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## Characterization of the Environment

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16. Abstract  The study on which this report is based sought to compile data on both accelerated and natural exposure of coating and corrosion test panels and then to relate their deterioration to environmental conditions. The report presents data gathered over a 5-year period, incorporating seven different test sites across the United States. Specifically, the report looks at how the local environment affects the performance of eight coating systems and two weathering steels. For coated steel, the report concludes that an absolute humidity of 0.015 moles H <sub>2</sub> O/mole of dry air is the critical level for increasing the likelihood of corrosion. In such environments, a bridge engineer should utilize a zinc-rich coating system to prevent premature failures. Blistering failure is predominant in panels with high initial salt contamination on the substrate. To minimize failure due to blistering, the substrate should be as clean as possible. Cutback is chiefly affected by the high amount of rainfall and salt-fall (marine environments). A zinc-rich coating system is the best method for preventing cutback and should be incorporated unless the environment exhibits low annual rainfall and little salt contamination. Loss of gloss was mainly related to southern latitudes, while color change was most closely related to high relative humidity. For weathering steels, it was concluded that most high-chloride marine sites are unsuitable environments. It is expected that the information found and presented will be a useful resource to bridge maintenance engineers for coating selection decisions.					
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# SI\* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS FROM SI UNITS

APPROXIMATE CONVERSIONS TO SI UNITS		APPROXIMATE CONVERSIONS FROM SI UNITS							
Symbol	When You Know	Multiply By	To Find	Symbol	When You Know	Multiply By	To Find	Symbol	
<b>LENGTH</b>				<b>LENGTH</b>					
in	inches	25.4	millimeters	mm	millimeters	0.039	inches	in	
ft	feet	0.305	meters	m	meters	3.28	feet	ft	
yd	yards	0.914	meters	m	meters	1.09	yards	yd	
mi	miles	1.61	kilometers	km	kilometers	0.621	miles	mi	
<b>AREA</b>				<b>AREA</b>					
in <sup>2</sup>	square inches	645.2	square millimeters	mm <sup>2</sup>	square millimeters	0.0016	square inches	in <sup>2</sup>	
ft <sup>2</sup>	square feet	0.093	square meters	m <sup>2</sup>	square meters	10.764	square feet	ft <sup>2</sup>	
yd <sup>2</sup>	square yards	0.836	square meters	m <sup>2</sup>	square meters	1.195	square yards	yd <sup>2</sup>	
ac	acres	0.405	hectares	ha	hectares	2.47	acres	ac	
mi <sup>2</sup>	square miles	2.59	square kilometers	km <sup>2</sup>	square kilometers	0.386	square miles	mi <sup>2</sup>	
<b>VOLUME</b>				<b>VOLUME</b>					
fl oz	fluid ounces	29.57	milliliters	mL	milliliters	0.034	fluid ounces	fl oz	
gal	gallons	3.785	liters	L	liters	0.264	gallons	gal	
ft <sup>3</sup>	cubic feet	0.028	cubic meters	m <sup>3</sup>	cubic meters	35.71	cubic feet	ft <sup>3</sup>	
yd <sup>3</sup>	cubic yards	0.765	cubic meters	m <sup>3</sup>	cubic meters	1.307	cubic yards	yd <sup>3</sup>	
NOTE: Volumes greater than 1000 l shall be shown in m <sup>3</sup> .									
<b>MASS</b>				<b>MASS</b>					
oz	ounces	28.35	grams	g	grams	0.035	ounces	oz	
lb	pounds	0.454	kilograms	kg	kilograms	2.202	pounds	lb	
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T	
<b>TEMPERATURE (exact)</b>				<b>TEMPERATURE (exact)</b>					
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F	
<b>ILLUMINATION</b>				<b>ILLUMINATION</b>					
fc	foot-candles	10.76	lux	lx	lux	0.0929	foot-candles	fc	
f	foot-Lamberts	3.426	candela/m <sup>2</sup>	cd/m <sup>2</sup>	candela/m <sup>2</sup>	0.2919	foot-Lamberts	f	
<b>FORCE and PRESSURE or STRESS</b>				<b>FORCE and PRESSURE or STRESS</b>					
lbf	poundforce	4.45	newtons	N	newtons	0.225	poundforce	lbf	
lbf/in <sup>2</sup>	poundforce per square inch	6.89	kilopascals	kPa	kilopascals	0.145	poundforce per square inch	lbf/in <sup>2</sup>	

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

(Revised September 1993)

## TABLE OF CONTENTS

<b>BACKGROUND .....</b>	<b>1</b>
<b>OBJECTIVES .....</b>	<b>3</b>
<b>CONCLUSIONS .....</b>	<b>5</b>
<b>RECOMMENDATIONS.....</b>	<b>7</b>
<b>EXPERIMENTAL APPROACH .....</b>	<b>9</b>
<b>1. OVERVIEW.....</b>	<b>9</b>
<b>2. TEST SITES.....</b>	<b>9</b>
2.1. Location.....	9
2.2. Exposure Testing.....	10
<b>3. TEST MATERIALS.....</b>	<b>13</b>
3.1. Coated Samples .....	13
3.2. Bare Steel Samples .....	15
<b>4. ENVIRONMENTAL MONITORING .....</b>	<b>15</b>
4.1. Rainwater Contamination .....	16
4.2. Temperature, Humidity, and Time-of-Wetness .....	16
<b>5. ACCELERATED TESTING.....</b>	<b>18</b>
<b>6. DATA ANALYSIS.....</b>	<b>19</b>
6.1. Rating Procedures .....	19
6.2. General Corrosion Rates .....	21
<b>RESULTS AND DISCUSSION .....</b>	<b>23</b>
<b>1. ENVIRONMENTAL CONDITIONS .....</b>	<b>23</b>
<b>2. PAINT DETERIORATION .....</b>	<b>23</b>
2.1. Accelerated Testing.....	23
2.2. Natural Exposure Testing.....	29
2.3. Effects of the Environment.....	38
2.4. Correlations Between Accelerated Tests and Environmental Exposure .....	48
<b>3. GENERAL CORROSION RATE TESTING.....</b>	<b>51</b>
3.1. Accelerated Tests.....	51
3.2. Natural Exposure Tests .....	52
3.3. Discussion of Corrosion Rate Data .....	52
<b>REFERENCES.....</b>	<b>57</b>
<b>APPENDIX I. DATA PLOTS.....</b>	<b>59</b>
<b>APPENDIX II. SUMMARY OF COATING MATERIAL SELECTION AS A FUNCTION OF THE ENVIRONMENT .....</b>	<b>93</b>

## LIST OF FIGURES

### RESULTS

1(a). Typical test panel exposure rack.....	11
1(b). Test assemblies for weathering and coated steel test coupons.....	12
2. Panel layout with U-channels and holidays.....	13
3. Time-of-wetness gauge.....	17
4. Accelerated testing rust ratings, all systems, SSPC SP-10 substrate.....	24
5. Accelerated testing rust ratings, all systems, SSPC SP-3 substrate.....	25
6. Accelerated testing blister ratings, all systems, SSPC SP-10 substrate.....	26
7. Accelerated testing blister ratings, all systems, SSPC SP-3 substrate.....	27
8. Accelerated testing cutback, all systems, SSPC SP-10 substrate.....	28
9. Accelerated testing cutback, all systems, SSPC SP-3 substrate.....	29
10. Natural exposure testing rust ratings, all systems, SSPC SP-10 substrate.....	30
11. Natural exposure testing rust ratings, all systems, SSPC SP-3 substrate.....	31
12. Natural exposure testing blister ratings, all systems, SSPC SP-10 substrate.....	32
13. Natural exposure testing blister ratings, all systems, SSPC SP-3 substrate.....	33
14. Natural exposure testing cutback, all systems, SSPC SP-10 substrate.....	34
15. Natural exposure testing cutback, all systems, SSPC SP-3 substrate.....	35
16. Change in gloss ratings vs. initial data.....	36
17. Percent area rusting vs. time-of-wetness (SP-10).....	39
18. Percent area rusting vs. relative humidity (SP-10).....	40
19. Percent area rusting vs. absolute humidity (SP-10).....	40
20. Percent area rusting vs. absolute humidity (SP-3).....	41
21. Percent area rusting, SSPC SP-3 vs. SSPC SP-10 substrate.....	42
22. Percent area rusting vs. rain conductivity (SP-3).....	43
23. Blistering vs. relative humidity (SP-3).....	44
24. Blistering vs. rainfall and temperature (SP-3).....	45
25. Blistering vs. time-of-wetness and corrosion rate (SP-3).....	45
26. Cutback vs. rainfall (SP-3).....	46
27. Cutback vs. rainfall (SP-10).....	47
28. Cutback as a function of daily temperature change.....	48
29. Spearman ranking of Prohesion test results vs. Arizona test results.....	49
30. Spearman ranking of Prohesion test results vs. Florida test results.....	50
31. Corrosion rate for steel alloys in accelerated tests.....	51
32. Total metal loss vs. time, all orientations.....	53
33. Corrosion loss vs. conductivity (modified Oregon data point).....	55

### ACCELERATED TEST RESULTS

#### Rusting Data

I-1. SSPC SP-10 substrates, systems 1-4.....	61
I-2. SSPC SP-10 substrates, systems 5-8.....	62
I-3. SSPC SP-3 substrates, systems 1-4.....	63
I-4. SSPC SP-3 substrates, systems 5-8.....	64

## LIST OF FIGURES (continued)

### Blistering Data

I-5. SSPC SP-10 substrates, systems 1-4 .....	65
I-6. SSPC SP-10 substrates, systems 5-8 .....	66
I-7. SSPC SP-3 substrates, systems 1-4 .....	67
I-8. SSPC SP-3 substrates, systems 5-8 .....	68

### Cutback Data

I-9. SSPC SP-10 substrates, systems 1-4 .....	69
I-10. SSPC SP-10 substrates, systems 5-8 .....	70
I-11. SSPC SP-3 substrates, systems 1-4 .....	71
I-12. SSPC SP-3 substrates, systems 5-8 .....	72

## NATURAL ENVIRONMENT EXPOSURE

### Rusting Data

I-13. SSPC SP-10, systems 1-4 .....	73
I-14. SSPC SP-10, systems 5-8 .....	74
I-15. SSPC SP-3, systems 1-4 .....	75
I-16. SSPC SP-3, systems 5-8 .....	76

### Blistering Data

I-17. SSPC SP-10, systems 1-4 .....	77
I-18. SSPC SP-10, systems 5-8 .....	78
I-19. SSPC SP-3, systems 1-4 .....	79
I-20. SSPC SP-3, systems 5-8 .....	80

### Cutback Data

I-21. SSPC SP-10, systems 1-4 .....	81
I-22. SSPC SP-10, systems 5-8 .....	82
I-23. SSPC SP-3, systems 1-4 .....	83
I-24. SSPC SP-3, systems 5-8 .....	84

### Gloss Data

I-25. ASTM D523, systems 1-4.....	85
I-26. ASTM D523, systems 5-8.....	86
I-27. Composite of all systems.....	87

### Color Data

I-28. Systems 1-4.....	88
I-29. Systems 5-8.....	89

### Corrosion Rate

I-30. A588 steel samples (bold and sheltered) .....	90
I-31. A36 steel samples (bold and sheltered) .....	91

## LIST OF TABLES

1. Coating systems tested .....	14
2. Conversion table – D714 to numerical rating .....	20
3. Water chemistry data .....	23
4. Wetness data.....	23
5. Corrosion rust-through (ASTM D610) for each coating system, average of all sites .....	31
6. Coating cutback for each coating system, average of all sites .....	35
7. Percent extrapolation of exposure data to the 5-year point.....	38
8. Projected coating deterioration at 5 years.....	39
9. Spearman ranking development for rusting of coatings over SSPC SP-10 substrates .....	49
10. Estimated material corrosion rates at 5 years of exposure time .....	52
11. Average corrosion rate ( $\mu\text{m}/\text{year}$ ) by exposure orientation.....	53
12. Summary of regression coefficients and predicted metal loss – A588 weathering steel.....	54

## BACKGROUND

Corrosion control of structural steel remains a critical issue for bridge engineers. For low-alloy carbon steels, the most common corrosion control method is the application of protective coatings. Alternatively, these structures may be fabricated from uncoated weathering steel.

There are a vast number of protective coatings marketed for the protection of low-alloy carbon steel. These systems may be applied over abrasive-blasted steel or power-tool-cleaned steel, depending on the system design requirements. The coating materials may range from low-cost resins to highly complex polymers, both organic and inorganic. To a significant degree, the more costly systems are suggested for use in more aggressive environments.

For low-alloy carbon steel, as an alternative to paint, weathering steel may be used as a structural material. Corrosion on weathering steel results in an oxide layer that can protect the steel from significant (structural) corrosion. This allows the bridge to survive uncoated for many years.<sup>(1-2)</sup> The protective quality of this oxide film can be a function of the local environment. In salt-laden environments, the material corrosion rate has been shown to increase significantly.<sup>(3)</sup> An exact threshold for this effect has not been determined.

Coating or material selection for a specific environment is typically based on performance reports. Performance reports contain historical data collected from coating/material manufacturers or independent studies. In many cases, these studies may not be indicative of the severity of the intended service environment. Instances can be found of material recommendations for a marine environment based on historical performance in a rural environment, which is generally less corrosive. Without reports that are "calibrated" for the intended environment, the performance of a coating system or a weathering steel cannot be forecast.

Lack of environmental exposure-specific performance data is a concern because material selection ultimately affects life-cycle cost. With exposure-specific performance data, material selection (coatings or substrate steel) can be optimized for the design life of the structure, maintenance cycle, and cosmetic concerns.

Recognizing these issues, the Federal Highway Administration (FHWA) initiated this program.

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## **OBJECTIVES**

The primary objectives of the program were to:

- Characterize the corrosivity of seven environments by exposing bridge structural materials, both with and without protective coatings, to conditions at these locations. Monitor their deterioration and the local conditions to provide a correlation, if any, between the environmental conditions and material performance.
- Conduct accelerated corrosion testing and compare these data to the data from the natural environmental exposure to illustrate the correlation of such tests and field performance.



## CONCLUSIONS

The following are the most significant conclusions regarding the program objectives:

1. The predominant environmental characteristics that increase the risk of through-film rusting appear to be increasing absolute humidity and, to a lesser degree, temperature. This is true for coatings applied over either The Society for Protective Coatings Surface Preparation level 10 or 3 (SSPC SP-10 or SP-3) surfaces. The critical level of increasing likelihood of corrosion is nominally 0.015 moles H<sub>2</sub>O/mole of dry air. Corrosion does not correlate with relative humidity.
2. The behavior described above suggests that corrosion is controlled by through-film moisture diffusion.
3. The predominant factor influencing blistering is the presence of substrate contamination. Without such salts, there is little tendency toward blistering.
4. Over the SSPC SP-3 prepared surfaces, blistering appears to increase with increased time-of-wetness and temperature. There also appears to be a corrosivity effect; in a non-corrosive environment, blistering will be reduced regardless of the time-of-wetness or surface contamination.
5. Coating cutback over an SSPC SP-3 substrate appears to increase significantly with rainfall, especially with annual levels above 130 cm. Over an SSPC SP-10 substrate, the relationship is not as clear. For an SP-10 substrate, there will be little cutback in arid environments (e.g., Arizona). Cutback will tend to increase with rainfall, yet some contamination of the rain is required (conductivity > 10 microsiemens per centimeter (μS/cm)). Over the SP-10 substrates, cutback in heavy rain environments (such as in Oregon) will be low, due to the purity of the rainfall. In areas of moderate rainfall, high salt-fall (such as in severe marine environments) will increase cutback. In areas of moderate rainfall and conductivity, cutback appears to increase with larger average daily temperature changes, suggesting a thermal cycling effect on coating stress.
6. Loss of gloss tends to accelerate in the southern latitudes. Over the course of the natural exposure (maximum time < 5 years), all systems lost the majority of their initial gloss.
7. The only characteristic that seemed to distinguish the degree of color change was relative humidity. This was most predominant in comparing the results from Arizona and Florida. In Arizona, there was little color change vs. that found in Florida.
8. The accelerated tests evaluated in the current study showed little general utility in predicting the rankings of material in natural environments. While there were some occurrences of a good correlation between a laboratory test and the environment, this was not a consistent behavior, suggesting that the correlations were more coincidental than repeatable.

9. The current data for the weathering steels are not of sufficient exposure duration to provide for a good assessment of environmental conditions causing corrosion. The only site where the steels appeared to be unsuitable was the high-chloride Sea Isle City, NJ site.
  
10. Appendix II provides a summary of the corrosivity and coating selection protocols developed by the program for the different test sites.

## RECOMMENDATIONS

1. To best use the data in coating selection for bridge structures, the design engineer should consider the local absolute and relative humidity, the local rainfall, and the presence of salts. These data can be obtained for a wide variety of locations across the United States from the National Oceanic and Atmospheric Administration (NOAA) and the National Atmospheric Deposition Program/National Trends Network (NADP/NTN) databases. Refer to Appendix II for a more comprehensive discussion of material selection.
2. If the principal concern is rust-through, the designer should utilize a zinc-rich system unless low absolute humidities are expected or unless the design life of the structure is limited.
3. To minimize blistering, make sure that the substrate is as clean as possible, unless the structure is in a low-rainfall area.
4. To minimize cutback, use a zinc-rich system unless the bridge will be in a low-rainfall area or one with little salt contamination.
5. Continue to monitor the corrosion of the weathering steel coupons exposed at each test site. This process should extend nominally for another 5-year period.
6. In order to improve the predictions of accelerated testing, further research should focus on a parametric evaluation of the key environmental parameters on coating performance. At a minimum, key elements include absolute humidity, temperature, temperature cycling, electrolyte conductivity, and time-of-wetness.



## EXPERIMENTAL APPROACH

### 1. OVERVIEW

This research project was conducted to characterize the corrosiveness of environments across the continental United States with respect to bridge coating systems and weathering steel. To determine the effects of the environment on corrosion at these sites, several environmental elements were examined. By correlating these elements to corrosion and paint deterioration rates, an understanding of their effects can be obtained.

Testing was conducted at seven different sites across the United States. Each of these sites had distinctive characteristics of temperature, rainfall, and chemical (especially chloride) contamination. At each site, both coated and uncoated material samples were exposed for nominal durations of up to 4.3 years.

During the natural exposure testing, environmental conditions were monitored at each site using different techniques. This included common atmospheric data, as well as local conditions such as hourly temperature, relative humidity, and time-of-wetness.

Periodically, corrosion rate and paint deterioration data were gathered using standard techniques. These data were eventually correlated to the environmental data obtained.

In addition to the testing in natural environments, accelerated testing was also conducted. These results were compared to those from the natural environments to show the utility of the accelerated tests for predicting real-world environmental effects.

### 2. TEST SITES

#### 2.1. Location

There were seven test sites selected for the current program. The following summarizes these sites. Four of the seven sites are NADP/NTN test locations. Such sites were selected to allow for cost-effective, concurrent acquisition of local atmospheric pollutant data. Three other sites are located at commercial panel exposure sites.

NADP/NTN is a 200-station wet deposition monitoring network. Sites are located nationally. The NADP/NTN program characterizes regional patterns of deposition on a national scale by excluding monitoring site locations in close proximity to point sources or large urban centers. The data are able to suggest the local trends with respect to deposition of sulfur oxides (SO<sub>x</sub>), nitrogen oxides (NO<sub>x</sub>), chlorides (Cl<sup>-</sup>), and rainfall.

**Oregon Site (OR):** Known as OR-10 (NADP/NTN), this site is located outside of Eugene, Oregon. The station is in the H.J. Andrews Experimental Forest in Lane County, Oregon. The exact location is latitude 44°12'44", longitude 122°15'21", and elevation 450 m. The site is intended to be representative of a high time-of-wetness area with low levels of atmospheric pollutants.

**Louisiana Site (LA):** Known as LA-12 (NADP/NTN), this site is located near Lafayette, Louisiana. The station is the Iberia Research Station in Iberia County, Louisiana. The exact location

is latitude 29°55'47", longitude 91°42'55", and elevation 6 m. The site is intended to be representative of a high time-of-wetness, high-temperature area, with average levels of atmospheric pollutants.

**Massachusetts Site (MA):** Known as MA-01 (NADP/NTN), this site is located near the northernmost point of Cape Cod, on the ocean side. The station is the North Atlantic Coastal Laboratory in Barnstable County, Massachusetts. The exact location is latitude 41°58'33", longitude 70°01'29", and elevation 41 m. This was a lower temperature area with mid- to high-level chloride exposure, average time-of-wetness, and few atmospheric pollutants.

**Indiana Site (IN):** Known as IN-34 (NADP/NTN), this site is located in the northwest corner of Indiana, southeast of Chicago, near Michigan City. The station is the Indiana Dunes National Lakeshore in Porter County, Indiana. The exact location is latitude 41°37'57", longitude 87°05'16", and elevation 208 m. This site was representative of high SO<sub>x</sub>, high NO<sub>x</sub>, low-level chlorides, and average time-of-wetness.

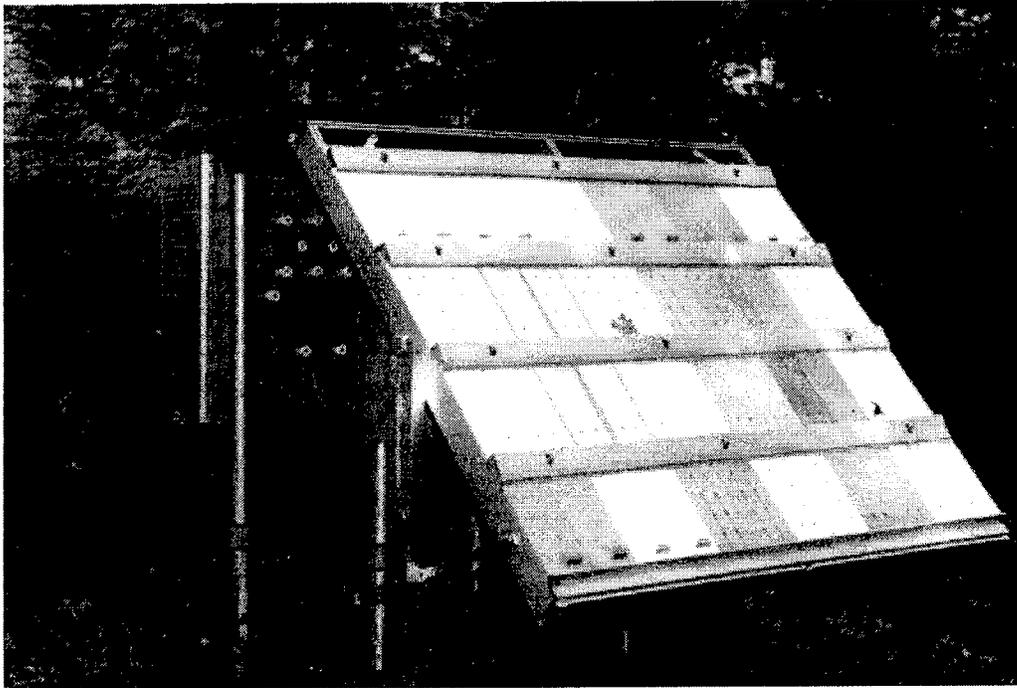
**New Jersey Site (NJ):** This site is not an NADP/NTN location. The site is in Sea Isle City, New Jersey. The exact location is latitude 39°10'00", longitude 74°40'00", and elevation 0 m. It is located within 30 m (100 ft) of the mean high tide of the Atlantic Ocean. This site represents a high-chloride location with a high time-of-wetness.

**Florida Site (FL):** This site is not an NADP/NTN site. It is located in the Miami, Florida area, several miles inland from the ocean. The exact location is latitude 25°56'00", longitude 80°25'00", and elevation 2 m. This was to be a high-temperature and high time-of-wetness site.

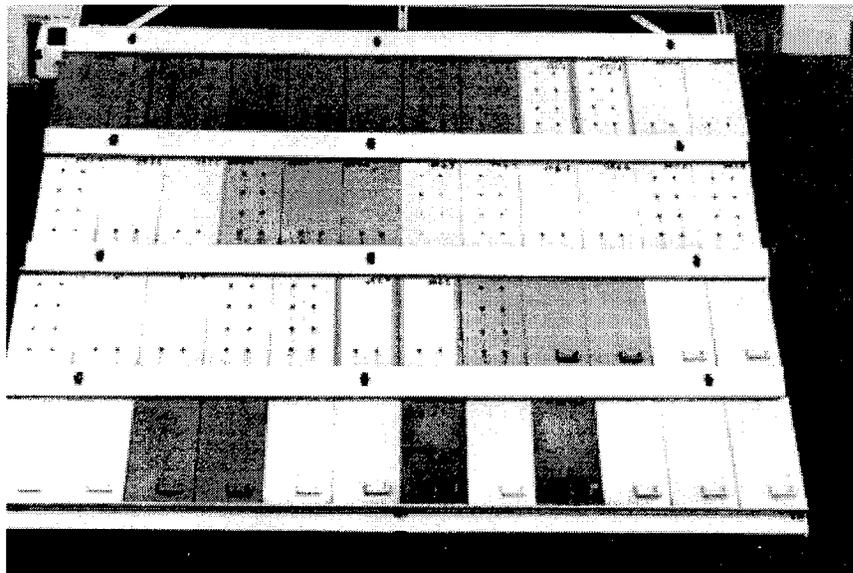
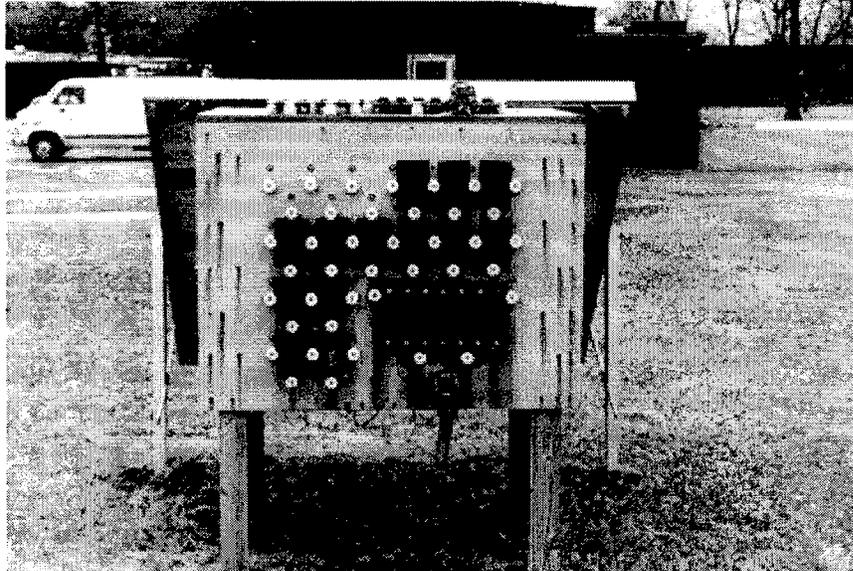
**Arizona Site (AZ):** This site is not an NADP/NTN site. It is located just north of Phoenix, in New River, AZ. The exact location is latitude 33°54'00", longitude 112°08'00", and elevation 610 m. This was intended to be a site with a low time-of-wetness, a high temperature, and few atmospheric pollutants.

## 2.2. Exposure Testing

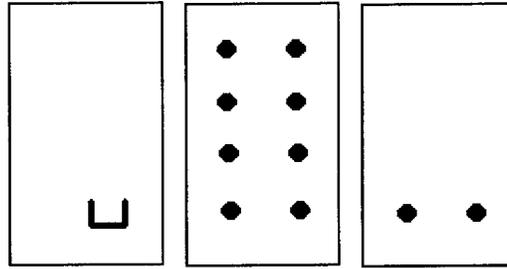
Each test site was similarly configured with painted test samples. All sites, with the exception of the Florida and Arizona sites, were outfitted with uncoated steel samples for corrosion rate determinations. Eight coating systems were tested at each location. These panels were prepared and placed on racks that faced South at a 45° angle, in accordance with ASTM D1014. Six panels of each coating system were exposed at the test sites. This included two U-channel panels painted over an SP-10 prepared surface, two flat panels painted over an SP-10 prepared surface, and two flat panels painted over an SP-3 prepared surface. Figure 1(a) shows a typical exposure rack and weathering steel test box. Figure 1(b) shows individual photographs of these test assemblies. Figure 2 describes the panel layout and intentional U-channels and holidays on each panel. The U-channel panel was holiday-free, the second SP-10 surface preparation panel had eight holidays on each face, and the SP-3 surface preparation panel had two holidays on the lower portion of the panel face.



**Figure 1(a). Typical test panel exposure rack.**



**Figure 1(b). Test assemblies for weathering (above) and coated steel test coupons (below).**



**Figure 2. Panel layout with U-channels and holidays.**

Uncoated, low-carbon alloy steel and weathering steel coupons were exposed in a variety of arrangements within an elevated test box. The test box was designed to simulate a number of orientations, both boldly exposed and sheltered, that might occur on a bridge. It was thought that the different orientations and sheltering conditions might affect the deposition of corrosive materials or the surface time-of-wetness. ASTM A588 weathering steel materials were exposed in the box at different orientations. The box was open only at the bottom. A door was on the east side. The south and east sides were vented, but minimal sunlight was allowed to enter. Twelve A588 weathering steel and four A36 steel coupons (100 mm by 150 mm by 6.3 mm) were exposed at each orientation. Four orientations were of interest:

- External on the north wall in a vertical position (north bold).
- Internal on the north wall in a vertical position (north sheltered).
- External on the top in a horizontal position (horizontal bold).
- Internal on the top in a horizontal position (horizontal sheltered).

### 3. TEST MATERIALS

#### 3.1. Coated Samples

This research project tested eight coating systems. Note that the intent of the project was to select a range of potential bridge coating materials to show how their performance may vary in different environments. It was not the specific intent to demonstrate “best performing” materials. Table 1 lists the coating system numbers, trade names, system type, specified dry film thickness (DFT’s), and rationale for inclusion. Ocean City Research Corporation prepared the panels in-house. Panels were prepared according to the manufacturer’s recommendations and environmental data were recorded during application.

**Table 1. Coating systems tested.**

System No.	Coating Trade Name	Coating System Type	Specified DFT (μm)	Rationale for Testing
1	<u>Carboline</u> Carbo-Zinc 11 HS Carboline 893 Carboline 834 (white)	Inorganic Zinc (IOZ)/Epoxy/Urethane	51-76/ 76/ 51-76	Low-VOC* system used in prior FHWA programs. Serves as a control.
2	<u>Rohm &amp; Haas</u> Rohm & Haas HG-56 Rohm & Haas G-46-1 Rohm & Haas P-46-1 (white)	3-Coat Waterborne Acrylic	51-76/ 51-76/ 51-76	System containing SZP-391; a calcium, strontium, zinc phosphosilicate inhibitive pigment, and HG-56; a new generation of waterborne acrylic resins.
3	<u>Ameron</u> Amercoat 3310 Amercoat 3301 (white)	Waterborne IOZ/Siloxane	76/ 76	Zero-VOC alternative, zinc-based system.
4	<u>Keeler and Long</u> Tri Polar Primer Silicone Enamel F-Series (gray)	3-Coat Silicone Alkyd	102-152/ none specified	Oil/alkyd; inhibitive primer with silicone alkyd topcoat; popular for bridge use.
5	<u>Watson</u> Armor Shield 8100 (gray)	Calcium Sulfonate Alkyd	203	Calcium sulfonate-based coating technology.
6	<u>Sherwin Williams</u> Zinc-Clad IV Heavy-Duty Epoxy High Solids Poly Urethane (white)	Organic Zinc (OZ)/Epoxy/Urethane	127-203/ 51-76	Low-VOC version of generic coating type.
7	<u>Valspar</u> Val Chem Epoxy Mastic 75-W-9W Urethane Enamel V40 Series (white)	Epoxy/Urethane	127-203/ 51-76	Generic epoxy-mastic/urethane with best performance to date in FHWA field tests evaluating compliant coatings.
8	<u>Xymax</u> Mono Prime Bridge Miox Bridge Finish (blue)	Moisture-Cured Urethane	51-76/ 76-102/ 38-51	Evaluate moisture-cured urethane coatings.

\*VOC-Volatile Organic Compound

Each coating system was applied over two substrate surface preparations. The first preparation method used abrasive blasting to an SSPC SP-10-rated substrate (near-white metal blast). The second preparation method used pre-rusted panels (from a marine environment) that were power-tool cleaned to an SSPC SP-3-rated substrate. These substrates represent traditional preparation methods used during bridge coating replacement and maintenance coating.

Application of the coating systems was done over three types of panels as described in figure 2. The nominal panel dimensions were 150 mm by 300 mm by 6.3 mm thick. The first type of panel was a U-channel panel (a flat panel with a U-shaped piece of steel welded on front) blasted to an SP-10 condition before painting. The second type of panel was a flat steel panel blasted to an SP-10 condition before painting and having eight 6.35-mm- (0.25-in-) diameter circular holidays made through the cured coating system to the substrate underneath. The third type of panel was a flat steel panel power-tool cleaned to an SP-3 condition before painting and having two 6.35-mm- (0.25-in-) diameter circular holidays made through the cured coating system to the substrate underneath. This panel had been pre-weathered in a marine environment before cleaning. Holidays were made using a 6.35-mm- (0.25-in) diameter drill bit that was specially fabricated to allow removal of the coating system without significant removal of the substrate material underneath. Duplicates of each coating system/panel type were evaluated in all accelerated and exposure test environments.

Each of these panel configurations was used to address certain issues often encountered during bridge painting. The U-channel panels were used to address possible problems encountered by hard-to-coat edges and surfaces that catch water. The panels with holidays were used to determine the ability of the coating to resist undercutting at a defect that penetrates to the substrate.

### **3.2. Bare Steel Samples**

All of the bare steel (A36 and A588) samples were uniformly prepared before exposure by abrasive blasting to remove any mill scale. The abrasive was commercial sand. No significant profile was produced.

## **4. ENVIRONMENTAL MONITORING**

The program attempted to gather a wide range of environmental data at each test site. A significant effort was made to obtain data in a uniform fashion. It was found that several sites had the benefit of a local National Atmospheric Deposition Program/National Trends Network (NADP/NTN) site, which collects environmental data in a uniform fashion. However, certain locations, that were chosen to capture a specific environmental effect, were not collocated with a NADP/NTN site making the data collection at these sites non-uniform. In the non-NADP/NTN sites, a technique that could be correlated or translated with each other was used. The specific data of interest can be broken down into two areas:

- Rainwater contamination (e.g., chlorides, SO<sub>x</sub>, conductivity).
- Temperature, humidity, and time-of-wetness.

#### 4.1. Rainwater Contamination

For the rainwater contamination data, the most significant source of data was the NADP/NTN database. The NADP/NTN rainwater contamination data was collected during the 1994/1995-exposure period for the Indiana, Louisiana, Massachusetts, and Oregon sites. There is no NADP/NTN site at the Arizona, Florida, or New Jersey test sites. For the Florida test site, 1996/1997 data from Cape Canaveral are displayed. For the Arizona site, 1996/1997 data from three sites in Arizona were averaged to be representative of the Phoenix area test site. For the New Jersey site, personnel obtained local 1996 pollutant data using slightly different methodologies than NADP/NTN. The most significant of these was the use of open collection apparatus during rain periods. Analysis of these samples followed conventional instrument and analytical chemistry techniques.

NADP/NTN test locations monitor many environmental factors, including chlorides, sulfides, and total rainfall. The NADP/NTN samples are collected in an AeroChem Metrics Model 301 wet/dry sampler. The wet side-sampling container is removed every Tuesday and mailed to the Central Analytical Laboratory. The pH and conductivity are measured if there is an adequate sample size. The chemical variables measured are concentrations of  $\text{SO}_4^{-2}$ ,  $\text{NO}_3^-$ ,  $\text{Cl}^-$ ,  $\text{PO}_4^{-3}$ ,  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{+2}$ ,  $\text{Mg}^{+2}$ ,  $\text{NH}_4^+$ , and  $\text{H}^+$ ; pH value; and conductivity. The cations and anions are analyzed by ion chromatography ( $\text{SO}_4^{-2}$ ,  $\text{NO}_3^-$ ,  $\text{Cl}^-$ , and  $\text{PO}_4^{-3}$ ), automated colorimetry ( $\text{NH}_4^+$ ), atomic absorption spectroscopy ( $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{+2}$ , and  $\text{Mg}^{+2}$ ), and ion-specific electrode ( $\text{H}^+$ ). Precipitation amounts are measured using a Belfort Model 5-780 dual-traverse recording rain gauge with a 305-mm (12-in) capacity.

#### 4.2. Temperature, Humidity, and Time-of-Wetness

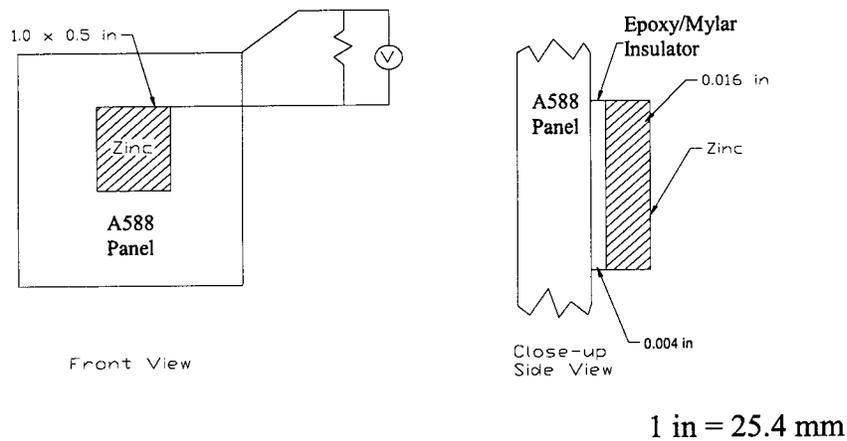
All sites other than the Florida and Arizona sites maintained local temperature, relative humidity, and time-of-wetness gauges. Data acquisition was facilitated by an Omega Model OM 220 data logger. These units have the capability of monitoring and storing up to 16 channels of data at varying rates. The OM 220 is capable of being accessed via a 9600-baud modem to download stored data and restart logging. The data logger could also store data for manual retrieval.

Due to periodic equipment failures at almost all the sites, it was difficult to obtain continuous data collection. Problems occurred with winter storms, animal damage, insect infestation, and electrical storms. However, sufficient data were collected over the complete program to allow a "composite" year to be constructed. Here, missing data were filled in with data from other exposure years for the same calendar period. The data should provide a fair portrait of the climatological trends at each location. Temperature and relative humidity data were also supplemented by other sources, such as NOAA data.

