COMPARISON OF LABORATORY TESTING METHODS FOR BRIDGE COATINGS

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1. SUMMARY

A wide variety of low solvent-containing coating systems for steel bridges were evaluated by various laboratory test methods and the results were compared with the results of duplicate systems exposed at Sea Isle City, New Jersey. The amount of volatile organic compounds (VOCs) in each of the coating systems selected for this study was less than 340 g/L. A combined freeze, ultraviolet-condensation, and salt plus pollutant fog/dry (Prohesion) test was found to generate a much more promising performance trend when compared to the outdoor exposure than did salt-fog test and Prohesion test alone. Method correlations were studied by a statistical analysis.

Low-VOC solvent-based zinc-rich polyurethane/polyurethane/polyurethane coating systems showed superior performance. The epoxy mastic system and the epoxy urethane mastic system developed serious undercuttings at the scribe. The waterborne acrylic and waterborne acrylic epoxy systems did not protect steel effectively and they blistered rapidly at the scribe. Waterborne vinyl blistered badly on the panel surface in all the laboratory tests, but performed fairly well after 28 months of outdoor exposure.

2. INTRODUCTION

The U.S. Environmental Protection Agency is mandating a strict limit on the amount of volatile organic compounds (VOCs) allowed in architectural and industrial maintenance coatings. The rule development for the VOC contents is currently at the final stage and the soon-to-be announced rule will enforce a large reduction in VOC contents in steps in the years 1996, 2000, and 2004.

A reliable accelerated laboratory test method for predicting field performance and durability of the low-VOC coating systems for bridge coatings is imperative in order to ensure cost-effectiveness of newly formulated coatings and to meet a short deadline. Salt-fog testing, as delineated in ASTM (American Society for Testing and Materials) method B117, does not accurately predict the field performance of many of the new generic low-VOC systems. An inclusion of a dry cycle in the conventional wet salt-fog test (made by Timmins, Sherwood, Lyon and Guest, and Jackson) had avoided unrealistic failures.[1-4] When a dry cycle, pollutants, and ultraviolet (UV)/condensation (QUV) exposure were incorporated into the salt-fog cycle, "A EVEN BETTER" correlation with field exposure was obtained by Simpson et al.[5] Chong and Peart added a freeze cycle to a salt-fog exposure and this cyclic test, in conjuction with a UV/condensation test, has resulted in performance rankings similar to that obtained by an outdoor weathering of 15 coating systems for steel bridges.[6] Freezing is an important part of the weather cycle in cold climates; the volume expansion of water absorbed by a coating at freezing temperatures results in significant mechanical stresses being placed on the coating systems. It is of interest to determine the effect of the addition of a freezing cycle to the combined wet/dry/QUV regimen on its ability to predict field performance. To resolve this question, a combined cycle of freeze, QUV, and salt plus pollutant fog/dry (Prohesion test) was employed to evaluate a number of high-solids and water-based coating systems for steel bridges. The results were compared with those obtained by salt-fog and Prohesion exposures alone. The 15- and 28-month outdoor exposure results of these coating systems at a marine environment site were used for determining which of the accelerated laboratory methods was most reliable for predicting coating performance for steel bridges. A statistical technique was employed to compare the test methods.

The coating performance data developed in the study will be used to provide a guideline for the selection of durable low-VOC coatings for protecting steel bridges.

3. EXPERIMENTAL PROCEDURES

3.1. Coating Systems

The 13 coating systems tested are described in table 1. The coating systems evaluated in this study were water-based systems of acrylic, acrylic epoxy, inorganic zinc potassium silicate, vinyl, and zinc-rich epoxy, and solvent-based systems of calcium sulfonate/alkyd, high-solids epoxy, zinc-rich polyurethanes, epoxy mastics, epoxy urethane mastic, and low-VOC epoxy. All of the tested coating systems contain VOC amounts of less than 340 g/L. All coatings were applied on SSPC SP-5 (blast white) steel panels. A 5.1-cm (2-in) diagonal scribe was made on the face of the test panels to study blister and rust creepage from the scribe.

