sections are being prepared with this method, and these areas should not have any loose scale or dirt on them. Finally, the systems to be applied must be either a high solids epoxy mastic or a proven inhibitive oil alkyd (note: SSPC-Paint 25 is a candidate). In addition, the hand tool cleaning should not be used to prepare joint areas or other areas which may in the future be exposed to salt runoff or splash.

- Coatings for Repaint: For blast cleaned surfaces, the coatings described previously for the corroded areas are suitable. These include epoxy polyamide zinc-rich, inorganic ethyl silicate zinc-rich, high solids epoxy mastic, and zinc-filled moisture-cured urethane as primers. Recommended second coat is a high solids epoxy polyamide with an aliphatic urethane topcoat considered optional.

  For power tool cleaned surfaces, all of the above with the exception of the inorganic zinc-rich are suitable. For hand tool cleaned surfaces or pressurized water jetting the recommended systems are inhibitive oil alkyd or high solids epoxy mastic.

- Application and Film Thickness: The methods of application again include conventional air or airless spray. The former is preferred for joints and other confined areas, but most contractors prefer airless spray for the webs and other large areas because of its production rate.

  The dry film thickness should be a minimum of 3 mils (75 microns) above the peaks (as measured by SSPC-PA 2) for the primers.

  The primer will require an additional 25 percent of material compared to similar surface areas over carbon steel, because of the inherent roughness of the weathering steel.

APPENDIX A

ANALYSIS OF SOLUBLE SALTS

PART 1: LABORATORY AND FIELD ANALYTICAL AND EXTRACTION PROCEDURES

A. Chloride Analysis by Selective Ion Electrode

The exact method employed by the user will depend upon the equipment at hand. In the case of the current study, the concentration of chloride ion was obtained by interpolation from a plot on 4-cycle semilogarithmic paper of millivolts vs. concentration of chloride ion using potassium chloride solutions of known concentrations. In performing the analyses a chloride ion selective electrode was used, along with a silver/silver chloride reference electrode. Both were fitted to a standard pH/millivolt meter such as the Orion 301 pH/mV meter, with manual temperature compensation in the range 0 °C-100 °C. (Many different models of chloride ion selective electrode and reference electrodes are available from manufacturers such as Orion, Corning, etc. Those employed in the study were manufactured by Corning).

Four standards were prepared with 1.0, 10.0, 100.0, and 1000.0 ppm chloride ion (Cl^-) concentration by serial dilution from a National Institute of Standards and Technology (NIST) traceable source. (Such standard, NBS traceable solutions are available from laboratory supply houses.) To prepare the calibration plot, 100 ml of the 1.0 ppm Cl^- ion sample solution was measured into a 150 ml beaker, a magnetic follower was added, and 2.0 ml of ionic strength adjuster (ISA) added to the sample. (For chloride ion determinations the standard ISA is 5.0 M sodium nitrate available in low/free chloride form from laboratory supply houses.)

The sample was placed on an insulating pad (e.g., ceramic gauze) on a magnetic stirrer. It is important that the sample be insulated from the heat created by the stirrer, as a 2 °F (1 °C) increase in sample temperature will cause a 2-percent increase in observed chloride ion concentration/mv reading. A thermometer was placed in the sample and the sample allowed to stabilize at or near 77 °F (25 °C). The recorded temperature was used as the manual temperature compensation setting. Both electrodes were rinsed with deionized water, blotted dry with Kim-Wipes, and placed in the sample beaker. The sample was allowed to restabilize at the set temperature and the millivolt conductivity reading was taken. The electrodes were removed from the sample beaker, washed with deionized water, and blotted dry.

This procedure was repeated with the three remaining hardened samples in ascending order of chloride ion concentration. A plot of Cl^- ion concentration vs. millivolts was then made on semi-log paper (figure 1).

<u>Treatment of the Unknown Samples</u>

Samples of unknown chloride ion concentration were obtained using the acquisition techniques outlined above in part I. One fl oz (30 ml) aliquots of these samples were taken and to these were administered 0.02 fl oz (0.6 ml) of the ISA solution. This volume was chosen to ensure uniform ionic strength relative to the standards of 3.37 fl oz (100 ml) which required 0.067 (2.0 ml) of the ISA. The millivolt conductivity reading for these samples was obtained in exactly the manner described above for the standard calibration solutions. The millivolt readings are converted to chloride ion concentration directly from the calibration plot prepared above.

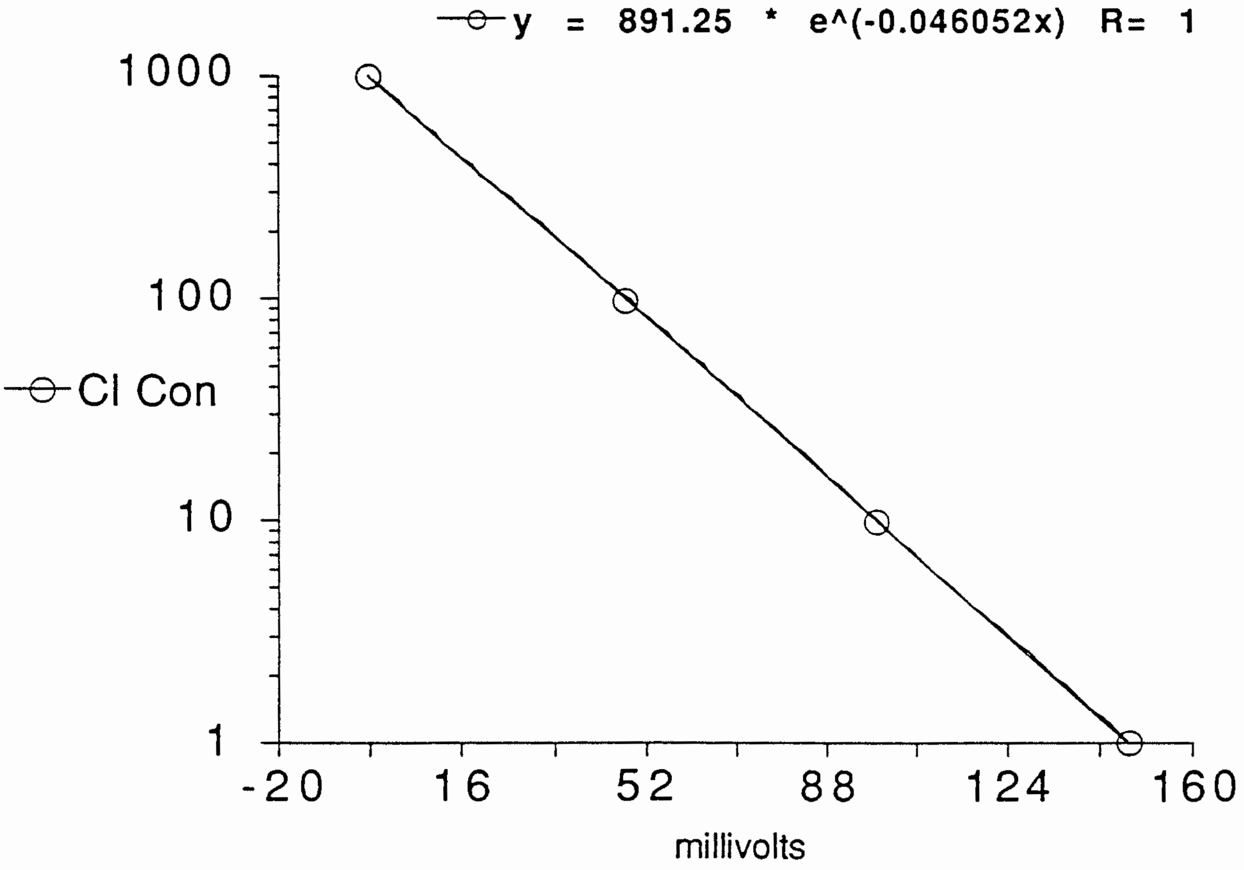


Figure 1. Calibration of chloride selective ion electrode.

Although this was the method employed in the current study, various modifications may be made by the use of more advanced instrumentation. For instance, one might employ a configuration chloride ion electrode; this obviates the need for a reference electrode and models are available (e.g., Orion's 96-17B) which permit determination of chloride ion in small volume samples without stirring. In addition, pH/mV meters are available which have ports for automatic temperature sensor probes and will permit direct reading of chloride ion concentration in ppm or any other convenient unit. In these cases, only two calibration points are required, spanning the expected range of chloride ion concentration.

B. Measurement of Conductivity

In an attempt to make a field sample method, conductivity measurements were taken on samples using a Nalcometer Model MLN portable instrument. This instrument was chosen because the conductivity results agree closely with the more precise laboratory data derived from the conductivity bridge by Leeds & Northrup Co.

The standard curve for the Nalcometer (figure 2) is a log-log plot of KCl concentration, moles per liter versus the conductivity in micromhos per centimeter.

The MLN Nalcometer is a compact, light-weight, self-contained conductivity meter. It is a multirange unit with a range selector switch. It provides accurate readings with no warm-up time required. This battery-powered meter contains a permanent, built-in cell with automatic temperature compensation to correct for variations in solution temperature over a range of 50 to 160 °F (10 to71 °C). Samples outside this range must be cooled or heated before measurement (Note: the standard temperature for measuring conductivity is 25 °C). The MLN has an automatic regulator circuit that corrects for decreases in battery voltage as the batteries age. There are four selector switches: X1, X10, X100, and X1000.

The MLN Nalcometer should be checked approximately every 6 months using Nalco conductivity standards. The calibration adjusts all ranges, so calibrating in one range automatically calibrates all ranges. The MLN Nalcometer costs approximately $335.00.

Freshly distilled water has a conductivity of 1.3 to 5 micromhos/in (0.5 to 2 micromhos/cm), increasing after a few weeks of storage to5 to 13 micromho/in (2 to 5 micromhos/cm). This increase is caused mainly by absorption of atmospheric carbon dioxide, and, to a lesser extent, ammonia. The conductivity of potable waters in the United States ranges from 125 to 4,000 micromhos/in (50 to 1500 micromhos/cm).

Conductivity cells containing platinized electrodes are available in either paper or immersion form. Cell choice depends on expected range of conductivity and resistance range of the instrument. Instruments can be checked by comparing instrumental results with the true conductivities of KCl solutions.

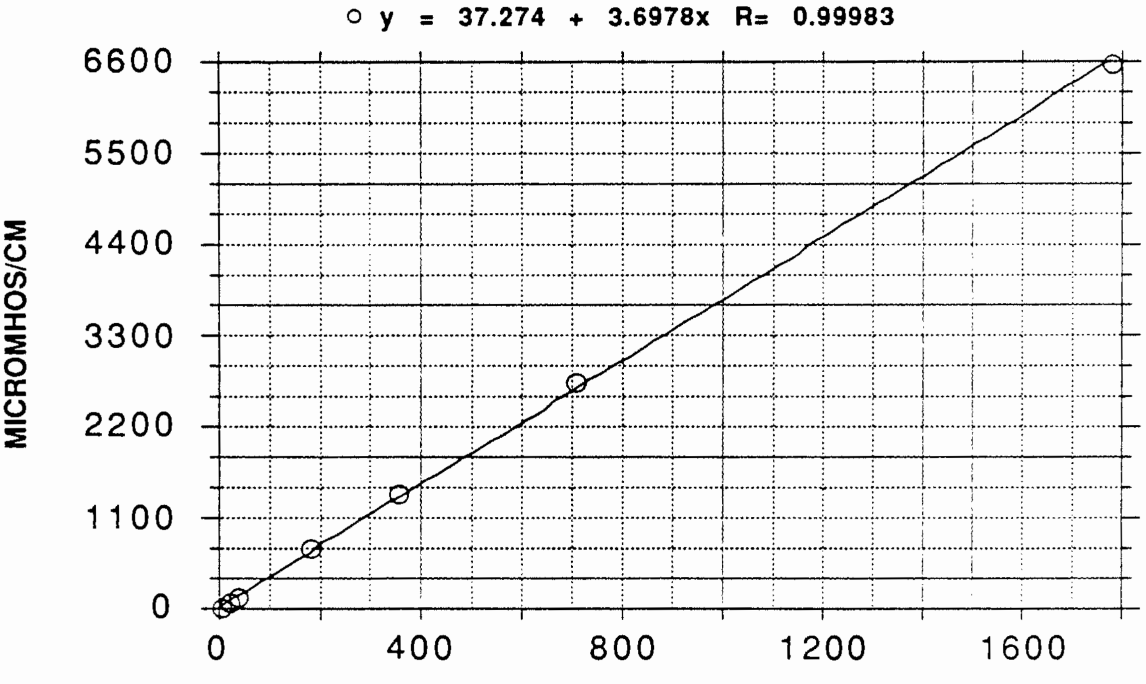


Figure 2. Conductivity vs. chloride concentration.

Conductivity of Potassium Chloride Solutions at 25 °C.

Concentration N	Conductivity micromhos/centimeter
0.001	14.94
0.001	147.00
0.01	1,413.00
0.1	12,900.00

Data drawn from Handbook of Chemistry & Physics, Chemical Rubber Co., Cleveland, Ohio.

C. Chloride Analysis by Quantab Strips

Lower end of Quantab strip is placed in solution to be tested (immersion of entire strip will trigger completion signal). Allow test solution to saturate column. This is accomplished 2 minutes after the yellow test completion signal across the top of the column begins to turn dark blue. This usually requires about 20 minutes. Results may be read from 30 seconds to 5 minutes after complete signal color change occurs. The readings are given in ppm which can be converted to micrograms/cm^2 (see figure 3).

The test strip is moistened using a few drops of the solution to be sampled or by immersion in it for only a few seconds. The color is compared to the color chart furnished with the strips. This gives a reading in ppm, which can be converted to micrograms ferrous ion per square centimeter, using same equations as given for chloride.

D. Boiling Water Extraction Procedure for Soluble Salts

Materials Needed

- Metal test plate approximately 4 by 6 in (10 by 15 cm)
- Pyrex or stainless steel pan larger than plate (22 by 12 by 7cm deep)
- Glass beads
- Hot plate
- Rubber tipped metallic tongs
- Deionized water - conductivity less than 2 micromhos/cm (microsiemen)
- Graduated 1000 ml beaker
- Glass or plastic sample bottles
- Conductivity meter

Procedure

Add 500 ± 5 ml of deionized water to Pyrex pan filled with single layer of glass beads. Place on hot plate at high. When water starts boiling, place metal plate on top of beads, ensuring it is fully immersed. Continue boiling for 30 minutes, replacing water which evaporates. Remove the panel with tongs and rinse it off into the dish using a stream of deionized water from a plastic squeeze bottle. The panel is air dried, wrapped, and put away. Remove pan from heat. When cool, pour water into graduated beaker and refill to 500 ml mark. Pour off a small sample and measure conductivity. Repeat conductivity measurement with another small sample. Collect additional samples and retain for additional analyses (e.g., chloride selective ion electrode or Quantab).

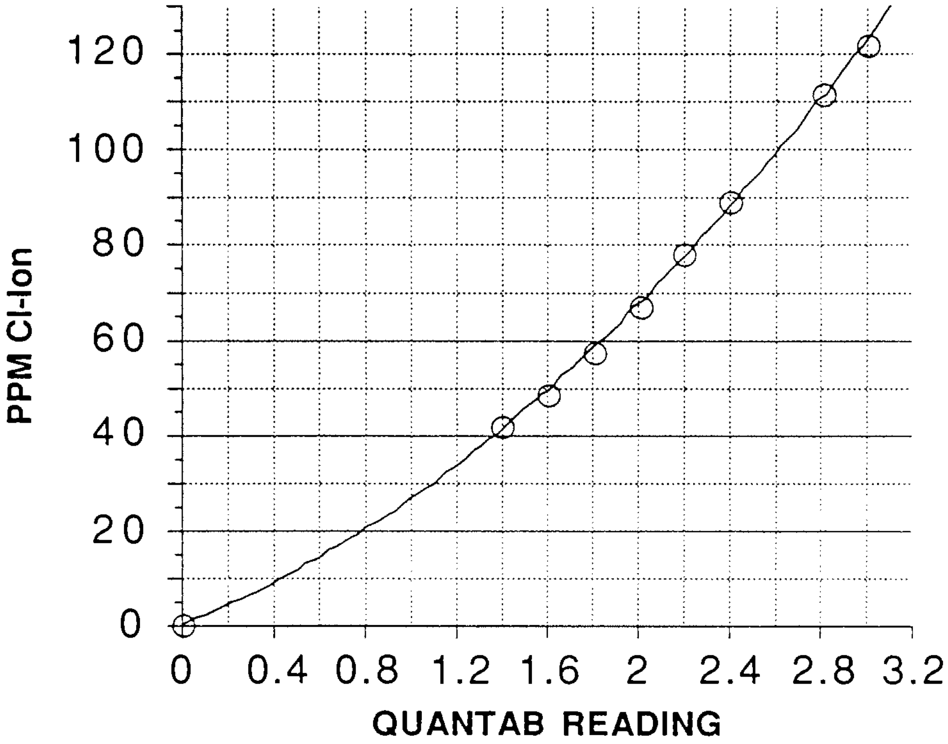


Figure 3. Chloride ion specific electrode vs. Quantab readings.

E. Field Extraction Procedure for Soluble Salts

Materials & Equipment

1. Reagent Water: Distilled or deionized water with a specific conductance of less than 2 micromho/cm. Distilled water may be purchased at retail grocery stores for about $1.00 per gallon.

2. Cotton: Use cotton balls of the highest quality, absorbent cotton, sterile (about $2.00).

3. Gloves: Disposable vinyl medical gloves to prevent contamination of the samples by salt found on the hands. Example: B-D Tru-Touch medical gloves, non-sterile, box of 100, $15.00 per box.

4. Conductivity Meter: Full-scale meter 1 to 10, with a four-range selector switch, 1, 10, 100, 1000 (about $300-$350).

5. Standard Curve: a log-log plot of the specific conductance in micromhos/cm versus chloride ion concentration in ppm (figure 2).

Procedure

Clean off an area of corroded steel (6 by 8 in [15 by 20 cm]). If possible, sand blast the area, otherwise scrape or chip off the heavily rusted scale, then clean with abrasive embedded discs. Using a water-proof tape mark off a specific area, for example, 4 by 4 in (10 by 10 cm).

Start with about 30 ml of distilled water in a 50 ml graduated plastic beaker. Wear protective vinyl gloves to prevent sample contamination from salt found on the hands. Dampen a cotton ball in the beaker of water and thoroughly swab the precleaned area. After swabbing, rinse the cotton ball in the water and squeeze it against the side of the beaker. Repeat. Set aside the cotton ball in a protected place, since it will be added back into the beaker before the final determination. Using a second cotton ball, repeat the entire procedure, then use a dry cotton ball to dry off the area. Rinse the cotton ball into the beaker and squeeze dry. After recording the final volume, place the three cotton balls back into the water and mix with a glass rod.

Pour 15 ml of sample into the conductivity meter cell cup. Measure the specific conductance (μmhos/cm).

Refer to a standard log-log plot, of specific conductance (figure 2) versus chloride ion concentration (ppm Cl^- ion) to determine the Cl^- concentration from the conductance reading (e.g., 100 micromho/cm is equivalent to 23 ppm chloride).

The chloride ion concentration can be converted to weight of chloride per unit area (micrograms per square centimeter) as shown in the following example (NOTE: 1 ppm = 1 mg chloride per liter):

chloride ion concentration: A (ppm) (e.g., 23 ppm)
area cleaned: C (cm^2) (e.g., 4 by 4 in [10 by 10 cm])
volume of sample water: B (cm^3) (e.g., 30 cc [cm^3 = cc = ml])

Convert ppm chloride as follows:

$$A\ (\text{ppm}) \times \frac{1\ \text{mg Cl}^-}{1\ \text{liter}} \times \frac{1\ \text{liter}}{1000\ \text{cm}^3} \times \frac{1000\ \text{microgram}}{1\ \text{mg}} \times \frac{B\ \text{cm}^3}{C\ \text{cm}^2}$$

$$\frac{A \times B}{C} \quad \frac{\text{micrograms Cl}^-}{\text{cm}^2}$$

e.g. $$\frac{(23\ \text{ppm}) \times (30\ \text{cm}^3)}{(100\ \text{cm}^2)} = \frac{6.9\ \text{micrograms Cl}^-}{\text{cm}^2}$$

F. Clarke's Solution Method for Removing Corrosion Products

This method is described in ASTM G1-85, "Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens." After loose scale is removed by wire brushing, the panel is dipped into Clarke's Solution and vigorously stirred or rubbed with a wooden or rubber implement. Clarke's Solution is comprised as follows:

Hydrochloric acid	(HCl, sp gr. 1.19)	1 liter
Antimony trioxide	(Sb_2O_3)	20 g
Stannous chloride	($SnCl_2$)	50 g
Temperature		room
Time		up to 25 min.

G. KTA SCAT Kit

The purpose of the SCAT Kit is to provide the necessary equipment to enable one to conduct quick, convenient, reliable analysis of surfaces for chlorides and soluble ferrous salts.

Design of the SCAT Kit

The SCAT Kit has been designed to determine the presence of three different species: chlorides, soluble ferrous salts (such as sulfates), and alkaline/acidic contaminants. Chlorides (such as common road salt) are detected with the use of the Quantab test strips. Soluble ferrous (Fe++) salts, such as ferrous sulfate, are detected with the use of the Fe++ test strips. The pH of the surface is determined with the use of the pH paper.

Directions for Use

Chlorides

The chloride test method employed by the SCAT Kit is based on the NACE (National Association of Corrosion Engineers) Task Group T6G-22 report published in *Materials Performance* 26, No. 3, p. 49, 1987.

1. Use a ruler and chalk or pencil to measure out an area 6 by 6 in (15 by 15 cm) on the surface to be tested.

2. Use only distilled or deionized water to perform the test. The portable demineralizer included in the SCAT Kit is a convenient way of obtaining this water. Simply pour tap water into the plastic bottle, attach the demineralizer cartridge in the direction indicated, invert, and squeeze out the desired amount of water (22.5 ml per test). The cartridge can be used until the blue color turns brown, as indicated on the side of the cartridge. Once this occurs, discard the cartridge and replace. Each cartridge should be good for approximately 3000 ml of water.

3. Use the graduated cylinder to measure out 22.5 ml of distilled or deionized water into one of the small plastic beakers.

4. Dampen one of the cotton balls in the beaker of water and thoroughly swab the area. After swabbing, swirl the cotton ball in the water and squeeze it against the side of the beaker each time. Repeat this procedure four times, then place the cotton ball in the beaker of water. Use a fresh cotton ball to dry off the test area. Place it in the beaker as well, and repeat with another cotton ball to be certain the area is completely dry.

5. Stir or swirl the contents of the beaker containing the water and cotton balls for at least 2 minutes to ensure thorough mixing.