The environmental conditions monitored were local temperature, relative humidity, and time-of-wetness. These are considered important factors leading to general corrosion of painted and bare steel structures. Temperature and humidity were monitored using commercially available gauges. The temperature probe was capable of monitoring from  $-20$  to  $75^\circ\text{C}$  ( $-4$  to  $167^\circ\text{F}$ ) and outputting a 0 to 1V signal corresponding to the measured temperature. The humidity probe was similar in design to the temperature probe. It was capable of monitoring 0 to 100% relative humidity and outputting a 0 to 1V signal corresponding to the measured humidity. For reporting, the tempera-

ture and humidity were averaged over a 1-year period and compared with climatological data obtained from NOAA. The NOAA data supplemented the local data where there was less than 1 year of collected data. The values reported were a yearly average temperature and percent relative humidity at each exposure site. An absolute humidity was calculated at each site from the relative humidity and temperature data.

The time-of-wetness was monitored in all four exposure orientations by an apparatus developed by Ocean City Research Corporation personnel. This consisted of a weathering steel (A588) panel with an electrically isolated, centrally located zinc plate. Figure 3 shows a sketch of this apparatus (not to scale). The weathering steel panel was chosen (instead of the gold or platinum devices that were available) since the presence of a corrosion product may affect the time-of-wetness readings. If the surface wetness was not able to generate a corrosion current, then it would not be considered a significant surface wetness for the purposes of this experiment.



**Figure 3. Time-of-wetness gauge.**

Lead wires were attached to the steel panel and zinc plate. A 0.5-mega-ohm shunt resistor shorted the lead wires and the data logger measured the voltage across this resistor. This resistor was chosen due to the low internal resistance of the data logger (2 mega-ohms) and the fact that the logger attempts to read a voltage even at resistances exceeding its internal value. This results in the measurement of finite, unstable values. The 0.5-mega-ohm resistor minimizes the problem of extraneous recorded voltages.

When the panel is wet, whether due to rainwater or condensation, the circuit between the panel and the zinc is completed by the electrolyte (in this case, water). This will result in a current flow between the two and a resulting voltage drop across the shunt resistor. As the surface of the panel dries, little or no current flows through the resistor, resulting in no measurable voltage. A potential drop of 0.05V was chosen to indicate a wet surface; anything less than this value was chosen to indicate a dry surface. Using this criterion, it is possible to calculate the number of hours or monitor the hours that the panel was wet or dry. This process was determined to be reasonable through extensive trial testing.

The Florida and Arizona test sites did not have environmental monitors and were not located at an NADP/NTN weather station. These facilities maintain their own environmental equipment, which monitors daily temperature, relative humidity, and time-of-wetness. These data were treated the same as that collected by data loggers or provided by NOAA.

## **5. ACCELERATED TESTING**

Accelerated testing was conducted in accordance with ASTM B117, Standard Test Method of Salt Spray (Fog) Testing; the Mebon Prohesion test; and the Ocean City Research Corporation procedure for natural marine exposure testing accelerated with daily seawater spray. Testing was conducted for a total of 5,000 h salt fog (ASTM B117), 5,000 h Prohesion, and 14 months seawater accelerated marine exposure.

Panels were tested in accordance with ASTM B117. Test samples were placed on a non-metallic rack at a 15° angle from vertical. Environmental conditions within the chamber were maintained at 35°C +1.1°C or -1.7°C (95°F +2°F or -3°F). The fog was an atomized sodium chloride solution, which was 5% by weight. The collection rate throughout the test was maintained at 1 to 2 mL of solution collected per hour of testing (with an 8,000-mm<sup>2</sup> horizontal collection area). Samples remained in testing for 5,000 h, with inspections made at 1,000; 2,000; 4,000; and 5,000 h. At the end of testing, panels containing intentional holidays were destructively evaluated to determine maximum cutback from the holiday. Inspections were conducted in accordance with the methods listed below.

Panels underwent the Mebon Prohesion test. Test samples were placed on a non-metallic rack at a 15° angle from vertical within an accelerated corrosion test chamber. Environmental conditions within the chamber were cycled between a 1-h salt fog exposure at an ambient temperature and a 1-h dry-off exposure at 35°C (95°F). Samples remained in testing for 5,000 h, with inspections made at 1,000; 2,000; 4,000; and 5,000 h. At the end of testing, panels containing intentional holidays were destructively evaluated to determine maximum cutback from the holiday. Inspections were conducted in accordance with the methods listed below.

Accelerated marine exposure testing was done in accordance with Ocean City Research Corporation standard test procedures. Panels were exposed at a harsh marine atmospheric exposure site located in Sea Isle City, NJ. Exposure orientation was done in accordance with ASTM D1014, Standard Test Method for Conducting Exterior Exposure Tests of Paints on Steel. Panels were installed on wooden racks facing directly South at a 45° angle from horizontal. To accelerate the natural corrosion of the test panels, natural seawater was sprayed to wet each sample 5 days per week. Panels were exposed for a period of 14 months, with inspections at 4, 6, and 14 months. Inspections were conducted in accordance with the methods listed below.

## 6. DATA ANALYSIS

Paint deterioration was monitored in three accelerated test procedures and at all seven exposure locations. Exposed panels were evaluated for through-film rusting, corrosion at the U-channel, film blistering, and under-film corrosion at the intentional holidays. Panels under natural exposure testing were also evaluated for changes in gloss and color by instrumental methods. Regular inspections were made throughout the testing.

General corrosion was monitored in two of the accelerated tests and at five of the seven exposure locations (excluding Florida and Arizona). Uncoated steel samples (both structural and weathering steels) were exposed in these tests. Periodically, these samples were retrieved and all corrosion was removed from the surfaces. The mass loss due to corrosion was used to show the local corrosion at each site throughout the test period.

Inspections of these panels typically took place on a yearly basis and the panels still remain in testing at five of the seven exposure sites. The methods used to rate these observations and measurements are discussed below.

### 6.1. Rating Procedures

Paint deterioration was monitored using visual ratings of the condition of the coating system during accelerated and natural exposure tests. Visual ratings for rusting (ASTM D610), blistering (ASTM D714), under-film cutback at the scribes, gloss of the coating (ASTM D523), and color change of the coating (ASTM D2244) were obtained during each inspection.

**Rusting:** Panels were rated for through-film corrosion (rusting) in accordance with ASTM D610, Standard Test Method for Evaluating Degree of Rusting on Painted Steel Samples. Test samples are given a rating between 0 and 10, based on the percentage of the painted surface area showing rusting. These percentages are determined by comparison of the test pieces with visual standards contained within the procedure. The reported rating is the average rating observed on all panels in one test or at one exposure site with the same coating system and surface preparation. The composite rating is the average of all coating systems in one test or at one exposure site with the same surface preparation. Rusting, or lack thereof, was also noted at the U-channel.

**Blistering:** Panels were rated for film blistering in accordance with ASTM D714, Standard Test Method for Evaluating Degree of Blistering of Paints. Test panels are given a rating between 0 and 10, based on the size of the blister observed. Panels are also given a rating of N, F, M, MD, or D (none, few, medium, medium dense, and dense, respectively), based on the blister pattern

observed. These ratings are determined by comparison of the test pieces with visual standards contained within the procedure. For reporting purposes, this rating, containing both numbers and letters, was converted into a numerical rating. This new rating uses a 0-to-10 scale. Table 2 was used to convert the D714 rating to the new numerical rating.<sup>(4)</sup> The reported rating is the average observed on all panels in one test or at one exposure site with the same coating system and surface preparation. The composite rating is the average of all coating systems in one test or at one exposure site with the same surface preparation.

**Table 2. Conversion table – D714 to numerical rating.**

Density→	F	M	MD	D
Blister Size*				
None	10	10	10	10
8	8.44	7.5	6	2.5
6	6.89	5	3.7	1.1
4	5.33	3.8	2.5	0.75
2	3.78	2.6	1.65	0.35
0	0	0	0	0

\*ASTM D714

**Coating Cutback:** Panels were rated for coating cutback from the intentional holidays by measuring the **maximum** distance corrosion proceeded from the edge of the circular holiday. This distance was measured in inches and converted to the metric system. Cutback was observed as blistering and lifting of the coating directly adjacent to the holiday. The measurements were made by placing a clear sheet marked with concentric circles over the center of each holiday. The reported cutback is the average of the maximum cutback observed on all the panels in one test or at one exposure site with the same coating system and surface preparation. The composite cutback is the average of all coating systems in one test or at one exposure site with the same surface preparation.

**Gloss:** Panels were rated for change in gloss in accordance with ASTM D523, Standard Test Method for Specular Gloss. Readings were taken by using a Gardco Novogloss gloss meter at a 60° angle of reflectance. Measurements were taken in the center of each U-channel panel. Gloss measurements were taken prior to and during exposure testing, after cleaning the painted surface with potable water. The gloss reading provided by the instrument was recorded to show the change in gloss vs. exposure time at each site. The reported change in gloss is the average change observed on all panels in one test or at one exposure site with the same coating system and surface preparation.

**Color:** Panels were rated for overall change in color in accordance with ASTM D2244, Standard Test Method for Calculation of Color Differences From Instrumentally Measured Color Coordinates. Readings were taken using a Minolta ChromaColor CR231 colorimeter. Three readings were taken on each U-channel panel prior to and during exposure testing, after cleaning the painted surface with potable water. These readings were taken in the “L,” “a,” and “b” color spaces. Each of these components relates to the change in color of the coating. The “L” component is the change in brightness (a positive value is brighter and a negative value is darker). The

“a” component is the change in redness (a positive value is redder and a negative value is greener). The “b” component is the change in yellowness (a positive value is more yellow and a negative value is bluer). The “L,” “a,” and “b” measurements were plotted individually to discuss the trends demonstrated by each coating system at each exposure site.

## 6.2. General Corrosion Rates

General corrosion rate testing was performed on A36 structural steel and A588 weathering steel. These uncoated panels were exposed in both accelerated tests and in atmospheric exposure testing.

Accelerated exposure testing was done in one orientation since all locations within the environmental chamber receive similar exposure to environmental parameters. Prior to exposure, each panel was drilled with an identification code, blasted to an SP-10 surface condition, and had initial weight measurements taken. Replicate panels (two A36 and two A588) were tested in the Prohesion and salt fog test chambers. Panels were removed from the accelerated tests after 1,000 h.

Atmospheric exposure testing was done in the four unique orientations. Prior to exposure, each panel was drilled with an identification code, blasted to an SP-10 surface condition, and had initial weight measurements taken. Replicate panels (three A36 and twelve A588) were exposed in each orientation at the atmospheric exposure sites. One A588 panel was removed during each inspection at the exposure sites. One A36 panel was removed at varying intervals from the exposure sites, due to the limited number of samples available.

De-scaling was performed in one of two ways. The first method utilized a concentrated hydrochloric acid solution to remove the corrosion from each panel (in accordance with National Association of Corrosion Engineers (NACE) Standard TM-01-69). Although effective in removing corrosion, it often left voluminous waste products that had to be neutralized before disposal.

The second method used a fine glass bead abrasive blasting media (120 to 140 mesh) to remove the corrosion product (in accordance with the de-scaling procedure in General Motors Specification 9540P, Accelerated Corrosion Test). By using a fine medium, the corrosion present on the panel could be removed with negligible mass loss of good, non-corroded steel. In-house comparison of both methods on non-corroded panels shows that neither method, when used properly, removes significant amounts of intact steel.

Once de-scaled, the panels are weighed a second time to determine the total amount of non-corroded steel present. The net difference between the initial and final weights is the mass loss of steel due to corrosion. By knowing the total surface area of the panel and the density of the steel material, this mass loss value can be transformed into a penetration value. This was reported in micrometers. To quantify the corrosion rate of the sites, the penetration value is divided by the time interval over which the panel was exposed. This provides the penetration rate of the steel as a function of the exposure environment.



## RESULTS AND DISCUSSION

### 1. ENVIRONMENTAL CONDITIONS

The following table summarizes the yearly averages for key parameters related to the local environmental conditions.

**Table 3. Water chemistry data.**

Location	Ave. Temp., °C	pH	Cl <sup>-</sup> , ppm	SO <sub>4</sub> <sup>2-</sup> , ppm	NO <sub>3</sub> <sup>-</sup> , ppm	Conductivity, μS/cm
AZ	22.0	5.1	0.3	0.9	1.0	11.3
FL	24.0	5.0	1.4	1.2	0.7	20.1
IN	10.6	4.7	0.2	2.5	2.0	21.9
LA	21.8	4.8	0.7	1.1	0.8	13.3
MA	7.2	4.5	2.4	1.6	1.3	27.0
NJ	9.1	4.2	27.0	25.0	N/A	163.0
OR	8.6	5.2	0.3	0.3	0.27	4.7

- N/A: Not Available

**Table 4. Wetness data.**

Location	Precipitation, cm	% Time Wet	Relative Humidity, %	Absolute Humidity, moles H <sub>2</sub> O/mole of dry air
AZ	24.0	4.0	35.0	0.0105
FL	125.0	48.0	75.0	0.0241
IN	90.0	27.0	74.0	0.0096
LA	140.0	55.0	78.0	0.0180
MA	122.0	55.0	67.0	0.0097
NJ	150.0	51.0	70.0	0.0103
OR	223.0	70.0	79.0	0.0106

### 2. PAINT DETERIORATION

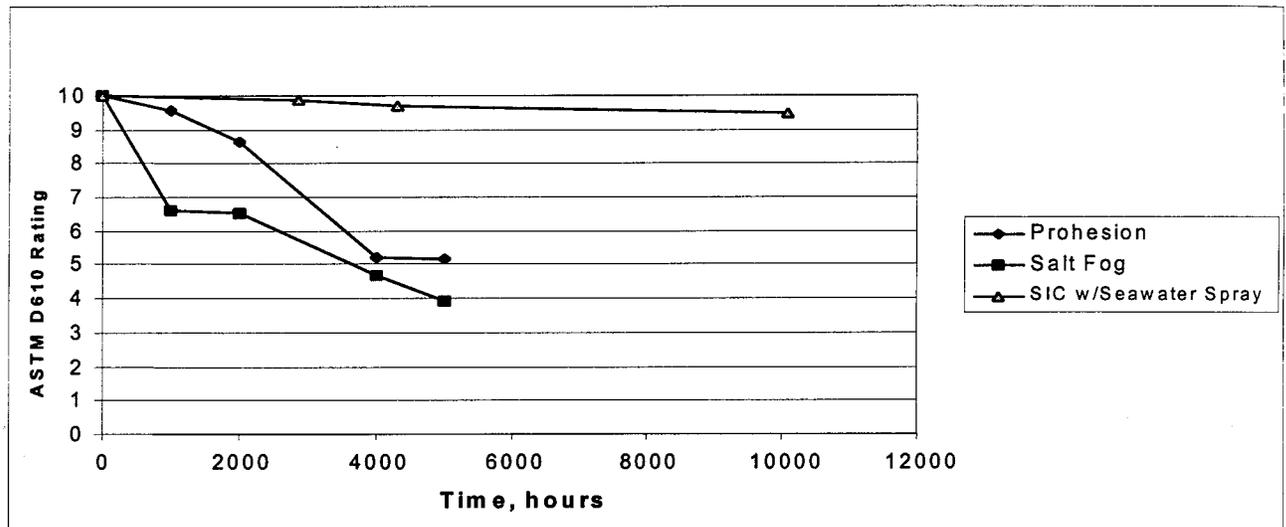
Appendix I provides plots of the pertinent experimental results vs. time. Summary plots are incorporated into the body of the current section to facilitate a discussion of the results.

#### 2.1. Accelerated Testing

**Rusting:** Figures I-1 and I-2 show through-film rusting (ASTM D610) for each coating system over an SSPC SP-10 substrate in each accelerated test procedure. Some systems were removed from testing early due to the high level of deterioration observed early in the testing. These are noted as those systems with a rating of zero (0) on the plots. From these graphs, it can be seen that inorganic zinc (IOZ) and organic zinc (OZ) primers afford the highest level of protection in the laboratory tests (salt fog and Prohesion). However, all of the systems, except the silicone al-

kyd, maintained a rust rating above 9 for natural exposure accelerated by daily seawater spray. (These are listed in the graph legends as “SIC w/Seawater Spray.”)

Figure 4 shows the composite rusting (ASTM D610) for all coating systems over an SSPC SP-10 substrate in all accelerated test procedures. This composite rating is an average of rust ratings received by all eight systems. The composite rating is meant to show the overall corrosiveness of the test environment. From this, it can be seen that the accelerated natural exposure test is much less corrosive, from a rusting standpoint, than the salt fog and Prohesion tests. Prohesion and salt fog testing environments were considerably more aggressive, with salt fog showing the most rusting.

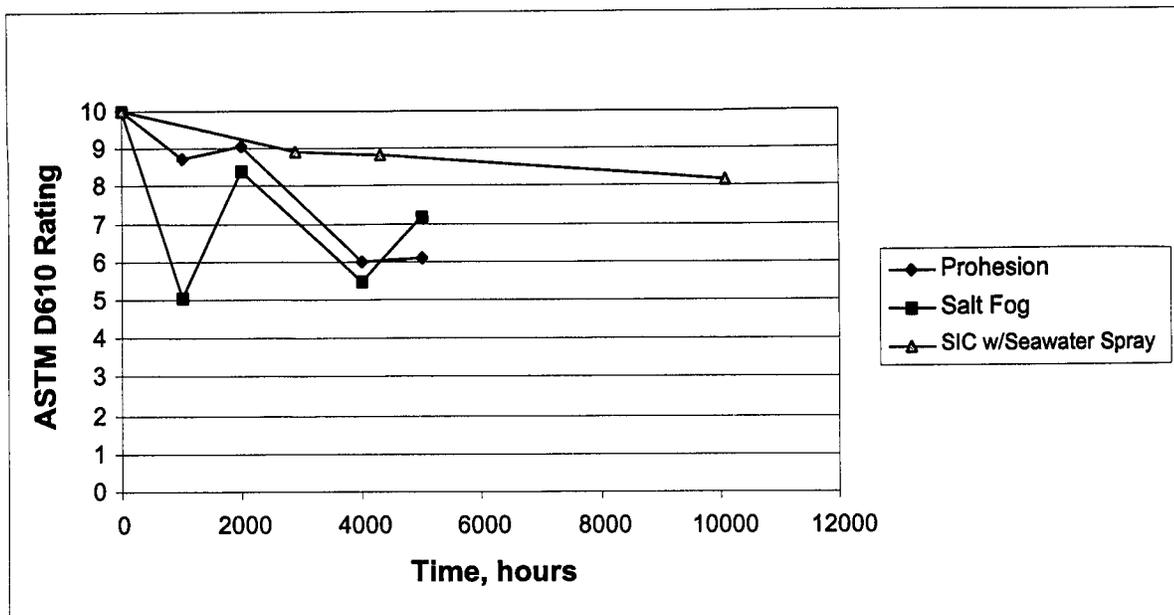


**Figure 4. Accelerated testing rust ratings, all systems, SSPC SP-10 substrate.**

Figures I-3 and I-4 show the through-film rusting (ASTM D610) for each coating system applied over an SSPC SP-3 substrate in all accelerated test procedures. From these graphs, it can be seen that all of the systems topcoated with a urethane or polysiloxane had similar levels of rusting in the laboratory tests. The acrylic and alkyd coating systems showed the most rusting in the laboratory tests. As with the SSPC SP-10 prepared panels, the accelerated natural exposure testing typically showed rusting with better than a 9 rating. However, the waterborne IOZ, moisture-cured urethane (MCU), and calcium sulfonate alkyd systems on SSPC SP-3 panels all had rusting below 7 at the end of testing, with the calcium sulfonate system having the lowest rating (a rating of 4).

Figure 5 shows the composite rusting (ASTM D610) for all coating systems over the SSPC SP-3 substrate in all accelerated test procedures. This composite rating is an average of rust ratings received by all eight systems. The composite rating is meant to show the overall corrosiveness of the test environment. From this, it can be seen that the test produces roughly the same trends as the SSPC SP-10 prepared panels. This graph suggests that in the accelerated natural exposure test, the coatings do not perform as well over the SSPC SP-3 substrate vs. the SSPC SP-10 substrate.

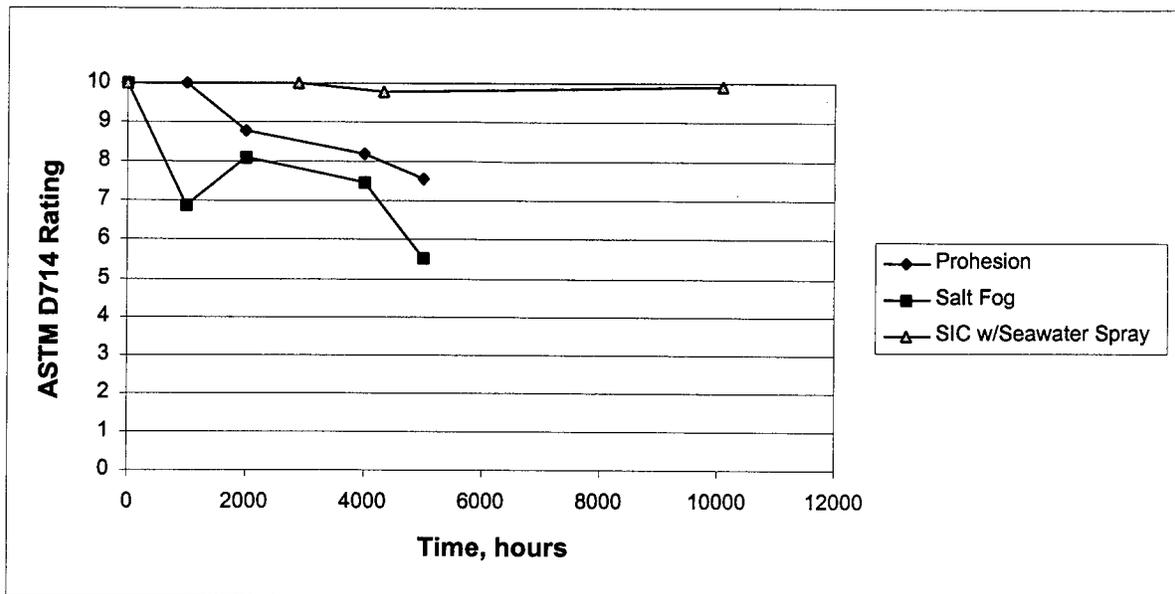
The influence of the substrate is less of a factor in the highly accelerated conditions of the Prohesion and salt fog tests.



**Figure 5. Accelerated testing rust ratings, all systems, SSPC SP-3 substrate.**

**Blistering:** Figures I-5 and I-6 show the film blistering (ASTM D714) for each coating system in all accelerated test procedures. Coating systems were applied over an SSPC SP-10 prepared substrate. Several of the systems have only one or two data points for the salt fog and Prohesion tests. These systems were removed prior to completion due to the high levels of deterioration observed early in the testing. From these graphs, it can be seen that for the IOZ, OZ, and epoxy/urethane systems, both the Prohesion and accelerated natural exposure tests showed no signs of blistering. The epoxy/urethane system also showed no signs of blistering in the salt fog chamber. This rating shows the same general trend as when rating the panels for rusting. The systems using IOZ, OZ, and epoxy/urethane are among the best performers; waterborne IOZ and MCU are the next best performers; and the worst performers are the acrylic and alkyd systems.

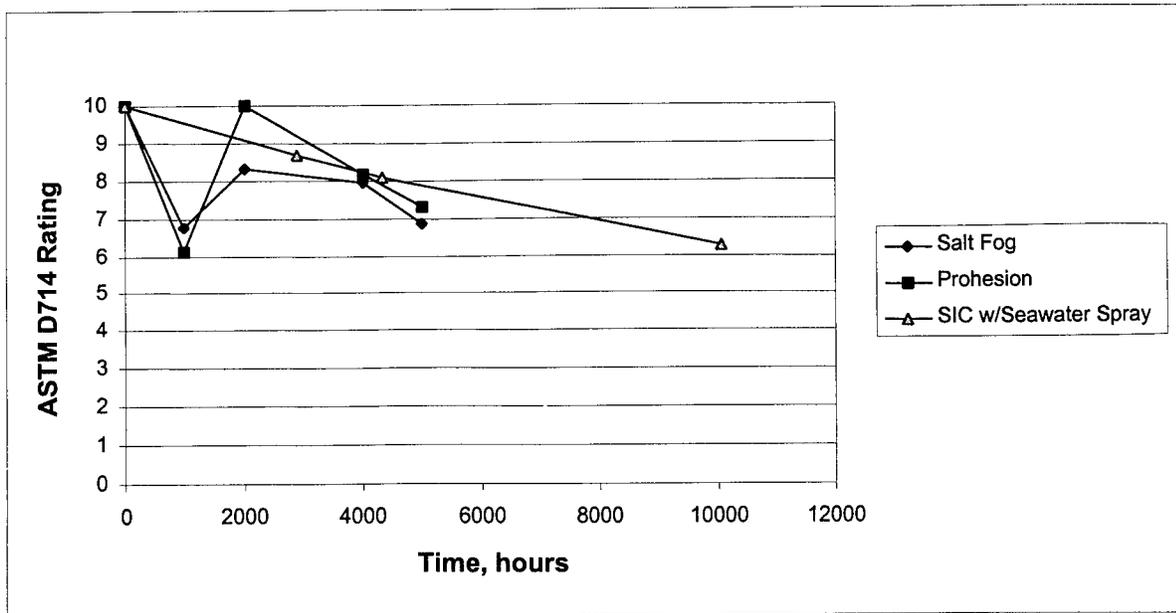
Figure 6 shows the composite blistering (ASTM D714) for all coating systems in all accelerated test procedures over an SSPC SP-10 prepared substrate. From this, it can be seen that when testing over an SSPC SP-10 substrate, salt fog provides the harshest environment, followed by Prohesion, and then accelerated natural exposure, where the average rating is above 9.



**Figure 6. Accelerated testing blister ratings, all systems, SSPC SP-10 substrate.**

Figures I-7 and I-8 show the film blistering (ASTM D714) for each coating system in all accelerated test procedures over an SSPC SP-3 prepared substrate. Several of the systems have only one or two data points for the salt fog and Prohesion tests. These systems were removed prior to completion due to the high levels of deterioration observed early in the testing. From these graphs, it can be seen that the use of an IOZ, OZ, or MCU system reduced the blistering in the Prohesion and salt fog tests. The other systems showed blister ratings of 6 or below at the end of testing, with the acrylic and alkyd systems showing the greatest blistering. The accelerated natural exposure testing had lower blister ratings (below 7) for all systems except the IOZ/epoxy/urethane system. However, the systems do tend to follow the same trend as the SSPC SP-10 substrates, with the IOZ and urethane topcoat systems having the highest blister resistance and the acrylic and alkyd systems having the least.

Figure 7 shows the composite blistering (ASTM D714) for all coating systems in all accelerated test procedures. Coating systems were applied over an SSPC SP-3 prepared substrate. From this, it can be seen that the accelerated natural exposure test provided a level of blistering at the end of testing (10,000 h) that was comparable to the level of blistering at the end of Prohesion and salt fog testing (5,000 h). However, it took the accelerated natural exposure test almost twice as long to reach that level of blistering. It is also seen that while the blister ratings for the laboratory tests vary from inspection to inspection, the blistering of the accelerated natural exposure test follows a more linear trend.

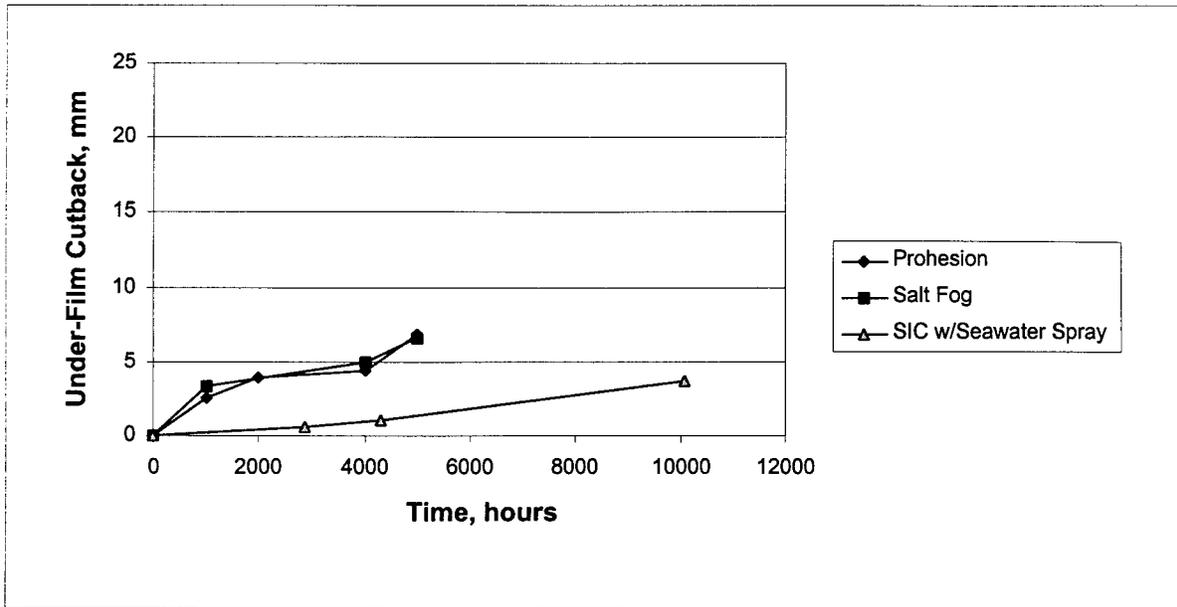


**Figure 7. Accelerated testing blister ratings, all systems, SSPC SP-3 substrate.**

**Coating Cutback:** Coating cutback was measured from intentional holidays on panels painted over an SSPC SP-10 and an SSPC SP-3 prepared substrate. It was theorized that the performance of SSPC SP-10 prepared panels would be better than that of SSPC SP-3 prepared panels. Because of this, the test results have been grouped by like preparation methods.

Figures I-9 and I-10 show the under-film cutback for each coating system in all accelerated test procedures. These plots are similar to those employed by Chong et al.<sup>(5)</sup> Coating systems were applied over an SSPC SP-10 prepared substrate. From these graphs, it can be seen that the systems using IOZ or OZ had the lowest cutback in the accelerated natural exposure test. The acrylic and alkyd systems had only slightly higher cutback in the same test and the epoxy/urethane and MCU systems had the most. The laboratory tests showed similar levels of cutback on the IOZ, OZ, and MCU systems. The salt fog test was more aggressive than the Prohesion test for the epoxy/urethane system. The Prohesion test was worse for the zinc-rich-based systems. The acrylic and alkyd coatings typically showed high levels of cutback following 1,000 h of laboratory testing. This, combined with other corrosion phenomena observed during testing, resulted in early removal of all of these systems from the laboratory tests.

Figure 8 shows the composite under-film cutback for all coating systems in all accelerated test procedures. Coating systems were applied over an SSPC SP-10 prepared substrate. This composite rating is an average of cutback experienced by all eight systems. From this, it can be seen that the Prohesion and salt fog tests have comparable levels of cutback. This is similar to findings by Chong.<sup>(6)</sup> The accelerated natural exposure testing, however, is less aggressive than the two laboratory tests.



**Figure 8. Accelerated testing cutback, all systems, SSPC SP-10 substrate.**

Figures I-11 and I-12 show the cutback for each coating system in all accelerated test procedures over an SSPC SP-3 prepared substrate. From these graphs, it can be seen that these results are similar to those observed for the SSPC SP-10 prepared panels. The IOZ and OZ systems have the lowest overall cutback (for all tests). However, the epoxy/urethane and MCU systems did not perform better than the acrylic and alkyd systems. Although the acrylic and alkyd systems showed increased cutback in the salt fog and Prohesion tests, the epoxy and MCU systems had the highest cutback in the accelerated natural exposure test. The best overall system was the waterborne IOZ/polysiloxane, which had the lowest final cutback (less than 2.5 mm) for both laboratory tests, and among the lowest final cutback in the accelerated natural exposure test. The acrylic and alkyd systems were removed from the salt fog and Prohesion tests prior to completion due to high levels of cutback and extensive surface corrosion.

Figure 9 shows the composite under-film cutback for all coating systems in all accelerated test procedures. From this, it can be seen that the Prohesion cabinet provides the highest level of average cutback, indicating that it is a more aggressive environment than the salt fog or the accelerated natural exposure tests, both of which had similar levels of cutback at the end of testing. The total cutback is also more than that experienced over the SSPC SP-10 substrate.

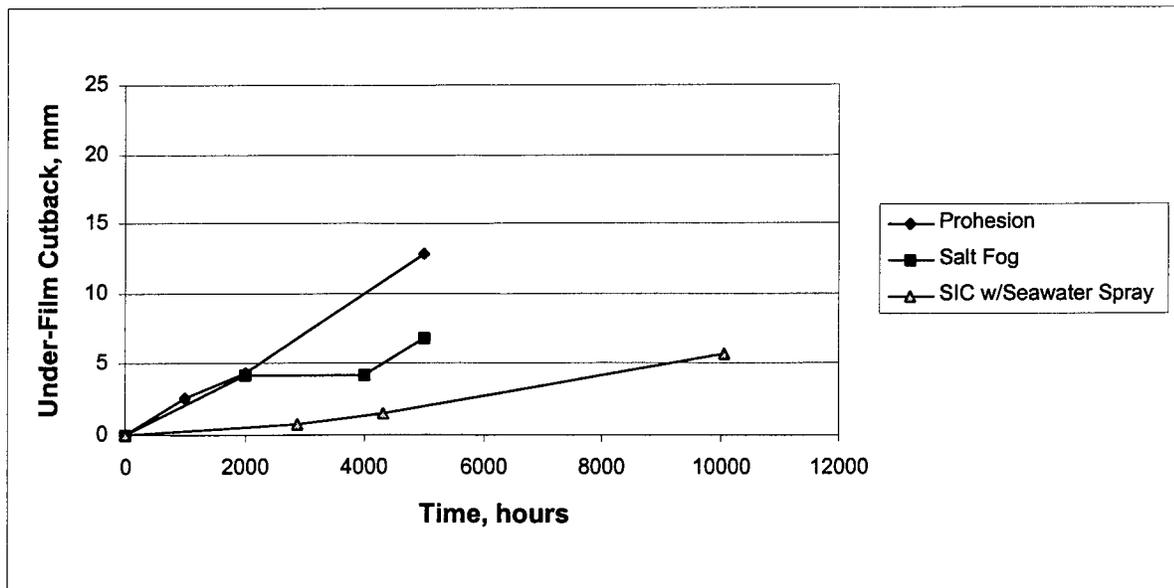
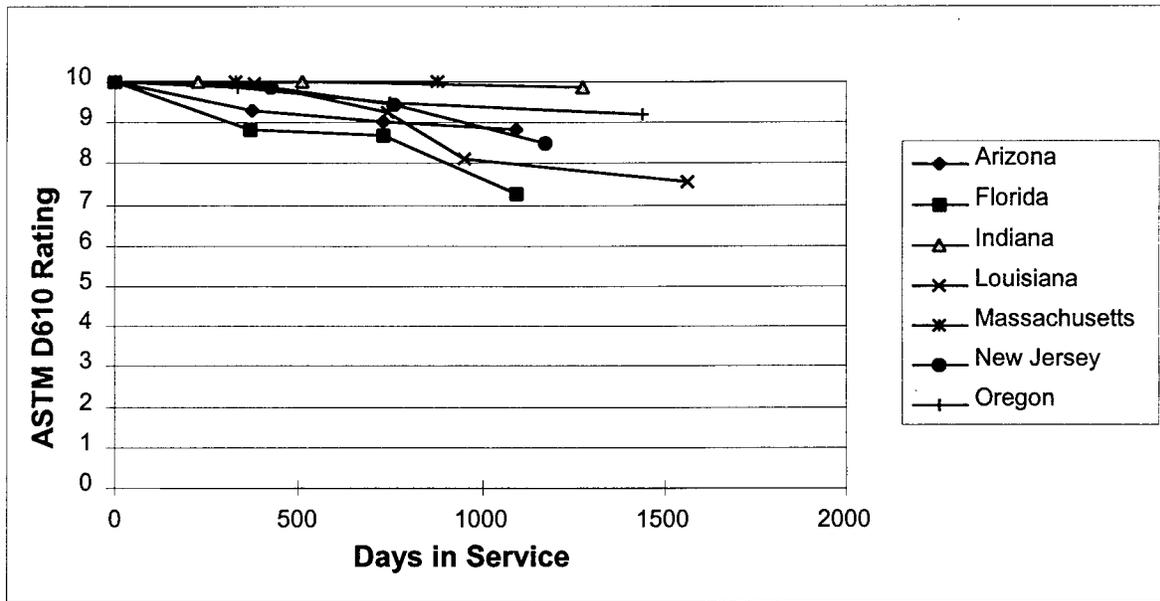


Figure 9. Accelerated testing cutback, all systems, SSPC SP-3 substrate.

## 2.2. Natural Exposure Testing

**Rusting Over an SSPC SP-10 Substrate:** Figures I-13 and I-14 show through-film rusting (ASTM D610) for each coating system over an SSPC SP-10 substrate at the exposure sites. From these graphs, it can be seen that none of the IOZ or OZ coating systems achieved a rust rating below 8 and the waterborne IOZ/polysiloxane system showed no rusting at any of the sites. The epoxy/urethane, MCU, and waterborne acrylic systems had approximately the same level of rusting observed; however, rusting was observed at four or more of the exposure sites, compared to three or fewer for the IOZ and OZ systems. The silicone and calcium sulfonate alkyd systems showed the most rusting. Both of these systems had readings below 8 for most exposure locations. The silicone alkyd achieved a final reading below 3 at the Florida site and the calcium sulfonate alkyd achieved a final reading below 1 for the Louisiana site. Coating systems typically achieved their lowest rating at the Florida exposure site.

Figure 10 shows the composite rusting (ASTM D610) for all coating systems over an SSPC SP-10 prepared substrate tested at all exposure sites. This composite rating is an average of ratings received by all eight systems. The composite rating is meant to show the overall corrosiveness of the test environment.

