Publication No. FHWA- RD-91-060
September 1992

Environmentally Acceptable Materials for the Corrosion Protection of Steel Bridges:

Task C, Laboratory Evaluation

U.S Department of Transportation
Federal Highway Administration

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

FOREWORD

This report, "Environmentally Acceptable Materials for the Corrosion Protection of Steel Bridges: Task C, Laboratory Evaluation," FHWA-RD-91-060, deals with laboratory screening and limited outdoor exposure tests on several high and low volatile organic compound (VOC) coating systems. Several environmentally acceptable coating systems were identified; these systems will be used in a long-term (7-year) study to more fully assess their performance.

Donald G Fohs

for Thomas J. Ptak
Director, Office of Engineering and Highway
Operations Research and Development

NOTICE

Technical Report Documentation Page

1. Report No. FHWA-RD-91-060	2. PB93-175099	3. Recipient's Catalog No.

4. Title and Subtitle
ENVIRONMENTALLY ACCEPTABLE MATERIALS FOR THE
CORROSION PROTECTION OF STEEL BRIDGES:
Task C, Laboratory Evaluation

5. Report Date
September 1992

6. Performing Organization Code

7. Author(s)
Robert Kogler and William Mott

8. Performing Organization Report No.
OCRC-1

9. Performing Organization Name and Address
Ocean City Research Corporation
Tennessee Avenue & Beach Thorofare
Ocean City, New Jersey 08226

10. Work Unit No. (TRAIS)
3E4A 0122

11. Contract or Grant No.
DFTH61-88-C-00010

12. Sponsoring Agency Name and Address
Office of Engineering and Highway Operations R&D
Federal Highway Administration
6300 Georgetown Pike
McLean, Virginia 22101-2296

13. Type of Report and Period Covered
Interim Report
June 1988-February 1991

14. Sponsoring Agency Code

15. Supplementary Notes

FHWA Contracting Officer's Technical Representative: John W. Peart, HNR-30

16. Abstract

ABSTRACT

The recently promulgated environmental regulations concerning volatile organic compounds (VOC's) and certain hazardous heavy metals have had a large impact on the bridge painting industry. As a response to these regulations, many of the major coating manufacturers have begun to offer "environmentally acceptable" alternative coating systems to replace those traditionally used on bridge structures. In the interest of determining the relative corrosion control performance of these newly available coating systems, the Federal Highway Administration contracted for a seven-year study.

As a precursor to long-term, natural exposure testing of various environmentally acceptable coating systems, a battery of accelerated laboratory screening tests were performed. These tests included 13 high solids or waterborne, conventionally applied coatings; 14 powder coating or metallized coatings; and 7 high VOC control coatings. These systems were tested in a cyclic salt fog/natural marine exposure, a cyclic brine immersion/natural marine exposure, and a natural marine exposure. Adhesion and water penetration tests were also performed on each system. The results of these various tests were used to develop a matrix of test coatings to be used in the follow-on, long-term natural exposure testing.

In the accelerated laboratory screening tests, several of the low VOC coating systems performed as well, or better than the high VOC controls. In general, the low VOC zinc-based systems (both inorganic and organic zinc) and the epoxymastic type systems performed the best in the accelerated tests. These types of systems were included in the long-term exposure test matrix.

17. Key Words
Volatile organic compounds, alternative coating systems corrosion control, accelerated tests, salt fog, water penetration

18. Distribution Statement
No restrictions. This document is available to the public through the National Technical Information Service, Springfield

19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 113	22. Price

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

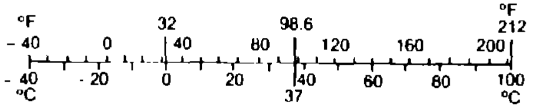
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



* SI is the symbol for the International System of Measurement

(Revised April 1989)

BIBLIOGRAPHIC INFORMATION

PB93-175099

Report Nos: OCRC-1

Title: Environmentally Acceptable Materials for the Corrosion Protection of Steel Bridges: Task C, Laboratory Evaluation.

Date: Sep 92

Authors: R. Kogler, and W. Mott.

Performing Organization: Ocean City Research Corp., NJ.

Performing Organization Report Nos: FHWA/RD-91/060

Sponsoring Organization: *Federal Highway Administration, McLean, VA. Office of Engineering and Highway Operations Research and Development.

Contract Nos: DTFH61-88-C-00010

Type of Report and Period Covered: Interim rept. Jun 88-Feb 91.

Supplementary Notes: Sponsored by Federal Highway Administration, McLean, VA. Office of Engineering and Highway Operations Research and Development.

NTIS Field/Group Codes: 71E, 50A, 50C

Price: PC A06/MF A02

Availability: Available from the National Technical Information Service,
Springfield, VA. 22161

Number of Pages: 117p

Keywords: *Protective coatings, *Steel bridges, *Accelerated tests, *Environmental impacts, Paints, Corrosion environments, Corrosion resistance, Adhesion, Corrosion prevention, Test methods, Corrosion tests, Organic coatings, Bridge maintenance, *Volatile organic compounds.

Abstract: The recently promulgated environmental regulations concerning volatile organic compounds (VOC's) and certain hazardous heavy metals have had a large impact on the bridge painting industry. As a response to these regulations, many of the major coating manufacturers have begun to offer 'environmentally acceptable' alternative coating systems to replace those traditionally used on bridge structures. In the interest of determining the relative corrosion control performance of these newly available coating systems, the Federal Highway Administration contracted for a seven-year study. As a precursor to long-term, natural exposure testing of various environmentally acceptable coating systems, a battery of accelerated laboratory screening tests were performed. These tests included 13 high solids or waterborne, conventionally applied coatings; 14 powder coating or metallized coatings; and 7 high VOC control coatings. These systems were

Continued on next page

BIBLIOGRAPHIC INFORMATION

Continued...

tested in a cyclic salt fog/natural marine exposure, a cyclic brine immersion/natural marine exposure, and a natural marine exposure. Adhesion and water penetration tests were also performed on each system. The results of these various tests were used to develop a matrix of test coatings to be used in the follow-on, long-term natural exposure testing. In the accelerated laboratory screening tests, several of the low VOC coating systems performed as well, or better than the high VOC controls. In general, the low VOC zinc-based systems (both inorganic and organic zinc) and the epoxymastic type systems performed the best in the accelerated tests. These types of systems were included in the long-term exposure test matrix.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF TABLES

BACKGROUND

In the 20 years since the passage of the first Clean Air Act, the industrial coatings industry has undergone significant changes. Due to the increasingly stringent regulations imposed by the Clean Air Act and other environmental legislation, coating specifiers must now consider the environmental acceptability as well as the performance, cost, and ease of application of particular materials and processes. In fact, the relatively new rules limiting the allowable levels of volatile organic compounds (VOC's) and certain metallic pigments (i.e. lead and chromates) have become the major driving force behind massive reformulation and respecification efforts in both the private and public sectors.

These new environmental regulations have caused large problems for end-users of coatings in many industries. One of the major stumbling blocks for end users in the specification of new coating systems is a lack of information. Many of the traditionally used systems are quickly becoming non-compliant due to the new regulations. Although new, environmentally acceptable coating systems are available, there is no data concerning the long-term performance of any of these formulations. Therefore, coatings specifiers are often forced into specification decisions based on environmental acceptability alone, rather than a sensible combination of environmental acceptability and coating performance.

The Federal Highway Administration maintains an effort to provide the State Departments of Transportation with information concerning coating systems which are environmentally acceptable and provide excellent corrosion control performance. As part of this effort, a 7-year laboratory and field evaluation of alternative, environmentally acceptable coating systems for the corrosion protection of steel bridge components was initiated. This study is currently in its third year. The laboratory phase of the testing has been completed and the extended, field evaluation of candidate coating systems is presently ongoing. This report documents the procedures and results of the accelerated laboratory test phase.

OBJECTIVES

The objectives of the overall study are as follows:

- Based on long-term testing, identify cost-effective, environmentally acceptable materials and methods for the corrosion protection of steel bridge structures.
- Provide a projected life-cycle cost comparison for the identified corrosion control options for each bridge component or area.

As a subset of the overall program, the specific objectives for the laboratory accelerated screening testing are as follows:

- Perform a battery of accelerated screening tests on selected candidate, environmentally acceptable coating systems.
- Use the results of this testing to generate a matrix of candidate coating systems for long-term (5-year) natural exposure testing.

TECHNICAL APPROACH

General

The basic approach taken in the laboratory testing phase of the program was to use a battery of accelerated screening testing to define a matrix of the best performing coating systems. This matrix would then be used for the long-term natural exposure testing.

The motivation for using a battery of accelerated tests rather than a single, standardized one stems from the nature of the typical results obtained through accelerated testing. The use of several accelerated test methods in parallel allows for a reasonable screening process to be completed in a short period of time. In general, the results from single tests cannot be related directly to coating performance in a natural environment. However, through analysis of results obtained from a series of different accelerated tests, some judgment can be used to anticipate the relative performance of various systems in a natural environment. At the very least, the battery of accelerated tests will indicate the potential for any extremely poor performing coating systems.

Substrates and Surface Preparation

Five separate substrate/surface preparation combinations were tested. With the exception of any inorganic zinc systems and powder coating and metallized systems,[1] all systems were applied to replicate 6-in (152.4-mm) by 12-in (304.8-mm) by 0.25-in (6.35-mm) panels of each of the following substrate/surface preparation combinations for each of the accelerated tests.

	Steel	Surface Preparation
1.	ASTM A-36	SSPC SP-10.
2.	ASTM A-36	SSPC SP-2.
3.	ASTM A-36	Adherent millscale.
4.	ASTM A-588	SP-10.
5.	ASTM A-588	SP-2.

Two types of steel substrates were tested; ASTM A-36 mild steel and ASTM A-588 weathering steel. These substrates were chosen as representative of the materials commonly used in bridge construction. One interest of the overall program is the

---

[1] The inorganic zinc, powder coating, and metallized systems were applied only to the A-36 and A-588 steel surfaces with an SP-10 [near white blast] surface preparation.

determination of any difference in performance of coatings applied over these two types of steels. Selected A-36 steel panels with an SP-10 surface preparation included a 2-in (50.8-mm) by 2-in (50.8-mm) U-channel welded to the panel face to evaluate coating performance over a complex shape.

Three separate surface preparations were tested. These were Steel Structures Painting Council (SSPC) SP-10 [near white metal blast], SSPC SP-2 [hand tool-cleaned], and SSPC VIS 1-89 Rustgrade A [adherent millscale]. These three surface conditions were considered representative of the majority of shop painting applications, and both accessible and inaccessible areas for maintenance painting applications.

For the A-36 steel panels, all three surface preparations were tested. For the A-588 steel panels, only the SP-2 and SP-10 surface preparations were tested.

Prior to surface preparation, the A-36/SP-2, A-588/SP-10, and A-588/SP-2 panels were weathered at the Sea Isle Natural Exposure Site. During this time the panels developed a well rusted surface.

After surface preparation, selected panels from this group were tested for surface chloride contamination. This was accomplished using the following procedure:

> The chloride contamination of the panel surface was determined by dissolving the chlorides remaining on the panel surface into deionized water and titrating the solution to determine the total chloride content. To dissolve chlorides from the surface, a 2.5-cm diameter cell was secured to the panel surface. Fifty milliliters of deionized water was added to the cell, stirred, and allowed to set for 20 minutes. The water was decanted and titrated for chlorides. This procedure was repeated over the same area until no additional chlorides were detected. The total surface chloride contamination was then determined by summing the chlorides detected in each decantation. The titrations for chlorides were carried out using standard method 407B (Mercuric Nitrate Method) of the APHS, AWWA, and WPCF, "Standard Methods for the Examination of Water and Wastewater." Appendix A provides data concerning the measured chloride levels for A-36 and A-588 steel after weathering and subsequent surface preparation.

After the required surface preparations were completed, the panel surface was inspected to determine the resultant cleanliness and surface condition. The surface profile of the blasted steel panels was determined in accordance with ASTM D-4417, method C. The method utilized a composite plastic tape which, when impressed into the blast-cleaned surface, forms a reverse image of the profile. The peak-to-valley height on the tape was then measured with a micrometer. Profile range and average were determined through measurements of randomly sampled panels.

Coatings

Thirty-four separate coating systems were evaluated in the laboratory accelerated testing phase of the program. This total included 7 control systems, 13 high-solids or waterborne [low VOC] systems, and 14 powder coating or metallized systems. These coatings were selected through an extensive survey of the 50 State DOT's and over 40 coating and resin manufacturers. Attempts were made to obtain diversity in the generic types of coatings tested (e.g. zinc-based vs. epoxymastic vs. acrylic) as well as in the manufacturers of the tested systems.

Control Systems

Table 1 provides specific data concerning the type, applied thickness, and rationale for selection of the seven control coating systems. In general, these are systems with well documented performance histories in bridge applications. These systems are not considered to be environmentally acceptable with respect to current and pending VOC and HAZMIN regulations.

High-Solids/Waterborne Systems

Table 2 provides data concerning the type, commercial designation, applied thickness, VOC content, and rationale for selection for each of the 13 high-solids or waterborne systems. For the purposes of this program, a VOC content of 340 g/L (2.8 lb/gal) was established as a maximum for environmental acceptability. While these are exceptions, for all practical purposes the present VOC regulations for architectural coatings set the limit at 420 g/L (3.5 lb/gal). However, it is anticipated that this limit will decrease at least to the 340 g/L level over the next few years. All of the test systems listed in table 2 meet the 340 g/L criterion and many fall well below this level.

Powder Coating and Metallized Systems

Table 3 provides data concerning the material, application method, applied thickness, and rationale for selection for each of the powder coating and metallized systems tested. All systems listed in table 3 are zero VOC coatings except for the VOC compliant, solvent borne seal coats and powder coating topcoats.

Table 1. Control systems.

System #	Coating System	MILSPEC or Commercial Designation	Dry Film Thickness Per Coat (mils)	Rationale
1	BLSC Oil-Alkyd/ BLSC Oil-Alkyd/ BLSC Oil-Alkyd	TT-P-615/ TT-P-615/ TT-P-615	2.0/1.5/1.5	Widespread use on bridges for many years.
2	Red Lead- Linseed Oil/ Red Lead-Iron Oxide/ BLSC Oil-Alkyd	TT-P-86E/ TT-P-86/ TT-P-615	2.0/1.5/1.0	Widespread use on bridges for many years.
3	Inorganic Zinc Alkyl Silicate/ Vinyl Wash Primer/ High Build Vinyl	Carbozinc 11/ Carboline 1037 WP/ Carboline Polyclad 936	3.0/0.5/5.0	Presently in use in many states.
4	Inorganic Zinc Alkyl Silicate/ Polyamide Epoxy/ Aliphatic Urethane	Carbozinc 11/ Carboline 190 HB Epoxy/ Carboline 134 Urethane	3.0/4.0/2.0	Presently in widespread use on bridges. Considered to be high performance system.
5	Zinc Rich Epoxy/ Zinc Rich Epoxy/Wash Primer/ Vinyl Aluminum	Carboline 811 Z red/ 811 Z green/1037 WP/ 811 V	3.0/2.0/2.0	System currently being used by Louisiana DOT. LA qualified products list system.
6	Zinc Rich Urethane/ Polyamide Epoxy/ Aliphatic Urethane	62-Y-001 Zinc Filled/ Corlar 823 Epoxy Enamel/ Imron 326 Polyurethane	4.0/3.5/1.0	System now specified by Michigan DOT.
7	Polyamide Epoxy (3 coats)	MIL-P-24441,F150/ MIL-P-24441,F152/ MIL-P-24441,F151	3.0/3.0/3.0	Extremely well documented performance history. Wide use on U.S. Navy ships. Excellent benchmark to compare VOC-compliant coatings.

Table 2. Waterborne/high solids systems.

System #	Generic Description	Commercial Designation	Dry Film Thickness (mils)	VOC Content (grams/liter) (lb/gal)	Rationale
1	Water-Based Inorganic Zinc	Inorganic Coatings - IC-531	3-5	0 0	Has been used in several states. 1 coat system.
2	Water-Based Inorganic Zinc/Acrylic	Koppers P1500/600	2.0/1.5	0/160 0/1.3	Similar to solvent-based systems now being widely used.
3	Epoxy/Urethane	Ameron Amerlock 400/Porter Hythane	5/5	175/263 1.5/2.2	Has performed well in other tests evaluating VOC-compliant coatings.
4	Epoxymastic/Urethane	Carboline Carbomastic 90 Al/D834	8/2	84/300 0.7/2.5	Carbomastic 15 precursor to Carbomastic 90, has been widely used by bridge industry for 15 years.
5	Organic Zinc/Epoxy/ Urethane	Ameron Amercoat 68HS/Amercoat 385/ Porter Hythane	4/4/5	292/323/263 2.4/2.7/2.2	Similar systems used in several states.
6	Al Epoxy/ Water-Based Acrylic	Sherwin Williams- Al Epoxy Mastic/ DTM Acrylic Gloss	6/3	250/250 2.1/2.1	Low VOC,No lead,No Zinc
7	Epoxy/Water Based Enamel	Devoe Bar-Rust 239/Devflex 602	6/2	86/200 0.7/1.7	Demonstrated good performance in previous testing.
8	Styrene Acrylic/ 100% Acrylic Finish	CALTRANS - non proprietary formulation	4-8/4-8/4-8/ 4-8	140/30 1.2/0.25	System has shown good performance on bridges in CA.
9	Solvent-Based Inorganic Zinc/Epoxy/Urethane	Carboline D11HS/Carboline 893RCP/ Carboline D834	3/4/2	264/144 2.2/1.2	High solids version of a typical system used today
10	Water-Based Acrylic	Rohm & Haas Maincote HG 54	3/3/3	150 1.3	Now being evaluated on bridges in NC, SC, GA, ME, LA. Well documented performance history.
11	Waterborne Vinyl/ Waterborne Vinyl	Formula IV TL-2000	2-4/2-4	205 1.7	Unorthodox system, only 1 component. Only low VOC vinyl system proposed by suppliers.
12	Acrylic Latex	Hydrozo Coatings- CSMR/CSMR	3.5/2.5	150 1.3	One component system. Uses non-toxic barium metaborate as inhibitive pigment.
13	High Solids Phenolic/ 100% Acrylic Finish	CALTRANS - non proprietary formulation	4-8/4-8/4-8/ 4-8	287/140 2.4/1.2	System has shown good performance on bridges in CA.

Table 3. Metallized/powder coated systems.

System #	Material	Application	Dry Film Thickness (mils)	Rationale
1	Zinc	Wire Spray Metal	5-7	Control System, used on bridges in past.
2	Zinc/Vinyl seal coat	Wire Spray Metal	5-7/3	Control System, used on bridges in past.
3	85-15	Wire Spray Metal	5-7	Control System, used on bridges in past.
4	85-15/Vinyl seal coat	Wire Spray Metal	5-7/3	Control System, used on bridges in past.
5	Aluminum	Wire Spray Metal	5-7	To compare with zinc. In extensive testing by Navy and American Welding Society, aluminum has shown excellent performance.
6	Aluminum/Vinyl seal coat	Wire Spray Metal	5-7/3	To compare with unsealed zinc.
7	Zinc	Powder Spray Metal	5-7	To evaluate powder vs. wire.
8	Aluminum	Powder Spray Metal	5-7	To evaluate powder vs. wire.
9	Zinc/Flame Spray Epoxy	Powder Spray Metal and Epoxy	5-7/3	Uses the same equipment for application of metal and powder. Therefore application costs are kept down.
10	Epoxy	Flame Spray Powder	8-10	To compare to flame sprayed epoxy with and without zinc.
11	TGIC-Cured Polyester	Electrostatic	8-10	Shop-applied powder with excellent gloss retention.
12	ASTM A775 Epoxy	Electrostatic	8-10	System presently in use on PA bridges.
13	ASTM A775/Urethane solvent based topcoat	Electrostatic/ Conventional Spray	8-10/4	System presently in use on PA bridges.
14	ASTM A775/Acrylic water-based topcoat	Electrostatic/ Conventional Spray	8-10/3	Inexpensive powder system.

Application Procedures

With the exception of the powder coating and metallized coatings, all systems were applied using conventional air spray equipment. Application technique, dry-to-recoat time, application thickness, etc. followed the manufacturers recommendations.

The application equipment consisted of a 10.3 SCFM, 3.0 HP air compressor with a 4.0-ft^3 (0.112-m^3) tank and accompanying oil/moisture filter. The supply hoses included a 3/8-in (9.525-mm) diameter fluid hose and a 1/4-in (6.35-mm) diameter air line. The fluid reservoir was an air-agitated, 2-gal (7.57-L), dual-regulated pressure pot. The atomizing gun was a Devilbiss model QM-5507 with both 0.043-in (1.09-mm) [Type E] and 0.070-in (1.778-mm) diameter [Type F] fluid tips and needles.

The ambient environmental conditions during application were monitored. The dry and wet bulb temperatures were monitored using a Check-It Electronics Co. Model 424 wet bulb/dry bulb thermocouple assembly with a digital thermometer. The surface temperature was determined using the same gauge with a surface temperature thermocouple attachment. The relative humidity and dew point were determined using a psychometric chart. Prior to application, it was necessary to ensure that the surface temperature was at least 5 degrees higher than the dew point to avoid coating over condensation on the panel surfaces.

All panel edges were stripe-coated prior to spray application. The required film build was generally applied in several passes of the spray-gun to ensure uniform coverage. Adequate application over the U-channel was accomplished by narrowing the gun fan angle and applying paint over the channel in short bursts.

The film build was monitored during application using a wet film thickness gauge. Dry film thickness (DFT) readings for each of the coatings in each system were obtained using an Elcometer model 150 electronic dry film thickness gauge. A template with five apertures was used to facilitate acquisition of DFT measurements at consistent locations from panel to panel. Five DFT readings were taken on each side of each panel for each coating layer. (See Appendix B - System Summary Sheets for specified and applied dry film thicknesses.)

Accelerated Performance Tests

Five separate tests were performed on each of the candidate coating systems. These tests are described in detail below.

Natural Marine Exposure

One group of duplicate panels for each coating system/substrate/surface preparation combination was exposed for the 6-month test period at the Natural Marine Exposure Site. This site is located between the Atlantic Ocean and the Intracoastal Waterway in Sea Isle City, New Jersey. The east side of the site is approximately 100 yd (91.4 m) from mean high tide of the Atlantic Ocean. This location provides an extremely aggressive natural environment for coatings and materials testing on a year-round basis.

All test panels were placed at a 45-degree angle on wooden racks, facing directly south. During the 6-month test period, each panel was sprayed daily with natural seawater. Panels were inspected for rusting [ASTM D-610], blistering [ASTM D-714], linear cutback at an intentional scribe, and rusting at the U--channel (if attached). Both sides of each panel were evaluated for rusting and blistering. These inspection were performed three times during the first 6 months of exposure.

Cyclic Natural Marine Exposure/Salt Fog

A second set of panels was subjected to a cycle of 1 month of natural marine exposure at the Sea Isle Site followed by 1 month of salt fog testing. The salt fog testing was carried out in an Atlas Electric Devices Company Model SF 500 salt fog chamber according to a modified ASTM B-117 procedure (panels were placed vertically in the chamber, rather than at the specified 15 to 30° angle). Each 2-month cycle was repeated three times for a total of 6 months of testing. During each natural marine exposure period of the cyclic testing, the panels were inspected for rusting [ASTM D-610], blistering [ASTM D-714], and linear cutback at an intentional scribe.

Cyclic Natural Marine Exposure/High Pressure Brine Immersion

A third set of panels was subjected to a cycle of 1 month of natural marine exposure at the Sea Isle Site followed by 1 month of immersion in a high pressure, high temperature brine solution. This 2-month cycle was repeated three times for a total of 6 months of testing. For the brine immersion testing, the panels were placed in PVC racks inside a fiberglass pressure vessel. This vessel was filled with a 5 percent deicing salt brine solution heated to 150°F (65.56°C) and pressurized to 25 psig. During the test, the temperature was maintained by circulating the brine solution through a titanium tube heat exchanger placed outside the pressure vessel. The 5 percent brine solution was obtained by mixing standard $CaCl_2$ road deicing salt with tap water. The pressure, temperature, and salt solution chemistry were monitored continuously throughout the three, 1-month brine immersion test periods.

Water Penetration

The detrimental effects of water penetration through a coating are well documented. In general, rapid water penetration can be associated with substrate corrosion and premature coating failure. Water penetration in the subject program was evaluated by the concepts of ASTM G-9, "Water Penetration into Pipeline Coatings." In this method, two, 3-in (76.2-mm) diameter acrylic cylinders were adhesively bonded to one side of a coated test panel of each system. These cylinders were covered with an acrylic top fitted with a carbon rod extending into the test cell. The carbon rod served as a counter electrode. For testing, the cylinders were filled with a 5 percent deicing salt solution. Water penetration measurements were made by monitoring the electrical capacitance and dissipation factor for the coating.

The relationship between the electrical measurements and water penetration are given by the following formulae:

$C = 35 \times K \times A / t$

where,

C = Capacitance (pF)
K = Dielectric Constant
A = exposed Surface Area (cm^2)
t = Effective Coating Thickness (mils) (1)

For a parallel resistance/capacitance circuit utilized to model coatings, the dissipation factor is determined by the following formula:

$D = 1/(R \times C \times w)$

where,

R = resistance, ohms
C = capacitance, F
w = frequency, rads/sec (2)

In theory, water penetration through the coating would be expected to decrease the effective film thickness. As is predicted by formula (1), this would tend to increase the capacitance of the coating. If water penetrates in an even, continuous layer, the capacitance will increase in direct proportion to the depth of the water penetration. If the water penetrates only through a few minute pinholes in the coating, the capacitance will increase slightly and the dissipation factor will increase sharply. As indicated in formula (2), the increase in dissipation factor occurs due to a large decrease in the parallel resistance component. The capacitance increases only slightly because the area of the pinhole path represents such a small portion of the overall coating area. As the number of pinholes increases, the capacitance will also increase. Water penetration through the coating in a discontinuous layer of through water vapor transmission may not be sensed by such capacitance measurements.

Prior to exposing the coated sample to the test electrolyte, the dielectric constant of the coating was determined. The test cell was filled with mercury and the capacitance measured between the coated substrate and a counter electrode in the mercury. Because of mercury's extremely high surface tension, it will not penetrate the barrier coating in either a general mode or through pinholes. Therefore, the capacitance, as measured, includes the entire coating thickness. Having determined the coatings's dry film thickness by an independent means, the dielectric constant can be calculated by applying the measured capacitance and the known coating thickness and surface area to the above formula.

After dielectric constant determination, the mercury was totally removed and replaced with the 5 percent deicing salt solution. Capacitance and dissipation factor (resistance) measurements were made periodically using a GenRad 1657 Digi-Bridge at 1000Hz. One lead from the bridge was connected to the carbon rod, while the other lead was connected to a bare steel holiday in the test panel outside of the test cell areas. For each system, the data obtained was plotted against time to observe any changes in capacitance or resistance (calculated from the dissipation factor) that might indicate water penetration or pinholing.

Coating Adhesion

Representative panels from each system were subjected to coating adhesion testing according to ASTM D-4541. For this testing, a standard pull-off adhesion dolly is adhesively bonded to the coating surface. The coating is scribed to the substrate around the perimeter of the dolly. A spring-loaded test apparatus is then used to apply an increasing load on the coating/adhesive interface until a disbondment failure occurs. At the failure point, the load (in psi) is recorded. In addition, the percentage of coating (as opposed to adhesive) that fails is also recorded. For multiple coat systems, the location of the failure is recorded (e.g. primer/intermediate failure, primer/substrate failure, intermediate/topcoat failure, etc.).

Adhesion tests were performed on each system before testing and after the cyclic salt fog and brine immersion testing.

Rating System

The panels subjected to the natural marine exposure testing, the cyclic natural marine exposure/salt fog testing, and the cyclic natural marine exposure/brine immersion testing were rated on four separate parameters; rusting, blistering, scribe cutback, and U-channel rusting [for the natural marine exposure panels only]. In an attempt to assimilate the results of these four rating systems, a single system for ranking the relative performance of the various systems was devised. The overall results of the accelerated testing and the subsequent selection of the systems for the long-term exposure testing are based on this ranking system. The paragraphs below describe the specific methods used to obtain the data as well as the methods used to achieve the final ranking of the coating systems.

Rusting

The rust rating for each test panel was determined by placing a clear acrylic sheet, marked with 8 equal-sized sections, over the panel. The sections which had a rust rating of 7 or less in accordance with ASTM D-610 were considered failing. A rating of 7 corresponds to 0.3 percent of the surface area. The number of sections not failing was recorded. This gave a rust rating for each side of each panel ranging between 0 and 8, (i.e. 0 = all sections failing, 8 = no sections failing).

Blistering

The degree of blistering was determined for each side of each panel. The blister rating was based directly on ASTM D-714 and produced a rating which took into consideration blister size (0-10, 10 being no blistering) and density (f = few, m = medium, md = medium dense, d = dense).

Scribe Cutback

The scribe cutback was a direct measurement (in inches) of the maximum distance of undercutting from the center of the intentional scribe.

U-Channel Rusting

The inspection for rusting at the U-channel was a simple notation as to whether rusting was visible.

Unified Rating System

In order to summarize and analyze the data, it was necessary to convert some of the qualitative ratings to a quantitative value. Of the four inspection criteria, rusting was considered to be the most important failure mode. Therefore, the 0 to 8 rust rating for both panel sides was normalized to a scale of 0 to 30.

The blistering rating was converted from the qualitative ASTM rating to a single quantitative value. This was accomplished by retaining the blister size value (0-10), but converting the density letter designation to a quantitative value (none = 10, few = 8, med = 6, med. dense = 4, dense = 2). The size and density values were summed. This value was then divided by 2. This produced a rating on a scale of 1 to 10 which represented both blister size and density.

The scribe undercutting data was converted from a direct measurement (inches) to a quantitative rating. This was accomplished by assigning 1-in (25.4-mm) undercutting as a total failure. For each panel, the undercutting was subtracted from 1 inch and multiplied by 10. This produced a 1 to 10 rating for undercutting (i.e., 1-in (25.4-mm) undercutting = 0, 0.5-in (12.7-mm) undercutting = 5, no undercutting = 10).

The channel rusting data was quantified by assigning a value of 0 for panels with channels displaying rust and 10 for panels with channels displaying no rust.

To total and summarize the panel rating system:

	Maximum Possible
Rusting (30 pts x 3 tests)	90
Blistering (10 pts x 3 tests)	30
Scribe Undercutting (10 pts x 3 tests)	30
Channel Rusting (10 pts x 1 test)	10
Total	160

The rating obtained for each system was divided by 160 and multiplied by 100. This resulted in a normalized 0 to 100 rating for each system over each substrate/surface preparation.

RESULTS AND DISCUSSION

The following is a summary of the results of the accelerated laboratory testing performed on the various candidate coatings. These results are accompanied by appropriate discussion and comments. Detailed "system-by-system" results concerning the performance of individual coating systems in the various tests as well as detailed notes concerning application of the coatings may be found in Appendix B - System Summary Sheets.

A-36 Steel vs. A-588 Steel

As an initial step in the data analysis, a comparison was made between the results of coating performance over the two steel substrates. Figures 1 and 2 show the average rust rating versus time for all systems tested over the five various substrate/surface preparation combinations. Figure 1 shows these results for the cyclic natural marine exposure/salt fog testing, and figure 2 shows the results for the cyclic natural marine exposure/brine immersion testing.

Two key results are apparent from these figures. First, the performance of the coating systems over SP-10 surfaces is clearly superior to performance of the same coating systems applied over an SP-2 surface preparation. Second, the difference in performance of the coatings systems tested over A-36 and A-588 steel, regardless of surface preparation, is negligible. That is, the performance of the coating systems tested appears much more dependent upon the surface preparation than on the particular alloy substrate.

