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PREDICTION OF PAINT PERFORMANCE FROM A COMBINATION OF
ACCELERATED LABORATORY TESTS

Robert L. Alumbaugh, et al

Civil Engineering Laboratory (Navy)
Port Hueneme, California

November 1975

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CIVIL ENGINEERING LABORATORY
Naval Construction Battalion Center
Port Hueneme, California 93043

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OF ACCELERATED LABORATORY TESTS

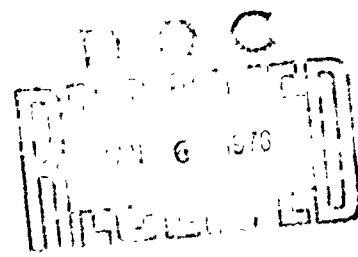
By

Robert L. Alumbaugh, Ph D and Peter J. Hearst, Ph D

November 1975

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performance of the paint systems on steel panels exposed to a wet-and-dry-cycle test procedure. Results of the accelerated laboratory tests on 12 paint systems were correlated with their long-term performance in two different marine atmospheric environments using linear regression analysis. Long-term performance data were based on visual ratings of the paints exposed on metal panels to the marine atmosphere at both Kaneohe and Kwajalein test sites. Data obtained from the accelerated laboratory tests were correlated individually and in various combinations with results of the long-term performance of the paint systems at the two test sites. Where good correlation was obtained, linear prediction equations were derived. Results of the linear regression analysis indicated that individual accelerated laboratory tests were not particularly good predictors of paint performance. However, certain combinations of the different accelerated laboratory test results showed promise as good predictors of paint performance when the paint systems correlated were of the same generic type. Coefficients are given for linear prediction equations where good correlation was obtained between the accelerated laboratory test results and long-term performance of the paint systems.

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The Civil Engineering Laboratory investigated various accelerated laboratory test procedures for use in predicting the long-term performance of paint systems for steel exposed to a marine atmosphere. These procedures included determining the electrical properties of the paint systems on steel panels (AC and DC resistance and AC capacitance), the water vapor permeability of free films of the paint systems, and the performance of the paint systems on steel panels exposed to a wet-and-dry-cycle test procedure. Results of these laboratory tests on 12 paint systems were correlated with their long-term performance in two different marine atmospheric environments using linear regression analysis. Long-term performance data were based on visual rating of the paints exposed on metal panels at both Kaneohe and Kwajalein test sites. Laboratory test data were correlated individually and in various combinations with results of the long-term performance of the paint systems. Where good correlation was obtained linear prediction equations were derived. Results of the linear regression analysis indicated that individual accelerated laboratory tests were not particularly good predictors of paint performance. However, certain combinations of the different accelerated laboratory test results showed promise as good predictors of paint performance when the paint systems correlated were of the same generic type. Coefficients are given for linear prediction equations where good correlation was obtained.

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INTRODUCTION

The Navy has shore installations located in different geographical areas throughout the world and uses large quantities of paint to preserve construction materials and protect them against deterioration. The varied and often extremely hostile environmental conditions encountered require use of the best protective materials and methods available to Public Works personnel. Consequently the Naval Facilities Engineering Command (NAVFAC) has maintained an active interest in new paints and protective coatings.

NAVFAC has sponsored a number of work units at the Civil Engineering Laboratory (CEL) concerned with the performance of paints and protective coatings. The determination of the relative performance of protective coatings often requires long-term tests. It would thus be desirable to develop valid accelerated test procedures that facilitate selection of the most promising new paints and coatings as they are introduced on the market and particularly to compare the performance of these to the specification paints that are normally used. NAVFAC has therefore sponsored investigations at CEL to find or develop accelerated test procedures for predicting the performance of paints exposed to marine atmospheric and immersed environments.

The paint industry as well as other industrial and government laboratories has directed a great deal of effort toward this same end. The fact that past investigations have been only partially successful is indicative of the variety, complexity, and interaction of the factors that contribute to the degradation of paint systems. This report describes the Laboratory's efforts to develop accelerated or rapid laboratory procedures for determining paint performance.

BACKGROUND

Investigations at CEL began with a literature survey of methods and procedures that were available [1, 2]. Initial experimental work was directed toward investigation of the photodegradation of organic coatings in an attempt to adapt this type of degradation for use as an accelerated test procedure. This work resulted in several reports [3-6] that included investigations of volatile products by conventional infrared spectroscopy and of irradiated free films by attenuated total reflectance spectroscopy. Although results were promising, it became apparent that great effort would be required before a test procedure could be developed for predicting field performance, and further work on this procedure was deferred indefinitely.

Concurrently with the investigations into the photodegradation of coating films, research was initiated to find or develop methods for determining the electrical properties of paint systems on steel. The primary objective was to investigate possible relationships between the electrical properties of immersed coating systems and the performance of these paint systems when exposed in the field. Changes in electrical properties during short-term exposures were determined; and, thus, the emphasis was on techniques of accelerated detection of the degradation of the coating films, rather than on methods of accelerated degradation of the coating films.

The results of these investigations [7-10] indicate that there is some correlation between the electrical measurements and the field performance of the same coating systems. However, the correlation is not sufficiently high to allow prediction of field performance.

Finally, a new method of using a Weather-Ometer was investigated as a method of accelerating the degradation of coating systems [11]. In this procedure, the painted panels were scribed in the upper and lower portions, and the lower scribe was dipped periodically in salt water. The panels were then subjected to a dew cycle which provided exposures to cycling conditions of light, heat, and high humidity in a salty environment. While results indicated the relative performance of the paint systems exposed to this environment, there was no conclusive evidence of correlation between these data and field exposures.

In some of the investigations mentioned above, as well as in many of the test procedures described in the literature [1, 2], limited correlation of laboratory test results with field performance was obtained. In a number of cases described in the literature, the results of one laboratory test on three or four coating systems showed relatively good correlation with field performance [1]. However, the original papers generally had no follow-up work reported even though it was often indicated that additional work was in progress. In such cases, it appeared that the additional work showed little if any correlation, and it was not considered worthwhile to further investigate the reported tests for predicting field performance.

While individual results from CEL tests described above do not exhibit sufficient correlation to reliably predict performance, it appeared that the data from such tests when used in conjunction with data from other accelerated tests might yield results which would show good correlation with field performance. The investigations were therefore expanded to explore this new approach; that is, the correlation of data from several accelerated or rapid laboratory tests with field performance, using linear regression analysis.