3.2. Laboratory and Outdoor Tests

Three accelerated laboratory exposures were used to evaluate the candidate coating systems. These tests are as follows:

a. Salt-Fog
American Society for Testing and Materials (ASTM B117).

b. Prohesion — 1-h (hour) wet/1-h dry cycle.
Wet cycle: Harrison mixture of 0.35 percent ammonium sulfate and 0.05 percent sodium chloride. The collected condensate has a pH of 5.0.
Dry cycle: forced-air purging (6.8 m^3/h).

c. Cyclic Freeze/QUV/Prohesion — 70-h freeze/215-h QUV/215-h Prohesion cycle.
Freeze temperature: -23 °C (-10 °F)
QUV: UV/Condensation test
Test cycle: 4-h UV/4-h condensation cycle
UV lamp: UVA-340
UV temperature: 60 °C

Condensation temperature: 40 °C
Prohesion: same as test above.

One set of panels was also exposed outdoors at Sea Isle City, New Jersey, a marine exposure site. All the test panels were placed at a 45 degree angle on wooden racks, facing directly south. Each panel was sprayed three times daily with sea water (pH = 7.7, specific gravity at 15.6 °C = 1.021).

The exposure of most of the salt-fog test panels was terminated after 6.4 mm (0.25 in) of creepage at the scribe occurred (a general standard criterion for a pass or fail classification). A few panels were exposed for a longer time due to their peculiar failure modes to obtain additional information. The Prohesion tests and the cyclic freeze/QUV/Prohesion tests were conducted for a full period of 3,000 hours for all the coating systems; this long exposure time was essential because both of these tests included a dry cycle that resulted in a reduced failure rate when compared to the salt-fog results. The additional sets of data points obtained for the later two tests were highly beneficial in comparing test methods using a linear regression analysis. All the tests were carried out in duplicate to ensure statistical reliability and the results presented are an average of the data from the two panels.

3.3. Evaluation Methods

The accelerated test panels were examined every 500 hours to record their failure modes and to study the rate of deterioration. Evaluation criteria were blistering, rusting, and creepages at scribe. Degree of blistering was evaluated by ASTM method D714. Surface failures (unscribed area) and creepages at scribe were rated in accordance with ASTM method D1654. To improve accuracy, a grid of 6.4-mm (1/4-in), instead of 12.7-mm (1/2-in), squares was used for measuring surface failure. Creepages were measured in millimeters to the accuracy of 0.5 mm.

4. RESULTS AND DISCUSSION

4.1. Failure Results

Two types of coating failures were investigated in this study, plane-surface failure and scribe failure.

The plane failures are summarized in Table 2. Several coating systems exhibited plane failures. The calcium sulfonate/alkyd system developed topcoat delamination in all cases. The waterborne vinyl system blistered severely in all laboratory tests, but did not show any plane failure after the 28 month outdoor exposure. The water-based inorganic zinc potassium silicate/acrylic/acrylic system blistered badly after 500 hours of the salt-fog test; however the zinc primer remained in good condition. Two epoxy mastic systems developed extensive underfilm corrosion in the salt-fog test, a condition that was not duplicated in other test regimens or in the 28-month marine exposure.

All of the coating systems developed creepage or cutback at the scribes except the calcium sulfonate/alkyd system and several coating systems containing zinc primers. The creepages produced by various coating systems from different exposure methods are plotted in figure 1. Some notable changes at the scribe are described here. The waterborne acrylic, solvent-based zinc-rich polyurethane/waterborne polyurethane/waterborne polyurethane, epoxy urethane mastic, and water-based zinc-rich epoxy/acrylic/acrylic exhibited extensive creepage at scribe in the salt-fog test. The Prohesion test produced severe scribe failure after 1,000 hours for the waterborne acrylic epoxy and the solvent-based low-VOC epoxy/acrylic modified epoxy systems. Overall, the cyclic freeze/QUV/Prohesion exposure appears to give the closest performance correlation to the outdoor exposure in terms of degree of creepage. In general, the resemblance to the outdoor exposure is in the decreasing order of cyclic freeze/QUV/Prohesion > Prohesion > salt-fog. The line plot of the salt-fog results (figure 1) showed an extremely different pattern as compared to the cyclic freeze/QUV/Prohesion and the outdoor exposure results.