6. Determine the chloride level by placing the lower end of one of the Quantab test strips in the water in the beaker.

7. Allow the water to wick up and saturate the test strip. Saturation is achieved 2 minutes after the yellow strip across the top of the column begins to turn dark blue. This takes about 20 minutes.

8. The presence of chlorides is indicated by a color change of the tan scale to white. Note the scale number at the top edge of the white, and compare to the enclosed chart to obtain the concentration of chloride.

Ferrous Ion

Ferrous ion can be determined on the same extract used for chlorides above. Use the Ferrous Ion Test Strips. Simply moisten a test strip and compare the color change to the color-coded chart on the label.

Evaluation of Chloride and Ferrous Ion Results

The charts on the test strips give the concentration of chloride and ferrous ion as parts per million (ppm). If the appropriate 6- by 6-in (15- by 15-cm) area and 22.5 ml of water were used, the concentrations determined in ppm are identical to milligrams per square meter. Therefore, if one obtains a reading of 50 ppm chloride on the Quantab test strip, this correlates to 50 mg/m^3 chloride on the surface tested. NOTE: Divide mg/m^2 by 10 to give results in µg/cm^2.

pH

pH is determined with the pH paper included in the kit. The pH can be determined on the water extract obtained in the above section by dipping the strip into the extract and comparing the resulting color with that on the color scale included with the paper. Alternately, the pH of the steel surface itself can be determined by placing a small strip of the paper on the surface and moistening it with 1 or 2 drops of deionized water, making sure that the pH paper is in intimate contact with the steel surface. Again, compare the resulting color with the color chart. It is always a good idea to check the pH of the water used, since this may or may not be 7 (neutral).

PART 2: DATA FROM SURFACE EXTRACTIONS AND SAMPLE ANALYSES

The preceding extractions and analytical procedures were used to determine chloride level and conductivity of various ASTM A-588 surfaces.

A. Evaluation of Multi-Replicate Extracts

Table 13 presents detailed data on the extractions and analyses of seven replicate A-588 plates. The plates had been exposed to 100 cycles of salt spray followed by dry-out. Each specimen was swabbed three times, with each extract analyzed for the following: conductivity, chloride level (ion-selective electrode), chloride level by Quantabs, pH, Fe++ by EM-Quant. In addition, the quantity of chloride on the surface is computed based on the surface area of the steel. The major findings are discussed in chapter 4 and summarized in table 4.

Figures 4 and 5 depict the chloride level and conductivity of the three successive extracts for each of the seven plates. The conductivity readings were higher for the third extract for all seven plates than the second extract. There is no ready explanation for this phenomenon. For the chloride level, it occurred only for panel #185.

Figure 6 compares the level of chloride from three different analytical methods: direct reading from ion-selective electrode, calculated from conductivity (assuming that only chloride ions are present), and direct reading from Quantabs. As noted in chapter IV, the conductivity method gives much higher levels than the direct method. This indicates that other soluble species besides chloride are present in the extract. The Quantab readings are generally lower than the ISE readings but are normally within 25 to 40 percent of the former.

B. Efficiency of Various Surface Preparation Methods in Removing Soluble Salts

Table 14 gives the results of extractions and analyses of surfaces prepared by different methods. Three or four test panels were cleaned with each method, which includes wet and dry blasting, along with pressurized water jetting and some chemical methods. The panels were first extracted by swabbing the fronts and backs twice each. Following this, the panel was extracted by boiling. The quantity reported is the equivalent chloride surface concentration in $\mu g/cm^2$. (NOTE: This quantity has been calculated from the conductivity and the known volume of extract and surface area; however, see later discussions for relationship between equivalent chloride concentration and actual concentration as derived from ion specific electrode method.) The relative success of the various methods in reducing the quantity of soluble salts is presented in table 5 and discussed in chapter IV.

Of note here is the relative efficiency of the swabbing method compared to the boiling method. The boiling is expected to produce essentially quantitative removal of any water-soluble

Table 13. Comparison of methods for chloride analysis.

Extract number	Plate ID	Sample Volume (ml)	Cond. µmhos/ cm	Specific Ion Electrode (millivolts)	Chloride Level ppm ISE	Chloride in Sample µg	Surface Chloride Level µg/cm2	Quantab Scale Reading	EM Quant Fe ++	pH
1	177	30	140	97.5	10.0	300.0	3.0	0.4	0.0	3.8
1	176	30	160	96.8	10.3	309.8	3.1	0.4	0.0	3.8
1	187	30	160	101.2	8.4	253.0	2.5	0.2	3.0	4.5
1	190	30	120	107.2	6.4	191.9	1.9	0.2	3.0	4.5
1	184	31	130	88.6	15.1	467.0	4.7	0.6	10.0	4.7
1	185	30	200	94.6	11.4	342.9	3.4	0.4	3.0	4.2
1	183	30	120	90.7	13.7	410.3	4.1	0.0	3.0	4.7
AVG	-	-	**147.1**	**96.7**	**10.8**	**325.0**	**3.2**	**0.3**	**3.1**	**4.3**
STD DEV	-	-	**26.6**	**5.8**	**2.7**	**85.8**	**0.9**	**0.2**	**3.1**	**0.4**
2	177	30	64	116.6	4.1	124.5	1.2	0.0	0.0	4.6
2	176	30	120	102.1	8.1	242.7	2.4	0.4	3.0	4.7
2	187	30	90	114.1	4.7	139.7	1.4	0.0	0.0	4.6
2	190	30	90	109.6	5.7	171.8	1.7	0.0	3.0	4.6
2	184	30	50	109.2	5.8	175.0	1.8	0.0	3.0	4.9
2	185	30	40	125.7	2.7	81.9	0.8	0.0	0.0	4.7
2	183	32	38	116.1	4.2	135.9	1.4	0.0	0.0	4.9
AVG	-	-	**70.3**	**113.3**	**5.1**	**153.1**	**1.5**	**0.1**	**1.3**	**4.7**
STD DEV	-	-	**28.4**	**6.9**	**1.6**	**46.7**	**0.5**	**0.1**	**1.5**	**0.1**
3	177	20	120	120.6	3.5	69.0	0.7	0.0	0.0	4.8
3	176	20	130	118.7	3.8	75.3	0.8	0.0	0.0	4.8
3	187	20	160	115.8	4.3	86.1	0.9	0.0	0.0	4.1
3	190	20	130	106.6	6.6	131.5	1.3	0.0	0.0	4.8
3	184	20	110	102.4	8.0	159.6	1.6	0.0	3.0	4.6
3	185	20	120	121.5	3.3	66.2	0.7	0.0	3.0	4.4
3	183	20	76	116.0	4.3	85.3	0.9	0.0	0.0	4.5
AVG	-	-	**120.9**	**114.5**	**4.8**	**96.2**	**1.0**	**0.0**	**0.9**	**4.6**
STD DEV	-	-	**23.4**	**6.7**	**1.6**	**32.9**	**0.3**	**0.0**	**1.4**	**0.2**

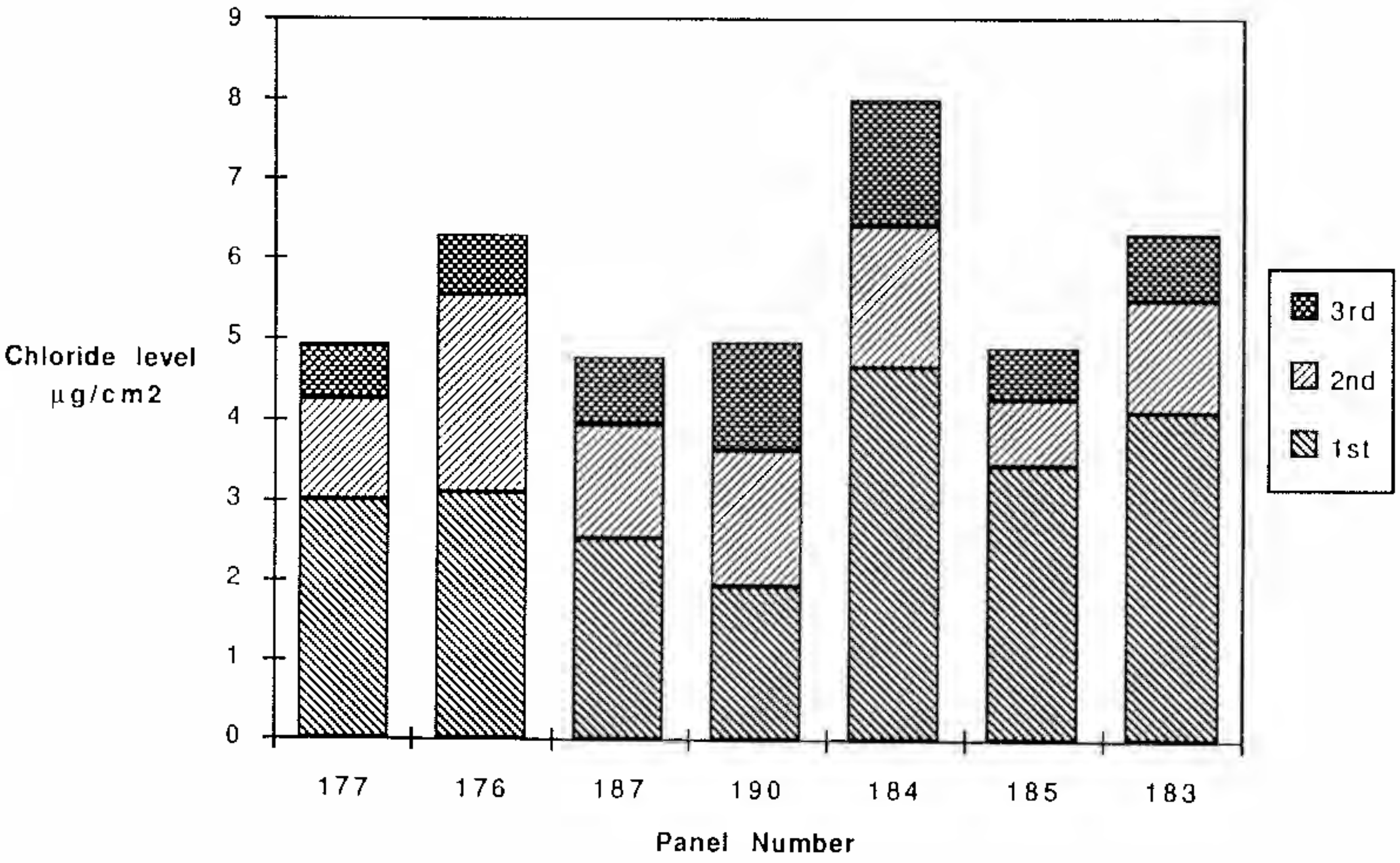


Figure 4. Chloride levels from three successive extractions.

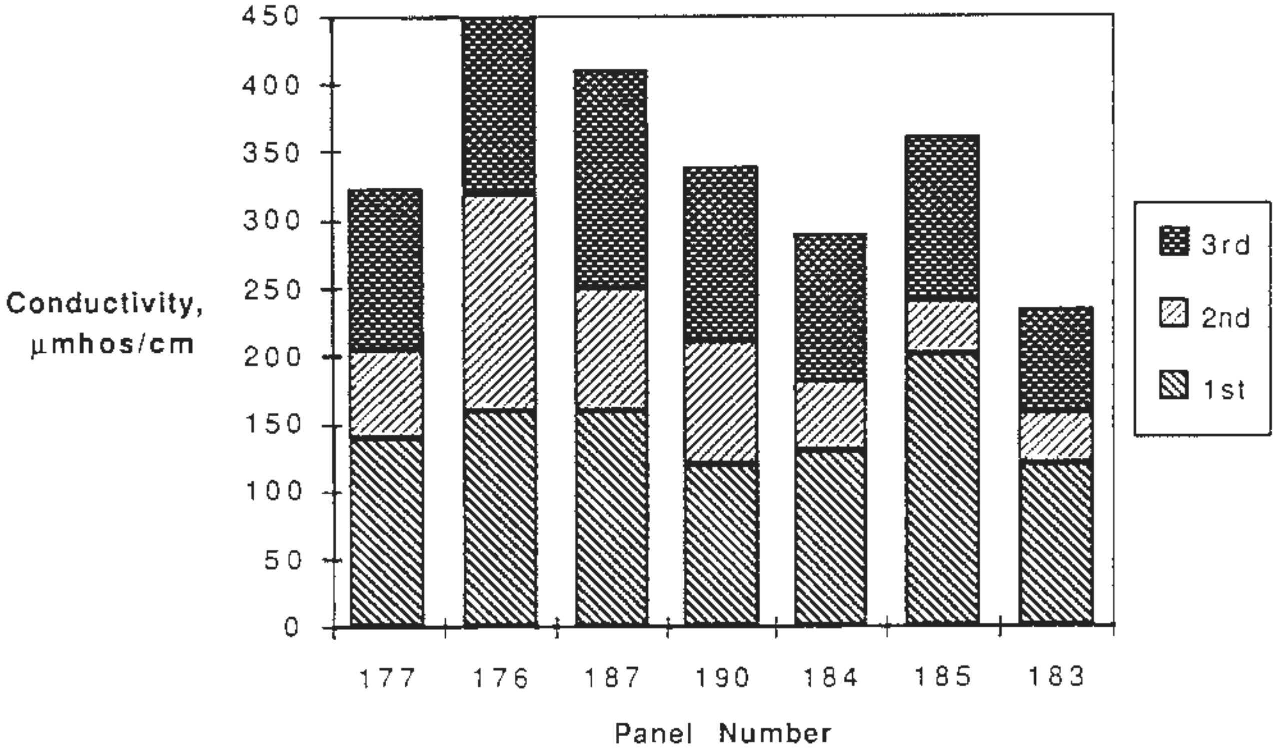


Figure 5. Conductivity readings from three successive extractions.

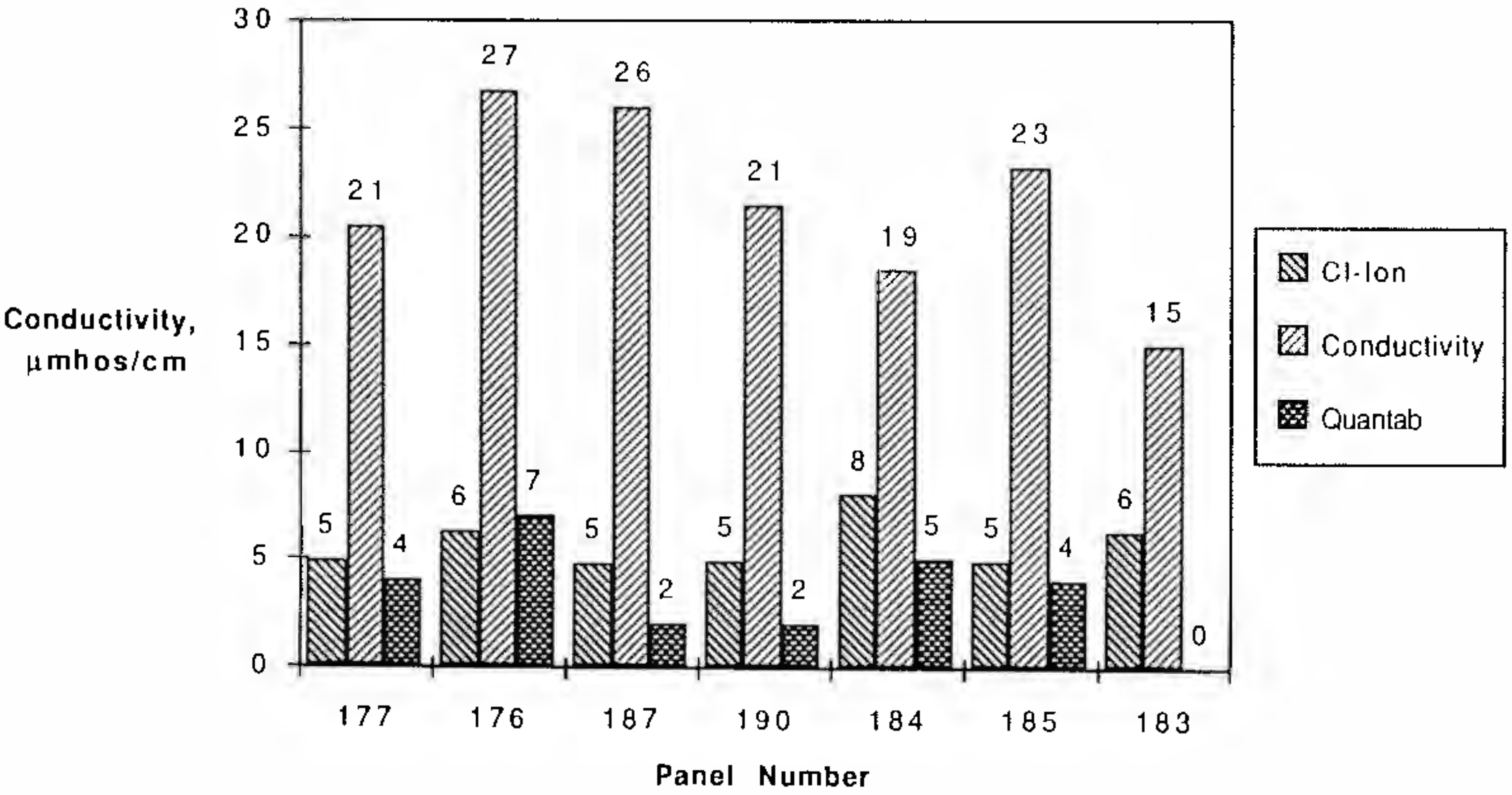


Figure 6. Comparison of chloride levels derived from three methods of analysis.

Table 14. Swabbing efficiency and soluble salt levels from various cleaning methods.

Set	Cleaning Method	Abrasive Size	Panel Number	SWAB 1 % EXTRACT	SWAB 2 % EXTRACT	SWAB 1+2 % EXTRACT	Total of Swabbing & Boiling	S.D. of Total
1	Dry	Medium	219	19.0	10.5	29.5	105.0	
			301	20.7	8.1	28.8	111.0	
			300				111.0	
			AVG	19.9	9.3	29.2	109.0	3.5
4	Dry	Fine	274	23.4	10.8	34.2	111.0	
			306	21.4	10.7	32.1	84.0	
			290	19.1	8.5	27.7	94.0	
			242				101.0	
			AVG	21.3	10.0	31.3	97.5	11.4
2	Dry plus Water Wash	Medium	245	15.1	8.2	23.3	73.0	
			296	15.9	11.1	27.0	63.0	
			291	23.8	11.1	34.9	63.0	
			281				73.0	
			AVG	18.3	10.1	28.4	68.0	5.8
6	Dry plus Water Wash	Fine	287	17.8	5.0	22.8	101.0	
			222	11.4	5.7	17.0	88.0	
			205	11.2	5.6	16.8	107.0	
			239				88.0	
			AVG	13.5	5.4	18.9	96.0	9.6
3	Air Wet	Medium	277	12.5	6.3	18.8	48.0	
			248	8.3	6.3	14.6	48.0	
			285	13.6	4.5	18.2	44.0	
			236				48.0	
			AVG	11.5	5.7	17.2	47.0	2.0
5	Air Wet	Fine	240	10.7	5.4	16.1	56.0	
			258	10.3	5.2	15.5	58.0	
			223	8.9	5.4	14.3	56.0	
			189				48.0	
			AVG	10.0	5.3	15.3	54.5	4.4
8	Water Jet	Medium	277	16.7	10.4	27.1	48.0	
			246	8.1	5.4	13.5	37.0	
			299	10.3	3.4	13.8	58.0	
			295				35.0	
			AVG	11.7	6.4	18.1	44.5	10.7
9	Water Jet	Fine	200	19.6	11.8	31.4	51.0	
			234	23.7	10.5	34.2	38.0	
			298	18.8	8.3	27.1	48.0	
			262				48.0	
			AVG	20.7	10.2	30.9	46.3	5.7
7	Water Jet	None	252	20.0	18.4	38.4	190.0	
			284	18.5	14.9	33.3	168.0	
			263	21.7	12.6	34.3	175.0	
			279				162.0	
			AVG	20.1	15.3	35.3	173.8	12.1
11	Roto-Peen plus Water Wash	None	265	25.7	10.5	36.2	105.0	
			282	13.6	6.1	19.7	132.0	
			206	18.8	9.4	28.2	117.0	
			217				183.0	
			AVG	19.4	8.6	28.0	134.3	34.3

Table 14. Swabbing efficiency and soluble salt levels from various cleaning methods (continued).

Set	Cleaning Method	Abrasive Size	Panel Number	SWAB 1 % EXTRACT	SWAB 2 % EXTRACT	SWAB 1+2 % EXTRACT	Total of Swabbing & Boiling	S.D. of Total
14	No	None	227	19.6	11.8	31.4	51.0	
	Treatment		229	31.6	15.8	47.4	38.0	
			230	36.4	15.9	52.3	44.0	
			289				56.0	
			AVG	29.2	14.5	43.7	47.3	7.9
10	Steam	None	204	50.0	18.8	68.8	16.0	
	Cleaned		272	40.6	15.6	56.3	32.0	
			196	30.8	11.5	42.3	26.0	
			226				18.0	
			AVG	40.5	15.3	55.8	23.0	7.4
12	Flame	None	233	39.6	6.3	45.8	48.0	
	Cleaned		199	30.2	12.7	42.9	63.0	
			221	27.6	6.9	34.5	58.0	
			203				51.0	
			AVG	32.4	8.6	41.1	55.0	6.8
13	Pentek-603	None	257	21.6	23.5	45.1	51.0	
	plus		23	38.6	18.2	56.8	44.0	
	Water Wash		237	54.5	13.6	68.2	44.0	
			251				56.0	
			AVG	38.3	18.4	56.7	48.8	5.9
11	Roto-Peen	None	265	25.7	10.5	36.2	105.0	
	plus		282	13.6	6.1	19.7	132.0	
	Water Wash		206	18.8	9.4	28.2	117.0	
			217				183.0	
7A			AVG	19.4	8.6	28.0	134.3	34.3
	35,000 psi	None	523				107.0	
	Water Wash		533				59.0	
	ADMAC		539				67.0	
13A			AVG				77.7	25.7
	Pentek-603	None	776	23.5	18.0	41.5	183.0	
	plus		781	50.3	14.2	64.5	183.0	
	pretreatment		774	32.9	8.4	41.3	155.0	
13B			AVG	35.6	13.5	49.1	173.7	16.2
	Pentek-603	None	776	66.7	72.7	139.4	33.0	
	double		781	70.4	25.9	96.3	27.0	
	application		774	56.8	21.6	78.4	37.0	
			AVG	64.6	40.1	104.7	32.3	5.0

salts that are not chemically complexed to or embedded in the steel. It is of interest to examine the percentage of the soluble salts extracted after 1 and 2 swabs. These are shown in table 14. Swab #1 is the sum of the first swab on the front and the first swab on the back, divided by the total amount of soluble salts extracted from the test panel (front and back). A similar analysis is done for swab #2 and for the sum of swabs #1 and #2.