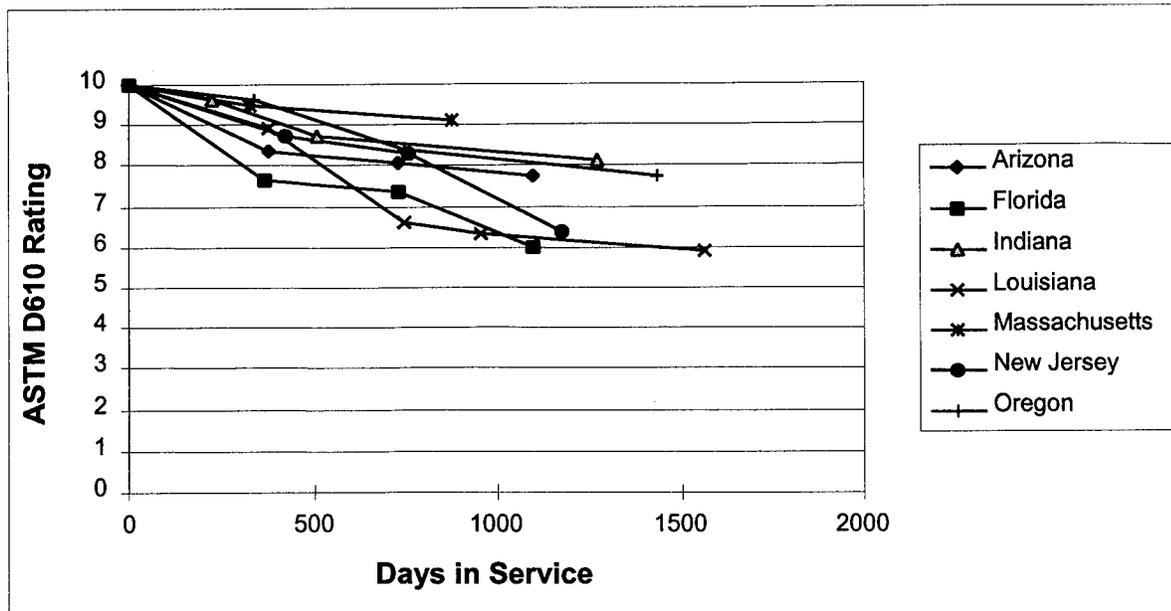


**Figure 10. Natural exposure testing rust ratings, all systems, SSPC SP-10 substrate.**

From this data over the differing exposure periods, it can be seen that relatively little, if any, through-film rusting occurred at the Indiana and Massachusetts sites. The Arizona, New Jersey, and Oregon sites have a composite rating between 8.5 and 9.5. The Florida and Louisiana sites appear to be the most aggressive. Both achieved ratings below 8; however, the Florida site had the lowest final rating, which was achieved approximately 400 days prior to the Louisiana site's final reading.

**Rusting Over an SSPC SP-3 Substrate:** Figures I-15 and I-16 show the through-film rusting (ASTM D610) for each coating system over an SSPC SP-3 prepared substrate tested at all exposure sites. From these graphs, it can be seen that through-film rusting is more prominent over a pre-rusted surface than over a surface that was abrasive-blasted to near-white metal. Even the IOZ systems showed low corrosion ratings, with one system completely failing at the Louisiana test site and the waterborne system having a final rating below 5 at the New Jersey test site. Despite these low ratings, the IOZ and OZ systems were generally the best coating systems. The epoxy/urethane and waterborne acrylic also showed levels of performance similar to the best systems. The MCU and silicone alkyd systems, although not completely failing, did show ratings below 7 at most sites and had some level of rusting at all sites. The calcium sulfonate alkyd was the worst performing system, having ratings below 3 for most sites. With its consistently lower readings and the complete failure of an IOZ system, the Louisiana site appears to be the most aggressive with respect to the rusting of the inorganic zinc-rich system.

Figure 11 shows the composite rusting (ASTM D610) for all coating systems tested over the SSPC SP-3 substrate at the exposure sites. This composite rating is an average of rust ratings received by all eight systems.



**Figure 11. Natural exposure testing rust ratings, all systems, SSPC SP-3 substrate.**

From this, it can be seen that over an SSPC SP-3 prepared substrate, rusting was observed at all of the test sites. This rusting was more significant than that observed over the SSPC SP-10 substrate. This rusting ranged from a high rating (above 9) to a low rating (below 6). The order of these sites, from lowest to highest ratings, is: Florida, Louisiana, New Jersey, Arizona, Oregon, Indiana, and Massachusetts. This order is determined using the final rust rating obtained by each location and the slope of the line showing the rating trends.

**Rusting Performance Summary by Coating:** Table 5 provides a summary of the rusting data as a function of coating type after 5,000 h of exposure. These are the same data presented in the above figures, organized by coating type as opposed to location.

**Table 5. Corrosion rust-through (ASTM D610) for each coating system, average of all sites.**

Coating Performance Rating - Rusting Over SSPC SP-10							
(1) IOZ/E/U	(2) H <sub>2</sub> O Acr.	(3) IOZ/Sil.	(4) Sil. Alk.	(5) CaSulf.	(6) OZ/E/U	(7) E/U	(8) MCU
9.70	9.20	10.00	6.60	6.90	9.60	8.90	8.90
Coating Performance Rating - Rusting Over SSPC SP-3							
(1) IOZ/E/U	(2) H <sub>2</sub> O Acr.	(3) IOZ/Sil.	(4) Sil. Alk.	(5) CaSulf.	(6) OZ/E/U	(7) E/U	(8) MCU
7.90	8.00	8.40	7.00	3.40	9.20	8.40	6.10

The zinc-based coating systems exhibited the least breakdown. The calcium sulfonate system showed the most rust-through.

**Blistering Over an SSPC SP-10 Substrate:** Figures I-17 and I-18 show the film blistering

(ASTM D714) for each coating system tested at all exposure sites. From these graphs, it can be seen that with one or two exceptions, none of the coating systems applied over an SSPC SP-10 substrate showed signs of blistering. The exceptions are the waterborne IOZ system, which had a final rating below 1 for the Florida site; the waterborne acrylic, which had a final rating below 9 for the Oregon site; and the silicone alkyd, which had a final rating below 8 for the Oregon site. The Florida site appears to be the most aggressive, with respect to blistering of the IOZ/polysiloxane, over an SSPC SP-10 substrate.

Figure 12 shows the composite blistering (ASTM D714) for all coating systems tested at all exposure sites. Coating systems were applied over an SSPC SP-10 prepared substrate. This composite rating is an average of blister ratings received by all eight systems.

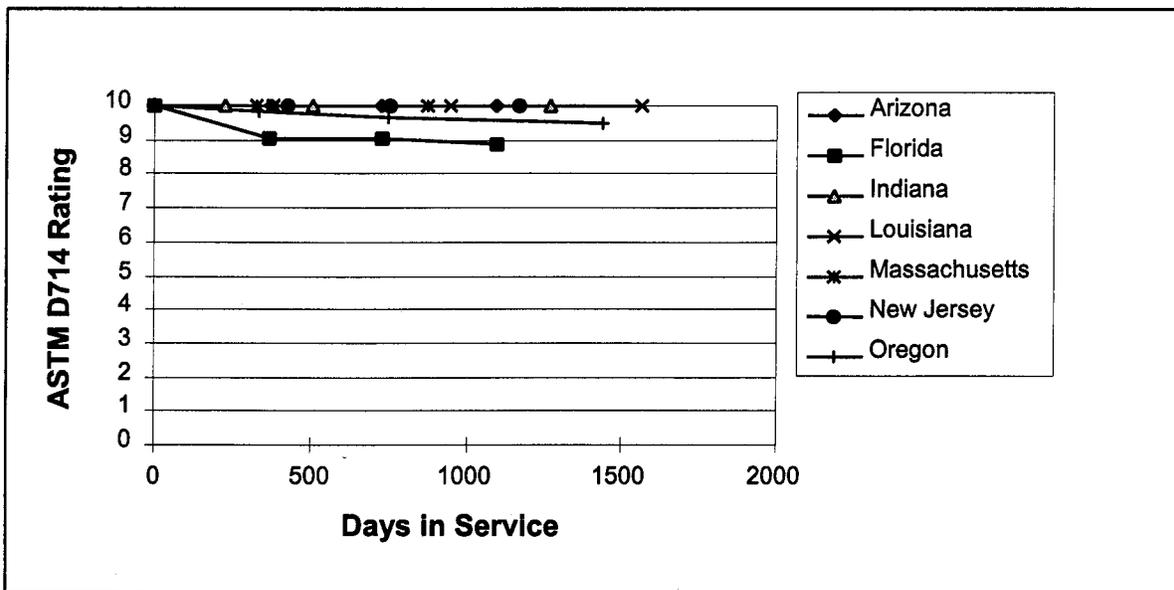


Figure 12. Natural exposure testing blister ratings, all systems, SSPC SP-10 substrate.

From this, it can be seen that, overall, none of the exposure locations produced an average blister rating much below 9. The two sites that show composite blister ratings below 10 were the Oregon site (between 9 and 10) and the Florida site (just below 9).

**Blistering Over an SSPC SP-3 Substrate:** Figures I-19 and I-20 show the film blistering (ASTM D714) for each coating system tested at all exposure sites. From these graphs, it can be seen that an SSPC SP-3 substrate had a higher incidence of blistering at all exposure locations. The IOZ/epoxy/urethane system showed no blistering at any of the sites, except for Louisiana, where the coating completely failed at approximately 750 days. The waterborne IOZ/polysiloxane experienced blistering at four of the seven test sites, with the lowest rating (below 5) occurring at the Louisiana site. The remainder of the coating systems all showed

significant blistering and achieved at least one rating below 3 for an exposure location. The lowest blister ratings for these systems typically appeared at the Louisiana site.

Figure 13 shows the composite blistering (ASTM D714) for all coating systems tested at all exposure sites. From this, it can be seen that all exposure locations experienced blistering when an SSPC SP-3 painted sample was tested. The Arizona and Massachusetts sites appeared to be the most benign, having an average final blister rating above 9. The most aggressive site appeared to be Louisiana, which had an average final blister rating below 5. The order of these sites, from lowest to highest ratings, is: Louisiana, New Jersey, Oregon, Florida, Indiana, Massachusetts, and Arizona.

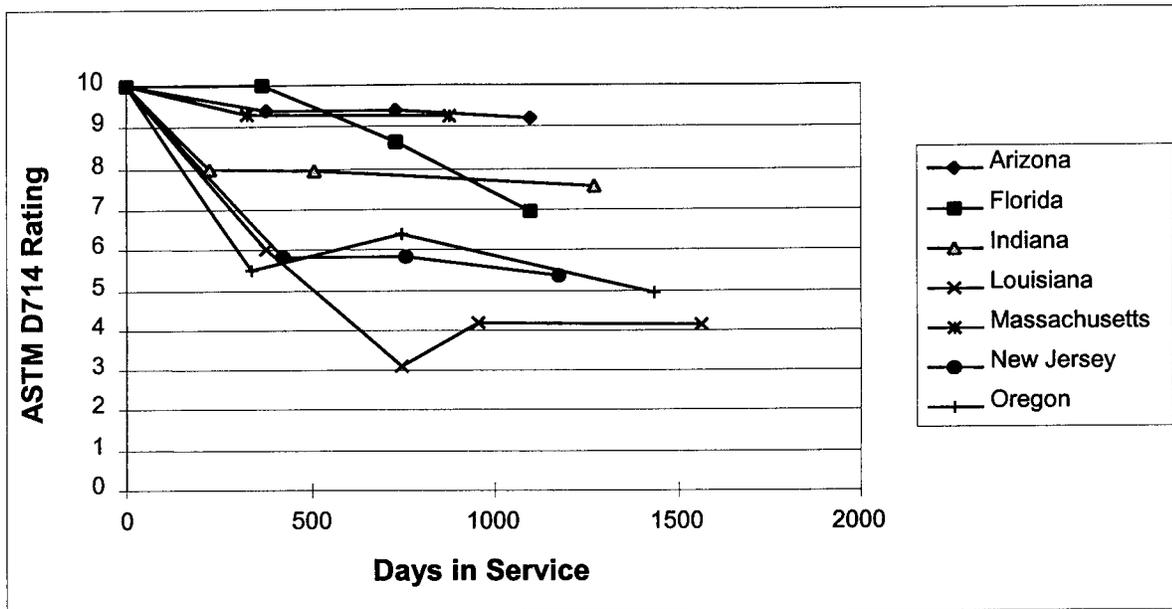
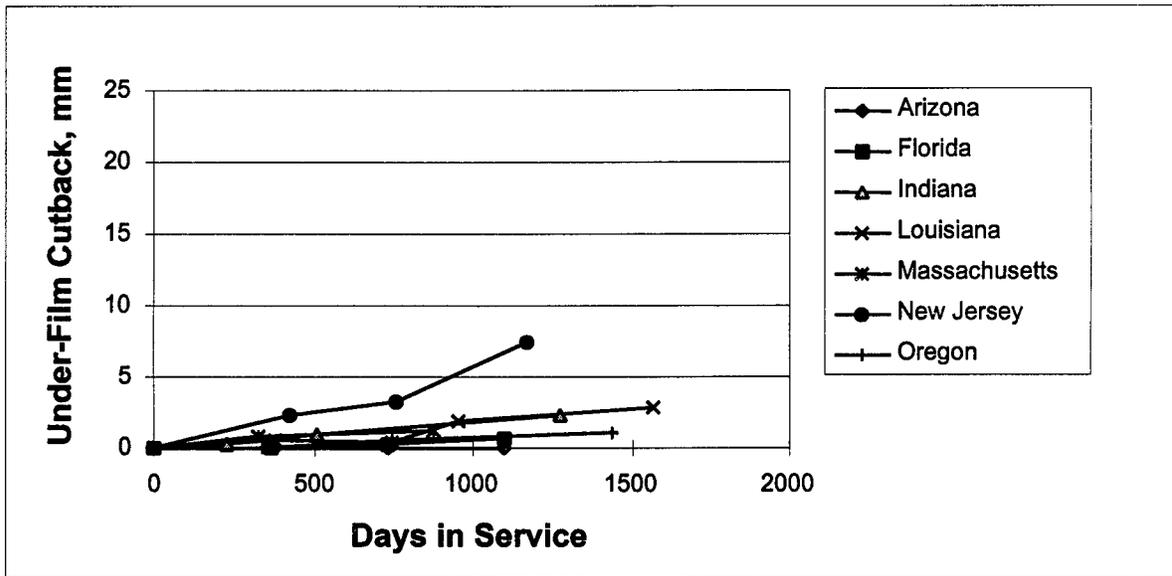


Figure 13. Natural exposure testing blister ratings, all systems, SSPC SP-3 substrate.

**Cutback Over an SSPC SP-10 Substrate:** Figures I-21 and I-22 show the under-film cutback for each coating system tested at the exposure sites. From these graphs, it can be seen that the solvent-borne IOZ and OZ coating systems experienced little or no cutback. The waterborne IOZ showed no cutback throughout testing at all exposure sites. All of the other systems showed similar levels of cutback, except the epoxy/urethane and MCU systems, which showed very high levels of cutback at the New Jersey exposure site. This site typically exhibited the highest level of cutback for all coating systems.

Figure 14 shows the composite under-film cutback for all coating systems tested at the exposure sites. From this, it can be seen that the most aggressive site was the New Jersey site, having an average final cutback of 7.6 mm (0.3 in). The most benign site was the Arizona site, which showed no average cutback. The order of these sites, from greatest to least cutback, is: New Jersey, Louisiana, Indiana, Massachusetts, Oregon, Florida, and Arizona.



**Figure 14. Natural exposure testing cutback, all systems, SSPC SP-10 substrate.**

**Cutback Over an SSPC SP-3 Substrate:** Figures I-23 and I-24 show the under-film cutback for each coating system tested. From these graphs, it can be seen that the waterborne IOZ/polysiloxane and calcium sulfonate alkyd systems were the best performers, all having under-film cutback of less than 7.6 mm (0.3 in). The OZ/epoxy/urethane system also had cutback of less than 7.6 mm at most sites. However, it reached almost 12.7 mm (0.5 in) at the Indiana site and was greater than 25.4 mm (1 in) at the Oregon site, precluding it from being ranked with the best performers. The epoxy/urethane system was the worst performer. This system experienced cutback greater than 12.7 mm (0.5 in) at most exposure sites and was greater than 25.4 mm at two of those locations. The MCU system was only slightly better, having high levels of cutback at two locations. The waterborne acrylic and silicon alkyd systems did not show significant cutback at most locations, but did experience cutback greater than 12.7 mm (0.5 in) at the New Jersey site. This site typically was among the highest observed cutback for all coating systems.

Figure 15 shows the composite under-film cutback for all coating systems tested at all exposure sites. From this, it can be seen that, overall, the New Jersey, Oregon, and Louisiana sites are the most aggressive with respect to under-film cutback. The most benign site was the Arizona site, which showed no average cutback. The order of these sites, from highest to lowest cutback, is: New Jersey, Oregon, Louisiana, Indiana, Florida, Massachusetts, and Arizona.

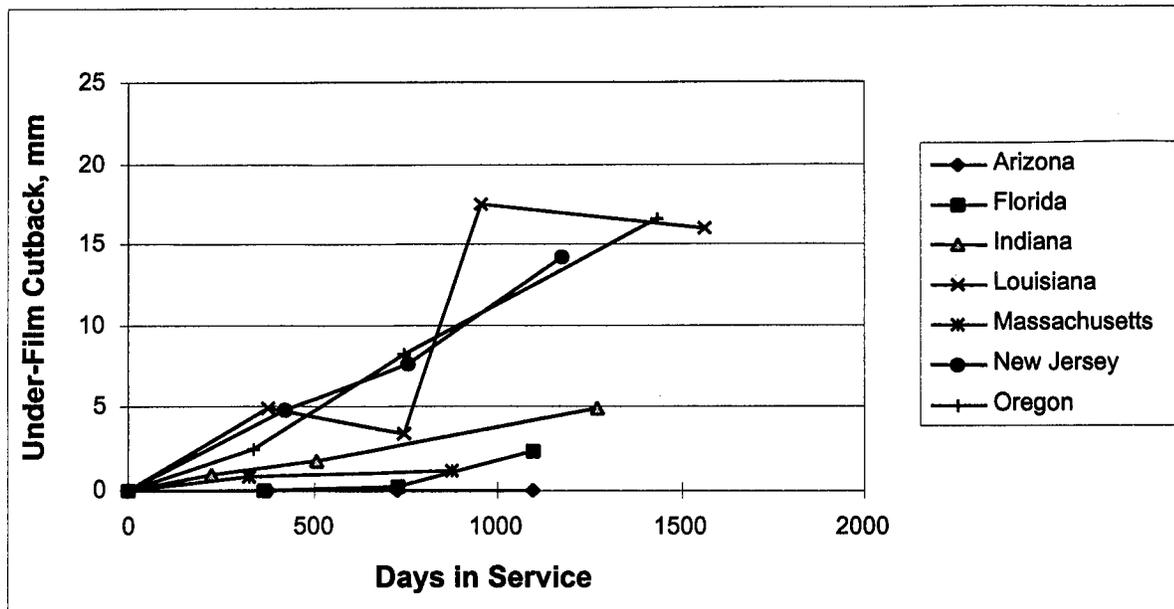


Figure 15. Natural exposure testing cutback, all systems, SSPC SP-3 substrate.

**Cutback Performance Summary by Coating:** Table 6 provides a summary of the cutback performance data.

Table 6. Coating cutback for each coating system, average of all sites.

Coating Performance Rating - Cutback (mm) Over SSPC SP-10							
(1) IOZ/E/U	(2) H <sub>2</sub> O Acr.	(3) IOZ/Sil.	(4) Sil. Alk.	(5) CaSulf.	(6) OZ/E/U	(7) E/U	(8) MCU
1.5	1.9	0.0	1.7	1.8	0.3	6.3	4.3
Coating Performance Rating - Cutback (mm) Over SSPC SP-3							
(1) IOZ/E/U	(2) H <sub>2</sub> O Acr.	(3) IOZ/Sil.	(4) Sil. Alk.	(5) CaSulf.	(6) OZ/E/U	(7) E/U	(8) MCU
9.1	4.2	0.7	4.1	2.2	10.4	20.2	12.2

Over the SSPC SP-10 substrates, the zinc-rich systems were again the best performing systems. Over the SSPC SP-3 substrates, the waterborne IOZ/polysiloxane exhibited the least cutback. Over each preparation, the epoxy/urethane systems showed the most coating cutback from the scribe.

**Change in Coating Gloss:** Figures I-25 and I-26 show the measured gloss (ASTM D523) for each coating system tested at all exposure sites. From these graphs, it can be seen that systems that have a high initial gloss (greater than 30 gloss units) show a lot of scatter between initial readings and have a final gloss anywhere from 20 to 70 units less than the original reading. For systems with a low initial gloss (between 10 and 30 gloss units), the initial readings are more consistent and all tend to have a final gloss approximately 15 units less than the initial readings.

For systems with an ultra-low initial gloss (less than 10 gloss units), the initial readings are almost identical and the final gloss is no more than 2 to 3 gloss units less than the original.

Figures I-25 and I-26 can also be analyzed to determine the effect that each exposure site has on the rate of gloss loss. Looking at the data site-by-site, it can be seen that the locations that generally are thought of as having higher levels of solar radiation (Arizona and Florida) generally have the steepest slopes, indicating a higher rate of gloss loss. These sites also show some of the lowest final gloss readings for each system. However, the Massachusetts and New Jersey sites also have data plots with steep slopes and are also among the lowest final gloss readings. The Oregon site, which had high mountains and trees surrounding it, generally had the least amount of gloss loss and the highest final gloss. The Louisiana site, which was located in a primarily flat rural location, did have a final gloss comparable to the other sites; however, the loss rate was lower (a less steep slope of the data curve) for most systems.

Figure 16 shows the composite gloss for all coating systems tested at all exposure sites. This composite rating is an average of the gloss measurements taken for all eight systems before and during testing. The data show the percent change from the initial readings. The composite rating is meant to show the overall effect that each site has on the change in gloss of a coating system. From this, the sites can be ranked in order from most to least harsh; they are Florida, Massachusetts, Arizona, New Jersey, Louisiana, Indiana, and Oregon. The harshness of the sites is estimated based on the rate of gloss loss (the slope of the curve) and the final gloss measurement.

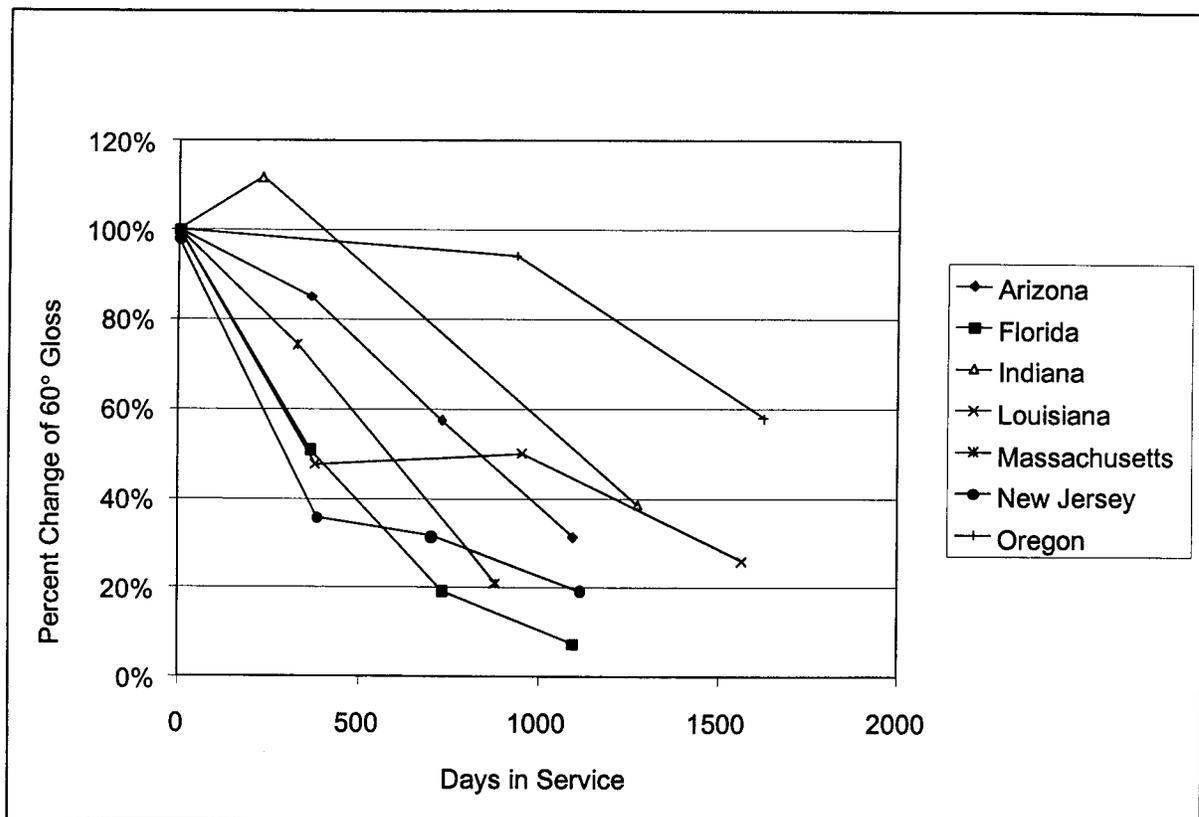


Figure 16. Change in gloss ratings vs. initial data.

**Color Changes:** Figures I-27 and I-28 show the color data (ASTM D2244) obtained for each coating system tested at all exposure sites. Two panels for each system at each site were measured and are shown next to each other. These graphs indicate the  $\Delta E$  for each coating system at each site at the end of the exposure duration.  $\Delta E$  describes color changes for three variables – “L,” “a,” and “b.” “L” measures brightness, “a” measures redness, and “b” measures yellowness; each describes a certain variable in the color space. The most dramatic color change is observed in the calcium sulfonate alkyd and the moisture-cured urethane systems. In seven out of the eight coating systems, Arizona exhibited the least amount of change in  $\Delta E$ , and the most change was exhibited in Florida for five of the eight coating systems.

To facilitate the discussion on color change, the coating systems were grouped together by like topcoat colors and chemistries in the following manner:

1. Blue urethane topcoat: System 8.
2. Gray calcium sulfonate and silicone alkyd: Systems 4 and 5.
3. White urethane topcoats: Systems 1, 6, and 7.
4. White topcoats: Systems 1, 2, 3, 6, and 7.
  - Group 1: The moisture-cured urethane system was the only blue coating used in the test. The other topcoat colors tested were white and gray, which absorb less ultraviolet (UV) light and, therefore, may be less susceptible to color change. The moisture-cured urethane coating did show a significant color change.
  - Group 2: From the results section, it can be seen that the calcium sulfonate alkyd and the moisture-cured urethane systems exhibited the highest or largest  $\Delta E$ . The calcium sulfonate alkyd system tended to show rust-through and hold dirt and other contaminants that contributed to the drastic change in color. Therefore, it would be inaccurate to consider any environmental effects to be the cause of color changes on this coating system. The silicone alkyd did not show the same degree of color change and showed a response that was closer to the average.
  - Group 3: The systems in this group are the most consistent with one another, with Arizona always exhibiting the least  $\Delta E$  and Florida exhibiting the largest  $\Delta E$ . A high level of sunlight exposure defines both sites, but Arizona has lower relative humidity and less atmospheric contamination than Florida.
  - Group 4: The results for this group are similar to that of Group 3, except those for the polysiloxane, which exhibited less color change in Arizona and Florida and more in Louisiana.

The only consistent observable trends were that Arizona exhibited very little color change and Florida exhibited the largest color changes. From this, general statements can be made about the basic environmental differences between the two sites to explain the variation in  $\Delta E$  for the two sites. Arizona’s environment is defined by an extended time of sun exposure, high average temperatures, very low relative humidity, and low atmospheric contamination. Florida’s environment is similar in that it is defined by an extended time of sun exposure and high average temperature,

but is different in that it exhibits high relative humidity and higher atmospheric contamination. Therefore, it seems that atmospheric contamination and relative humidity have more effect on color change than does total sun exposure time.

### 2.3. Effects of the Environment

Analysis of the effects of the environment is a complicated issue. To facilitate an analysis of the subject data, initially it was felt that it was necessary to bring the exposure data to a common time basis. As conducted, the study resulted in different exposure durations for the painted samples. To bring them to a common exposure time, the ASTM ratings vs. time were linearly regressed and the deterioration expected at 5 years was determined. Table 7 provides the actual exposure duration and the percent extrapolation to 5 years. In performing this function, it was realized that not all data sets exhibited an high correlation coefficient with time on a linear basis. Yet the influence of non-linearity was judged to be less significant than the obvious influence of different exposure times. This process is the linear extension of the data depicted in figures 10 through 15. For the rusting data of figures 10 and 11, correlation coefficients ( $R^2$  values) of 0.86 to 0.98 were observed for the coatings over the SSPC SP-10 substrates and values of 0.82 to 0.96 were observed for the coatings over the SSPC SP-3 substrates. The correlations were generally worse for blistering, with values of 0.72 to 0.99 for the SSPC SP-10 substrates and 0.67 to 0.88 for the SSPC SP-3 substrates. For the cutback data, the correlation coefficients ranged from 0.86 to 0.99 and 0.67 to 0.99 for the SSPC SP-10 and SP-3 substrates, respectively.

**Table 7. Percent extrapolation of exposure data to the 5-year point.**

Location	Actual Exposure, years	% Extrapolation
Arizona	3.0	167%
Florida	3.0	167%
Indiana	3.5	143%
Louisiana	4.3	117%
Massachusetts	2.4	208%
New Jersey	3.2	156%
Oregon	3.9	127%

Table 8 presents the results of these extrapolations as a function of exposure location. Data are the average of the eight coating systems at each location.

**Table 8. Projected coating deterioration at 5 years.**

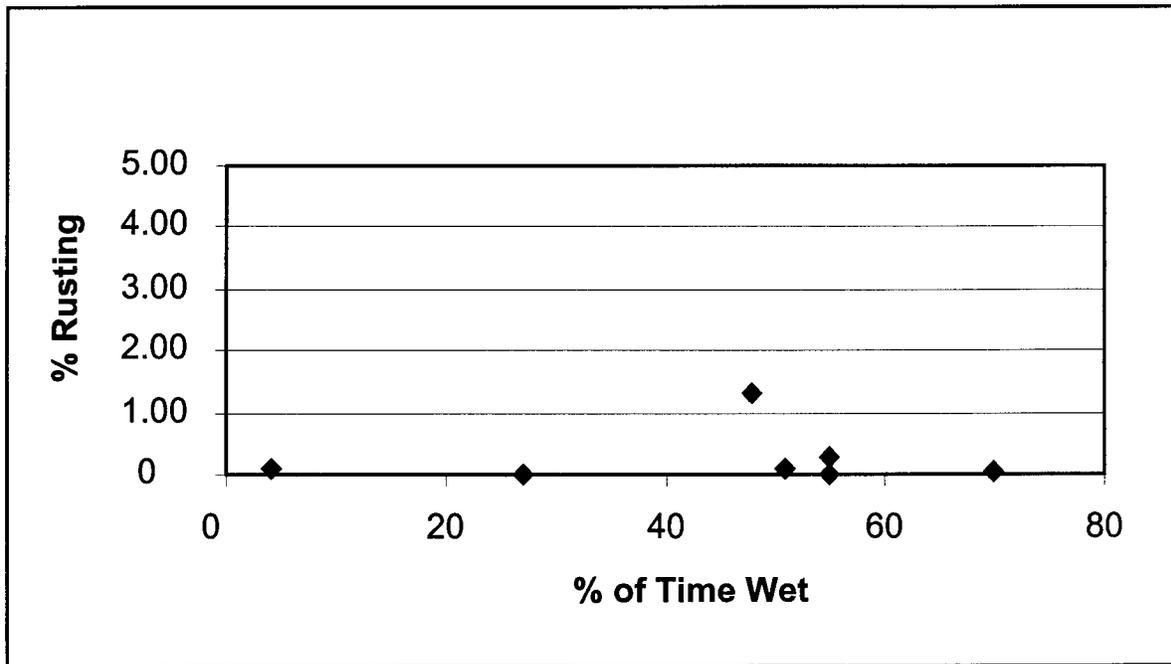
Failure Mode	Arizona	Florida	Indiana	Louisiana	Massachusetts	New Jersey	Oregon
<u>SSPC SP-10 Surface Preparation</u>							
Rusting (D610)	7.9	5.8	9.8	7.1	10.0	7.9	8.9
Cutback, mm	0.0	1.0	3.4	3.2	2.6	10.8	1.3
Blistering (mod. D714)	10.0	8.0	10.0	10.0	10.0	10.0	9.3
<u>SSPC SP-3 Surface Preparation</u>							
Rusting (D610)	6.1	3.5	7.2	4.5	8.2	4.7	7.0
Cutback, mm	0.0	3.1	7.0	20.6	2.5	21.3	21.0
Blistering (mod. D714)	8.7	5.2	6.5	1.6	8.4	2.2	3.4

**Through-Film Rusting:** The first parameter to be considered is the rust-through data as indicated by the ASTM D610 ratings. For the purposes of this analysis, the ASTM D610 ratings were converted to the actual area of coating with deterioration (as listed within the ASTM specification, i.e., a 9 rating = 0.03% deterioration) using the following:

$$\text{ASTM D610 rating 10 to 4: \% area} = 0.0096 \cdot \exp(1.1558 \cdot (10 \text{ rating}))$$

$$\text{ASTM D610 rating } <4: \% \text{ area} = 0.3079 \cdot \exp(0.5745 \cdot (10 \text{ rating}))$$

These equations were derived from the regression relationship of rust-through data. R<sup>2</sup> values exceeded 0.99. Through the conversion, the actual differences in site corrosivity are accentuated. There are several possible (single) elements to be considered. The following are plots vs. several single parameters. Figures 17 and 18 show the percent area rusting vs. time-of-wetness and relative humidity. There are no reasonable correlations here.



**Figure 17. Percent area rusting vs. time-of-wetness (SP-10).**

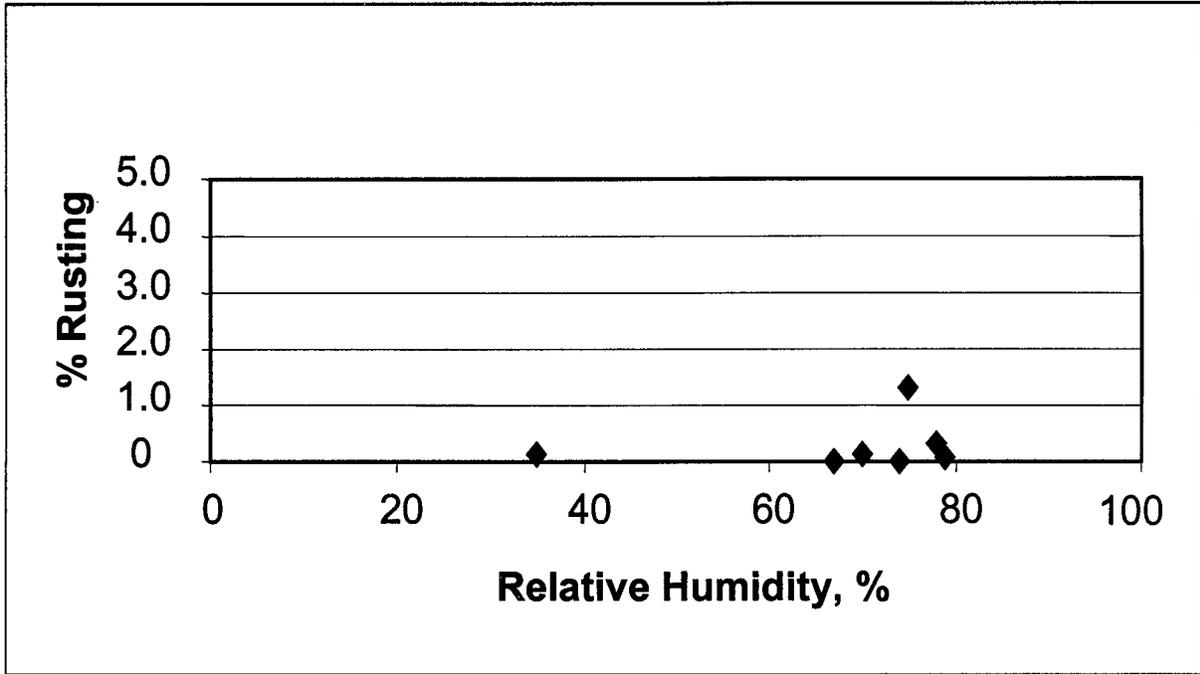


Figure 18. Percent area rusting vs. relative humidity (SP-10).

Figure 19 shows the same corrosion data plotted vs. absolute humidity.

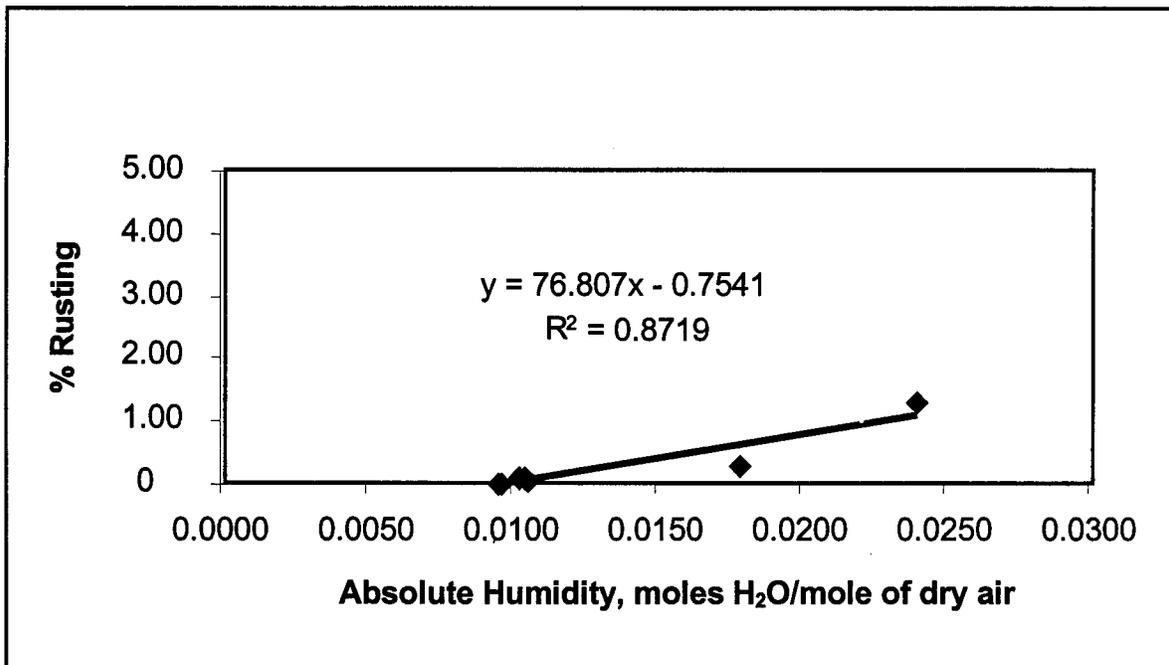
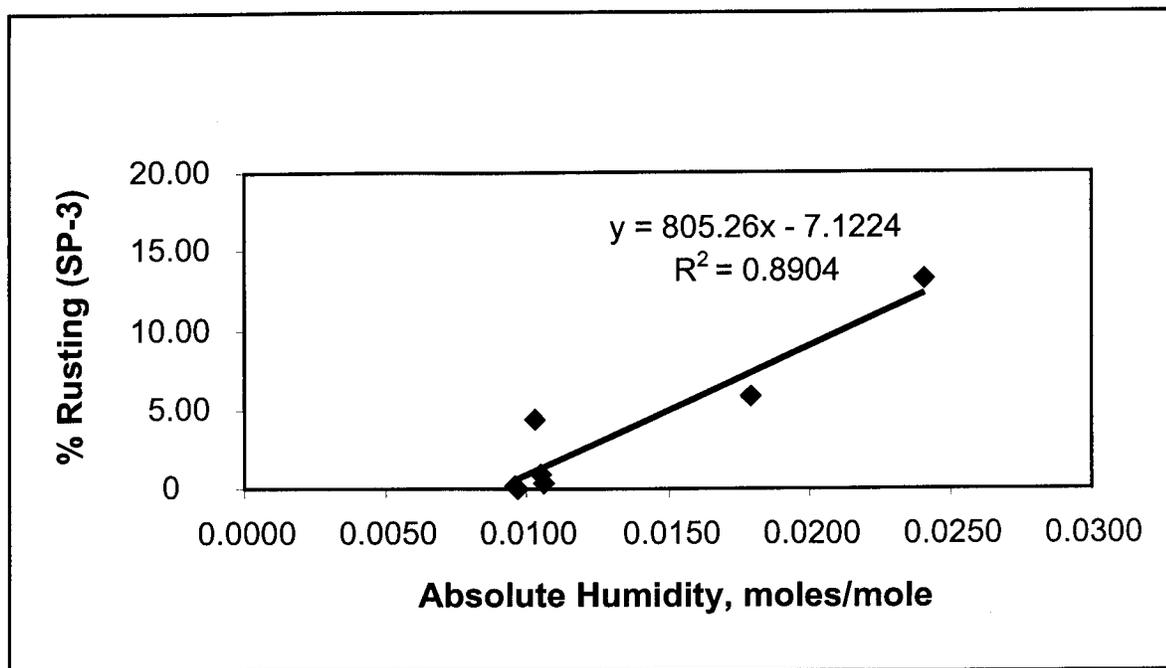


Figure 19. Percent area rusting vs. absolute humidity (SP-10).