4.2. Comparison of performance ratings

A rating system for an overall performance was established for the candidate coating systems; it is based on summing the ratings for surface failure (unscribed area) and scribe creepage (ASTM D1654), resulting in "20" as the best possible overall rating (In each of the individual rating systems, "10" indicates perfect performance and "0" indicates total failure). Using this method, the rating results for all the laboratory tests and the 15-month as well as the 28-month outdoor exposures are presented in table 3. A rating for unscribed area covers both blistering and rusting on the plane and is a very logical method to use because little rusting was found on most of these coating systems.

An attempt was made to calculate the correlations of performance ratings for all thirteen coating systems between the outdoor exposure and the Prohesion test or the cyclic freeze/QUV/Prohesion exposure. The best fit by least squares method produced the correlation coefficients shown in table 4. The correlation coefficients of 0.55 and 0.62 clearly suggest that the cyclic freeze/QUV/Prohesion test exposure corresponds more closely to the outdoor exposure than does the other accelerated test regimen. Other correlation were calculated for all the coating systems except the waterborne vinyl system which exhibited severe blistering in all three laboratory tests but showed no surface failure after the 28 months outdoor exposure. The exclusion of the waterborne vinyl system (Code No. 12) in the linear regression analysis significantly improves the correlations between the laboratory test results and the outdoor exposure results. The recalculated correlation coefficients, 0.81 and 0.80, obtained for the relationship between the cyclic freeze/QUV/Prohesion test and the 15- and 28-month outdoor exposures further confirm this test regimen produced failure results closer to the natural marine exposure results than did the Prohesion test alone. It is not surprising that the performance of the three-coats waterborne vinyl system with a minimal solvent content (VOC = 2/2/64 g/L) showed a large discrepancy between laboratory tests and natural marine exposure. This waterborne coating material with high hyrophilic character easily absorbs water and does not allow sufficient time for water to diffuse out under the experimental conditions established in the accelerated testers as compared to the presumably less humid and longer drying cycles in the natural environment.

The correlation between the salt-fog test and the outdoor exposure could not be obtained for all thirteen coating systems due to some early terminations of the salt-fog test. However, a correlation was attempted between the 2,000 hours of salt-fog test results and the 28 month outdoor exposure results for the eight coating systems (code nos. 2, 4, 5-9, and 11) which had complete data points; the correlation coefficient was found to be 0.20. This extremely low value strongly suggests that using the salt-fog test result to predict field performance is inappropriate.

4.3. Statistical Analysis

Additional statistical analysis was carried out to study the variation of results among the three laboratory test methods employed in this work. The creepages at the scribe were used for the analysis because they are more accurate than the percentage of surface failures in terms of measurements. Eight coating systems (code nos. 2, 4-9, and 11) yielded a complete set of scribe creepage results from 500 to 2,000 hours for all three test methods. These data were evaluated by an analysis of variance as shown in table 5.(7) The analysis was conducted as a 2-way factorial design in which one of the factors is method of testing (3 methods) and the other factor is type of coating (8 types) with 8 measurements for each of the 24 combinations.

The statistical results of show low probabilities (0.09 and 0.06) of obtaining the reported F-ratio values in table 5; this indicates reveals that all three tests and coatings have statistically significant difference at the 10-percent level. In other words, different laboratory exposure methods generated different amounts of creepage at the scribe as did different coating systems. In fact, the actual difference is much bigger than that presented here because the extremely severe creepages developed for the waterborne acrylic (code no. 3) and the water-based zinc-rich epoxy/acrylic/acrylic (code no. 13) and the creepage of the waterborne vinyl system were not included in the analysis due to their earlier termination in the salt-fog test.

To distinguish the degree of failure by each test method, the mean creepage at the scribes at exposed times of 0, 500, 1,000, 1,500, and 2,000 hours is plotted in Figure 2. The extent of creepage for the salt-fog test and the Prohesion test are similar up to 1,500 hours; above 1,500 hours, the salt-fog test caused larger creepage than did the Prohesion test. The cyclic freeze/QUV/Prohesion test produced the least amount of scribe creepage among all three test methods. The differences in methods and coating systems can also be seen in the plot of averages for scribe creepage using three methods (figure 3).