The percentage of soluble salts extracted by swabbing varies among the different preparation methods as illustrated in figure 7. For a single swabbing, the percentage recovery ranges from 10 to 40 percent; the average is about 22 percent, with a standard deviation of about 9. For double swabbing, the average is about 31 percent, with a standard deviation of 12 percent. The differences within a different surface preparation method (for which three or four specimens were analyzed) are much smaller than the differences among the surface preparation methods. This indicates that the method itself affects the efficiency of the swabbing procedure.

In figure 7, the highest efficiency extractions were for nonconventional cleaning methods such as steam cleaning, flame cleaning, and use of chemical treatment. If these treatments are excluded, one computes the following quantities:

Average for first swabbing:	16.6 percent (4.2 percent standard deviation)
Average for second swabbing:	8.6 percent (2.9 percent standard deviation)
Sum of first two swabbings:	25.3 percent (6.8 standard deviation)

Thus, the 95 percent confidence interval for double swabbing is approximately 12 to 39 percent.

C. Analysis of Bridge Specimens

Extractions and analyses were also performed for specimens cut from corroded A-588 bridge steel. The sources included structures from New Jersey, Michigan, Illinois, Wisconsin, and West Virginia, along with test panels exposed to the salt fog cabinet. Cleaning methods investigated were dry blasting to SSPC-SP 6 (commercial) using sand and staurolite, sand blasting with water to conditions SSPC-SP 6 and SSPC-SP-7 (brush-off blast) and "overblast" (extensive blasting beyond SSPC-SP 5 [white metal]). For each set, four specimens were extracted, three by the double swabbing followed by boiling, and one by boiling only (an exception is set #15, which included only two specimens). For the three swab specimens, there are four quantities shown, the conductivity of the extract for swabs #1 and #2 on the front side of the specimen and swabs #1 and #2 on the back side of the specimen. The extracts from the swabbing were also added to the solution in which the boiling was performed. The conductivity of this solution was measured and converted to oz/ft^2 (µg/cm^2) of chloride on the steel surface, and recorded in table 15. This table also shows the percentage of the total extract obtained from the front and back (each the sum of 2 swabbings). For the field-exposed specimens, the "front" is usually designated as the side with greatest exposure to the environment, and thus the percentage extractions are higher for the front than the back side. In the salt fog test, however, the backs frequently had comparable quantities of chloride to the fronts. Also as expected, typically the first swabbing extracted a considerably higher amount of soluble salts than the second swabbing. This is consistent with data discussed previously.

The five methods used did not show an appreciable difference in the level of chloride left on the surface. For the New Jersey Turnpike bridge specimens, the average chloride levels range from2 x 10^{-4}oz/ft^2 (7 µg/cm^2) for overblast to 4.6 x 10^{-4} oz/ft^2 (14 µg/cm^2) for SSPC-SP 6 with medium silica sand. For the salt fog cabinet, the range is from 7.2 to 11 x 10^{-4} oz/ft^2 (22 to 33 µg/cm^2) with the most efficient technique being that of overblast (as per NJ Turnpike) and least efficient being

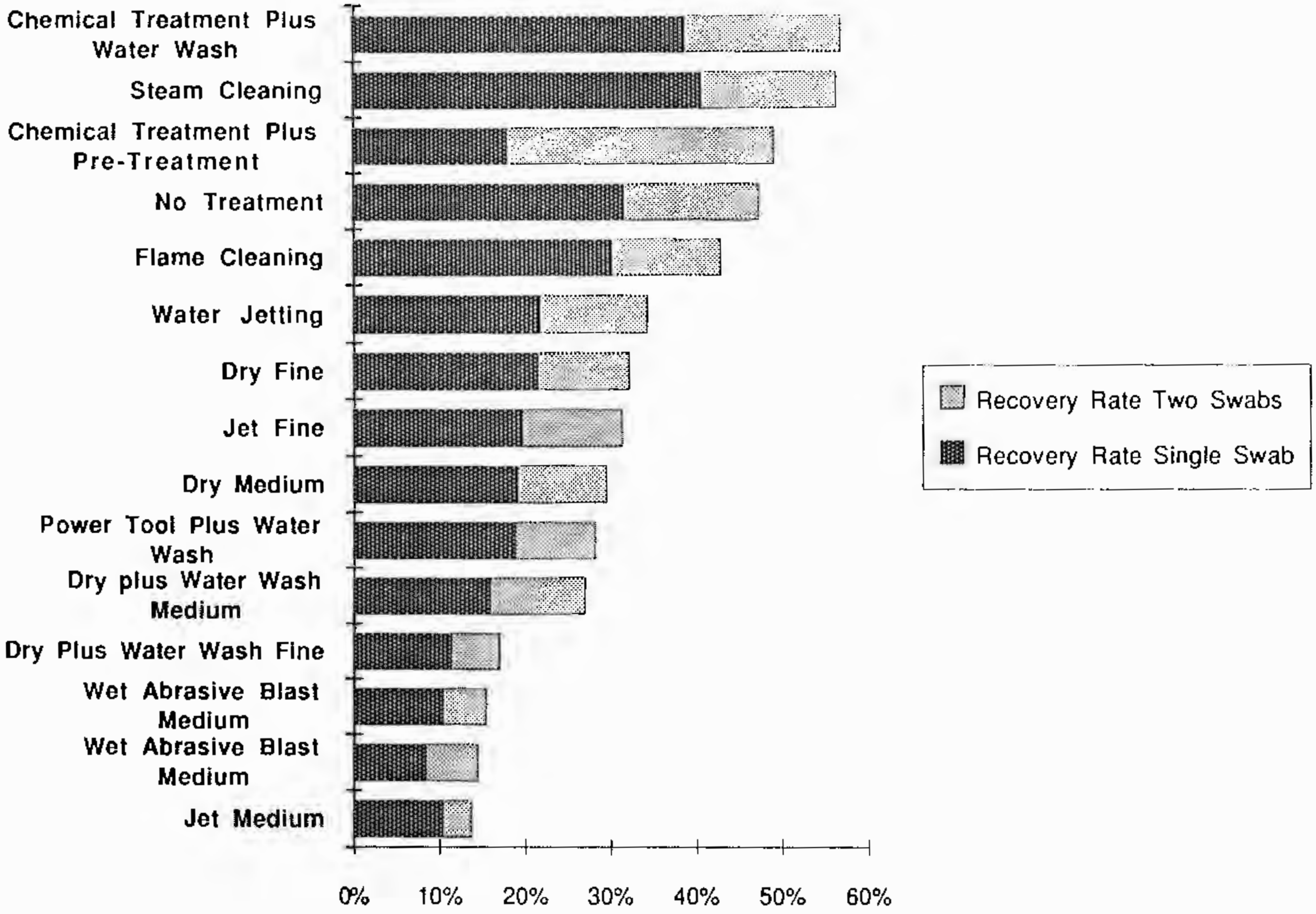


Figure 7. Percentage of soluble salts extracted from single and double swabbing.

Table 15. Conductivity and chloride level of bridge specimens by swabbing and boiling methods.

		Conductivity results				TOTAL	PERCENT	PERCENT	DESCRIPTION
		Front	Front	Back	Back	CHLORIDE			
Set #	Panel ID	1	2	1	2	µg/cm2	FRONT	BACK	
15	590-A.1.B	46	22	36	28	10	34	31	NJ DOT A-441 STEEL
	590-A.1.A	42	37	32	24	13	30	25	STAUROLITE ABRASIVE
	AVG	44	30	34	26	12	32	28	
16	569-A.1.A	96	89	120	42	35	27	24	
	569-A.1.B	90	40	74	30	35	19	15	MI DOT A-588 STEEL
	569-A.1.C	95	39	55	27	35	19	12	STAUROLITE
	569-A.1.D					35			
	AVG	94	56	83	33	35	22	17	
17	590-A.2.A	47	31	24	18	11	36	19	NJ DOT A-441 STEEL
	590-A.2.B	37	26	14	15	9	32	15	SP-6 WITH WATER,
	590-A.2.C	26	15	21	11	10	20	15	MEDIUM SILICA SAND
	590-A.2.D								
	AVG	37	24	20	15	8	29	16	
18	590-A.3.A	30	15	21	14	13	16	13	NJ DOT A-441 STEEL
	590-A.3.B	32	13	19	9	15	15	9	SP-7 WITH WATER,
	590-A.3.C	24	14	15	8	9	20	12	MEDIUM SILICA SAND
	590-A.3.D					11			
	AVG	29	14	18	10	12	17	11	
19	613-1	250	110	100	30	19	102	34	IL DOT A-588 STEEL
	613-2	280	92	100	62	17	117	50	SP-6
	613-3	110	64	200	80	26	35	56	MEDIUM SILICA SAND
	613-4					18			
	AVG	213	89	133	57	20	85	47	
20	569-A.2.A	100	85	100	100	11	35	14	MI DOT A-588 STEEL
	569-A.2.B	40	33	42	17	16	22	18	SP-6
	569-A.2.C	27	26	17	9	18	14	7	MEDIUM SILICA SAND
	569-A.2.D					14			
	AVG	56	48	53	42	15	24	13	
21	604-1	40	22	26	23	12	24	19	WV DOT A-588 STEEL
	604-2	38	33	33	16	17	20	14	SP-6
	604-3	34	21	29	18	14	19	16	MEDIUM SILICA SAND
	604-4					17			
	AVG	37	25	29	19	15	21	16	
22	590-A.4.A	28	20	18	12	8	29	18	NJ DOT A-441 STEEL
	590-A.4.B	19	13	9	11	8	19	12	OVER-BLAST(SP-5 +)
	590-A.4.C	20	11	10	9	6	24	14	MEDIUM SILICA SAND
	590-A.4.D					7			
	AVG	22	15	12	11	7	24	15	
23	S.F.A.-1	100	25	98	24	32	19	19	SSPC SALT FOG(A-588)
	S.F.A.-2	200	55	91	31	34	39	18	OVER-BLAST(SP-5 +)
	S.F.A.-3	55	19	65	21	21	18	21	MEDIUM SILICA SAND
	S.F.A.-4								
	AVG	118	33	85	25	22	25	19	
24	S.F.B.-1	77	72	100	80	22	35	43	SSPC SALT FOG(A-588)
	S.F.B.-2	72	86	100	98	24	34	42	SP-6 WITH WATER,
	S.F.B.-3	84	98	100	87	25	38	39	MEDIUM SILICA SAND
	S.F.B.-4					15			
	AVG	78	85	100	88	22	36	41	

Table 15. Conductivity and chloride level of bridge specimens by swabbing and boiling methods (continued).

		Conductivity results				TOTAL	PERCENT	PERCENT	DESCRIPTION
Set #	Panel ID	Front	Front	Back	Back	CHLORIDE	FRONT	BACK	
25	S.F.C.-1	200	84	200	130	36	41	48	SSPC SALT FOG(A-588)
	S.F.C.-2	130	84	130	100	26	43	48	SP-7 WITH WATER,
	S.F.C.-3	130	105	150	97	35	35	22	MEDIUM SILICA SAND
	S.F.C.-4					22			
	AVG	153	91	160	109	30	40	39	
26	590-M.1	55	19	19	12	11	35	14	NJ COVER PLATE(A-588)
	590-M.2	22	12	22	16	11	15	17	SSPC-SP 6
	590-M.3	20	25	28	10	8	26	22	MEDIUM SILICA SAND
	590-M.4					11			
	AVG	32	19	23	13	10	25	18	
27	S.F.D.-1	340	160	190	100	37	71	41	SSPC SALT FOG(A-588)
	S.F.D.-2	90	38	65	29	30	21	16	SP-6
	S.F.D.-3	220	60	200	56	25	60	54	STAUROLITE
	S.F.D.-4					33			
	AVG	217	86	152	62	31	51	37	
28	S.F.E.-1	180	64	120	60	20	65	48	SSPC SALT FOG(A-588)
	S.F.E.-2	80	30	50	19	29	62	41	SP-6
	S.F.E.-3	64	28	36	25	22	21	14	MEDIUM SILICA SAND
	S.F.E.-4					26			
	AVG	108	41	69	35	24	49	34	
29	590-A.5.A	36	32	70	47	13	26	46	NJ DOT A-441 STEEL
	590-A.5.B	40	24	13	10	13	23	8	SSPC-SP 6
	590-A.5.C	68	39	66	40	19	28	28	MEDIUM SILICA SAND
	590-A.5.D					11			
	AVG	48	32	50	32	14	26	27	
30	606-1	170	95	80	36	60	24	10	WI DOT A-588 STEEL
	606-2	140	80	550	250	60	19	71	SSPC-SP 6
	606-3	100	72	100	68	55	16	15	MEDIUM SILICA SAND
	606-4					51			
	AVG	137	82	243	118	57	20	32	
31	M-1	240	47	98	64	37	41	22	MELLON INST SAMPLES
	M-2	100	49	82	52	44	17	16	SSPC-SP 6
	M-3	140	37	80	55	48	4	15	MEDIUM SILICA SAND
	M-4					51			
	AVG	160	44	87	57	45	21	18	
32	569-A.3.A	100	100	94	83	26	38	35	MI DOT A-588
	569-A.3.B	46	42	68	22	20	22	23	STEEL WET BEFORE BLAST
	569-A.3.C	33	42	77	78	24	15	34	SP-6, MEDIUM SILICA
	569-A.3.D					14			
	AVG	60	61	80	61	21	25	31	
	TOTAL AVG						31.7	25.6	

SSPC-SP 6 using staurolite abrasive. The data from the Michigan DOT specimens also suggest that staurolite is less effective in removing chlorides than silica sand. A comparison of the chloride levels using a similar method (SSPC-SP 6 with silica sand) for the different bridge steels shows that the Wisconsin bridge had by far the greatest amount of chloride, yielding a value of 1.9 x 10 $^{-3}$oz/ft^2 (57 μg/cm^2). The Michigan, West Virginia and Illinois DOT specimens gave results of 4.9 x 10^{-4}, 5.5. x 10^{-4}, and 6.10 x 10^{-4} oz/ft^2 (15, 17, and 20 μg/cm$^{2)}$ respectively, whereas the New Jersey cover plate had a value of 3.6 x 10^{-4} oz/ft^2 (11 μg/cm^2). It should be noted that these chloride levels were not determined directly, but were computed from the conductivity readings and the conversion scale derived earlier. Other data presented in this report have shown that the chloride often accounts for less than half of the total soluble salts. Thus, the actual levels of chlorides on these bridges may be substantially less than those noted here.

Another set of swabbing and boiling results are presented in table 16. Specimens included test panels that had been exposed in a cyclic salt spray cabinet for 10 and 100 cycles, along with several specimens from New Jersey and Ontario bridges. Cleaning methods included wet blast, dry blast, power and hand tool cleaning. The data give further evidence that wet abrasive blasting is superior to dry blasting in removing the soluble salts from corroded steel. It is also seen that rotary cleaning power tools, although considerably better than hand cleaning, are much worse than dry blasting. The data also show that exposing specimens for 100 cycles results in substantially higher levels of residual chloride than does an exposure for 10 cycles.

D. Additional Chloride and Conductivity Analyses

Table 17 presents data from additional specimens for which both chloride and conductivity were measured. The chloride was determined using an ion-specific electrode, which gives readings in millivolts which can be converted to ppm. The equivalent conductivity resulting from the chloride concentrations was also computed. This quantity can be compared with the conductivity as measured from a conductivity meter to show the portion of the conductivity resulting from chloride. The specimens listed in table 17 include laboratory panels which were exposed to continuous and cyclic salt fog and extracted using swab techniques and a technique in which the surface was simply rinsed into a beaker.

The table also shows the data on analysis of rust scale which was scraped from several Louisiana and Michigan bridges. Scrapings were pulverized and added to deionized water and conductivity and chloride readings taken after 1, 24, and 96 hours. The data showed that there is a considerable variation in the percentage of the conductivity arising from chloride. The specimens exposed in salt spray showed higher percentages (50 to 98 percent) than those shown in table 13. The salt fog exposures shown in table 17 were of shorter duration than those in table 13 (approximately 3 weeks). The data from the bridge scrapings indicate that, at very high chloride levels, the relationship between chloride and conductivity becomes further skewed. The last column in table 7 shows the weight percent of chloride in the rust samples, which range from 0.08 percent at the Luling Bridge to 12 percent at one of the Michigan bridges.

Table 18 presents results of analyses of the conductivity of test specimens used for the field evaluation phase of this project. The specimens included test beams that had been included in a Maryland DOT/Maryland University research program. The bridge beams had been assembled in a bridge-like configuration in an area near Washington, DC and sprayed several times a week during the winter season to simulate the application of deicing salt. In addition, several T-beams from Louisiana were also selected for this evaluation. The origin and condition of these beams is further discussed in appendix B. The figure at the bottom of table 18 shows the locations where the swabbing took place. At each location, two swabs were performed. Prior to swabbing, the

Table 16. Soluble salts on additional surfaces and preparations.

			CONDUCTIVITY (SWABBING)				Cl(BOIL)	
Set No.	Panel No.	Original Condition/ Surface Preparation	Front 1	Front 2	Back 1	Back 2	Total µg/cm2	1st SWAB %
33	536	100 Cycles Salt Fog/	128	128	147	101	48	29
	537	Wet Blast, Clemco	128	128	167	101	55	27
	AVG		128	128	157	101	52	28
34	103	100 Cycles Salt Fog/	446	209	283	136	88	42
		Dry Blast, Clemco						
35	740	100 Cycles Salt Fog/	620	380	698	248	168	39
		Roto-Peen, MI						
36	105	100 Cycles Salt Fog/	1356	550	1163	736	409	31
	106	Hand Cleaned, MI	1318	620	1356	651	380	35
	AVG		1337	585	1260	694	395	33
37	865	10 Cycles Salt Fog/	134	64	419	101	55	50
		Roto-Peen, MI						
38	915	10 Cycles Salt Fog/	533	248	426	98	99	48
		Hand Cleaned, MI						
39	102	Mill Scale/	25	19	21	21	4.4	53
		Dry Blast, Clemco						
40	100	Mill Scale/	67	39	50	48	8.0	73
	101	Wet Blast, Clemco	ND	ND	ND	ND	5.9	ND
	AVG						7.0	
41	111	New Jersey Bridge/	59	42	59	29	9.4	63
	112	Wet Blast, Clemco	73	53	54	39	10	62
	AVG		66	48	56	34	10	62
42	113	New Jersey Bridge/	29	23	33	19	13	24
	114	Dry Blast, Clemco	26	16	0	16	12	23
	AVG		28	20	17	18	12	23
43	20	New Jersey Bridge/	147	54	50	25	73	14
	21	Roto-Peen, MI	209	39	41	25	63	20
	AVG		178	47	46	25	68	16
44	117	Ontario Bridge	3	ND	ND	ND	ND	3
	118	3"X12" Angles/	3	ND	ND	ND	ND	3
	AVG	Wet Blast, Clemco	3					3
45	115	Ontario Bridge	3	ND	ND	ND	ND	3
	116	3"X12" Angles/	2	ND	ND	ND	ND	2
	AVG	Dry Blast, Clemco	2					2
46	119	Ontario Bridge	17	ND	ND	ND	ND	17
	120	3"X12" Angles/	10	ND	ND	ND	ND	10
	AVG	Roto-Peen, MI	14					14

Table 17. Additional comparisons of chloride & conductivity.

0

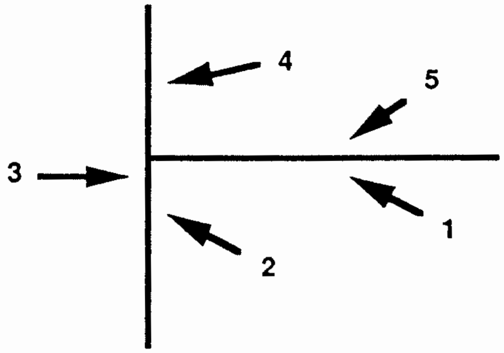
NO	EXPOSURE	SAMPLE	CL-	CL	EQUIV		MEASURED	% COND
		ACQUISITION	Millivolts	PPM	CONDUCTIVITY		CONDUCTIVITY	FROM
		METHOD			U-MHO/CM		U-MHO/CM	CL
A-1	CYCLED SS	SWAB	54	74	294		300	98%
B-1	CONTINUOUS SS	SWAB	69.2	36.8	149		220	68%
C-1	CONTINUOUS SS	RINSE	74.3	29.1	119		130	91%
D-1	CONTINUOUS SS	RINSE	67.6	39.6	160		180	89%
E-1	CYCLED SS	SWAB	57.4	63.9	255		320	80%
X-1	CYCLED SS	RINSE	60.9	54	216		230	94%
F-1	CYCLED SS	SWAB	90.5	13.8	59		110	54%
TP-1	DULUTH BR(LA)	SCRAPING: 1 HR	46	100	396		91	435%
TP-1	DULUTH BR(LA)	SCRAPING:24 HR	77		5		230	2%
TP-1	DULUTH BR(LA)	SCRAPING:96 HR	40		5		820	1%
TP-2	LULING BR(LA)	SCRAPING: 1 HR	41	105	416		91	457%
TP-2	LULING BR(LA)	SCRAPING:24 HR	91.7		5		200	3%
TP-2	LULING BR(LA)	SCRAPING:96 HR	73.1		5		400	1%
TP-3	LULING(PIER3)	SCRAPING: 1 HR	55	80	318		350	91%
TP-3	LULING(PIER3)	SCRAPING:24 HR	61.9		5		540	1%
TP-3	LULING(PIER3)	SCRAPING:96 HR	73.4	27	111		1200	9%
TP-4	MI BRIDGE #4	SCRAPING: 1 HR	-52.9	3000	11740		1800	652%
TP-4	MI BRIDGE #4	SCRAPING:24 HR	-1.9		5		4000	0%
TP-4	MI BRIDGE #6	SCRAPING:96 HR	-24.9		5		7500	0%
TP-5	MI BRIDGE #4	SCRAPING: 1 HR	-27.3	2000	7829		1500	522%
TP-5	MI BRIDGE #4	SCRAPING:24 HR	-19.5		5		2200	0%
TP-5	MI BRIDGE #4	SCRAPING:96 HR	-13.3	2000	7829		4700	167%

Table 18. Soluble salts on bridge steel components.