Because of this result, the remaining data analysis presented below is for the various surface preparations over A-36 steel. In all cases, the data for A-588 steel was similar.

Over the test period of 6 months, the data show the general coating performance over adherent millscale appears to be somewhere between the performance over an SP-10 and an SP-2 surface preparation. However, at the 6-month point in both graphs, the rate of coating degradation (slope of the line) for the coatings over millscale appears to be similar to the slope for SP-2. From this observation, the coatings applied over millscale would be expected to perform much worse than those over SP-10 over an extended evaluation period.

Cyclic Natural Marine Exposure/Salt Fog Testing

Figures 3, 4, and 5 provide the data obtained in the cyclic natural marine exposure/salt fog testing for rusting, blister-

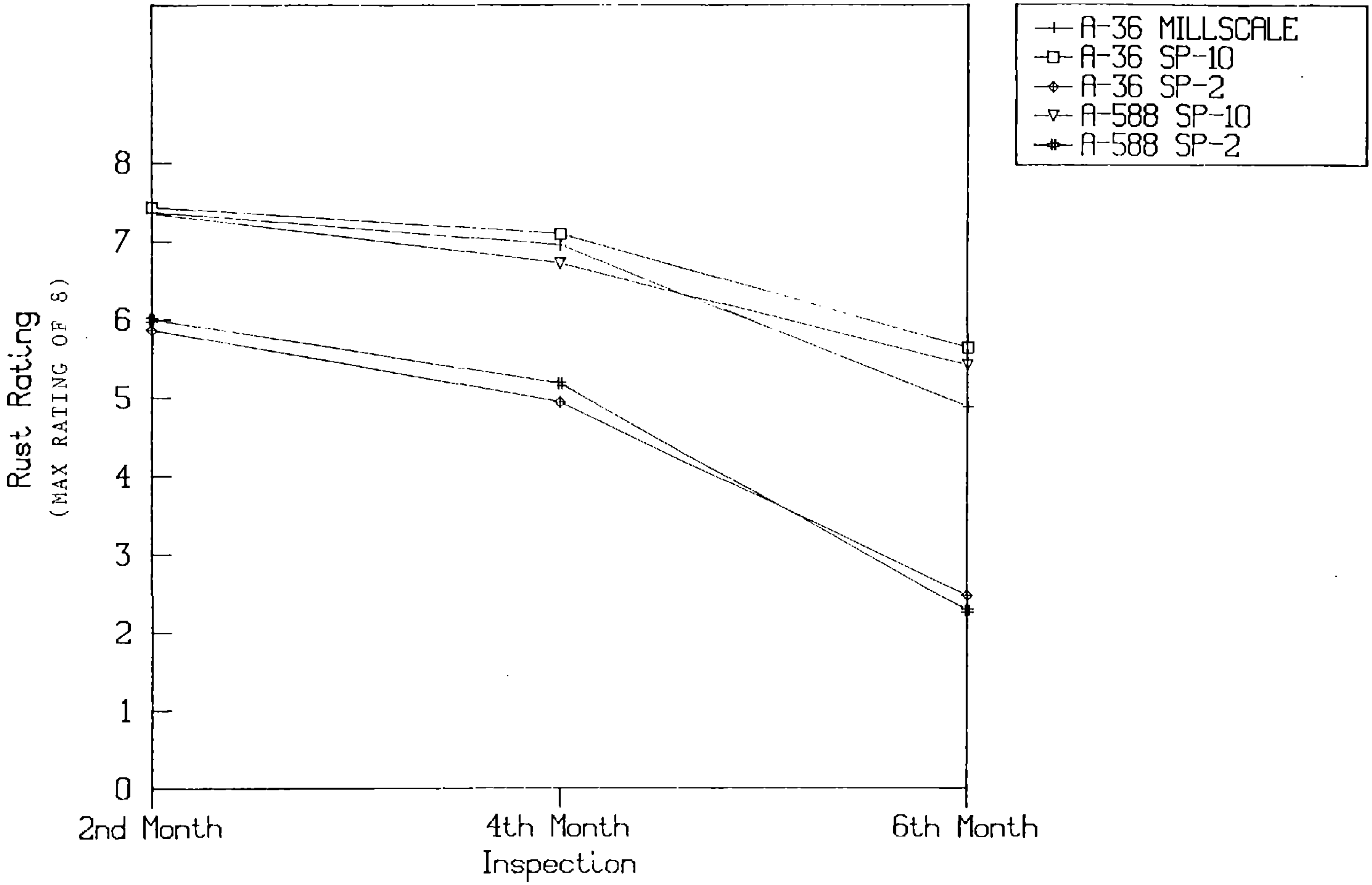


Figure 1. Salt fog tests; effect of substrate and surface preparation, all systems.

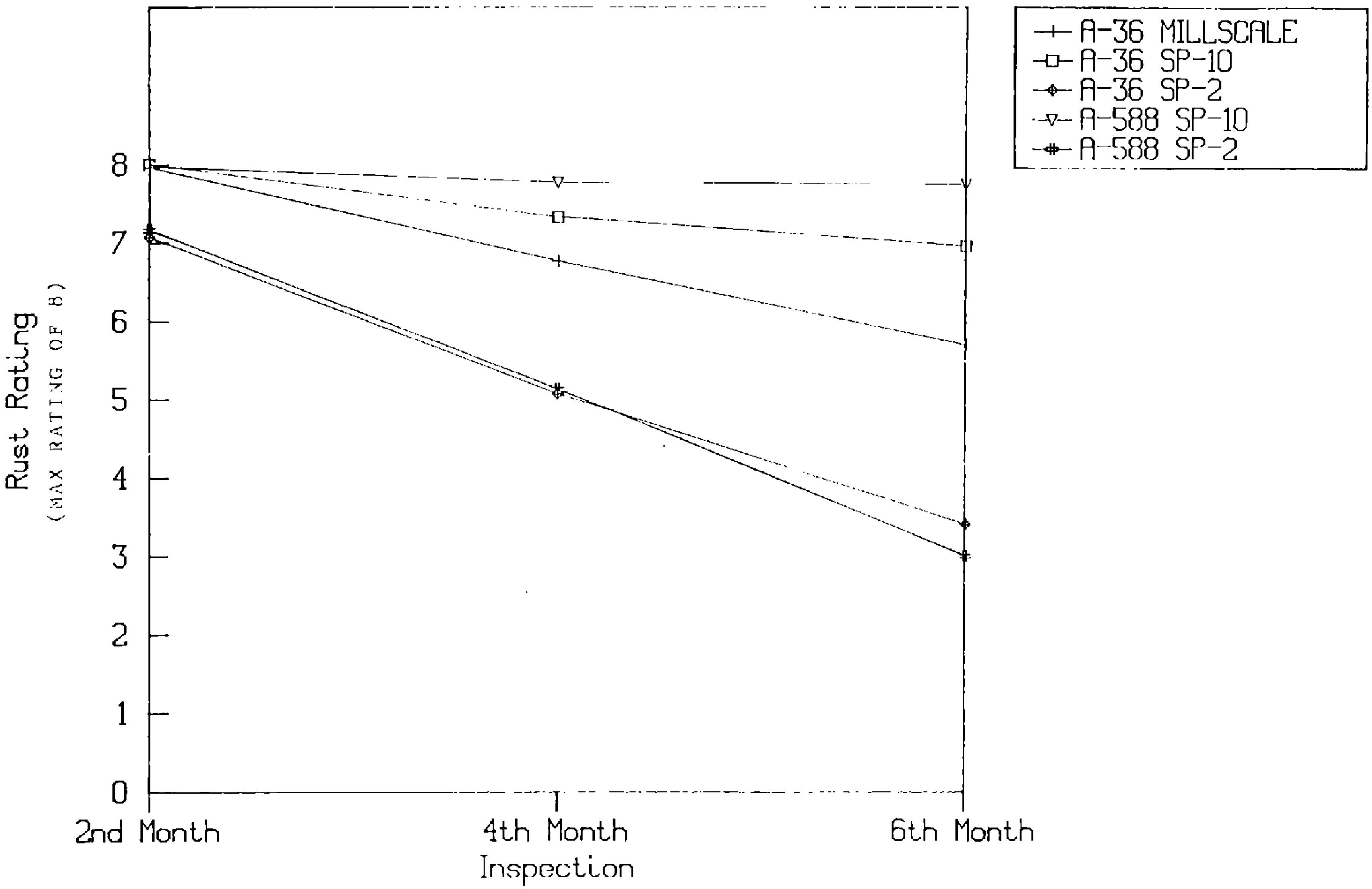


Figure 2. Brine immersion tests; effect of substrate and surface preparation, all systems.

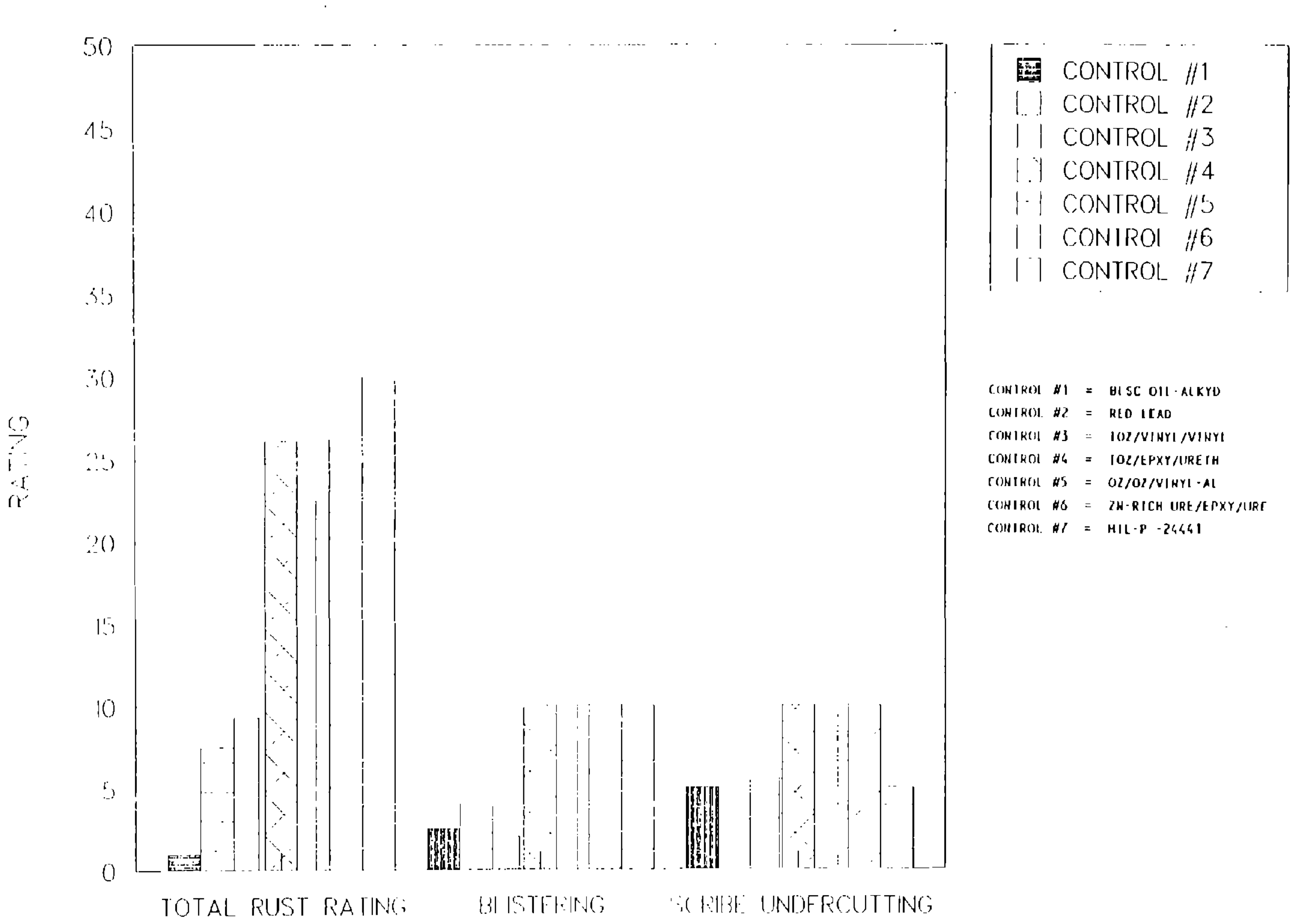


Figure 3. A36 test panels; performance rating for all tests, salt fog tests, (control systems).

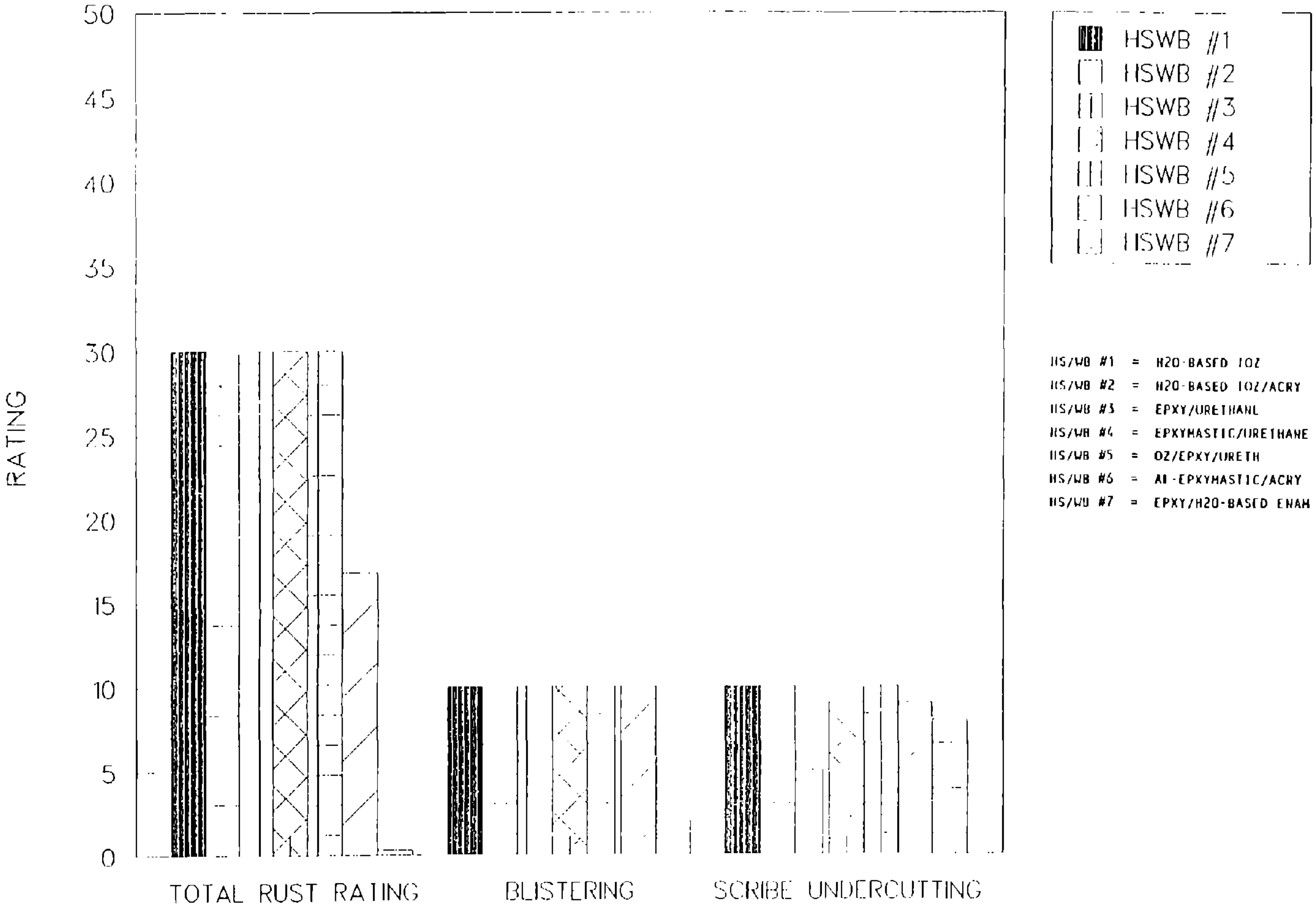
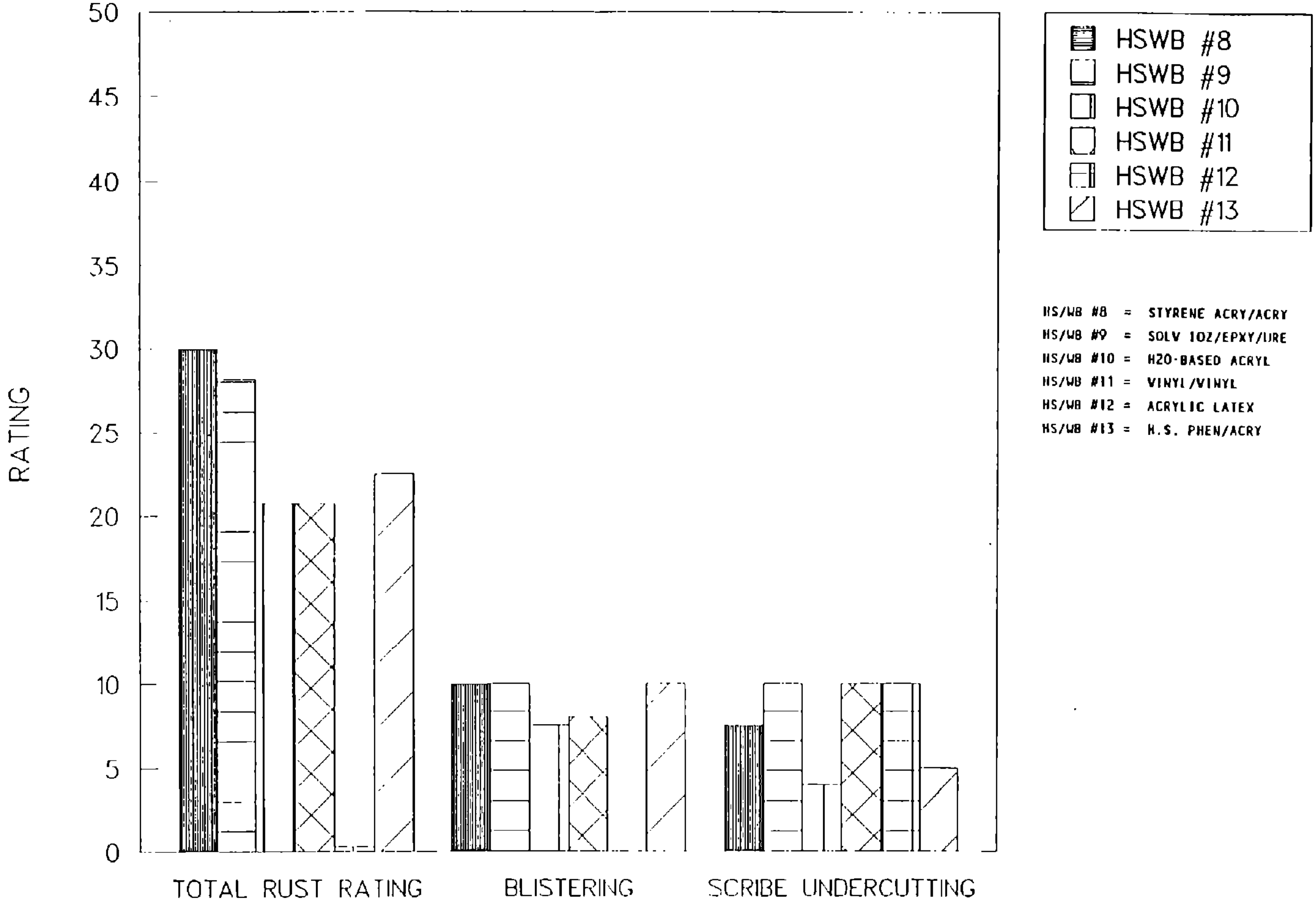


Figure 4. A36 test panels; performance rating for all tests, salt fog tests, (HS/WB systems 1-7).



HS/WB #8 = STYRENE ACRY/ACRY
HS/WB #9 = SOLV 10Z/EPXY/URE
HS/WB #10 = H2O-BASED ACRYL
HS/WB #11 = VINYL/VINYL
HS/WB #12 = ACRYLIC LATEX
HS/WB #13 = H.S. PHEN/ACRY

Figure 5. A36 test panels; performance rating for all tests, salt fog tests, (HS/WB systems 8-13).

ing, and scribe undercutting for the seven control systems and the 13 high solids and waterborne systems applied over an A-36 steel/ SP-10 surface. In these figures, rust ratings are on a scale of 0 to 30, blistering is on a scale of 0 to 10, and scribe undercutting is on a scale of 0 to 10.

Control Systems

From figure 3 the best performing control systems were:

4. Inorganic zinc/epoxy/urethane.
6. Zinc-rich urethane/epoxy/urethane.
7. MIL—P—24441, polyamide epoxy.

The MILSPEC system showed excellent resistance to rusting and blistering with only marginal resistance to scribe cutback (see figure 6). The IOZ/epoxy/urethane and zinc-rich urethane/epoxy/urethane systems showed slightly less rusting resistance, but performed well in the blistering and scribe cutback tests.

Figure 3 also clearly points out the three worst performing control systems. These were:

1. 3-Coat basic lead silico chromate (BLSC) oil-alkyd.
2. Red lead/red lead/BLSC.
3. Inorganic zinc/vinyl/vinyl.

These systems showed poor performance with respect to rusting and blistering and marginal performance in the scribe undercutting test. For the lead-based systems, these results are not surprising. Lead-based systems have a history of poor performance in salt fog testing that does not necessarily correlate with their performance in a natural environment (see figure 7).

High Solids/Waterborne Systems

Figures 4 and 5 provide the results of the cyclic salt fog testing for the high solids/waterborne test systems. From these figures, the best performers were:

1. Water-based inorganic zinc.
2. Water-based inorganic zinc/acrylic.
3. Epoxy/urethane.
4. Epoxymastic/urethane.
5. Organic zinc/epoxy/urethane.
8. Styrene acrylic/acrylic.
9. Inorganic zinc/epoxy/urethane.

All of the above systems performed reasonably well in rusting, blistering, and scribe undercutting. One exception to this rule is the blistering of the acrylic topcoat applied over the inorganic zinc in system 2. In spite of this topcoat blister-

Figure 6. MIL-P-24441 control system panels after 6 months cyclic salt fog testing.

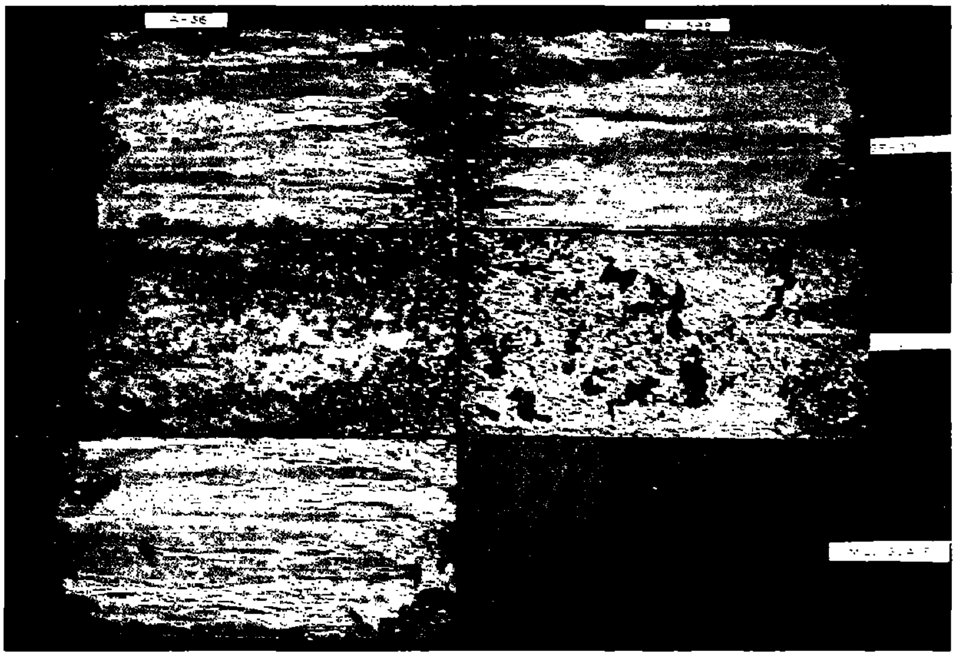


Figure 7. Red lead oil alkyd control system panels after 6 months cyclic salt fog testing.

ing, system 2 performed very well with respect to rusting and scribe undercutting.

Significantly, these systems all performed as well or better than the best performing control systems. It is interesting to note that none of the systems with a zinc primer [IOZ or OZ] showed any signs of scribe undercutting in the cyclic salt fog testing (see figures 8 and 9).

Two of the high solids/waterborne test systems performed extremely poorly in the cyclic salt fog testing. These were:

7. Epoxy/water-based enamel.
12. Acrylic latex (see figure 10).

These systems both failed completely due to rusting.

Powder Coating/Metallized Systems

With the exception of the flame-sprayed epoxy and the triglycidyl isocyanurate (TGIC) polyester powder coatings, all of the metallized and powder coating systems performed very well in the cyclic salt fog testing. Figure 11 shows the typical performance of the powder coating/metallized systems in this testing.

SP-2 (Hand Tool Cleaned) Surface Preparation

Figures 12 and 13 provide the rusting, blistering, and scribe undercutting data for the control and high solids/waterborne systems in the cyclic salt fog testing. [Note: The systems with inorganic zinc primers were not tested over SP-2 surfaces.]

The data in figure 12 shows MIL-P-24441 polyamide epoxy to be the best performing control system in the cyclic salt fog testing. Most of the control systems failed badly over SP-2 surfaces.

Figure 13 shows several high solids/waterborne test systems outperforming the bulk of the controls over an SP-2 surface. Epoxy/urethane (system 3) and epoxymastic/urethane (system 4) performed well versus all three evaluation criteria. Styrene Acrylic/Acrylic (system 8) blistered, but performed well in the rusting and scribe undercutting evaluations.

Cyclic Natural Marine Exposure/Brine Immersion Testing

Figures 14, 15, and 16 provide the data obtained in the cyclic natural marine exposure/brine immersion testing for rusting, blistering, and scribe undercutting for the seven control

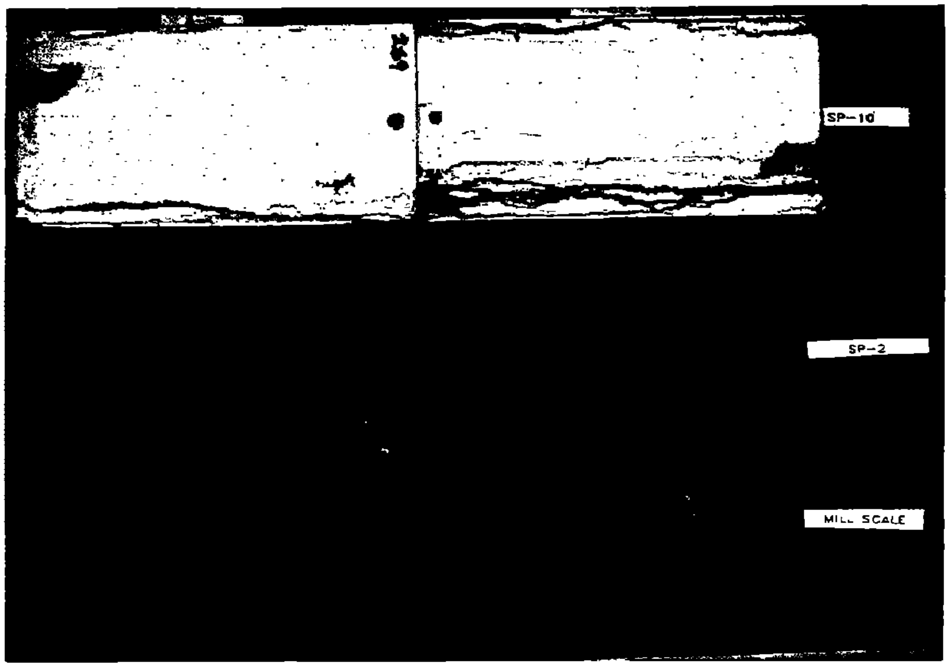


Figure 8. Low VOC inorganic Zn/epoxy/urethane system after 6 months cyclic salt fog testing (system applied over SP-10 surfaces only).

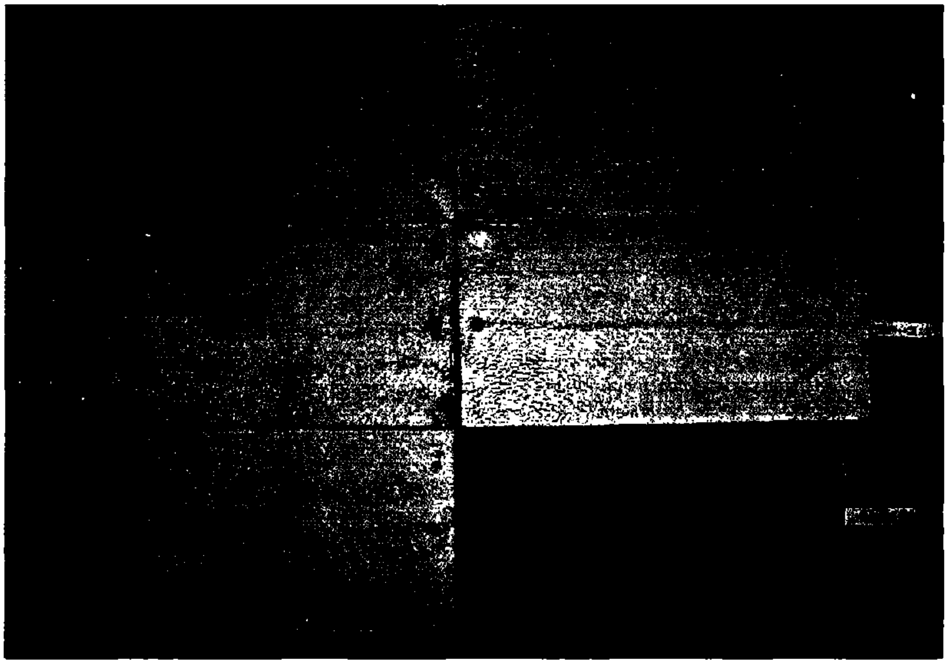


Figure 9. Low VOC organic Zn/epoxy/urethane system after 6 months cyclic salt fog testing.

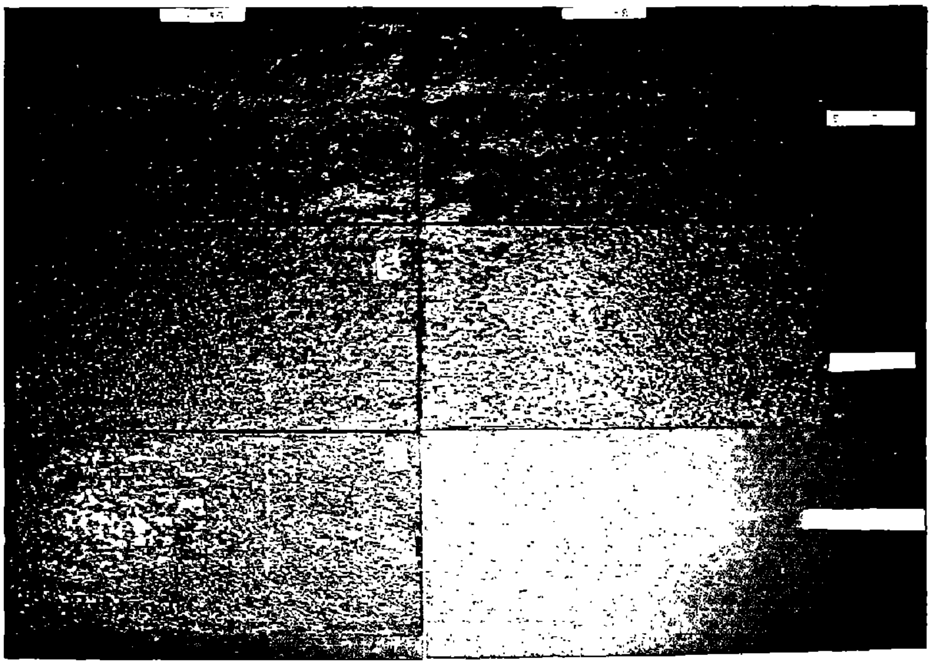


Figure 10. Low VOC acrylic latex system after 6 months cyclic salt fog testing.