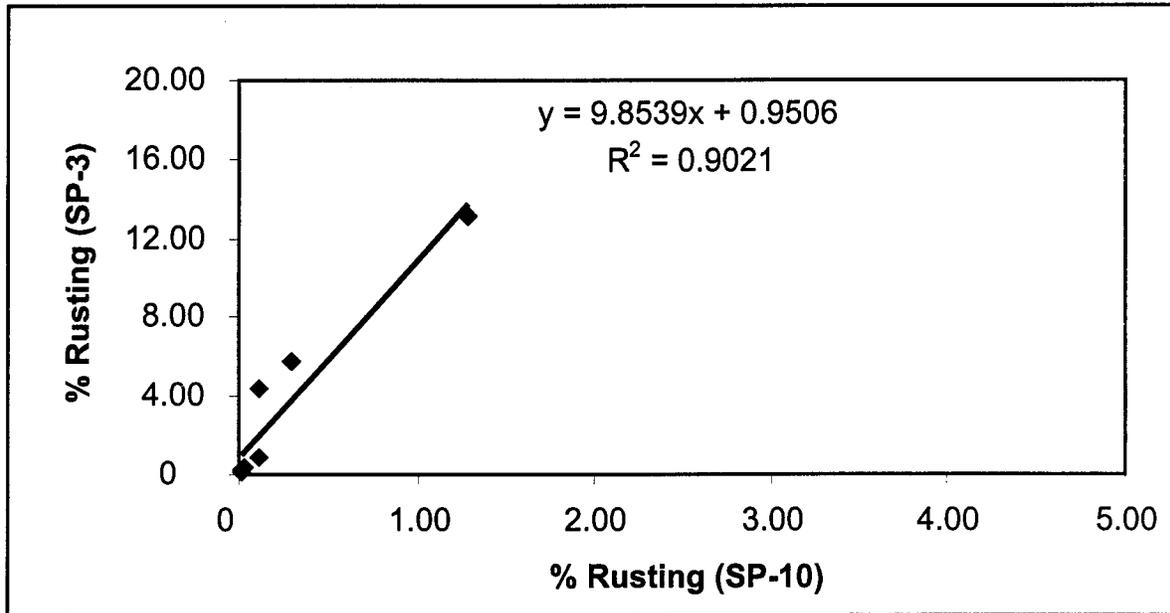
To some degree, the improved correlation results from a close grouping of data at low absolute humidity; however, the suggestion of a better correlation with absolute humidity may make sense. If corrosion is considered to be driven primarily through the diffusion of water through the coating, then the diffusion rate should be controlled in large part by the concentration gradient of moisture across the coating. While moisture in the atmosphere is most commonly thought of as relative humidity, this parameter does not correlate with corrosion since it does not indicate the absolute amount of water in the atmosphere; absolute humidity does indicate this. This also helps explain the high rate of deterioration of coatings at the Arizona location, despite a low relative humidity. In absolute terms, there is as much water in the air in Arizona as there is in Oregon. It is simply the lower average temperature in Oregon that creates a higher relative humidity and thus the sense of being “wetter.”

Figure 20 shows the same correlation with the coatings over the SSPC SP-3 surface.



**Figure 20. Percent area rusting vs. absolute humidity (SP-3).**

Again, a similar reasonable correlation is seen. The fact that both of these parameters correlate well with absolute humidity suggests that they ought to relate well to each other. Figure 21 presents this relationship.



**Figure 21. Percent area rusting, SSPC SP-3 vs. SSPC SP-10 substrate.**

This correlation suggests that both are affected by the same environmental parameters; corrosion is simply accelerated on the SSPC SP-3 coated panels. In this case, the acceleration is the result of surface salts remaining after the substrate was cleaned. In either case, corrosion is the net result of water coming through the coating.

Figure 22 shows the lack of correlation between through-film rusting and the conductivity of the rainfall. This suggests no consistent effect of airborne salts on through-film corrosion within the natural environment.

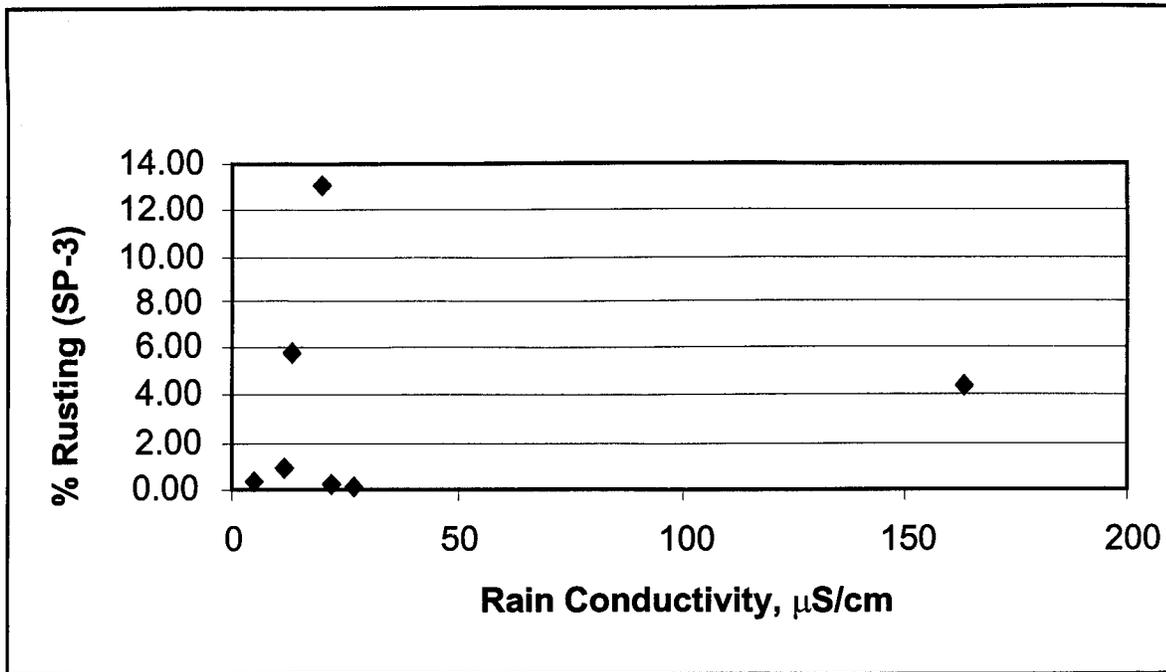
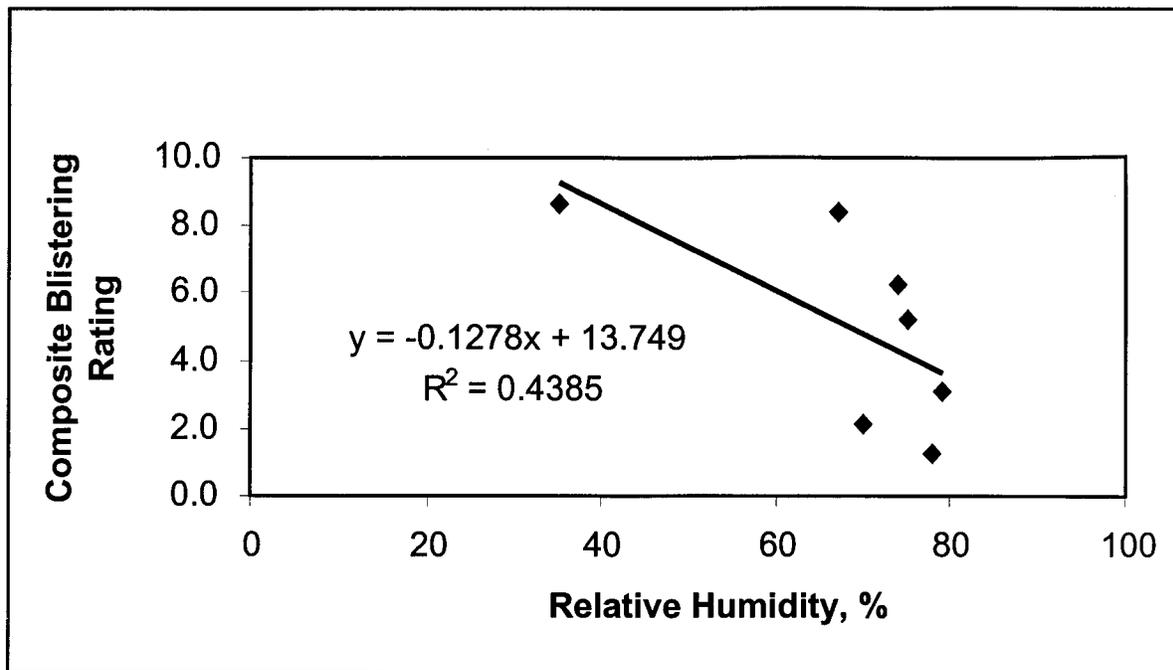


Figure 22. Percent area rusting vs. rain conductivity (SP-3).

There is not a great correlation between the rusting data and the local temperature. However, in general, the area rusted does tend to increase with increases in the local average temperature. This is consistent with an increase in the diffusion rate of moisture through the coating.

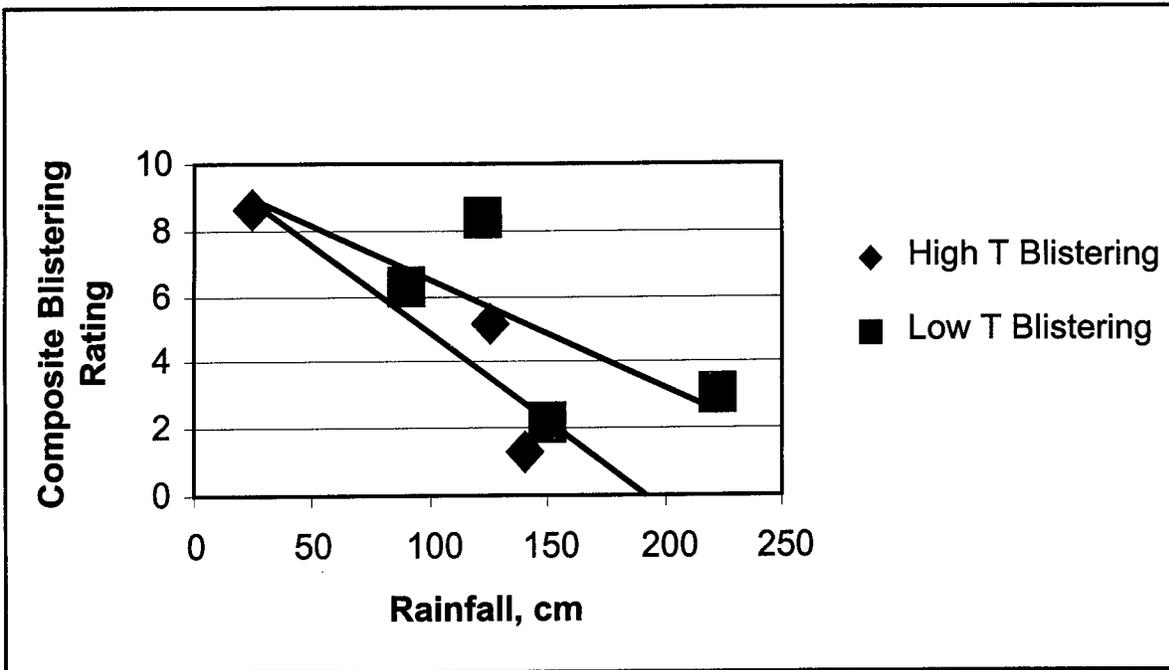
**Blistering:** With respect to blistering, there is not a lot of blistering over the SSPC SP-10 prepared surfaces. There was substantially more blistering over the SSPC SP-3 prepared surfaces. This suggests that the root cause of the blistering is related to the surface contaminants. The current discussion will focus only on blistering over the SSPC SP-3 substrates.

Figure 23 plots the observed blistering vs. the local relative humidity of the test sites.



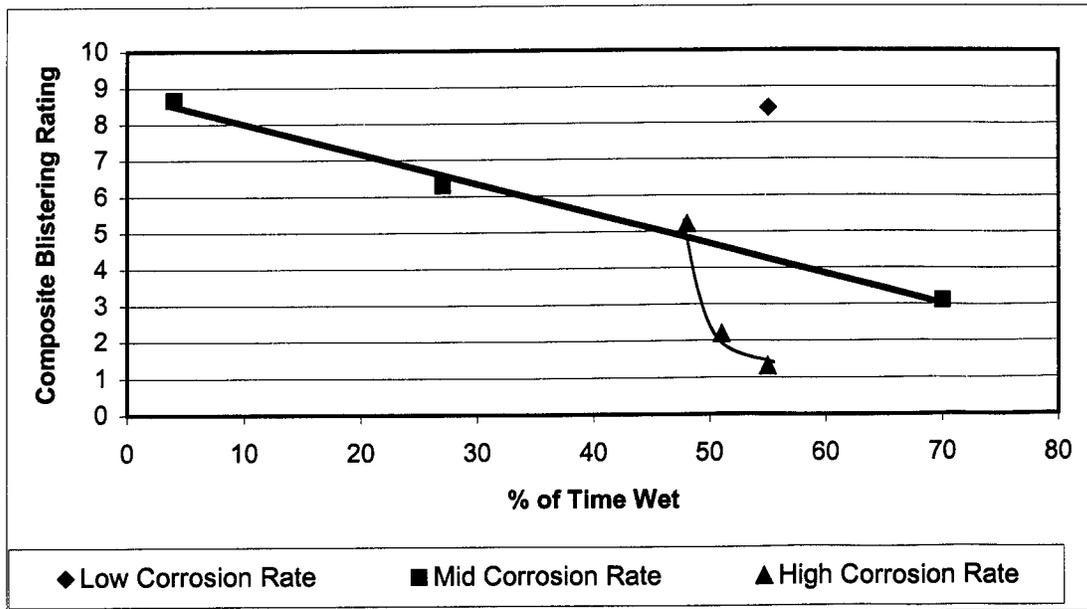
**Figure 23. Blistering vs. relative humidity (SP-3).**

This plot does not exhibit a substantial correlation, yet blistering appears to increase with some form of increased wetness. Figure 24 shows the same relationship with respect to rainfall. In this plot, the data are divided by site temperature, where the low-temperature sites had a nominal temperature of 8.9°C vs. 22.6°C at the higher temperature sites. Blistering appears to increase with rainfall and with temperature.



**Figure 24. Blistering vs. rainfall and temperature (SP-3).**

Looking at this data, there is still some interest due to the lack of significant blistering at the Massachusetts site and the lack of more blistering at the Oregon site. These are the outlier data points. To attempt to address this issue, the blistering data were organized by the severity of the corrosion observed and the time-of-wetness. In this program, time-of-wetness correlated quite well with rainfall. Figure 25 shows this plot.



**Figure 25. Blistering vs. time-of-wetness and corrosion rate (SP-3).**

The data are segregated by site and by corrosion rate. This description was determined from the SSPC SP-3 rust-through data. While there does not seem to be a direct relationship between blistering and rusting, the above plot suggests that there is some effect of corrosion. At mid-range corrosion rates, the extent of blistering seems to have a direct relationship with time-of-wetness. At very low corrosion rates, such as in Massachusetts, the blistering is light, despite a high time-of-wetness. At the sites with high corrosion rates, the blistering is worse than might be expected due to the time-of-wetness. The exception to this is the Florida site, which showed blistering more in line with the mid-range corrosivity sites. This may simply be a data anomaly. The corrosion in Florida over the SSPC SP-3 surface preparation was so significant that it may tend to obscure any blistering.

The concept discussed above suggests that local corrosivity and time-of-wetness both influence eventual blistering. Corrosion or water ingress at the steel/coating interface leads to the disbondment and osmotic forces aiding the development of blisters. In Massachusetts, there was little corrosion, so there was little tendency for blistering. If the tendency for corrosion is equivalent, time-of-wetness will control blistering. Temperature seems to increase blistering tendencies.

**Coating Cutback:** Cutback of the coatings was similarly analyzed. Figure 26 shows the nominal cutback of the coatings applied over the SSPC SP-3 surface preparation as a function of total rainfall.

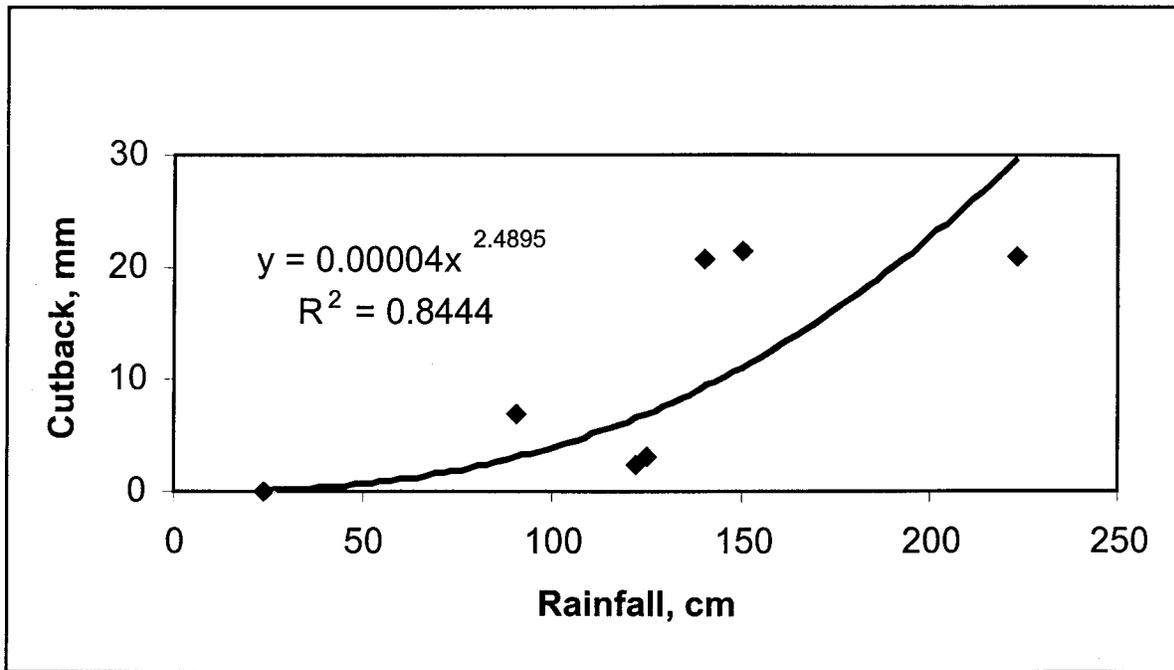
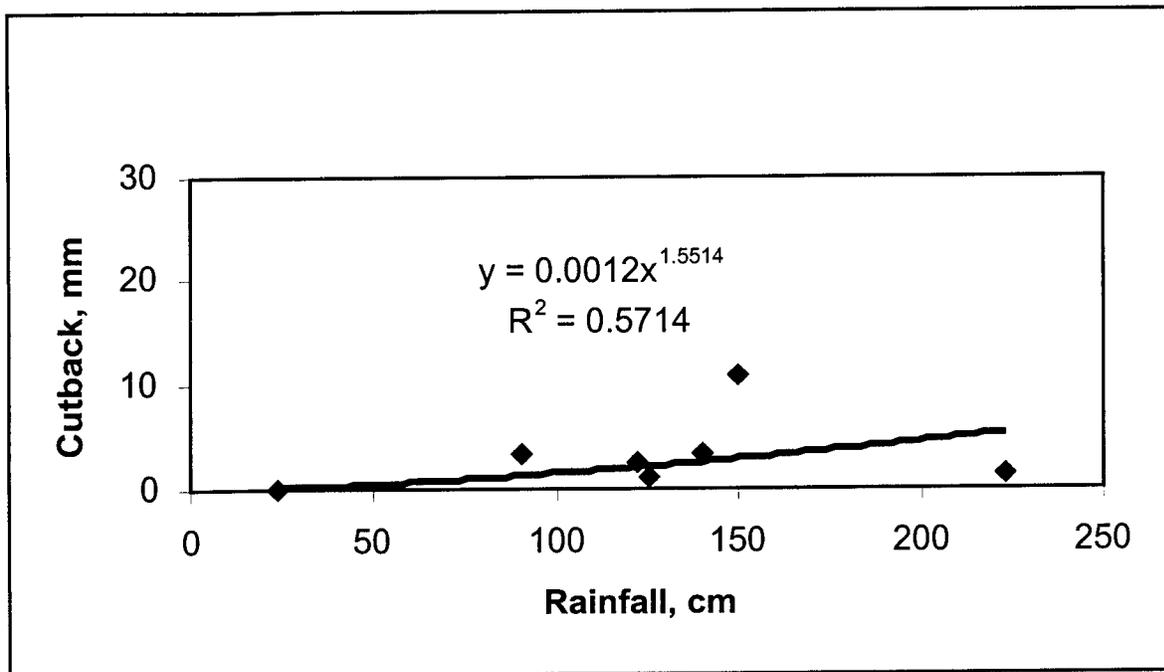


Figure 26. Cutback vs. rainfall (SP-3).

The general correlation between these factors is reasonable. Because rainfall also correlates well with time-of-wetness, a similar relationship may be derived between time-of-wetness and cutback.

Figure 27 shows the same analysis for the coatings applied to the SSPC SP-10 substrate. It can be seen that the correlation is not as good.



**Figure 27. Cutback vs. rainfall (SP-10).**

The lack of a better correlation may very well be due to the influence of salts. With the SSPC SP-3 panels, contamination already exists beneath the coating. So the rate-determining step in the cutback process is the time and availability of moisture. With the SSPC SP-10 panels, the undercutting needs both salt and water for propagation.

With the SSPC SP-10 panels, there are four distinct groups of data. These distinctions are developed from levels of rainfall and salt-fall. At the lowest rainfall, there is the Arizona site; Oregon is the highest rainfall site. With the low rainfall in Arizona, there was little cutback, much like the SSPC SP-3 panels. Arizona only had 10% of the rainfall of Oregon (the highest rainfall site). The other five sites had 40% to 67% of the Oregon rainfall. Of these five sites, four showed a similar cutback, and one, New Jersey, had the highest cutback. The New Jersey site showed the most cutback over the SSPC SP-10 substrates due to the copious amount of salts present. The Oregon site, which had the highest rainfall, had less cutback than might be expected due to the lack of salts in the water. Oregon showed rainwater with the lowest conductivity. It was only about 3% of the conductivity of the water at the New Jersey site. The remaining four sites showed 7% to 17% of the water conductivity of the New Jersey site, similar rainfall to each other, and, thus, similar levels of cutback.

Looking at just the four sites with similar rainwater conductivities and levels of rainfall, there were still some differences in cutback. Figure 28 shows these plotted against the average daily temperature variation at each site.

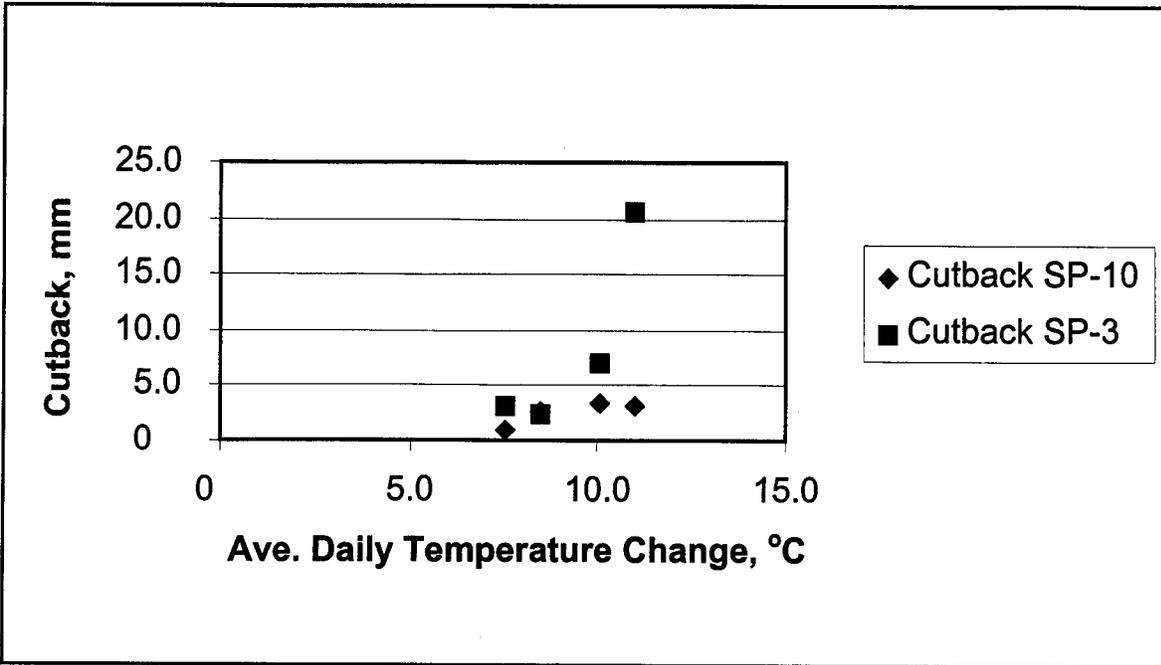


Figure 28. Cutback as a function of daily temperature change.

For both the SSPC SP-10 and the SSPC SP-3 surface preparations, there seems to be a positive correlation between these two events. Thus, increasing cyclical thermal stresses on the coatings would appear to increase their tendency to experience cutback.

#### 2.4. Correlations Between Accelerated Tests and Environmental Exposure

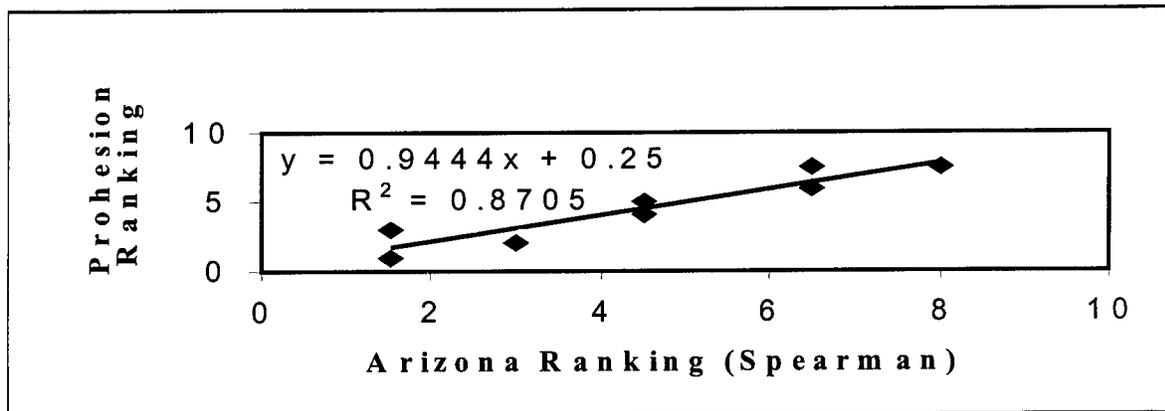
Comparisons were made between the rankings of coating performance in the accelerated tests and those in the natural environment. This was an attempt to illustrate the performance *rankings* of multiple systems, *not* the actual extent of deterioration. This seems to be the appropriate goal given the wide range of performance exhibited in this program's varied natural environments. While it is conceivable to design an accelerated procedure to mimic the results of a specific coating system in a natural environment, this program has shown that such predictions will not hold in an alternative environment. For example, designing a harsh salt-fall test to simulate corrosion in a marine environment will not simulate corrosion in a benign environment.

Ranking correlations were developed using the Spearman rank correlation coefficient. The process used on the raw data was similar to that illustrated in the literature.<sup>(7)</sup> In summary, the data for each test site were ordered from the best to the worst performing coating system. A Spearman rank was assigned to each placeholder. Ties were assigned the same rating (the average of the consecutive values for the number of ties). For the eight systems being investigated, the sum of all rankings was always 36. Table 9 provides an example of this analysis for some rusting data over SSPC SP-10 panels.

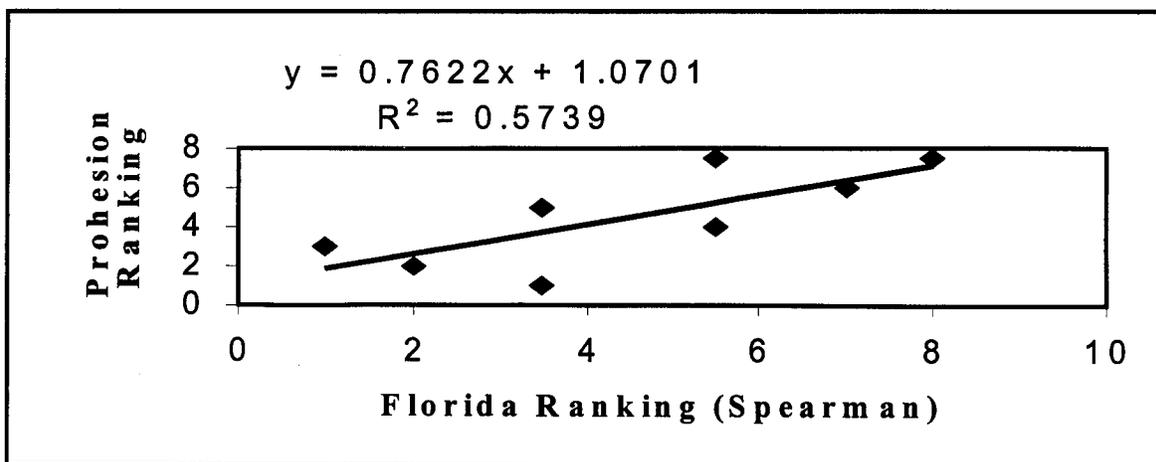
**Table 9. Spearman ranking development for rusting of coatings  
over SSPC SP-10 substrates.**

Arizona Coating Data								
Rank	(1) IOZ/E/U	(2) H <sub>2</sub> O Acr.	(3) IOZ/Sil.	(4) Sil. Alk.	(5) CaSulf.	(6) OZ/E/U	(7) E/U	(8) MCU
Final Rust Rating	10.0	8.0	10.0	8.0	7.0	9.5	9.0	9.0
Rank	1.0	4.0	1.0	4.0	5.0	2.0	3.0	3.0
Spearman Rank	1.5	6.5	1.5	6.5	8.0	3.0	4.5	4.5
Florida Coating Data								
Rank	(1) IOZ/E/U	(2) H <sub>2</sub> O Acr.	(3) IOZ/Sil.	(4) Sil. Alk.	(5) CaSulf.	(6) OZ/E/U	(7) E/U	(8) MCU
Final Rust Rating	8.0	7.5	10.0	3.0	5.5	8.5	7.5	8.0
Rank	3.0	4.0	1.0	6.0	5.0	2.0	4.0	3.0
Spearman Rank	3.5	5.5	1.0	7.0	8.0	2.0	5.5	3.5
Prohesion Coating Test								
Rank	(1) IOZ/E/U	(2) H <sub>2</sub> O Acr.	(3) IOZ/Sil.	(4) Sil. Alk.	(5) CaSulf.	(6) OZ/E/U	(7) E/U	(8) MCU
Final Rust Rating	7.75	1.75	7.00	4.00	1.75	7.25	6.75	5.00
Rank	1.00	7.00	3.00	6.00	7.00	2.00	4.00	5.00
Spearman Rank	1.00	7.50	3.00	6.00	7.50	2.00	4.00	5.00

Figures 29 and 30 show the Spearman ranking of the systems in Arizona and Florida vs. the predicted rankings in the Prohesion test.



**Figure 29. Spearman ranking of Prohesion test results vs. Arizona test results.**



**Figure 30. Spearman ranking of Prohesion test results vs. Florida test results.**

The graphs in Figures 29 and 30 show that the Spearman ranking of the Arizona and Prohesion data have a better correlation than that of the Florida and Prohesion data. A Spearman rank correlation coefficient is defined by:

$$\rho = 1 - \{ [6\sum (x-y)^2] / [N(N^2-1)] \}$$

where  $\rho$  = correlation coefficient

$x, y$  = Spearman ranking for a material in each exposure

$N$  = number of observations

(Note that this correlation coefficient is not the same as the regression coefficient shown in the above plots.) The critical value for correlation at the 90% level is 0.600.

Tables I-1 and I-2 show the results of this analysis for the rusting and cutback data. Similar correlations for blistering are not presented and are not considered to be meaningful. This is due to the lack of any significant blistering over the SSPC SP-10 substrates, as well as the inconsistent blister growth behavior.

For rusting, the best rank correlation for the SSPC SP-10 substrates was obtained vs. the standard salt fog test. The Prohesion test was only slightly less likely to provide a similar ranking. Over the SSPC SP-3 substrates, neither the salt fog nor the Prohesion test was likely to provide the right product ranking. The 14-month Sea Isle City, NJ test was much more meaningful, as evidenced by the correlation coefficient. In general, the rankings of the accelerated tests concerning coatings applied over an SSPC SP-10 substrate were more likely to correlate with the harsh environments of Arizona, Florida, and New Jersey. Interestingly, over the SSPC SP-3 substrate, the best relationship was found between accelerated testing and the Oregon site. The tests were not as meaningful for the Arizona, Florida, and New Jersey exposures.

For the cutback testing, neither the salt fog nor the Prohesion test showed much utility for all the exposure environments. The Prohesion test was a uniformly bad predictor of cutback ranking,

with the exception of Oregon for the SSPC SP-10 substrate. The salt fog testing, on average, was a better predictor of ranking than the Prohesion test, but was still only mediocre across all the exposure locations. It was best in predicting the behavior in the harsh marine environment over the SSPC SP-10 substrate.

The best overall correlation seemed to be with the Sea Isle City, NJ exposure for coatings applied over the SSPC SP-10 substrate. This exposure correlated well with the Indiana, Louisiana, Massachusetts, and, of course, the New Jersey test site.

The most telling example of an accelerated test's failure to predict behavior is exhibited in its prediction for the epoxy/urethane systems. The epoxy/urethane systems demonstrated extensive cutback in most of the natural environments. Yet the Prohesion test showed the same systems to be one of the best performers.

### 3. GENERAL CORROSION RATE TESTING

#### 3.1. Accelerated Tests

Figure 31 shows the corrosion rate observed in each of these accelerated tests following 1,000 h. From this, it can be seen that the salt fog test provides an environment that is more aggressive to bare steel than the Prohesion test. This graph also shows that the weathering steel (A588) has a higher corrosion rate than the structural steel (A36) in the accelerated tests. The corrosion rates are nominally 10 times higher than might be expected in a natural environment. The lower salt concentration in the Prohesion test, as compared to that in the salt fog test, may reduce corrosion, although the corrosion rate remains high.

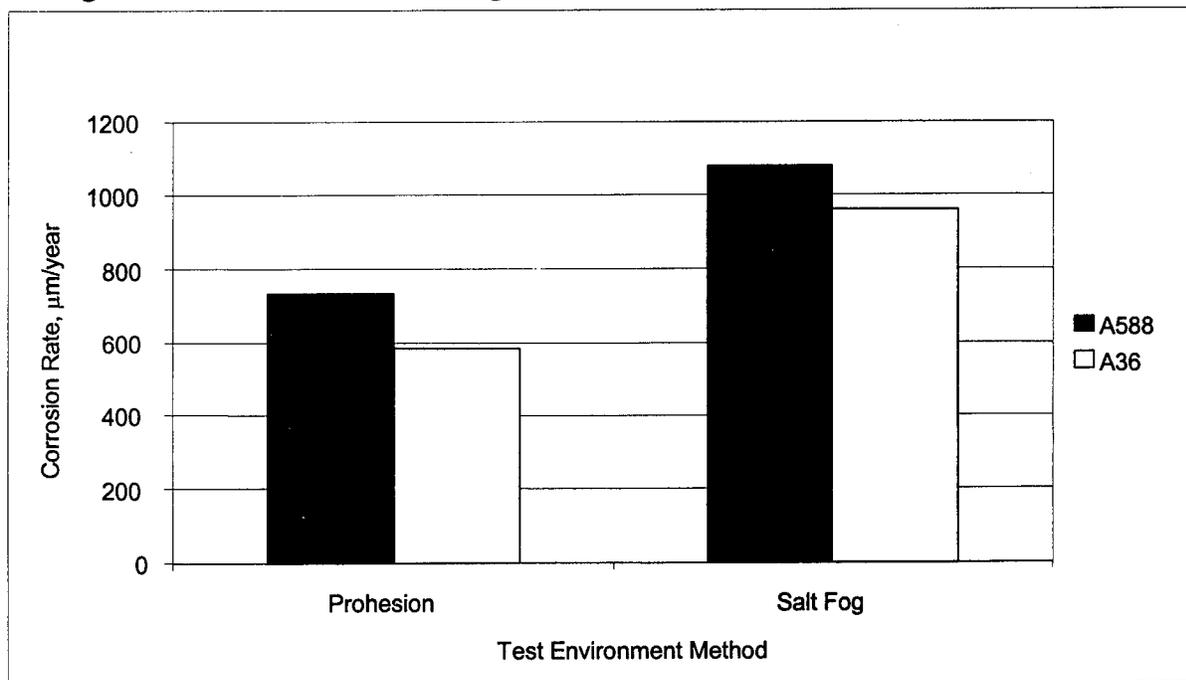


Figure 31. Corrosion rate for steel alloys in accelerated tests.