Conductivity (µmhos/cm)

Set Description	Panel IDs	1A	1B	2A	2B	3A	3B	4A	4B	5A	5B	Mean of Conductivity
Set No1 MD Top Salted Wet Blast	TEL	66	78	142	135	86	50	75	68	61	67	82.8
	TEM	27	32	51	36	34	29	48	80	92	52	48.1
Set No 2 MD Top Salted Dry Blast	TEJ	52	34	58	58	36	36	28	15	34	28	37.9
	TEK	66	50	89	80	86	96	53	58	110	86	77.4
Set No 3 LA Beam Wet Blast	TGC	91	39	60	51	44	40	52	36	53	44	51
	TGD	50	27	40	28	25	22	34	30	32	27	31.5
Set No 4 LA Beam Dry Blast	TGA	42	25	48	54	43	24	48	35	29	26	37.4
	TFZ	28	18	62	48	18	20	31	38	20	18	30.1
Set No 5 MD Salt Beam Dry Blast	TFB	25	20	31	35	27	17	32	30	30	16	26.3
	TFA	36	28	40	80	36	21	34	35	23	20	35.3
Set No 6 MD Salt Beam Wet Blast	TFC	43	14	45	32	27	27	47	32	22	16	30.5
	TFD	52	18	52	42	30	17	42	32	28	22	33.5
Mean of Conductivity		48	32	60	57	41	33	44	41	45	35	

Key to Piece Sections
Indication of T-sides.



specimens were cleaned by wet or dry blasting. The results showed a wide variation in the amount of soluble salts remaining on the steel after blast cleaning. There was generally substantial variation among the two beams of each type selected and among the locations on the beam. There was little systematic difference between the wet and dry blasted specimens.

APPENDIX B
BRIDGE INSPECTIONS, SPECIMENS, AND CASE HISTORIES

PART 1 -- FIELD INSPECTIONS OF BRIDGES

The following inspection reports are included, as described in table 2.

1. Detroit, MI - 11/84
2. New Orleans, LA - 11/84
3. West Virginia - 12/8/84
4. New Jersey Turnpike - 2/85
5. North Carolina - 3/85
6. NL Test Fence, NJ - 5/85
7. Ontario, Canada - 8/85
8. Garden State Parkway, NJ - 10/85
9. New Jersey Turnpike - 10/85
10. University of Maryland, College Park, MD - 10/85

1. Inspection of Weathering Steel Bridges in Detroit (November 6, 1984)

Bridge No. 1

I-279 over Northline Road, bridge built in 1975. This bridge is in a semi-rural environment, suburb of Detroit, Michigan. It has measured corrosion rates on the lower web right above the bottom flange of 5 to 7 mils (125 to 175 microns) per year. This bridge shows typical corrosion. Not too bad on the outer plates, but some of the inner plates have extensive laminar corrosion, particularly on the bottom flange. The standard procedure now is to remove and replace hanger plates. Although fascia looks good now, in 8 or 10 years it will attain a crescent appearance, indicating presence of salt.

Bridge No. 2 -- No comments

Bridge No. 3 -- Observed flaking off of sections on the bottom flange.

Bridge No. 4 -- Bridge on I-94. Noticed orange and black pattern. Also some white scale, which may be chloride. Samples taken from top of bottom flange. Chips of rust.

Bridge No. 5 -- Shaefer Road Bridge over I-94 approximately 4 years old. For this bridge, leaky joints are not a problem. However, there were extensive amounts of rust flaking and scaling, particularly for a four-year-old bridge. There was also millscale coming off from the bottom flange.

Bridge No. 6 -- I-75 over Ford Street, second oldest weathering steel in the U.S. The problem in this bridge is primarily due to leaky joints rather than salt being sprayed up by cars. Michigan will paint entire bridge even though signs of damage only appear on the approximately 30 ft (9 m) on either side of the expansion joint shows signs of damage, because they do not know how far the damage might extend over longer periods of time. They believe this is more cost-effective than to water-jet the surface every year. Michigan lab studies have shown that corrosion of A-588 in an intermittent chloride immersion is greater than that of A-36. This severe corrosion extends about

4 in (10 cm) above the bottom flange. According to Tinklenberg, capillary action causes the salts to migrate up the beams to this level.

Bridge No. 7 -- Overpass, West Grand Blvd. over Route 96. Bridge is from 1972. Entire bridge shows the discoloration and loss of steel, primarily due to salt spray. There is no real problem of leaking joints on this bridge. Bottom flange and edges of bottom flange showed flaking and discoloration due to loss of scale.

Bridge No. 8 -- Similar type of pattern, except that the flaking laminar scale was worse at the center of the roadway than at the edges of the beams because of the effect of salt spray. Inorganic zinc was applied over the joints of this bridge after a near-white blast. It was not successful. Severe pitting results in inorganic zinc not properly sealing the surface, allowing water to get in and corroding again at the pits.

Bridge No. 9 -- This is the infamous Mile 8 Bridge, from which the test racks were hung by Bethlehem, and which originated the concept of the tunnel effect. This is also the first bridge that was painted with the organic zinc epoxy and urethane topcoat system. Thickness was about 15 mils (5, 5, 4) (or 375 microns, 125, 125, and 100 per coat) in a few spots, compared with specified thicknesses of 3, 3, and 1-1/2 mils (or 75, 75, and 37 microns). This is the service road for 8 Mile Run.

Bridge No. 10 -- This is the actual bridge for 8 Mile Run, built in 1964, the first weathering steel bridge in the U.S. The main problem here is leaking joints, however there is also a problem due to cracks in the deck which allowed salt to come down and cause accelerated corrosion in some of the flanges. They also tried to have a water stop - a piece of metal to prevent the water from running all the way down the flange. This was unsuccessful. On this bridge they also tried painting the joints from 5 ft (1.7 m) in either end with an inorganic zinc. However, there was a problem of poor inspection, poor contractor work, and the inorganic zinc failed.

Bridge No. 11 -- Grand Rapids, MI -- Ann Street Bridge over Grand River. Most of the beams were in good shape. For a few, there were some leaky joints in the deck, causing the water to run along the bottom of the flange and produce the pattern of white tinged rust which in other bridges has resulted in excessive scaling. This pattern extended only up about 2 in (5 cm) on this bridge, compared to 6 or more in (15 cm or more) on some other bridges. Gary Tinklenberg concluded that there was much less salt that had leaked here than for other bridges. Webs did exhibit streaking pattern of corrosion that had been noticed in other bridges. Three photographs taken. Also, some of the galvanized steel showed some evidence of corrosion due to salt. Patina has numerous red specks in it on much of the web surface. According to Gary, AISI states that this is what is supposed to form and represents the natural roughness of the steel. Under the 30 power microscope, there is evidence of substantial surface roughness. The color is a combination of silver, reddish brown, and darkish brown, with the highest proportion being silver (probably millscale). The top of the bottom flange where salt leaking had occurred was considerably more pitted than the flat of the web. Top of the bottom flange on salted areas was considerably rougher. The bridge was built in 1971 over the Grand River, and does not have any salt spray associated with vehicle traffic under the bridge; however, there are leaky joints on the deck. The beams accessible from shore showed that about one-half to two-thirds of them had some chloride contamination due to leaky joints. An inspection was made from a boat under the bridge. There was additional evidence of leaking joints. The second beam in from the end on either side showed severe corrosion on the bottom of the bottom flange. These leaks were attributed to small cracks in the deck. It would be very difficult to avoid these types of cracks. There is no way of knowing where they might occur.

Discussion on painting of bridges. Met with the city engineer. We discussed the possibility of painting only the contaminated areas. However, this would require sandblasting these areas and rigging the entire bridge. This would probably cost 50 percent of the cost of total sandblasting and repainting. We discussed the possibility of deferring painting for 5 to 8 years. This would have the advantage of allowing Michigan and SSPC to develop data on the best cleaning and painting systems. However, it would be necessary to make a determination that the fatigue problem would not be too severe. Gary Tinklenberg suggested they remove two of the hanger plates to inspect for corrosion on the web behind. This is where he has experienced a significant amount of pitting corrosion. On some bridges the pits are as deep as 1/2 in (13 mm). This could be a weak point in the bridge's structure if not corrected. However, removing the hanger plates apparently involves a good deal of work. Gary recommended that they replace the brass washers, which also result in bi-metallic corrosion.

2. Inspection of Bridges in Louisiana

Bridge 1 -- Duluth Canal Bridge, Empire, LA - Bottom flange of the outer beam has remained wet.

Fascia beam and steel along curb on top of bridge appear to have very good patina. Sliding hand across removes a little debris; a small amount could be scraped off with a knife.

First Pier -- Scale is heavier on inside than on fascia beam. Little accumulation on the top flange. It scrapes off very easily with a knife. Samples were retained. Some areas were sandblasted but not painted. In one of these areas very small pits were observed under 30x microscope, which were hemispherical in shape. Estimated depth is 1/16 in (1.5 mm) or less. In some areas, the pits were even smaller. On some of these there was some evidence of corrosion, which may have occurred after the blast cleaning which was done about a year ago. Noted the streaking pattern observed on the interior flanges.

Second Pier -- Scale seems a little flakier than on first pier interior. The painted portions showed small points of rust. According to Kirt Clement, this is because they painted over sand. The scale on the outer portion is finer, the inner portion is more flaky with larger specks. On the bottom of one of the main floor beams we observed paint overspray pattern on which occurred numerous scale spots. It appeared that some of the scale spots might have formed after the paint was applied, which was about a year ago, indicating a fairly rapid degradation.

Third Pier -- The middle pier of the bridge was the most scaly of all. Scale came off as soon as the surface was touched. It was particularly bad in the most sheltered areas of the structure. Scale flakes were slightly larger in this portion of the bridge.

There was a darkening appearance where Louisiana DOTD had written identification marks on the steel. It appeared that these had developed some type of drainage pattern on the steel. The outer surface is a relatively tight patina. Scraping with a knife removes a small amount. On the inside, the scale can be scraped with a finger. In addition, in some of the most sheltered areas, there were large flakes coming off. A few samples were retained, some of which were on the order of 2 to 3 in (5 to 8 cm) in dimension. Unlike in Michigan, however, there were no large flakes coming from the bottom of the bottom flange. However, some of the flakes were on the order of 1/8 in (3 mm) in diameter.

Bridge 2 -- Luling Bridge

This bridge has two main towers.

First tower -- Inside tower there are large sheets of very thin rust flakes. However, there does not appear to be any subsequent reformation of flaking or corrosion. There is some evidence of water streaking down the sides, which could result in subsequent flaking. In addition, there is a buildup on the floor of some very fine scale.

On the exterior of the tower, I observed the streaking pattern, in some areas the streaks were white, normally they are brown or orange. On the bottom of the flanges above the water, the scaly pattern was again apparent. Scraping yielded Sample #3. Scaling was even worse in the more sheltered areas above the water. The scaly appearance was visible throughout the entire tower. Portions of floor on part of the tower came up in fairly thick flakes, of approximately 1/16 to 1/8 in (1.5 to 3 mm). However, in other areas of the floor it was very hard and could not even be scraped. Towers were littered with pigeon debris.

The bridge rail and deck are also A-588 steel, and are painted with Mobilzinc 7, an inorganic zinc-rich primer, with Valchem hi-build vinyl. Same for the median barrier. The steel deck was white metal blasted and primed with Mobilzinc 7 and topcoated with an epoxy hot mix at 2-1/2 in (7 cm).

Second Tower -- The blasted area on the interior of bridge was more flaky and darker than the one on the exterior. The wire brushed surface was considerably darker and had a rougher appearance under the microscope.

Side Pier #1 - This segment is constructed of Cor-Ten from U.S. Steel. The remainder of the structure is from a Japanese type of weathering steel. There is still some mill scale on some of the steel, but it also has the appearance of the streaks. Only a small amount of scale was removed by rubbing a hand over the surface. Kirt Clement pointed out that there is considerable industry along the river here, including refineries, etc. Overall the scaling here does not appear to be as bad as on the two main towers, which could be because we are located at the tower closest to the bank of the river (100 or 200 ft [30 to 60 m]). The river has very little salt content.

Inside Towers (#2) -- Kirt Clement pointed out that it would be a horrendous job to have to sand blast inside the towers because of the confined space and the limited access. He had a difficult job in blast cleaning the small areas required for the surface treatment tests. If it is necessary to repaint the towers, he would like to use some high pressure water jetting followed by a water-based coating or some other solventless system. It is also possible that the inside of the towers may not need painting because of the relatively small amount of condensation. Both Kirt and Al Dunn felt that the scaling problem on this bridge is becoming worse. It is clear that the type of patina described by the steel companies is not being properly formed. It remains to be conclusively established that the corrosion rate is such that structures cannot be left unpainted. In particular, it must be decided how much of the structure requires painting. For the two bridges observed, it appears that a very strong case can be made that the entire structure needs repainting, however it may be possible to defer painting for some time.

3. Inspection of New River Gorge Bridge in West Virginia

New River Gorge Bridge is Cor-Ten from U.S.Steel. Bridge was completed and opened to traffic in 1977.

First location -- Size of scale less than 1/16 in (1.5 mm). A small to moderate amount could be scraped off by hand in certain locations (Sample #1). It was more severe on underside of flanges. Appearance similar to that at Luling Bridge in Louisiana. Under 30X magnification, scale appeared mostly darkish brown or black, more so than at bridges at Louisiana and Michigan, which had more orange color in the scale.

Second location, main catwalk across bridge. Safety handrail -- bulging black scale which could be removed with a knife with difficulty. Also, flaking seemed to be a bit heavier than at other locations. The vertical handrails were more flaky than the top or bottom of the angles. In some cases it was moderate flaking, in others light to moderate.

Third location, near box beam and inside beams -- Inside box beams there was very little flaking. The appearance of the scale was dark grey and brown. Very little came off on the hands. The top of the box was extremely tight and a little bit sticky. Could not rub anything off. Bottom of the box was more moderate flaking, scaling. Side of box was very light flaking.

Fourth location, main support beams -- Noticed large orange spots on top surfaces of main beams and at gusset place on outer portions of bridge. Orange colored spots looked slightly pitted from up close. These were just adjacent to some darker areas. Scale was very tight and difficult to scrape off. Apparently very little corrosion has occurred at these locations. Looked at bottom of main cross beam above box beam. It was black in color. At 30X magnification, there was a laminar grayish brown film which appeared to be tightly adhering and relatively uniform. Removed some scraping, which is sample #4. These may correspond to where water puddles.

4. Inspection of New Jersey Turnpike Bridge

Bridge located over New Jersey Turnpike near Exit 74. Date on galvanized cover of 4/4/73. Very hard salt deposits noted at corners of joints which could not be removed by wire brush from area around the salt deposits; when clean showed very minor signs of pitting, which was no worse than the rest of the structure. Overall the entire structure showed loose scaly rust similar to that seen in Michigan and Louisiana. Every single joint showed some evidence of leaking at one time. Salt deposits had built up under joints. Vigorous wire brushing of web portion showed a slight roughening pattern, but could not definitely be called pitting. If there is a pitting problem, I don't see it here. The appearance of the webs and edges of the bottom flange is whitish. This is similar to what was described by Gary Tinklenberg as what happens in Michigan when salt runs along the girders. Also note this is the end of the beam furthest from the truck side. On the bottom flange the edges (with the salt deposit) had a much rougher appearance than the center portion of the bottom flange, which did not have the salt. This is determined after wire brushing. It also had a rougher feeling before wire brushing. Corrosion appears to be worse than on the webs. Sample #5 is top of bottom flange.

This bridge also showed evidence of the streaking pattern on both the fascia and interior girders. There was substantial evidence of leaking joints, including frozen icicles through the joints. Each of the interior joints showed some hard salt deposits which could not be easily scraped. The salt deposits on the side of the webs and the bottom flange could be removed by wire brushing. (NOTE: Deposits were white and assumed to be salt.)

I checked down by the center lanes of the bridge. The salt pattern was also apparent there. At the very center of the roadway, the bottom of the beam appeared to be almost entirely white in some sections. It could be caused by spray from the trucks. This again is reminiscent of what we observed in Michigan. A similar pattern as on the Turnpike was observed on this second span. The surface of the bottom flanges and the webs was very grainy and could easily be removed by rubbing with the hand. The material on top of the bottom flange accumulated to a moderate degree, much less so than in Michigan. However, this can be a function of the exposure to wind and rain, etc. In one confined section of about 6 inches (15 cm) width, I collected a large sample of what looked to be very fine corrosion scale (Sample #6).

The Oakmont Viaduct bridge that we observed is the New Jersey Bridge judged to be in the most corroded condition. There is substantial leakage from the joints onto the beams below. There were significant white deposits, which were probably salt.

Additional Notes About New Jersey Turnpike

NJ Turnpike is still constructing bridges of weathering steel. The most recent is the Interchange at Exit 13A. For this bridge, and other new structures, they are painting the beams just underneath leaky joints in the shop with an inorganic zinc/vinyl system. We observed the beams painted on the Exit 13A bridge. At the very end of the bridge, the paint extends about 10 feet (3 m) from the abutment. But for the center joints, only the cross beam is painted, not the longitudinal (main) beams.

5. North Carolina

North Carolina started A-588 bridges in about 1976, with one earlier. I saw several bridges over Interstate 64. These are in very good shape, a slight amount of the scale could be scraped off by hand. The joints were good, with no observable leaking. A small amount of salt was used on the decks. One sample of the scale was taken. On the second bridge visited, there was some millscale on the bottom flanges. In addition, the stencilled-in description of the steel was still readily visible, indicating that virtually no metal loss had taken place.

The second structure had specially designed drain holes from the deck, with pipes leading to about 1 foot (0.3 m) below the bottom of the flange so that no water could drip onto the steel.

The Green River Bridge over Interstate 26 in the western part of the state is in an area which uses lots of salt. Photos showed some areas having large amounts of scaling, the type that can be pried away with a knife, perhaps 1/8 in (3 mm) of corrosion scale, similar to that found in Michigan and some of the Louisiana Bridges. This is mainly in the areas where joints are leaking from the deck. It is over a river, so there is no salt spray from below.

6. NL Test Fence, New Jersey

a. Paint Systems Tested on Corroded Weathering Steel by NL Industries

1. Nalzin-2, Rohm & Haas MV 23, latex vehicle primer with MV-9 topcoat.

2. Nalzin-2 (2 lbs/gal [0.24 kg/l]) and 1:1 oil alkyd primer (2 coats) and topcoat of 100% alkyd vehicle.

3. Same system at 5 lb/gallon (0.6 kg/l)

4. Two coats of TT-P-615, Type II with basic lead silico-chromate (BLSC) and topcoat of 100 percent alkyd with basic lead silico-chromate.

The roughness of the surface is visible underneath the coatings. Date of exposure 3/15/83. Paints applied to Cor-Ten at 1.5 and 2 mils (38 and 50 microns) or 1.0 and 1.5 mils (25 and 38 micons). Latex applied at 1.5 mils (38 microns), oil-alkyd at 1.0 and 1.5 mils (25 and 38 microns). Latex systems used were Arolon 820 and MV-23. Pigment used was Nalzin SC-1. In oil-alkyd pigment used was BLSC, plus other experimental inhibitive pigments. Exposed in August 1981.

b. Tests of Paints Applied to New Weathering Steel

Steel was 50 percent rusted originally, but not salted or immersed. Types of steels were Mayari, medium manganese, low-alloy carbon, and Cor-Ten. First system was oil-alkyd with BLSC (NY State green, 3 coats) or TT-P-86, Type I.

Bottom portion of the panel has one coat of primer only, but after a period of time it was repainted. Middle section has two coats of primer, top section (largest section) has two coats of primer and one of topcoat. These panels were exposed at Kure Beach, 500 ft (150 m) from the ocean. First system primer was NY State BLSC (three coats); second system was TT-P-86, Type I plus non-leafing aluminum alkyd, topcoat was leafing aluminum alkyd from Triborough. A set of unpainted panels was exposed since 1961 in a rural atmosphere (first on Long Island, then in Hightstown).

Scored, coated panels were exposed at the three sites: Perth-Amboy (heavy industrial); Kure Beach (marine), and Hightstown (mild).

c. Additional Comments from NL

NL has found that latex paints perform about the same over commercial blast as over white metal blast. Test panels painted with vinyls showed severe deterioration at the scribe mark in several locations, including high-acid plant, and industrial. NL feels that oil-alkyds or latexes perform better than vinyls on scribed areas but not on flat areas.

NL has tested and compared the performance of paint systems using lead pigment only in the primer against paint systems in which lead was used in all three coats of paint. They indicate that better protection is obtained when Oncor M-50 (basic lead silico-chromate) is used in all three coats (i.e., two primers and one topcoat).

NL studies also show that the basic lead silico chromate gives superior performance to red lead pigment. In particular the BLSC is less susceptible to chalking and erosion. Over a long period of time, this contributes to increased performance life.

7. London, Ontario, Canada

Bridge 1 -- Fanshaw Dam Bridge, Site 19-47 River crossing, Clarkside Road, northeast of London, Ontario

This bridge is referenced in Ontario R&D Report ME-84-03, "Accelerated Corrosion in Weathering Steel Bridges," Figure 7, page 22, and is also described on page 7 of that report.

Observed degradation of cross-bracing. Large amount of scale located on bracing between 3rd and 4th stringers. Scale thickness about 1/16 in (1.5 mm). Also some scale noted on lower part of web, about 4 in (10 cm) up the web, similar to conditions that occurred in Michigan. Observed scale about 1/16 in (1.5 mm). Specimen #1 is scale from lower portion of web on stringer #3.

Test #1 -- Conductivity of distilled water, 2.8. Conductivity from first rinsing was 200 micromhos, conductivity of second sampling of distilled water was 2.8. Second rinsing, conductivity 150 micromhos. Sample size 30 ml. Approximate dimension 14.8 by 9.6 cm. Then rinsed the area with about 100 cc of distilled water, conductivity of about 88 micromhos after rinsing with distilled water. Approximate area of second test is 14.2 by 8.2 cm.

Test #2 - Taken about 2 ft (0.6 m) up the beam, near the edge of the structure, on opposite side of the structure from previous sample, on Stringer #4. Reading was 80 micromhos, with 30 ml sample. Conductivity of distilled water from the second batch was 2.2 micromhos.

Similar type of corrosion was observed on other side of bridge. This (south) side seemed to be slightly worse in overall scaling and corrosion.

Bridge #2

This is a box girder with three spans, grade separation, near airport road on Route 402. The ID number is 14-340. Bridge has 6 inspection hatches. They are about 24 by 20 in (61 by 51 cm) and are located about 1/3 and 2/3 distance across bridge length. Protective coating (some type of black paint) was applied at the far end of the box girder. The coating was cracking and appeared to be flaking off in certain areas. However, in the areas where coating was intact, corrosion underneath the coating was less than on the adjacent steel.

Underneath the exterior scale was a large amount of white deposit which could be salt. White deposits were also evident on the lower portion of the box girder near the joints. It appeared to be most severe just at the end of the seam where the salt would leak down. Only extended for about 12 to 15 inches (31 to 36 cm) along the beam. The salt did not seem to go beyond where the coating was applied. The coating may have sealed in the salt which collected during the winter. For the uncoated surfaces, rain may have washed away these salt deposits. Salt was not evident on top of stiffener flange, but was evident on the bottom of the flange where it would also be more difficult to wash away.