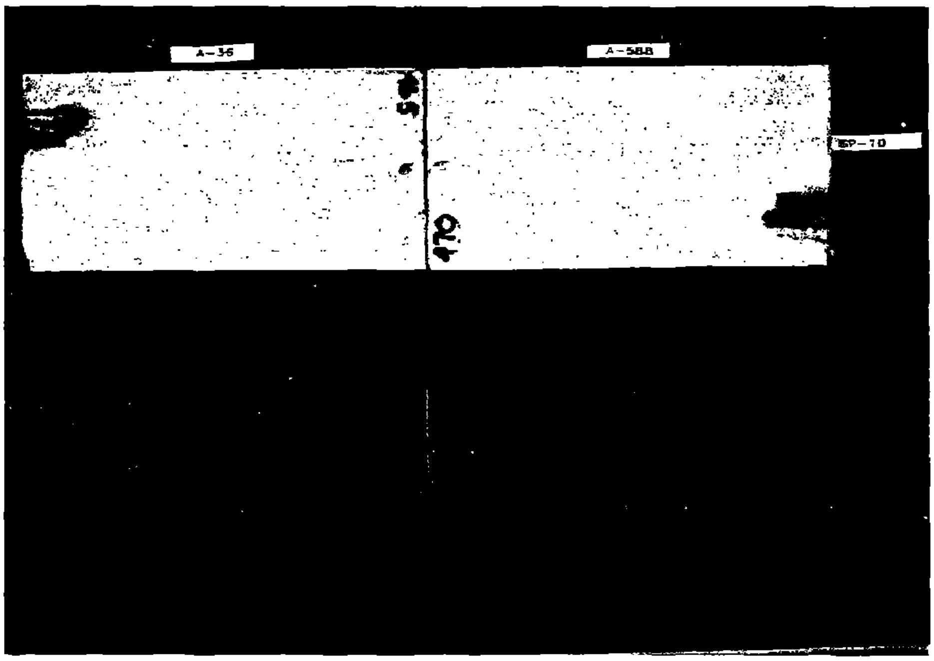
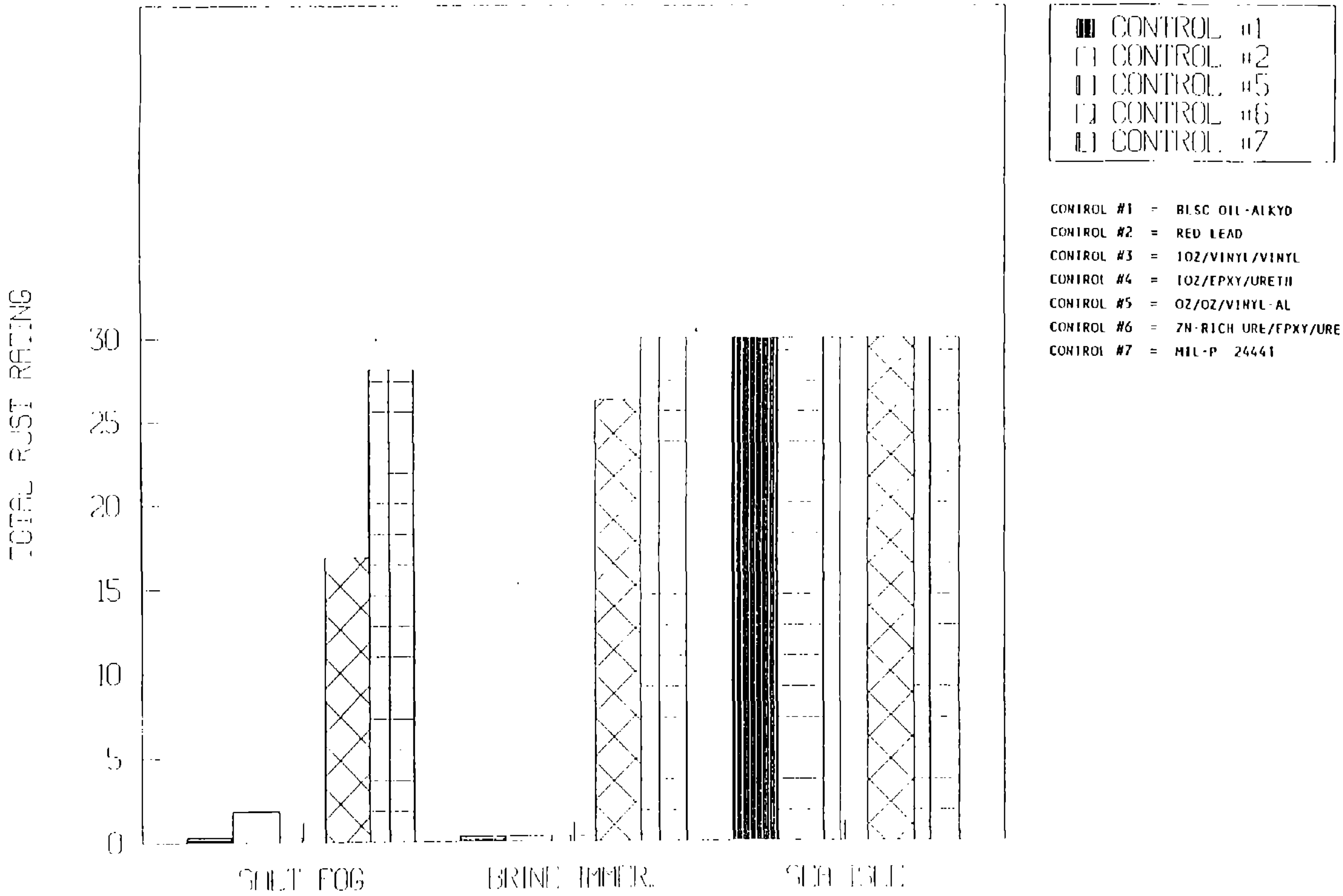


Figure 11. ASTM A 775 powder epoxy/urethane system after 6 months cyclic salt fog testing.



CONTROL #1 = BLSC OIL-ALKYD
CONTROL #2 = RED LEAD
CONTROL #3 = IOZ/VINYL/VINYL
CONTROL #4 = IOZ/EPXY/URETH
CONTROL #5 = OZ/OZ/VINYL-AL
CONTROL #6 = ZN-RICH URE/EPXY/URE
CONTROL #7 = MIL-P 24441

Figure 12. A36 test panels; performance rating for all tests, salt fog tests, SP-2 surface prep., (control systems).

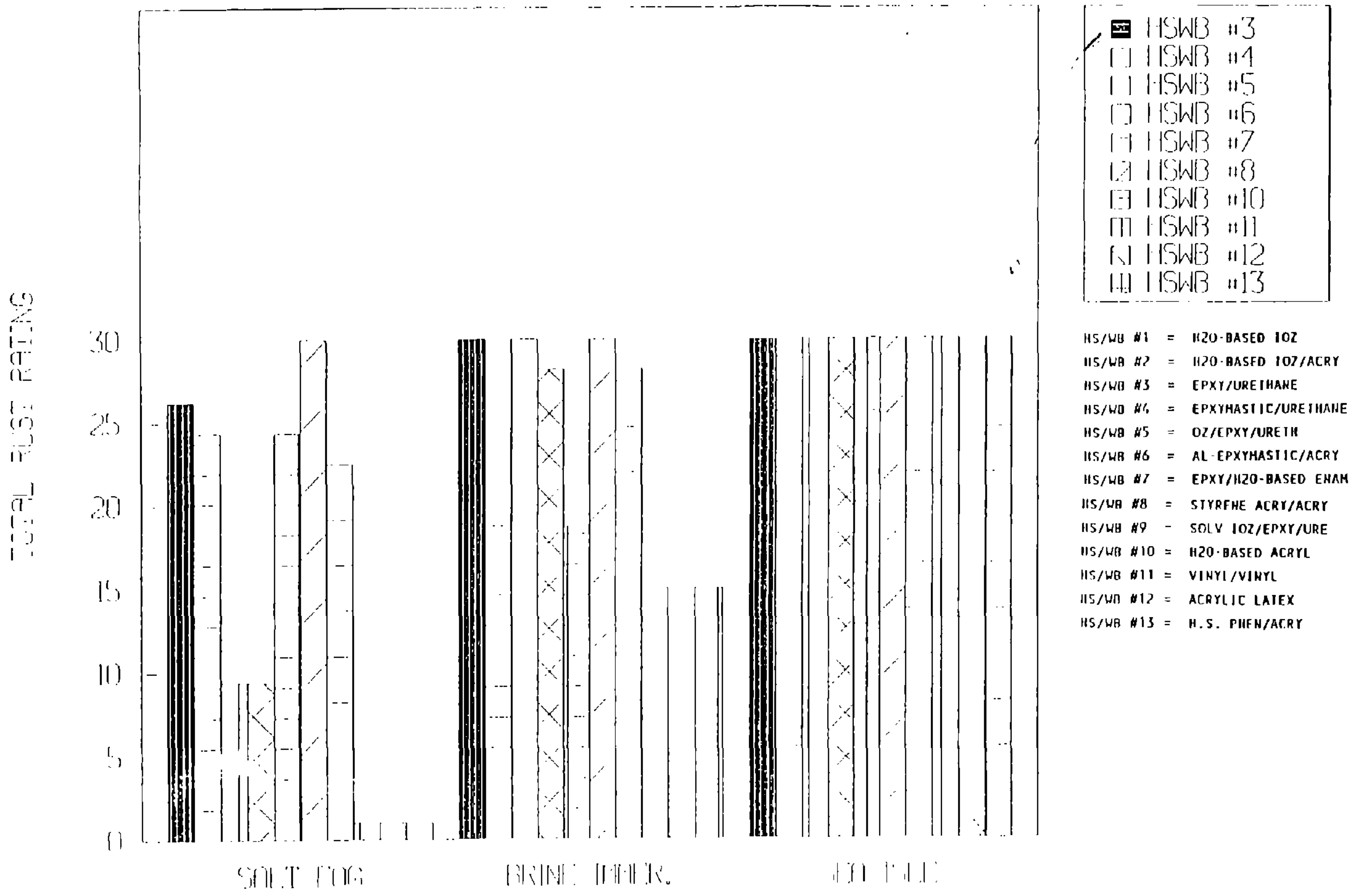
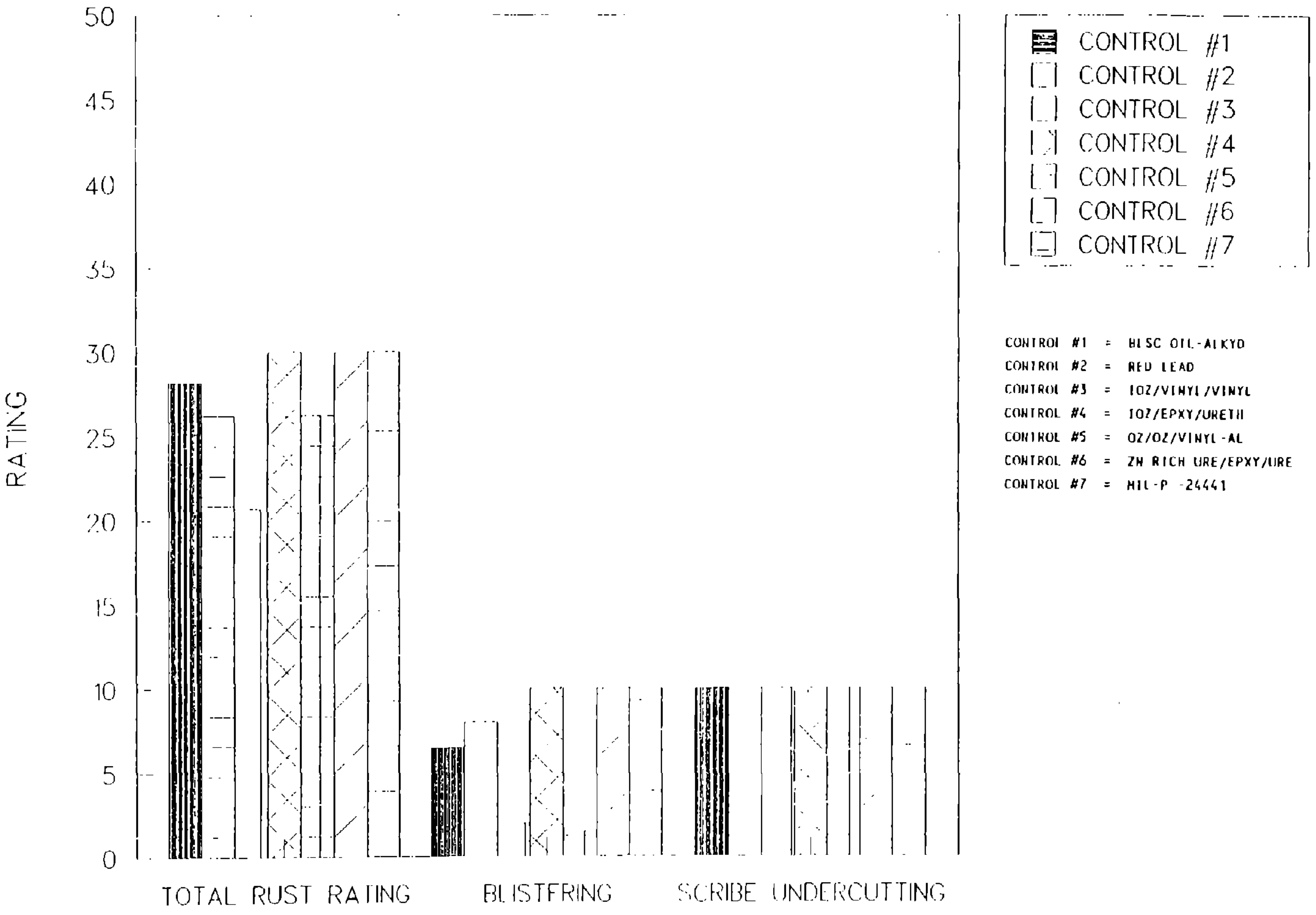


Figure 13. A36 test panels; performance rating for all tests, salt fog tests, SP-2 surface prep., (HS/WB systems).



CONTROL #1 = MISC OIL-ALKYD
CONTROL #2 = RED LEAD
CONTROL #3 = IOZ/VINYL/VINYL
CONTROL #4 = IOZ/EPXY/URETH
CONTROL #5 = OZ/OZ/VINYL-AL
CONTROL #6 = ZN RICH URE/EPXY/URE
CONTROL #7 = MIL-P -24441

Figure 14. A36 test panels; performance rating for all tests, brine immersion tests, (control systems).

systems and the 13 high solids and waterborne systems applied over A-36 steel/SP-10 surfaces. In these figures, rust ratings are on a scale of 0 to 30, blistering is on a scale of 0 to 10, and scribe undercutting is on a scale of 0 to 10.

Control Systems

From figure 14, the best performing control systems were:

4. Inorganic zinc/epoxy/urethane.
6. Zinc-rich urethane/epoxy/urethane.
7. MIL-P-24441, polyamide epoxy.

In the cyclic brine immersion testing, these three systems showed no deterioration with respect to to any of the three rating systems. These are the same systems that performed best in the cyclic salt fog testing. Figure 17 shows the MIL-P-24441 cyclic brine immersion test panels after 6 months.

Although the lead-based systems were not the best performers in this test, it is interesting to note the significant increase in performance of systems 1 and 2 in the brine immersion testing as opposed to the performance of the same systems in the salt fog testing. Figure 18 shows the performance of the Red Lead Oil Alkyd system after 6 months of cyclic brine immersion testing.

The control systems with vinyl topcoats performed worst in the cyclic brine immersion testing. These systems were:

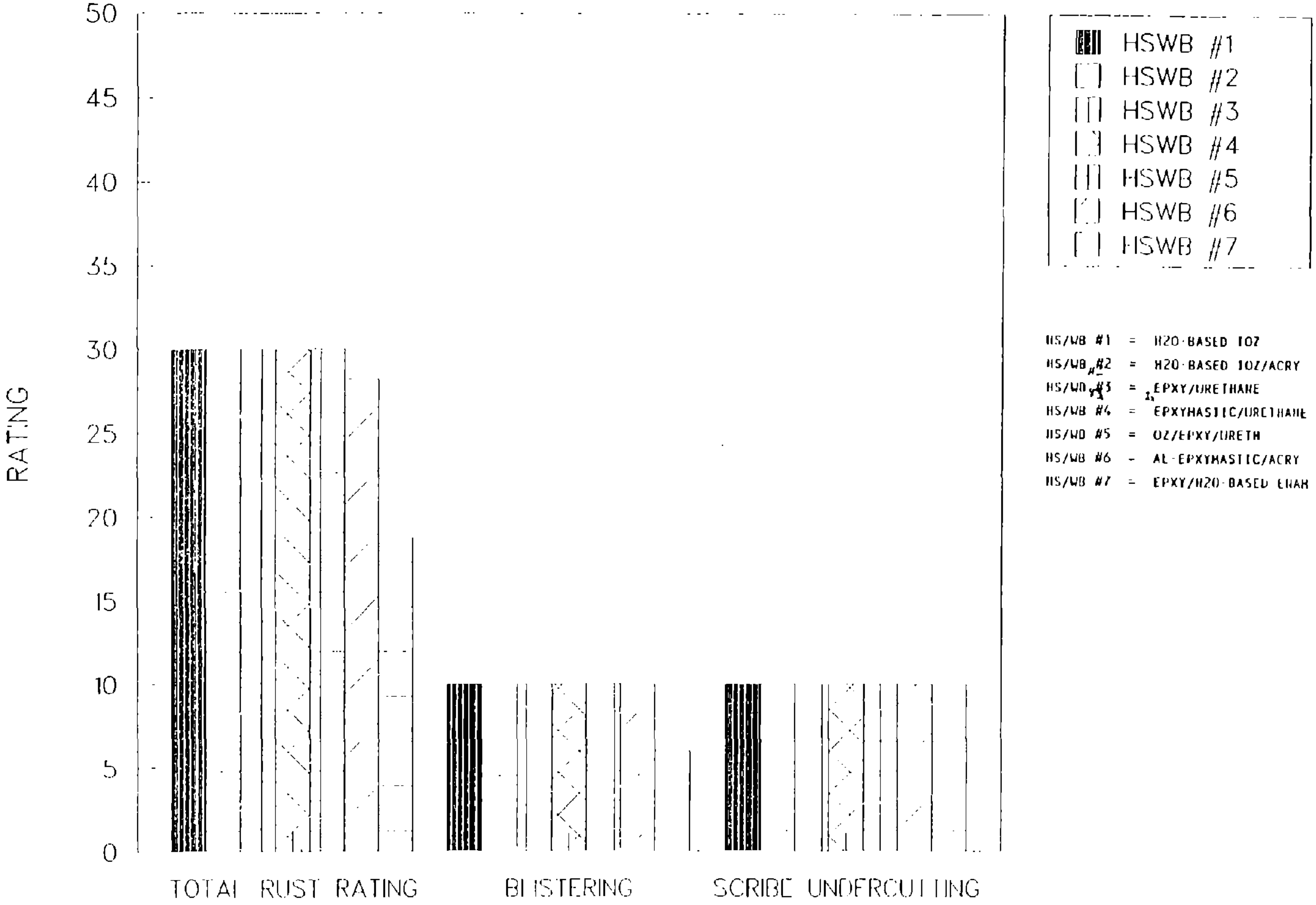
3. Inorganic zinc/vinyl wash primer/vinyl.
5. Organic zinc/organic zinc/vinyl wash primer/vinyl-Al.

Both of these systems showed some rusting and severe blistering in the cyclic brine immersion testing. System 3 was also one of the poor performers in the cyclic salt fog testing.

Although these systems performed poorly in rusting and blistering evaluations, they did not show any scribe undercutting, possibly due to the zinc-based primers used in each system.

High Solids/Waterborne Systems

Figures 15 and 16 show the data obtained for the high solids and waterborne test systems in the cyclic brine immersion testing. With the exception of the three systems listed below, all of the systems tested showed excellent overall performance in the cyclic brine immersion test. The poor performers were:



HS/WB #1 = H2O-BASED IOZ
HS/WB #2 = H2O-BASED IOZ/ACRY
HS/WB #3 = EPXY/URETHANE
HS/WB #4 = EPXYMASTIC/URETHANE
HS/WB #5 = OZ/EPXY/URETH
HS/WB #6 - AL-EPXYMASTIC/ACRY
HS/WB #7 = EPXY/H2O-BASED ENAM

Figure 15. A36 test panels; performance rating for all tests, brine immersion tests, (HS/WB systems 1-7).

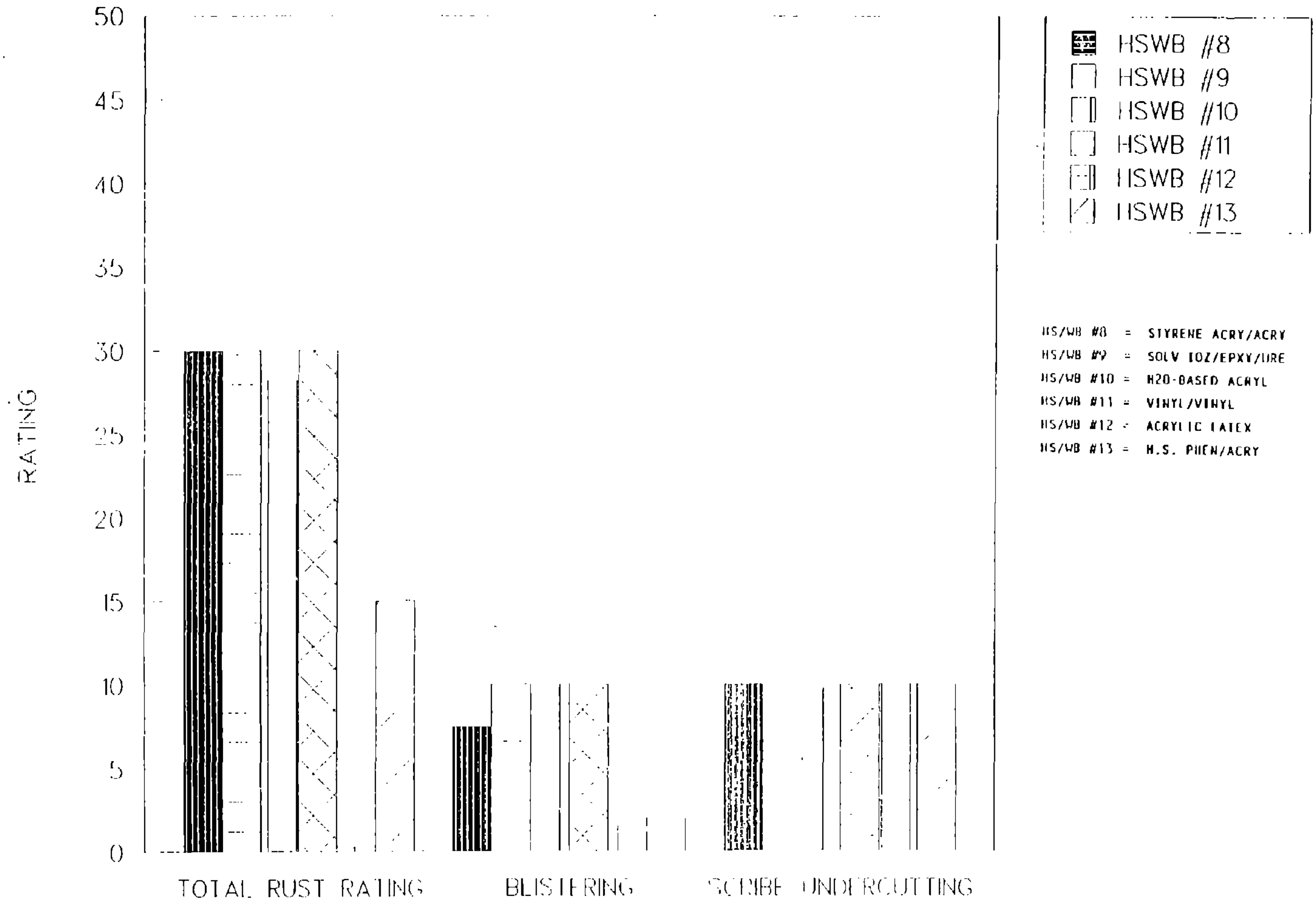


Figure 16. A36 test panels, performance rating for all tests, brine immersion tests, (HS/WB systems 8-13).

Figure 17. MIL-P-24441 test panels after 6 months cyclic brine immersion testing.

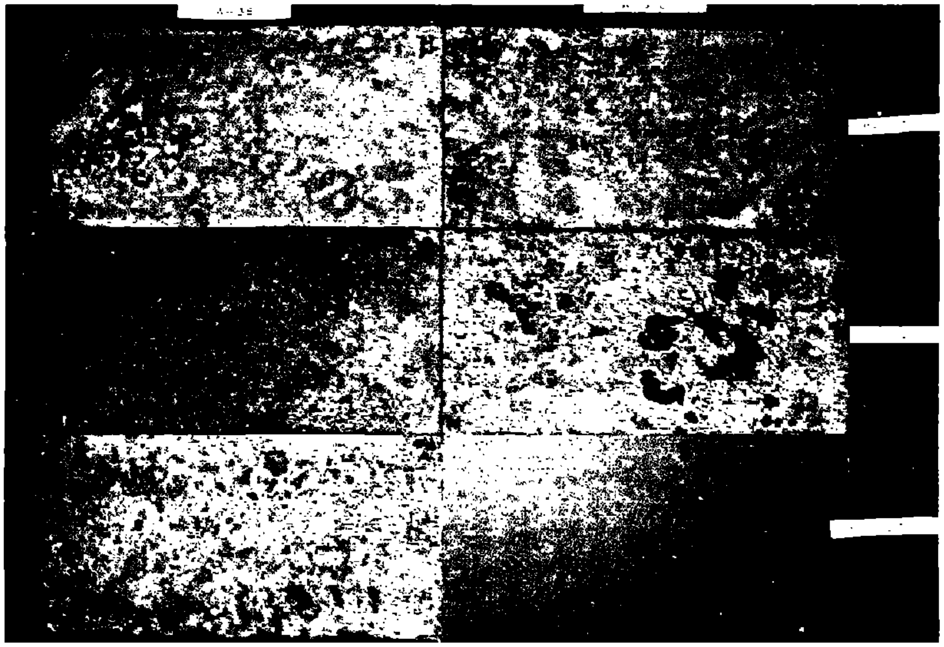


Figure 18. Red lead oil alkyd system after 6 months cyclic brine immersion testing.

7. Epoxy/water-based enamel.
12. Acrylic latex.
13. High solids phenolic/acrylic.

Systems 7 and 12 also performed poorly in the cyclic salt fog testing.

As was the case in the cyclic salt fog testing, system 2 [IOZ/acrylic] performed well with respect to rusting and undercutting in spite of the blistering observed in the acrylic topcoat.

In the cyclic brine immersion testing, the OZ/epoxy/urethane system showed severe blistering (figure 19), whereas the IOZ/ epoxy/urethane (figure 20) system showed no signs of blistering.

Powder Coating/Metallized Systems

All of the powder coating and metallized systems tested performed very well in the cyclic brine immersion testing. There were no significant failures of these coatings during the test period.

SP-2 (Hand Tool Cleaned) Surface Preparation

Figures 21 and 22 provide the rusting, blistering, and scribe undercutting data for the control and high solids/waterborne systems in the cyclic brine immersion testing. [Note: The systems with inorganic zinc primers were not tested over SP-2 surfaces.]

The data in figure 21 shows zinc-rich urethane/epoxy/urethane (system 6) and MIL-P-24441 polyamide epoxy (system 7) to be the best performing control systems in the cyclic brine immersion testing for an SP-2 surface. As in the cyclic salt fog testing, most of the control systems failed badly over SP-2 surfaces.

Figure 22 shows several high solids/waterborne test systems outperforming the bulk of the controls over an SP-2 surface. Several of the systems did quite well in the rusting evaluation Considering all three evaluation criteria, epoxy/urethane [system 3] was the best performer of the systems tested over an SP-2 surface.

Natural Marine Exposure Testing

Of all of the coating systems tested, only one system had shown any significant deterioration due to natural marine exposure after a 6-month period. This system was the high solids/

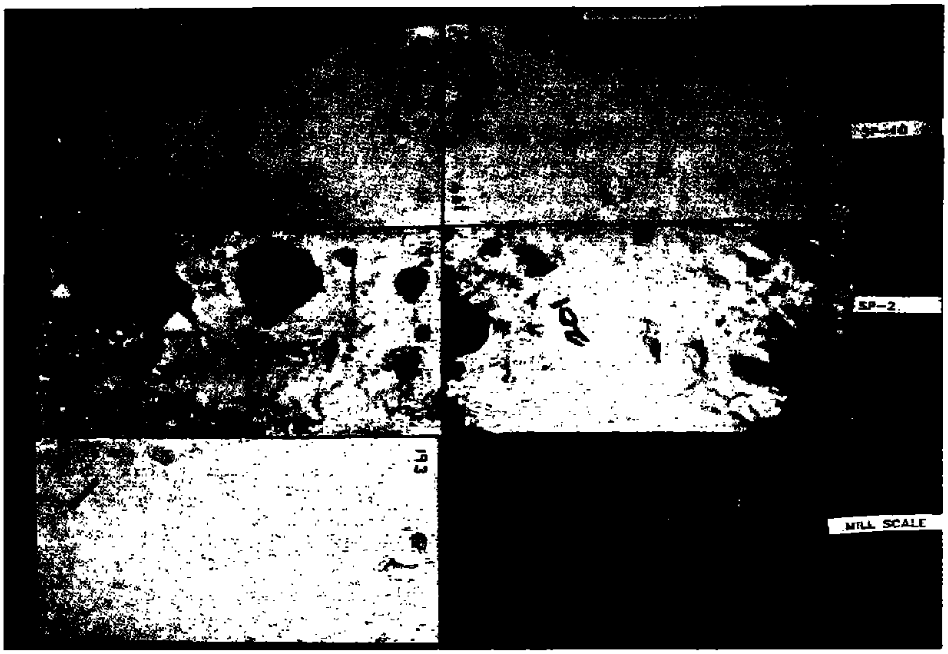


Figure 19. Organic Zn/epoxy/urethane system after 6 months cyclic brine immersion testing.