EXPERIMENTAL METHODS

Selection of Test Paints

In order to correlate laboratory tests with the performance of coating systems in the field, it was first necessary to select a series of coatings with known field performance. The performance data presented in NCEL Technical Report R-501 [12] were reviewed for both plain and scribed panels exposed to the marine atmosphere at Kaneohe, Hawaii, and Kwajalein, Marshall Islands, and the coatings in the study were selected from those included in that report. Attempts were made to select only systems for which both plain and scribed panels had failed at the two exposure sites.^a However, to include a sufficient number of coatings in the study, it was necessary to select some coating systems that had not failed. These latter coatings had exhibited long-term performance, and their time-to-failure was estimated.

Each coating system was given a protection ranking for performance on unscribed panels and for performance on scribed panels at each of the atmospheric test sites. This protection ranking is approximately 10 times the number of years of exposure required to produce failure of the coating system. Failure of a system was considered to have occurred when the general protection rating [12] decreased to a value of 7. This rating was essentially the same as the ASTM rusting rating, and failure was thus generally the point where 30% of the area had rusted.

To provide comparative ratings among several coatings that failed at the same time, the protection rankings were weighted on the basis of other performance factors. For coating systems that had not yet failed at the time of the last rating, an approximate protection ranking was assigned, which was obtained by multiplying the years of exposure by 10 and adding additional points, depending on the condition of the coating at the last rating. These additional points were about 10 for a protection rating of 8, 20 for a protection rating of 9, and 40 for a protection rating of 10, but were varied somewhat depending on other performance factors. Thus, the protection ranking in effect ranked each of the selected coating systems relative to one another according to their performance in the field.

To obtain valid laboratory data for correlation with the field performance, it was necessary to use coatings that were identical in composition to those previously exposed and reported in Reference 12. Therefore, the selected coatings were purchased only after the manufacturers had indicated that no significant changes had been made in formulation since the original purchase. A total of 46 coatings, comprising 25 different coating systems, were procured and tested to determine

^a The same coatings had also been exposed at Port Hueneme, but many of these had not failed; therefore, the performance of the coatings at Port Hueneme was not included in the study.

whether they conformed to the original formulation. Comparison of these results with those given in Reference 12 indicated no significant changes in composition.

Two different generic types of coating systems were included; thus, epoxy and vinyl coating systems were selected for this initial series of accelerated tests. In addition, an asphalt-emulsion system was included because it had shown by far the best field performance of any of the systems tested and had the highest protection ranking in the baseline group of coatings. The test group of 12 paint systems included six epoxies, five vinyls, and the asphalt emulsion.

A description of the 12 systems is given in Table 1. For continuity, the same system numbers that were used for these coatings in References 10 and 11 are continued in this report. The protection rankings for these 12 systems for both plain and scribed panels exposed at the two sites are given in Table 2.

Accelerated and Rapid Laboratory Tests

Several different rapid laboratory test procedures were considered for possible inclusion in the regression analysis and three were selected. These were the electrical measurements of immersed coated panels, the moisture permeability measurements of free paint films, and the exposure of scribed panels to the wet-and-dry-cycle test. Data for all 12 coating systems exposed to the three procedures are presented in Table 2.

Of the different procedures described in the background of this report, only the electrical measurements were included. The coating degradation studies gave results that would be difficult to relate quantitatively to performance associated with rusting, and the dew-cycle Weather-Ometer results were difficult to quantify for numerical calculations. The electrical measurements consisted of the DC resistance, the AC resistance, and AC capacitance. The electrical readings were taken on the painted steel panels immediately after immersion in seawater, after 6 hours (1/4 day), and after 10 days of immersion. Between measurements, the panels were exposed in flowing seawater. Details of the experimental procedure as well as theoretical considerations have been presented in earlier reports covering electrical measurements [7-10]. The data for seven of the twelve systems were presented previously in Reference 10.

The water/vapor permeability data were determined on free films of these systems using the radioisotope tracer technique developed by Matsui [13, 14]. This procedure consists of placing the free film as a barrier in the center of a permeability cell which is then evacuated. Tritiated water is introduced on one side of the film to give a vapor pressure differential of about 20 mm. Water vapor permeating through the film is condensed, and the amount of water obtained in a given time is determined radiometrically. The diffusion rates and permeability constants given in Table 2 were calculated by computer. Details of the experimental procedure and theoretical considerations are presented in References 13 and 14.

Table 1. Descriptions of the Coating Systems

System Number ^a	System Description and Color	No. of Coats	Thickness (mils)
Asphalt			
125 (16)	Mica-filled asphalt emulsion (black)		
	MIL-P-15328 (Formula 117), pretreatment primer	1	0.5
	TT-P-645 (Formula 84), alkyd-zinc chromate primer	1	1.5
	Mica-filled asphalt-emulsion finish	8	33.5
			Total 35.5
Epoxies			
111 (56)	Epoxy-phenolic (medium grey)		
	Epoxy metal primer	1	2.5
	Epoxy-phenolic finish	3	11.0
			Total 13.5
113 (57)	Epoxy (white)		
	Epoxy-zinc chromate primer	1	3.0
	Epoxy finish	2	10.5
			Total 13.5
115 (34)	Epoxy (grey)		
	Catalyzed epoxy primer	1	1.0
	Catalyzed epoxy intermediate	1	2.0
	Catalyzed epoxy finish	3	4.5
			Total 7.5
119 (41)	Epoxy (tan)		
	Catalyzed epoxy primer	1	1.0
	Catalyzed epoxy intermediate	1	2.5
	Catalyzed epoxy finish	2	2.5
			Total 6.0
124 (3)	Epoxy (white)		
	Epoxy red-lead primer	1	3.0
	Epoxy finish	3	5.5
			Total 8.5
126 (29)	Epoxy (grey)		
	Catalyzed epoxy primer	1	3.5
	Catalyzed epoxy finish	2	7.0
			Total 10.5

Table 1. Continued

System Number ^d	System Description and Color	No. of Coats	Thickness (mils)
Vinyls			
118 (5)	Vinyl (grey) Vinyl-phenolic strontium chromate iron oxide primer Vinyl finish	1 3	1.0 4.5 <hr/> Total 5.5
120 (6)	Vinyl mastic (black) Vinyl-phenolic strontium chromate iron oxide primer Vinyl mastic finish	1 4	1.5 11.0 <hr/> Total 12.5
122 (1)	Aluminum-pigmented vinyl (aluminum) MIL-P-15328 (Formula 117), pretreatment primer MIL-C-15929 (Formula 119), vinyl red-lead primer Aluminum-pigmented vinyl finish	1 2 2	0.5 3.5 2.5 <hr/> Total 6.5
127 (59)	Vinyl-alkyd (gloss black) MIL-P-15328 (Formula 117), pretreatment primer MIL-P-15929 (Formula 119), vinyl red-lead primer MIL-P-15932A (Formula 122-1), vinyl-alkyd finish	1 3 2	0.5 6.0 4.0 <hr/> Total 10.5
128 (71)	Vinyl-alkyd (grey) MIL-P-15328 (Formula 117), pretreatment primer MIL-P-15929 (Formula 119), vinyl red-lead primer MIL-P-15936B (Formula 122-27), vinyl-alkyd finish	1 2 1	0.5 3.5 3.0 <hr/> Total 7.0

^d System numbers in parentheses indicate the number of the original system as described in Reference 12.