### 3.2. Natural Exposure Tests

**Weathering Steel:** Figure I-30 shows the corrosion rate of weathering steel at each site for all four orientations. From this, it can be seen that for most sites and exposures, the initial corrosion rate (after approximately 1 year of testing) is higher than the subsequent readings. For orientations and sites where the initial level of corrosion was low, the subsequent rates did not vary greatly from this value. Overall, the harshest environment was the New Jersey site, which typically attained corrosion rates two times higher than any other site.

**Structural Steel:** Figure I-31 shows the corrosion rate of structural steel at each site for all four orientations. As with the weathering steel, it can be seen that over the test period, the corrosion rates drop substantially from their initial rates.

### 3.3. Discussion of Corrosion Rate Data

Before embarking on a discussion of the significance of the corrosion rate data, it is important to note the relatively short exposure duration of the materials in the test. The longest exposure period for the materials of interest was less than 5 years. Studies have shown that exposure periods longer than 10 to 15 years may be necessary to illustrate the long-term steady-state corrosion rate of weathering and carbon steels. Such exposure durations were beyond the scope of the current project. However, samples remain in testing to facilitate a more thorough data analysis following a longer exposure time. Therefore, the following discussions include this caveat.

**Corrosion Rate of A588 Steel vs. A36 Steel:** To illustrate the differences in corrosion rate between the two steel alloys, the corrosion rate vs. time data were regressed. The data for each orientation were included in this average. This was performed on a log-log basis. Except for the New Jersey site, the correlation coefficients were above 0.85 for this analysis. The corrosion rate at 5 years was then estimated. Table 10 provides this data.

**Table 10. Estimated material corrosion rates at 5 years of exposure time.**

Corrosion Trends at 5 Years, $\mu\text{m}/\text{year}$					
Steel Type	IN	LA	MA	NJ	OR
A588	3.2	3.4	1.3	125.1	2.3
A36	41.0	12.4	10.0	161.1	4.3

The data clearly show a significant reduction in corrosion rate of the A588 weathering steel vs. the A36 steel. This is true at each location. Corrosion rates for each material were highest at the New Jersey site. Presumably, this was the result of the local salt-fall. The other sites showed similar corrosion rates.

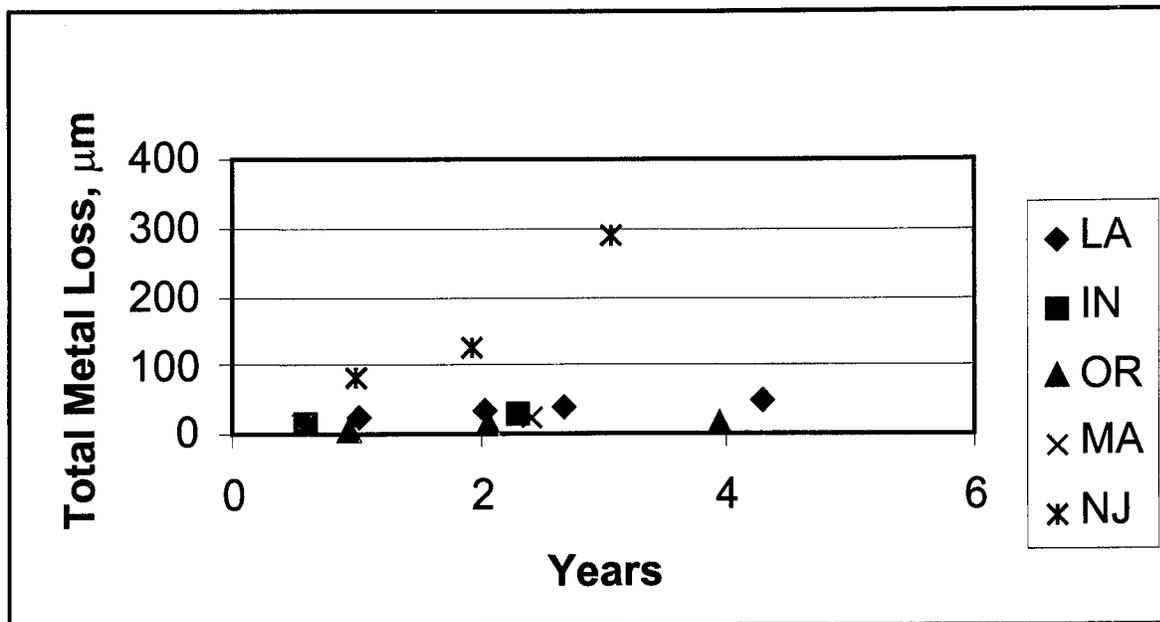
**Effect of Material Orientation:** To consider the effect of orientation on material performance, data for all exposure sites were averaged by exposure orientation. Table 11 provides this data.

**Table 11. Average corrosion rate ( $\mu\text{m}/\text{year}$ ) by exposure orientation.**

Average Corrosion Rate by Orientation, $\mu\text{m}/\text{year}$				
Steel Type	North Bold	North Sheltered	Horizontal Bold	Horizontal Sheltered
A588	17.3	19.3	20.8	50.8
A36	19.3	19	48.3	36.4
Average by Orientation (w/NJ)				
A588	11.4	10	15.9	16.4
A36	13.1	14.7	21.4	13.2

The data are shown with and without the strong influence of the New Jersey exposure site. Considering the data without the New Jersey influence, the horizontal surfaces appear to have a corrosion rate about 50% higher than the vertical coupons (North facing). The effect of sheltering is less important.

**Effects of the Environment:** To facilitate a discussion on the effects of the environment, the data were further analyzed in a manner consistent with previous studies.<sup>(3,8)</sup> This process looked at the cumulative metal loss vs. time as opposed to the corrosion rate. Figure 32 shows this data. Data are the average for all exposure orientations.



**Figure 32. Total metal loss vs. time, all orientations.**

As has been used in other studies,<sup>(9-10)</sup> these data were regressed to fit the following equation:

$$\ln(c) = \ln(a) + b \times \ln(t)$$

where: c= thickness loss,  $\mu\text{m}$ ; a, b = constants, t = time

Table 12 provides the results of this analysis for the five exposure sites. It also shows the predicted total thickness loss at various time intervals up to 100 years.

**Table 12. Summary of regression coefficients and predicted metal loss – A588 weathering steel.**

	Location				
Constant	LA	IN	OR	MA	NJ
a	22.300	3.500	6.900	3.600	74.000
b	0.519	0.813	0.722	0.706	1.134
R <sup>2</sup>	0.991	1.000	0.823	1.000	0.946
Time (years)	Steel Loss, $\mu\text{m}$				
1	22	3	7	4	74
5	51	13	22	11	459
10	74	23	36	18	1,008
25	118	48	70	35	2,851
50	170	84	116	57	6,258
100	243	147	192	94	13,738

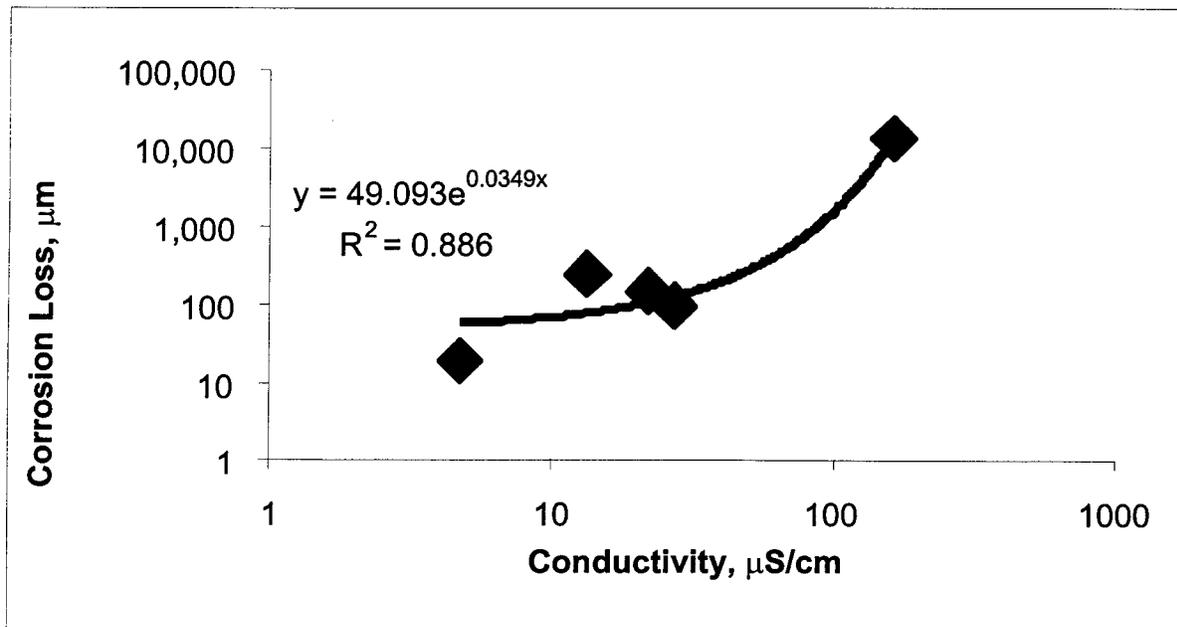
In general, considering the short exposure duration and the limited number of data points to date, the data obtained in the current program agree reasonably well with previously published data.<sup>(10)</sup>

Based on the guidance established in reference 6, the corrosion rate of the weathering steels would be acceptable in each of the environments with the obvious exception of the New Jersey site. The next most corrosive environment was the Louisiana test site. Here, especially for horizontal surfaces, the materials may not last for a 100-year design life. (Note that this program does not account for local effects such as road salt applications. Such contaminants would probably increase the corrosion rate of any steel surface.)

The predictions for the Oregon site may be skewed upwards by the influence of a lower initial corrosion rate, which suggests an increasing corrosion rate at this site. This forces the regression analysis to suggest that the corrosion rate is increasing, despite the fact that each measured rate is lower than that for the other sites. Without this first data point, the predicted deterioration in Oregon would be the lowest of all the sites with 19  $\mu\text{m}$  at 100 years. The effect of limited data on the predicted corrosion rate supports the need for additional exposure time for these materials.

The New Jersey site is assumed to be the most corrosive due to the high local salt-fall. This site is directly adjacent to the ocean and the surface is essentially contaminated with seawater. If this site is eliminated from consideration, the effect of the environment vs. the predicted corrosion loss at 100 years may be tested.

The data do not correlate well with time-of-wetness, which appears to follow rainfall. Assuming that the corrosion rate of the Oregon site appears to settle at the low levels currently observed, the A588 steel corrosion rate may eventually be shown to be a best fit to the local rainfall conductivity. Figure 33 shows the effect on this analysis after removing the first observed corrosion rate at the Oregon test site and calculating a corrosion loss at 100 years.



**Figure 33. Corrosion loss vs. conductivity (modified Oregon data point).**



## REFERENCES

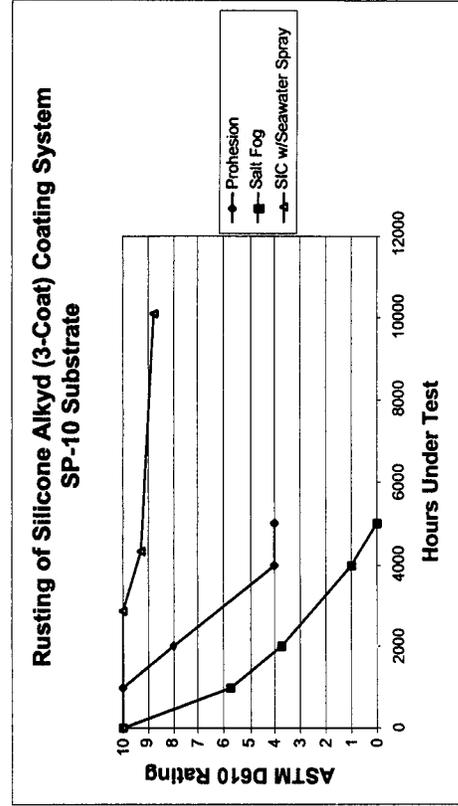
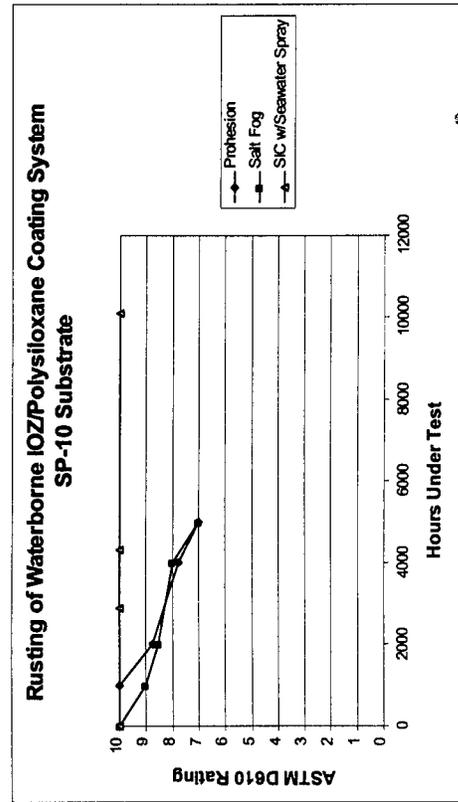
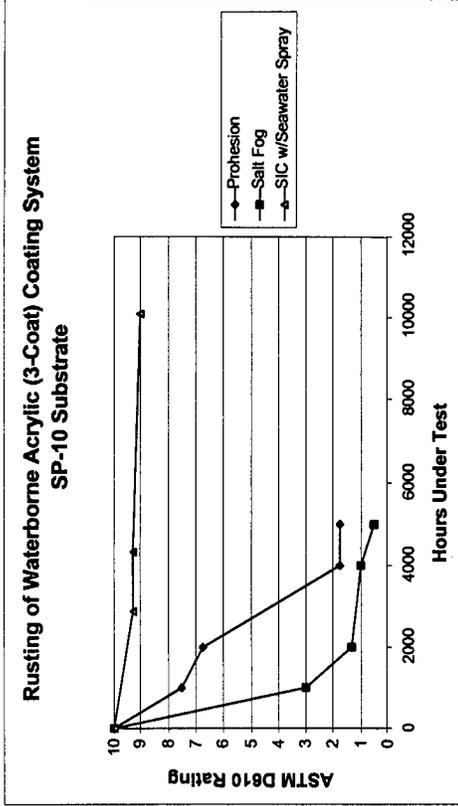
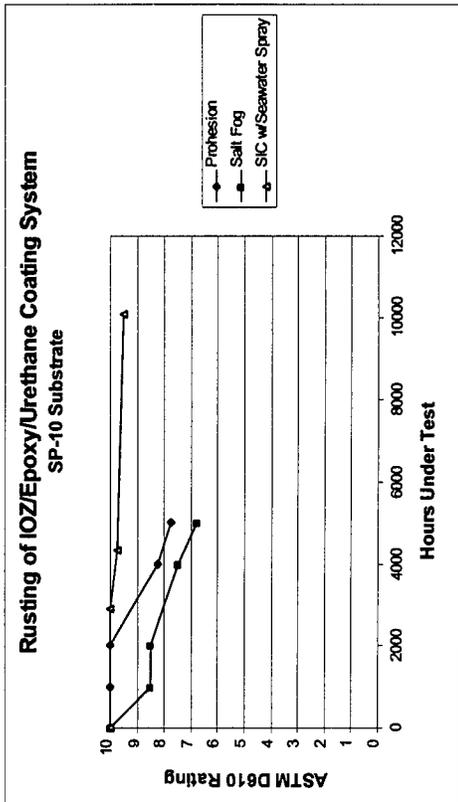
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## **APPENDIX I. DATA PLOTS**



Figure I-1. Accelerated test results, rusting data, SSPC SP-10 substrates, systems 1-4.



**Figure I-2. Accelerated test results, rusting data, SSPC SP-10 substrates, systems 5-8.**

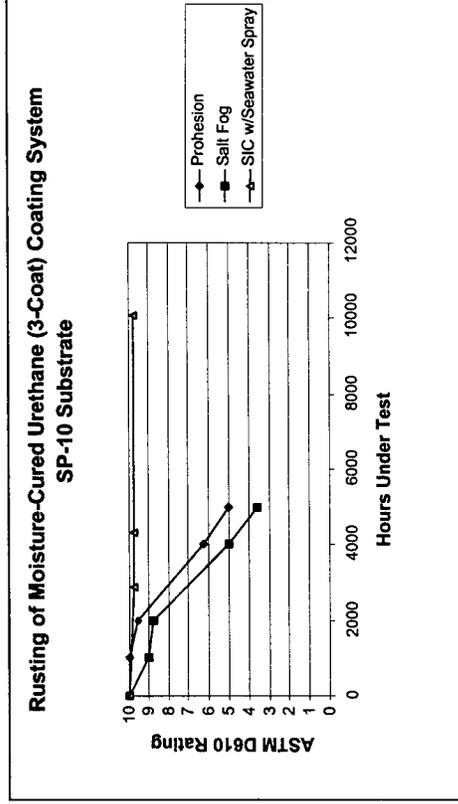
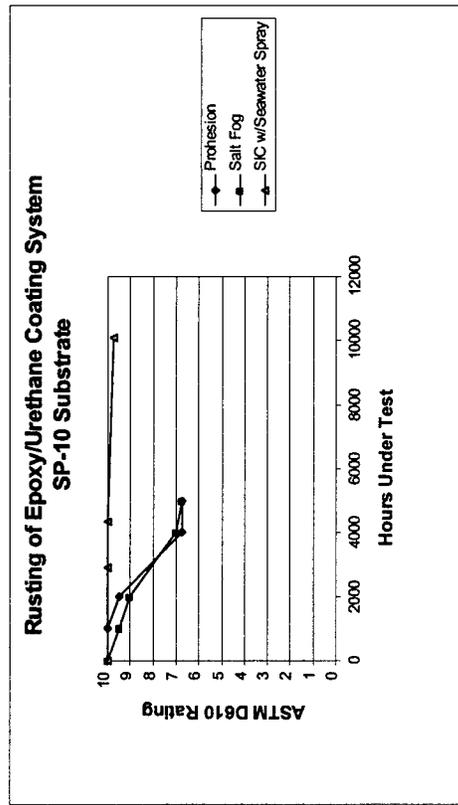
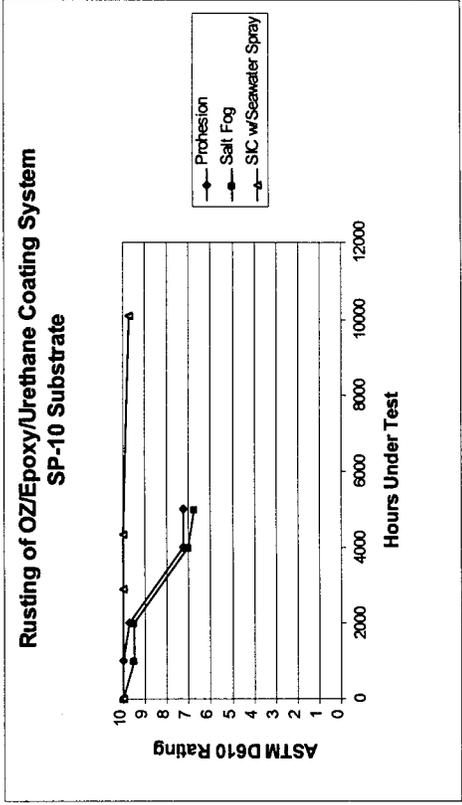
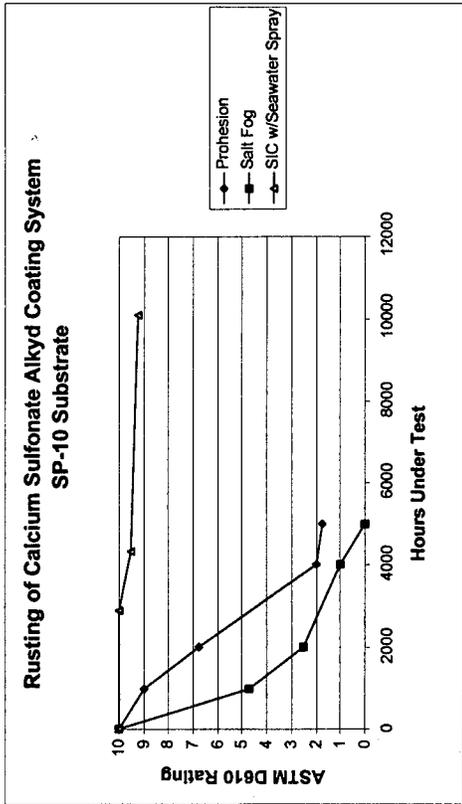


Figure I-3. Accelerated test results, rusting data, SSPC SP-3 substrates, systems 1-4.

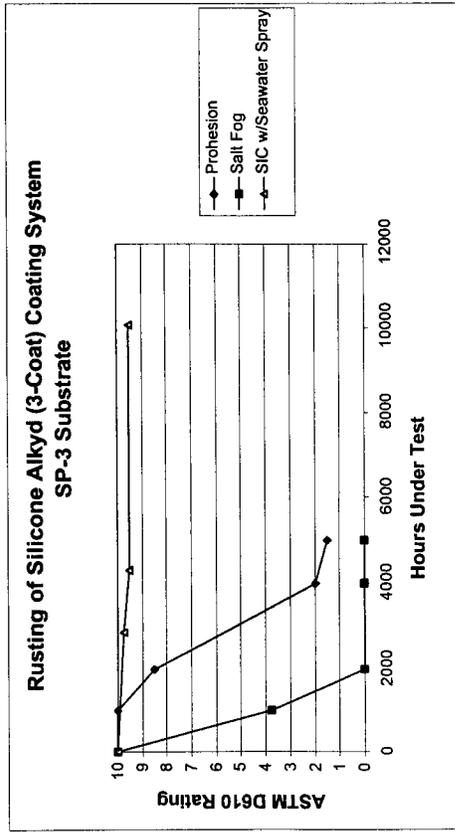
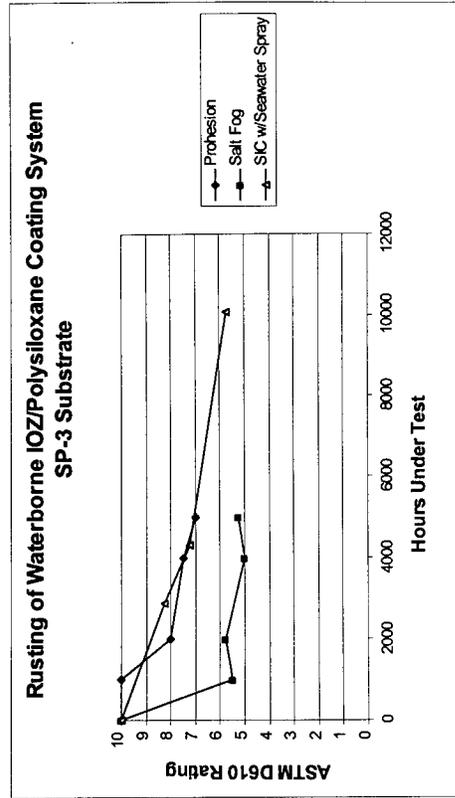
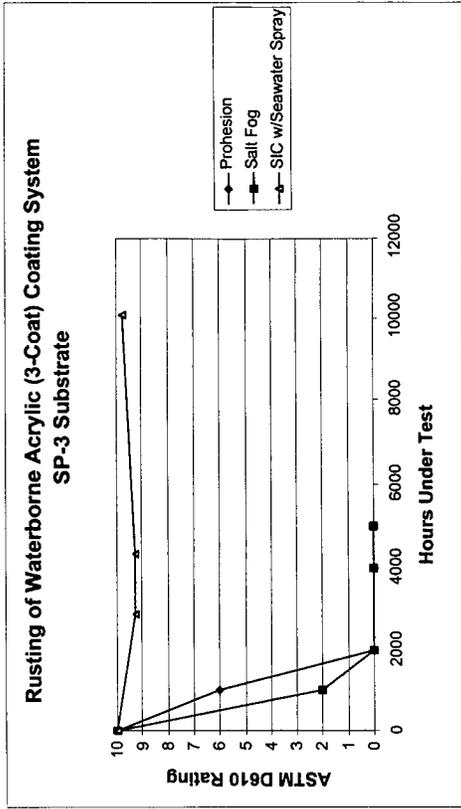
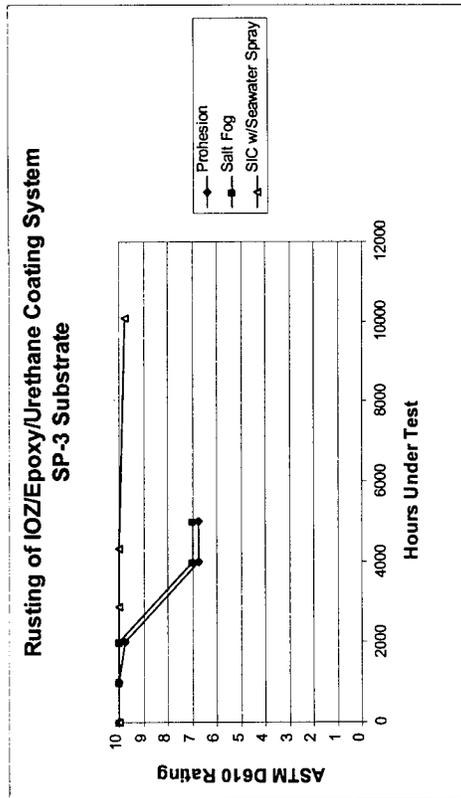


Figure I-4. Accelerated test results, rusting data, SSPC SP-3 substrates, systems 5-8.

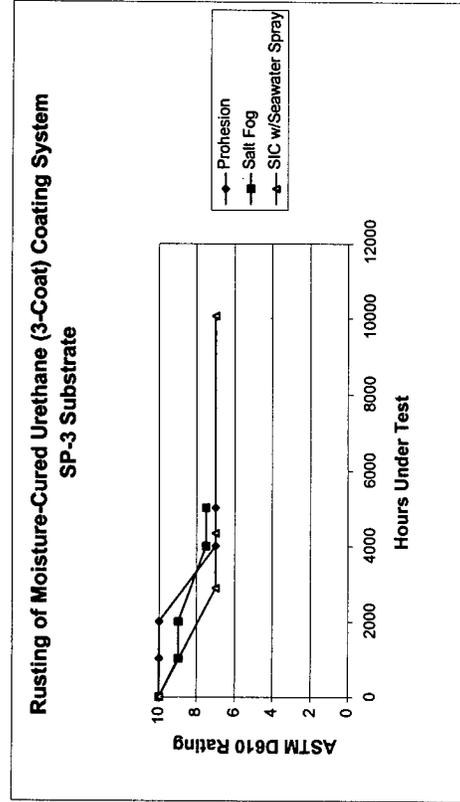
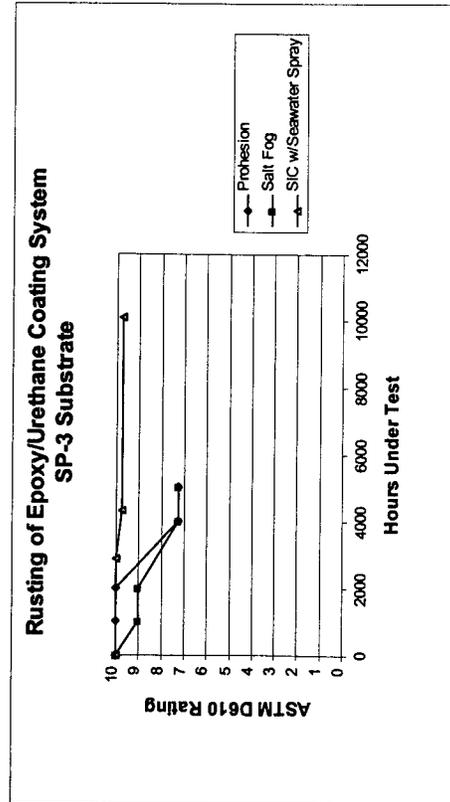
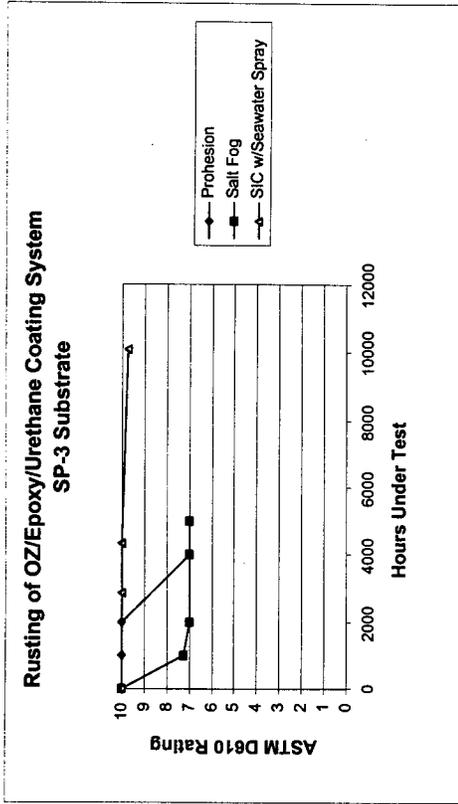
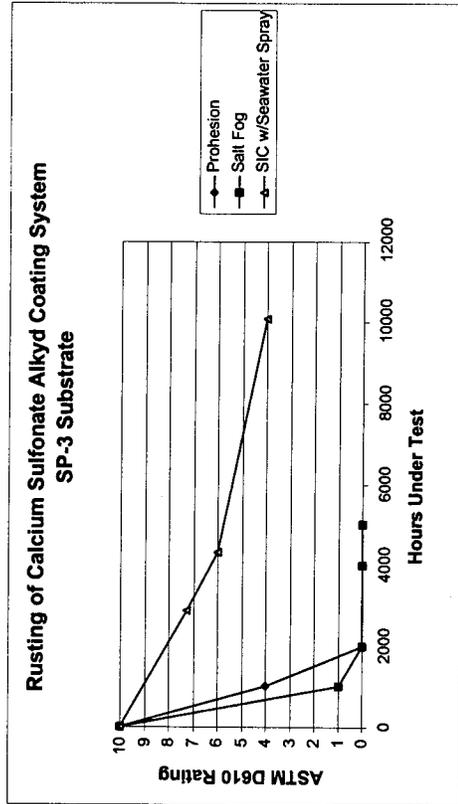


Figure I-5. Accelerated test results, blistering data, SSSPC SP-10 substrates, systems 1-4.

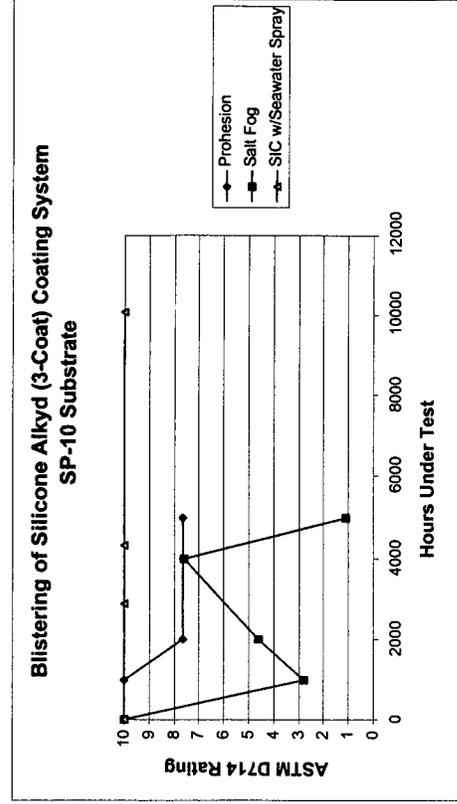
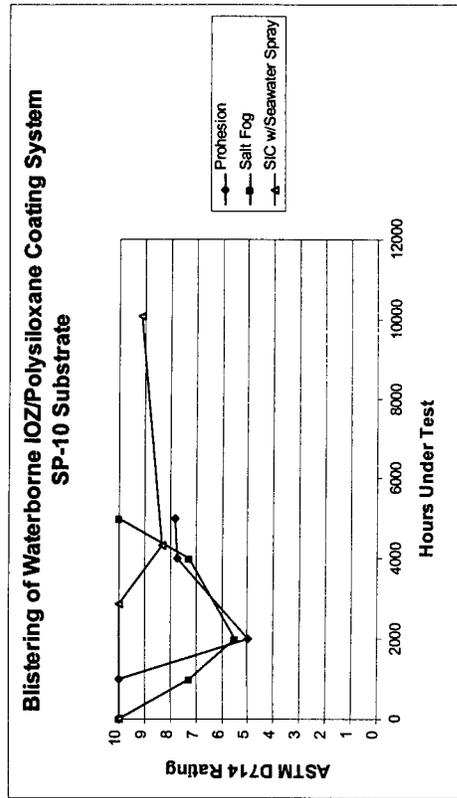
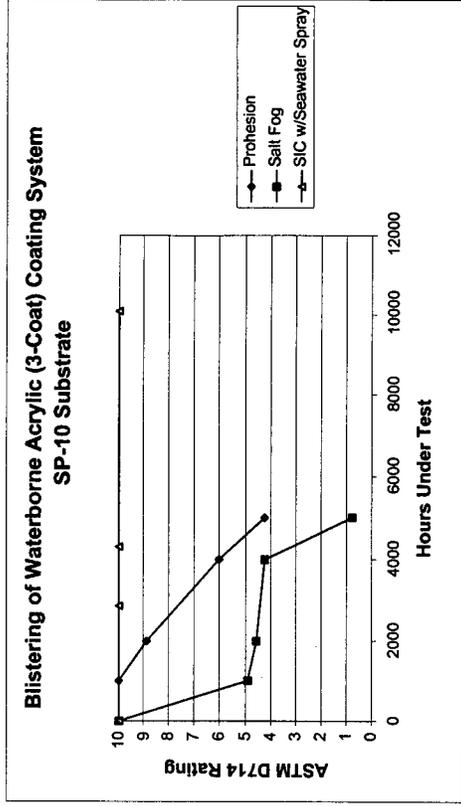
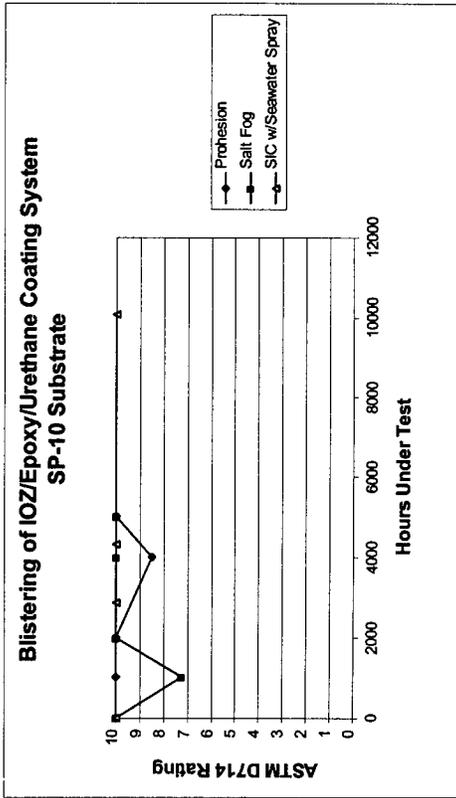


Figure I-6. Accelerated test results, blistering data, SSPC SP-10 substrates, systems 5-8.

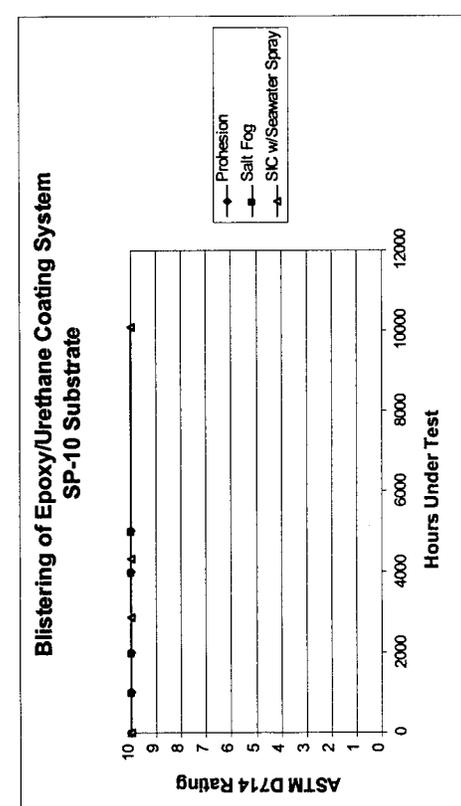
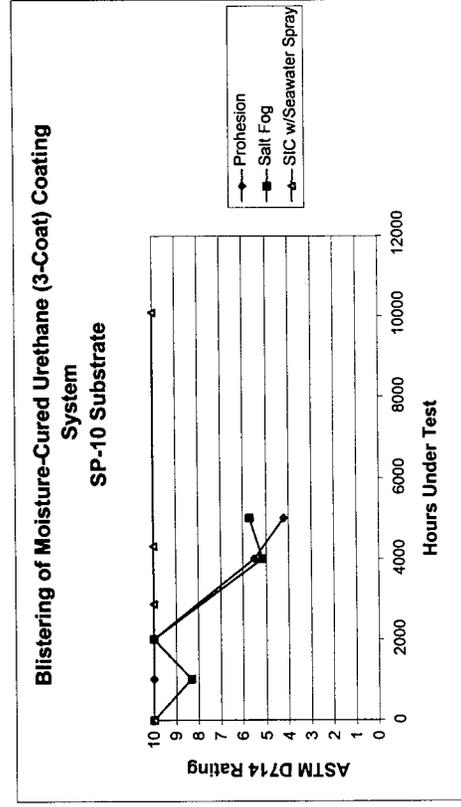
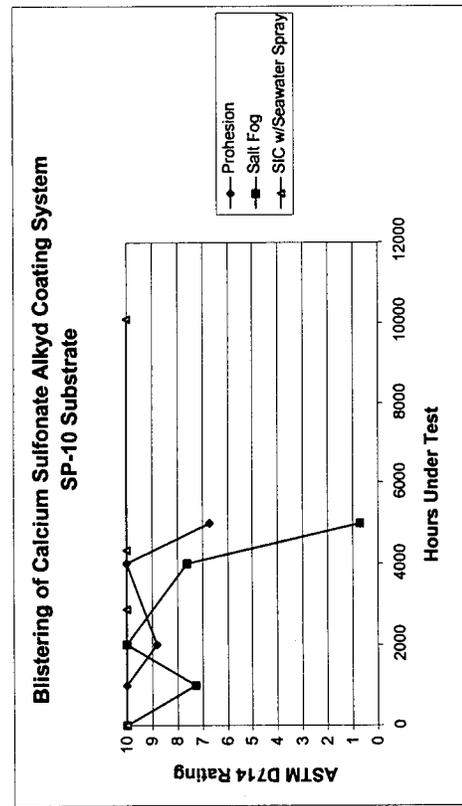
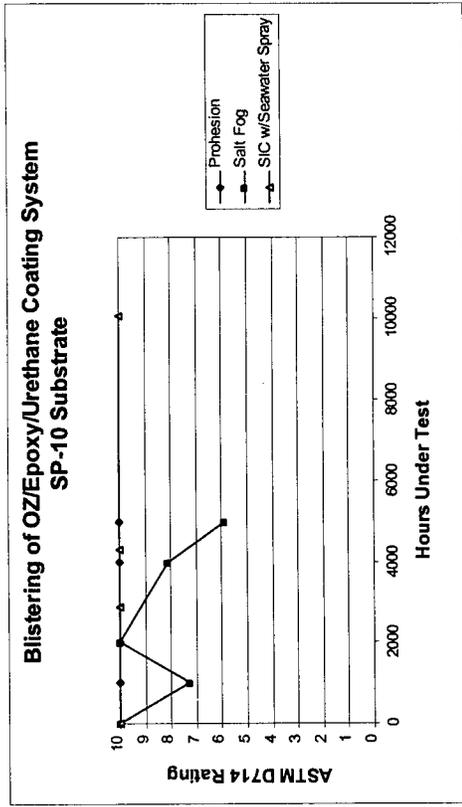


Figure I-7. Accelerated test results, blistering data, SSPC SP-3 substrates, systems 1-4.