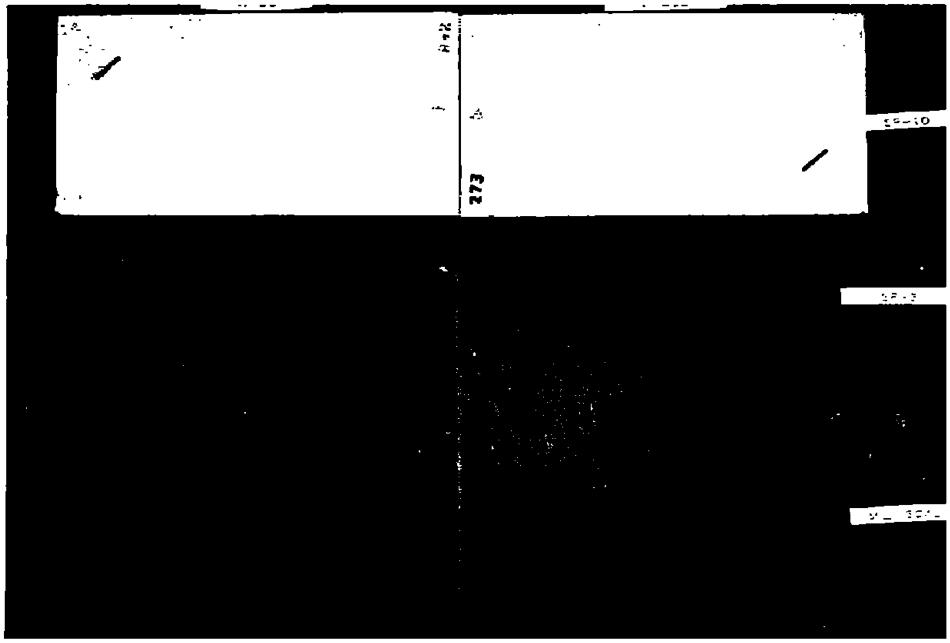
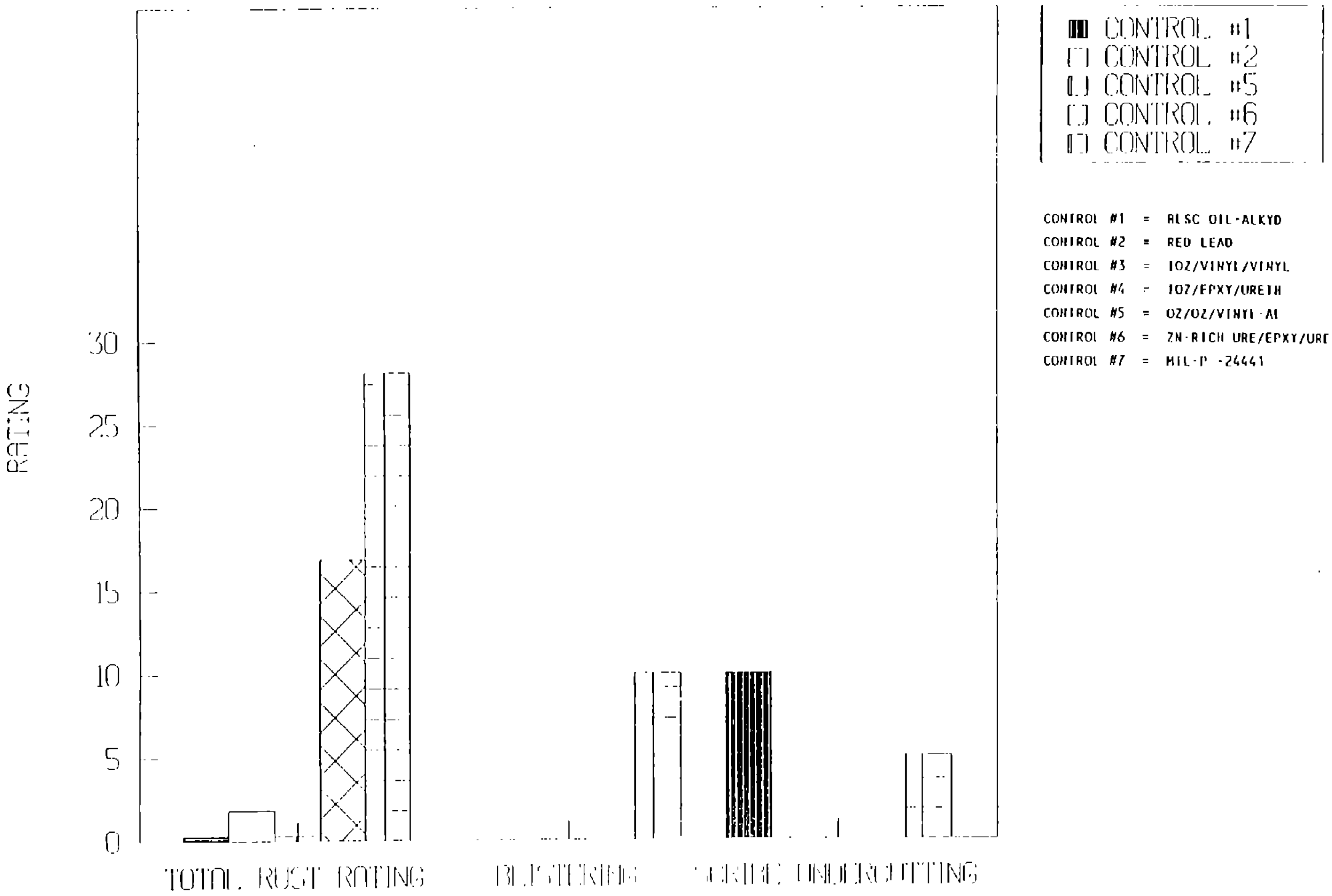


Figure 20. Inorganic Zn/epoxy/urethane system after 6 months cyclic brine immersion testing.



CONTROL #1 = ALSC OIL-ALKYD
CONTROL #2 = RED LEAD
CONTROL #3 = IOZ/VINYL/VINYL
CONTROL #4 = IOZ/EPXY/URETH
CONTROL #5 = OZ/OZ/VINYL-AL
CONTROL #6 = ZN-RICH URE/EPXY/URE
CONTROL #7 = MIL-P-24441

Figure 21. A36 test panels; performance rating for all tests, salt fog tests, SP-2, (control systems).

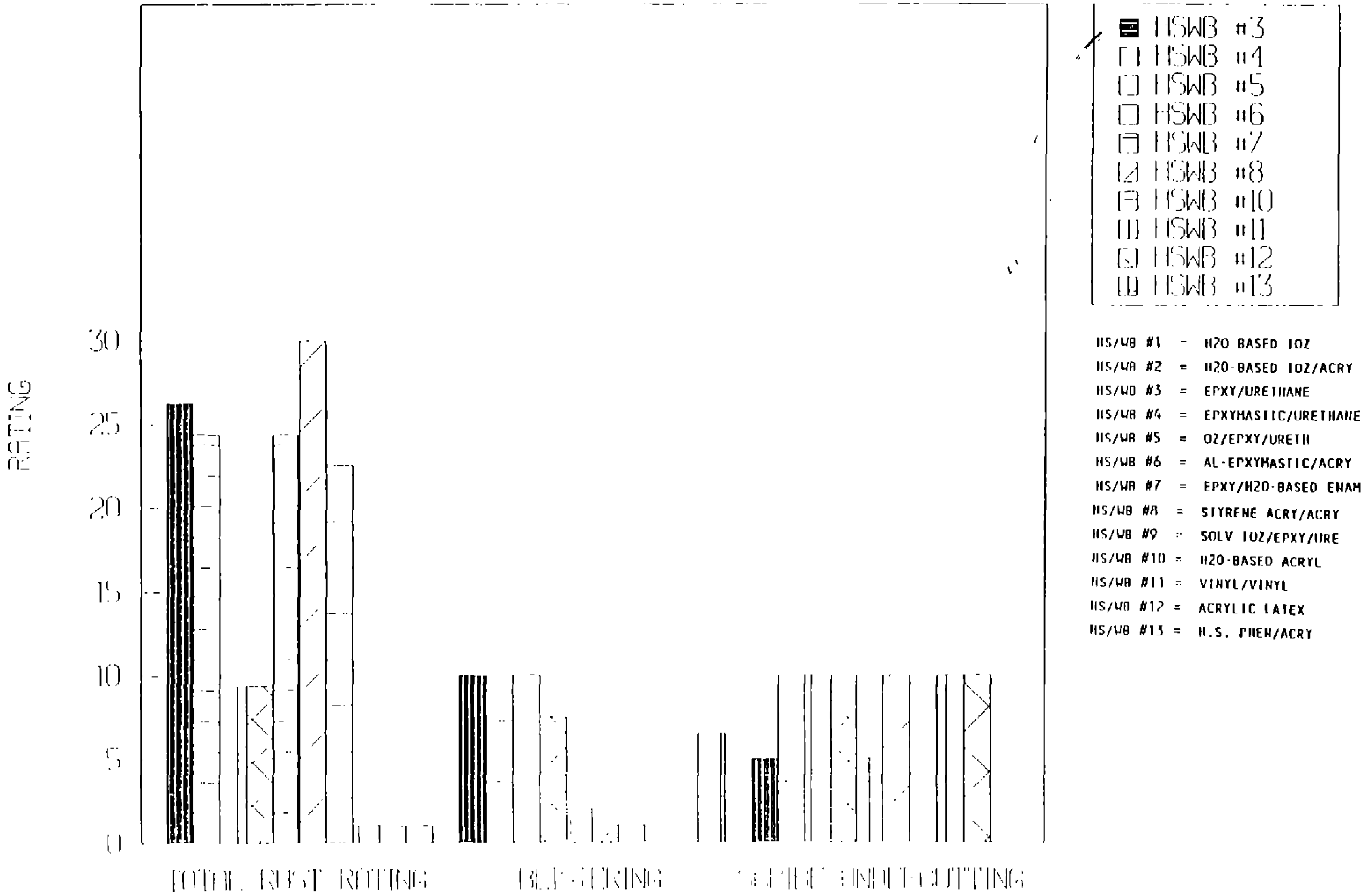


Figure 22. A36 test panels; performance rating for all tests, salt fog tests, SP-2, (HS/WB systems).

waterborne acrylic latex system (system 12). This system was also the poorest performer in the other accelerated testing.

Comparison of Data From Cyclic Salt Fog, Cyclic Brine Immersion, and Natural Marine Exposure

Since the purpose of the laboratory testing phase of this program was to use a battery of accelerated tests to determine a reasonable long-term test matrix, it is interesting and necessary to directly compare the results of the various tests.

In general, (with a few notable exceptions) the relative performance of any particular coating system in one accelerated test reflects the relative performance of that same system in the other accelerated tests. This fact is demonstrated by figures 23 to 27. These figures plot the performance, in terms of rust rating, of the control and high solids/waterborne systems over SP-10 and SP-2 surfaces for the cyclic salt fog, the cyclic brine immersion, and the natural exposure (Sea Isle) tests through 6 months of exposure. In the majority of instances, the coatings that did poorly in the salt fog testing also did poorly in the brine immersion testing. The data obtained from the natural exposure panels is less pronounced due to the 6-month test duration; however, it is significant that the worst performing coating in the accelerated tests, high solids/waterborne system 12 [acrylic latex], was also the only coating that failed in 6 months of natural exposure. This data is shown clearly on figure 25.

Similar trends can be seen in figures 26 and 27 for SP-2 surfaces. In general, the best performers performed best in both accelerated tests. Likewise, the worst performers generally performed worst in both accelerated tests.

The notable exceptions to the above observations are control systems 1 and 2 [the lead-based systems] (see figure 23), and high solids/waterborne systems 10 and 11 [the water-based acrylic and vinyl/vinyl systems, respectively] (see figure 25). All of these systems showed poor performance in the salt fog testing, but improved performance under brine immersion. In general, it is not surprising to see a lack of correlation in failure rates and failure modes between various accelerated test methods.

For systems that show inconsistent behavior in the separate accelerated tests, the unified rating system used in the following section to provide an overall ranking for the coating systems may be somewhat skewed. For example, the effect of the poor performance of the lead-based and water-based acrylic systems in the cyclic salt fog testing brings the overall rating for these coating systems down to some degree. This is true

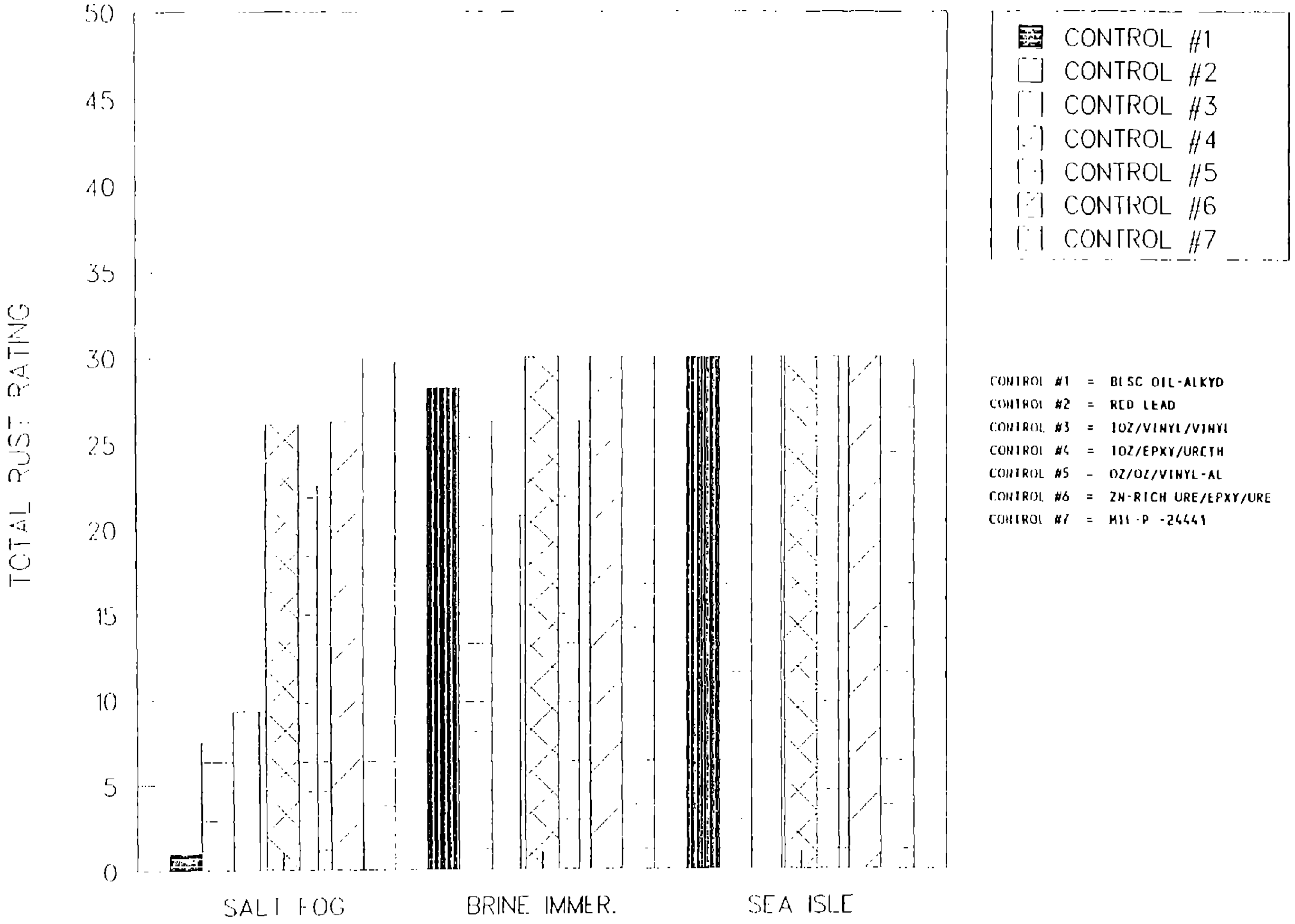


Figure 23. A36 test panels; performance rating for all tests, (control systems).

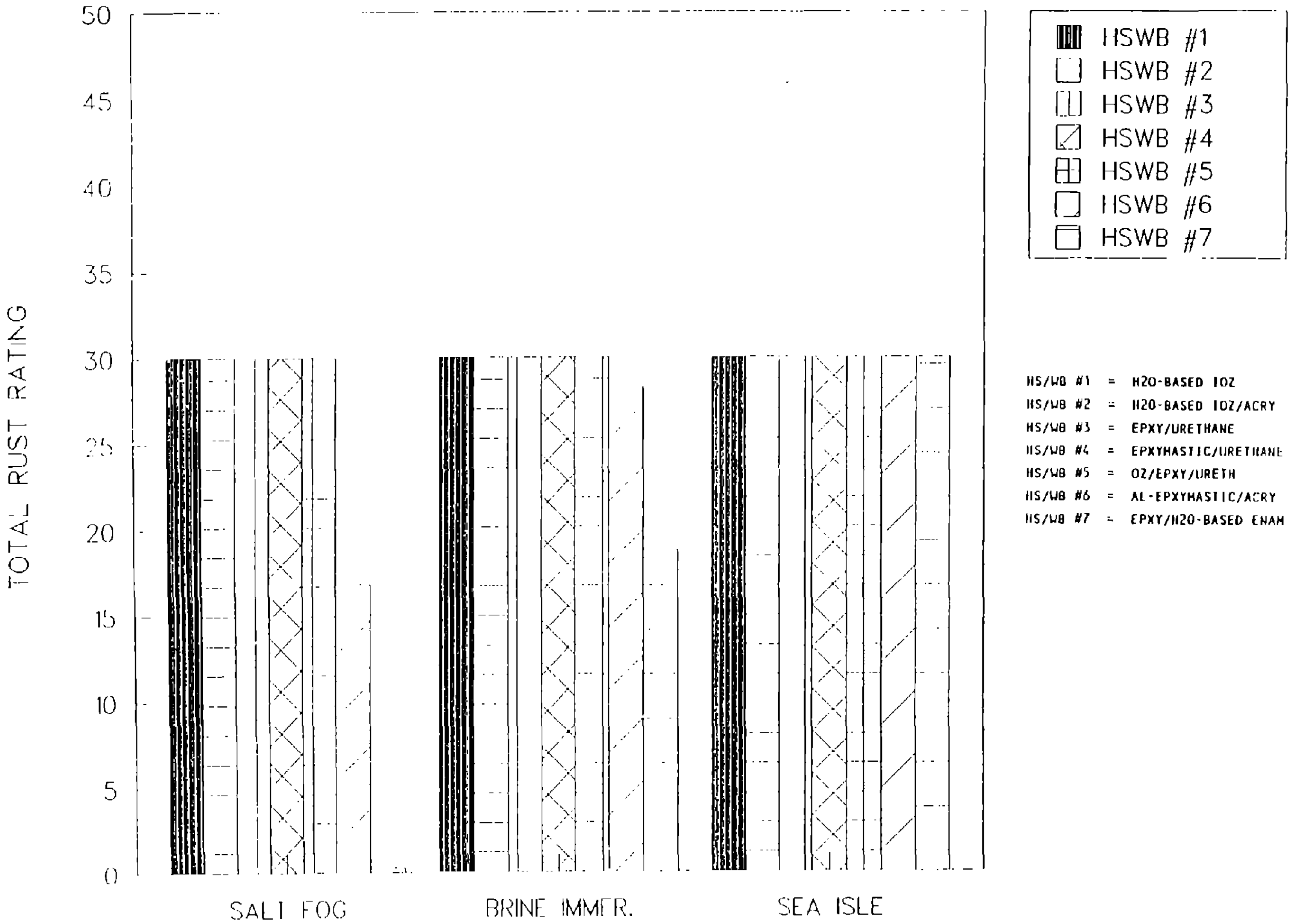


Figure 24. A36 test panels; performance rating for all tests, (HS/WB systems 1-7).

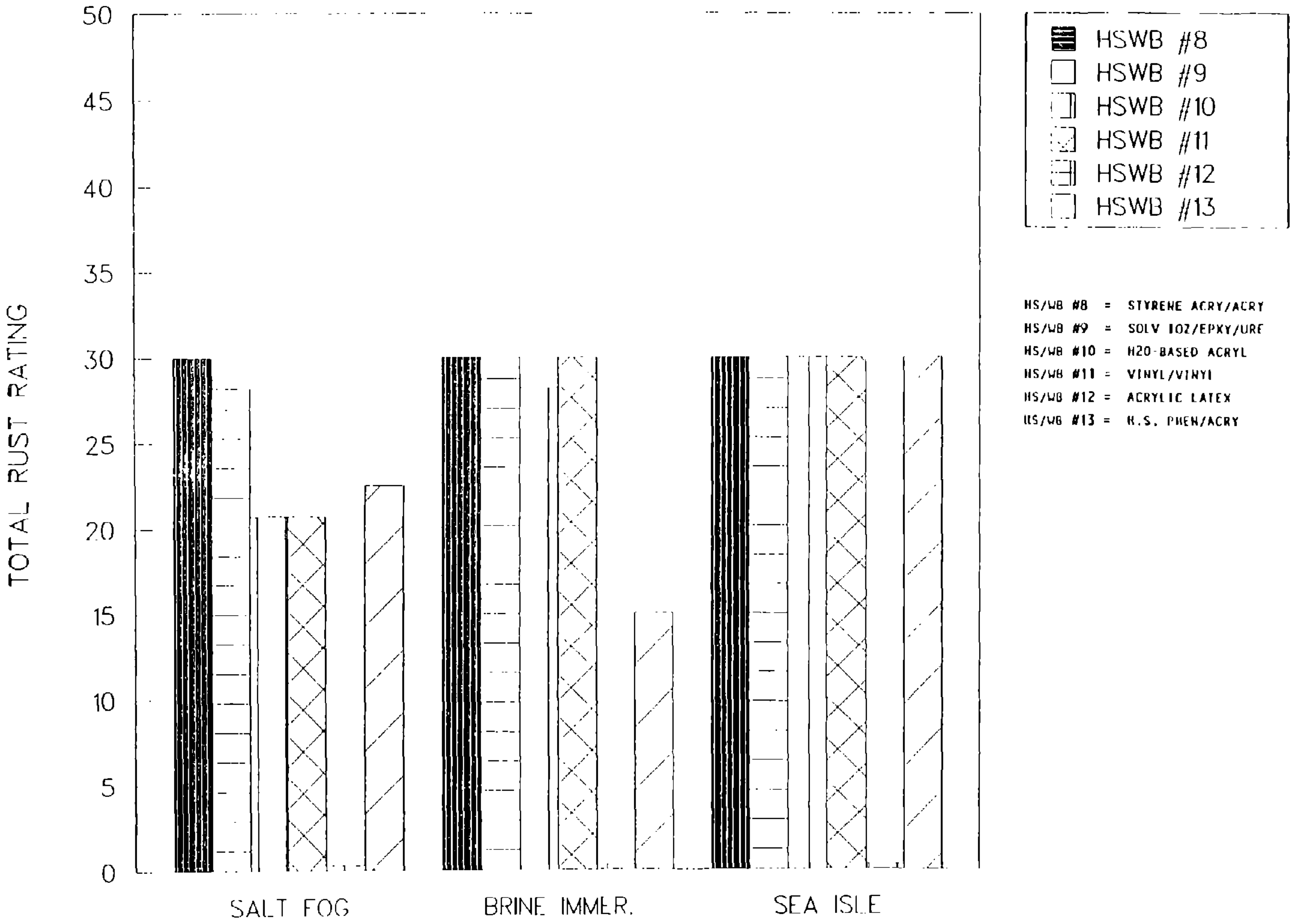
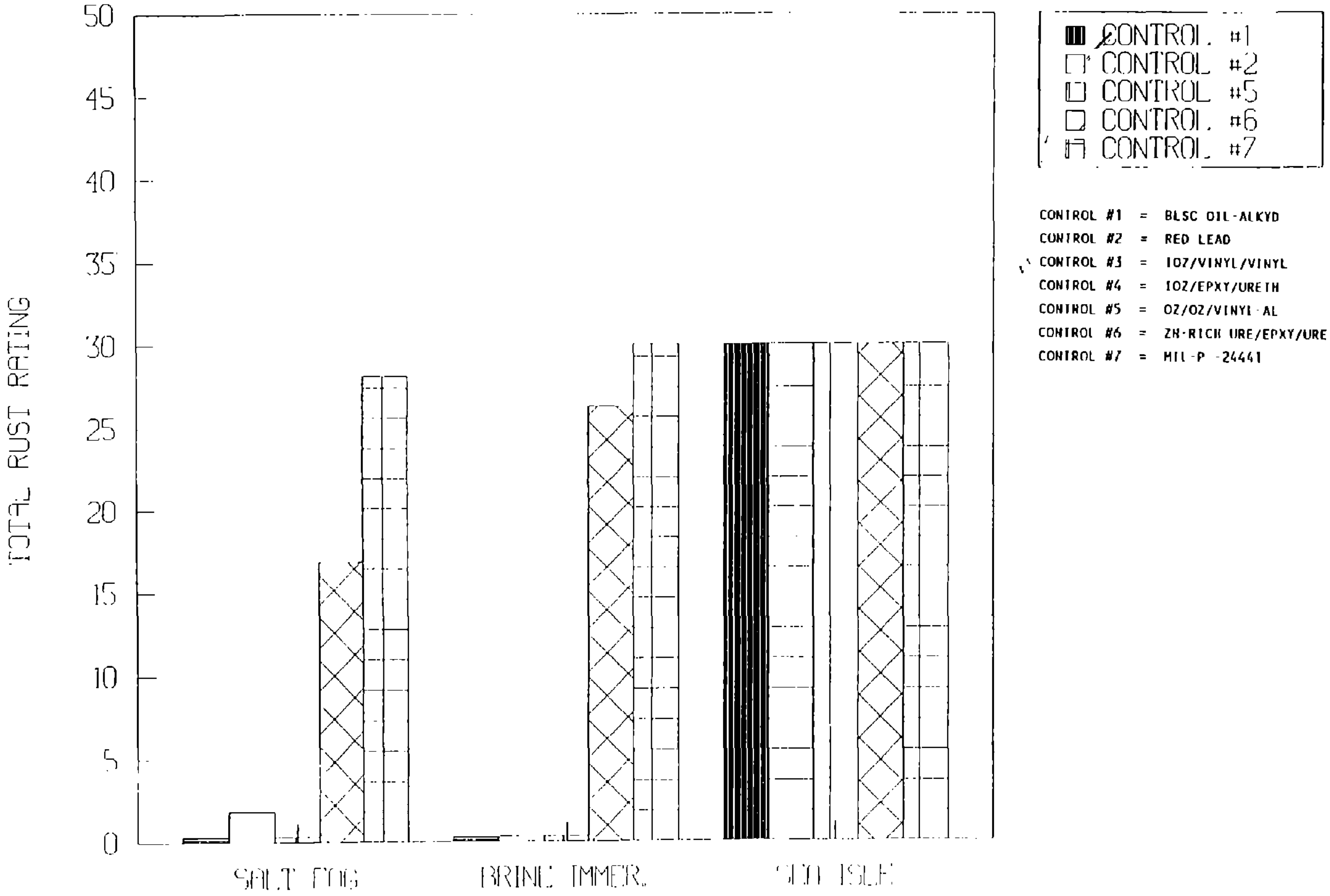


Figure 25. A36 test panels; performance rating for all tests, (HS/WB systems 8-13).



CONTROL #1 = BLSC OIL-ALKYD
CONTROL #2 = RED LEAD
CONTROL #3 = IOZ/VINYL/VINYL
CONTROL #4 = IOZ/EPXY/URETH
CONTROL #5 = OZ/OZ/VINYL-AL
CONTROL #6 = ZN-RICH URE/EPXY/URE
CONTROL #7 = MIL-P -24441

Figure 26. A36 test panels; performance rating for all tests, SP-2 surface prep., (control systems).

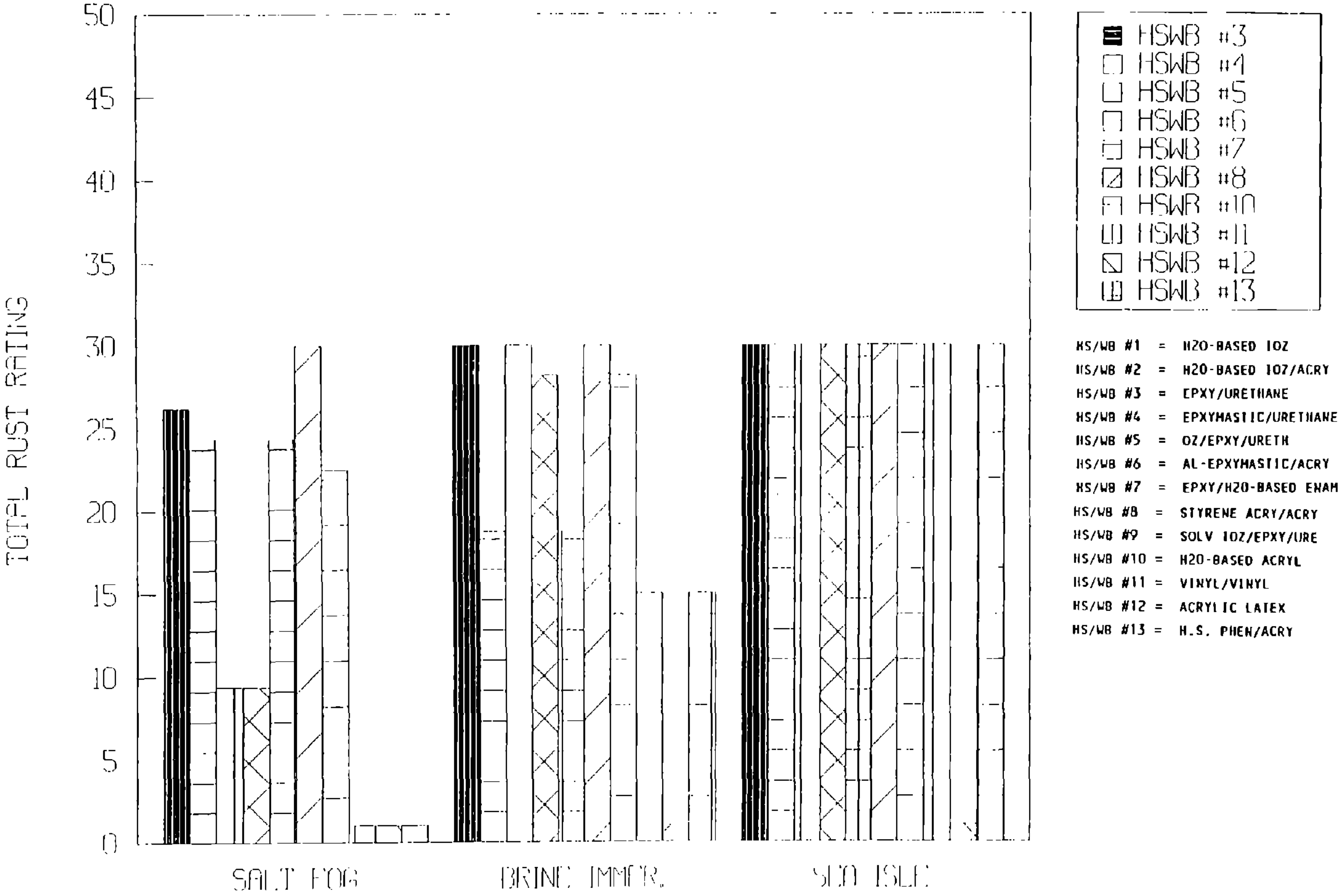


Figure 27. A36 test panels; performance rating for all tests, SP-2 surface prep., (HS/WB systems).

even though the performance of these systems in salt fog testing does not correlate with the performance of the same systems in the natural environment. Inconsistencies such as these are the tradeoff for the expedient results provided by accelerated test methods. These inconsistencies may often be compensated for through the use of experience and good engineering judgment in the selection of coatings.

Overall Results - Unified Rating System

The overall ratings for the systems tested are provided as figures 28 to 34.

Control Systems

Overall, as indicated by figures 28 and 29 (for SP-10 and SP-2 surfaces, respectively), the best performing control systems were:

6. Zinc-rich urethane/epoxy/urethane.
7. MIL-P-24441, polyamide epoxy.

High Solids/Waterborne Systems

Overall, as indicated by figures 30 and 31, the best performing high solids or waterborne test systems applied over an SP-10 surface were:

1. Water-based inorganic zinc.
2. Water-based inorganic zinc/acrylic.
3. Epoxy/urethane.
4. Epoxymastic/urethane.
5. Organic zinc/epoxy/urethane.
8. Styrene acrylic/acrylic.
9. Solvent-based (low VOC) inorganic zinc/epoxy/urethane.