The wet-and-dry-cycle test procedure developed at CEL used a cyclic testing machine obtained from Villanova University [15]. The modified cyclic test machine and the procedure are described in detail in Appendix A. The coated panels, which have an X scribed on the lower half, were rotated alternately through aerated synthetic seawater at ambient temperature and then through warm air at approximately 50°C. Each wet-and-dry cycle required about 3 hours, and the machine cycled continuously except when stopped for rating of the panels.

A description of the rating procedures as well as the performance ratings for the 12 systems is presented in the discussion and Table A-1 of Appendix A. The panels were rated in the manner described in Reference 12. The wet-and-dry-cycle dururances given in Table 2 were the number of cycles required to cause failure of the coating systems at the scribe mark, divided by 10.

Linear Regression Analysis

The laboratory test data and the field performance data were correlated by linear regression analysis. A more detailed explanation of linear regression analysis is given in Appendix B, but a brief description is given below.

In the linear regression analysis it is assumed that various properties of the paints, which can be changed independently of each other, will contribute to a result that is dependent on the cumulative effect of these factors. This relationship is expressed by the equation

$$y = A_1x_1 + A_2x_2 + A_3x_3 + \dots + A_nx_n + C$$

where x is an independent variable, A is a coefficient expressing the effect and importance of the independent variable, C is a constant, and y is the dependent variable or the result of the cumulative effects of the independent variables.

The independent variables (x_n) used are the following laboratory test data:

- x_1 = Days of exposure before electrical measurements
- x_2 = Log resistance, DC
- x_3 = Log initial resistance (R_0)/final resistance (R), DC
- x_4 = Resistance, AC
- x_5 = Log initial resistance (R_0)/final resistance (R), AC
- x_6 = Capacitance, AC
- x_7 = Log final capacitance (C)/initial capacitance (C_0), AC
- x_8 = Water vapor diffusion rate
- x_9 = Water vapor permeability constant
- x_{10}, x_{11} = Endurance for wet-and-dry-cycle test panels.

The dependent variables (y_n) are the field performances of the coating systems under the various exposures given as protection rankings:

y_1 = Scribed panels at Kwajalein

y_2 = Plain panels at Kwajalein

y_3 = Scribed panels at Kaneohe

y_4 = Plain panels at Kaneohe

y_5 = Combination of all protection rankings for both scribed and plain panels at both sites.

In the linear regression analysis program, one independent variable for each of the coating systems is first correlated with the performance under one type of exposure (the dependent variable) and a correlation coefficient is computed. Additional independent variables are then introduced into the program, one at a time, and the linear regression equation giving the best fit is calculated.

The closeness with which the dependent and independent variables fit this equation is calculated. This closeness of fit is the multiple correlation coefficient, R^2 . The values obtained for R^2 are given in Table 3. If the independent variables give a perfect fit to the linear equation, R^2 would equal ± 1.0 . If no fit or relationship to the linear equation exists, R^2 would equal 0.0. Coefficients and constants for equations having R^2 greater than 0.9 are given in Table 4.

The regression analysis was first carried out by correlating results from each of the three test methods individually (the independent variables) with each of the five different protection rankings or dependent variables (that is, scribed panels exposed at Kwajalein and at Kaneohe, plain panels exposed at these sites, and a combination of the protection rankings for all panels at both sites). This was done for all 12 paints as a group, for all epoxy paints as a group, and for all vinyl paints as a group. Thus, in runs 1, 8, and 16 (Table 3), the independent variables consisted only of the electrical measurements, x_1 through x_7 . In runs 2, 9, and 17, the independent variables consisted only of the permeability data, x_8 and x_9 ; in runs 3, 10, and 18, only the durances in the wet-and-dry-cycle test procedure, x_{10} and x_{11} , were utilized for correlation. This was to find if any of the three test methods alone gave results which correlated well with long-term field exposures.

In all other runs in Table 3, with two exceptions, correlations were obtained through use of independent variables from two or three of the three test methods. The objective was to include all possible combinations of independent and dependent variables. Results given in Table 3 are, in general, for those combinations exhibiting the best multiple correlation coefficients, R^2 . Other possible combinations not shown had potentially lower multiple correlation coefficients and were eliminated from further consideration in the linear regression analysis program. In all the calculations, the number of independent variables was kept lower than the number of observations for the dependent variable, to avoid an accurate but meaningless fit.

Table 2 Field Performance and Laboratory Test Data for the

System Number ^a	Protection Ranking ^b				Electrical Measurements ^c						
	Kwajalein		Kaneohe		Exposure Time (days)	DC		AC			
	Scribed	Plain	Scribed	Plain		Log R	Log R ₀ /R	R (kilo ohms)	Log R ₀ /R		
	y ₁ ^f	y ₂	y ₃	y ₄	x ₁ ^f	x ₂	x ₃	x ₄	x ₅		
Asphalt											
125 (16)	145 ^g	145 ^g	170 ^g	170 ^g	0	7.9		89		0.1	0.1
					1/4			70		0.1	0.1
					10	5.3	2.6	26		0.5	0.1
Epoxies											
111 (56)	28	110 ^g	90 ^g	110 ^g	0	10.1		2,200			0.1
					1/4			1,800		0.1	0.1
					10	7.7	2.4	510		0.6	0.1
113 (57)	14	90 ^g	9	100 ^g	0	9.9		2,000			0.1
					1/4			1,600		0.1	0.1
					10	8.0	1.9	790		0.4	0.1
115 (34)	40	55	35	64	0	9.9		1,680			0.1
					1/4			900		0.3	0.1
					10	7.8	2.1	510		0.5	0.1
119 (41)	45	47	58	60	0	9.9		1,500			0.1
					1/4			770		0.3	0.1
					10	7.0	2.9	110		1.1	0.1
124 (3)	17	69	59	122	0	10.8		1,210			0.1
					1/4			990		0.1	0.1
					10	8.8	2.0	260		0.7	0.1
126 (29)	28	54	39	80	0	9.4		1,110			0.1
					1/4			560		0.3	0.1
					10	6.9	2.5	120		1.0	0.1
Vinyls											
118 (5)	36	60	84	120	0	8.9		740			0.1
					1/4			280		0.4	0.1
					10	8.8	0.1	190		0.6	0.1
120 (6)	37	79	85	118	0	7.8		1,040			0.1
					1/4			250		0.6	0.1
					10	5.5	2.3	17		1.8	0.1
122 (1)	39	79	60	90	0	11.0		1,480			0.1
					1/4			1,380		0.0	0.1
					10	10.7	0.3	1,040		0.2	0.1
127 (59)	18	70	47	80 ^g	0	10.4		1,000			0.1
					1/4			770		0.1	0.1
					10	10.1	0.3	580		0.2	0.1
128 (71)	9	90 ^g	10	90 ^g	0	10.4		960			0.1
					1/4			660 ^f		0.2	0.1
					10	9.8	0.6	480		0.3	0.1