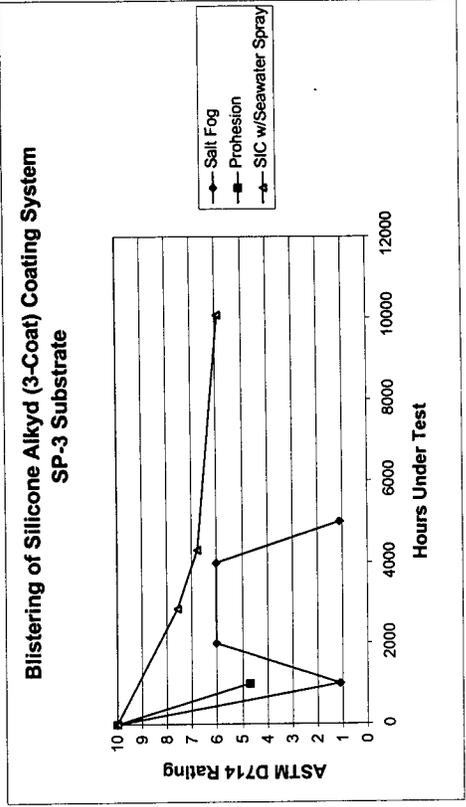
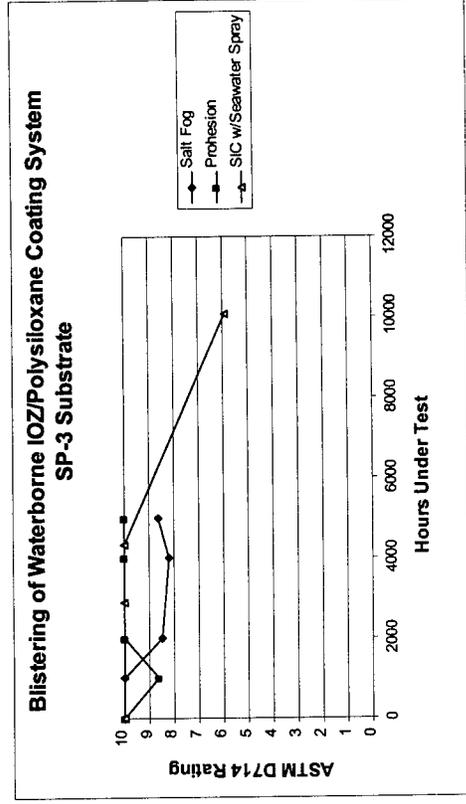
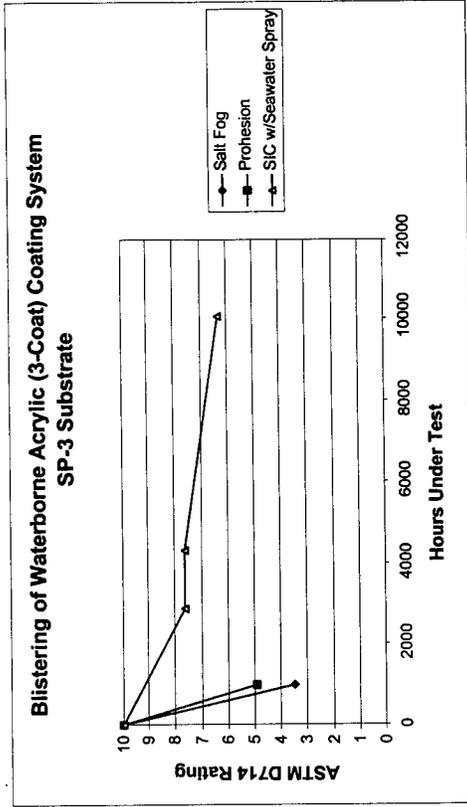
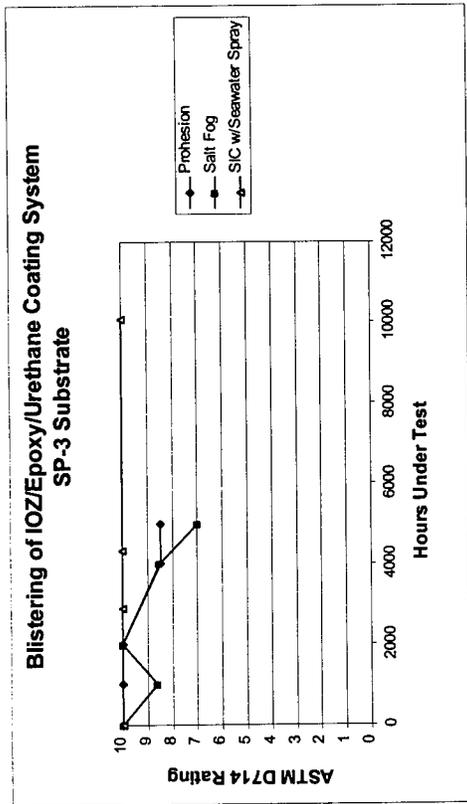


Figure I-8. Accelerated test results, blistering data, SSPC SP-3 substrates, systems 5-8.

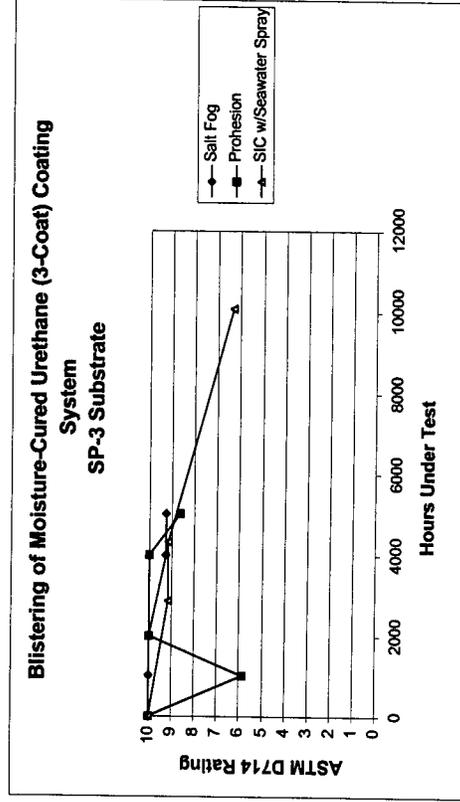
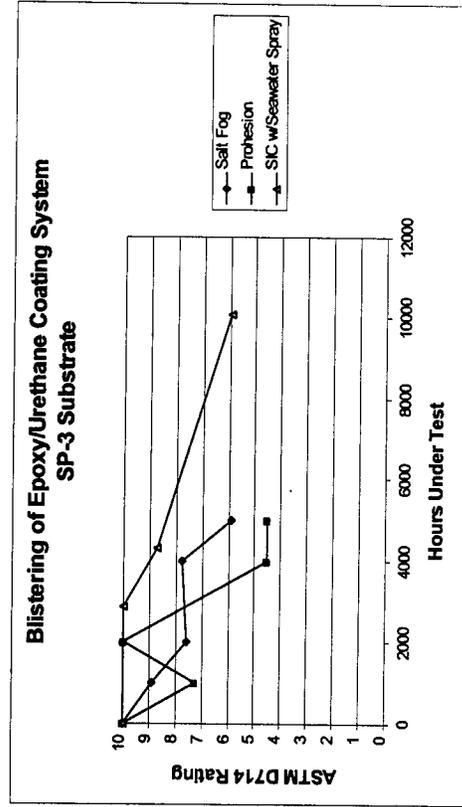
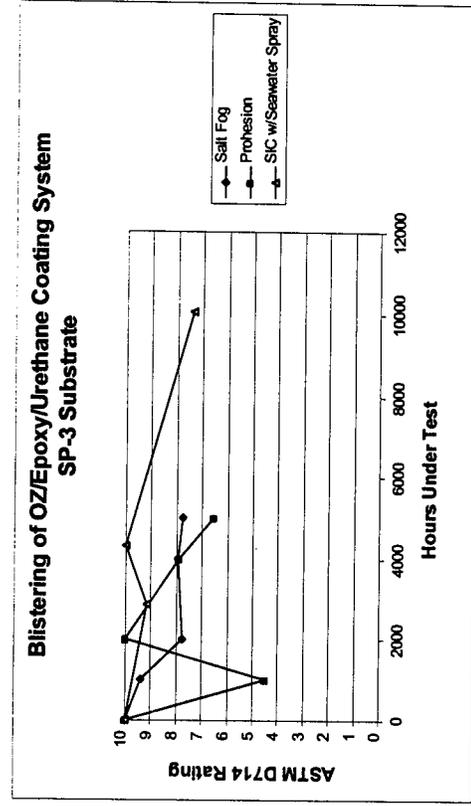
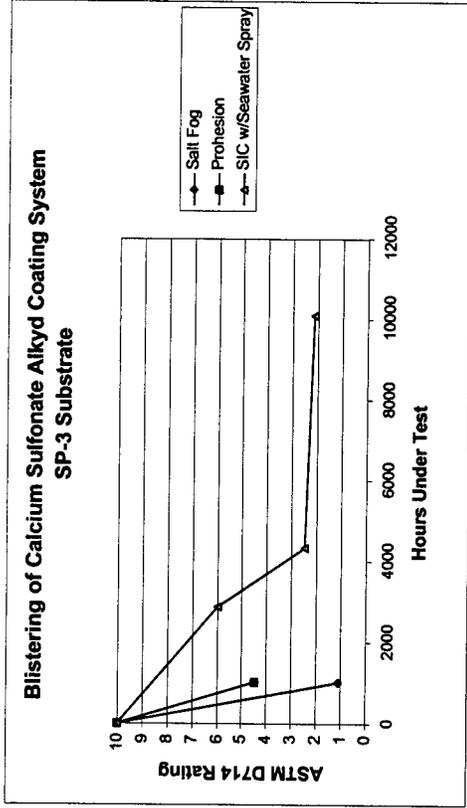


Figure I-9. Accelerated test results, cutback data, SSPC SP-10 substrates, systems 1-4.

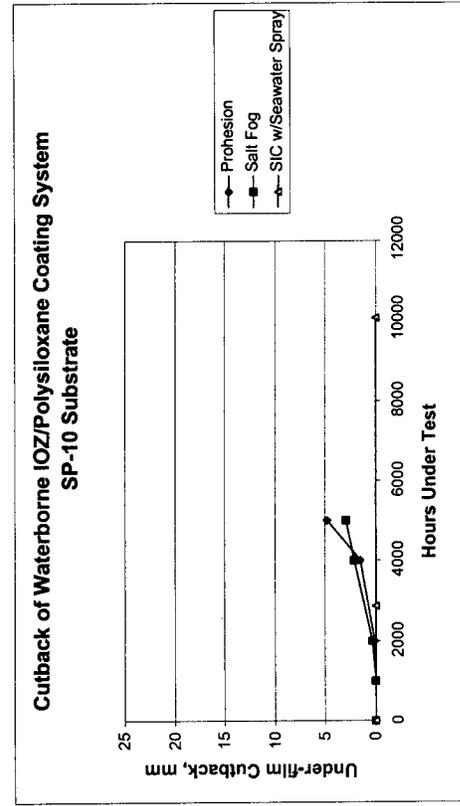
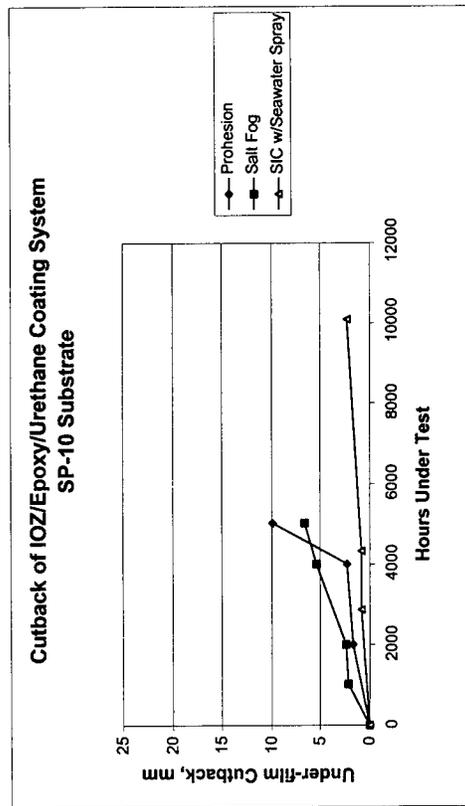
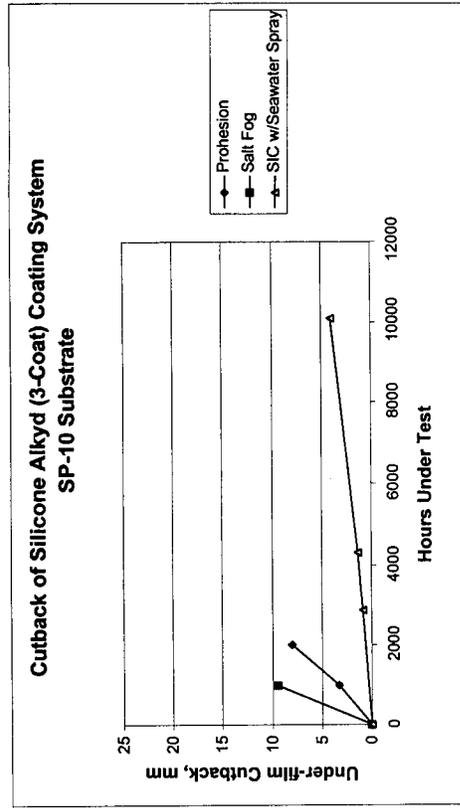
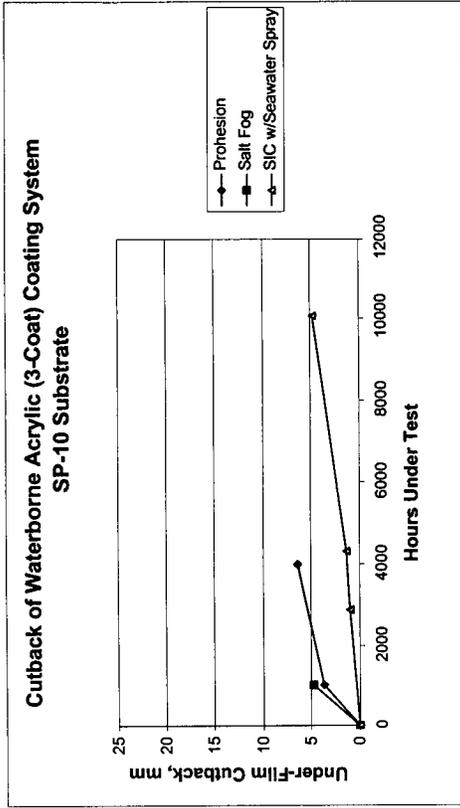


Figure I-10. Accelerated test results, cutback data, SSPC SP-10 substrates, systems 5-8.

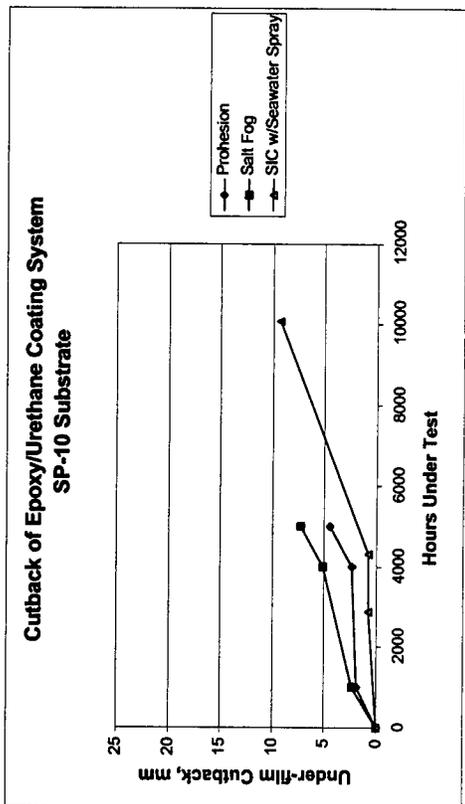
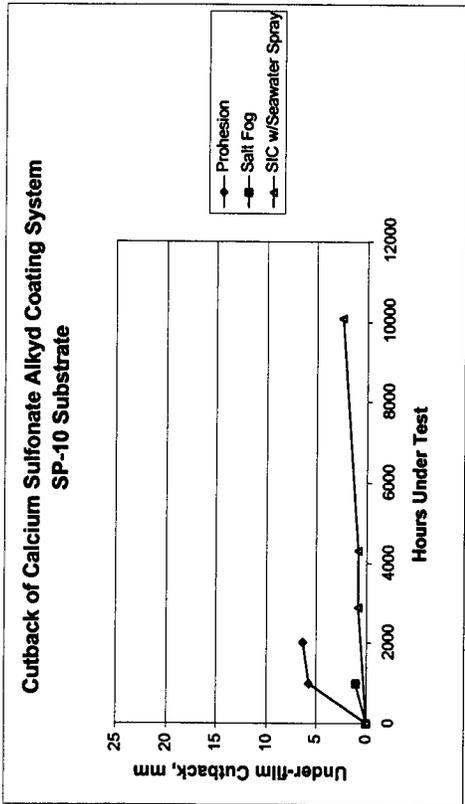
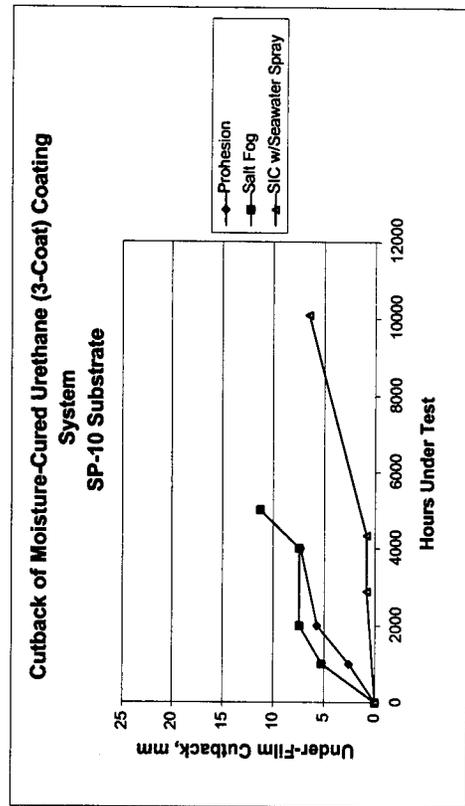
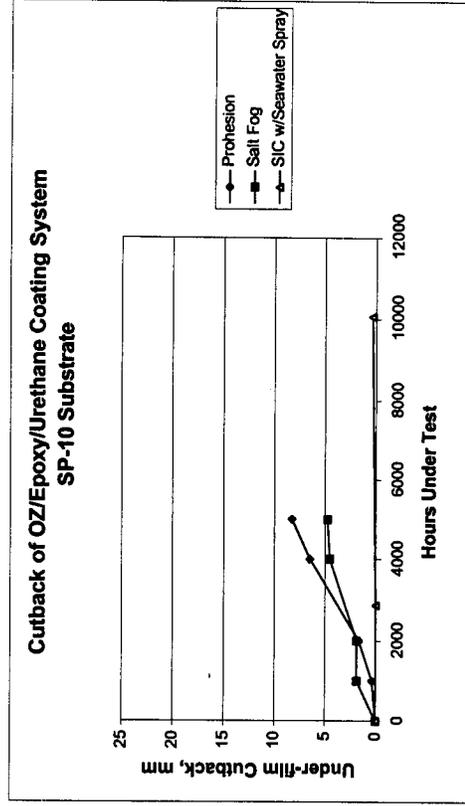


Figure I-11. Accelerated test results, cutback data, SSPC SP-3 substrates, systems 1-4.

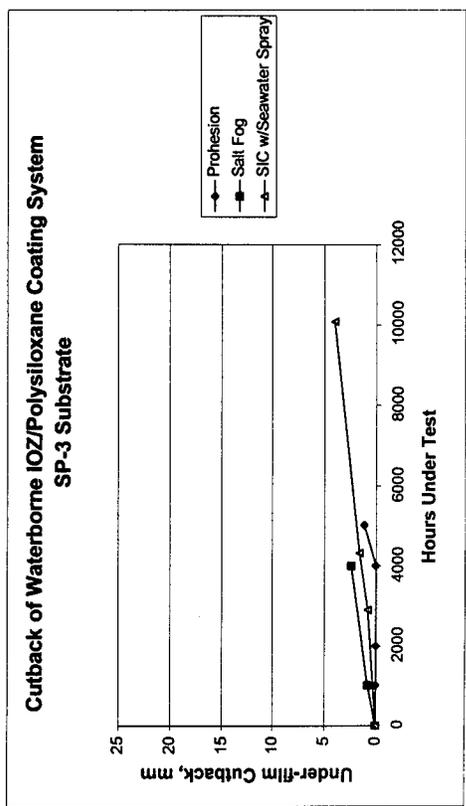
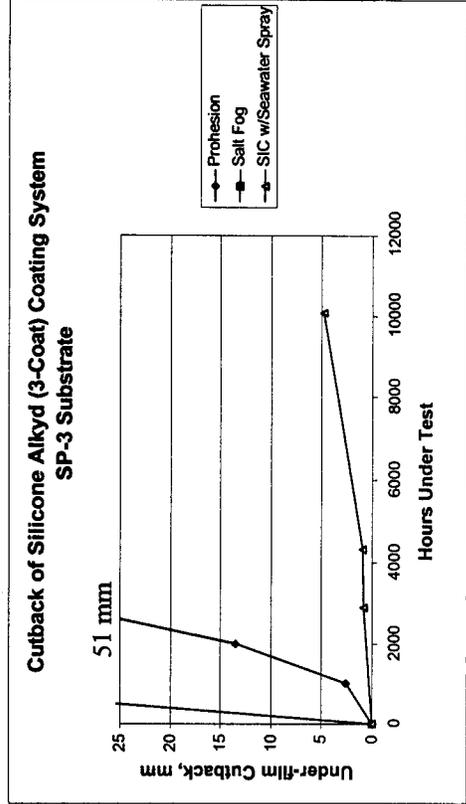
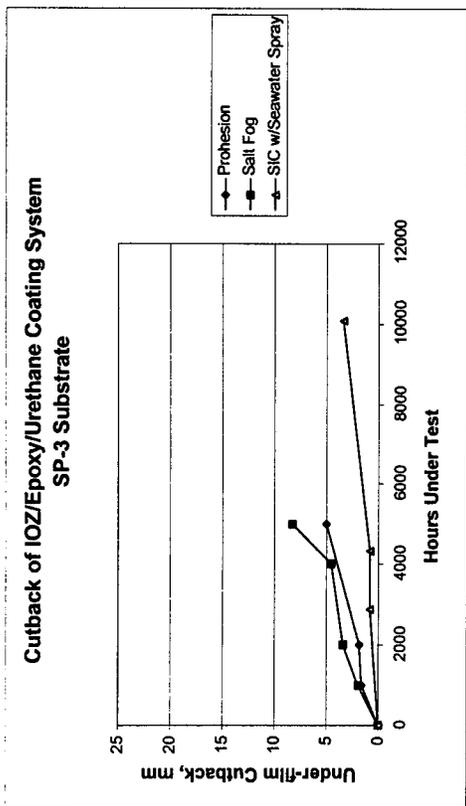
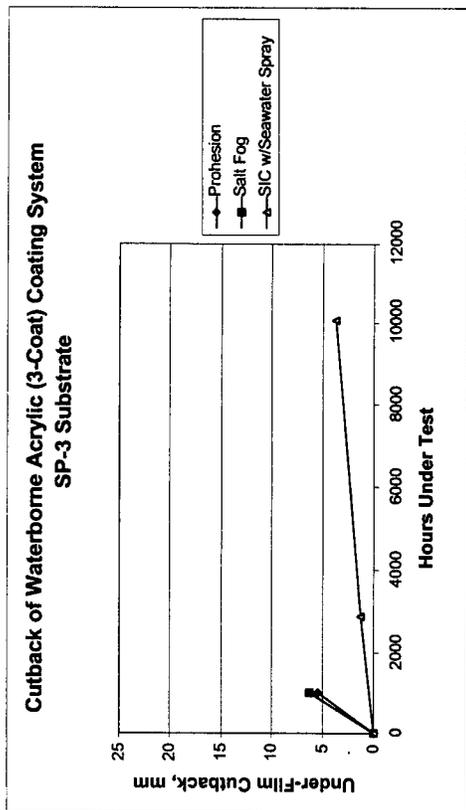


Figure I-12. Accelerated test results, cutback data, SSPC SP-3 substrates, systems 5-8.

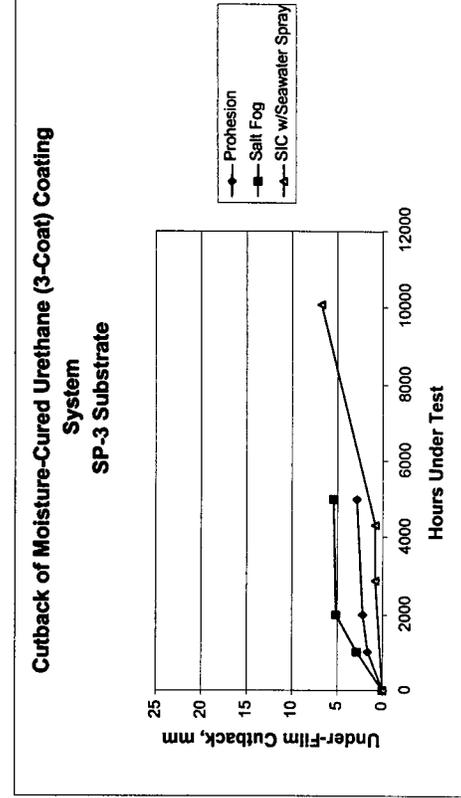
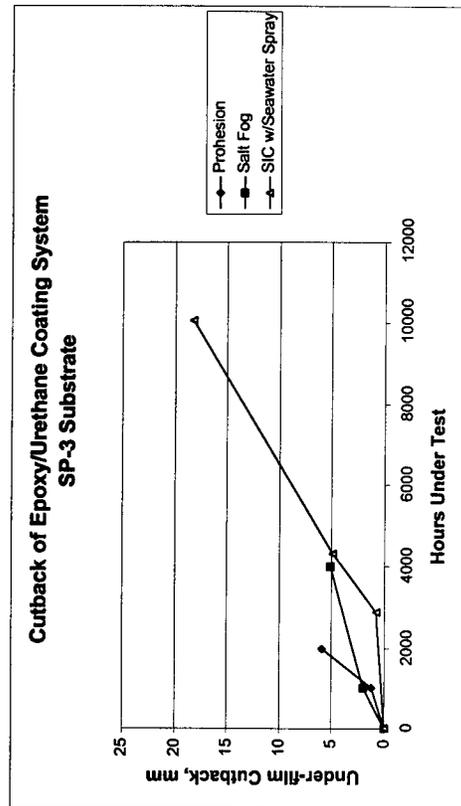
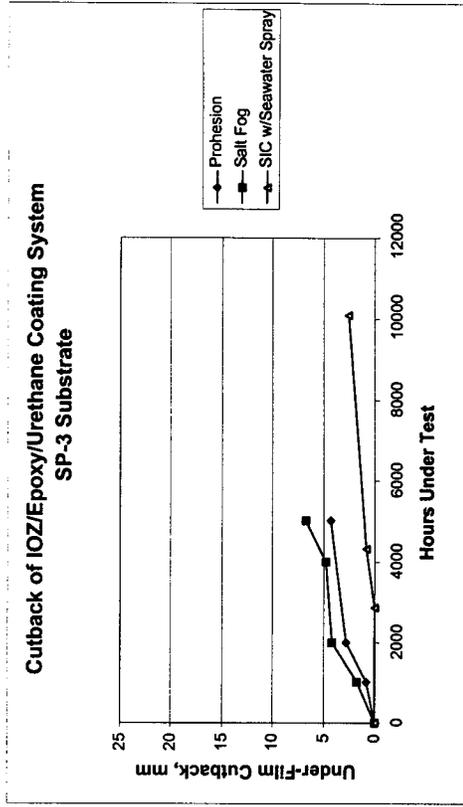
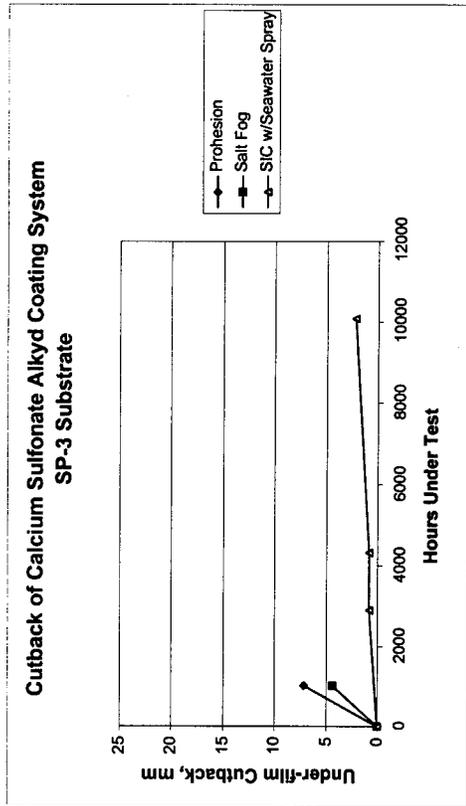


Figure I-13. Natural environment exposure, rusting data, SSPC SP-10, systems 1-4.

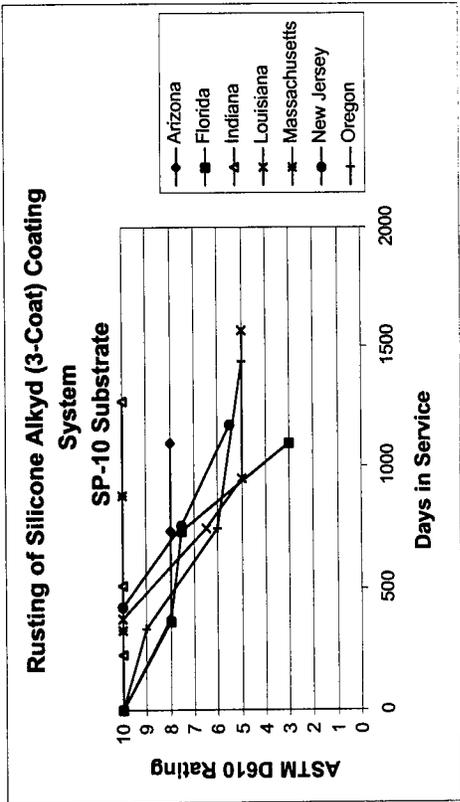
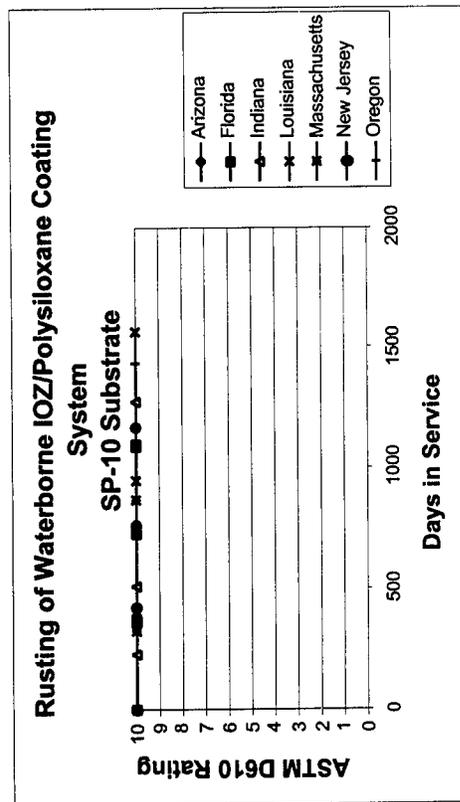
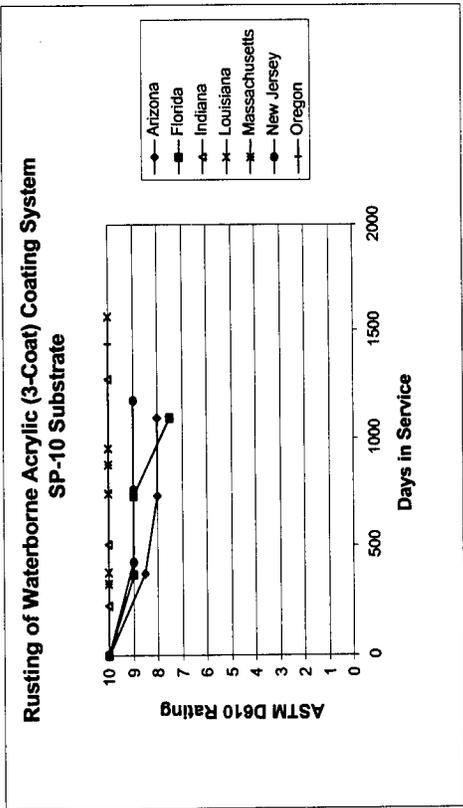
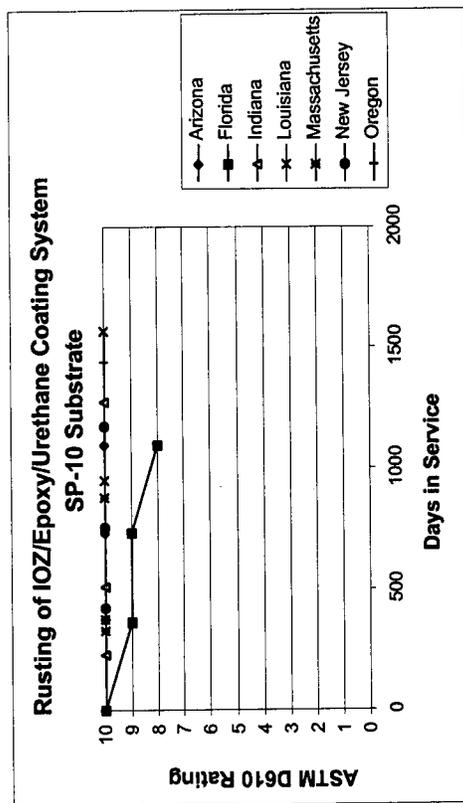


Figure I-14. Natural environment exposure, rusting data, SSPC SP-10, systems 5-8.

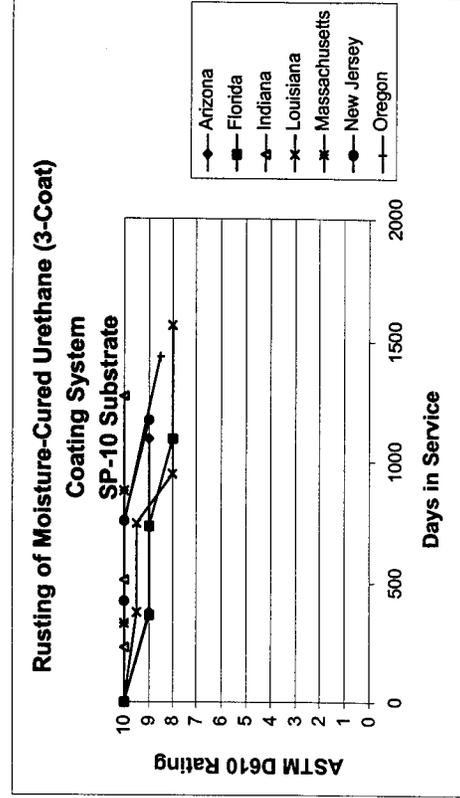
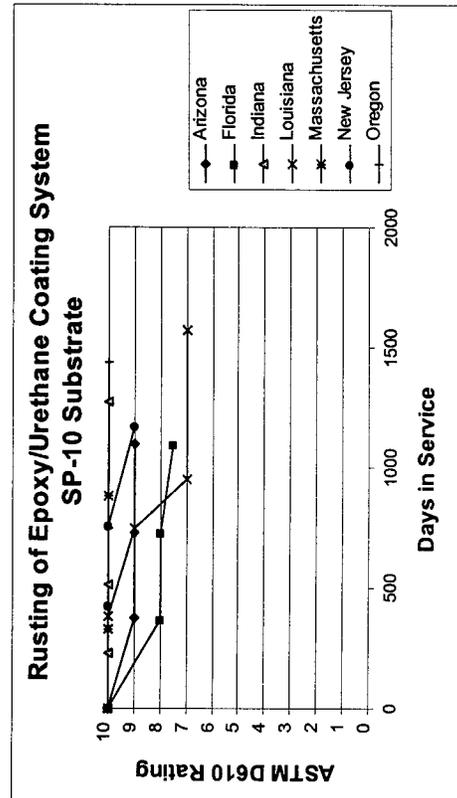
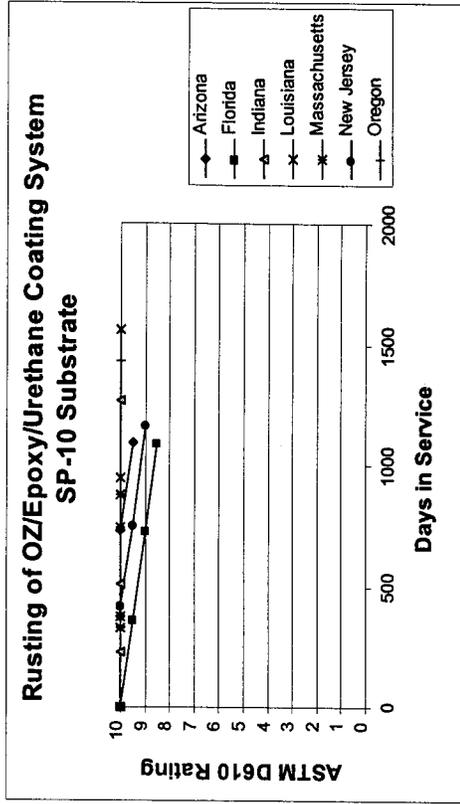
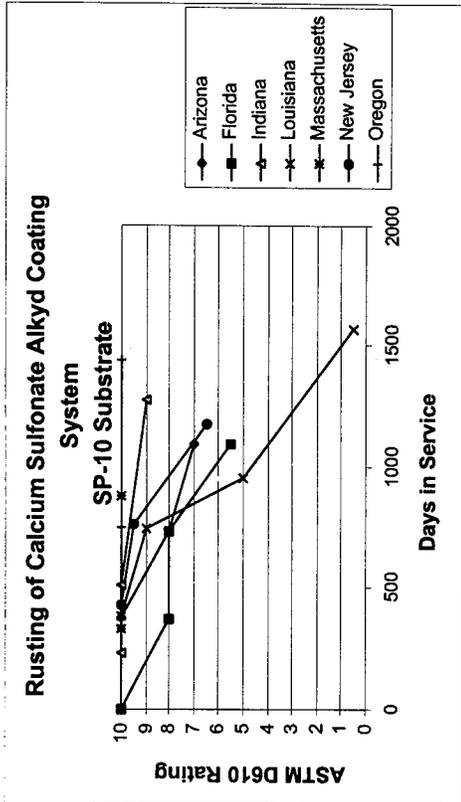


Figure I-15. Natural environment exposure, rusting data, SSPC SP-3, systems 1-4.