5. SUMMARY AND CONCLUSIONS

- The cyclic freeze/QUV/Prohesion accelerated test evaluated in this study generated a failure trend closest to the 28-month outdoor exposure results when compared to the salt-fog test and the Prohesion test.

- The statistical analysis showed large differences between the coating systems and between the testing methods.

- Among the 13 coating systems, the solvent-based zinc-rich polyurethane/polyurethane/polyurethane (VOC = 336 g/L) performed the best. In general, the performance of three zinc-rich polyurethane systems are fairly similar except that the lowest-VOC coating system with the waterborne topcoat (VOC = 24 g/L) exhibited severe topcoat blistering at the scribe without the undercut.

- The zinc-rich primers with water-based topcoats did not undercut or rust at the scribe, but exhibited topcoat blisters at the panel surface. These systems include the water-based inorganic zinc/acrylic/acrylic, the water-based zinc-rich epoxy/acrylic/acrylic, and the solvent-based zinc-rich polyurethane/waterborne polyurethane/waterborne polyurethane. In conclusion, the majority of the water-based topcoats tested showed a tendency to blister regardless of whether the zinc-rich primer is solvent or water-based. The results verified that the zinc-rich primers protected steel from rusting and undercutting even though topcoat blistering occurred.

- The waterborne vinyl systems blistered badly on panel surfaces in all three laboratory tests, but did not show such failures after the 28-month outdoor exposure.

- The epoxy mastic systems undercut severely at the scribe after all three laboratory tests. The solvent-based high-solid epoxy system was fairly corrosion-resistant, but was prone to UV attack. The solvent-based low-VOC epoxy/acrylic modified epoxy system performed the worst and developed severe undercutting.

- Both the waterborne acrylic system and the waterborne acrylic epoxy system did not perform well and exhibited severe scribe creepage.

- The calcium sulfonate/alkyd system did not develop undercutting, but experienced extensive topcoat delamination.

6. REFERENCES

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Table 1. Coating systems.

Code No.	Description	VOC (g/L)[1]
1	Solvent-based Calcium Sulfonate/Alkyd, 2 coats	276/288
2	Solvent-based High-solids Epoxy	180
3	Waterborne Acrylic, 3 coats	132/109/109
4	Waterborne Acrylic Epoxy, 3 coats	134/133/133
5	Solvent-based Zinc-rich Polyurethane/ Polyurethane/Polyurethane	336/336/336
6	Solvent-based Zinc-rich Polyurethane/ Polyurethane/Polyurethane	336/250/250
7	Solvent-based Zinc-rich Polyurethane/ Waterborne Polyurethane/Waterborne Polyurethane	336/24/24
8	Solvent-based Epoxy Mastic/Polyurethane	84/288
9	Solvent-based Epoxy Urethane Mastic/ Polyurethane	327/288
10	Water-based Inorganic Zinc Potassium Silicate/ Water-based Acrylic/Water-based Acrylic	0/237/241
11	Solvent-based Low-VOC Epoxy/Acrylic Modified Epoxy	308/282
12	Waterborne Vinyl, 3 coats	2/2/64
13	Water-based Zinc-rich Epoxy/Acrylic/Acrylic	86/230/230

[1] 120 g/L = 1 lb/gal

Table 2. Results of plane failures.

Code No.	Salt-Fog	Prohesion	FQP[1]	15-m Outdoor	28-m Outdoor
1	TD[2]	TD	TD	TD	TD
	500 h				
2	-	-	-	-	-
3	-	-	-	-	-
	1,000 h				
4	-	-	-	-	-
5	-	-	-	-	-
6	-	-	-	-	-
7	8VF[3]	8VF, P[4]	9VF	P	8VF
	2,500 h				
8	8M	-	-	-	P
9	9D	-	-	P	P
	2,000 h				
10	2F&6M	-	1VF	1VF	1VF&6F
	500 h				
11	-	-	-	-	P
	2,500 h				
12	6M	8MD	4M	-	-
	500 h				
13	6D	-	-	-	-
	1500 h				

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1 Cyclic freeze/QUV/Prohesion test
2 Topcoat delamination
3 Method ASTM D714, Evaluating Degree of Blistering of Paints.
4 A few Pits

Table 3. Comparison of ratings in various exposures.