The poorest performing systems over SP-10 were:

7. Epoxy/water-based enamel.
12. Acrylic latex.

As indicated by figure 32, the best performing high solids or waterborne systems over an SP-2 surface were:

3. Epoxy/urethane.
4. Epoxymastic/urethane.
5. Organic zinc/epoxy/urethane.
6. Aluminum epoxymastic/acrylic.
7. Epoxy/water-based enamel.
8. Styrene acrylic/acrylic.
10. Water-based acrylic.

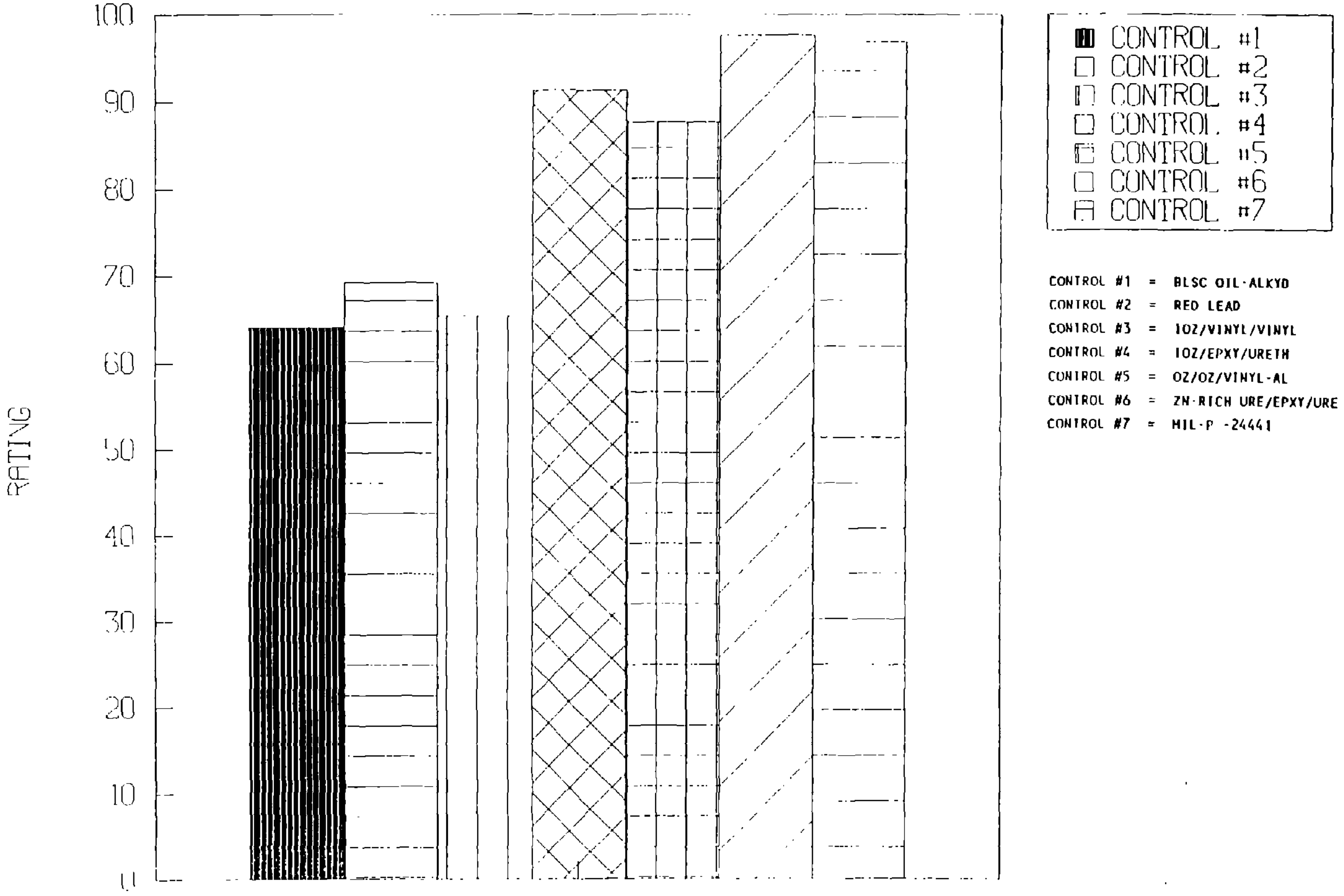
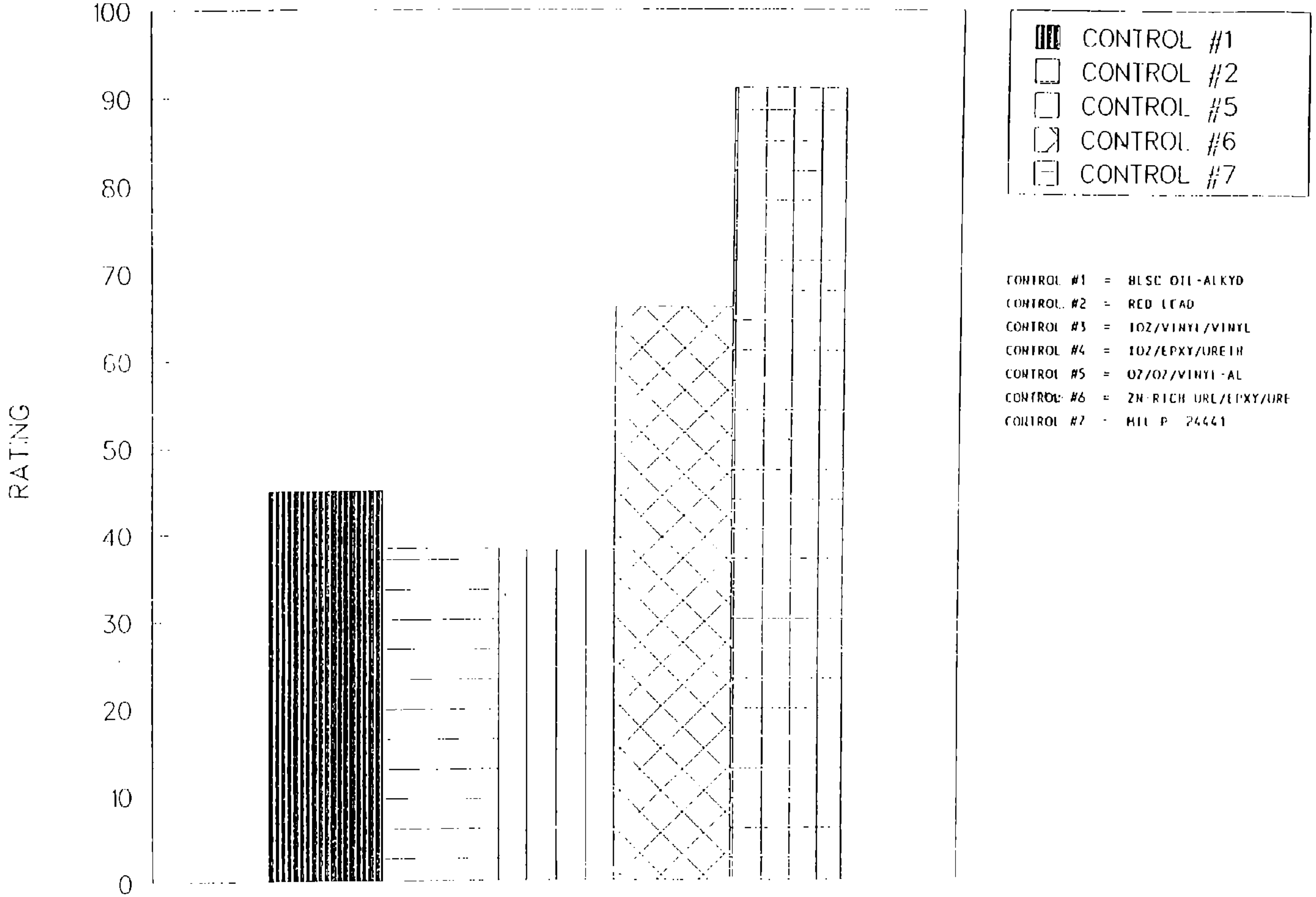


Figure 28. A36 test panels; performance rating for all tests, SP-10 surface prep., (control systems).



CONTROL #1 = BASIC OIL-ALKYD
CONTROL #2 = RED LEAD
CONTROL #3 = IOZ/VINYL/VINYL
CONTROL #4 = IOZ/EPXY/URETH
CONTROL #5 = OZ/OZ/VINYL-AL
CONTROL #6 = ZN-RICH URE/EPXY/URE
CONTROL #7 - MIL P 24441

Figure 29. A36 test panels; performance rating for all tests, SP-2 surface prep., (control systems).

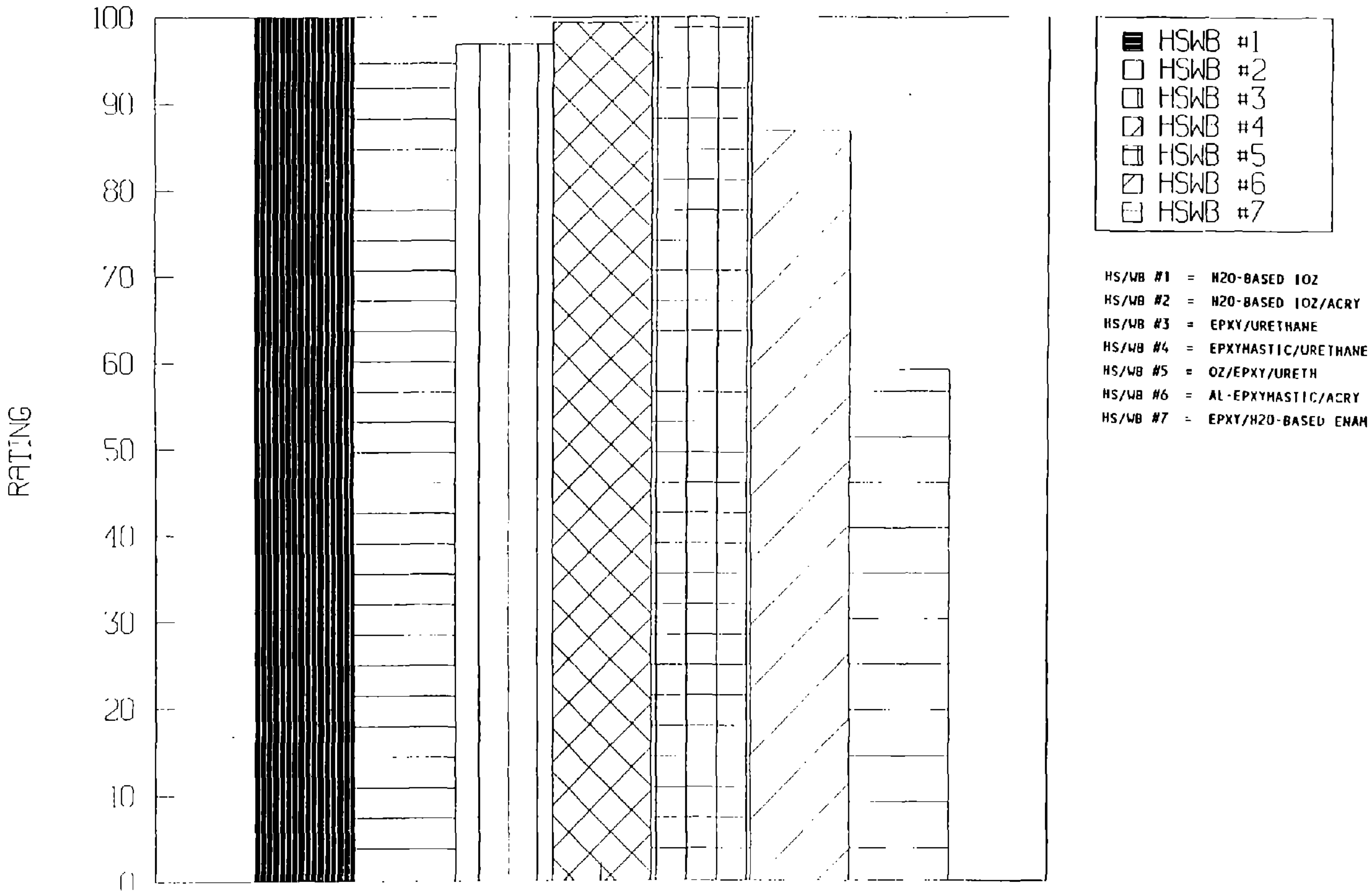


Figure 30. A36 test panels; performance rating for all tests, (HS/WB systems 1-7).

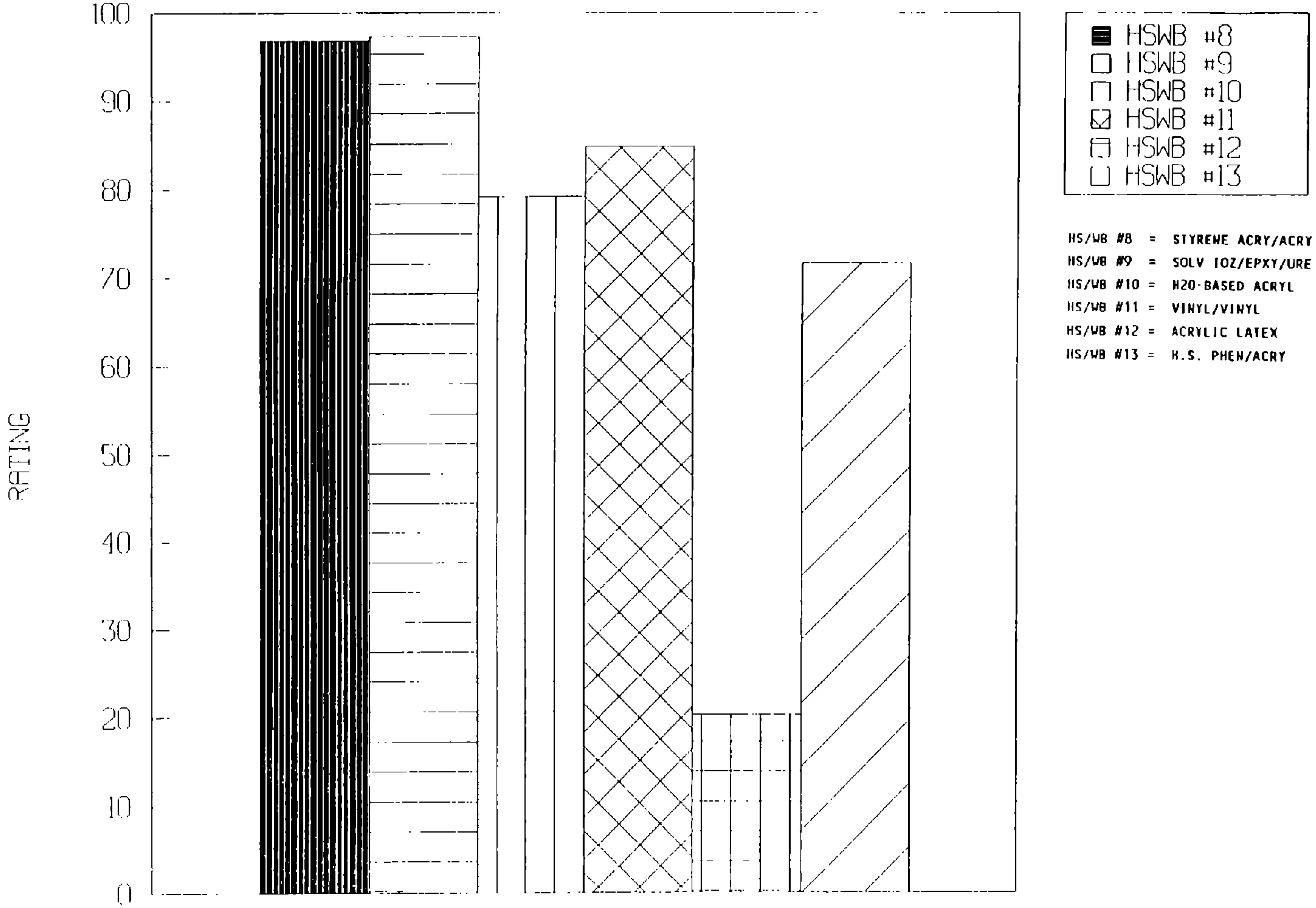
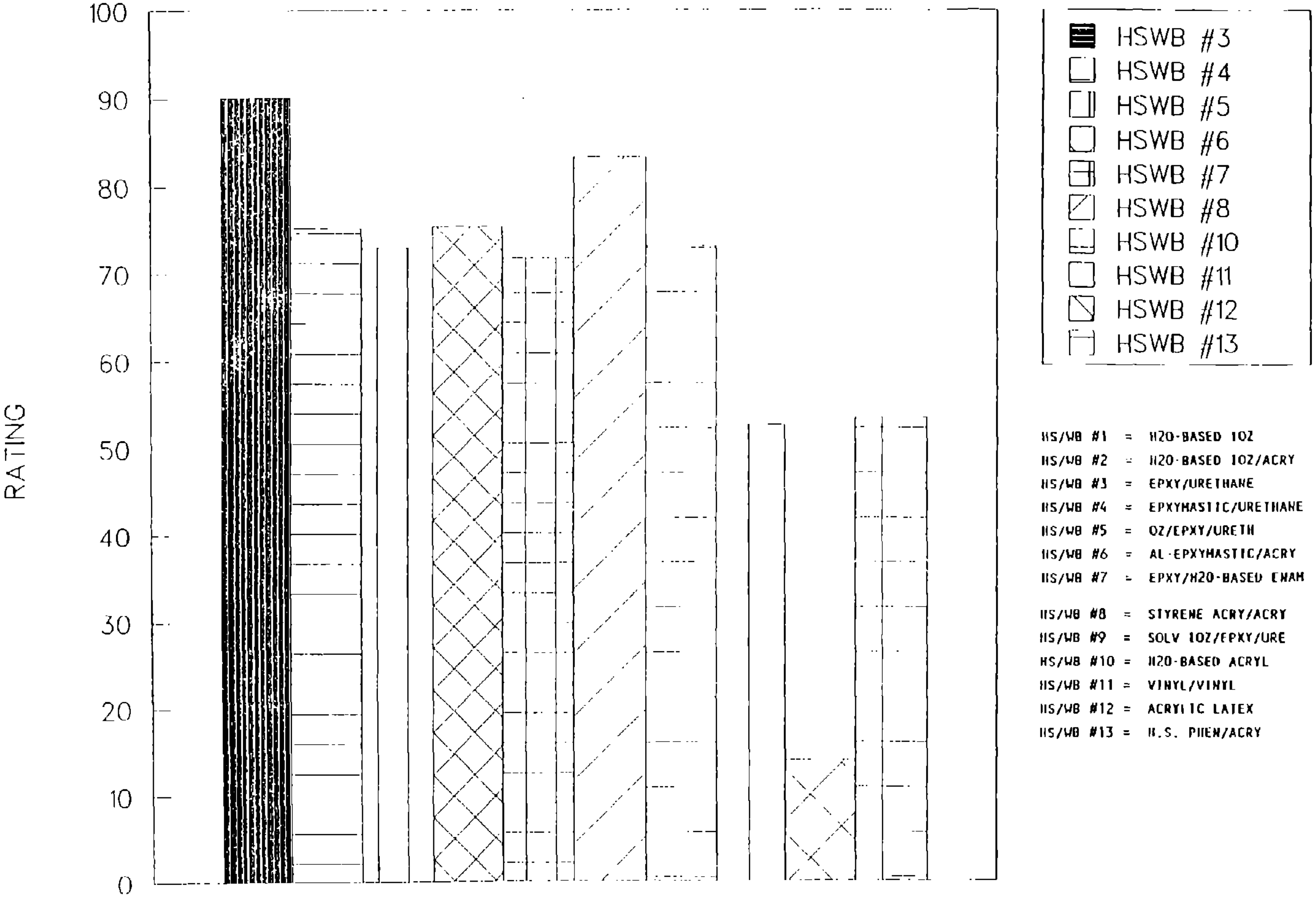


Figure 31. A36 test panels; performance rating for all tests, (HS/WB systems 8-13).



HS/WB #1 = H2O-BASED IOZ
HS/WB #2 = H2O-BASED IOZ/ACRY
HS/WB #3 = EPXY/URETHANE
HS/WB #4 = EPXYMASTIC/URETHANE
HS/WB #5 = OZ/EPXY/URETH
HS/WB #6 = AL-EPXYMASTIC/ACRY
HS/WB #7 = EPXY/H2O-BASED ENAM
HS/WB #8 = STYRENE ACRY/ACRY
HS/WB #9 = SOLV IOZ/EPXY/URE
HS/WB #10 = H2O-BASED ACRYL
HS/WB #11 = VINYL/VINYL
HS/WB #12 = ACRYLIC LATEX
HS/WB #13 = H.S. PHEN/ACRY

Figure 32. A36 test panels; performance rating for all tests, SP-2 surface prep., (HS/WB systems).

Overall, the acrylic latex (system 12) performed very poorly over an SP-2 surface.

Powder Coating/Metallized Systems

Figures 33 and 34 shows the overall unified rating system results for the powder coated and metallized systems. With the exception of flame sprayed powder epoxy (system 10) and TGIC-cured polyester (system 11), all powder coating and metallized systems had excellent overall ratings.

Adhesion Testing

The complete results of the laboratory adhesion testing performed on each coating system are contained in appendix C.

Figures 35 through 37 present the results of the adhesion testing performed on each coating system. This data was obtained using a simple "pull-off" adhesion test apparatus as outlined in ASTM D-4541. For each coating system, three adhesion tests were performed. These tests were performed; before testing, to acquire baseline adhesion data; after cyclic salt fog testing, to determine the effect, if any, of the salt fog testing on coating adhesion; and, after cyclic brine immersion testing, to determine the effect of brine immersion on the adhesion of each coating system.

In figures 35 through 37, the load at failure is given on the vertical axis, while the percentage of coating that failed (as opposed to failure of the adhesive bonding material) is given at the top of each bar in the graphs. Interpretation of the data is semi-quantitative at best and must consider both the load at failure and the percent of coating failed (i.e., disbonded from the substrate).

There are a few interesting points brought out by the adhesion test data. Figure 35 shows the adhesion of the control systems. The MIL-P-24441, polyamide epoxy system shows the best overall adhesion characteristics. As is indicated by the graph, this coating system showed very little failure in all three adhesion tests (i.e., the vast majority of the disbondment seen was between the adhesive and the topcoat). This was also one of the best performing control systems in the other testing.

In figures 36 and 37, three of the coating systems showing poor adhesion characteristics are the epoxy/water-based enamel (system 7), the acrylic latex (system 12), and the high solids phenolic/acrylic (system 13). These three systems were also some of the poorer performers in the other testing.

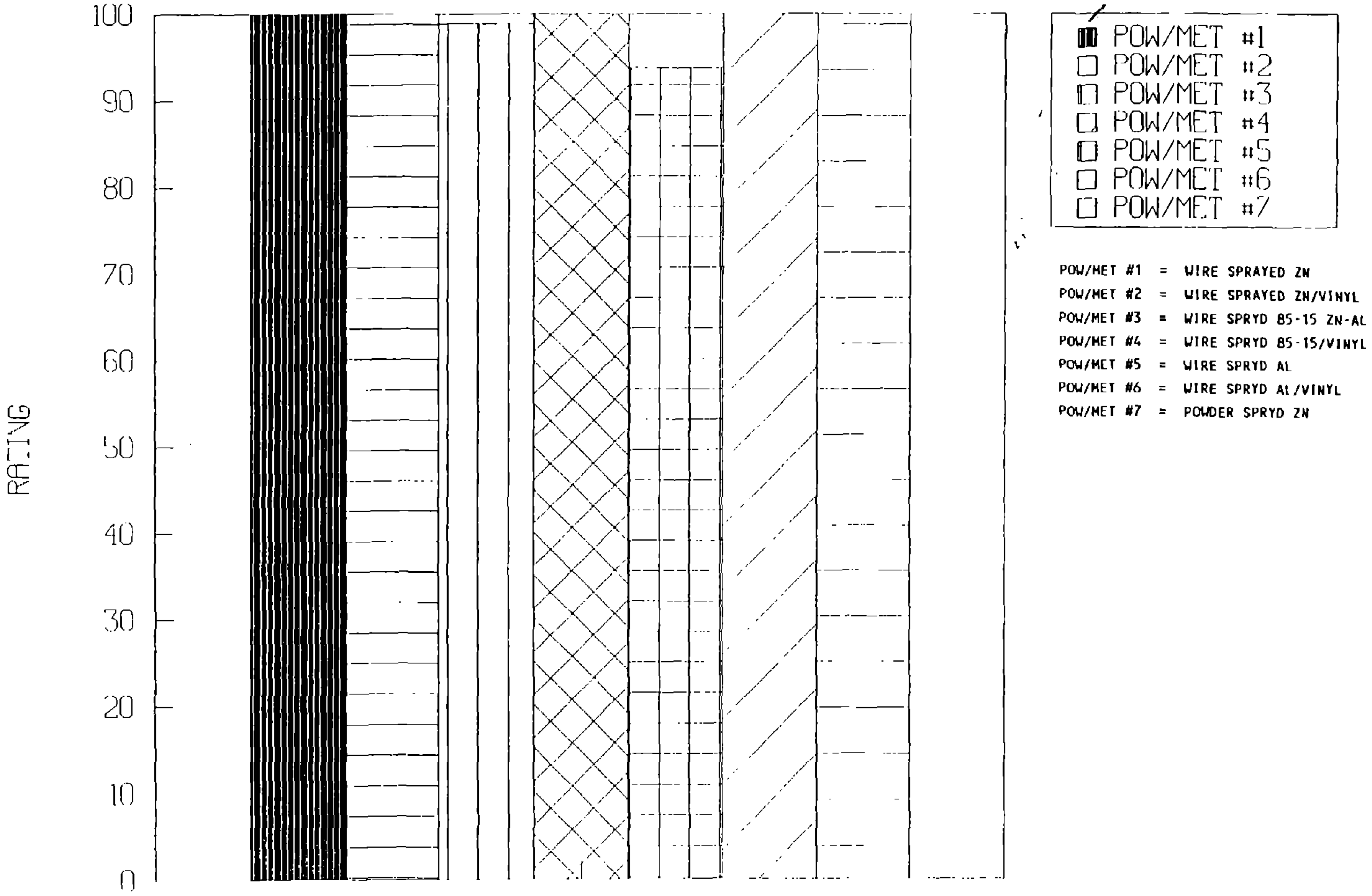


Figure 33. A36 test panels; performance rating for all tests, SP-10 surface prep., (systems 1-7).

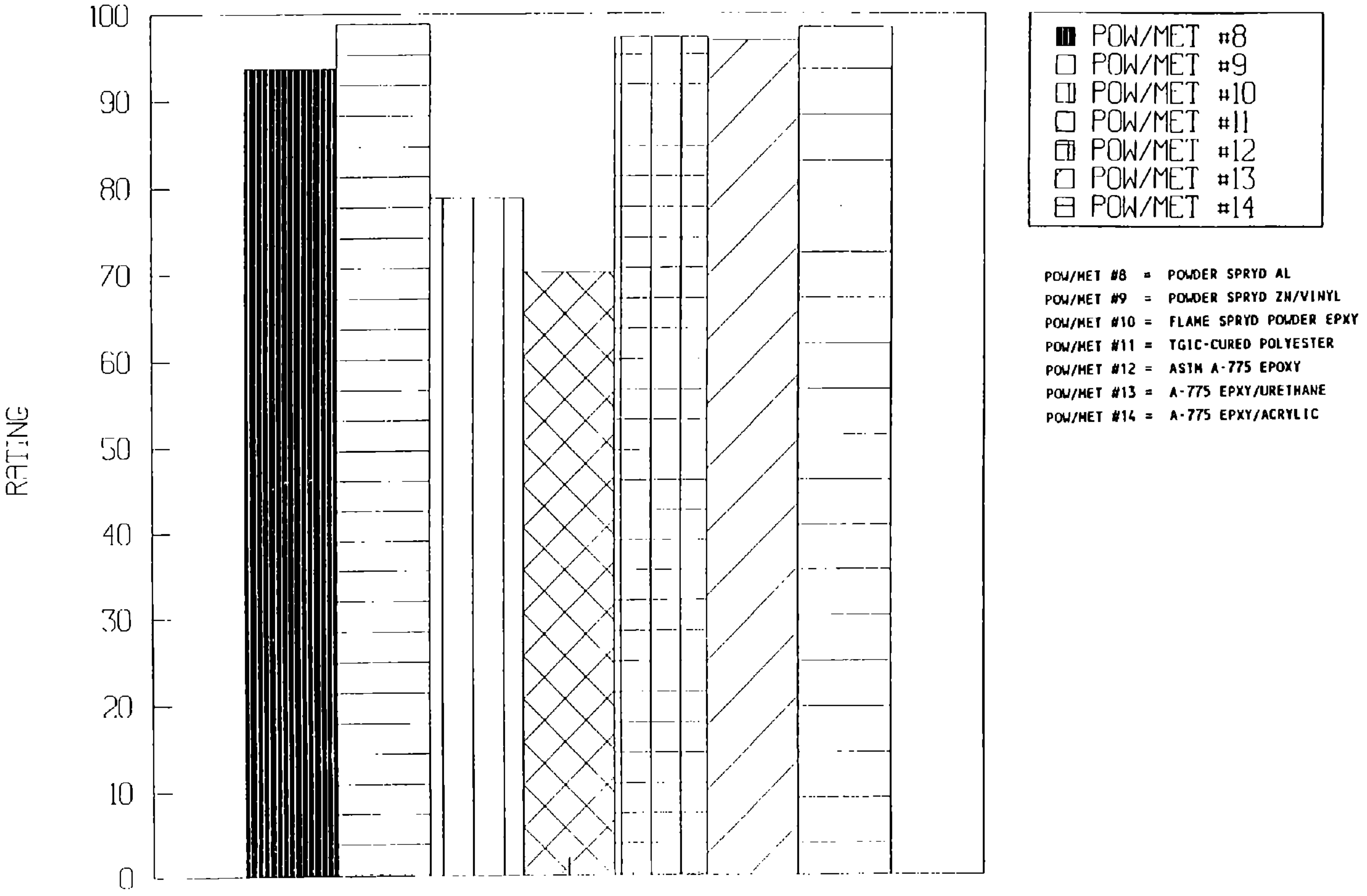


Figure 34. A36 test panels; performance rating for all tests, (systems 8-14).