Ontario Ministry of Transportation has specified box girders rather than I-beams for all grade separations. This is primarily for corrosion protection (i.e., to avoid a bottom flange or shelf where moisture could collect and cause wicking action as evident in other bridges). The box girder weathering steel bridges on Route 402 were built in about 1978. They are also reported in the Manning research report referenced above.

Bridge 3 - Box Girder with Two Spans - about 1 km west of second bridge on Route 402

Test #3 - Conductivity about 500 micromhos. Area of sample approximately 4 to 5 in^2 (26 to 33 cm^2). Chloride levels did not appear to be as bad on this one, based on the amount of white salt deposits.

8. New Jersey Garden State Parkway

Raritan Bridge - location on west side. The area painted is the outer (fascia) beam. There were four separate panels painted. Two larger ones and two smaller ones, starting from left to right, numbered 1-4. The painting systems were as follows:

- Panel 1: Blast cleaned, Carbomastic 15, plus Carboline aliphatic urethane (133).
- Panel 2: Blast cleaned surface, Carbomastic 96 primer, Carboline urethane topcoat.
- Panel 3: Hand-tool cleaned, primer Carbomastic 96, topcoat Carboline polyurethane.
- Panel 4: Same as panel 3.

Another section on the upper level perpendicular to this area was painted with Con-Lux system.

NOTE: Conductivity Test: Distilled water had a conductivity of between 2 and 4 micromhos. Rinsing from rubber gloves had conductivity of 20 to 40 micromhos. Rinsing from fingers had conductivity of 50 to 160 micromhos.

Conductivities of areas inspected were as follows:

Area 1 - Bottom of flange (unpainted). Total area about 15 sq in (97 cm^2). Conductivity 150 micromhos (based on 30 cc of solution).

Area 2 - Top of flange at edge. Area about 15 to 20 in^2 (97 to 129 cm^2). Conductivity 140 micromhos. (125 to 175 microns). Volume of solution 30 cc.

Area 3 - Panel 2 (Carboline paint). Area about 20 in^2 (129 cm^2). Conductivity 35 micromhos. Volume 30 cc.

Overall the weathering steel bridge was in good condition. For most of the interior beams, one could see some millscale on the steel. On the bottom of the bottom flange there was some graininess but very little scaling. The bridge is about 15 years old, but apparently has not been subjected to that much salting. Also the fact that it is over a river means that there would not be any splashing from beneath. The river itself is only slightly brackish.

The Garden State Parkway routinely paints the fascia beams of the weathering steel bridges. These are painted with an alkyd paint (I think). The color is very close to that of natural weathering steel.

9. New Jersey Turnpike

Bridge ID 10518.18SO, South Oakridge Oak Island Yard under NSO. Paints tested as follows:

Ashland Petroleum - Tectyl (brown), Koppers 401 (vinyl, green), Seagrave 355 (black), Trenton Petrowrap 200-A (silver), Trenton Petrowrap 100 (brown).

Dates of Application:

Ashland, December 8, 1980
Seagrave, August 4, 1981
Trenton Wraps, January 7, 1982
Koppers August 18, 1981

System 1 - Koppers paint (4 yrs) showed extensive rust staining, but the paint itself appeared to be intact. In some areas on the bottom flange, the vinyl had been applied over rusted weathering steel and was easily removed. The vinyl applied over blast cleaned surfaces was difficult to remove intact. Could not be removed with a knife. In some areas the rust had broken through the vinyl. This may be due to the poor preparation, i.e., vinyl applied over a salty surface. The cross bracing and the lower part of the web showed the worst rusting condition. The bearing plate showed mainly rust staining, with the paint fairly well intact. There appeared to be some substantial pitting beneath the paint.

System 2 -- Petrowrap 200A -- Applied only around the bearing. Area covered by Petrowrap appeared to be well protected. Had a silver-white appearance. The white looks like some type of adhesive. However this area may not have been badly rusted in the beginning. There is not as much evidence of pitting here.

System 3 -- Petrowrap 100 -- Also applied to bearing. This is a petrolatum type paste and tape system. It remains soft and slippery. Did not see any evidence of corrosion underneath the coating. Surface Preparation was SP-6 with Black Beauty grit, following chipping of heavy rust with hammer.

System 4 -- Seagrave -- This is an elastomeric urethane spray applied in two coats at 10 mils (250 microns) each. Some rust was evident underneath the film which could be removed with some difficulty with a pocket knife. There was also some exposed metal at 50X magnification. On the bottom flange, the paint had apparently been applied over rust. It could easily be removed, showing large amounts of rust underneath.

System 5 -- Tectyl System -- This was a two-coat system. The top coat was supposed to be a semi-drying wax coating. It seems pretty firm and non-rubbery upon scraping with a knife. The metal underneath it was clean and dry with little evidence of any corrosion.

10. University of Maryland

Met with Pedro Albrecht, who brought me to the test facility. There were two sections for the racks. One of them, which had been completed, was for beams exposd in a semi-industrial area with no salt applied. The second was the one in which salt was applied three times a week with a garden sprayer for 3 months of the year. During the other 9 months, the beams were sprayed with pure water once a week. The beams were covered with aluminum plates, so that they would simulate the environment of a deck. This process was continued for 4 years. They are also planning to salt it this winter for a fifth season.

First beam examined: B-116. Solid sample taken from top of bottom flange of B-116. Scale about 1/16 to 1/8 in (1.5 to 3.0 microns) thick. Size of area 3-3/4 by 2-1/2 in (7.0 by 6.4 cm).

Conductivity 1,400 micromhos. Pitting clearly evident after wire brushing. Some of the fibers of the cotton adhered to the surface.

Solid sample #6 taken from bottom flange of B-12s. Fairly tightly adhering on upper portion of side beam above the bottom flange. Scale was much easier to remove, much less pitting observed. The portable power drill was unable to remove the tightly adhering corrosion products of the weathering steel. Even a small crowbar could only remove it with great difficulty. Hammer and chisel might be useful for future bridge inspections.

PART 2 -- BRIDGE STEEL SPECIMENS

The following illustrations of bridge specimens are given as described in table 3.

1. Michigan DOT (figure 8).
2. New Jersey Turnpike (figures 9 and 10).
3. Louisiana DOTD (figure 11).
4. University of Maryland (figure 12).
5. Ontario Ministry of Transportation (figures 13 and 14).

Table 19 summarizes the specimens available for coating evaluation studies after cutting up bridge steel.

Examination of New Jersey Beam

This damaged beam was shipped to SSPC for use in testing. The (apparent) front side showed the streaking pattern that was evident in Michigan and some of the Louisiana bridges. A hand rubbed over the surface felt grainy and was able to remove some of the loose material. The grain size in this area was fairly small - it appeared to be less than 1/16 in (1.5 mm). In certain areas some of the dark brown grain had been removed, revealing an orange-colored, tightly adhering scale. This orange scale, however, was chalky when rubbed with a finger. The bottom of the top flange was also dark and flaky in appearance. However, the top of the bottom flange was much lighter in color, with very little flaking rust. The bottom of the top flange on the back side had the same type of grainy appearance as the front side of the beam and the bottom of the top flange on the front side. The outer portion of the side flange had a very rough corroded appearance. The scale, however, was not easily removed by hand, but could be removed with a scraper.

There were two cover plates sent with the New Jersey beams. The bottom side of one cover plate had a very rough corroded appearance. Some fairly large chips of rust could be scraped off with a scraper. The top of the cover plate was much less rough than the under side. Scraping produced only a small amount of scale.

PART 3 -- CASE HISTORIES OF PAINTED WEATHERING STEEL

Table 20 identifies a number of painted weathering steel bridges, including the year the bridge was opened to traffic, the year it was painted, the surface preparation, and the coating materials.

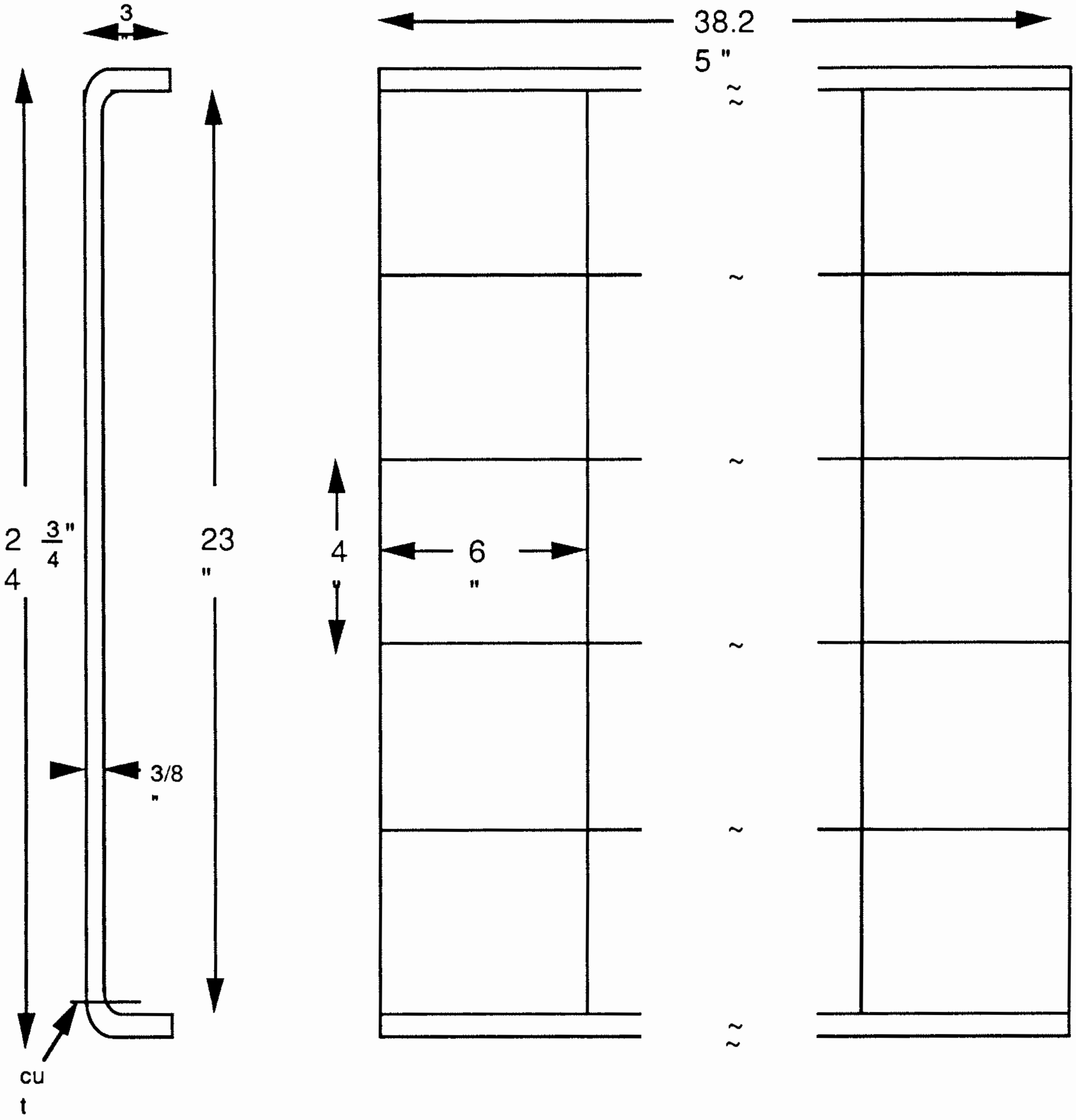


Figure 8. A-588 channels from the Michigan DOT.

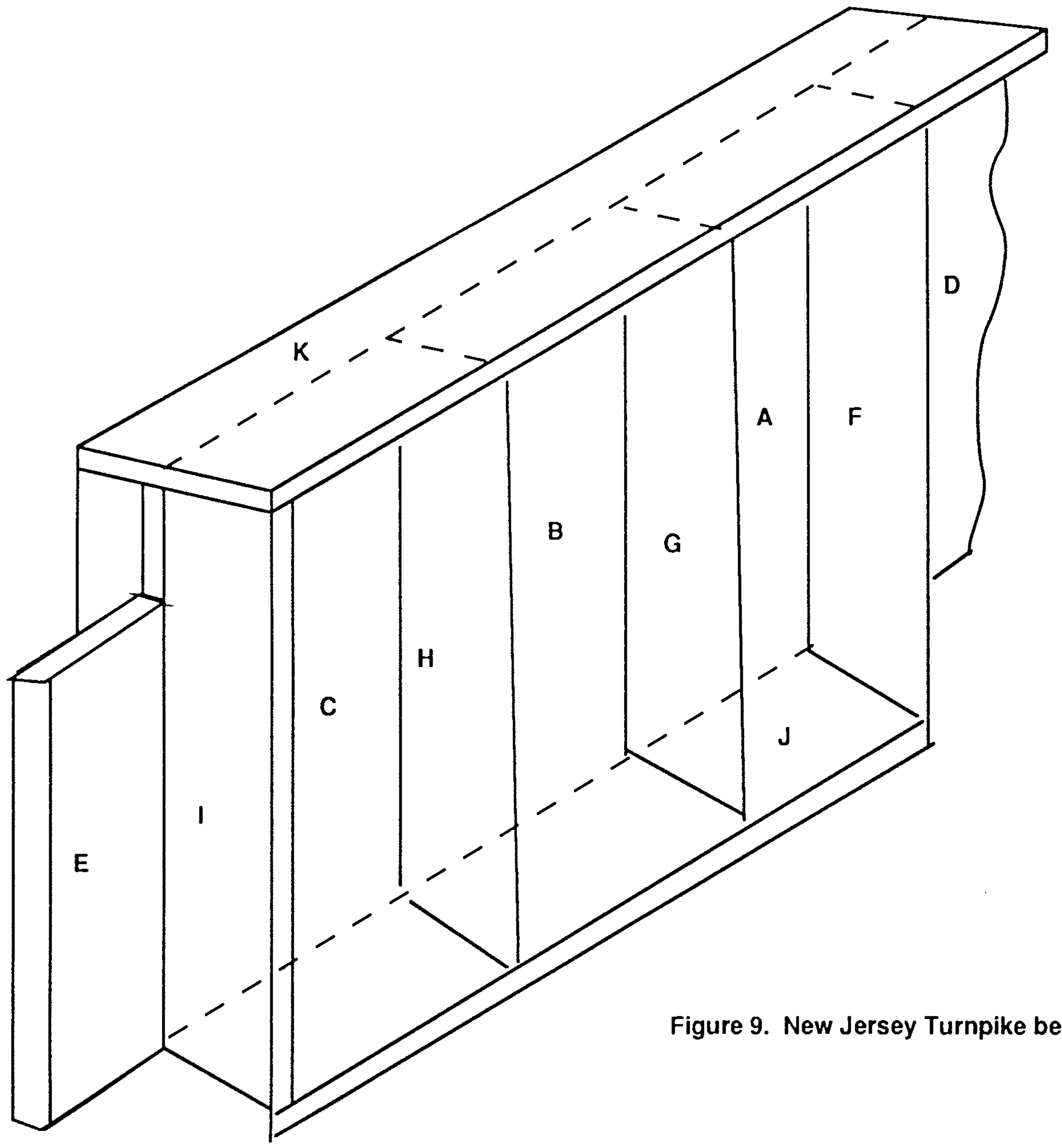


Figure 9. New Jersey Turnpike beam confirguration.

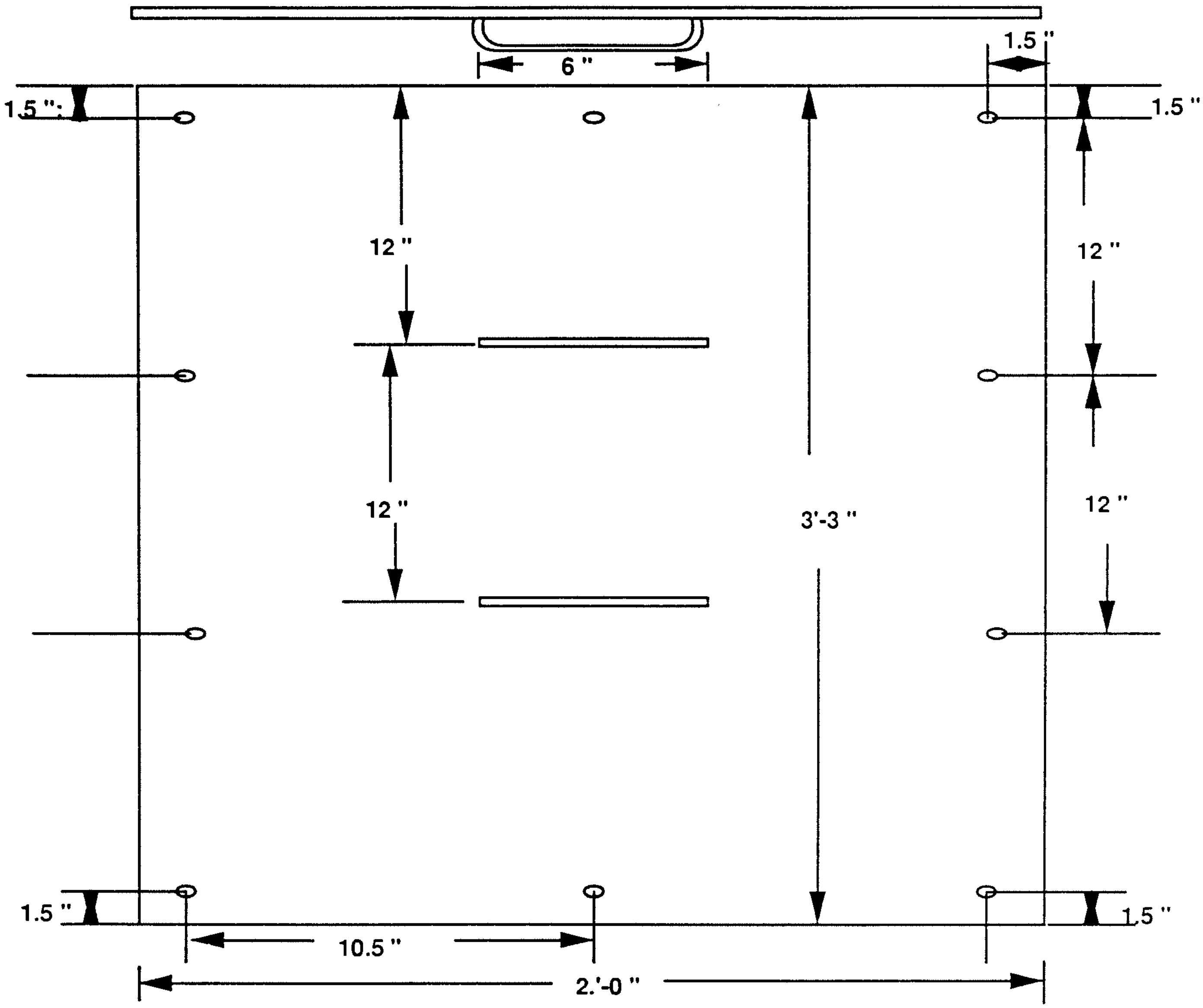


Figure 10. New Jersey Turnpike box girder access cover configuration.

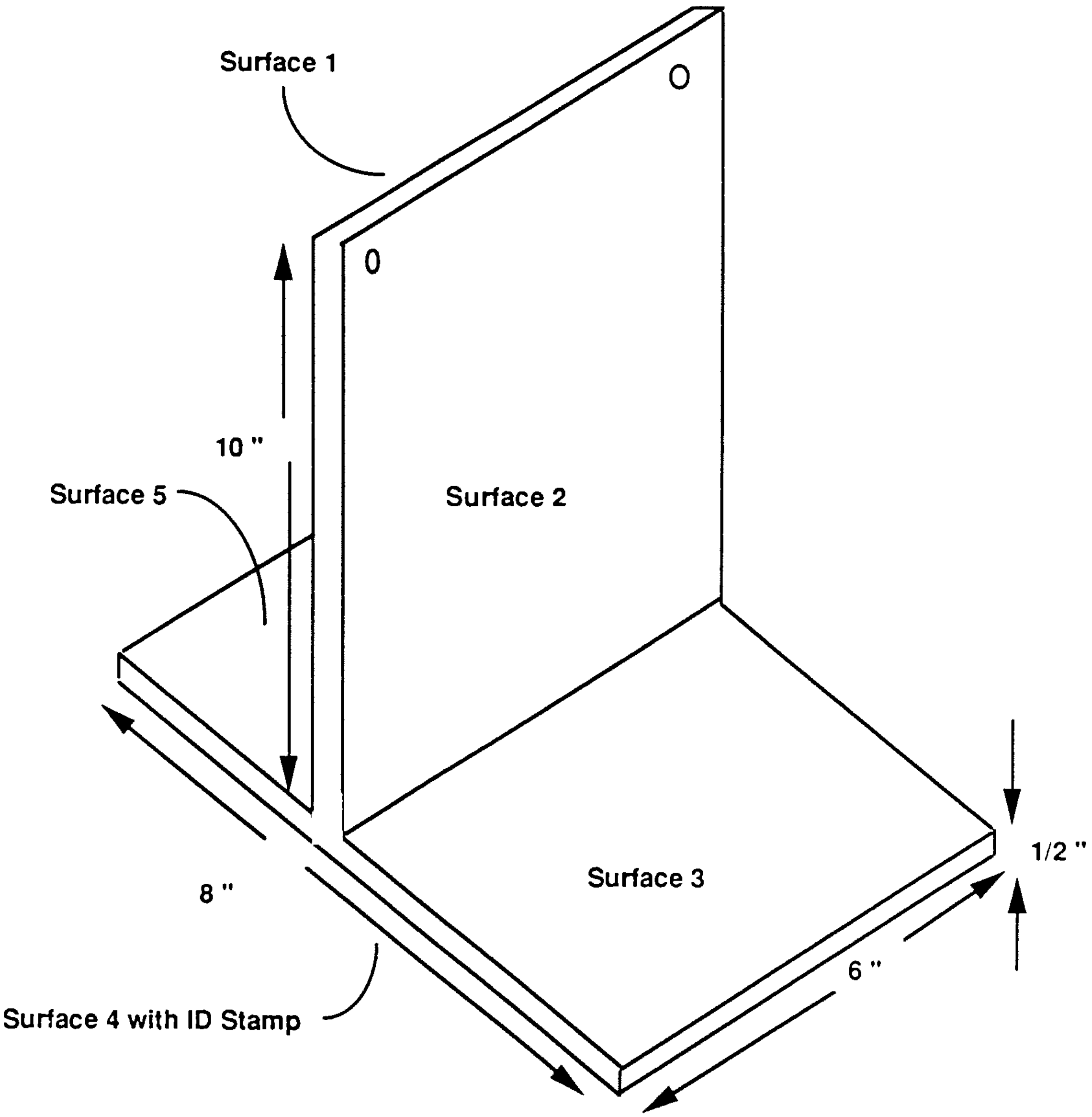


Figure 11. Louisiana DOTD "T" beam configuration.