Code No.	Salt-Fog 3,000 h	Prohesion 3,000 h	FQP 3,000 h	15 Months Outdoor	28 Months Outdoor
1	10[1]	10	10	10	10
2	14	14	15	19	15
3	12[2]	15	14	14	14
4	10	13	13	15	13
5	16	15	19	20	20
6	16	15	17	20	20
7	9[3]	15	17	19	19
8	12	14	15	15	14
9	6[4]	14	16	15	13
10	16[1]	15	17	16	13
11	13[3]	12	13	12	11
12	10[1]	7	11	20	17
13	9[5]	12	15	18	16

[1] 500 h
[2] 1,000 h
[3] 2,500 h
[4] 2,000 h
[5] 1,500 h

Table 4. Correlation coefficients for performance ratings.

	Prohesion	Cyclic Freeze/QUV/Prohesion
a. For 13 coating systems		
15 Month outdoor exposure	0.14	0.55
28 Month outdoor exposure	0.27	0.62
b. For 12 coating systems[1]		
15 Month outdoor exposure	0.64	0.81
28 Month outdoor exposure	0.65	0.80

[1] Excluding the waterborne vinyl system.

Table 5. Analysis of variance: salt-fog, Prohesion, and cyclic freeze/QUV/Prohesion exposures for scribe creepage.

Component	Sum of Squares	df	Mean Square	F-ratio	P-value
Test	223.757	2	111.878	2.323	0.09
Coating	666.972	7	95.282	1.978	0.06
Residual	1633.019	182	48.170		
Total	2523.748	191			

df = Degree of freedom.
F-ratio = Fisher F-ratio.
P-value = Probability of obtaining a reported F-ratio value.