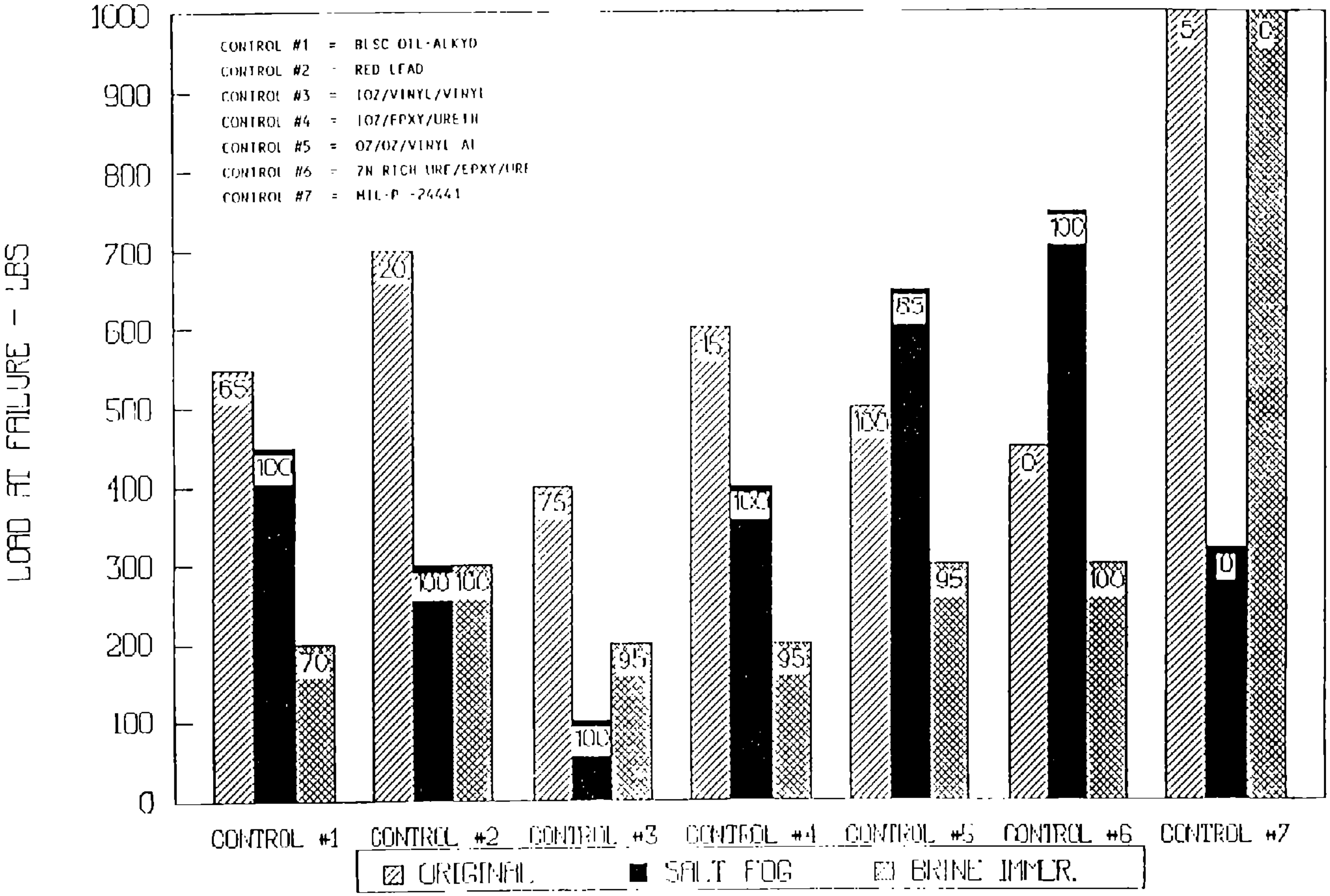


Figure 35. Coating adhesion test results, (control systems).

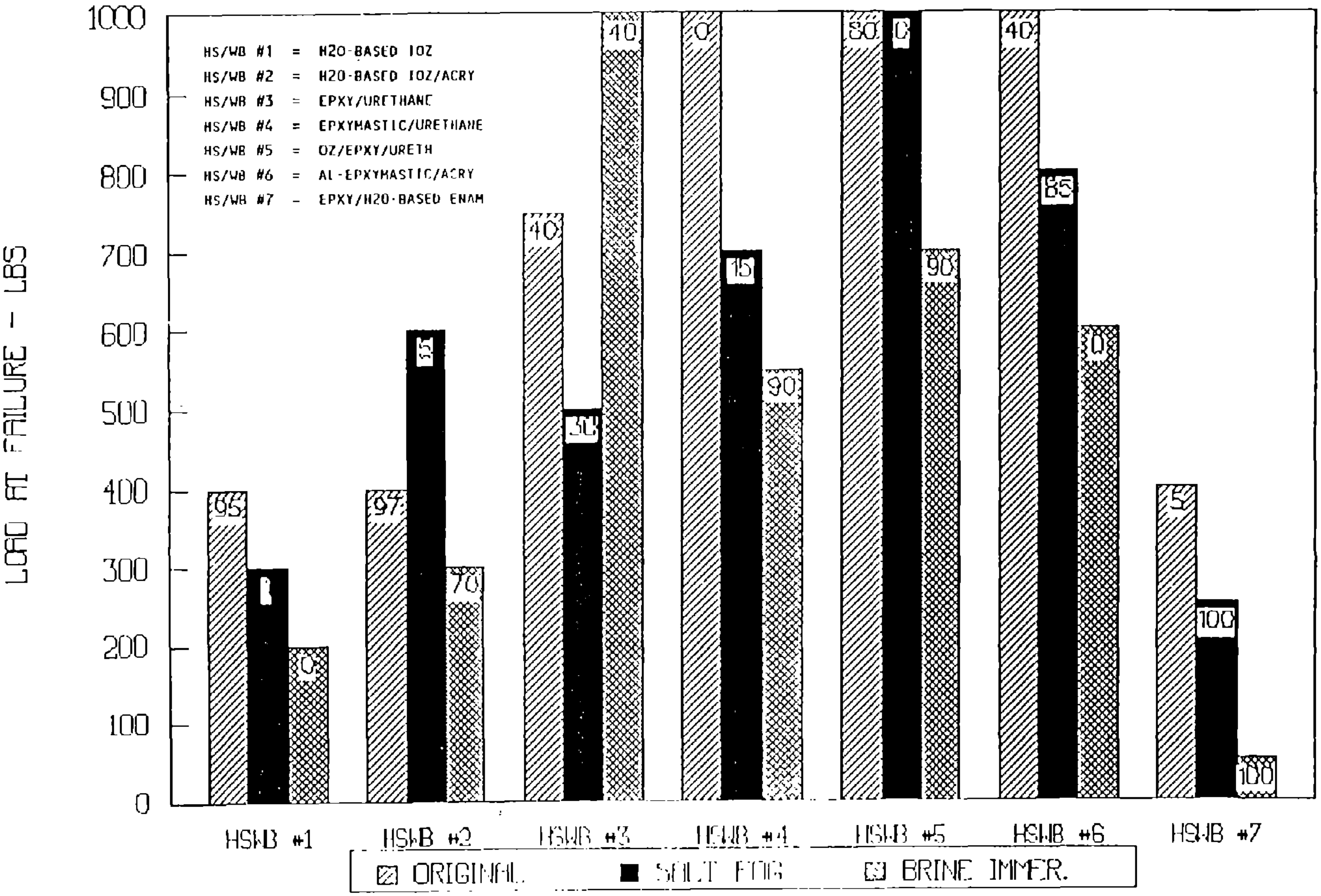


Figure 36. Coating adhesion test results, (HS/WB system 1-7).

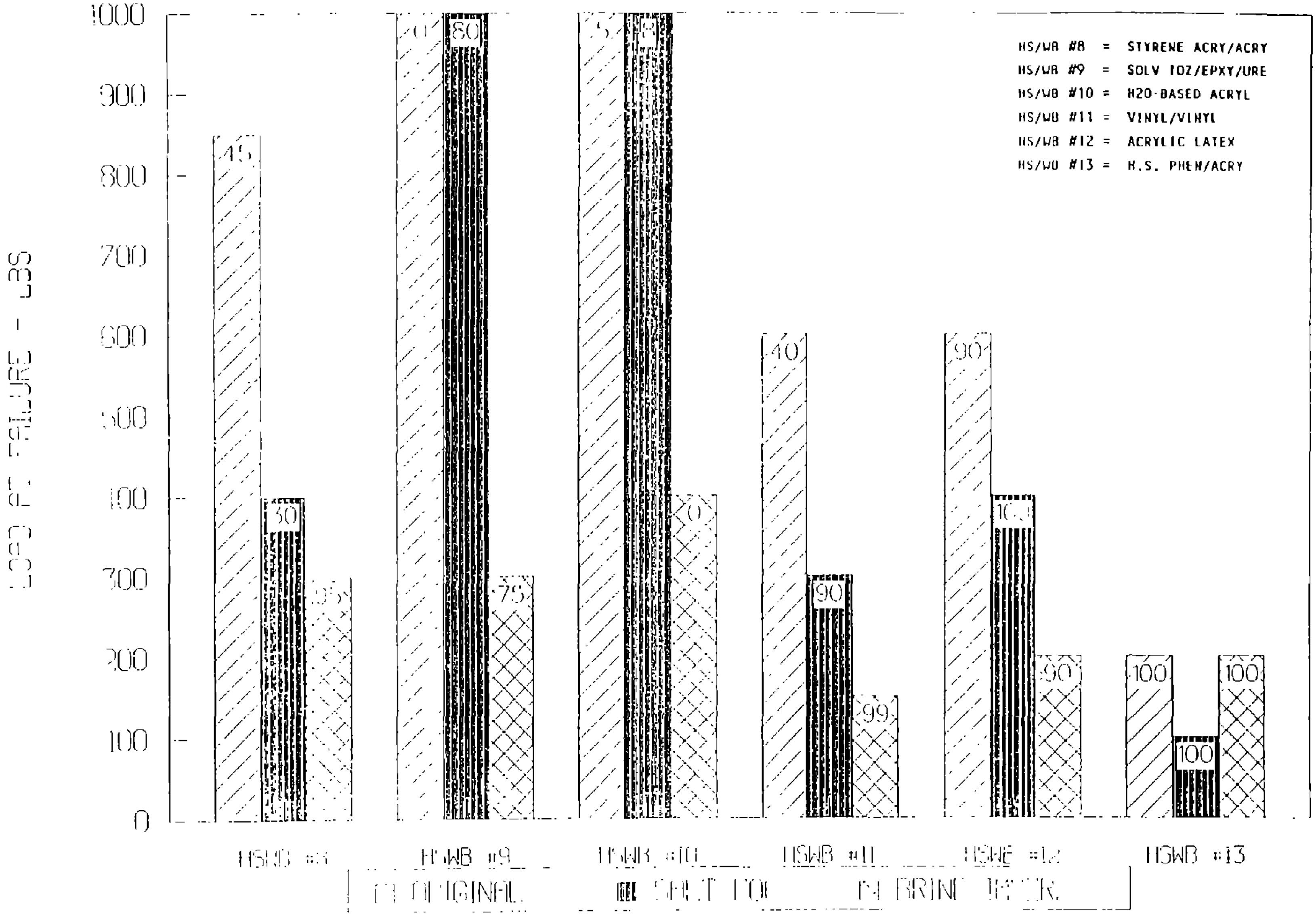


Figure 37. Coating adhesion test results, (HS/WB system 8-13).

Water Penetration Testing

The complete results of the laboratory water penetration testing performed on each coating system are contained in appendix D.

Figures 38 through 41 present the data obtained in the water penetration testing of each coating system.

In figure 38, water appears to rapidly penetrate control systems 3, 4, and 5. These were three of the worst performing control systems. The same data suggest that control systems 1, 2, and 7 were most resistant to water penetration. System 7 (MIL-P-24441) was the best performing control overall. Systems 1 and 2 did not perform well in the accelerated testing; however, these systems did perform quite well in 16 months of natural marine exposure.

In figure 39, HS/WB system 7 appears to be the most susceptible to water penetration. This result is consistent with the poor performance of this system in the testing. In this figure, the erratic behavior of systems 1, 2, and 4 may be attributed to the conductive metallic pigments in the primers of these systems.

Another interesting point concerns the performance of the styrene acrylic/acrylic coating (high solids/waterborne system 8). This was one of the very best performing systems in the other testing; however, as is clear from figure 40, this system showed signs of water penetration after only a few days in test. Since this system is applied comparatively thick (total DFT of 16-32 mils), this water penetration may not have proceeded all the way to the steel substrate in the relatively short test period. In spite of the acceptable performance of this system in the other accelerated tests, the results of the water penetration test suggest eventual failure of this system.

Also in figure 40, the data for systems 11 and 12 cannot be attributed to metallic pigments. This data indicates rapid water penetration into coating systems that also performed poorly in the other testing.

Figure 41 shows the excellent water barrier properties of the powder coatings tested. Also evident is the ineffectiveness of sealing the metallized systems. All sealed metallized systems showed data indicative of rapid water penetration through the sealer topcoat.

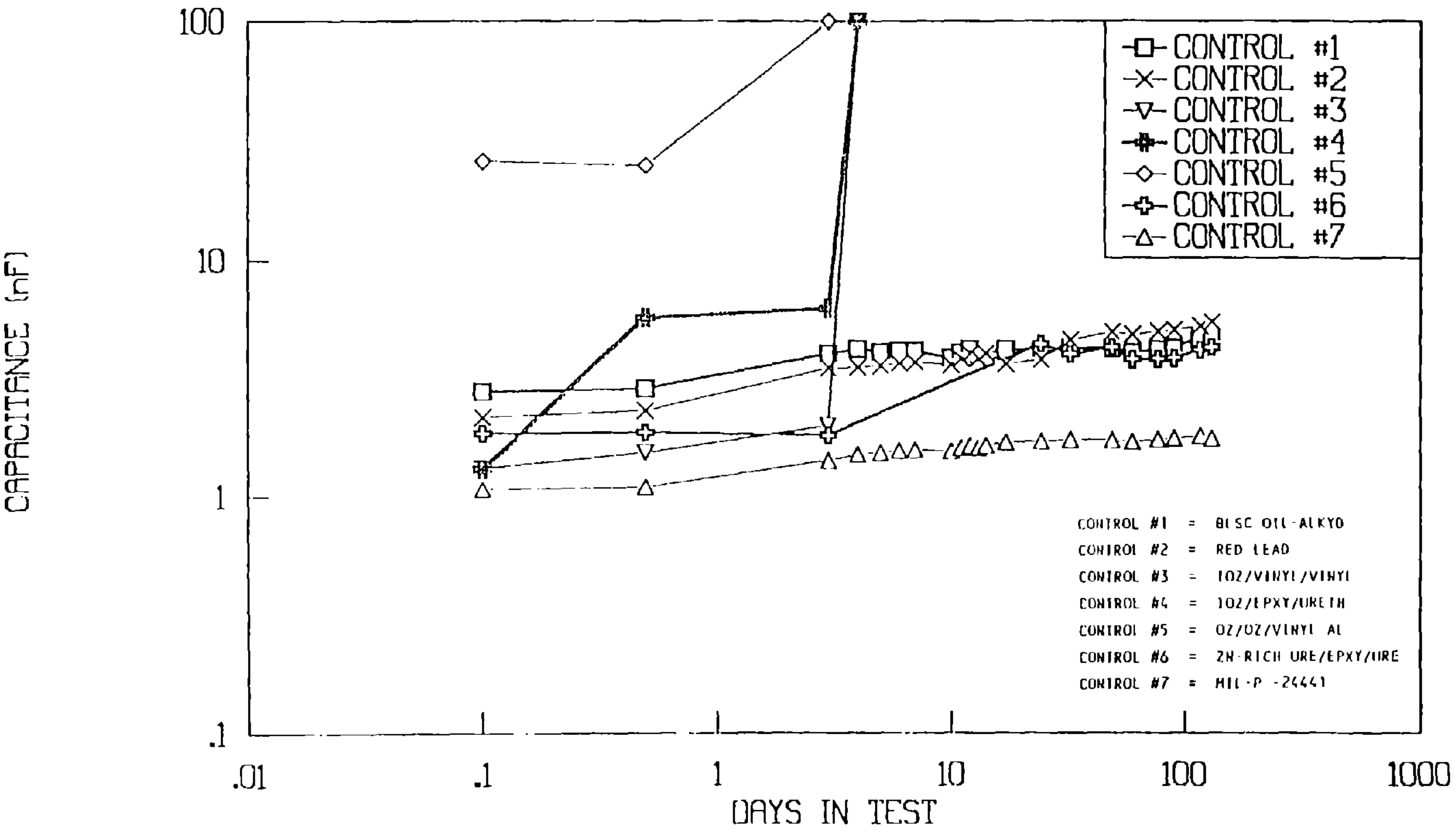


Figure 38. Water penetration tests (Controls 1-7).

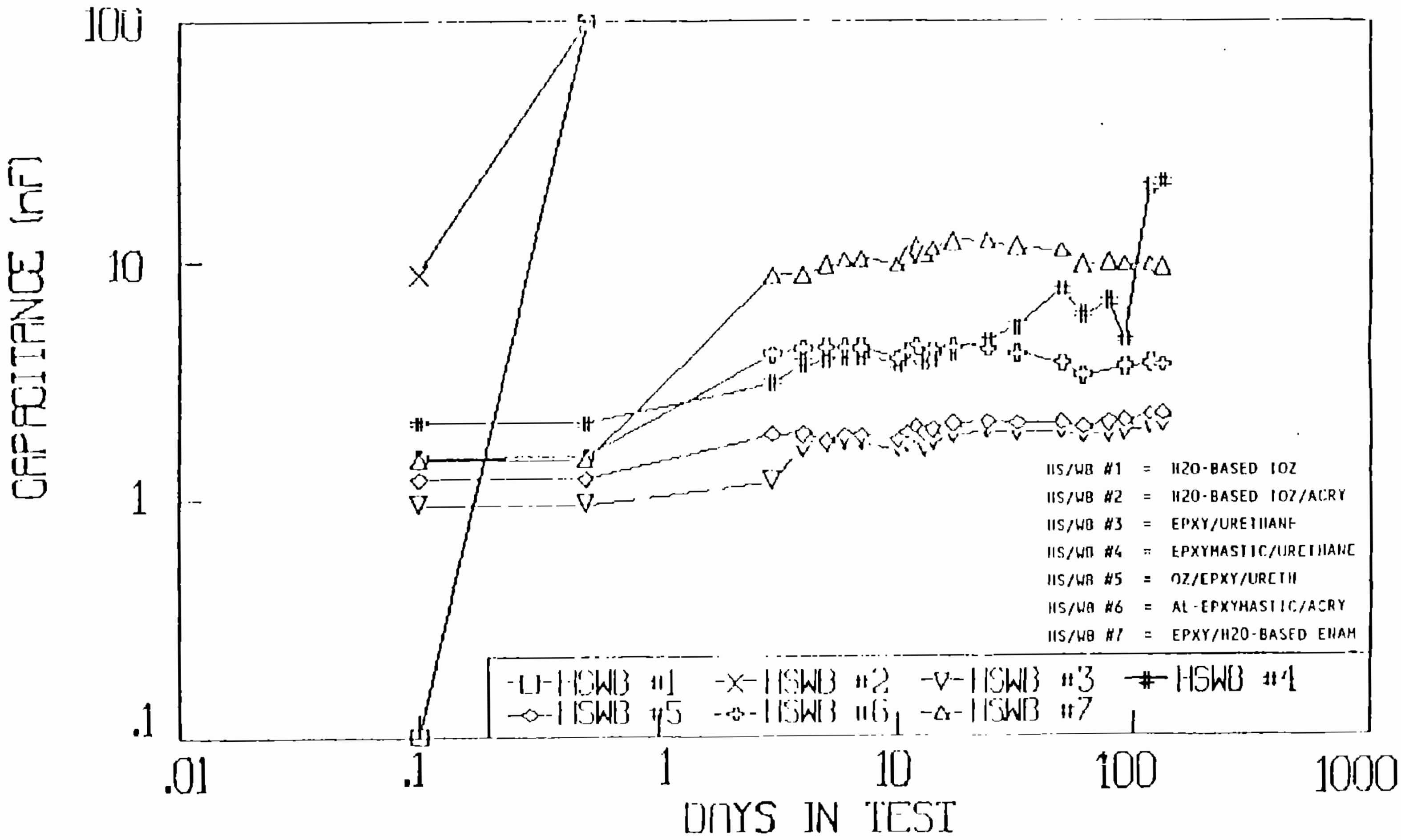


Figure 39. Water penetration tests (HS/WB 1-7).

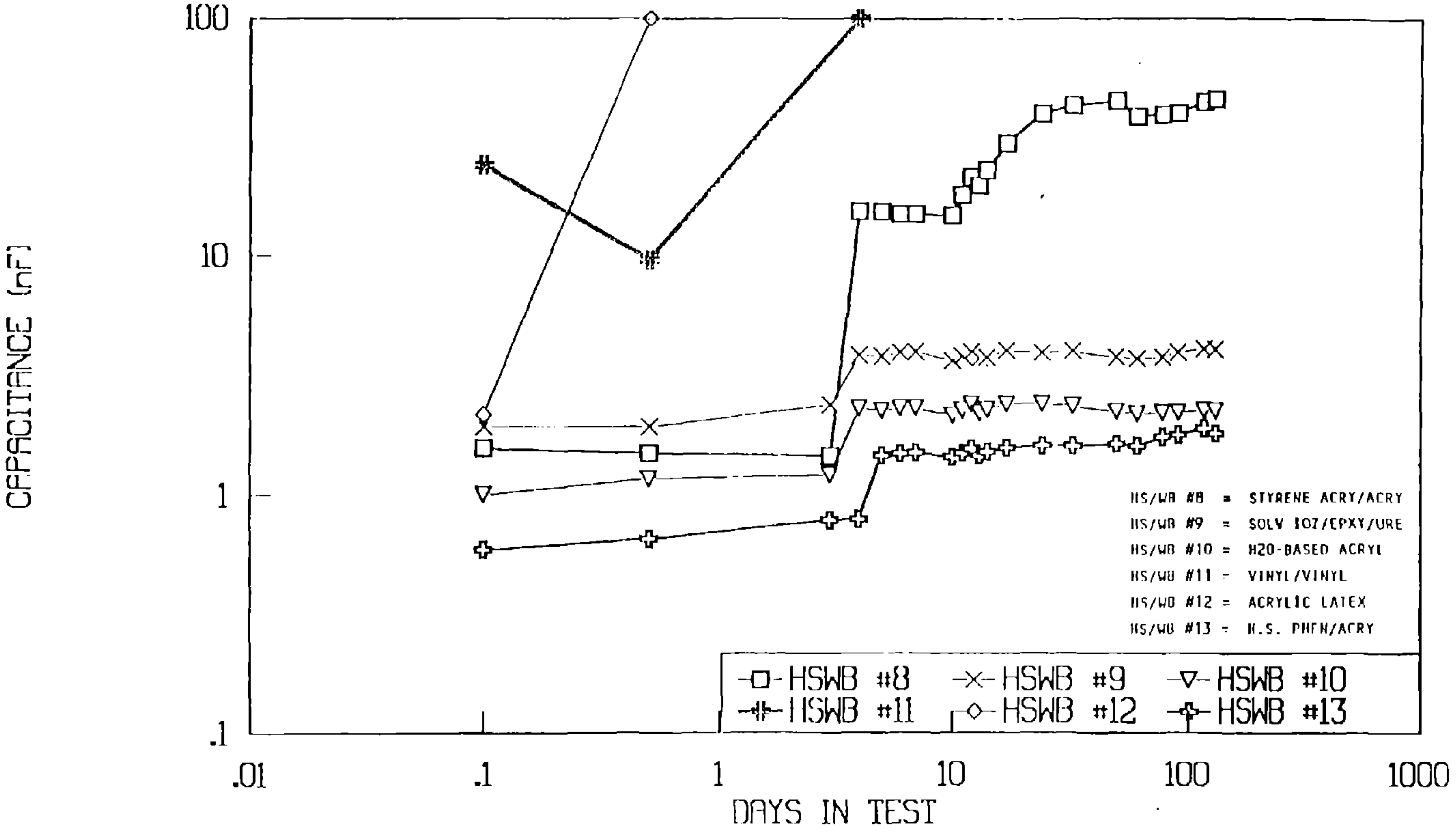


Figure 40. Water penetration tests (HS/WB 8-13).

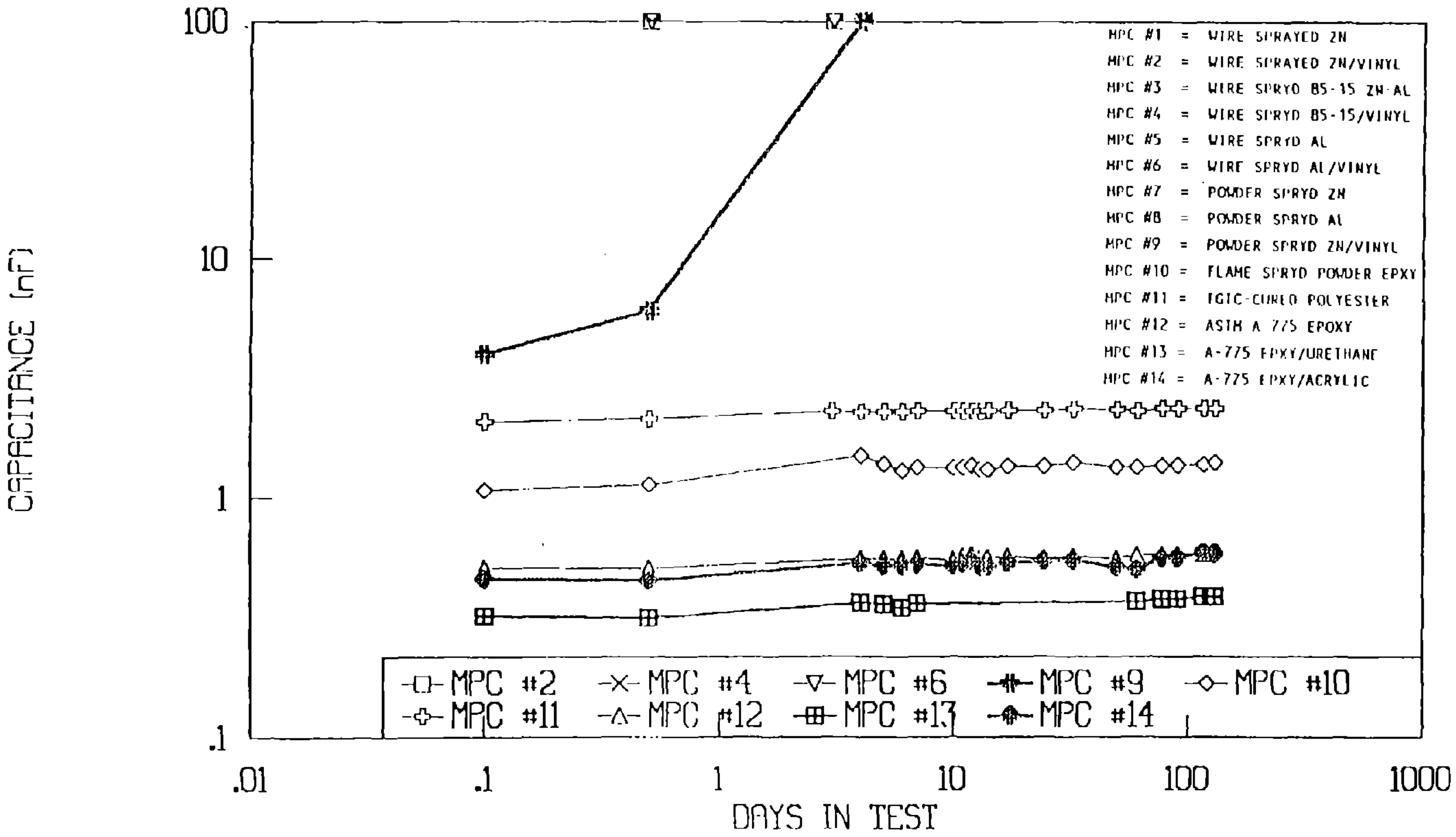


Figure 41. Water penetration tests (Metallized/ powder coatings).

Evaluation of Natural Marine Exposure Panels at 16 Months

After the conclusion of the accelerated testing portion of this program, the natural marine exposure panels were allowed to remain exposed to the natural marine environment at the Sea Isle Site. A further inspection of these panels was performed after 16 months of exposure in the natural marine environment.

The inspection was performed using modified inspection techniques to enhance the overall accuracy of the procedure. The inspection was performed by overlaying a transparent acrylic sheet on the surface of each panel. The areas of deterioration due to rusting were then traced directly onto the transparent sheet. These sheets were placed over a sheet of graph paper divided into 1 mm^2 sections. The number of sections impacted by a traced rust spot was recorded. By dividing the number of squares on the graph paper intersected by rust by the total number of squares, a value for percent degradation of the test panel was determined. The percentage rusted data obtained with this method was compared to data obtained using the traditional ASTM D-610 evaluation technique. The two methods proved to correlate well on a qualitative basis. However, the continuous and objective nature of the results obtained using the rust tracing technique provides a more accurate value for percent degradation than is obtained using the discrete, subjective results of an ASTM D-610 inspection.

Figures 42, 43, and 44 provide the data obtained using the technique described above after 16 months of natural marine exposure. On these figures, the vertical axis represents the percentage of each panel that was rusted. For purposes of comparison with ASTM D-610: 0.0 percent rust = ASTM D 601 #10, 0.03 percent = 9, 0.1 percent = 8, 0.3 percent = 7, and 1.0 percent = 6.

SP-10 Surface - Control Systems

From figure 42, the following systems are the best performing control systems over the 16-month natural exposure period:

1. 3-coat BLSC oil-alkyd.
2. Red lead/red lead/BLSC.
7. MIL-P-24441, polyamide epoxy.

The results for MIL-P-24441 are consistent with the performance of this system in the accelerated tests. However, the lead-based systems, which performed well in the natural environment, performed poorly in the accelerated testing (especially the cyclic salt fog testing).

Control systems 5 [organic zinc/organic zinc/vinyl-Al] and 6 [zinc-rich urethane/epoxy/urethane] did not perform as well as

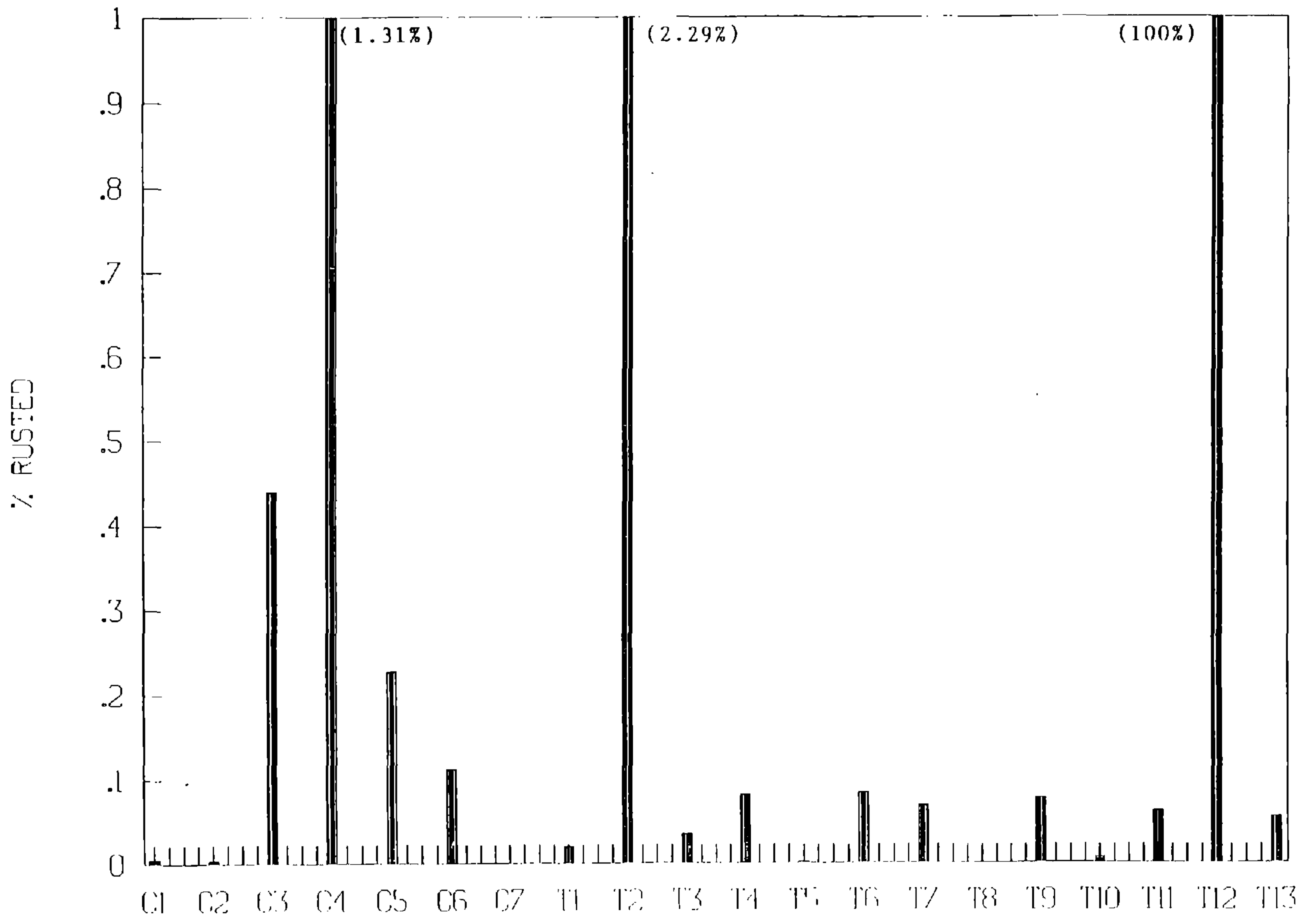


Figure 42. SP-10 surface; average % rust 16 months natural exposure, controls & HS/WB coatings.