A

Dry Test Data for the Coating Systems

Parameters ^c				Permeability Data ^d		Wet-and-Dry-Cycle Endurance ^e	
AC				Diffusion Rate	Permeability Constant	Panel 1	Panel 2
(ohms)	Log R ₀ /R	C (μf)	Log C/C ₀				
	x ₅	x ₆	x ₇	x ₈	x ₉	x ₁₀	x ₁₁
79	0.1	0.0038		1.34	0.708	165 ^g	155 ^g
70	0.5	0.0050	0.12				
26	0.5	0.0310	0.92				
80	0.1	0.0017		6.48	1.253	142	142
80	0.6	0.0023	0.16				
80	0.1	0.0018		2.86 ^b	0.502 ^b	24	24
80	0.4	0.0023	0.09				
80	0.3	0.0029		7.69 ^b	1.056 ^b	97	54
80	0.5	0.0032	0.04				
80	0.5	0.0039	0.13				
70	0.3	0.0044		5.65	0.639	125	147 ^g
10	1.1	0.0050	0.06				
10	1.1	0.0086	0.29				
80	0.1	0.0048		5.73	0.725	110	125
80	0.1	0.0050	0.02				
80	0.7	0.0069	0.15				
80	0.3	0.0028		2.04 ^b	0.295 ^b	75	84
80	0.3	0.0033	0.08				
80	1.0	0.0081	0.47				
40	0.4	0.0031		12.56	1.094	86	86
80	0.6	0.0042	0.12				
80	0.6	0.0058	0.27				
40	0.6	0.0021		5.47	1.091	155 ^g	142
50	1.8	0.0033	0.20				
17	1.8	0.0210	1.00				
80	0.0	0.0034		4.62	0.406	144 ^g	144 ^g
80	0.2	0.0035	-0.01				
40	0.2	0.0035	0.02				
80	0.1	0.0034		12.24 ^b	1.846 ^b	109	74
70	0.1	0.0036	0.02				
80	0.2	0.0039	0.06				
60	0.2	0.0053		10.60 ^b	0.956 ^b	58	58
60	0.2	0.0058	0.04				
80	0.3	0.0066	0.10				

FOOTNOTES

- ^a System numbers in parentheses indicate the numbers of the original systems as described in Reference 12.
- ^b The protection ranking is 10 times the years to failure, with minor adjustments.
- ^c Values are averages for three panels, each with 120 sq cm of exposed paint surface; R = resistance in ohms, unless otherwise noted; C = capacitance; R₀ and C₀ are the values immediately after immersion.
- ^d The values are the averages of five readings, except as noted; the water diffusion rate is in units of mg/cm²/hr at a vapor pressure differential of 20 mm Hg; the permeability constant is in units of mg-mm/cm²/hr/cm Hg.
- ^e The endurance is one tenth of the number of cycles to failure (from Table A-1 in Appendix A).
- ^f y_n = dependent variables; x_n = independent variables.
- ^g These values were estimated because the paint systems had not failed.
- ^h Average of five readings for each of two samples.
- ⁱ Average for two panels.

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Table 3. Correlation Coefficients for Prediction Equations

Run Number	Kwajalein Panels				Kaneohe Panels		
	Scribed (y_1) ^a		Plain (y_2) ^a		Scribed (y_3) ^a		Plain (y_4) ^a
	Independent Variable ^c	R ^{2d}	Independent Variable	R ²	Independent Variable	R ²	Independent Variable
All Paints							
1	1, 3-7	0.5492	1-7	0.3633	1-7	0.4483	1-7
2	8, 9	0.2651	8, 9	0.3022	8, 9	0.2390	8, 9
3	10, 11	0.3434	10, 11	0.1148	10, 11	0.6182	10, 11
4	2, 4, 6, 8-11	0.7662	2, 4, 8, 9	0.3874	2, 4, 6, 8-11	0.8426	2, 4, 6, 8-11
5	4, 6, 8, 10, 11	0.6903	4, 6, 8, 9	0.3660	4, 6, 8-11	0.7408	4, 8-11
6	2, 4, 6, 8-11	0.7550	2, 4, 6, 8-11	0.7440	2, 4, 6, 8-11	0.7841	2, 4, 6, 8-11
7	1, 4, 6, 8-11	0.6723	1, 4, 6, 8-11	0.3415	1, 4, 6, 8-11	0.7360	1, 4, 6, 8-11
Epoxy Paints							
8	1-7	0.2615	1-4, 6	0.6950	1-7	0.1182	1-7
9	8, 9	0.3556	8, 9	0.8237	8, 9	0.3718	8, 9
10	10, 11	0.3669	10, 11	^e	10, 11	0.8960	10, 11
11	4, 9, 11	0.1836	4, 6, 11	0.6863	4, 6, 9, 11	0.9904	4, 6, 11
12	4, 6, 9, 11	0.6037	4, 6, 9, 11	0.9511	4, 6, 9, 11	0.9769	4, 6, 9, 11
13	4, 6, 9, 11	0.5476	4, 6, 9, 11	0.9735	4, 6, 9, 11	0.9946	6, 9, 11
14	8, 10, 11	0.3765	8	0.0008	8, 10	0.9093	8, 10, 11
15	1, 4, 6, 8-11	0.6795	1, 4, 6, 8-11	0.9893	1, 4, 6, 8-11	0.9923	1, 4, 6, 8-11
Vinyl Paints							
16	3-7	0.7428	1-7	0.5609	1-7	0.8392	1, 2, 4-7
17	8, 9	0.3230	8, 9	0.2148	8, 9	0.0995	9
18	10, 11	0.7287	10, 11	0.0489	10, 11	0.4246	10, 11
19	4, 9, 11	0.8326	4, 9, 11	0.3560	4, 9, 11	0.8552	4, 9, 11
20	4, 9, 11	0.7552	4, 9, 11	0.2044	4, 9, 11	0.7170	4, 9, 11
21	4, 9, 11	0.7385	9, 11	0.1779	4, 9, 11	0.6783	4, 9, 11
22	8, 10, 11	0.9990	8, 10, 11	0.9822	8, 10, 11	0.9470	8, 10, 11

^a y_n = dependent variable.