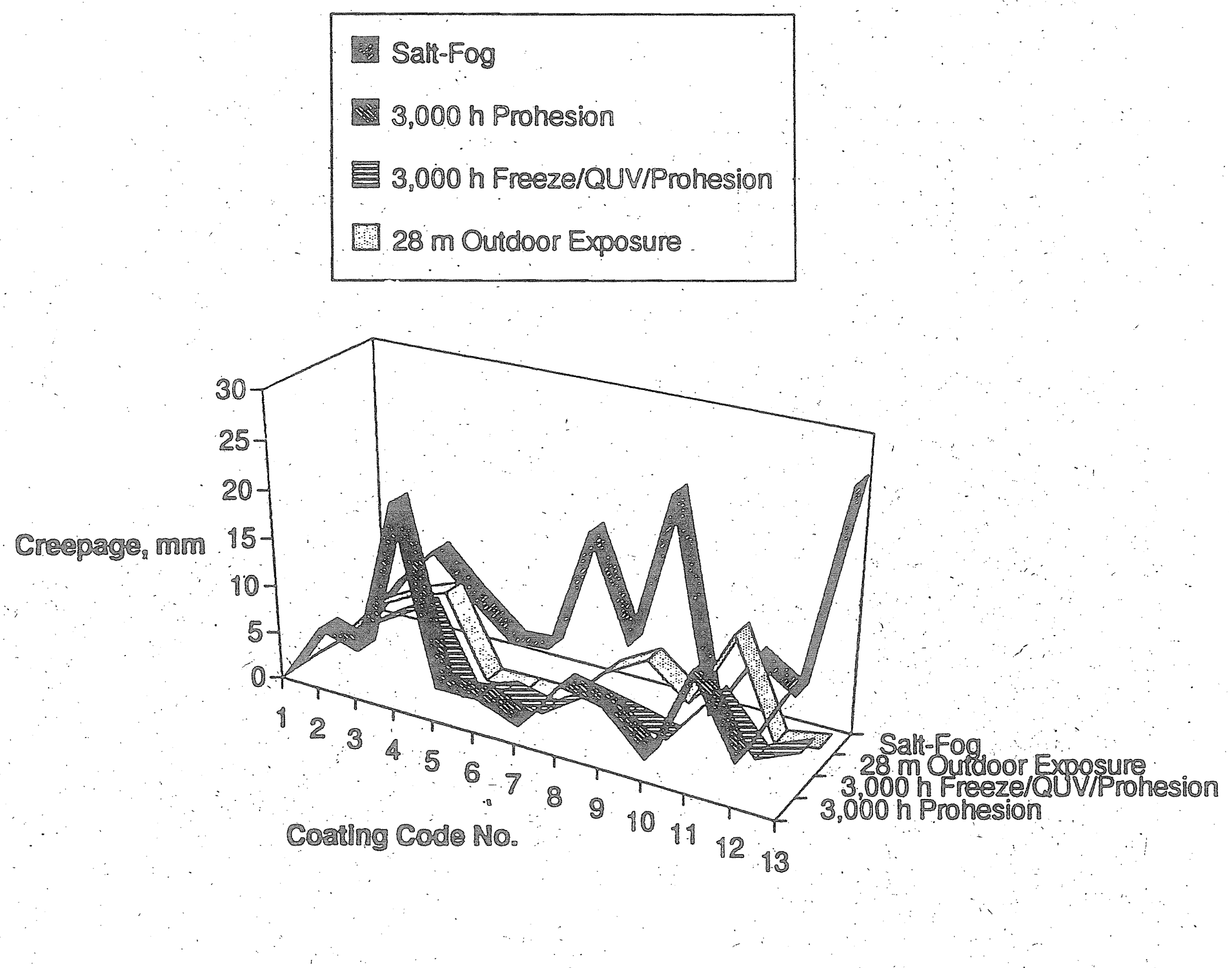

Figure 1. Comparison of creepage for salt-fog exposure, Prohesion exposure, cyclic freeze/QUV/Prohesion exposure, and 28-month outdoor marine exposure.