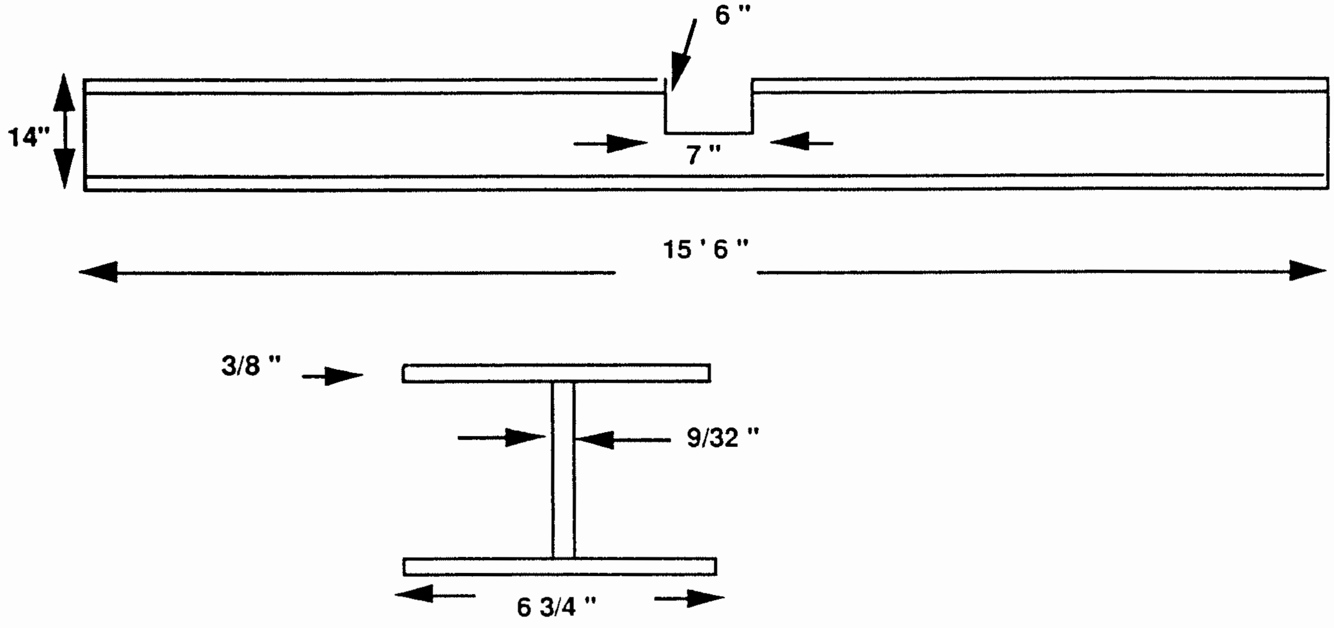


Figure 12. University of Maryland beam configuration.

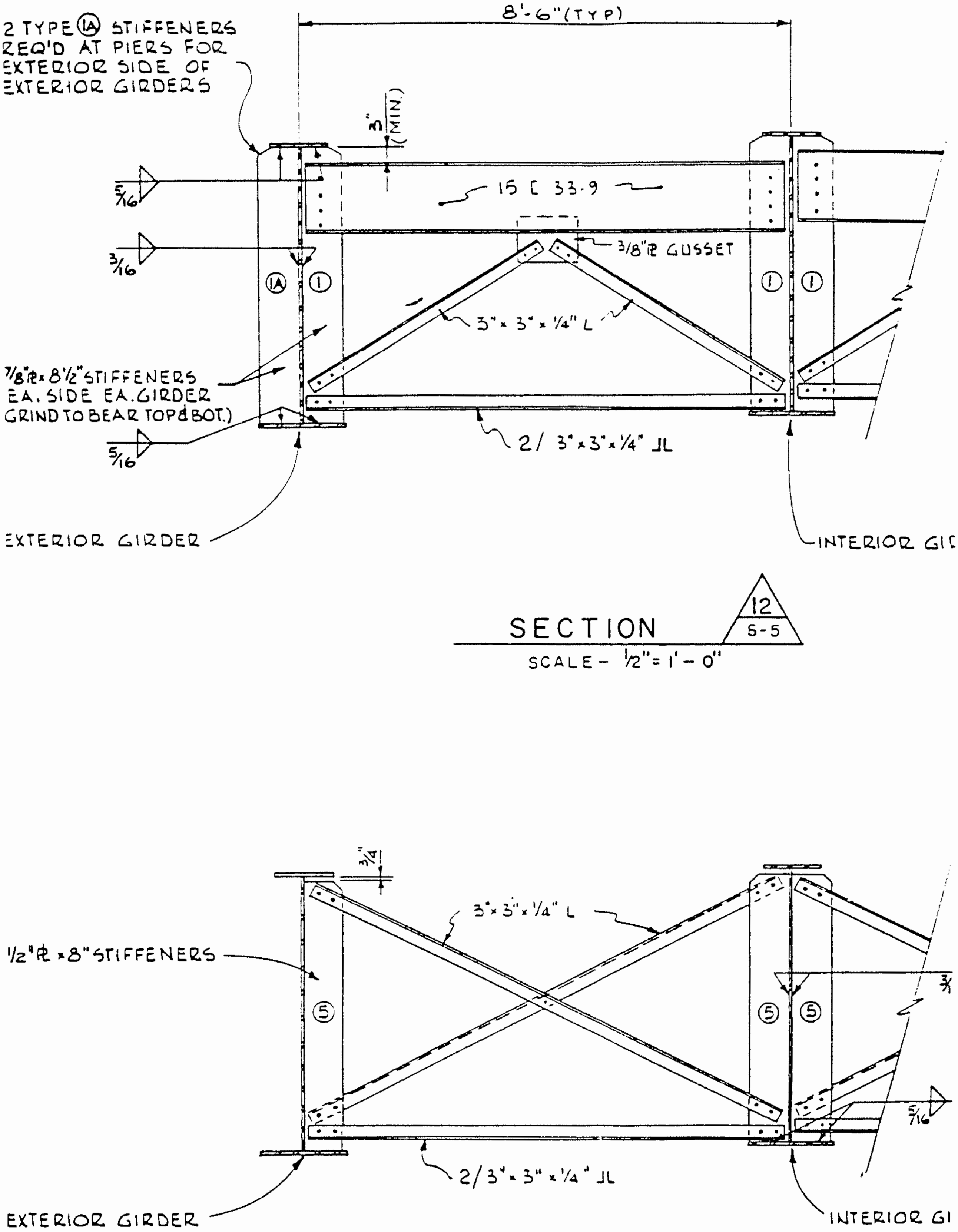


Figure 13. Ontario Ministry of Transportation stiffener configuration.

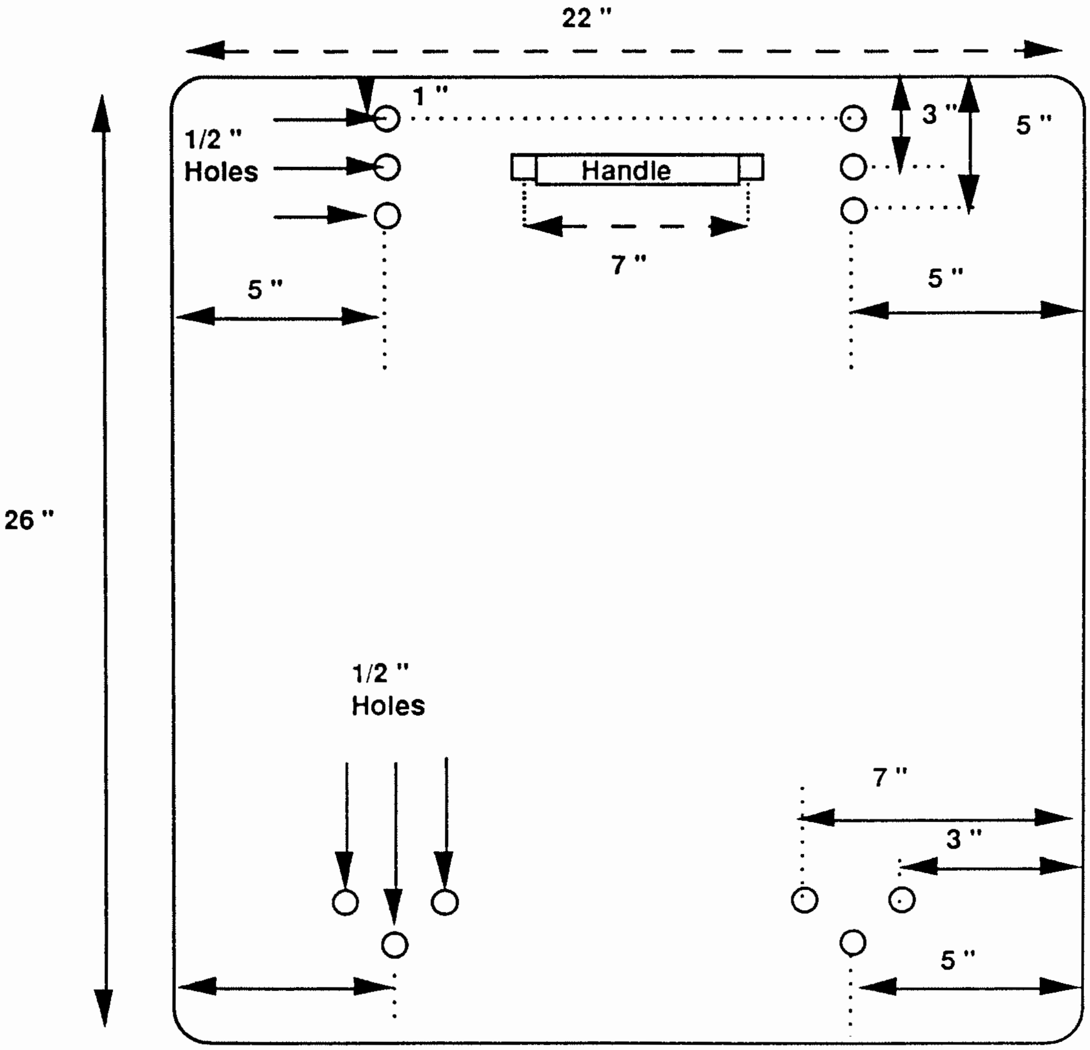


Figure 14. Ontario Ministry of Transportation hatch cover plate configuration.

Table 19. Inventory of steel from highway bridges.

SS No.	Source	No. Pcs	Size	Steel Type	Comments
590	New Jersey DOT	few	from 18" to 2' long, x 3" wide	A-441	bridge beam
590A	New Jersey DOT	96	4" x 6" x 1/2"	A-441	2 separate boxes
		1	4" x 6-1/2" x 1/2"	A-441	
590C	New Jersey DOT	47	4" x 6" x 1/2"	A-441	2 separate boxes (one odd piece)
590D	New Jersey DOT	12	4" x 6" x 1/2"	A-441	plus three odd pieces
590 E	New Jersey DOT	11	4" x 6" x 1/2"	A-441	
590F	New Jersey DOT	7	4" x 6" x 3/8"	A-441	plus bent 4" x 6" x 3/8"
590G	New Jersey DOT	7	4" x 6" x 7/16"	A-441	plus 4" x 6" bent plus 5" x 6"
590H	New Jersey DOT	8	4" x 6" x 3/8"	A-441	plus 6" x 5" x 3/8"
590I-J-K	New Jersey Dot	31	9" x 6" x 1"	A-588 (very heavy)	plus 12" x 16" x 1"
590L	New Jersey DOT	36	4" x 6" x 5/16"	A-588	2 separate boxes
590M	New Jersey Dot	34	4" x 6" x 5/16	A-588	2 separate boxes
596A	Michigan DOT	49	4" x 6" x 1/2"	A-588	19 panels have curved lip, 4 separate boxes
596B	Michigan DOT	5	4" x 6" x 7/16"	A-588	rounded edges
		3	4" x 12 x 7/16"	A-588	rounded edges
602	NL Industries	2	4" x 4" x 12" x 1/4"	A-588	angles from test site
604	WV DOT	20	4" x 6" x 1/4"	A-588	bridge inspection
606	Wisconsin DOT	17	5" x 6" x 3/8"	A-588	Wisconsin bridge T-beam
	Wisconsin DOT	9	3-1/2 x 12" x 3/8"	A-588	Wisconsin bridge T-beam
	Wisconsin DOT	1	5" x 7"	A-588	Wisconsin bridge T-beam
613	Illinois DOT	11	4" x 6" x 1/2"	A-588	w/lip (top flange)
	Illinois DOT	10	4" x 6" x 1/2"	A-588	+ 2 odd pieces
	Illinois DOT	20	5" x 6" x 3/8	A-588	w/rough edges (web)
	Illinois DOT	18	4" x 6" x 1/2"	A-588	w/lip (bottom flange)
	Louisiana DOTD		10" (3/8") x 8" (1/2")	A-588	T-beam

1 inch = 25.4 cm
1 foot = 0.30 m

Table 20. Case histories of painted weathering steel bridges.

Bridge Identification	Year Opened/ Year Painted	Surface Preparation	Coatings Primer/Mid/Topcoat
Port Isabel Causeway, Padre Island, TX[1]	1971/1984	brush blast, flush with water, blast to SSPC-SP 10	zinc-rich epoxy (5 mils[125 microns])epoxy (2 mils [50 microns])/vinyl toluene acrylate (1.5 mils [38 microns])
US-2 over Lake Champlain Albury, VT[2]	/1985	blast clean	zinc rich/epoxy/urethane (topcoat on fascias only)
Brand Road Bridge Franklin County, OH[3]	1973/1979	blast clean	zinc rich/modified alkyd
Road 19 over Sugar Creek Tuscorawas County, OH[3]	1979/1979	wire brush	zinc-rich rubberized paint
Dollut Canal Bridge Empire, LA[3]	1975/1983	SSPC-SP 10	2 coats epoxy zinc-rich (4.5 mils [115 microns])/vinyl (1.5 mils [38 microns])
6 Bridges Butler County, OH[3]	after 1971/ 1983	blast clean	asphalt base paint

[1] Raska (Ref. 18).

[2] Gausman (*JPCL* 3, (3), p. 32. (1986).

[3] Albrecht & Naeemi (Ref. 5)

APPENDIX C

DATA FROM ACCELERATED LABORATORY TESTS

The individual panel ratings for the various accelerated tests are tabulated as follows:

Branch A -- Coatings Applied Over Blast-Cleaned Steel

- Salt spray rust ratings (table 21)
- Salt spray blister ratings (table 22)
- Immersion rust ratings (table 23)
- Immersion blister ratings (table 24)
- UV-Condensation/freeze-thaw rust ratings (table 25)
- UV-Condensation/freeze-thaw blister ratings (table 26)

Branch B -- Coatings Applied over Power and Hand Tool Cleaned Steel

- Salt spray rust ratings (table 27)
- Salt spray blister ratings (table 28)
- UV-Condensation/freeze-thaw rust ratings (table 29)
- UV-Condensation/freeze-thaw blister ratings (table 30)

Branch C -- Comparison of Laboratory vs. Field Contaminated Steel

- Salt spray rust ratings (table 31)
- Salt spray blister ratings (table 32)

Branch D: Comparison of Thermal Spray Zinc vs. Organic Zinc System

- Salt spray rust ratings (table 33)
  NOTE: All panels were free of blisters (10 rating) for each rating period in salt spray.
- UV-Condensation/freeze-thaw rust and blister ratings (table 34)

Table 21. Branch A -- salt spray rust ratings.

ID	P.S.	TYPE	S.P.	24	48	72	144	216	360	408	960	1512
RIS	2	HCL	D	10	10	10	9	9	9-	9	7	7
RIS 1	2	HCL	D	10	10	10	10	9	9-	9	7	7
RIT	2	HCL	W	10	10	10	10	10	10	10	10	9+
RIT 1	2	HCL	W	10	10	10	10	10	10-	10	9	9
RIU	2	M	D	10	10	10	10	10	10	10	10	9+
RIU 1	2	M	D	10	10	10	10	10	10	10	9+	10
RIV	3A	HCL	D	9	9	9	9	9	9	9	9	9
RIV 1	3A	HCL	D	9	8	8	8	8	8+	8+	8	8
RIW	3A	HCL	W	10	8	8	8	8-	8	8	7	7
RIW1	3A	HCL	W	10	8	8	8	8	8	8	7	7+
RIX	3A	M	D	10	9+	10	9	9	9	9	9	9
RIX 1	3A	M	D	10	10	10	9	9	9	9	9	9
RIY	3B	HCL	D	8	8	8	8	8	8	8	8	8
RIY 1	3B	HCL	D	8	8	8	8	8	8	8	8	8
RIZ	3B	HCL	W	9	8	8	8	8	8	8	7	7
RIZ 1	3B	HCL	W	8	8	8	8	8-	7	8-	7	7
RJA	3B	M	D	##	10	9	9	9	9	9	9	9
RJA 1	3B	M	D	10	9	9	8	8	8	8	8	8-
RJB	4	HCL	D	10	10	10	10	10	10	10	9	9+
RJB 1	4	HCL	D	10	10	10	10	10	10	10	9	9
RJC	4	HCL	W	10	10	10	10	10	10	10-	8	8
RJC 1	4	HCL	W	10	10	10	10	10	9	9+	8	8
RJD	4	M	D	10	10	10	10	10	10	10	9	8+
RJD 1	4	M	D	10	10	10	10	10	10	10	10	9+
RJE	5	HCL	D	10	10	10	10	10	10	10	9	9
RJE 1	5	HCL	D	10	10	10	10	10	10	10	10	10
RJF	5	HCL	W	10	10	10	10	10	10	9	9	9
RJF 1	5	HCL	W	10	10	10	10	10	9	9	8	8+
RJG	5	M	D	10	10	10	10	10	10	10	10	10
RJG 1	5	M	D	10	10	10	10	10	10	10	10	10
RJH	6	HCL	D	10	10	10	10	10	10	10	10	10-
RJH 1	6	HCL	D	10	10	10	10	10	10	10	10	10-
RJI	6	HCL	W	10	10	10	10	10	10	10	10	10-
RJI 1	6	HCL	W	10	10	10	10	10	10	10	10	10
RJJ	6	M	D	10	10	10	10	10	10	10	10	10
RJJ 1	6	M	D	10	10	10	10	10	10	10	10	10

Table 22. Branch A -- salt spray blister ratings.

ID	P.S.	TYPE	S.P.	24	48	72	144	216	360	408	960	1512
RIS	2	HCL	D	10	10	10	10	10	10	10	6MD	6MD
RIS 1	2	HCL	D	10	10	10	10	10	10	10	6MD	6MD
RIT	2	HCL	W	10	10	10	10	10	10	10	6M	6M
RIT 1	2	HCL	W	10	10	10	10	10	10	10	6M	6M
RIU	2	M	D	10	10	10	10	10	10	10	6M	6M
RIU 1	2	M	D	10	10	10	10	10	10	10	6M	6M
RIV	3A	HCL	D	10	10	10	10	10	10	10	10	10
RIV 1	3A	HCL	D	10	10	10	10	10	10	10	10	10
RIW	3A	HCL	W	10	10	10	10	10	10	10	10	10
RIW1	3A	HCL	W	10	10	10	10	10	10	10	10	10
RIX	3A	M	D	10	10	10	10	10	10	10	10	10
RIX 1	3A	M	D	10	10	10	10	10	10	10	10	10
RIY	3B	HCL	D	10	10	10	10	10	10	10	10	10
RIY 1	3B	HCL	D	10	10	10	10	10	10	10	10	10
RIZ	3B	HCL	W	10	10	10	10	10	10	10	10	10
RIZ 1	3B	HCL	W	10	10	10	10	10	10	10	10	10
RJA	3B	M	D	10	10	10	10	10	10	10	10	10
RJA 1	3B	M	D	8D	*	10	10	10	10	10	10	10
RJB	4	HCL	D	8D	*	10	10	10	10	10	6D	8D
RJB 1	4	HCL	D	10	10	10	10	10	10	10	6M	8D
RJC	4	HCL	W	10	10	10	10	10	10	10	6VF	8F
RJC 1	4	HCL	W	10	10	10	10	10	10	10	6VF	6VF
RJD	4	M	D	10	10	10	10	10	10	10	10	10
RJD 1	4	M	D	10	10	10	10	10	10	10	10	8F
RJE	5	HCL	D	6F	8MD	10	6F	6D	10	10	10	10?
RJE 1	5	HCL	D	10	8F	10	8F	8MD	10	10	10	10?
RJF	5	HCL	W	6M	6D	10	8D	8D	10	10	10	10?
RJF 1	5	HCL	W	6M	6D	10	8D	8D	10	10	10	10
RJG	5	M	D	10	10	10	10	8F	10	10	10	10
RJG 1	5	M	D	10	10	10	10	8F	10	10	10	10
RJH	6	HCL	D	10	10	10	8M?	8M	8MD	8M	6MD	6MD
RJH 1	6	HCL	D	10	10	10	8F?	8M	8M	8M	6MD	6MD
RJI	6	HCL	W	10	10	10	8F?	8F	8F?	8F	8F	8F
RJI 1	6	HCL	W	10	10	10	8F?	8F	8F?	8F	8F	8M?
RJJ	6	M	D	10	10	10	10	8F	10	8F	8M	8M?
RJJ 1	6	M	D	10	10	10	10	8F	10	8F	8M	8M?

Table 23. Branch A -- immersion rust ratings.

ID	P.S.	TYPE	S.P.	48	456	1128	1502	2078	2462
RKU	2	HCL	D	10	10	10	10	10	10
RKU 1	2	HCL	D	10	10	10	10	10	10
RKV	2	HCL	W	10	10	10	10	10	10
RKV 1	2	HCL	W	10	10	10	10	10	10
RKW	2	M	D	10	9+	10	10	10	10
RKW 1	3A	M	D	10	10	10	10	10	10
RKX	3A	HCL	D	10	10	10	10	10	9+
RKX 1	3A	HCL	D	10	10	10	10	10	9+
RKY	3A	HCL	W	10	10	10	10	10	10-
RKY 1	3A	HCL	W	10	9+	10	9	10	9+
RKZ	3A	M	D	10	10	10	10	10	10
RKZ 1	3A	M	D	10	10	10	10	10	10
RLA	3B	HCL	D	10	10	10	10	10	10
RLA 1	3B	HCL	D	10	10	10	10	10	10
RLB	3B	HCL	W	10	10	10	10	10	10-
RLB 1	3B	HCL	W	10	9+	10	9+	10-	9+
RLC	3B	M	D	10	10	10	10	10	10
RLC 1	3B	M	D	10	10	10	10	10	10
RLD	4	HCL	D	10	10	10	10	10	10
RLD 1	4	HCL	D	10	10	10	10	10	10
RLE	4	HCL	W	10	10	10	10	10	10
RLE 1	4	HCL	W	10	10	10	10	10	10
RLF	4	M	D	10	10	10	10	10	10
RLF 1	4	M	D	10	10	10	10	10	10
RLG	5	HCL	D	10	10	10	10	10	10
RLG 1	5	HCL	D	10	10	10	10	10	10
RLH	5	HCL	W	10	10	10	10	10	10
RLH 1	5	HCL	W	10	10	10	10	10	10-
RLI	5	M	D	10	10	10	10	10	10
RLI 1	5	M	D	10	10	10	10	10	10
RLJ	6	HCL	D	10	10	10	10	10	10
RLJ 1	6	HCL	D	10	10	10	10	10	10
RLK	6	HCL	W	10	10	10	10	10	10
RLK 1	6	HCL	W	10	10	10	10	10	10
RLL	6	M	D	10	10	10	10	10	10
RLL 1	6	M	D	10	10	10	10	10	10

Table 24. Branch A -- Immersion blister ratings.