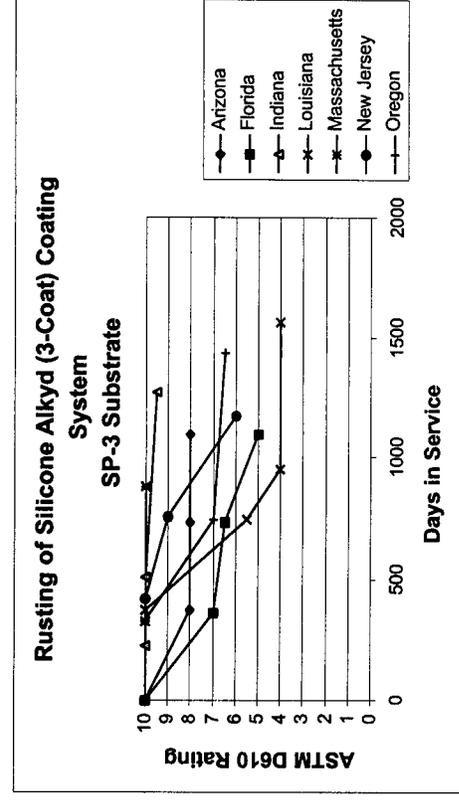
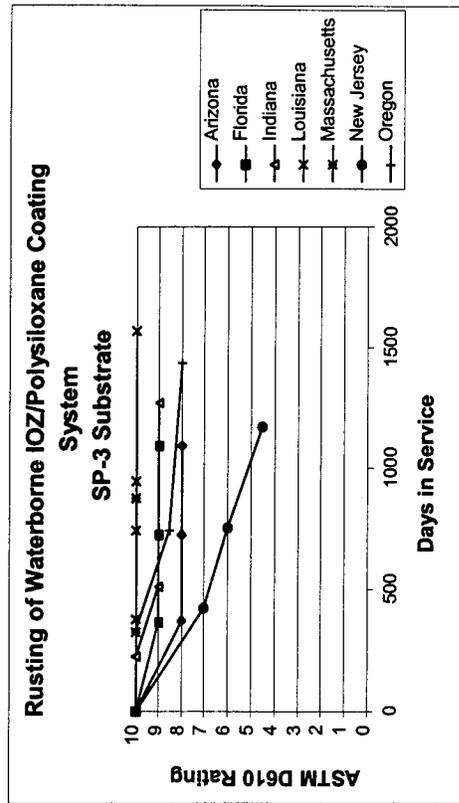
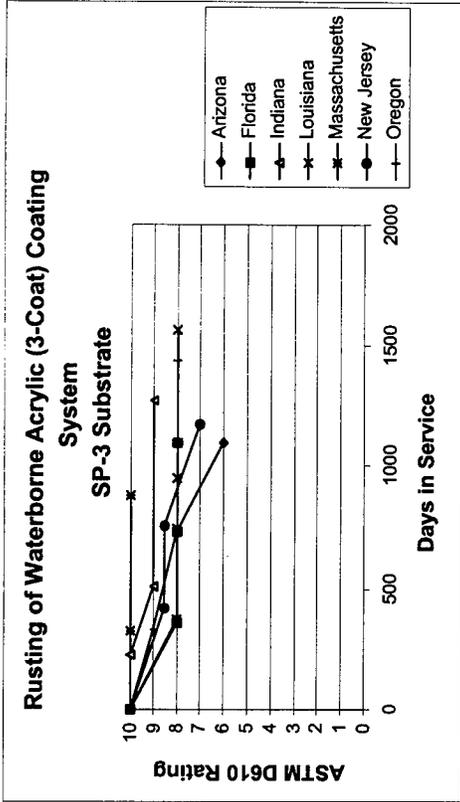
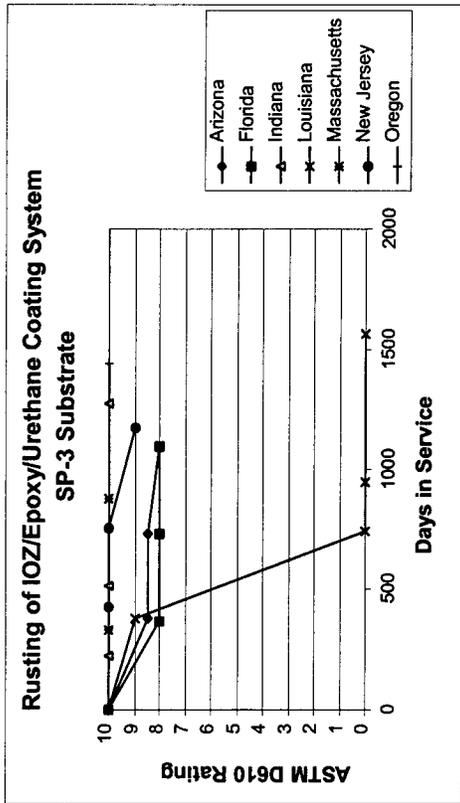


Figure I-16. Natural environment exposure, rusting data, SSPC SP-3, systems 5-8.

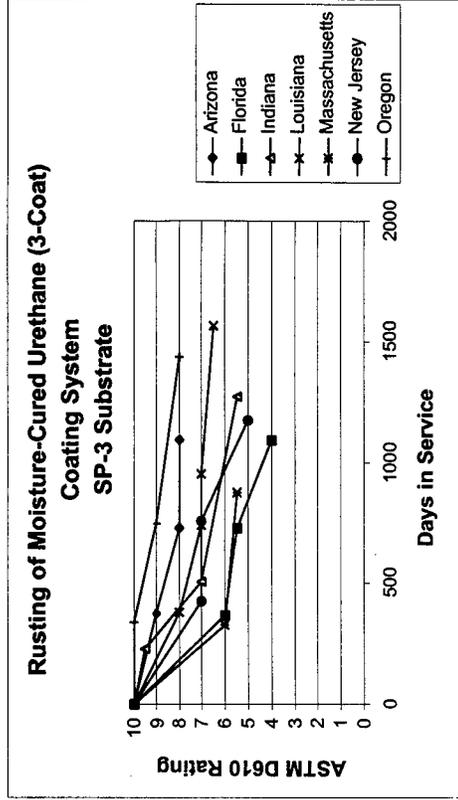
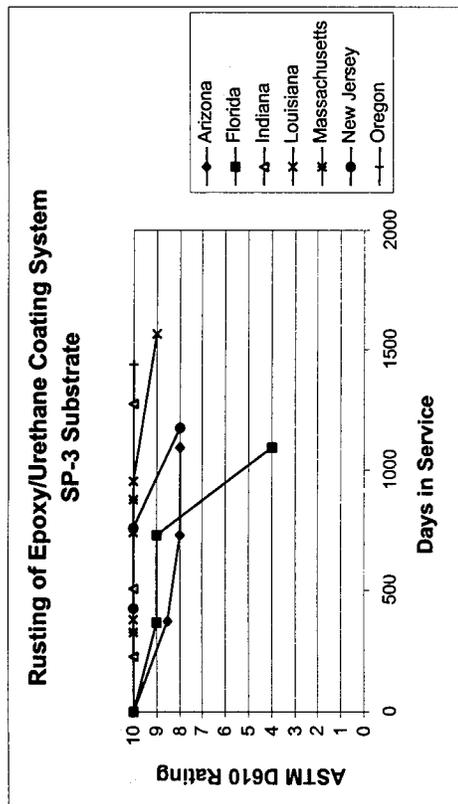
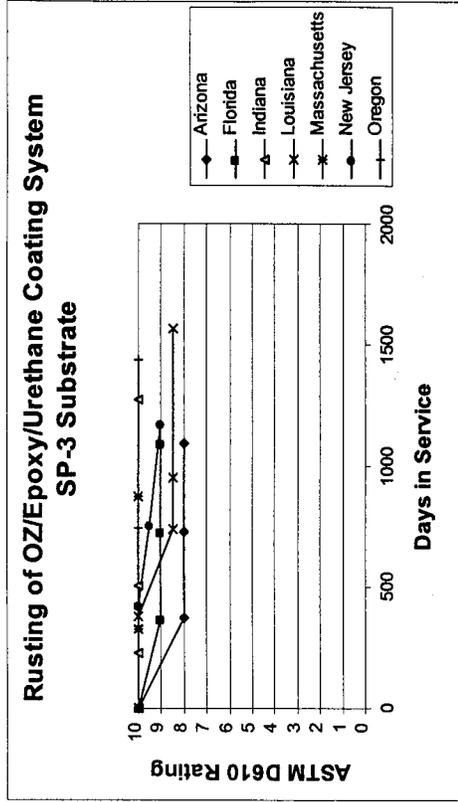
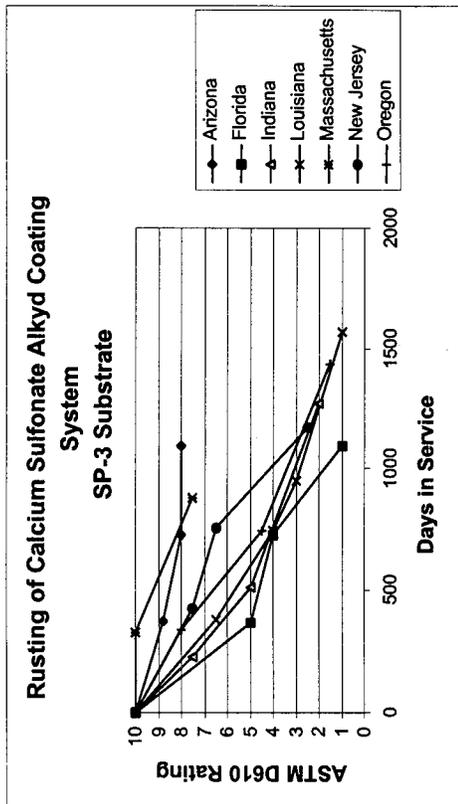


Figure I-17. Natural environment exposure, blistering data, SSPC SP-10, systems 1-4.

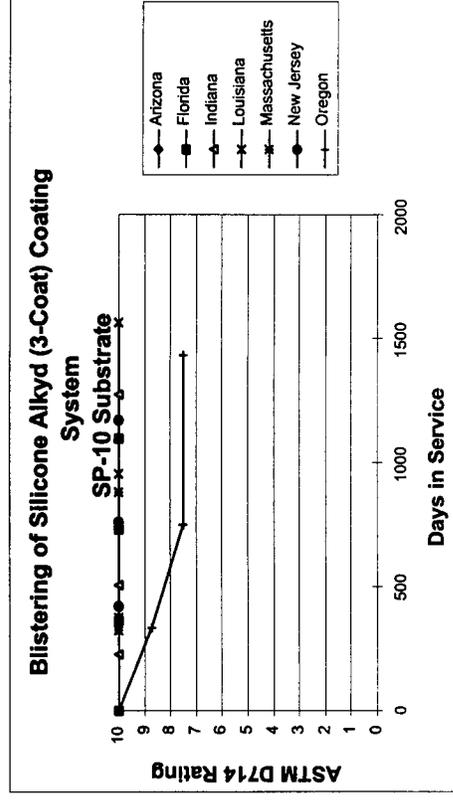
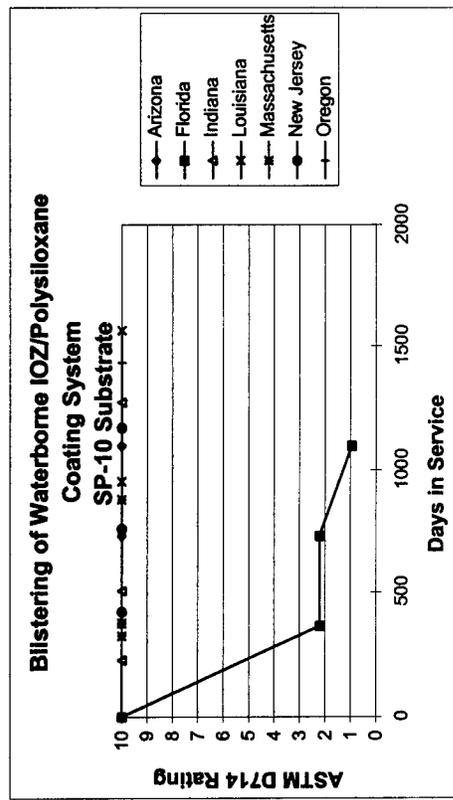
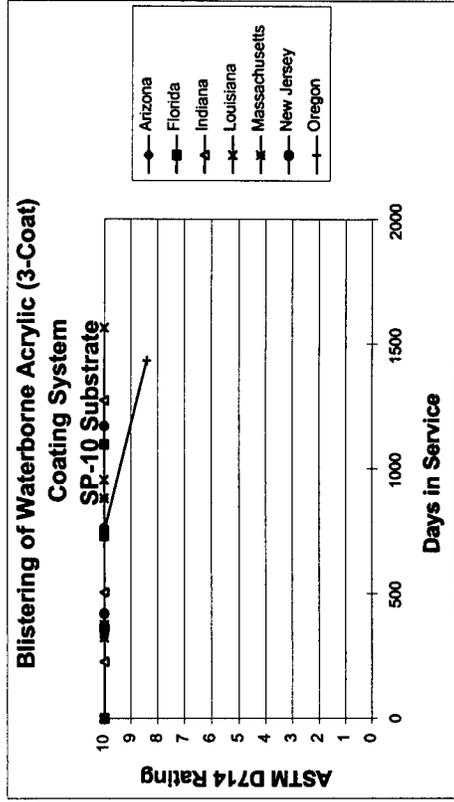
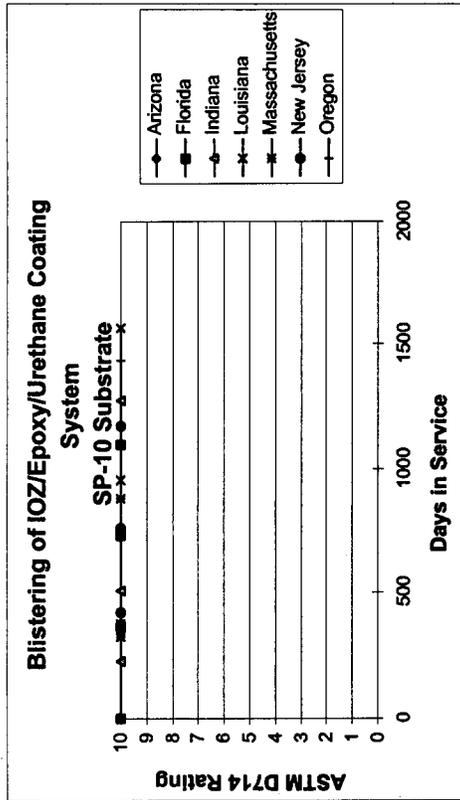




Figure I-19. Natural environment exposure, blistering data, SSPC SP-3, systems 1-4.

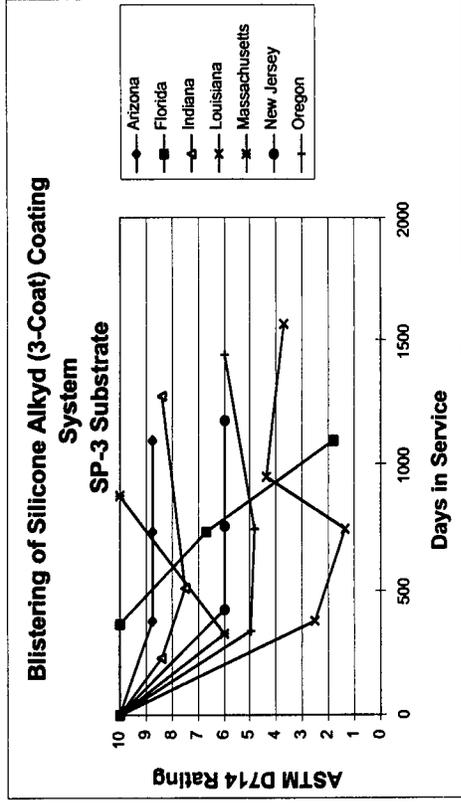
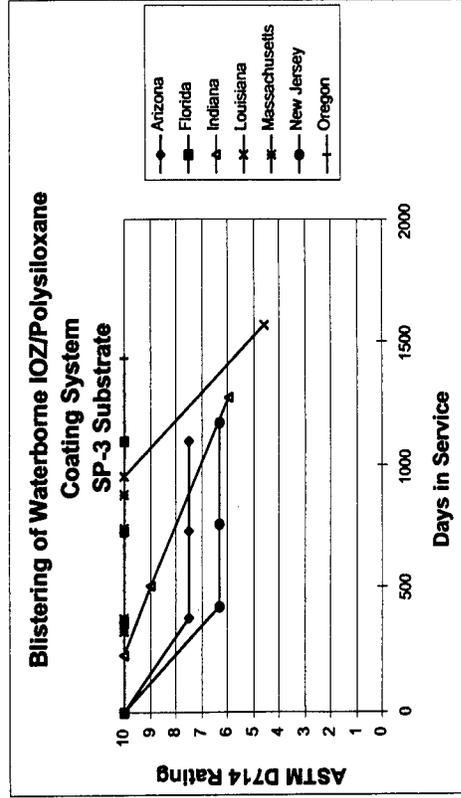
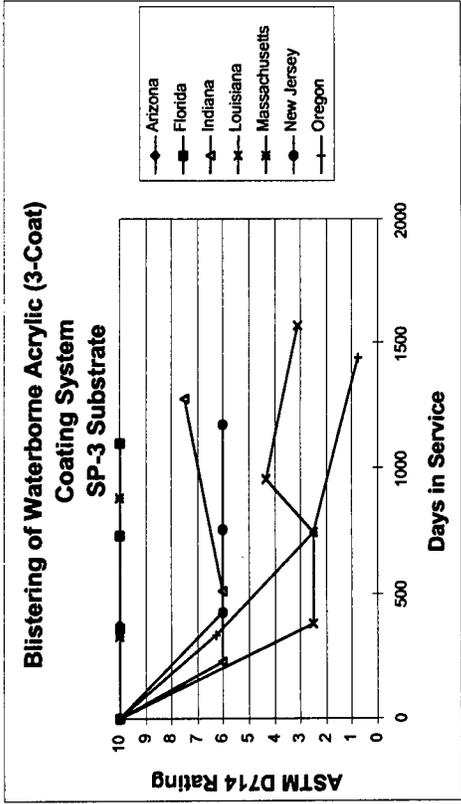
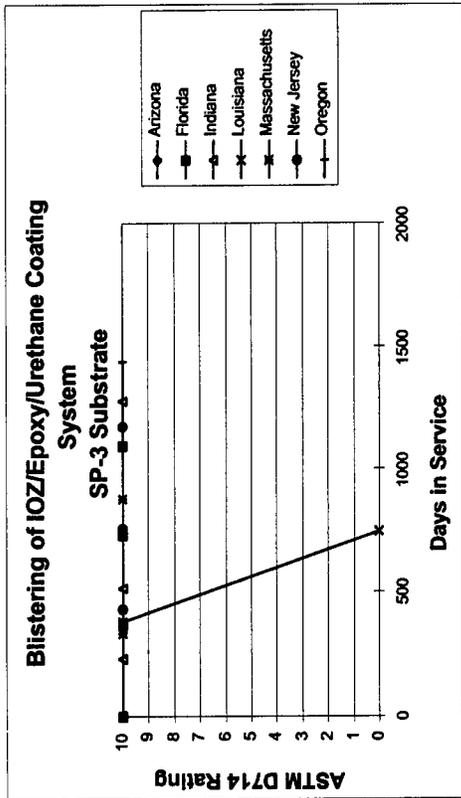


Figure I-20. Natural environment exposure, blistering data, SSPC SP-3, systems 5-8.

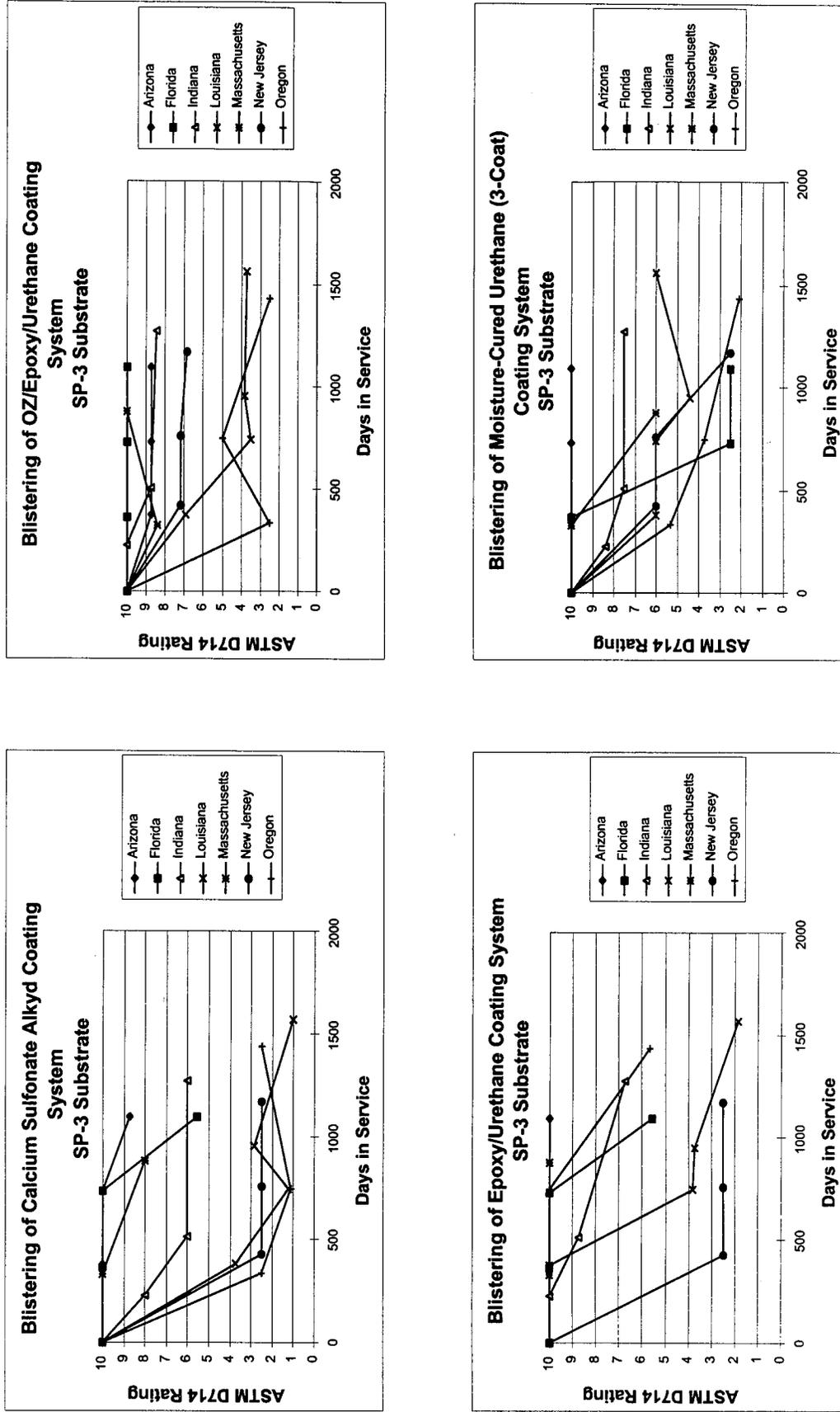


Figure I-21. Natural environment exposure, cutback data, SSPC SP-10, systems 1-4.

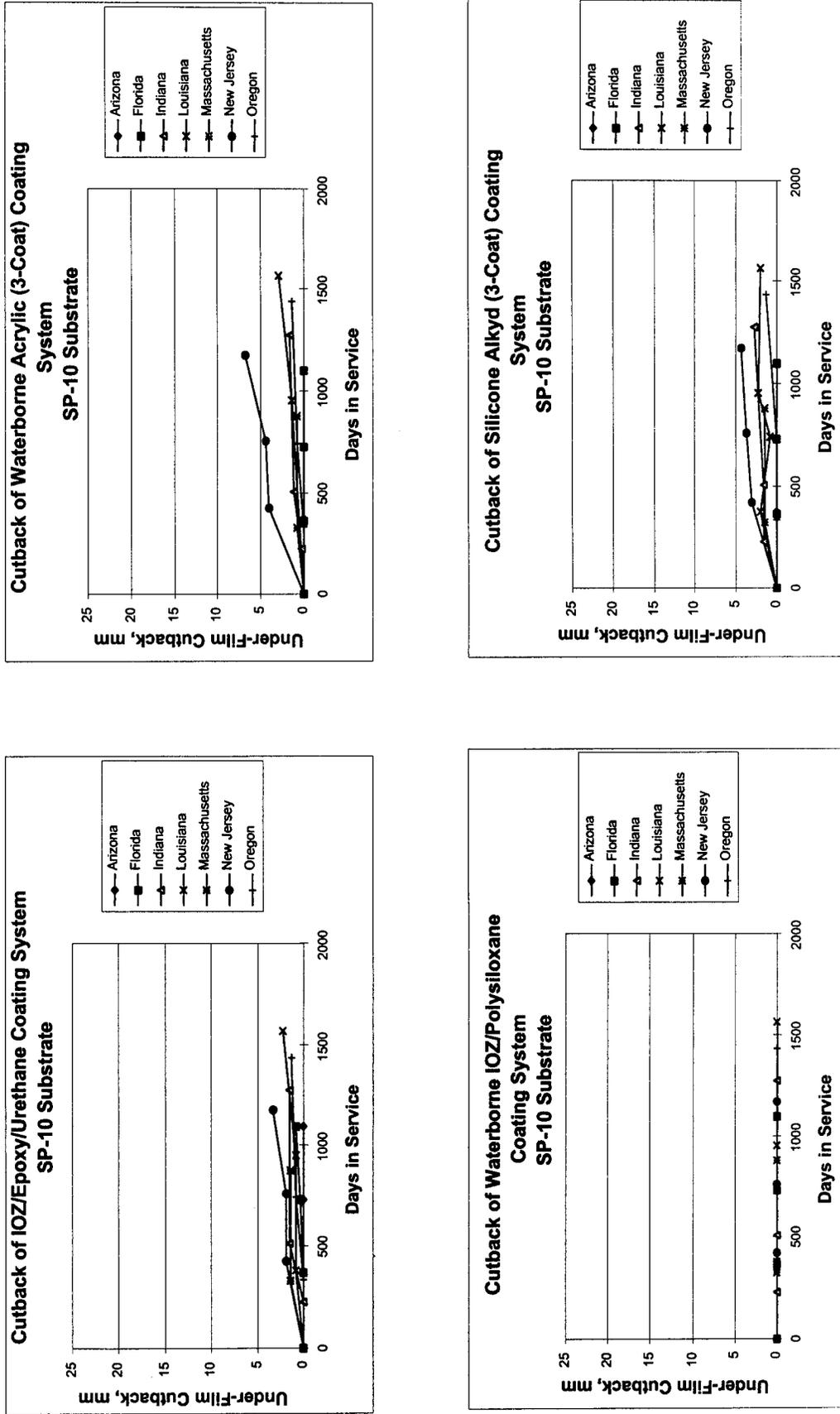


Figure I-22. Natural environment exposure, cutback data, SSPC SP-10, systems 5-8.

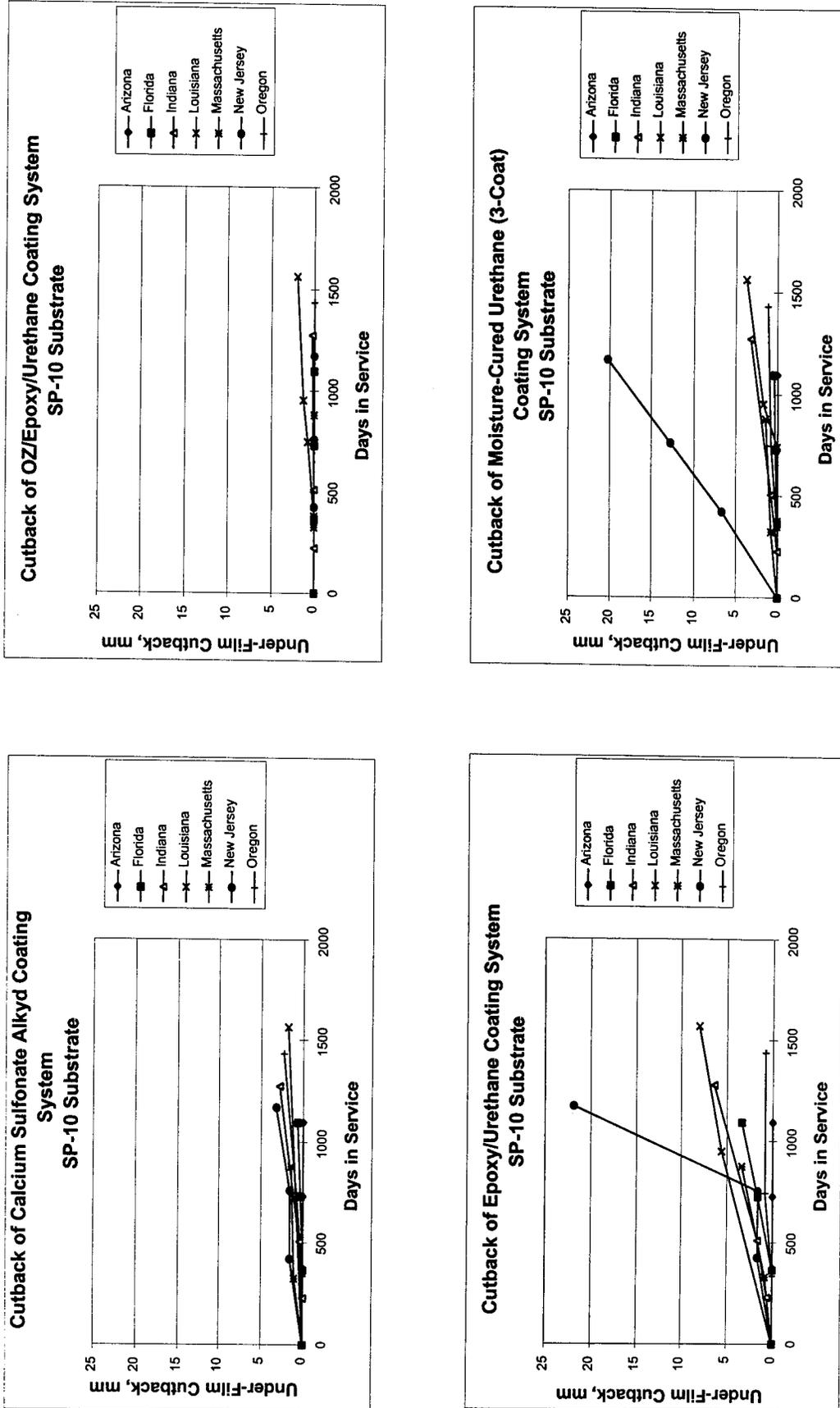


Figure I-23. Natural environment exposure, cutback data, SSPC SP-3, systems 1-4.

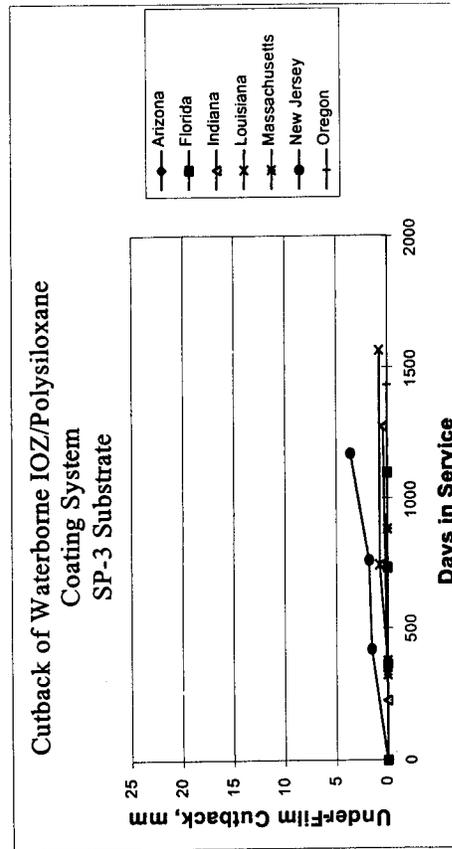
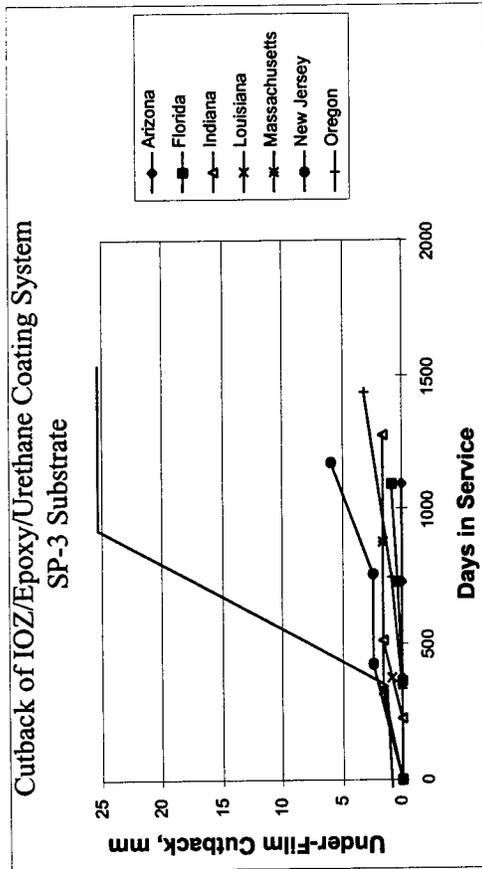
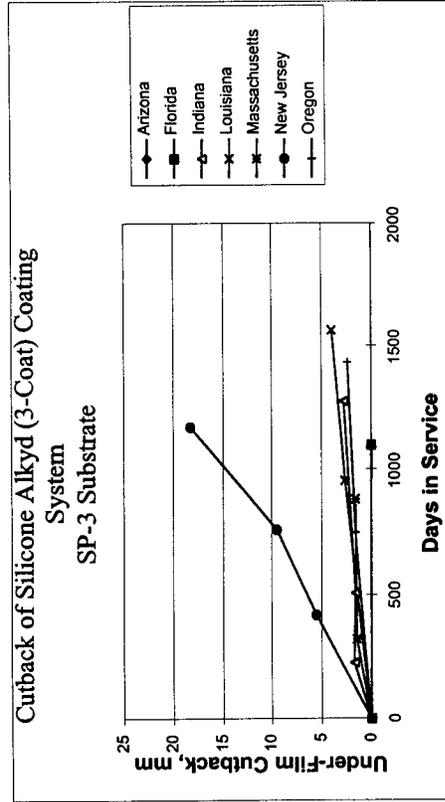
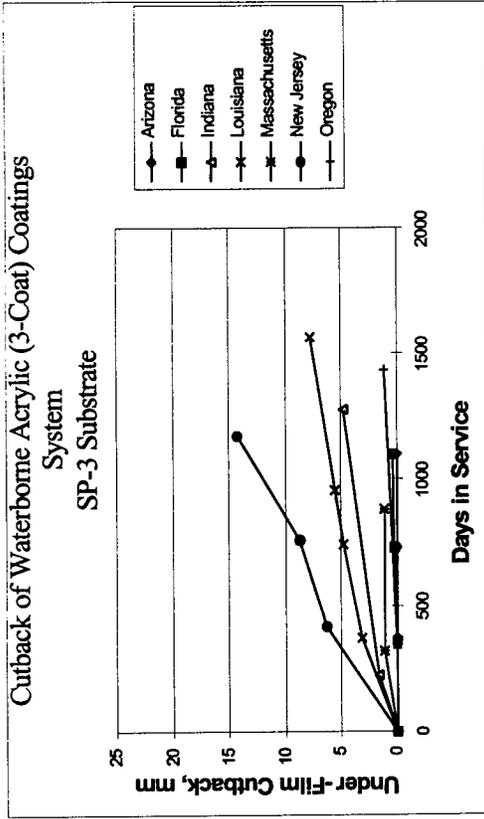


Figure I-24. Natural environment exposure, cutback data, SSPC SP-3, systems 5-8.