^b Exposure times, where given, indicate which of the electrical measurement data were used in the regression analysis (see Table 2).

^c The numbers listed are the subscripts of the independent variables, x_n :

x_1 = days of exposure (applicable to electrical measurements only)

$x_3 = \log \frac{\text{initial D.C. resistance}}{\text{final D.C. resistance}}$

$x_5 = \log \frac{\text{initial A. C. resistance}}{\text{final A. C. resistance}}$

$x_7 = \log \frac{\text{final capacitance}}{\text{initial capacitance}}$

x_9 = permeability constant

x_2 = log D.C. resistance

x_4 = A.C. resistance

x_6 = capacitance

x_8 = diffusion rate

x_{10}, x_{11} = protection rank

^d Correlation coefficient.

^e Data not sufficiently significant for computation of R^2 .

A

Coefficients for Prediction Equations

Kanebo Panels				All Panels At Both Sites		Exposure Time ^b (days)
Described (y ₃) ^a		Plain (y ₄) ^a		(y ₅) ^a		
Independent Variable	R ²	Independent Variable	R ²	Independent Variable	R ²	
All Paints						
	0.4483	1-7	0.4226	1, 3-7	0.5292	0, 1/4, 10
	0.2390	8, 9	0.1329	8, 9	0.2844	
	0.6182	10, 11	0.1575	10, 11	0.3860	
8-11	0.8476	2, 4, 6, 8-11	0.5752	2, 4, 6, 8, 9, 11	0.7227	0
11	0.74	4, 8-11	0.3360	4, 6, 8-11	0.5751	1/4
8-11	0.7841	2, 4, 6, 8-11	0.6014	2, 4, 6, 9-11	0.7584	10
8-11	0.7360	1, 4, 6, 8-11	0.3709	1, 4, 6, 8-11	0.5973	0, 1/4, 10
Epoxy Paints						
	0.1182	1-7	0.2235	1-7	0.2401	0, 1/4, 10
	0.3718	8, 9	0.2433	8, 9	0.6056	
	0.8960	10, 11	0.0877	10, 11	0.3517	
11	0.9904	4, 6, 11	0.0584	6, 9, 11	0.7100	0
11	0.9769	4, 6, 9, 11	0.4915	4, 6, 9, 11	0.8724	1/4
11	0.9946	6, 9, 11	0.4289	4, 6, 9, 11	0.9085	10
	0.9093	8, 10, 11	0.1122	10, 11	0.3517	
8-11	0.9923	1, 4, 6, 8-11	0.5850	1, 4, 6, 8-11	0.9341	0, 1/4, 10
Vinyl Paints						
	0.8392	1, 2, 4-7	0.6104	1-4, 6, 7	0.7492	0, 1/4, 10
	0.0995	9	0.0337	8	0.1900	
	0.4246	10, 11	0.2373	10, 11	0.5414	
11	0.8552	4, 9, 11	1.0000	4, 9, 11	0.9748	0
11	0.7170	4, 9, 11	0.9204	4, 9, 11	0.8778	1/4
11	0.6783	4, 9, 11	0.8705	4, 9, 11	0.8404	10
11	0.9470	8, 10, 11	0.5746	8, 10, 11	0.8521	

used in the regression analysis (see Table 2).

x₂ = log D.C. resistance

x₄ = A.C. resistance

x₆ = capacitance

x₈ = diffusion rate

x₁₀, x₁₁ = protection rankings for cyclic test panels.

L

Table 4. Regression Coefficients

Run Number ^a	Dependent Variable ^b	Correlation (R ²)	Coefficients		
			A ₁	A ₄	A ₆
11	y ₃	0.9904		-0.019	-8,736
12	y ₂	0.9511		0.041	-4,898
12	y ₃	0.9769		-0.008	-6,519
13	y ₂	0.9735		-0.046	-18,108
13	y ₃	0.9946		-0.110	-11,765
13	y ₅	0.9085		-0.153	-35,067
14	y ₃	0.9093			
15	y ₂	0.9893	-0.434	-0.003	746
15	y ₃	0.9923	-0.411	-0.003	707
15	y ₅	0.9341	-2.445	-0.015	4,208
19	y ₄	1.0000		-0.089	
19	y ₅	0.9748		-0.180	
20	y ₄	0.9204		-0.040	
22	y ₁	0.9990			
22	y ₂	0.9822			
22	y ₃	0.9470			

^a As shown in Table 3, runs 11 to 15 developed equations for the epoxy paints, and runs 19 to 22 developed equations for the vinyl paints.

^b The protection rankings are for the following exposures:

y₁ = scribed panels at Kwajalein

y₃ = scribed panels at Kaneohe

y₂ = plain panels at Kwajalein

y₄ = plain panels at Kaneohe

^c The regression coefficients, and the constant, are for the equation

$$y = A_1x_1 + A_2x_2 + \dots + A_nx_n + C$$

The independent variables, x_n, are described in footnote c of Table 3. Because x₂, x₃, x₅, and x₇ were not used in any of the runs, no corresponding regression coefficients are given.

Regression Coefficients for Prediction Equations

Regression Coefficients ^c						Constant ^c (C)
A ₄	A ₆	A ₈	A ₉	A ₁₀	A ₁₁	
-0.019	-8,736.735		32.409		0.508	32.930
0.041	-4,898.976		-7.646		0.112	36.575
-0.008	-6,519.320		22.423		0.524	11.643
-0.046	-18,108.284		-57.226		0.423	-0.046
-0.110	-11,765.786		3.018		0.404	112.692
-0.153	-35,067.088		-73.858		1.160	427.067
		-3.378		0.732		-4.477
-0.003	746.489	-12.435	163.414	-1.247	0.755	60.248
-0.003	707.122	-8.070	60.309	0.288	0.259	-6.680
-0.015	4,208.257	-26.018	331.216	-1.984	1.713	155.230
-0.089			-15.205		0.443	164.669
-0.180			-16.269		1.630	301.754
-0.040			-15.535		0.152	127.476
		4.445		0.258	0.908	-75.694
		-6.886		0.051	-0.630	196.076
		14.186		-0.216	1.918	-241.284

nts, and runs 19 to 22 developed equations for

panels at Kaneohe

y_5 = all panels at both sites

panels at Kaneohe

cause x_2 , x_3 , x_5 , and x_7 were not used in these

P

DISCUSSION

It is known that paints or protective coating systems will protect steel panels and will prevent their rusting because of certain inherent properties of the paints. If all these properties and the performance could be identified and quantified, it would be possible to write an accurate equation for predicting the performance on the basis of the properties. Such an equation might be quite complicated because of exponential relationships; but perhaps it could be approximated by a linear equation if, for example, logarithmic values are used for the properties. The equation could be further complicated by interactions in the effects of the various inherent properties.