ID	P.S.	TYPE	S.P.	48	456	1128	1502	2078	2462
RKU	2	HCL	D	10	10	10	10	10	10
RKU 1	2	HCL	D	10	10	10	10	10	10
RKV	2	HCL	W	10	10	10	10	10	10
RKV 1	2	HCL	W	10	10	10	10	10	10
RKW	2	M	D	10	10	10	10	10	10
RKW 1	3A	M	D	10	10	10	10	10	10
RKX	3A	HCL	D	10	4F	2F	4F	10	4VF
RKX 1	3A	HCL	D	10	4F	4F	4F	10	10
RKY	3A	HCL	W	10	10	10	10	10	10
RKY 1	3A	HCL	W	10	10	10	6VF	6VF	10
RKZ	3A	M	D	10	10	10	10	10	10
RKZ 1	3A	M	D	10	10	10	10	10	10
RLA	3B	HCL	D	10	10	10	10	10	10
RLA 1	3B	HCL	D	10	10	10	10	10	10
RLB	3B	HCL	W	10	10	10	10	10	10
RLB 1	3B	HCL	W	10	10	10	10	10	10
RLC	3B	M	D	10	10	10	10	10	10
RLC 1	3B	M	D	10	10	10	10	10	10
RLD	4	HCL	D	10	4M	4D	4D	6D	6D
RLD 1	4	HCL	D	10	6MD	4D	4D	6MD	6D
RLE	4	HCL	W	10	10	6F	8M	8F	8F
RLE 1	4	HCL	W	10	10	8M	8MD	8F	8F
RLF	4	M	D	10	10	10	8F	10	10
RLF 1	4	M	D	10	10	10	8D	8D	8D
RLG	5	HCL	D	10	10	10	10	10	10
RLG 1	5	HCL	D	10	10	10	10	10	10
RLH	5	HCL	W	10	10	10	8F?	8F	8F
RLH 1	5	HCL	W	10	10	10	10	10	10
RLI	5	M	D	10	10	10	10	10	10
RLI 1	5	M	D	10	10	10	10	10	10
RLJ	6	HCL	D	10	6MD	6MD	6MD	6M	6M
RLJ 1	6	HCL	D	10	6M	4D	5MD	6MD	6MD
RLK	6	HCL	W	10	10	6F	8M	8M	8M
RLK 1	6	HCL	W	10	6VF	6F	6M	8MD	6F
RLL	6	M	D	10	10	10	8M	8F	10
RLL 1	6	M	D	10	10	10	8F	8M	10

Table 25. Branch A -- UV-condensation/freeze-thaw rust ratings.

I.D.	P.S.	TYPE	S.P.	432	768	1152	COMMENTS
RJK	2	HCL	D	10-	10-	10-	
RJK1	2	HCL	D	10	10	10	
RJL	2	HCL	W	9+	10-	9+	
RJL1	2	HCL	W	10	10	10	
RJM	2	M	D	10	10	10	
RJM1	3A	M	D	10	10	10	
RJN	3A	HCL	D	9	10	10	slight fading (1152)
RJN1	3A	HCL	D	10	10	10	slight fading (1152)
RJO	3A	HCL	W	10	10	10	slight fading (1152)
RJO1	3A	HCL	W	9+	10	10	slight fading (1152)
RJP	3A	M	D	10	10	10	slight fading (1152)
RJP1	3A	M	D	10	10	10	yellowing (432) slight fading (1152)
RJQ	3B	HCL	D	10	10	10	
RJQ1	3B	HCL	D	10	10	10	
RJR	3B	HCL	W	10	10	10	
RJR1	3B	HCL	W	10	10	10	
RJS	3B	HCL	D	10	10	10	some dry spray (432)
RJS1	3B	HCL	D	10	10	10	some dry spray (432)
RJT	4	HCL	D	10	10	10	yellowing (432,768,1152)
RJT1	4	HCL	D	10	10	10	yellowing (432,768,1152)
RJU	4	HCL	W	10	10	10	yellowing (432,768,1152)
RJU1	4	HCL	W	10	10	10	yellowing (432,768,1152)
RJV	4	M	D	10	10	10	yellowing (432,768,1152)
RJV1	4	M	D	10	10	10	no gloss (432,768,1152)
RJW	5	HCL	D	10	10	10	no gloss (432,768,1152)
RJW1	5	HCL	D	10	10	10	no gloss (432,768,1152)
RJX	5	HCL	W	10	10	10	no gloss (432,768,1152)
RJX1	5	HCL	W	10	10	10	no gloss (432,768,1152)
RJY	5	M	D	10	10	10	no gloss (432,768,1152)
RJY1	5	M	D	10	10	10	no gloss (432,768,1152)
RJZ	6	HCL	D	10	10	10	slight loss of gloss (1152)
RJZ1	6	HCL	D	10	10	10	slight loss of gloss (1152)
RKA	6	HCL	W	10	10	10	slight loss of gloss (1152)
RKA1	6	HCL	W	10	10	10	slight loss of gloss (1152)
RKB	6	M	D	10	10	10	slight loss of gloss (1152)
RKB1	6	M	D	10	10	10	slight loss of gloss (1152)

Table 26. Branch A -- UV-condensation/freeze-thaw blister ratings.

I.D.	P.S.	TYPE	S.P.	432	768	1152	COMMENTS
RJK	2	HCL	D	10	8M	10	
RJK1	2	HCL	D	10	8F	10	
RJL	2	HCL	W	10	10	*	* 1 big blister near edge (1152)
RJL1	2	HCL	W	10	10	10	
RJM	2	M	D	10	10	10	
RJM1	3A	M	D	10	10	10	
RJN	3A	HCL	D	10	10	10	
RJN1	3A	HCL	D	10	10	10	
RJO	3A	HCL	W	10	10	10	
RJO1	3A	HCL	W	10	10	10	
RJP	3A	M	D	10	10	10	
RJP1	3A	M	D	10	10	10	
RJQ	3B	HCL	D	10	10	10	
RJQ1	3B	HCL	D	10	10	10	
RJR	3B	HCL	W	10	10	10	
RJR1	3B	HCL	W	10	10	10	
RJS	3B	HCL	D	10	10	10	8D or dry spray (768)
RJS1	3B	HCL	D	10	10	10	8D or dry spray (768)
RJT	4	HCL	D	10	10	10	
RJT1	4	HCL	D	10	10	10	
RJU	4	HCL	W	10	10	10	
RJU1	4	HCL	W	10	10	10	
RJV	4	M	D	10	10	10	
RJV1	4	M	D	10	10	10	
RJW	5	HCL	D	10	10	10	
RJW1	5	HCL	D	10	10	10	
RJX	5	HCL	W	10	10	10	
RJX1	5	HCL	W	10	10	10	
RJY	5	M	D	10	10	10	
RJY1	5	M	D	10	10	10	
RJZ	6	HCL	D	10	10	10	
RJZ1	6	HCL	D	10	10	10	
RKA	6	HCL	W	10	10	10	
RKA1	6	HCL	W	10	10	10	
RKB	6	M	D	10	10	10	
RKB1	6	M	D	10	10	10	

Table 27. Branch B -- salt spray rust ratings.

ID	P.S.	TYPE	S.P.	24	48	72	144	216	360	408	960	1512
RLM	1	HCL	P	10	9	10	8	8	7	7	0	- -
RLM1	1	HCL	P	10	10	10	9+	8+	8	8	0	- -
RLM2	1	HCL	P	10	9	10	8	8 -	7	7	0	- -
RLN	1	HCL	H	10	10	10	9	8	7	7	0	- -
RLN1	1	HCL	H	10	9	10	7	7	4	6	0	- -
RLN2	1	HCL	H	10	9	10	8	7+	6	7	0	- -
RLO	1	LCL	P	10	10	10	10	10	10	10	7	6
RLO1	1	LCL	P	10	10	10	10	10	10	10	7	6
RLO2	1	LCL	P	10	10	10	10	10	10	9+	6	4
RLP	1	LCL	H	10	10	10	10	10	10 -	9	2	0
RLP1	1	LCL	H	10	10	10	10	10	9	8	0	0
RLP2	1	LCL	H	10	10	10	10	10	9	9	2	0
RLQ	4	HCL	P	10	10	10	10	9+	9+	9+	9	9
RLQ1	4	HCL	P	10	10	10	10	9+	9+	9+	9	9
RLQ2	4	HCL	P	10	10	10	10	10	10	10	9	9
RLR	4	HCL	H	10	10	10	9	9	9	9	8+	8+
RLR1	4	HCL	H	10	9	10	9	9	9	9	9	9
RLR2	4	HCL	H	10	10	10	9+	9+	9+	9+	9	9
RLS	4	LCL	P	10	10	10	10	10	10	10	10	10
RLS1	4	LCL	P	10	10	10		10	10	10	10	9 -
RLS2	4	LCL	P	10	10	10	10	10	10	10	10	9
RLT	4	LCL	H	10	10	10	10	10	10	10 -	10	9
RLT1	4	LCL	H	10	10	10	10	10	10	10 -	9	7
RLT2	4	LCL	H	10	10	10	10	8+	10	10	8	8
RLU	6	HCL	P	9	8+	9	8+	8+	9	9	9	8
RLU1	6	HCL	P	9	9	9	8+	9	9	9	8	8
RLU2	6	HCL	P	10	10	10	9	8 -	9	9	8	9
RLV	6	HCL	H	8	8	8	8	7	8	8	9	7
RLV1	6	HCL	H	8	8	8	7	7	7	7	7	7
RLV2	6	HCL	H	8	8	8 -	7	10	7	7	7	7
RLW	6	LCL	P	10	10	10	10	10	10	10	10	10
RLW1	6	LCL	P	10	10	10	10	10	10	10	10	10
RLW2	6	LCL	P	10	10	10	10	9+	10	10	10	10 -
RLX	6	LCL	H	10	9	10	9+	9+	9+	9+	9	10
RLX1	6	LCL	H	10	10	10	9+	10	9+	9+	9	9+
RLX2	6	LCL	H	10	10	10	10	6	10	10	10	10
RLY	7	HCL	P	8	8	- -	7	6	4	4	0	- - -
RLY1	7	HCL	P	8	8	- -	7	6	2	2	0	- - -
RLY2	7	HCL	P	8	8	- -	8	7	6	4	0	- - -
RLZ	7	HCL	H	8	8	- -	7	6	4	4	0	- - -
RLZ1	7	HCL	H	8	8	- -	7	7	4	4	0	- - -
RLZ2	7	HCL	H	8	8	- -	7	4	2	2	0	- - -
RMA	7	LCL	P	8	8	- -	8	8	7	7	0	- - -
RMA1	7	LCL	P	9	9	- -	9	9	8	8	0	- - -
RMA2	7	LCL	P	9	9	- -	9	8	8	7	0	- - -
RMB	7	LCL	H	9	8	- -	8	8	6	6	0	- - -
RMB1	7	LCL	H	8	8	- -	9	8	6	6	0	- - -
RMB2	7	LCL	H	8	8	- -	8	7	4	4	0	- - -

Table 28. Branch B -- salt spray blister ratings.

ID	P.S.	TYPE	S.P.	24	48	72	144	216	360	408	960	1512
RLM	1	HCL	P	10	6F	10	6F	6F	6MD	6D	--	--
RLM1	1	HCL	P	10	10	10	6F	6F	6MD	6MD	--	--
RLM2	1	HCL	P	10	6F	8MF	6F	6M	6D	6D	--	--
RLN	1	HCL	H	10	6M	8MF	6MD	4MD	4D	4MD	--	--
RLN1	1	HCL	H	10	6MD	8D	6D	6D	6D	6D	--	--
RLN2	1	HCL	H	10	6MD	8D	6D	4D	4D	4D	--	--
RLO	1	LCL	P	10	10	10	10	10	6VF	8VF	4M	4D
RLO1	1	LCL	P	10	10	10	10	8VF	6VF	8F	4M	6D
RLO2	1	LCL	P	10	10	10	10	6VF	6VF	8F	4M	6D
RLP	1	LCL	H	10	6F	10	8F	6F	6F	8F	6D	
RLP1	1	LCL	H	6F	6MD	6M	6MD	6MD	6D	6D		
RLP2	1	LCL	H	10	6F	8F	6F	6F	6F	6F	6D	
RLQ	4	HCL	P	10	10	10	10	6F	4M	4MD	2D	4D
RLQ1	4	HCL	P	10	10	10	10	6F	4M	4MD	2D	4D
RLQ2	4	HCL	P	10	10	10	10	4F	4M	4M	2D	4D
RLR	4	HCL	H	10	10	8VF	6F	6F	4MD	4MD	2D	3D
RLR1	4	HCL	H	10	10	8VF	6F	4M	4MD	4M	2D	3D
RLR2	4	HCL	H	10	10	8VF	6F	4M	3M	4MD	2D	3D
RLS	4	LCL	P	10	10	10	10	10	10	10	10	8D
RLS1	4	LCL	P	10	10	10	10	10	10	10	10	8D
RLS2	4	LCL	P	10	10	10	10	10	10	10	10	8D
RLT	4	LCL	H	10	10	10	10	8MD?	8D	8D	8D	6D
RLT1	4	LCL	H	10	10	10	10	8MD?	8MD	6MD	6D	6D
RLT2	4	LCL	H	10	10	10	4F	6M	6MD	6MD	6D	6D
RLU	6	HCL	P	10	10	8F	6F	6M	4M	4M	4MD	4MD
RLU1	6	HCL	P	10	10	8F	8M	6M	4M	4M	2MD	3MD
RLU2	6	HCL	P	10	10	10	8F	6F	4M	4M	2MD	3MD
RLV	6	HCL	H	10	10	8MD	6MD	6MD	4MD	4MD	4D	4D
RLV1	6	HCL	H	10	10	8MD	6M	6MD	4MD	4MD	4MD	6D
RLV2	6	HCL	H	10	10	8MD	6M	6MD	4M	4M	4MD	6D
RLW	6	LCL	P	10	10	10	10	10	6M	10	6MD	6MD
RLW1	6	LCL	P	10	10	10	10	10	10	10	8M	8M
RLW2	6	LCL	P	10	10	8F	6F	6M	6M	6M	6MD	6MD
RLX	6	LCL	H	10	10	10	6F	6F	6F	6F	6M	8D
RLX1	6	LCL	H	10	10	10	8F	8M	8M	8M	6MD	6MD
RLX2	6	LCL	H	10	10	10	6M	6M	6M	6M	4MD	6MD
RLY	7	HCL	P	10	10	10	*	*	*	*	*	*
RLY1	7	HCL	P	10	10	10	*	*	*	*	*	*
RLY2	7	HCL	P	10	10	10	*	*	*	*	*	*
RLZ	7	HCL	H	10	10	10	*	*	*	*	*	*
RLZ1	7	HCL	H	10	10	10	*	*	*	*	*	*
RLZ2	7	HCL	H	10	10	10	*	*	*	*	*	*
RMA	7	LCL	P	10	10	10	*	*	*	*	*	*
RMA1	7	LCL	P	10	10	10	*	*	*	*	*	*
RMA2	7	LCL	P	10	10	10	*	*	*	*	*	*
RMB	7	LCL	H	10	10	10	*	*	*	*	*	*
RMB1	7	LCL	H	10	10	10	*	*	*	*	*	*
RMB2	7	LCL	H	10	10	10	*	*	*	*	*	*

Table 29. Branch B -- UV-condensation/freeze-thaw rust ratings.

I.D.	P.S.	TYPE	S.P.	48	120	192	219	288	504	764	1128	1368
RMC	1	HCL	P		10		10				10	10
RMC1	1	HCL	P	10	10		10				10	10
RMC2	1	HCL	P			10			9	9	8	
RMD	1	HCL	H	9	9+		8				7	6
RMD1	1	HCL	H	10	10		9				7	6
RMD2	1	HCL	H			10		8	8	7	2	
RME	1	LCL	P	10	10		10				10	10
RME1	1	LCL	P	10	10		10				10	10
RME2	1	LCL	P			10			10	10	10	
RMF	1	LCL	H	10	10		10				10	10
RMF1	1	LCL	H	10	10		10				10	10
RMF2	1	LCL	H			10			10	10	10	
RMG	4	HCL	P	10	10		10				10	10
RMG1	4	HCL	P	10	10		10-				10	10
RMG2	4	HCL	P			10			10	10	10	
RMH	4	HCL	H	10-	9		9				8+	9
RMH1	4	HCL	H	9	9		9				8	7
RMH2	4	HCL	H			8		8	8	7	7	
RMI	4	LCL	P	10	10		10				10	10
RMI1	4	LCL	P	10	10		10				10	9+
RMI2	4	LCL	P			10			10	10	10	
RMJ	4	LCL	H	10	10		10				10	10
RMJ1	4	LCL	H	10	10		10				10	10
RMJ2	4	LCL	H			10			10	10	10	
RMK	4	HCL	P	9+	9		9+				9	10
RMK1	4	HCL	P	9 -	8		8				8	8
RMK2	4	HCL	P			9		8+	8+	8	8	
RML	4	HCL	H	8+	8	7	8		8		8	8
RML1	6	HCL	H	8	7		8				7	7
RML2	6	HCL	H					7		7	7	
RMM	6	LCL	P	10	10	10	10		10		10	10
RMM1	6	LCL	P	10-	10		9+				9	
RMM2	6	LCL	P							10	10	9+
RMN	6	LCL	H	9+	9	9	9+		8+		9	9
RMN1	6	LCL	H	9	9		9				9	9
RMN2	6	LCL	H					8+		8	8	
RMO	7	HCL	P	9	9		9				6	6
RMO1	7	HCL	P	9	9		9				8	8
RMP	7	HCL	H	8	8		7				4	2
RMP1	7	HCL	H	8	9		8				6	6
RMQ	7	LCL	P	9	10		10				10	10
RMQ1	7	LCL	P	9	10		10				10	10
RMR	7	LCL	H		10		9				6	4
RMR1	7	LCL	H	9	10		10				8	10

Table 30. Branch B -- UV-condensation/freeze thaw blister ratings.

I.D.	P.S.	TYPE	S.P.	48	120	192	219	288	504	764	1128	1368
RMC	1	HCL	P	10	10		10				10	10
RMC1	1	HCL	P	10	10		10				10	10
RMC2	1	HCL	P			10		8F?	8F	8F	6F	
RMD	1	HCL	H	10	10		10				2M	2M
RMD1	1	HCL	H	10	10		10				6M	4MD
RMD2	1	HCL	H			10		6M	6M?	6M	2D	
RME	1	LCL	P	10	10		10				10	6MD
RME1	1	LCL	P	10	10		10				10	10
RME2	1	LCL	P			10		10	10	10	10	
RMF	1	LCL	H	10	10		10				10	6F
RMF1	1	LCL	H	10	10		10				10	10
RMF2	4	LCL	H			10		8F	8F	8M	6MD	
RMG	4	HCL	P	10	10		10				10	10
RMG1	4	HCL	P	10	10		10				10	10
RMG2	4	HCL	P			10		10	10	10	10	
RMH	4	HCL	H	10	10		10				4VF	4F
RMH1	4	HCL	H	10	10		10				4VF	4M
RMH2	4	HCL	H			4VF		4F	4M	4M	4M	
RMI	4	LCL	P	10	10		10				10	10
RMI1	4	LCL	P	10	10		10				10	10
RMI2	4	LCL	P			10		10	10	10	8F	
RMJ	4	LCL	H	10	10		10				10	10
RMJ1	4	LCL	H	10	10		10				10	10
RMJ2	4	LCL	H			10		10	10	10	10	
RMK	6	HCL	P	10	10		10				6VF	10
RMK1	6	HCL	P	10	10		10				6M	4M
RMK2	6	HCL	P			8F		8M	6M	4M	4M	
RML	6	HCL	H	10	8F		8F				2MD	2MD
RML1	6	HCL	H	10	10		8F				4MD	4MD
RML2	6	HCL	H			8M		8M	4F/6M	4-6MD	4MD	
RMM	6	LCL	P	10	10		10				10	10
RMM1	6	LCL	P	10	10		10				10	8F
RMM2	6	LCL	P			10		10	10	10	8F	
RMN	6	LCL	H	10	8VF		10				2F	2F
RMN1	6	LCL	H	10	10		10				6F	6F
RMN2	6	LCL	H			8M		8M	8MD	4-6M	4M	
RMO	7	HCL	P	10	10		10				8M	6F
RMO1	7	HCL	P	10	10		10				10	8F
RMP	7	HCL	H	10	10		-				4F	6D
RMP1	7	HCL	H	10	10		-				6MD	6D
RMQ	7	LCL	P	10	10		10				10	6F
RMQ1	7	LCL	P	10	10		10				10	8F
RMR	7	LCL	H	10	10		-				8M	10
RMR1	7	LCL	H	10	10		10				10	8F

Table 31. Branch C -- salt spray rust ratings.

ID	P.S.	TYPE	S.P.	24	48	72	96	258	456	744	816	1128	1266	1388	1722	2010	2394
RMS	1	HCL	D	10	10		10	9			4		0				
RMS1	1	HCL	D	10	10		10	10			4		0				
RMS2	1	HCL	D			10			8	8		6					
RMT	1	HCL	W	10	10		10 -	8			4		0				
RMT1	1	HCL	W	10	10		10	8			6		2				
RMT2	1	HCL	W			10			8	7		4					
RMU	1	HCL	P	10	10		9	8			4		0				
RMU1	1	HCL	P	10	10		9+	8			2		0				
RMU2	1	HCL	P			9+			7	6		2					
RMV	1	HCF	D	10	10		9+	8			6		4				
RMV1	1	HCF	D	10	10		9	7			2		0				
RMV2	1	HCF	D			10			8	7		4					
RMW	1	HCF	W	10	10		10	9			7		4				
RMW1	1	HCF	W	10	10		9+	8			6		2				
RMW2	1	HCF	W			10			8+	7		4					
RMX	1	HCF	P	10	10		9	8			2		0				
RMX1	1	HCF	P	10	10		9 -	7			0		- - - -				
RMX2	1	HCF	P			9+			6	2		- - - -					
RMY	1	LCF	D	10	10		10	9			6		4				
RMY1	1	LCF	D	10	10		10	9			6		2				
RMY2	1	LCF	D			10			9+	8		6					
RMZ	1	LCF	W	10	10		10	9			6		4				
RMZ1	1	LCF	W	10	10		10	9			7		4				
RMZ2	1	LCF	W			10			8	8		6					
RNA	1	LCF	P	10	10		10	10			7		6				
RNA1	1	LCF	P	10	10		10	10			7		6				
RNA2	1	LCF	P			10			8+	8		6					
RNB	1	M	D	10	10		10	8			6		4				
RNB1	1	M	D	10	10		10	10			7		6				

Table 31. Branch C -- salt spray rust ratings (continued).