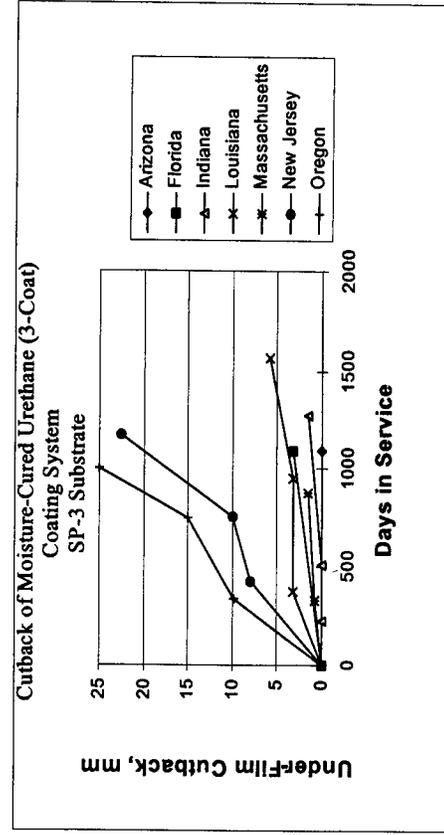
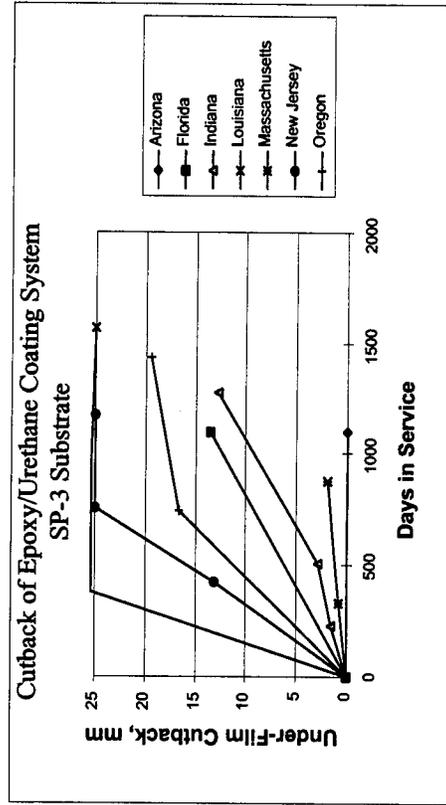
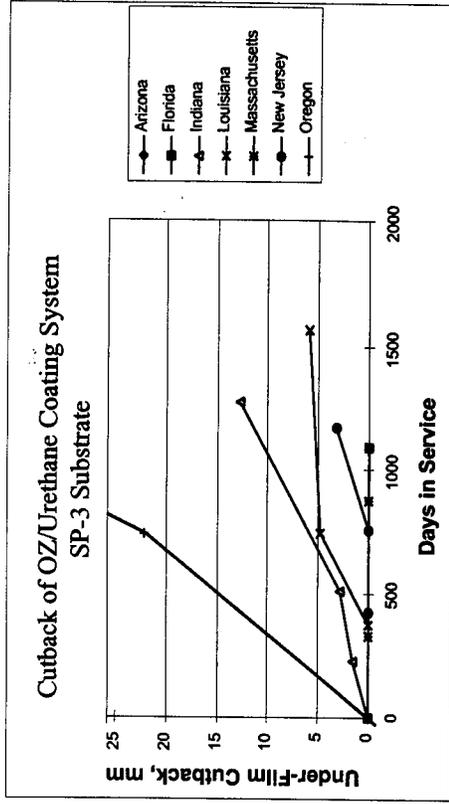
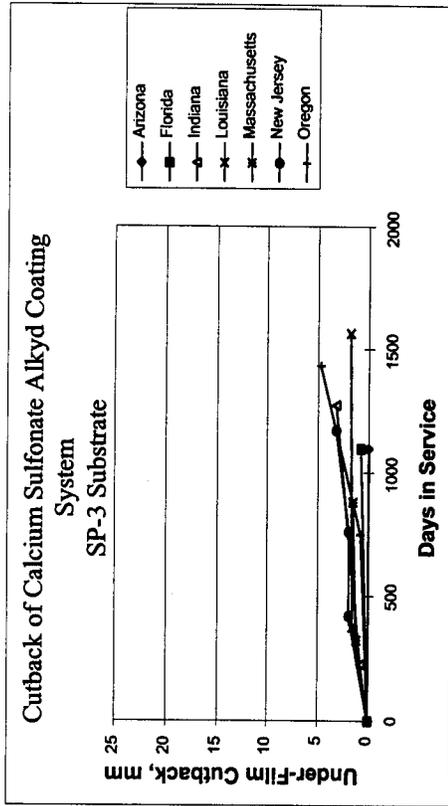


Figure I-25. Natural environment exposure, gloss data, ASTM D523, systems 1-4.

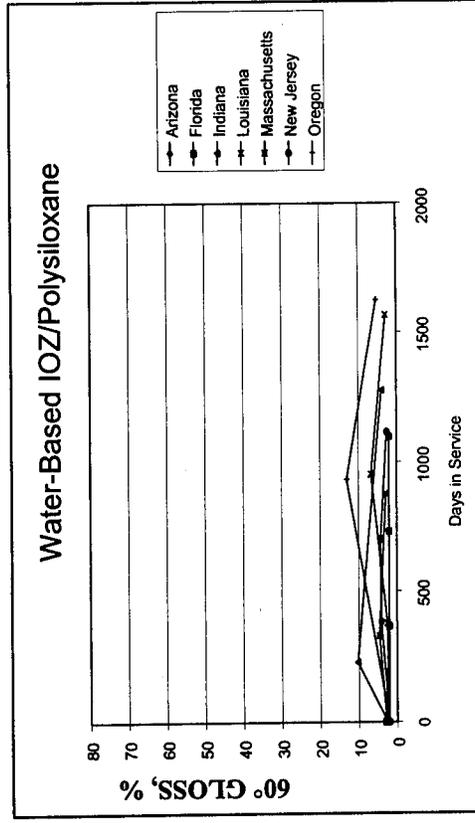
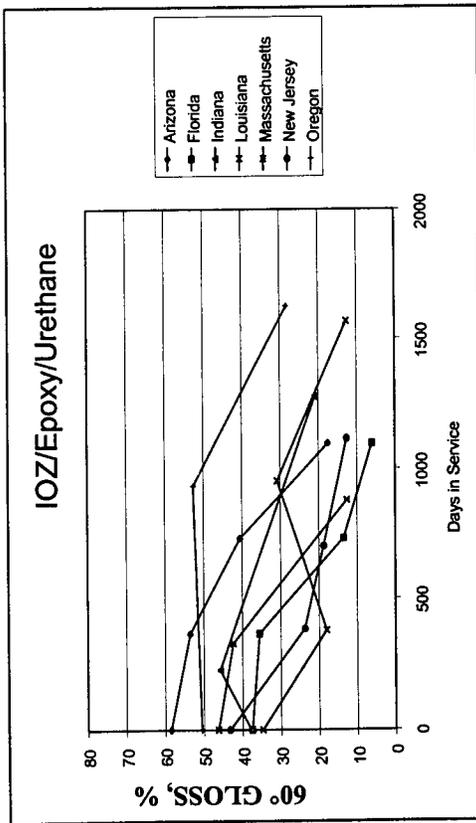
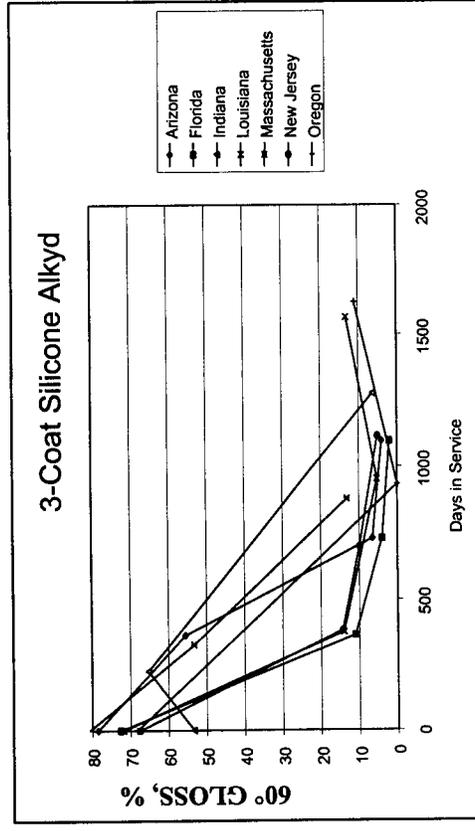
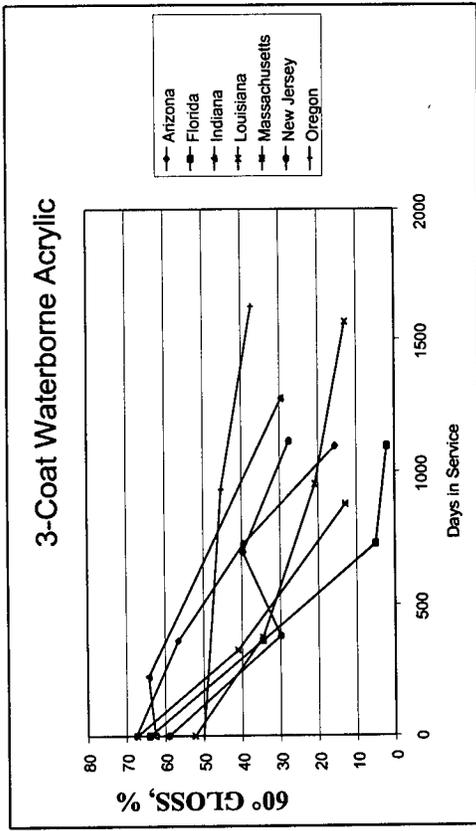


Figure I-26. Natural environment exposure, gloss data, ASTM D523, systems 5-8.

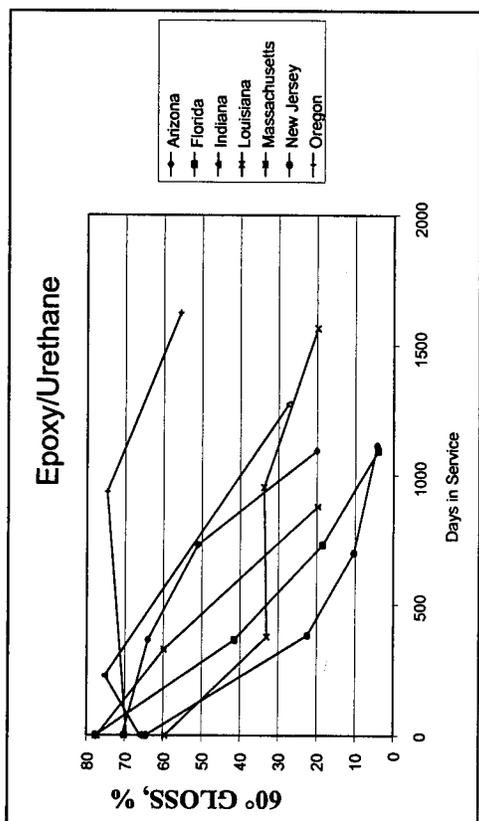
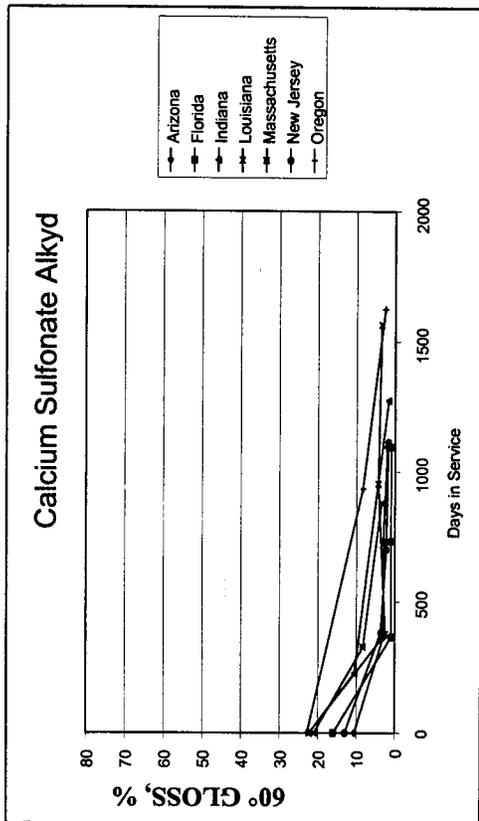
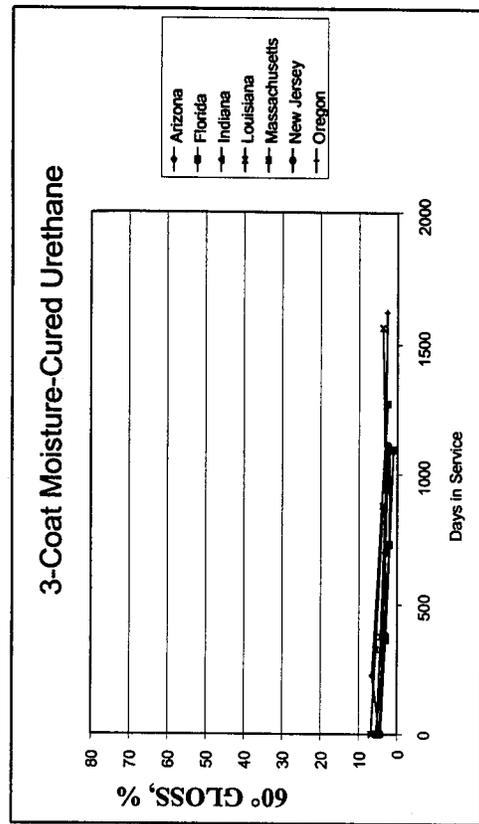
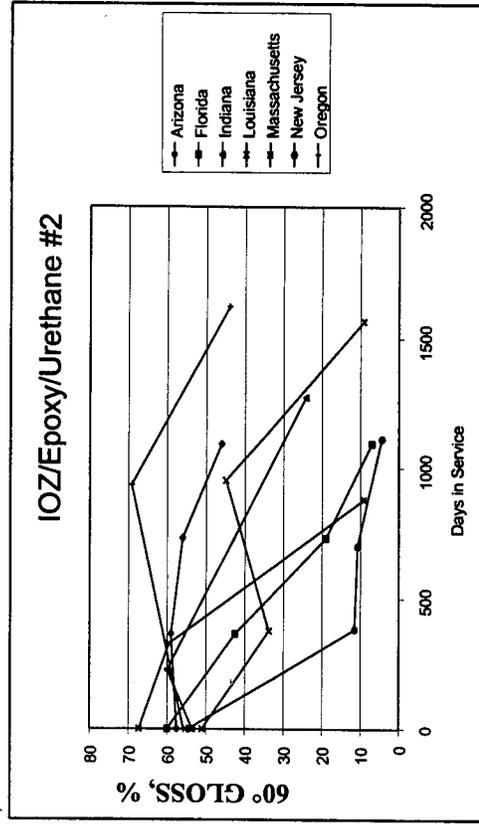


Figure I-27. Natural environment exposure, gloss data, composite of all systems.

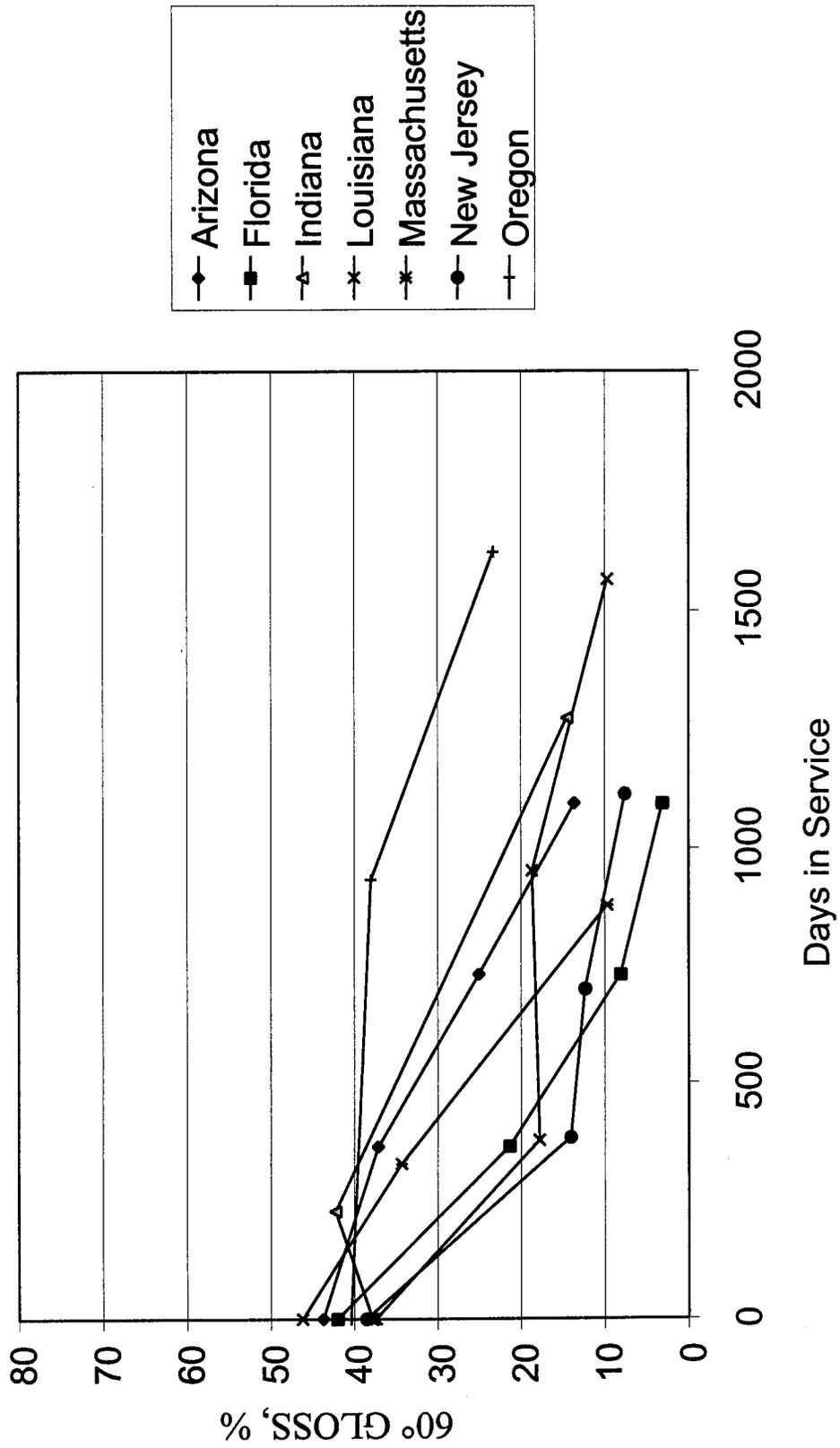


Figure I-28. Natural environment exposure, color data, systems 1-4.

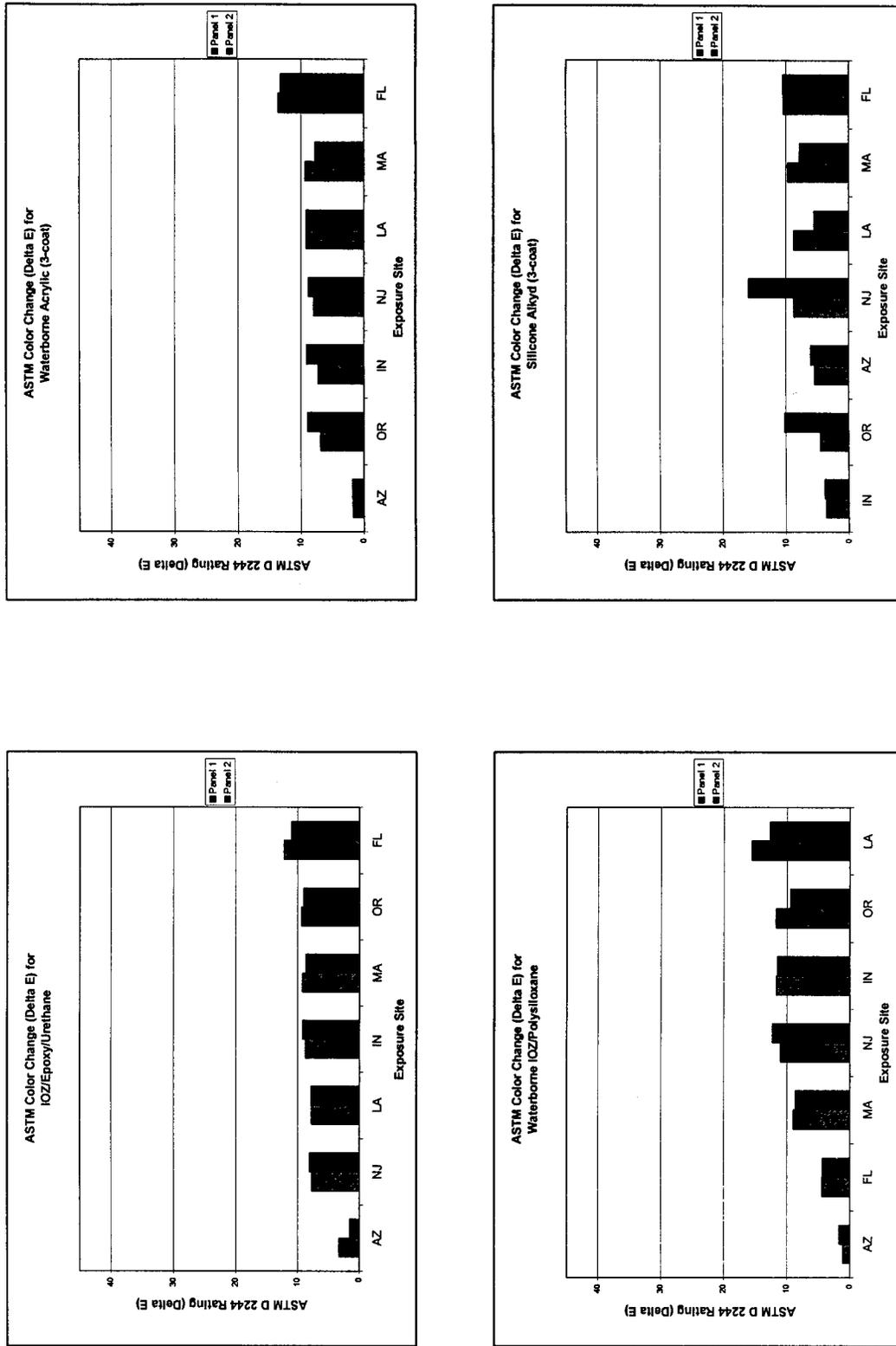


Figure I-29. Natural environment exposure, color data, systems 5-8.

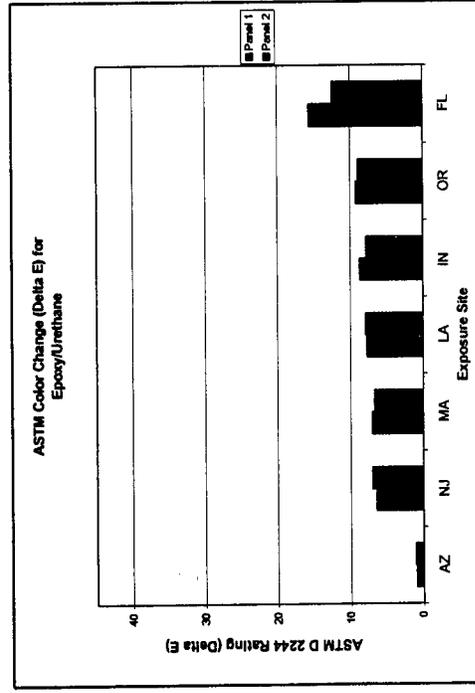
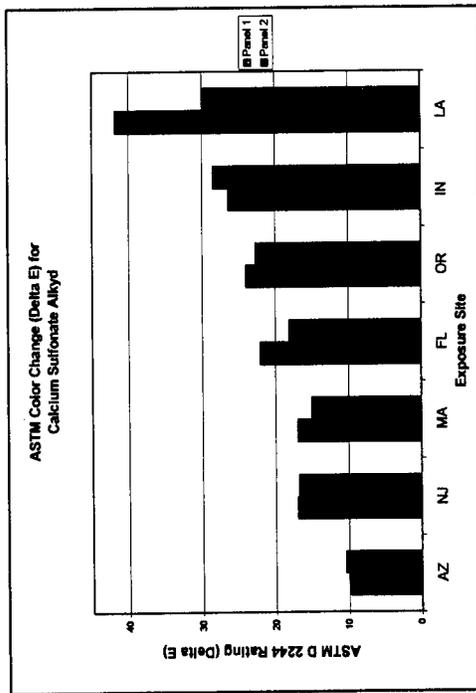
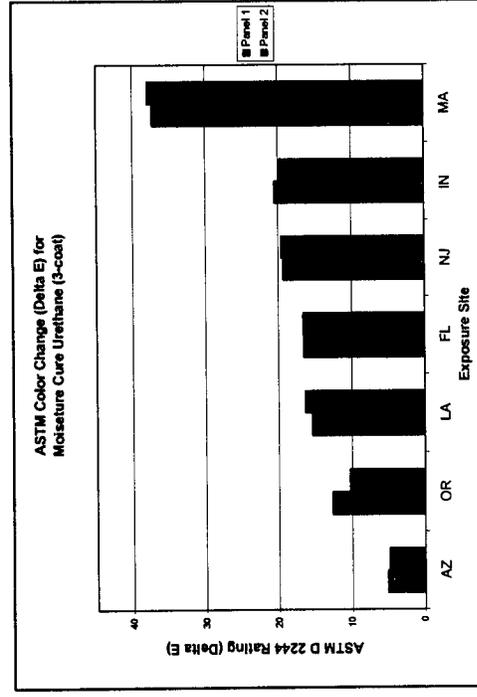
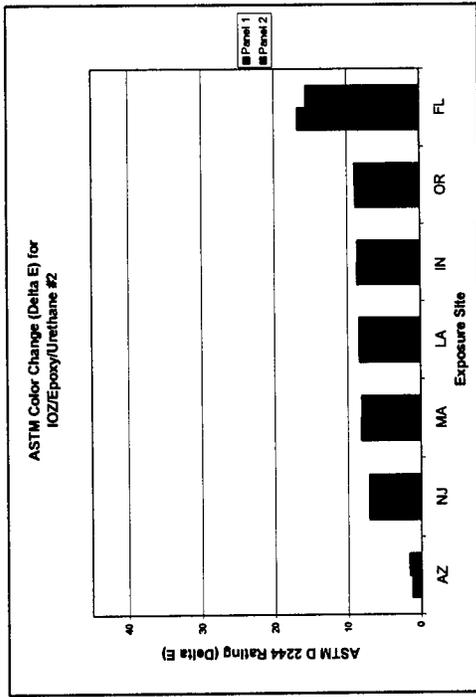
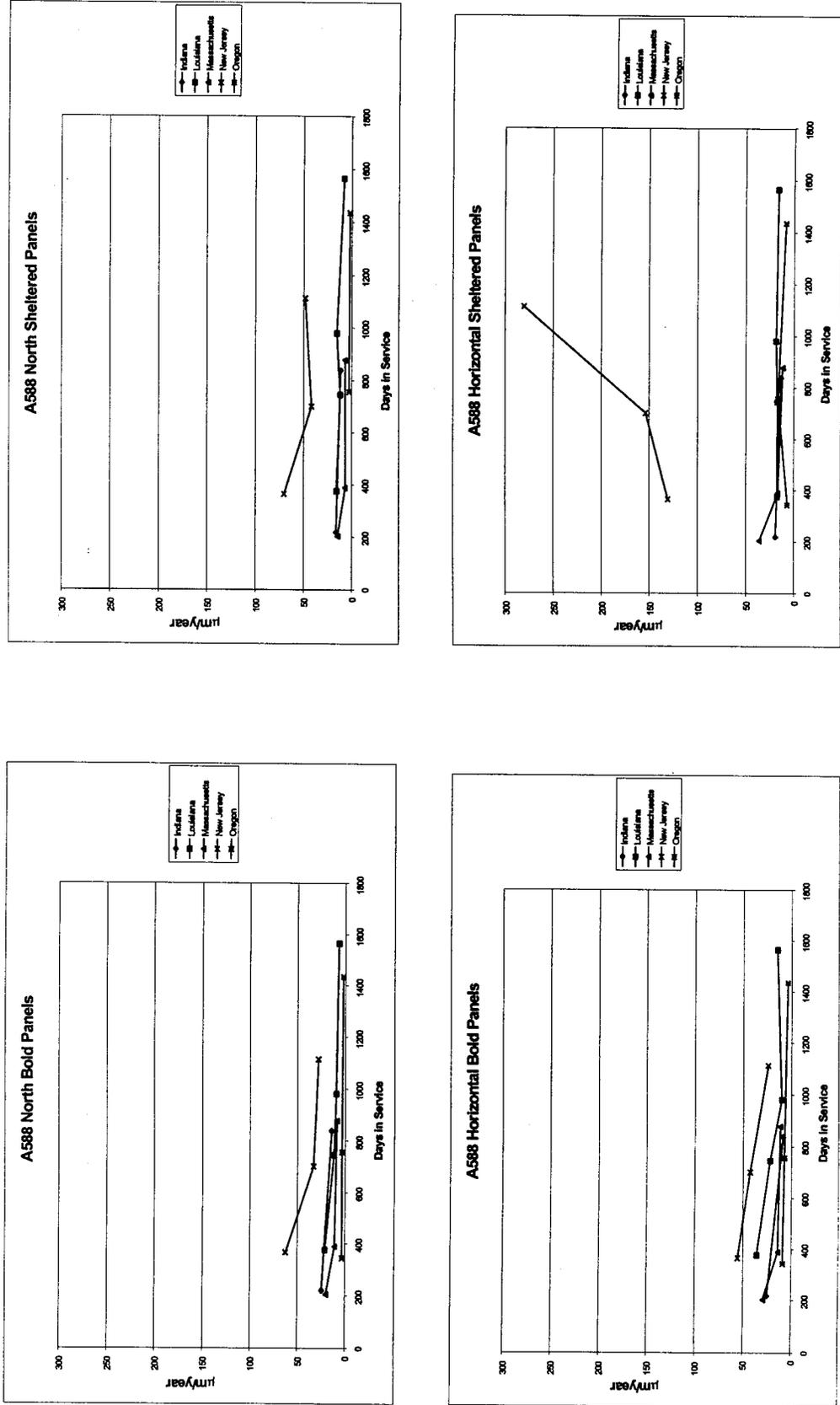
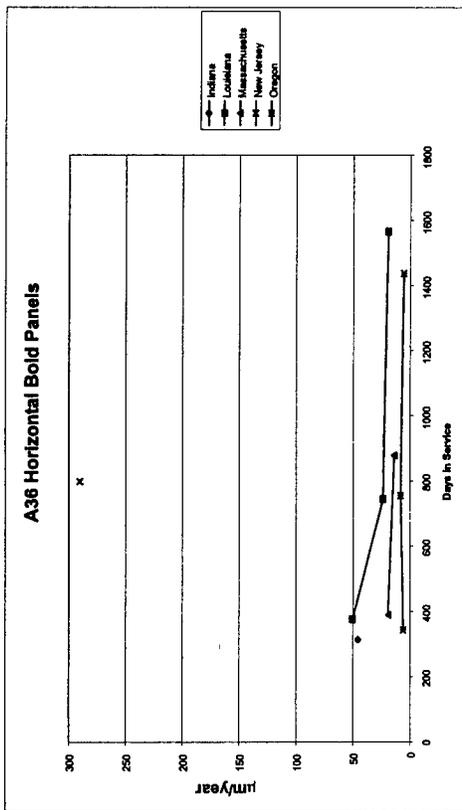
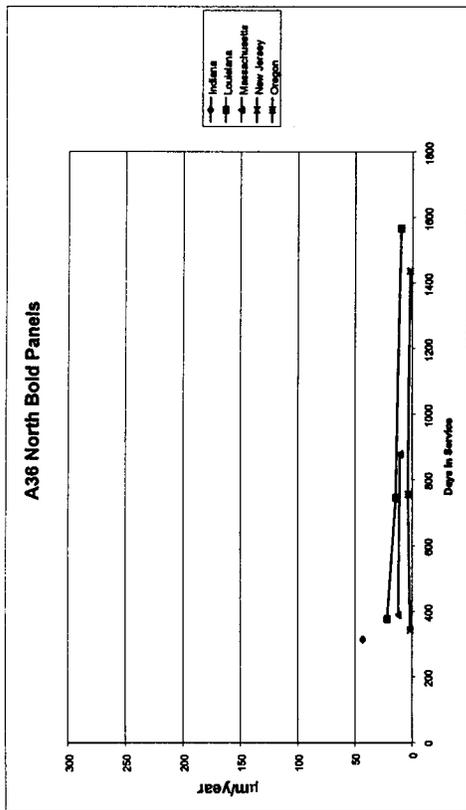
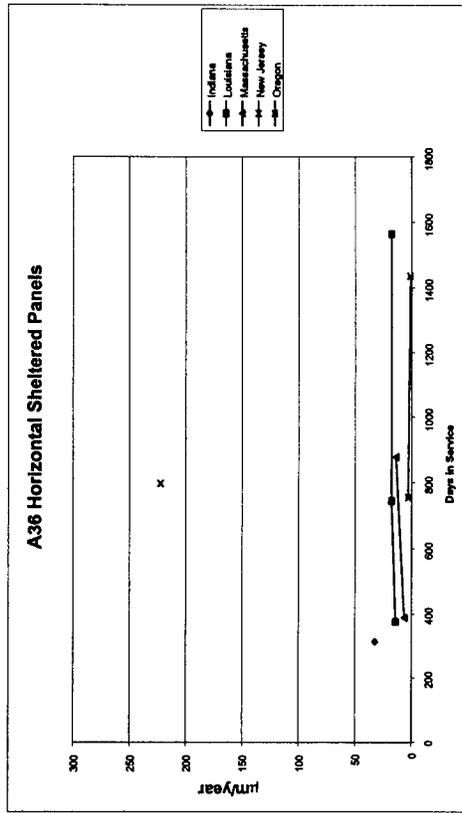
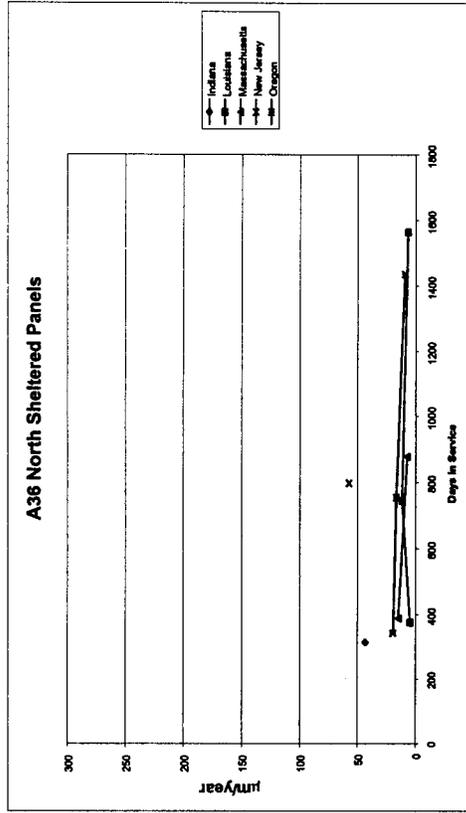


Figure I-30. Natural environment exposure, corrosion rate, A588 steel samples (bold and sheltered).



**Figure I-31. Natural environment exposure, corrosion rate, A36 steel samples (bold and sheltered).**





## APPENDIX II. SUMMARY OF COATING MATERIAL SELECTION AS A FUNCTION OF THE ENVIRONMENT

The following provides a summary guide for coating material selection as a function of the local environment. The following recommendations are made on the basis of an analysis of the program data.

As coating selection is considered, the following must be contemplated:

- While it is tempting to draw a map and define the harshness of individual areas, this program has demonstrated that local climates, indistinguishable on a map of the continental United States, will affect coating deterioration. This is probably best illustrated by the drastic performance differences between the New Jersey beach site exposure and the Massachusetts Cape Cod site, where the latter site was substantially less harsh despite being close to and elevated from the beach. There is a drastic reduction in salt-fall over this distance, creating a large performance difference.
- Primarily, the decision to recoat will be driven by cosmetic concerns. While there are certainly some exceptions, a significant portion of the coating would have to be missing for a long period of time before structural corrosion becomes a significant issue. Thus, an owner's tolerance for cosmetic deterioration plays a significant role in defining acceptable performance.
- The program evaluated several different performance parameters. Three of these – blistering, rust-through, and cutback – are interrelated; thus, it is difficult to discuss one without considering the other. Similarly, color change and gloss are also probably interrelated.
- In the program, great care was taken in the application of the coating system to minimize defects other than intentional holidays. An owner could not afford the same level of quality assurance in most field applications. Thus, additional weight might be given in a coating selection to the ability to resist coating cutback at holidays on real structures, especially in climates conducive to this type of deterioration.
- If concerns regarding coating selection are to be avoided, the best performing systems might be used regardless of the environmental effects. This is probably prudent on high-value structures or inaccessible structures where the cost of the paint system is a small portion of the cost of overall structure maintenance.

The following are generalized comments concerning the coating materials tested in the program:

1. If the exposure location is a marine location anywhere in the country, only coating systems employing a high-quality inorganic zinc primer should be used. Such materials are superior to organic zinc-rich systems. A marine location may be described as a location with continuous salt-air exposure adjacent to or over a body of saltwater. Certainly, any area with a moisture conductivity exceeding 100  $\mu\text{S}/\text{cm}$  would qualify for the best quality inorganic zinc-rich systems.

2. In other than marine environments, concerns with rust-through, blistering, or cutback should first be assessed by considering the local, annual, average absolute humidity. This may be estimated from the annual average temperature and relative humidity of the site.<sup>a</sup> For painting over SSPC SP-10 substrates:
- If the site will have an absolute moisture content above 0.015 moles H<sub>2</sub>O/mole of dry air and the local relative humidity will exceed 65% relative humidity, an inorganic zinc-rich primer would be recommended. This type of environment is typified by the Louisiana and Florida sites in the current program. Without the zinc-rich primer, there will be significant rust-through and cutback at any holidays.
  - If the site has a lower absolute humidity, e.g., 0.010 moles H<sub>2</sub>O/mole of dry air, yet has a high temperature (> 20°C average annual temperature), a zinc-rich primer to avoid rust-through should still be used. This behavior is typified by the Arizona site. Overall deterioration, such as blistering or cutback at the Arizona site (or a similar arid site), would be minimal. (So, if a bit of rust-through is not a concern, any coating of choice may be used.)
  - If the site has a low annual average absolute humidity (<0.010 moles H<sub>2</sub>O/mole of dry air) and a low temperature (< 10°C), any coating of choice may be used. Marginally better performance will be obtained with inorganic zinc-rich systems over organic zinc systems and acrylics, and these will perform better than the calcium sulfonate and silicone alkyds.
  - To avoid blistering, do not paint over a contaminated surface; there will be no blistering over an SSPC SP-10 substrate without residual surface salts. A recommended value to control surface salts is < 30 µg/cm<sup>2</sup>.<sup>b</sup>
3. If an SSPC SP-3 substrate is painted over, the coating performance is going to be highly dependent on the magnitude of salts left behind on the surface. (These exact effects were beyond the scope of this study.)
- The systems that exhibited the best properties over an SSPC SP-3 surface were the zinc-rich systems and the acrylic systems. All environments eventually caused failure for a coating over an SSPC SP-3 surface.
  - From a ranking perspective, performance will be very similar for the same coatings over an SSPC SP-10 substrate, only the degree of rust-through will be substantially worse. Therefore, similar advice would apply. If rust-through is to be avoided, the SSPC SP-3 surface preparation should not be used, especially in the marine or high absolute humidity environments.

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<sup>a</sup>  $VP = 10^{(7.96681 - (1668.21/(228+T)))}$ ; AH = RH\*VP, where VP = vapor pressure, T = temperature (°C), RH = relative humidity, and AH = absolute humidity.

<sup>b</sup> Appleman, B.R., *Effect of Surface Contaminants on Coating Life* (Report No. FHWA-RD-91-001), Federal Highway Administration, Washington, DC, November 1991.

4. For color retention, a combination of high average temperature, relative humidity, and high time-of-wetness and chloride contamination are of greatest concern. These areas are typically found in the southern latitudes of the United States and along the coast. In these environments, either a urethane or acrylic topcoat should be used to retain color.