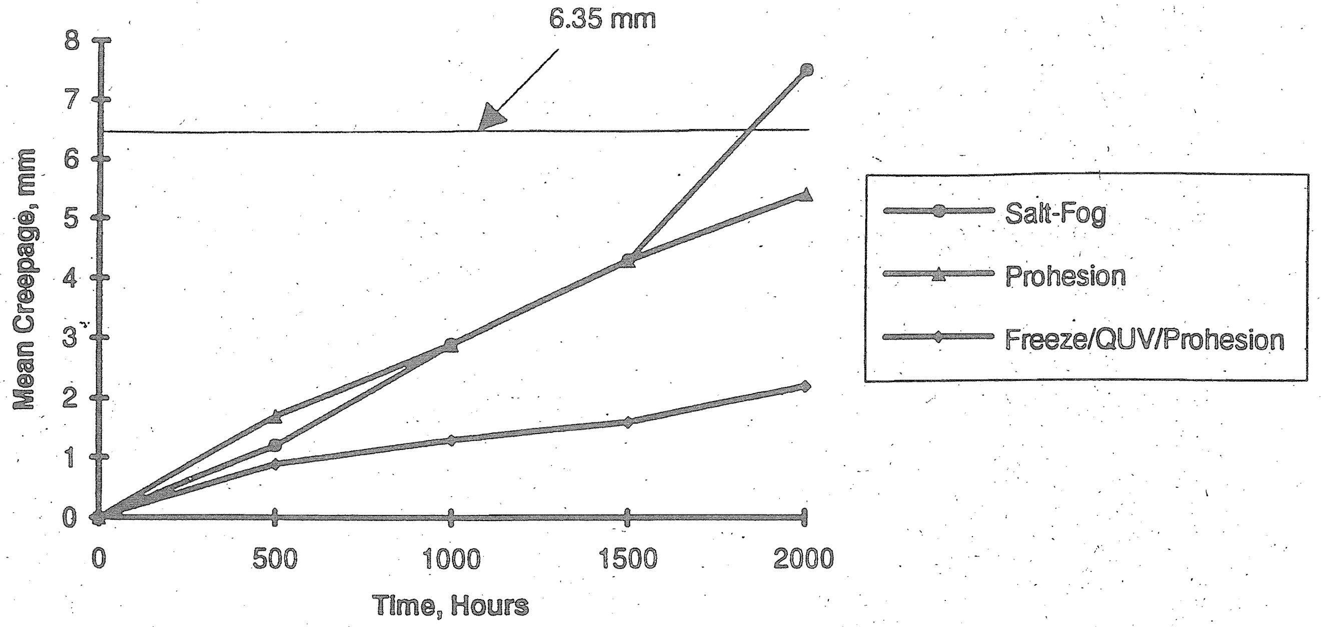

Figure 2. Mean creepage of exposure time of 500, 1,000, 1,500, and 2,000 h for cyclic

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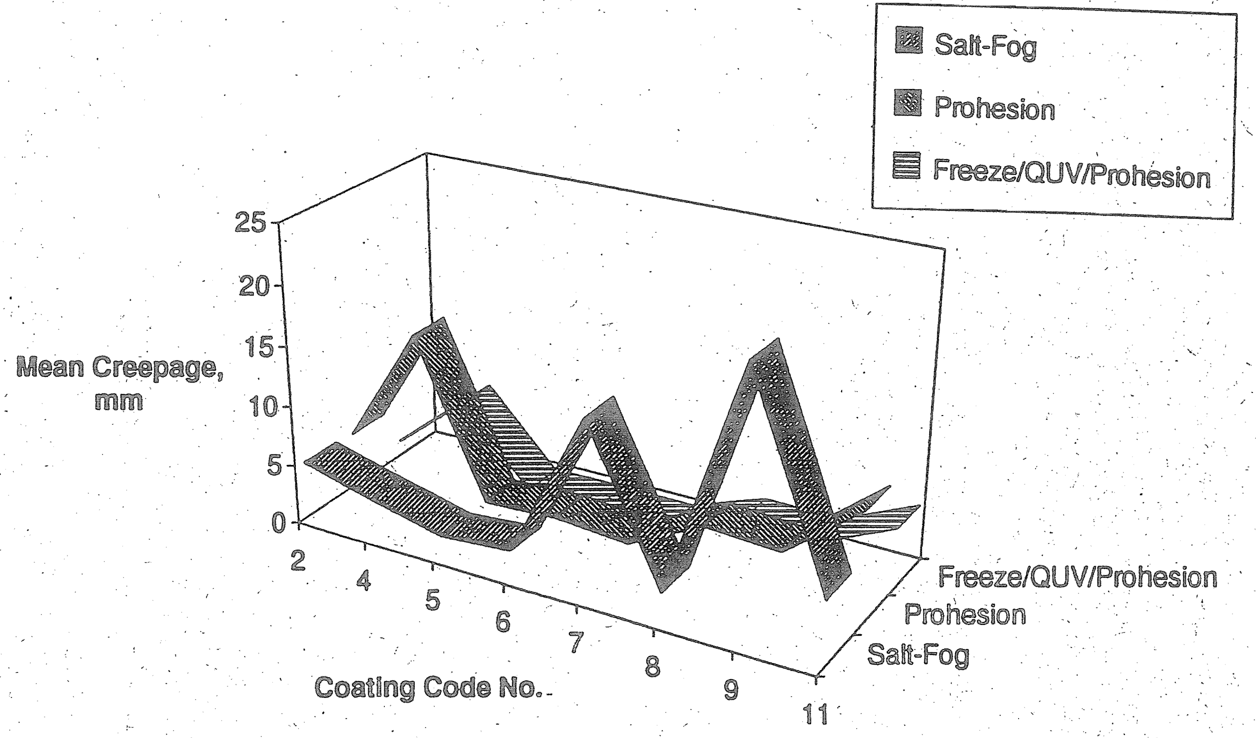

Figure 3. Plot of mean creepage of eight coating systems vs. exposure time for salt-fog test, Prohesion test, and cyclic freeze/QUV/Prohesion test.