Another problem in the development of such an equation is that the inherent properties that determine the performance of a paint generally cannot be measured directly. As an example, a paint that completely prevents access of water should give perfect protection. Yet, there is no way of defining or measuring the inherent property that affects the transmission of water through the paint. It is possible however, to measure the moisture permeability, and this property was included in the prediction equation. As a second example, a primer with good inhibitive pigments will prevent rusting at scratches. Although the inherent inhibitive quality cannot be defined or measured, this inherent quality should affect the results of the wet-and-dry-cycle test, which were included in the prediction equation. As a third example, a coating that has an inherent stability in a salt-water environment will give better protection than a coating that deteriorates readily. Again, the inherent quality of permanence cannot be defined or measured, but this quality will affect changes in the electrical properties of the coating that were measured in the laboratory.

One of the simplest methods of relating the properties of the coatings as independent variables with the field performances as dependent variables is by linear regression analysis, which has been described in the prior section. This method was therefore employed with the available data, with the knowledge that the independent variables chosen were not always independent.

The correlations between field exposure results and selected laboratory test results are discussed in detail in Appendix C.

Although the results described in Appendix C are not completely definitive because of the limited number of paints and laboratory test procedures included in the analysis program, some pertinent observations can be made. First, it appears that results from individual laboratory test methods are not good predictors of performance for paints exposed in the field. Presumably, no one test can accelerate or measure all of the variables that have a bearing on coating performance. Also as observed in References 1 and 2, a given accelerated test procedure might be useful in predicting relative field performance of three or four coating systems, but of less value in predicting the relative performance of a larger group of paint systems.

The initial concept--that better correlations could be obtained using results from more than one laboratory test procedure--appears to be verified by the fit of some of the data to the linear regression equation. The multiple correlation coefficients show a definite increase when results from all three laboratory procedures are correlated with field performance data for all 12 paints. Even so, these R^2 values are not considered sufficiently significant that the linear equations derived can be used with any degree of certainty to predict the field performance of paints.

One of the major problems in developing a system such as this for predicting the performance of paint systems was to arrive at a sound baseline of paints with known field performance with which to correlate accelerated laboratory test results. Since the field performance data or dependent variables are based on subjective visual ratings, these may show more variability than the independent variables, most of which are derived by physical measurements.

Some laboratory test data might give better performance predictions for scribed than for unscribed panels. Other laboratory test data might be more applicable for different field exposure sites. For example, the wet-and-dry-cycle test results might be emphasized in the correlation with the performance of scribed panels, and the permeability data might be emphasized in the correlation of the performance of plain panels. The laboratory data therefore was correlated with five different sets of protection rankings obtained under different exposures. These included protection rankings for scribed panels at Kwajalein and at Kaneohe, for plain panels at Kwajalein and at Kaneohe, and for a combination of the protection rankings for all panels at both sites.

Study of Table 3 indicates that the regression analysis technique shows more promise for predicting the performance of paints grouped generically. This is logical because the various factors that lead to deterioration of paints would be expected to degrade in the same manner as those materials that are chemically similar while degrading somewhat differently those paints that are chemically different.

Further, the independent variables chosen have a bearing on the results of the correlation. For instance, with epoxy paints, the results from the AC resistance, AC capacitance, permeability constant, and wet-and-dry-cycle tests correlate well with field performance while results from the diffusion constant and wet-and-dry-cycle test together show relatively poor correlation with the same dependent variables. For the vinyl paints, however, the results from the diffusion constant and the wet-and-dry-cycle tests together show very good correlation with field performance.

The results given and discussed above suggest that the linear regression analysis method shows some promise for predicting coating performance in the field on the basis of the results of accelerated laboratory tests when a multiple correlation coefficient of 0.9 or greater is obtained. This has been shown to be true when using data obtained from the same population of coating systems from which the predicting equations were derived. The chances for success in using

these equations for predicting the performance of a new population of epoxy paints or of vinyl paints is, of course, less certain. Also, they should not be used for predicting performance of other generic types of coatings. Finally, the validity of the prediction equations can only be established for a new population of epoxy or vinyl paints by obtaining field performance and accelerated laboratory test data. Once the system has been shown to be valid, additional research would be necessary to perfect the method so that the best accelerated measuring or testing procedures can be utilized.

CONCLUSIONS

1. Linear regression analysis appears to show promise as a method for predicting paint performance in the field using data from selected accelerated laboratory measuring or testing techniques on these same paint systems.
2. The method seems primarily useful for predicting the relative performance of a group of paints that are of the same generic type. The data also indicate that the laboratory results best suited to predict performance may vary with the generic type. For epoxy paints the best predictors are the group of independent variables: AC resistance, AC capacitance, permeability constant, and the wet-and-dry-cycle test results. For vinyl paints, the best predictors are the group of independent variables: the diffusion rate and the wet-and-dry-cycle test results; these are followed closely by the group of independent variables: AC resistance, permeability constant, and the wet-and-dry-cycle test results.
3. To prove the validity of the linear regression analysis method and to optimize the method by determining additional accelerated measuring or testing techniques that would be good predictors, a considerable amount of additional research would be required.

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REFERENCES

1. Naval Civil Engineering Laboratory. Technical Note N-549: Accelerated testing of paints, by P. J. Hearst. Port Hueneme, CA, Dec 1963.
2. ———. Technical Note N-640: Accelerated weathering of paints, by P. J. Hearst. Port Hueneme, CA, Aug 1964.
3. ———. Technical Note N-685: Degradation of organic coatings by irradiation with light. I. Volatile products from ultraviolet irradiation in air, by P. J. Hearst. Port Hueneme, CA, Dec 1964.
4. ———. Technical Note N-694: Degradation of organic coatings by irradiation with light. II. Attenuated total reflectance spectra of coating exposed to ultraviolet light, by P. J. Hearst. Port Hueneme, CA, Feb 1965.
5. ———. Technical Report R-460: Volatile photodegradation products of organic coatings, by P. J. Hearst. Port Hueneme, CA, Jul 1966.
6. ———. Technical Report R-479: Effect of photodegradation on attenuated total reflectance spectra of organic coatings, by P. J. Hearst. Port Hueneme, CA, Sep 1966.
7. ———. Technical Note N-706: Electrical methods for predicting paint performance--A literature survey, by P. J. Hearst. Port Hueneme, CA, Mar 1965.
8. ———. Technical Note N-795: Electrical properties of coatings as related to performance. I. Experiments with five immersed coating systems, by P. J. Hearst. Port Hueneme, CA, Dec 1965.
9. ———. Technical Note N-885: Electrical properties of coatings as related to performance. II. Experiments with seven additional coating systems, by P. J. Hearst. Port Hueneme, CA, Apr 1967.
10. ———. Technical Report R-683: Relation between changes in electrical properties and performance of coatings--Experiments with thirteen immersed coating systems, by P. J. Hearst. Port Hueneme, CA, May 1970.
11. ———. Technical Note N-1071: Protective properties of coatings as measured by dew-cycle accelerated weathering, by P. J. Hearst. Port Hueneme, CA, Jan 1970.
12. ———. Technical Report R-501: Nine year program on atmospheric exposures of protective coatings for steel, by C. V. Brouillette. Port Hueneme, CA, Jan 1967.