ID	P.S.	TYPE	S.P.	24	48	72	96	258	456	744	816	1128	1266	1388	1722	2010	2394
RNB2	1	M	D			10			8	7		4					
RNC	1	M	W	10	10		10	9			7		7				
RNC1	1	M	W	10	10		10	10			8		7				
RNC2	1	M	W			10			10	8		8					
RND	1	M	P	10	10		10	9			8		7				
RND1	1	M	P	10	10		10	10			8		7				
RND2	1	M	P			10			10-	8		8					
RNE	3A	HCL	D	9	9		9	9			9		9	9	9	9	
RNE1	3A	HCL	D	9	9		9	8+			8+		8				
RNE2	3A	HCL	D			9			9	9		8					
RNF	3A	HCL	W	9	8+		8+	8+			8		8	8	8	8	
RNF1	3A	HCL	W	9	8		8+	8			8		8				
RNF2	3A	HCL	W			8			8	8		8					
RNG	3A	HCL	P	8	7		8	8			7		7				
RNG1	3A	HCL	P	8	7		8	8			7		7	7	8	7	
RNG2	3A	HCL	P			8			8	8		7+					
RNH	3A	HCF	D	9+	9+		9	9+			9		9	9	9+	9	
RNH1	3A	HCF	D	9+	9+		9	9+			9		9				
RNH2	3A	HCF	D			9-			9	9							
RNI	3A	HCF	W	9	9		9	9			9		9-	8+	8+	9-	
RNI1	3A	HCF	W	9	9		9	9			9		9	8	9	10	
RNI2	3A	HCF	W			10			10-	10-							
RNJ	3A	HCF	P	8+	8		8	8			7		8				
RNJ1	3A	HCF	P	8	8		8	8			7		7				
RNJ2	3A	HCF	P			8			8	7							
RNK	3A	LCF	D	10	10		10	10			10		10	9+	10	9+	
RNK1	3A	LCF	D	10	10		10	10			10		10				
RNK2	3A	LCF	D			9+			10-	9+							
RNL	3A	LCF	W	9	9		9	9			8		9				

Table 31. Branch C -- salt spray rust ratings (continued).

ID	P.S.	TYPE	S.P.	24	48	72	96	258	456	744	816	1128	1266	1388	1722	2010	2394
RNL1	3A	LCF	W	9	9		9	9			8		8	8	8	8	
RNL2	3A	LCF	W			9			9	8+							
RNM	3A	LCF	P	9+	9+		9+	9+			9+		9				
RNM1	3A	LCF	P	10	10		10	9+			9+		9	9	9+	9+	
RNM2	3A	LCF	P			9			9	9							
RNN	3A	M	D	10	10-		10	10			10		9	9	9	9	
RNN1	3A	M	D	10	10		10	10			10-		10				
RNN2	3A	M	D			10			9+	9+							
RNO	3A	M	W	10	10		10	9+			9		9	8	9	9	
RNO1	3A	M	W	10	10-		10	9			8		8				
RNO2	3A	M	W			9+			9	8							
RNP	3A	M	P	10	10		10	10			10		9	9+	10-	9+	
RNP1	3A	M	P	9+	10		10-	9+			9+		9				
RNP2	3A	M	P			10-			9+	9+							
RNQ	4	HCL	D	10	10		10	10			10		9	9	9	9	
RNQ1	4	HCL	D	10	10		10	10			10		9	8	9	9	
RNQ2	4	HCL	D			10			10	10							
RNR	4	HCL	W	10	10		10	10			9+		9	9	9	9	
RNR1	4	HCL	W	10	10		10	10			10		9	9	9	9	
RNR2	4	HCL	W			10			10	9+							
RNS	4	HCL	P	10	10		9	9			9		9	8	9	8	
RNS1	4	HCL	P	10	10		10	10			9+		9+	9	9+	9	
RNS2	4	HCL	P			10			10-	9+							
RNT	4	HCF	D	10	10		10	10			10		10	10	10	10	
RNT1	4	HCF	D	10	10		10	10			10		10	10	10	10	
RNT2	4	HCF	D			10			10	10							
RNU	4	HCF	W	10	10		10	10			10		10	9	9	9+	
RNU1	4	HCF	W	10	10		10-	10-			9		9+	9	9	9	
RNU2	4	HCF	W			10			10	10							

Table 31. Branch C -- salt spray rust ratings (continued).

ID	P.S.	TYPE	S.P.	24	48	72	96	258	456	744	816	1128	1266	1388	1722	2010	2394
RNV	4	HCF	P	10	10		10	9			9		9	8+	9	10	
RNV1	4	HCF	P	9+	10		9+	10			10		10	10	9	9	
RNV2	4	HCF	P			10			10	10-							
RNW	4	LCF	D	10	10		10	10			10		10	10	10	10	
RNW1	4	LCF	D	10	10		10	10			10		10	10	10-	9+	
RNW2	4	LCF	D			10			10	10							
RNX	4	LCF	W	10	10		10	10			9		9	8	8	8	
RNX1	4	LCF	W	10	10		10	10			9+		9	8	9-	8	
RNX2	4	LCF	W			10			10	9+							
RNY	4	LCF	P	10	10		10	10			10		10	9	9	9	
RNY1	4	LCF	P	10	10		10	10			10		10	10	10	10	
RNY2	4	LCF	P			10			10	10							
RNZ	4	M	D	10	10		10	10			10		10	10	10	10	
RNZ1	4	M	D	10	10		10	10			10		10	10	10	10	
RNZ2	4	M	D			10			10	10							
ROA	4	M	W	10	10		10	10			10		10	10	10	10	
ROA1	4	M	W	10	10		10	10			10		10	10	10-	9	
ROA2	4	M	W			10			10	10							
ROB	4	M	P	10	10		10	10			9+		9	9	9+	9+	
ROB1	4	M	P	10	10		10	10			10		9+	10	10	10	
ROB2	4	M	P			10			10	10							

Table 32. Branch C -- salt spray blister ratings.

I.D.	P.S.	TYPE	S.P.	24	48	72	96	258	456	744	816	1128	1266	1338	1722	2010	2394
RMS	1	HCL	D	10	10		10	6F			4D		- - - -				
RMS1	1	HCL	D	10	10		10	4F			2D		- - - -				
RMS2	1	HCL	D			10			6F	4D		2D					
RMT	1	HCL	W	10	10		10	10			2D		- - - -				
RMT1	1	HCL	W	10	10		10	10			2D		- - - -				
RMT2	1	HCL	W			10			6VF	4MD		4D					
RMU	1	HCL	P	10	8M		6M	6D			4D		- - - -				
RMU1	1	HCL	P	10	8M		6M	6D			4D		- - - -				
RMU2	1	HCL	P			6F			6D	6D		4D					
RMV	1	HCF	D	10	10		10	10			1MD		6D				
RMV1	1	HCF	D	10	10		10	10			6D		- - - -				
RMV2	1	HCF	D			10			10	6F		6MD					
RMW	1	HCF	W	10	10		10	10			2M		4D				
RMW1	1	HCF	W	10	10		10	10			2M		4D				
RMW2	1	HCF	W			10			10	4F		4D					
RMX	1	HCF	P	10	10		10	8M			4D		- - - -				
RMX1	1	HCF	P	10	8F		6M	8MD			4D		- - - -				
RMX2	1	HCF	P			8M			8MD	6D		- - - -					
RMY	1	LCF	D	10	10		10	8F			2M		6D				
RMY1	1	LCF	D	10	10		10	8F			2D		6D				
RMY2	1	LCF	D			10			10	2F		4MD					
RMZ	1	LCF	W	10	10		10	10			2MD		2D				
RMZ1	1	LCF	W	10	10		10	10			2MD		2D				
RMZ2	1	LCF	W			10			10	2M		2D					
RNA	1	LCF	P	10	10		10	10			4M		4MD				
RNA1	1	LCF	P	10	10		10	8F			6M		6D				
RNA2	1	LCF	P			10			8F	6M		6MD					
RNB	1	M	D	10	10		10	4F			2D		6D				
RNB1	1	M	D	10	10		10	6VF			2D		6D				
RNB2	1	M	D			10			6F	2M		2MD					
RNC	1	M	W	10	10		10	10			2M		1D				
RNC1	1	M	W	10	10		10	10			2M		1D				
RNC2	1	M	W			10			4VF	2M		2MD					
RND	1	M	P	10	10		10	10			2M		2MD				
RND1	1	M	P	10	10		10	6VF			1M		1MD				

Table 32. Branch C -- salt spray blister ratings (continued).

778	P.S.	TYPE	S.P.	24	48	72	96	258	456	744	816	1128	1266	1338	1722	2010	2394
RND2	1	M	P			10			4F	2M		2MD					
RNE	3A	HCL	D	10	10		10	10			10		10	10	10	10	10
RNE1	3A	HCL	D	10	10		10	10			10		10				
RNE2	3A	HCL	D			10			10	10		10					
RNF	3A	HCL	W	10	10		10	10			10		10	10	10	10	10
RNF1	3A	HCL	W	10	10		10	10			10		10				
RNF2	3A	HCL	W			10			10	10		10					
RNG	3A	HCL	P	10	10		10	6F			6VF		10				
RNG1	3A	HCL	P	10	10		10	6F			6VF		10	10	10	10	8F
RNG2	3A	HCL	P			10			6F	10		10					
RNH	3A	HCF	D	10	10		10	10			10		10	10	10	10	10
RNH1	3A	HCF	D	10	10		10	10			10		10				
RNH2	3A	HCF	D			10			10	10		10					
RNI	3A	HCF	W	10	10		10	10			10		10	10	10	10	10
RNI1	3A	HCF	W	10	10		10	10			10		10	10	10	10	10
RNI2	3A	HCF	W			10			10	10		10					
RNJ	3A	HCF	P	10	10		10	10			6F		4F				
RNJ1	3A	HCF	P	10	10		10	10			10		10				
RNJ2	3A	HCF	P			10			10	8F		10					
RNK	3A	LCF	D	10	10		10	10			10		10	10	10	10	10
RNK1	3A	LCF	D	10	10		10	10			10		10				
RNK2	3A	LCF	D			10			10	10		10					
RNL	3A	LCF	W	10	10		10	10			10		10				
RNL1	3A	LCF	W	10	10		10	10			10		10	10	10	10	10
RNL2	3A	LCF	W			10			10	10		10					
RNM	3A	LCF	P	10	10		10	10			10		10				
RNM1	3A	LCF	P	10	10		10	10			10		10	10	10	10	10
RNM2	3A	LCF	P			10			10	10		10					
RNN	3A	M	D	10	10		10	10			10		10	10	10	10	10
RNN1	3A	M	D	10	10		10	10			10		10				
RNN2	3A	M	D			10			10	10		10					
RNO	4	M	W	10	10		10	10			10		10	10	10	10	10
RNO1	4	M	W	10	10		10	10			10		10				
RNO2	4	M	W			10			10	10		10					
RNP	4	M	P	10	10		10	10			10		10	10	10	10	10

Table 32. Branch C -- salt spray blister ratings (continued).

I.D.	P.S.	TYPE	S.P.	24	48	72	96	258	456	744	816	1128	1266	1338	1722	2010	2394
RNP1	4	M	P	10	10		10	10			10		10				
RNP2	4	M	P			10			10	10		10					
RNQ	4	HCL	D	10	10		10	6M			6MD		6D	8MD	8D	6D	6MD
RNQ1	4	HCL	D	10	10		10	6M			6MD		6D	8MD	8D	6MD	6MD
RNQ2	4	HCL	D			10			6F	8M		6MD					
RNR	4	HCL	W	10	10		10	10			10		8VF	8F	8F	6F	8F
RNR1	4	HCL	W	10	10		10	10			10		10	10	8F	6F	8F
RNR2	4	HCL	W			10			10	10		8F					
RNS	4	HCL	P	10	10		10	4MD			2D		4D	4D	4MD	4MD	4MD
RNS1	4	HCL	P	10	10		10	2MD			2D		2D	4D	4MD	4MD	4MD
RNS2	4	HCL	P			10			4MD	4D		4D					
RNT	4	HCF	D	10	10		10	10			10		10	8F	8VF	10	8F
RNT1	4	HCF	D	10	10		10	10			10		10	10	10	10	10
RNT2	4	HCF	D			8F			8M	8M		8M					
RNU	4	HCF	W	10	10		10	10			10		6VF	6F	6VF	6F	6F
RNU1	4	HCF	W	10	10		10	10			6VF		6F	6F	6VF	6F	6F
RNU2	4	HCF	W			10			10	10		8F					
RNV	4	HCF	P	10	10		10	6D			6D		6D	6MD	8MD	7MD	6MD
RNV1	4	HCF	P	10	10		10	8M			8M		8D	8MD	8MD	8MD	8MD
RNV2	4	HCF	P			8F			8MD	8MD		8MD					
RNW	4	LCF	D	10	10		10	10			10		10	10	10	10	10
RNW1	4	LCF	D	10	10		10	10			10		10	10	10	10	10
RNW2	4	LCF	D			10			10	10		10					
RNX	4	LCF	W	10	10		10	10			10		10	10	10	10	10
RNX1	4	LCF	W	10	10		10	10			10		10	10	8M	10	10
RNX2	4	LCF	W			10			10	10		10					
RNY	4	LCF	P	10	10		10	10			10		8MD	8M	8D	8MD	8D
RNY1	4	LCF	P	10	10		10	10			10		8MD	10	8D	8MD	8D
RNY2	4	LCF	P			10			10	10		10					
RNZ	4	M	D	10	10		10	10			10		6VF	10	6VF	6F	6F
RNZ1	4	M	D	10	10		10	10			10		10	10	8VF	10	8F
RNZ2	4	M	D			10			10	10		8F					
ROA	4	M	W	10	10		10	10			10		10	10	10	10	10
ROA1	4	M	W	10	10		10	10			10		10	10	8VF	10	8F
ROA2	4	M	W			10			10	10		10					

Table 32. Branch C -- salt spray blister ratings (continued).

I.D.	P.S.	TYPE	S.P.	24	48	72	96	258	456	744	816	1128	1266	1338	1722	2010	2394
ROB	4	M	P	10	10		10	10			10		10	10	10	10	10
ROB1	4	M	P	10	10		10	10			10		10	10	8M	10	8M
ROB2	4	M	P			10			10	10		10					

Table 33. Branch D -- salt spray rust ratings.

ID	P.S.	TYPE	S.P.	24	48	72	144	216	360	408	960	1512
ROC	3B	HCL	D	10	10	10	9+	9+	9+	9+	9	9+
ROC1	3B	HCL	D	9	9	9	9	9-	9	9	9	9
ROC2	3B	HCL	D	9	9	9	9	9-	9	9	8	8+
ROD	3B	HCL	W	10	10	10	10	9+	9	9+	9	9
ROD1	3B	HCL	W	10	10	10	10	10	10	10	9	9+
ROD2	3B	HCL	W	10	10	10	10	10-	10-	10-	9	9
ROE	8	HCL	D	10	10	10	10	10	10	10	10	10
ROE1	8	HCL	D	10	10	10	10	10	10	10	10	10
ROE2	8	HCL	D	10	10	10	10	10	10	10-	10	10
ROF	8	HCL	W	10	10	10	10	10	10	10	10	10
ROF1	8	HCL	W	10	10	10	10	10	10	10	10	10
ROF2	8	HCL	W	10	10	10	10	10	10	10	10	10

Table 34. Branch D -- UV-condensation/freeze-thaw rust and blister ratings.

BRANCH D-UV/FT (rust).												
I.D.	P.S.	TYPE	S.P.	48	120	192	219[1]	288	504	764	1128	1368
ROG[1]	3B	HCL	D	10	10		10				10	10
ROG1	3B	HCL	D			10		10	10	10	10	
ROG2	3B	HCL	D			10		10	10	10	10	
ROH[1]	3B	HCL	W	10	10		10				10	10
ROH1	3B	HCL	W			10		10	10	10	10	
ROH2	3B	HCL	W			10		10	10	10	10	
ROI[1]	8	HCL	D	10	10		10				10	10
ROI1	8	HCL	D			10		10	9+	10	10	
ROI2	8	HCL	D			10		10	10	10	10	
ROJ[1]	8	HCL	W	10	10		10				10	10
ROJ1	8	HCL	W			10		10	10	10	10	
ROJ2	8	HCL	W			10		10	10	10	10	

[1] panels were in freezer for several days while UV/CON was down

BRANCH D-UV/FT (blister).												
I.D.	P.S.	TYPE	S.P.	48	120	192	219[1]	288	504	764	1128	1368
ROG[1]	3B	HCL	D	10	10		10				10	10
ROG1	3B	HCL	D			10		10	10	10	10	
ROG2	3B	HCL	D			10		10	10	10	10	
ROH[1]	3B	HCL	W	10	10		10				10	10
ROH1	3B	HCL	W			10		10	8MD	10	10	
ROH2	3B	HCL	W			10		10	8MD	10	10	
ROI[1]	8	HCL	D	10	10		10				10	10
ROI1	8	HCL	D			10		10	10	10	10	
ROI2	8	HCL	D			10		10	10	10	10	
ROJ[1]	8	HCL	W	10	10		10				10	10
ROJ1	8	HCL	W			10		10	10	10	10	
ROJ2	8	HCL	W			10		10	10	10	10	

[1] panels were in freezer for several days while UV/CON was down

REFERENCES

1. J. D. Culp and G. L. Tinklenberg,"Interim Report on Effects of Corrosion on Bridges of Unpainted A588 Steel and Painted Steel Types," Research Report No. R-1142, Michigan Department of State Highways and Transportation, Lansing, MI 1980.

2 C. J. Arnold, "Unpainted Weathering Steel Bridges in Michigan," Michigan Department of State Highways and Transportation, Testing and Research Division, Lansing, Michigan, 1980. Paper presented at Transportation Research Board Meeting, Washington DC.

3. AISI Task Group on Weathering Steel Bridges, Performance of Weathering Steel in Highway Bridges, A First Phase Report, American Iron & Steel Institute, Washington, DC 1982.

4. D. G. Manning, Accelerated Corrosion in Weathering Steel Bridges ME-84-03, and Accelerated Corroosion in Weathering Steel Bridges - An Update, ME-84-04, Ontario Ministry of Transportation, Downsview, Ontario, Canada, December 1984.

5. P. Albrecht and A. H. Naeemi Performance of Weathering Steel in Bridges, NCHRP Report 272, Transportation Research Board, Washington DC, July 1984.

6 R. L. McCrum, C. J. Arnold, and R. P. Dexter, Current Status Report, Effects of Corrosion on Unpainted Weathering Steel Bridges, Research Report No. R-1255, Michigan Transportation Commission, Lansing Michigan, February 1985.

7. A. Raman, Evaluation of Surface Modification Methods to Mitigate Rusting and Pitting in Weathering Steel Bridges, Report FHWA/LA-87/197, Louisiana Transportation Research Center, Baton Rouge, LA, September 1986.

8. H. R. Copson and C. P. Larrabee, "Extra Durability of Paint on Low-Alloy Steels," ASTM Bulletin, American Society for Testing and Materials, Philadelphia, PA, December 1959.

9. R. J. Schmitt and W. L. Matthay, "Tests Show Performance of Low-Alloy Steels in Chemical Plant Environments," Materials Protection, Vol. 6, No. 9, 1967, pp. 37-42.

10. S. K. Coburn, "Increasing Container Service Life with Painted USS COR-TEN Steel," Container Technology, Volume II, Proceedings of 2nd Container Technology Conference, Brighton, England, December 1987, pp. 177-199.

11. A. S. Storad, "Coating Systems for High Strength, Low-Alloy Steels: Are They Necessary?" Paper 288, Proceedings of Corrosion/83, National Association of Corrosion Engineers, Houston TX (1983).

12. Y. Nakayama, "Durability of Paint on Atmospheric Corrosion-Resistant Steels," Chemical Abstracts, Vol. 76, 1972.

13. J. F. H. Van Eijnsbergen, "Weathering Steels Versus Ordinary Structural Steels as a Base for Paint," Cargo Systems International, Vol. 5, No. 6, 1979, pp. 101-103.

14. G. Kruska, L. Jenal, M. Krummenacher, and E. Seeber, "Weather and Corrosion Resistance of Coated and Uncoated Low-Alloy and Stainless Steels Versus that of Unalloyed Steel," Congress FATIPEC, Vol. 15, No. 3, pp. 166-177, 1980.

15. J. D. Keane, J. A. Bruno, R. E. F. Weaver and H. E. Hower, Remedial Painting of Weathering Steel: State of the Art Survey, SSPC Report 84-02, Steel Structures Painting Council, Pittsburgh, PA, 1984.

16. D. N. Nash, A. J. Eickhoff, and N. E. Pisani, , "Coatings Performance on Low-Alloy Weathering Steel: A 20-Year Study," Federation of Societies for Coatings Technology, Annual Meeting, Detroit, MI October 28-30, 1981.

17. H. W. Wonders and W. P. Gallagher, "The Use of Zinc-Rich Primers on Salt-Contaminated USS COR-TEN Steel," USS Research Report, USX, Pittsburgh, PA.

18. J. G. Raska, "A New Cleaning Procedure and Paint System for Weathering Steel in Marine Atmospheres", Journal of Protective Coatings & Linings, Vol. 3, No. 3, March 1986, p. 5.

19. G. L. Tinklenberg, "Corrosion of Unpainted Weathering Steel," Proceedings of Second World Congress on Coating Systems for Bridges and Steel Structures, (New York, NY 1982), University of Missouri, Rolla, MO, 1982.

20. J. R. O'Leary, P. Barton, B. G. Shuler, ., "Arresting Corrosion of Weathering Steel," Final Report, Research Project 66, West Virginia Dept. of Highways, Charleston WV, 1987.

21. Sakai, T., and Tokunaga, S., "Maintenance-Free Service of Weathering Steel by Rust Stabilization Accelerating Treatment," Corrosion/79, National Association of Corrosion Engineers, Houston, TX, 1979.

22. Nippon Steel Corporation, "Characteristics of Cor-Ten Steel With Weather-Coat Coating," 8th International Cor-Ten Conference, Borlange, Sweden, June 1974.

23. Congress, N., “Forum on Weathering Steel for Highway Structures: Summary Report,” FHWA-TS-89-016, Federal Highway Administration, Washington, DC, June 1989.