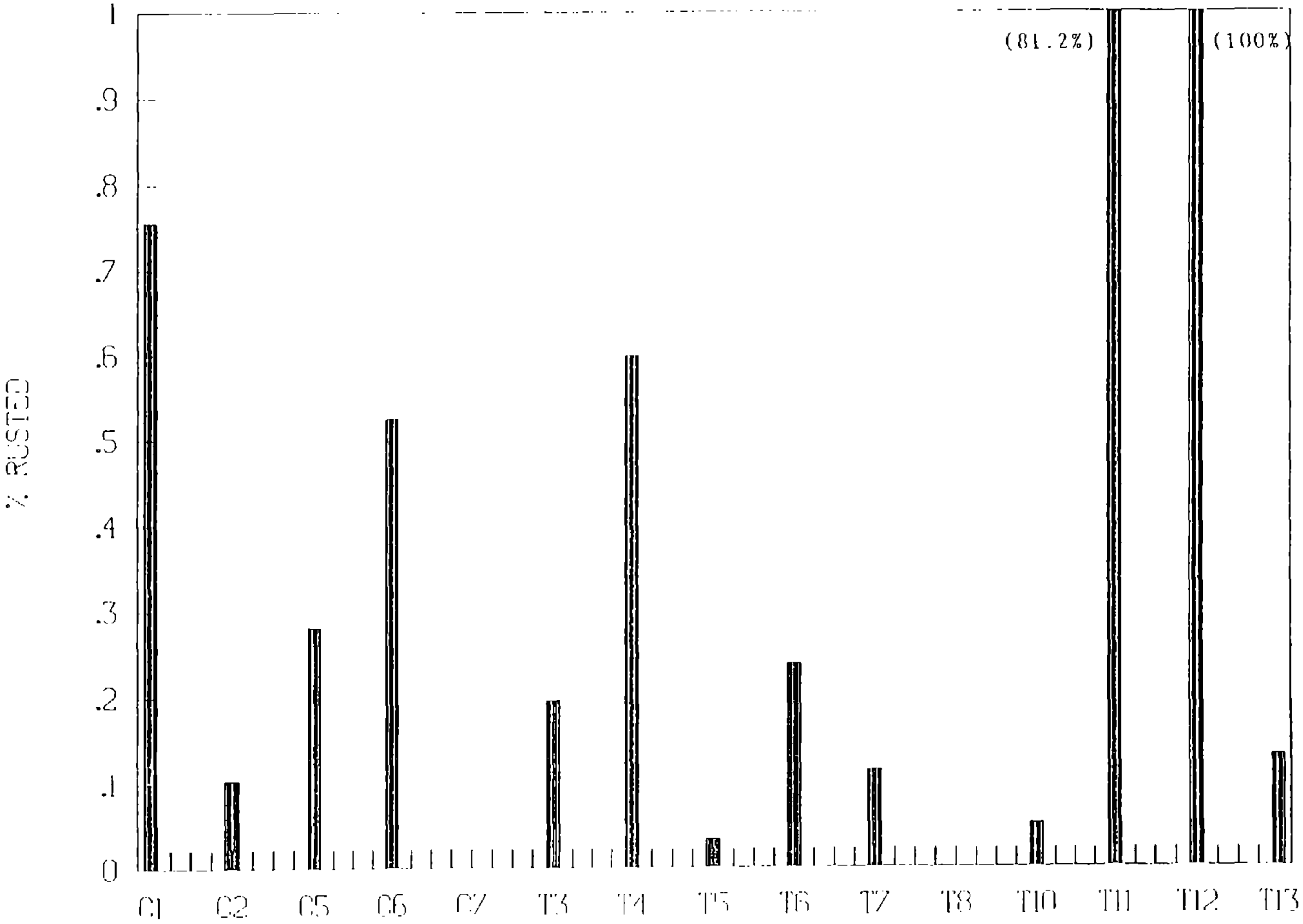


Figure 43. SP-2 surface; average % rust - 16 months natural exposure, controls & HS/WB coatings.

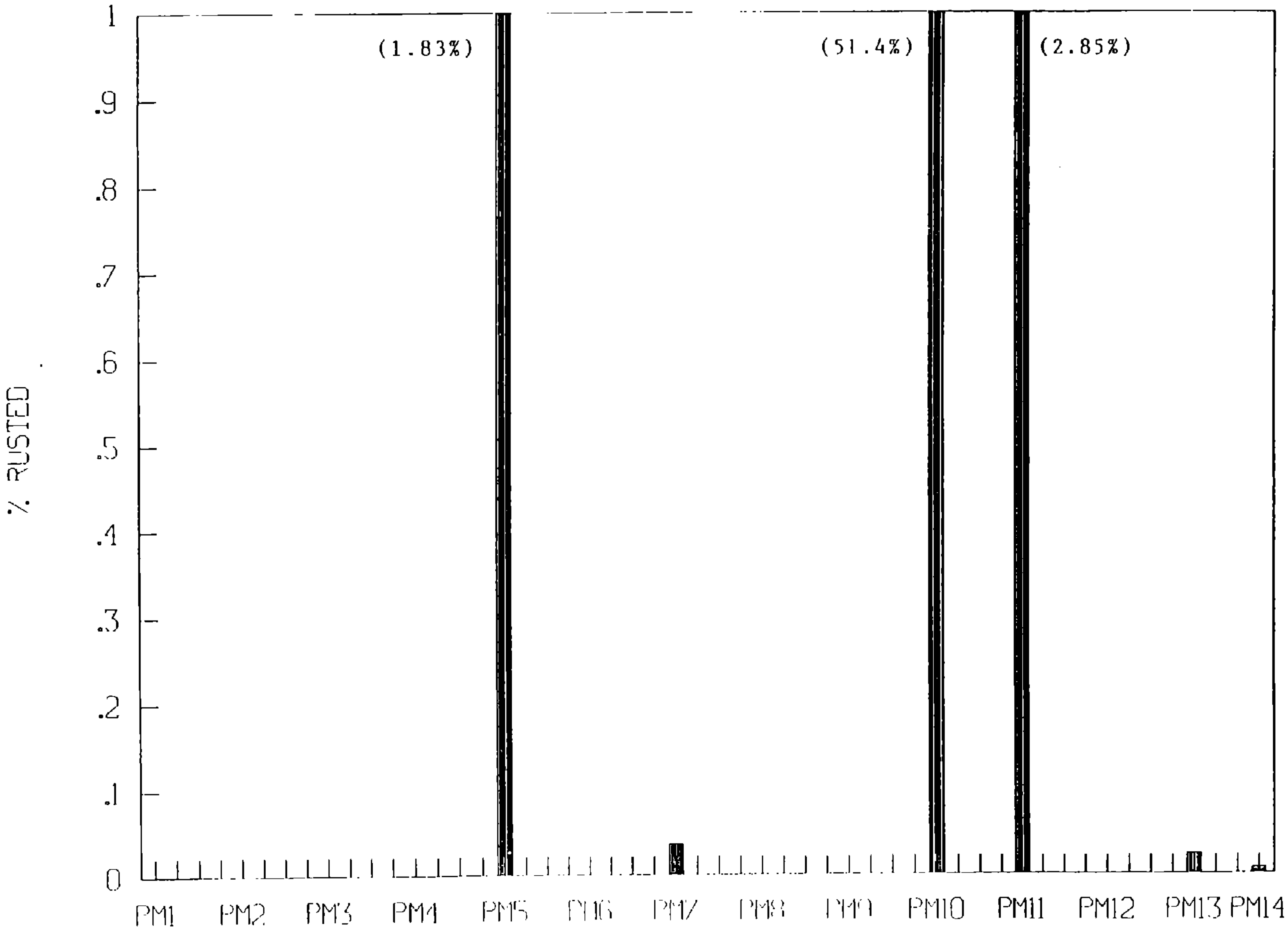


Figure 44. Powder coated & metallized systems; average % rust - 16 months natural exposure.

systems 1, 2, and 7. Systems 5 and 6 did outperform systems 3 [inorganic zinc/vinyl/vinyl] and 4 [inorganic zinc/epoxy/urethane], which did not perform well over the 16-month exposure period. Systems 3 and 4 had areas of failure exceeding 0.3 percent, an extent of degradation often requiring recoating.

SP-10 Surface - High Solids/Waterborne Systems

All of the high solids/waterborne test systems performed quite well in the 16 months of exposure with the exception of system 2 [water-based inorganic zinc/acrylic] and system 12 [acrylic latex]. System 12 had failed completely prior to the 6-month inspection of these panels. It is interesting that system 2 failed, while system 1 [single coat inorganic zinc] performed quite well. This result may be reflective of the different manufacturers of the inorganic zincs in these systems, or it may indicate a decrease in performance of inorganic zinc when topcoated.

The best performing systems over the 16-month period were:

5. Organic zinc/epoxy/urethane.
8. Styrene acrylic/acrylic.
10. Water-based acrylic.

Systems 5 and 8 did well in the accelerated tests. However, system 8 exhibited a significant affinity for moisture penetration, usually an indication of failure of the coating. System 10 did well in the cyclic brine immersion testing, but was not one of the best performers in the salt fog testing.

SP-2 Surface - Control Systems

Figure 43 provides the results of the 16-month inspection of the control and high solids/waterborne systems applied over an SP-2 surface. The best performing systems among the controls were:

2. Red lead/red lead/BLSC.
7. MIL-P-24441, polyamide epoxy.

The remaining control systems showed significant degradation over the 16-month exposure period.

SP-2 Surface - High Solids/Waterborne Systems

As was the case with the SP-10 panels, the best performing high solids/waterborne systems applied over an SP-2 surface were:

5. Organic zinc/epoxy/urethane.
8. Styrene acrylic/acrylic.
10. Water-based acrylic.

Systems 4 [epoxymastic/urethane], 11 [vinyl/vinyl], and 12 [acrylic latex] performed poorly in the 16 months of exposure over an SP-2 surface.

As in the accelerated testing, many of the high solids/waterborne coating systems performed as well or better than the majority of the control systems over both SP-10 and SP-2 surface preparations.

Powder Coating/Metallized Systems

Figure 44 provides the rusting data for the powder coating and metallized systems over the 16-month exposure period. With the exception of systems 5 [wire sprayed aluminum], 10 [flame spray powder epoxy], and 11 [TGIC-cured polyester], system 7 [powder sprayed zinc], system 13 [ASTM A-775 epoxy/urethane], and system 14 [ASTM A-775 epoxy/acrylic], the powder coating and metallized systems showed no signs of rusting over the 16-month period. Systems 5, 10, and 11 all failed within the period. Systems 7, 13, and 14 showed only slight rusting during the exposure.

Criticism of Accelerated Test Results Based on the 16-Month Natural Exposure Test Results

In general, there is a lack of an exact correlation between the results of the accelerated tests and the results of the 16-month natural exposure inspection. For the control systems, the best performers in the accelerated testing were the MIL-P-24441 epoxy polyamide system and the Zn-rich urethane/epoxy/urethane system. The worst performing controls in the accelerated tests were the two lead based systems. Conversely, in the natural exposure evaluation, the best performers were the MIL-P-24441 and the lead-based systems. In addition, the inorganic zinc/epoxy/urethane control system performed relatively well in the accelerated tests, but was the worst performing control under natural exposure, rusting more than 1 percent over only 6 months.

Similar inconsistencies in performance can be seen with respect to the high solids/waterborne test coatings. For example, the water-based inorganic zinc/acrylic system performed relatively well in the accelerated tests and poorly in 16-months of natural exposure. Conversely, the epoxy/water-based enamel system was one of the poor performers in the accelerated testing. The same system was not showing significant degradation after 16 months in the natural marine environment. One system exhibiting consistent behavior between the accelerated and natural marine exposure was the acrylic latex system. This system performed worst in both the natural exposure and the accelerated testing.

Table 4 provides a qualitative ranking of the best and worst performing control coating systems in the accelerated and the natural marine exposure testing over an SP-10 surface.

Table 4. Qualitative ranking of control coating systems.

Accelerated Testing	16-Month Natural Exposure
[Best Performers]	
Zinc-Rich Epoxy Urethane/ Epoxy/Urethane	MIL-P-24441, Polyamide Epoxy
MIL-P-24441, Polyamide Epoxy	Red Lead
IOZ/Epoxy/Urethane	BLSC Oil Alkyd
OZ/OZ/Vinyl-Al	Zn-Rich Epoxy Urethane/ Epoxy/Urethane
[Worst Performers]	
Red Lead	OZ/OZ/Vinyl-Al
IOZ/Vinyl/Vinyl	IOZ/Vinyl/Vinyl
BLSC Oil Alkyd	IOZ/Epoxy/Urethane

Table 4 shows the lack of a complete correlation between the results of the accelerated tests and the natural marine environmental exposure tests, even on a qualitative basis.

Table 5 presents similar data for the low VOC test systems. Table 5 also shows the lack of correlation between the natural exposure data and the accelerated test rankings. In spite of this, the worst performing system in the natural marine environment and in the overall rankings [encompassing the battery of accelerated tests] was the acrylic latex system.

Table 5. Qualitative ranking of low VOC coating systems.

Accelerated Testing	16-Month Natural Exposure
[Best Performers]	
Water-Based IOZ	OZ/Epoxy/Urethane
Water-Based IOZ/Acrylic	Styrene Acrylic/Acrylic
Epoxy/Urethane	Water-Based Acrylic
Epoxymastic/Urethane	Water-Based IOZ
OZ/Epoxy/Urethane	Epoxy/Urethane
Styrene Acrylic/Acrylic	Epoxymastic/Urethane
Sol-Based (Low VOC) IOZ/Epoxy/Urethane	Al-Epoxymastic/Acrylic
Al-Epoxymastic/Acrylic	Sol-Based IOZ/Epoxy/Urethane
Water-Based Acrylic	Vinyl/Vinyl
Vinyl/Vinyl	H.S. Phenolic/Acrylic
H.S. Phenolic/Acrylic	Epoxy/Water-Based Enamel
[Worst Performers]	
Epoxy/Water-Based Enamel	Water-Based IOZ/Acrylic
Acrylic Latex	Acrylic Latex

CONCLUSIONS

1. Based on the accelerated laboratory tests conducted, there are proprietary low VOC coating systems currently available which provide corrosion protection equivalent to or superior than traditional high VOC bridge coating systems.

2. Overall, the best performing low VOC systems in the battery of tests over an SP-10 surface were water-based organic zinc, water-based inorganic zinc with an acrylic topcoat, two high-build epoxy/urethane topcoat systems, organic zinc/epoxy/urethane, inorganic zinc/epoxy/urethane, and high-build styrene acrylic/acrylic. These systems performed better than or equal to the best performing control systems [MIL-P-24441 epoxy, and Zinc-rich urethane/epoxy/urethane].

3. In general, the coating systems which performed well in one accelerated test showed consistently good performances in the remainder of the tests. Likewise, the systems that performed poorly in any particular test were generally among the poorer performers in the remainder of the tests. Despite this general agreement, selected systems showed completely opposite behavior between the accelerated tests and the natural environmental exposure (e.g. lead-based paints in salt fog vs. natural exposure).

4. As a group, the powder coating and metallized test systems, with the exception of the TGIC-cured polyester and the flame sprayed epoxy powder coating, performed extremely well in the battery of accelerated testing.

5. For all systems and substrates, coatings over hand tool-cleaned (SP-2) surfaces did not perform as well as the same systems applied over a near-white metal blasted (SP-10) surface.

6. There were no discernible differences in performance of any of the coatings over A-36 steel or A-588 steel with similar surface preparations.

7. Given the high viscosity of some of the lower VOC coating systems, traditional paint application methods may need to be modified for successful paint application. Note that this holds for only some of the low VOC systems. There is not a direct correlation between ease of application and VOC content.

RECOMMENDATIONS FOR LONG-TERM TESTING

Table 6 shows the coating systems to be included in the long-term exposure testing. The matrix was formulated on the basis of the 6-month accelerated test program only. The results of the 16-month natural marine exposure presented in this report were not available at the time of selection of the above test matrix. This 16-month inspection was intended as a follow-up for comparison purposes. The 16-month inspection also serves as an additional data point for the overall exposure program. As presented the matrix provides a technical justification for each of the coatings selected for the long term exposure testing.

Table 6. Systems for long-term testing.

System #	Generic Description	Commercial Description	Thickness (mils)	Rationale
1	Inorganic Zinc/Epoxy/ Urethane	Carbozinc 11/Carboline 190 HB/ Carboline 134	3.0/4.0/2.0	High VOC control system. Used extensively on bridges in the past.
2	Organic Zinc/Epoxy/ Urethane	308 ZR Epoxy/4351 HB Epoxy/ 4610 Hythane	3.0/4.0/2.0	High VOC control system. Used extensively on bridges in the past.
3	Inorganic Zinc/Epoxy Urethane	Carbozinc D11 HS/Carboline 893 RCP/ Carboline D834	3.0/4.0/2.0	Low VOC version of control system #1.
4	Organic Zinc/Epoxy/ Urethane	Magna-Zinc 325/Magna-Coat 7510 Hythane Ultra 8731	3.0/4.0/2.0	Low VOC version of control system #2.
5	Inorganic Zinc	IC 531	4.0	Single coat system that performed well in screening tests and is receiving considerable interest in the bridge coating industry.
6	Epoxy Mastic/Urethane	Du Pont 25P/Imron 333	7.0/2.0	System performed well in screening tests. Epoxy mastic systems are popular maintenance coatings.
7	Epoxy Mastic/Urethane	75-W-9W/V-Thane	7.0/2.0	System performed well in screening tests. Similar to System 6, yet from a different manufacturer.
8	Epoxy Mastic/Acrylic	Sherwin Williams Epoxy Mastic Al/ DTM Acrylic Gloss	6.0/1.5/1.5	System performed well in screening tests. Similar to systems 6 and 7 with less expensive topcoat.
9	Acrylic/Latex	Rust Gone II/Rohm and Haas HG-54	2.0/3.0/2.0	Experimental LA DOT system. Added to matrix on their request. The water-based acrylic acrylic systems showed good performance in natural exposure.
10	ASTM A 775 Epoxy/Acrylic	Morton Thiokol/ Sherwin Williams DTM Acrylic Gloss	8-10/3.0	System performed best in screening tests of powder coatings. Acrylic topcoat used for gloss retention.
11	Metallized	Flame-Sprayed Zinc	5.0-7.0	System performed well in screening tests.
12	Metallized	Flame-Sprayed Zinc/Alum. (85-15)	5.0-7.0	System performed well in screening tests
13	Metallized	Flame-Sprayed Aluminum	5.0-7.0	System performed well in screening tests.

APPENDIX A: TOTAL DETECTED CHLORIDE

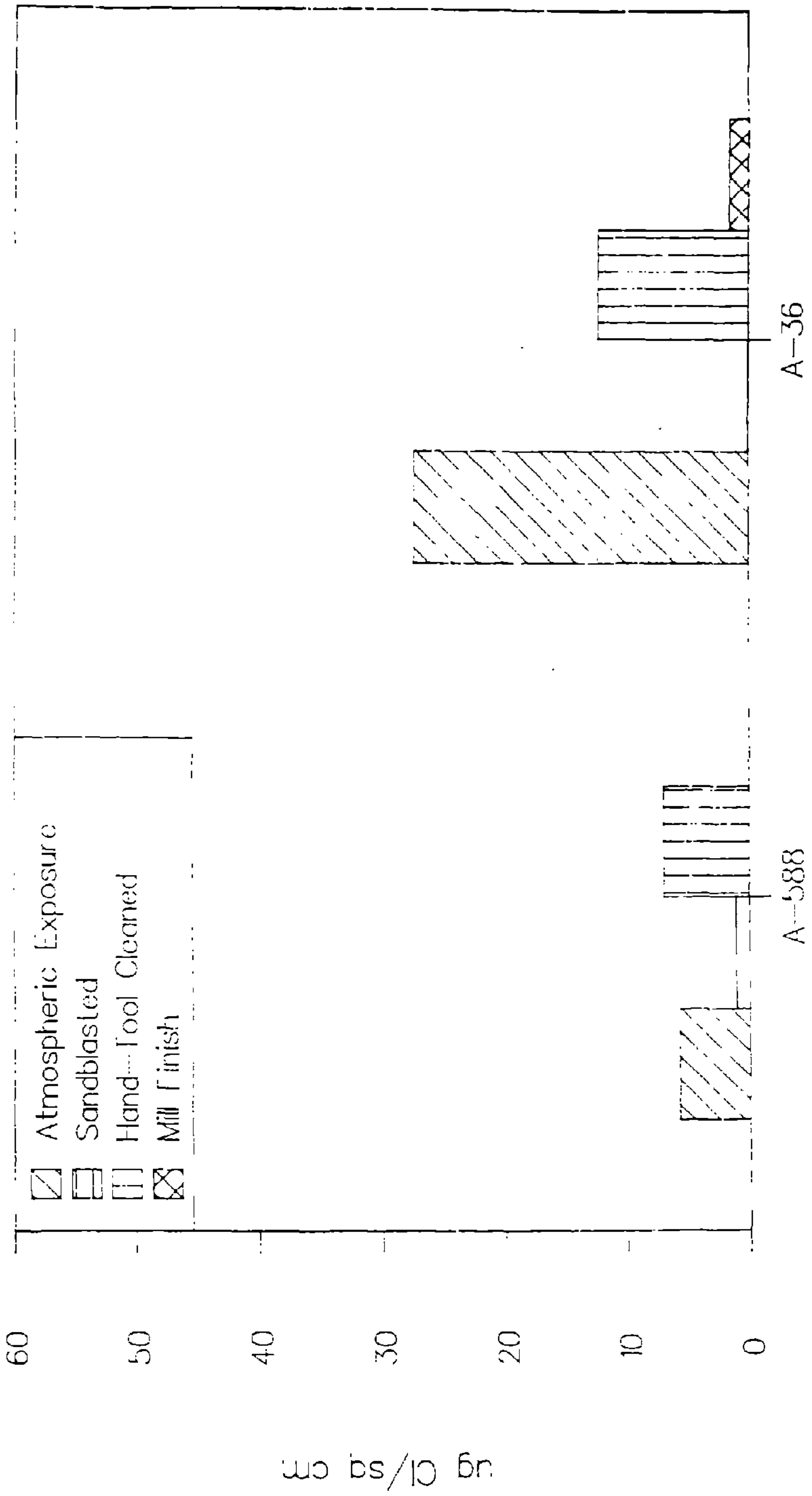


Figure 45. Total detected chloride.

APPENDIX B

SYSTEM SUMMARY SHEETS

Control System # 1

Film Thickness
Specified/Actual

Primer: Basic Lead Silico Chromate - 2.0 mils/1.8 mils
Intermediate Coat: Basic Lead Silico Chromate - 1.5 mils/2.0 mils
Topcoat: Basic Lead Silico Chromate - 1.5 mils/1.6 mils

Application Notes: Easy to apply and achieve film build.

Performance Testing

Salt Fog Test: General failure due to rusting of all panel sections. Most panels blistered beyond rating condition. No scribe cutback was determinable due to panel condition. Paint seemed to have very little cohesive strength. SP-2 panels were more severely deteriorated than SP-10 and mill-scale panels.

Brine Immersion Test: Millscale and SP-2 panels were severely deteriorated. SP-10 (A-36 and A-588) panels displayed a few failures due to rusting. The SP-10 panel displayed light to moderate blistering between the coating layers.

Marine Atmosphere/Sea Spray: The SP-2 and millscale panels had some failures from the top and bottom edges but not in the areas which influenced the test. They also showed some light rust stain running from the light blistering present (3M-4MD). The SP-10 panels were in excellent condition but displayed light rusting at the channel. The scribes were rusted but displayed no cutback.

Control System # 2

Film Thickness
Specified/Actual

Primer: Red Lead, Oil/Alkyd - 2.0 mils/1.7 mils
Intermediate Coat: Red Lead, Oil/Alkyd Chromate -
1.5 mils/3.3 mils
Topcoat: Basic Lead Silico Chromate - 1.0 mils/1.0 mils

Application Notes: Easy to apply and achieve film build.

Performance Testing

Salt Fog Test: General failure due to rusting of most SP-2 panel sections. Most panels were blistered beyond rating condition. No scribe cutback was determinable due to panel condition. Paint seemed to have very little cohesive strength. Cutback was not determinable because the paint merely comes off in fine pieces. SP-2 panels were more severely deteriorated than SP-10 and millscale panels.

Brine Immersion Test: Mill scale and SP-2 panels were severely deteriorated and displayed failure due to rusting in all sections. SP-10 (A-36 and A-588) panels displayed only 3 failed sections due to rusting. The SP-10 panels had light to moderate blistering between the coating layers.

Marine Atmosphere/Sea Spray: The SP-2 and millscale panels were beginning to show some failures from the top and bottom edges but not in the areas which influenced the test. They also showed some light rust stain running from the light blistering present (4F-3M). The SP-10 panels were in excellent condition but displayed light rusting at the channel. The scribes were rusted but displayed no cutback.

Control System # 3

Film Thickness
Specified/Actual

Primer: Carbozinc 11 (inorganic zinc) - 3.0 mils/3.6 mils
Intermediate Coat: 1037 Wash Primer - 0.5 mils/0.6 mils
Topcoat: Polyclad 936 (vinyl) - 5.0 mils/6.0 mils

Application Notes: Coating system was applied over SP-10 surface only. Primer achieved adequate film build easily and dried very quickly. Wash primer went on like water (very thin). Topcoat bubbled several minutes after application.

Performance Testing

Salt Fog Test: System had failures on most panel sections. A-36 panels displayed extensive blistering between coatings. Rust staining leached through the topcoat. The scribe was rusted and cutback 0.1-in (25.4-mm) on the A-588 panels and 0.5-in (12.7-mm) on the A-36 panels.

Brine Immersion Test: Panels did not show any failures due to rusting. All displayed dense blistering between the topcoat and primer (7D rating).

Marine Atmosphere/Sea Spray: The SP-10 panels were in excellent condition and did not rust at the channel. The scribes rusted but displayed no cutback.

Control System # 4

Film Thickness
Specified/Actual

Primer: Carbozinc 11 (inorganic zinc) - 3.0 mils/4.0 mils
Intermediate Coat: 190 HB Epoxy - 4.0 mils/5.0 mils
Topcoat: 134 Urethane - 2.0 mils/3.3 mils

Application Notes: This system was applied to SP-10 surfaces only. The primer dried very quickly. The epoxy intermediate coat was applied as a mist coat followed by a full 4.0 mil build.

Performance Testing

Salt Fog Test: System failed due to rusting on 20 to 25 percent of the test sections. Scribe rusted but did not cutback. System showed very little deterioration due to blistering (2F on one side of one panel A-588).

Brine Immersion Test: The brine immersion test panels did not deteriorate due to blistering or rusting. The scribe rusted but did not display any cutback.

Marine Atmosphere/Sea Spray: The sea spray panels failed due to rusting on only one section. No blistering occurred. There was slight rusting at the U-channels and the scribes rusted but did not cutback.

Control System # 5

Film Thickness
Specified/Actual

Primer: Carboline 811Z (organic zinc rich epoxy) - 2.5 mils/2.9 mils
Intermediate Coat: Carboline 811Z - 2.5 mils/2.2 mils
Topcoat: Carboline 811V (vinyl) - 2.0 mils/3.1

Application Notes: The primer was very difficult to atomize. This made application of a consistent coat difficult. The primer also dried quickly. The topcoat was difficult to build to the necessary wet film thickness (11 to 12 mils) to obtain the specified 2-mil dry film build without sagging and running.

Performance Testing

Salt Fog Test: Total failure of this system over SP-2 surface preparation. The millscale and SP-10 panels showed 25 to 50 percent failure due to rusting.

Brine Immersion Test: SP-2 panels were severely deteriorated, showing blistering between the primer and the substrate. The SP-10 and millscale panels had a few very large blisters between the topcoat and the primer.

Marine Atmosphere/Sea Spray: The A-36, SP-2 panels displayed slight blistering (4-5F). The U-channels rusted. The scribe rusted but did not undercut.

Control System # 6

Film Thickness
<u>Specified/Actual</u>

Primer: Imron 62ZF (zinc filled polyurethane) -
4.0 mils/4.0 mils
Intermediate Coat: Corlar 823 Epoxy - 4.0 mils/2.8 mils
Topcoat: Imron 326 Urethane - 1.0 mils/1.2 mils

Application Notes: This system was applied to all surfaces. The primer dried very quickly and was easy to atomize and maintain consistent builds. The epoxy intermediate coat was difficult to apply evenly and tended to flow in inconsistent patterns. The topcoat was also difficult to apply.

Performance Testing

Salt Fog Test: The panels which had an SP-2 surface preparation displayed severe blistering between the primer and the substrate. The A-36, SP-2 panel had 95 percent of its sections fail and the A-588, SP-2 panel had 55 percent of its sections fail due to rusting. The scribe cutback was difficult to determine due to severe blistering. The millscale and SP-10 panels had 12 to 25 percent of the sections fail due to rust. None of these displayed any blistering. The scribe undercutting ranged from 0.3 to 0.5-in (7.62 to 12.7-mm).

Brine Immersion Test: The SP-2 brine immersion test panels showed very severe blistering. For the SP-2 surface, 25 percent (A-588) and 45 percent (A-36) of the panel sections failed the rust rating. The SP-10 and millscale panels had no rusting or blistering. The scribe was rusted but not undercut.

Marine Atmosphere/Sea Spray: 15 percent of the A-36, SP-2 sections displayed failure due to rusting. Both the A-588 and the A-36 SP-2 panels displayed slight blistering (3F-4M). All other panels had no rusting and no blistering. The scribes rusted but did not undercut. The channels did not rust.

Control System # 7

Film Thickness
Specified/Actual

Primer: MIL-P-24441, Formula 150 - 3.0 mils/2.8 mils
Intermediate Coat: MIL-P-24441 Formula 151 - 3.0 mils/3.6 mils
Topcoat: MIL-P-24441 Formula 154 - 3.0 mils/2.8 mils

Application Notes: This System was applied to all surface preparations. These paints were easy to apply and provided consistent, even finishes.

Performance Testing

Salt Fog Test: This system displayed rust failures in 18 percent of the A-36 SP-2 panel sections. None of the other panels displayed failures due to blistering or rusting. This coating chalked slightly and was brittle and easily disbonded from the SP-2 and millscale substrates. The scribes showed 0.3 to 0.5-in (7.62 to 12.7-mm) undercutting.