13. ———. Technical Note N-992: Water vapor diffusion through protective coatings. Part 1, A method of measuring water vapor permeability of coating films by radioisotope tracer technique and its application, by E. S. Matsui. Port Hueneme, CA, Oct 1968.
14. ———. Technical Report R-674: Water permeability of coating films using a radioisotope tracer technique, by E. S. Matsui. Port Hueneme, CA, Apr 1970.
15. Navy Bureau of Yards and Docks. Progress Report NEY-4712: Preservation of vehicles and vehicle components, by G. N. Quam, D. Schwartz, and W. Barnhurst. Research and Development Division, Villanova University, Villanova, PA, Sep 1956.

Appendix A

WET-AND-DRY-CYCLE TEST PROCEDURE

The wet-and-dry-cycle test procedure was used to duplicate and to accelerate some of the factors known to contribute to the deterioration of paint systems. Moisture, oxygen, salts, heat and light, and the interaction of these--all play a significant role in the degradation of paint films. All of these factors, except for a light source, were incorporated into this cyclic test procedure. The performance data for coating systems exposed to severe marine atmospheric environments, such as at Kwajalein and Kaneohe, indicated that the wetting and drying of coating films is a particularly important consideration.

A cyclic testing machine, developed by Dr. Quam and coworkers [15] at Villanova University, was obtained and modified for this work. The modification gave a time for a complete cycle of about 3 hours, during which the coated steel specimens were subjected to aerated synthetic seawater for 1-1/2 hours and to warm air at 50°C for 1-1/2 hours. The apparatus was designed to operate continuously, thus giving approximately eight cycles during a 24-hour period. The modified machine is shown in Figures A-1 and A-2.

Basically the wet-and-dry-cycle apparatus consists of a 32-inch-diameter, coated steel wheel (A) that has 12 equally spaced rods (B) with insulators (C) attached perpendicularly to each side, near the outer periphery of the wheel. The wheel is rotated by means of a belt and pulley arrangement (D) which is driven by an electric motor (E) through a gear reduction box (F). The number of cycles through which the wheel and, hence, the panels revolve are counted by a digital counter (G) activated by a lever^b attached to the upper pulley (H).

Coated steel panels^b (I) measuring 2-3/4 by 5-7/8 inches and having an "X" scribed through the paint to the metal on one side of the lower half of the panel are attached to the insulators with nickel wires. The wires permit the panels to rotate around the insulator as the wheel rotates and also keeps the plane of the panels immediately between and parallel to the sides of both warm-air drying chambers (J) (one on each side of the wheel) through which the panels pass on rotation. Heat is supplied by a chromel wire embedded in asbestos on the sides and bottom of the warm-air chambers and the temperature is manually controlled to about 50°C with autotransformers (K). The temperature in the top and sides of the warm-air drying chambers is monitored by thermocouples (L) attached to a strip chart recorder (M). The entire upper half of the wheel, which constitutes the warm-air chamber, is enclosed on all sides and on top with asbestos board (N) to insulate and maintain a constant temperature.

^b The panels were sandblasted, and the coating systems listed in Table 1 were applied with an automatic paint spray machine.