Brine Immersion Test: The SP-2, A-36 panels had 6 percent of the test sections fail due to rusting. The A-588, SP-2 panels did not display any rusting. Both the A-36 and the A-588 panels had severe surface blistering. The coating had very large blisters between the primer and the substrate. The coating system was very easily removed from the SP-2 and millscale surfaces. None of the SP-10 or millscale panels displayed blistering or rusting. The scribe was rusted but not undercut.

Marine Atmosphere/Sea Spray: The sea spray panels showed no failure due to rusting. The A-36, SP-2 panels had 3F blistering on one side. No other panels blistered. There was no undercutting of the scribes. The channels did not rust. The coating showed some chalking.

High Solids/Waterborne System # 1

Film Thickness
Specified/Actual

Primer: IC 531 (waterborne inorganic zinc) - 3-5 mils/3.2 mils
Intermediate Coat: N/A
Topcoat: N/A

Application Notes: This system was applied to SP-10 surfaces only. This coating dried very quickly. Paint was very easy to apply. Proper atomization and film build was easily attained.

Performance Testing

Salt Fog Test: This system showed no deterioration (rusting, blistering or scribe cutback) on any of the panels. The test panel surfaces were covered with a white powdery film. The scribe did not rust or cutback.

Brine Immersion Test: The brine immersion test panels showed no deterioration either due to blistering or rusting. The scribe did not rust or undercut.

Marine Atmosphere/Sea Spray: The sea spray panels did not show failure due to rusting or blistering on any of the panels. The scribes did not rust or cutback. The channels did not rust.

High Solids/Waterborne System # 2

Film Thickness
Specified/Actual

Primer: Koppers P1500 (waterborne inorganic zinc) -
3-5 mils/4.9 mils
Intermediate Coat: N/A
Topcoat: Koppers 600 (waterborne acrylic) -
1.5 mils/2.1 mils

Application Notes: This system was applied to SP-10 surfaces only. The primer dried very quickly and was very easy to apply. Proper atomization and film build was easily attained for both primer and topcoat.

Performance Testing

Salt Fog Test: This system showed no deterioration due to rusting. There was a slight blistering problem between the primer and topcoat (one large blister on one panel). The scribe was only slightly rusted and was not undercut.

Brine Immersion Test: The brine immersion test panels showed deterioration due to rusting. The panels showed some blistering between the primer and topcoat (2M-8MD). The scribe was slightly rusted but did not display any undercutting.

Marine Atmosphere/Sea Spray: The sea spray panels did not fail due to rusting or blistering on any of the panels. The topcoat cracked along some of the edges. The scribes rusted slightly but did not undercut. There was no rusting on or around the channels.

High Solids/Waterborne System # 3

Film Thickness
Specified/Actual

Primer: Amerlock 400 (epoxymastic) - 5.0 mils/3.8 mils
Intermediate Coat: N/A
Topcoat: Porter Hythane (urethane) - 5.0 mils/5.8 mils

Application Notes: This System was originally supposed to have an Ameron topcoat. After attempting to spray the topcoat provided by Ameron and consulting with Ameron paint formulators, it was determined that this coating could not be applied without thinning. Since Amershield had a VOC content of 260 g/l as received, it was felt that applying it thinned would defeat the purpose of the program. Therefore, other suppliers were contacted to locate a comparable urethane topcoat that could be applied without thinning. Porter supplied Hythane, which also had a VOC content of 260 g/l. This coating was less viscous than Amershield and could be sprayed. It was therefore substituted into the program.

Performance Testing

Salt Fog Test: This system showed rusting over 56 percent of the A-36, SP-2 surface preparation panel sections. The A-588, SP-2 panels had rust failures on 6 percent of the panel sections. None of The SP-2 panels were blistering. The millscale and SP-10 panels displayed no rusted sections and no blistering. The A-36 SP-2 and SP-10 panels had 0.5-in (12.7-mm) undercutting at the scribe. The millscale panels had 0.75-in (19.05-mm) undercutting and the A-588 panels had 0.25-in (6.35-mm).

Brine Immersion Test: Twelve percent of the A-36, SP-2 test panel sections failed due to rusting. Fifty-six percent of the A-588 SP-2 sections failed the rust rating. The A-36 SP-2 panels had a few large blisters on the surface (1F). The A-588, SP-2 panels had 1F blistering on one side and 2MD blistering on the other side. The blistering was between the primer and the substrate. The A-588, SP-10 panel had one test section displaying rust failure. The remaining SP-10 and millscale test panels and sections did not show any rusting or blistering. None of the panels displayed undercutting of the scribe.

Marine Atmosphere/Sea Spray: The A-588 SP-2 panels showed 8M blistering on the back side of one of the panels. None of the other panels blistered or rusted. The millscale panels had 0.4-in (10.16-mm) undercutting at the scribe. The other systems did not undercut at the scribe.

High Solids/Waterborne System # 4

Film Thickness
Specified/Actual

Primer: Carbomastic 90 AL (aluminum epoxymastic) - 8.0 mils/7.2 mils
Intermediate Coat: N/A
Topcoat: D834 - 2.0 mils/2.5 mils

Application Notes: We could not atomize the primer, as received, sufficiently to get a smooth coating finish. We had to thin with carboline thinner #2 to apply. The paint was thinned to approximately 150 g/l VOC and applied. The topcoat was applied with no difficulties. This system was applied to all surface preparations.

Performance Testing

Salt Fog Test: Seventy-five percent of the A-36 and A-588, SP-2 panel sections failed the rust rating. The A-588 panel had 2F blistering on the front of the panel. There was no blistering on the remaining panels. The SP-2 and SP-10 panels had 0.1-in (2.54-mm) undercutting at the scribe. The millscale panels had 0.25-in (6.35-mm) undercutting at the scribe.

Brine Immersion Test: The SP-2 panels did not have an extensive amount of rusting visible on the surface; however, the panel surfaces were covered with large blisters which penetrated to the substrate. The entire coating could be removed from the panel with a utility knife. The SP-10 and millscale panels did not have any rusting, blistering, or scribe undercutting.

Marine Atmosphere/Sea Spray: The A-36, SP-2 panels showed 4F-6F blistering on the back side. The A-588, SP-2 panels had 8M blistering on the back side and 0.1-in (2.54-mm) undercutting of the scribe. Both the A-36 and A-588 test panels had rust failures on the back side of the panel only. The A-36 panels had rust failures in 12 percent of the back sections and the A-588 panels had 43 percent of the back sections failing. The millscale and SP-10 panels did not rust or blister and the U-channels did not rust. The mill scale panels had 0.25 to 0.5-in (6.35 to 12.7-mm) undercutting at the scribe. The A-588, SP-10 panels had 0.1-in (2.54-mm) scribe undercutting.

High Solids/Waterborne System # 5

Film Thickness
Specified/Actual

Primer: Amercoat 68HS (zinc rich epoxy) - 4.0 mils/5.2 mils
Intermediate Coat: Amercoat 385 (epoxy) -
4.0 mils/3.8 mils
Topcoat: Porter Hythane (urethane) - 5.0 mils/5.5 mils

Application Notes: The primer was easy to apply in even, consistent coats. The intermediate coat was difficult to spray in a consistent fashion and tended not to flow well on the panel surface. This system was originally supposed to have an Ameron topcoat [Amershield]. After attempting to spray the topcoat provided by Ameron and consulting with Ameron paint formulators, it was determined that this coating could not be applied without thinning. Since Amershield had a VOC content of 260 g/L as received, it was felt that applying it thinned would defeat the purpose of the program. Therefore, other suppliers were contacted to locate a comparable urethane topcoat that could be applied without thinning. Porter supplied Hythane, which also had a VOC content of 260 g/L. This coating was less viscous than Amershield and could be sprayed. It was therefore substituted into the program.

Performance Testing

Salt Fog Test: The panels from salt fog testing showed very little deterioration. None of the test sections displayed rusting or blistering. The millscale panel had 0.2-in (5.08-mm) undercutting at the scribe. None of the other panels showed any undercutting.

Brine Immersion Test: The coating on the SP-2 surface preparation was extensively damaged in the brine immersion. The coating formed large [3-in (76.2-mm) dia.] blisters between the primer and substrate. These blisters formed in the first test cycle. The remaining panels, SP-10 and millscale, showed no rusting or blistering. The scribes were rusted but not undercut.

Marine Atmosphere/Sea Spray: None of the panels were displayed rusting or blistering after the 6-month inspection. The millscale panels had 0.25-in (6.35-mm) undercutting at the scribe. There was no rusting on or around the channels.

Film Thickness
Specified/Actual

Primer: Epoxy Mastic Aluminum (Sherwin Williams) - 6.0 mils/6.6 mils
Intermediate Coat: N/A
Topcoat: Sherwin Williams DTM Acrylic Gloss (acrylic) - 3.0 mils/3.3 mils

Application Notes: The primer in this system was extremely viscous and did not flow well once on the panel surface. The topcoat went on easily and provided a high gloss finish to the panels. This system was applied to all surface preparations.

Performance Testing

Salt Fog Test: All the A-36 and A-588, SP-2 panel sections failed due to rusting. The panel surfaces were also extensively blistered, with rust leaching from the broken blisters. The A-36, SP-10 panels had 44 percent of the test sections fail the rust rating. The A-588 SP-10 panels had 75 percent of the test sections fail due to rusting. The millscale panels had the least number of failures with 6 percent of the test sections failing and about 0.5-in (12.7-mm) undercutting of the scribe.

Brine Immersion Test: Sixty-nine percent of the A-36, SP-2 test panel sections failed due to rusting. Forty-eight percent of the A-588, SP-2 sections failed the rust rating. The A-36, SP-2 panels were densely blistered between the primer and substrate (6D). SP-2 panels had 1F blistering on one side and 2MD blistering on the other side. The blistering was between the primer and the substrate. The A-588, SP-10 panel had one test section displaying rust failure. The remaining SP-10 and millscale test panels did not showing any rust failures or blistering. None of the panels displayed undercutting of the scribe.

Marine Atmosphere/Sea Spray: The A-588 and A-36, SP-2 panels showed 8F-8M blistering between the primer and the substrate. None of the other panels blistered or rusted. The millscale panels had 0.4-in (16.16-mm) undercutting at the scribe. The other systems had no undercutting at the scribe.

High Solids/Waterborne System # 7

Film Thickness
Specified/Actual

Primer: Devoe Bar-Rust 239 (epoxymastic) -
6.0 mils/5.0 mils
Intermediate Coat: N/A
Topcoat: Devflex 602 (acrylic) - 2.0 mils/3.9 mils

Application Notes: Bar-Rust 239 was not applicable as received. It was necessary to thin it to about 140 g/l VOCs using high flash naphtha. The topcoat was applicable without thinning and resulted in a smooth high gloss finish. This system was applied to all surface preparations.

Performance Testing

Salt Fog Test: This system displayed severe breakdown on all surfaces including SP-10. The panels were covered with running rust. After using oxalic acid to clean the panels it was difficult to locate the source of the rusting, however the panels all displayed severe blistering. Upon removal of some of the coating on an SP-10 panel it was discovered that the substrate was corroding beneath the coating.

Brine Immersion Test: Thirty-eight percent of the A-36 SP-10 and 6 percent of the millscale panels failed the rust rating. In areas where there was no apparent rusting, coating could be removed to find evidence of water penetration (i.e., staining). The SP-2 panels were so severely blistered that evaluation was not practical.

Marine Atmosphere/Sea Spray: The A-588 and A-36, SP-2 panels had 6M-6MD blisters on all of the panels. The SP-10 panels did not blister. None of the panels were rusted.

High Solids/Waterborne System # 8

Film Thickness
Specified/Actual

Primer: PWB 145 (CALTRANS) - 4-8 mils/3.9 mils
Intermediate Coat: PWB 145 (CALTRANS) 4-8 mils/5.5 mils
Topcoat: PWB - 87, 2 coats (CALTRANS) -
4-8 mils ea./8.9 mils

Application Notes: The primer in this system was very difficult to apply. Problems with the primer clogging the nozzle tip continued throughout the application period. The primer also did not cure in the specified cure time and had to be allowed an additional cure period. The topcoat was not a problem to apply. This system was applied to all surface preparations.

Performance Testing

Salt Fog Test: Forty-four percent of the A-588 SP-2 panel sections failed the rust rating and had 0.75-in (19.05-mm) undercutting at the scribe. None of the other panels had rusting severe enough to fail sections. The millscale, A-588, SP-10 and both SP-2 panels were blistered.

Brine Immersion Test: None of the test sections displayed rusting failure. All of the panels over an SP-2 surface preparation were densely blistered (4-5D). The back side of both the SP-10 panels were exhibiting blistering. The blisters on the SP-10 panels were between the primer and topcoat. The blisters over the SP-2 panels were between the primer and substrate.

Marine Atmosphere/Sea Spray: The A-588 and A-36, SP-2 panels showed 8F-8M blistering between the primer and the substrate. None of the other panels were blistered or rusted.

High Solids/Waterborne System # 9

Film Thickness
Specified/Actual

Primer: Carbozinc D11 HS (inorganic zinc) - 3.0 mils/3.6 mils
Intermediate Coat: 893 RCP (epoxy) - 4.0 mils/4.0 mils
Topcoat: Carboline D834 (urethane) - 2.0 mils/2.2 mils

Application Notes: The primer in this system was extremely viscous and very difficult to brush when edge coating. However, spray application was not a problem. The primer atomized well and went on in even consistent coats. The intermediate coat and topcoat were easy to apply.

Performance Testing

Salt Fog Test: There were no rusting failures or blistering on the test panels. The scribes were rusted but not undercut.

Brine Immersion Test: There were no rusting or blistering failures on the test panels. The scribes were rusted but not displaying any cutback.

Marine Atmosphere/Sea Spray: One of the A-36, SP-10 panels had clusters of blisters (2F) on both sides of the panel. None of the other panels were displaying any breakdown. The U-channels were not rusted.

High Solids/Waterborne System # 10

Film Thickness
Specified/Actual

Primer: HG-54 red (water based acrylic) - 3 mils/3.6 mils
Intermediate Coat: HG-54 red (water based acrylic) - 3 mils/3.7 mils
Topcoat: PWB - HG-54 green (water based acrylic) - 3 mils/2.8 mils

Application Notes: These coatings were easy to apply. They atomized well and readily flowed on the panel surface. This coating system was applied to all surface preparations and substrates (SP-10, SP-2, millscale).

Performance Testing

Salt Fog Test: One-hundred percent of the A-588, SP-2 panel sections failed the rust rating and had 2.0-in (50.8-mm) undercutting at the scribe. The A-36, SP-2 panel sections failed the rust rating in 100 percent of the cases and had 1.5-in (38.1-mm) undercutting at the scribe. Six percent of the A-36, SP-10 panel sections failed the rust rating and had 0.6-in (15.24-mm) undercutting at the scribe. The millscale panels had 31 percent of the sections rusted and 0.5-in (12.7-mm) undercutting at the scribe. Sixty-nine percent of the SP-10 sections failed the rust rating. All the panels had dense blistering ranging from 2-7 D in size.

Brine Immersion Test: The SP-2 panels exhibited very severe blistering extending down to the substrate. The blister on these panels was beyond the scope of ASTM rating system. Six percent of the A-36, SP-10 panel sections failed the rust rating. The millscale and A-588, SP-10 panels did not exhibit any rust failures.

Marine Atmosphere/Sea Spray: None of the panels at Sea Isle exhibited rust failures. All panels displayed blistering ranging from 6F to 9D.

High Solids/Waterborne System # 11

Film Thickness
Specified/Actual

Primer: TL-2000 (water borne vinyl) - 2-4 mils/2.8 mils
Intermediate Coat: N/A
Topcoat: PWB - TL-2000 (water borne vinyl) -
2-4 mils/3.1 mils

Application Notes: This coating was easy to spray. During brush application the coating tended to foam up and bubble. This coating was applied to all surface preparations.

Performance Testing

Salt Fog Test: Twelve percent of the SP-10 panels failed due to rusting and exhibited 6-8M blistering. Nearly all of the millscale and SP-2 panel sections failed due to rusting.

Brine Immersion Test: The A-36, SP-10 panels displayed no rusting or blistering. Ninety-six percent of the other panel sections failed the rust rating.

Marine Atmosphere/Sea Spray: The A-588 and A-36, SP-2 panels showed 2F-6F blistering between the primer and the substrate and 46 percent of the sections rusted. The SP-10 and millscale panels did not fail due to rusting or blistering.

High Solids/Waterborne System # 12

Film Thickness
Specified/Actual

Primer: CSMR, Hydrozo (acrylic latex) - 3.5 mils/4.3 mils
Intermediate Coat: N/A
Topcoat: PWB - CSMR, Hydrozo (acrylic latex) -
2.5 mils/2.4 mils

Application Notes: This system was applied to all surface preparations. There were no problems in the application. This coating atomized and flowed well. Within hours of primer application, brown spots appeared on all the SP-2 panels surfaces.

Performance Testing

Salt Fog Test: All of the panels displayed total failure in this test.

Brine Immersion Test: All of the panels displayed total failure in this test.

Marine Atmosphere/Sea Spray: All of the panels displayed total failure in this test.

High Solids/Waterborne System # 13

Film Thickness
Specified/Actual

Primer: PB 201, (CALTRANS) - 4-8 mils/3.2 mils
Intermediate Coat: PB 201 (CALTRANS) 4-8 mils/5.6 mils
Topcoat: PWB - 87, 2 coats (CALTRANS) -
4-8 mils ea./11.3 mils

Application Notes: The primer was easy to atomize and spread. The primer did not cure in the specified cure time and had to be allowed an additional cure period. The topcoat was not a problem to apply. This system was applied to all surface preparations.

Performance Testing

Salt Fog Test: The A-588, SP-2 panel had 0.75-in (1.9-mm) undercutting at the scribe. Fifty of the sections failed the rust rating. All of the other panels had 0.5-in (1.3-mm) undercutting at the scribe. Nineteen percent of the A-36, SP-10, 6 percent of the A-36, SP-2 and 50 percent of the A-588, SP-2 panel sections failed the rust rating. Only the A-36, SP-2 panel displayed any blistering (4MD one side).

Brine Immersion Test: The SP-2 panels were severely blistered. Fifty percent of the A-36, SP-10, 37 percent of the A-588, SP-10 and 31 percent of the millscale panel sections failed the rust rating. All of the panels displayed severe blistering between the substrate and primer.

Marine Atmosphere/Sea Spray: The A-588 and A-36, SP-2 panels had 8F-8M blistering between the primer and the substrate. None of the other panels are blistered or rusted. There was rusting in and around the U-channels.

Powder Coating/Metallized System # 1

Film Thickness
Specified/Actual

Primer: Wire Sprayed Zinc - 5-7 mils/5.6 mils
Intermediate Coat: N/A
Topcoat: N/A

Application Notes: This System was applied to SP-10 surfaces only. This coating was applied by Metal Weld Inc.

Performance Testing

Salt Fog Test: This system showed no deterioration (rusting, blistering or scribe cutback) on any of the panels. The test panel surfaces were covered with a white powdery film. The scribes were not rusted or cutback.

Brine Immersion Test: The brine immersion test panels did not show any deterioration either due to blistering or rusting. The scribe was not rusted or undercut.

Marine Atmosphere/Sea Spray: The Sea Spray panels did not show failure due to rusting or blistering on any of the panels. The scribes did not rust or cutback. The U-channels did not rust.

Powder Coating/Metallized System # 2

Film Thickness
Specified/Actual

Primer: Wire Sprayed Zinc - 5-7 mils/5.2 mils
Intermediate Coat: N/A
Topcoat: TL-2000 - 3.0 mils/2.1 mils

Application Notes: This system was applied to SP-10 surfaces only. The metallized coating was applied by Metal Weld Inc. The topcoat (sealer) was applied without any problems.

Performance Testing

Salt Fog Test: This system showed no deterioration (rusting, blistering or scribe cutback) on any of the panels. The scribes did not rust or cutback.

Brine Immersion Test: The brine immersion test panels did not show any deterioration either due to blistering or rusting. The scribes did not rust or undercut.

Marine Atmosphere/Sea Spray: The Sea Spray panels did not show failure due to rusting or blistering on any of the panels. The scribes did not rust or cutback. The U-channels did not rust.

Powder Coating/Metallized System # 3

Film Thickness
Specified/Actual

Primer: Wire Sprayed Zinc/Aluminum 85-15 -
5-7 mils/5.9 mils
Intermediate Coat: N/A
Topcoat: N/A

Application Notes: This System was applied to SP-10 surfaces only. This coating was applied by Metal Weld Inc.

Performance Testing

Salt Fog Test: This system showed no deterioration (rusting, blistering or scribe cutback) on any of the panels. The test panel surfaces were covered with a white powdery film. The scribes were not rusted or cutback.

Brine Immersion Test: The brine immersion test panels did not show any deterioration either due to blistering or rusting. The scribes were not rusted or undercut.

Marine Atmosphere/Sea Spray: The Sea Spray panels did not show failure due to rusting or blistering on any of the panels. The scribes did not rust or cutback. The U-channels did not rust.

Powder Coating/Metallized System # 4

Film Thickness
Specified/Actual

Primer: Wire Sprayed Zinc/Aluminum, 85-15 -
5-7 mils/5.7 mils
Intermediate Coat: N/A
Topcoat: TL-2000 - 3.0 mils/2.7 mils

Application Notes: This System was applied to SP-10 surfaces only. The metallized coating was applied by Metal Weld Inc. The topcoat was applied without any problems.

Performance Testing

Salt Fog Test: This system showed no deterioration (rusting, blistering or scribe cutback) on any of the panels. The scribe did not rust or cutback.

Brine Immersion Test: The brine immersion test panels did not show any deterioration either due to blistering or rusting. The scribe was not rusted or undercut.

Marine Atmosphere/Sea Spray: The Sea Spray panels did not show failure due to rusting or blistering on any of the panels. The scribes were not rusted or cutback. The U-channels did not rust.

Powder Coating/Metallized System # 5

Film Thickness
Specified/Actual

Primer: Wire Sprayed Aluminum - 5-7 mils/5.3 mils
Intermediate Coat: N/A
Topcoat: N/A

Application Notes: This system was applied to SP-10 surfaces only.

Performance Testing

Salt Fog Test: This system showed rusting on one section of an A-588, SP-10 panel, no other deterioration (rusting, blistering or scribe cutback) existed on any of the other panels. The test panel surfaces are covered with a white powdery film. The scribes were not rusted or cutback.

Brine Immersion Test: The brine immersion test panels did not show any deterioration either due to blistering or rusting. The scribe was not rusted or undercut.

Marine Atmosphere/Sea Spray: The sea spray panels did not show failure due to rusting or blistering on any of the panels. The scribes were slightly rusted but not undercut. There was rusting on the U-channels. The panels have a shadowing on the surface.

Powder Coating/Metallized System # 6

Film Thickness
Specified/Actual

Primer: Wire Sprayed Aluminum - 5-7 mils/5.6 mils
Intermediate Coat: N/A
Topcoat: TL-2000 - 3.0 mils/2.4 mils

Application Notes: This System was applied to SP-10 surfaces only. The metallized coating was applied by Metal Weld Inc. The topcoat was applied without any problems.

Performance Testing

Salt Fog Test: None of the panels showed any deterioration due to blistering or rusting. The scribes were slightly rusted but not undercut.

Brine Immersion Test: The brine immersion test panels did not show any deterioration either due to blistering or rusting. The scribes were slightly rusted but not undercut.

Marine Atmosphere/Sea Spray: The Sea Spray panels did not show failure due to rusting or blistering on any of the panels. The scribes were slightly rusted but not undercut. The U-channels did not rust.

Powder Coating/Metallized System # 7

Film Thickness
Specified/Actual

Primer: Powder Sprayed Zinc - 5-7 mils/9.5 mils
Intermediate Coat: N/A
Topcoat: N/A

Application Notes: This system was applied to SP-10 surfaces only.

Performance Testing

Salt Fog Test: This system showed no deterioration (rusting, blistering or scribe cutback) on any of the panels. The test panel surfaces were covered with a white powdery film. The scribes were not rusted or cutback.

Brine Immersion Test: The brine immersion test panels did not show any deterioration either due to blistering or rusting. The scribes were not rusted or undercut.

Marine Atmosphere/Sea Spray: The sea spray panels did not show any failures due to rusting or blistering. The scribes were not rusted or cutback. The U-channels were not rusted.

Powder Coating/Metallized System # 8

Film Thickness
Specified/Actual

Primer: Powder Sprayed Aluminum - 5-7 mils/9.7 mils
Intermediate Coat: N/A
Topcoat: N/A

Application Notes: This System was applied to SP-10 surfaces only. This coating was applied by Metal Weld Inc.

Performance Testing

Salt Fog Test: This system showed no deterioration (rusting or blistering) on any of the panels. The scribes were slightly rusted but not undercut.

Brine Immersion Test: The brine immersion test panels did not show any deterioration either due to blistering or rust ing. The scribes were slightly rusted but not undercut.

Marine Atmosphere/Sea Spray: The Sea Spray panels did not show any failure due to rusting or blistering. The scribes were slightly rusted but not undercut. The U-channels were slightly rusted.

Powder Coating/Metallized System # 9

Film Thickness
Specified/Actual

Primer: Powder Sprayed Zinc - 5-7 mils/8.4 mils
Intermediate Coat: N/A
Topcoat: TL-2000 (water borne vinyl) - 3.0 mils/4.7 mils

Application Notes: This system was applied to SP-10 surfaces only. The topcoat was applied without any problems.

Performance Testing

Salt Fog Test: This system showed no deterioration (rusting, blistering or scribe cutback) on any of the panels. The scribes were not rusted or cutback.

Brine Immersion Test: The brine immersion test panels did not show any deterioration either due to blistering or rusting. The scribes were not rusted or undercut.

Marine Atmosphere/Sea Spray: The sea spray panels did not show failure due to rusting or blistering on any of the panels. The scribes were not rusted or cutback. The U-channels were not rusted.

Powder Coating/Metallized System # 10

Film Thickness
Specified/Actual

Primer: Flame Sprayed Epoxy - 8-10 mils/10.3 mils
Intermediate Coat: N/A
Topcoat: N/A

Application Notes: This System was applied to SP-10 surfaces only. This coating was applied by UTP Welding Inc.

Performance Testing

Salt Fog Test: Seventy-five percent of the SP-10 panel sections failed the rust rating. There was no blistering of the coating. There was about 0.2-in (5.08-mm) undercutting of the scribes.

Brine Immersion Test: The brine immersion test panels did not show any deterioration either due to blistering or rusting. The scribes were rusted but not undercut.

Marine Atmosphere/Sea Spray: The A-36, SP-10 panels showed rusting failures in 44 percent of the test sections. There was no blistering on any of the panels. The U-channels were slightly rusted.

Powder Coating/Metallized System # 11

Film Thickness
Specified/Actual

Primer: TGIC Cured Polyester - 8-10 mils/5.8 mils
Intermediate Coat: N/A
Topcoat: N/A

Application Notes: This system was applied to SP-10 surfaces only.

Performance Testing

Salt Fog Test: All test panel sections failed the rust ratings.

Brine Immersion Test: The brine immersion test panels did not show deterioration either due to blistering or rusting. The scribes were rusted but not undercut.

Marine Atmosphere/Sea Spray: The A-36, SP-10 panels did not fail the rust rating. There was no blistering present. One of the U-channels was slightly rusted.

Powder Coating/Metallized System # 12

Film Thickness
Specified/Actual

Primer: ASTM A775 Epoxy - 8-10 mils/13.3 mils
Intermediate Coat: N/A
Topcoat: N/A

Application Notes: This system was applied to SP-10 surfaces only.

Performance Testing

Salt Fog Test: Only one of the test panel sections failed the rust rating. There was no blistering evident on the surface. The scribes were rusted and undercut 0.25 to 0.3-in (6.35 to 7.62-mm).

Brine Immersion Test: The brine immersion test panels did not show any deterioration either due to blistering or rusting. The scribes were rusted but not undercut.

Marine Atmosphere/Sea Spray: None of the panels failed the rust rating or displayed any blistering. The scribes were rusted but not undercut. The U-channels did not rust.

Powder Coating/Metallized System # 13

Film Thickness
Specified/Actual

Primer: ASTM A775 Epoxy - 8-10 mils/14.1 mils
Intermediate Coat: N/A
Topcoat: D834 Urethane (Carboline) - 4.0 mils/2.1 mils

Application Notes: This system was applied to SP-10 surfaces only. The urethane was applied without any problems.

Performance Testing

Salt Fog Test: None of the test panel sections failed the rust rating. There was no blistering evident on the surface. The scribes were rusted and undercut 0.25 to 0.5-in (6.36 to 12.7-mm).

Brine Immersion Test: The brine immersion test panels did not show any deterioration either due to blistering or rusting. The scribes were rusted but not undercut.

Marine Atmosphere/Sea Spray: None of the panels failed the rust rating or displayed any blistering. The scribes were rusted but not undercut. The U-channels were not rusted.

Powder Coating/Metallized System # 14

Film Thickness
Specified/Actual

Primer: ASTM A775 Epoxy - 8-10 mils/10.8 mils
Intermediate Coat: N/A
Topcoat: HG-54 Acrylic - 3 mils/3.1 mils

Application Notes: This system was applied to SP-10 surfaces only. The acrylic topcoat was applied without any problems.

Performance Testing

Salt Fog Test: One of the test panel sections failed the rust rating. There was no blistering on the surfaces. The scribes were rusted and undercut 0.25 to 0.45-in (6.36 to 11.43-mm).

Brine Immersion Test: The brine immersion test panels did not show any deterioration either due to blistering or rusting. The scribe was rusted but not undercut.

Marine Atmosphere/Sea Spray: None of the panels failed the rust rating or displayed any blistering. The scribes were rusted but not undercut. The U-channels did not rust.

APPENDIX C

COATING ADHESION TEST RESULTS

Figures C-1 through C-3 present the results of the adhesion testing performed on each coating system. This data was obtained using a simple "pull-off" adhesion test apparatus as outlined in ASTM D-4541. For each coating system, three adhesion tests were performed. These tests were performed; before testing, to acquire baseline adhesion data; after cyclic salt fog testing, to determine the effect, if any, of the salt fog testing on coating adhesion; and, after cyclic brine immersion testing, to determine the effect of brine immersion on the adhesion of each coating system.

In Figures C-1 through C-3, the load at failure is given on the vertical axis, while the percentage of coating that failed (as opposed to failure of the adhesive bonding material) is given at the top of each bar in the graphs.

APPENDIX D

WATER PENETRATION TEST RESULTS

Figures D-1 through D-4 present the data obtained in the water penetration testing of each coating system.

In Figure D-1, water appears to rapidly penetrate Control Systems 3, 4, and 5. These were three of the worst performing control systems. The same data suggest that Control Systems 1, 2, and 7 were most resistant to water penetration. System 7 (MIL-P-24441) was the best performing control overall. Systems 1 and 2 did not perform well in the accelerated testing; however, these systems did perform quite well in 16 months of natural marine exposure.

In Figure D-2, HS/WB System 7 appears to be the most susceptible to water penetration. This result is consistent with the poor performance of this system in the testing. In this figure, the erratic behavior of Systems 1, 2, and 4 may be attributed to the conductive metallic pigments in the primers of these systems.

In Figure D-3, the data for HS/WB System 8 (Styrene Acrylic/ Acrylic) indicates water penetration after approximately two days in test. This result, coupled with the extremely high build required for this coating, and the difficulty encountered in applying this system led to the decision not to include this particular system in the long term testing.

Also in Figure D-3, the data for Systems 11 and 12 cannot be attributed to metallic pigments. This data indicates rapid water penetration into coating systems that also performed poorly in the other testing.

Figure D-4 shows the excellent water barrier properties of the powder coatings tested. Also evident is the ineffectiveness of sealing the metallized systems. All sealed metallized systems showed data indicative of rapid water penetration through the sealer topcoat.