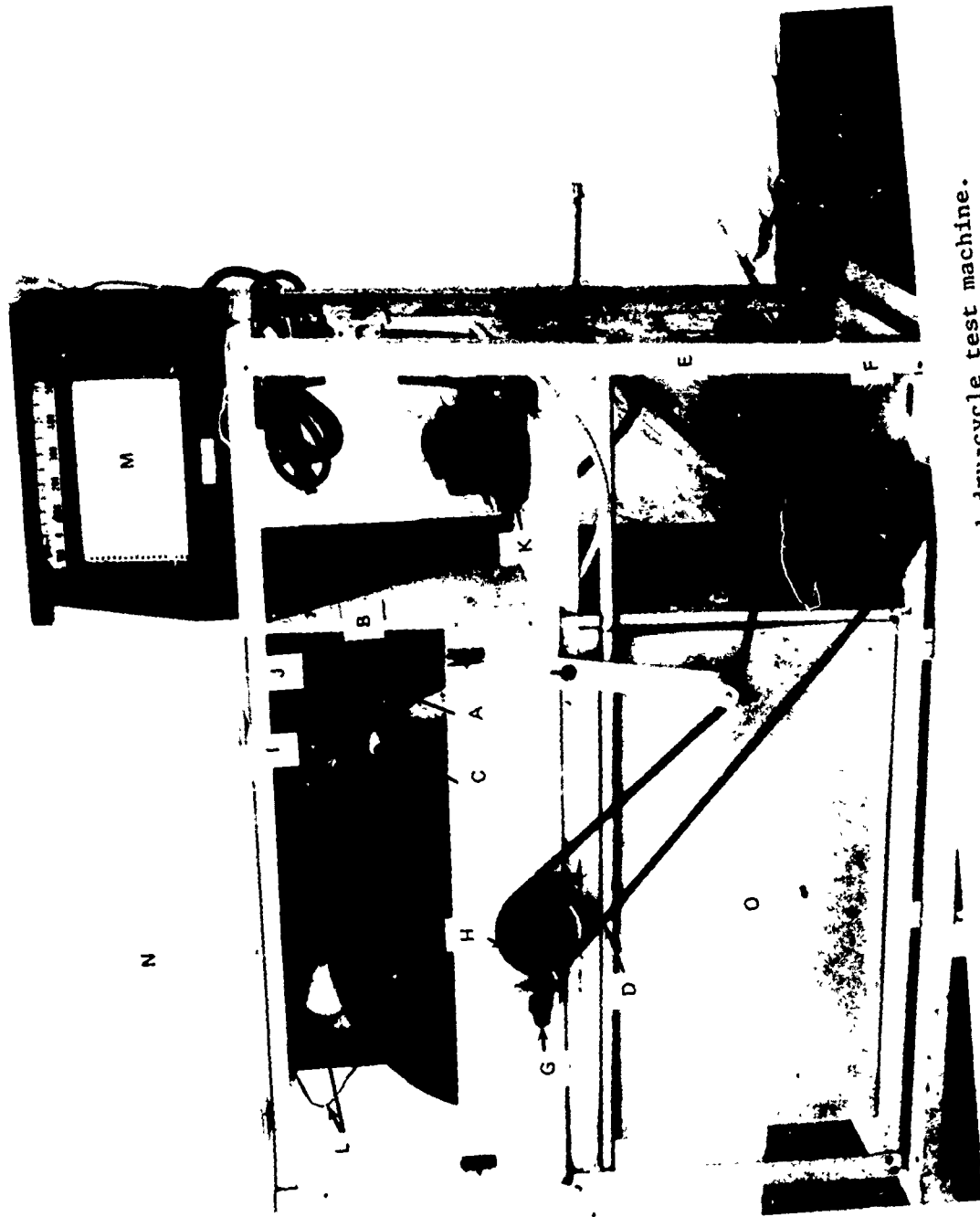


Figure A-1. Side view of wet-and-dry-cycle test machine.

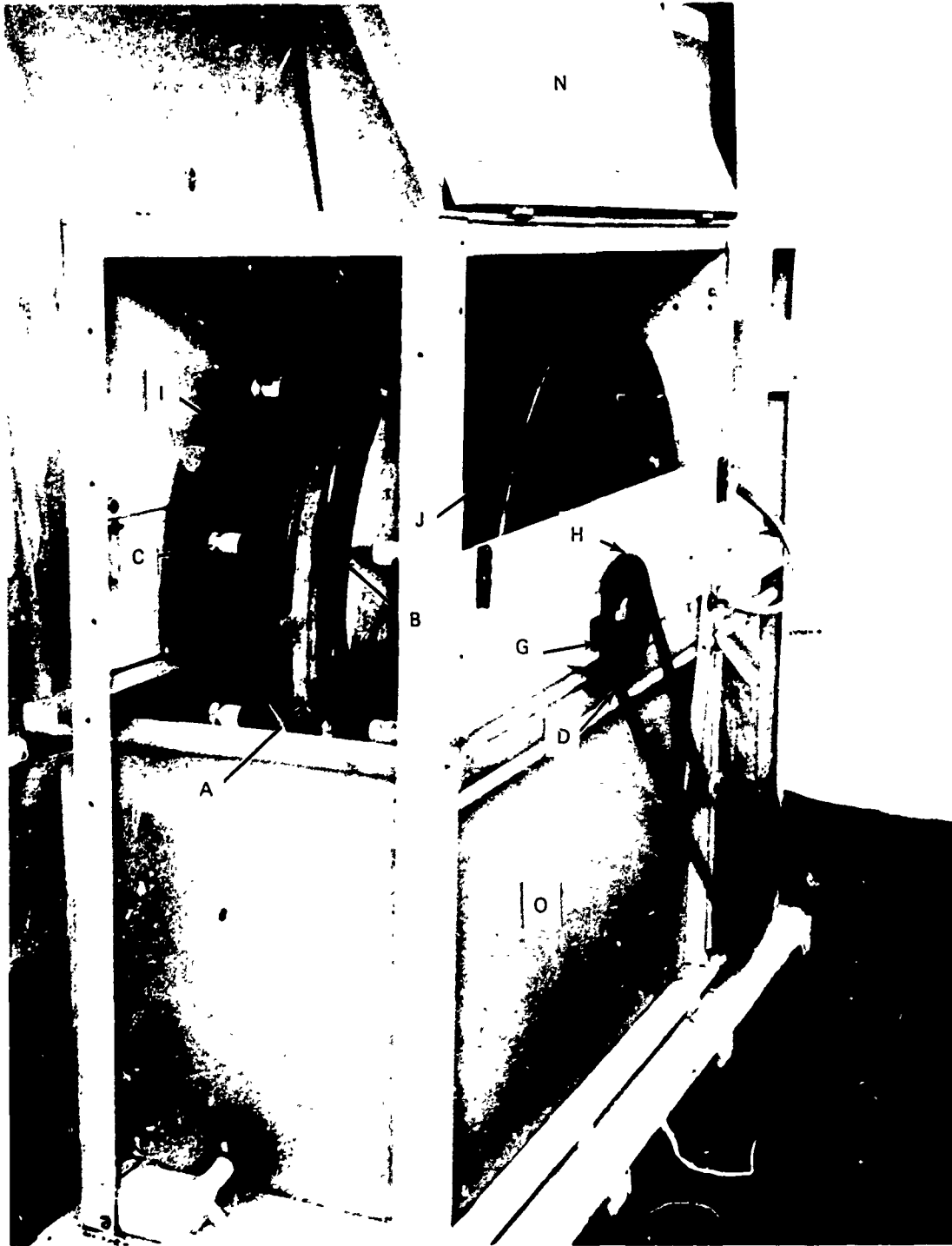


Figure A-2. End view of wet-and-dry-cycle test machine.

The bottom half of the wheel rotates into and through a large rectangular polyethylene container (O) filled with aerated synthetic seawater maintained at ambient temperature.

Duplicate scribed panels of the 12 paint systems listed in Table 1 were included in this phase to investigate the cyclic testing machine. The duplicate panels of a given system were attached to opposite sides of the wheel 180 degrees apart. Thus, when one panel of a given system was immersed in the synthetic seawater, the duplicate panel was subjected to the drying cycle. This was done to compensate for any irregularities that might occur during the cycling operation.

At periodic intervals, the cycle was interrupted, and the panels were removed and rated for performance. Ratings were assigned in accordance with ASTM Photographic Reference Standards, where applicable. The factors rated included checking (ASTM D 660-44); cracking (ASTM D 661-44); flaking, peeling, rusting (ASTM D 610-68); rusting at the scribe; blistering (ASTM D 714-56); blistering at the scribe; tuberculation; undercutting; and general protection. Thus, most of the ratings were on a 10 to 0 scale where 10 indicates a perfect coating system without defects while 0 indicates a coating that has failed completely in the rated category. For tuberculation, rusting in the scribe, and undercutting, factors were given alphanumerical ratings which indicated the frequency and severity of the coating deterioration; frequency was assigned a numerical rating as described above while severity was rated as L for light, M for medium, and H for heavy. The ASTM ratings for blistering include a numerical rating of 2, 4, 6, or 8 for the blister size and the letters F for few, M for medium, MD for medium dense and D for dense blistering.^c More definitive information on these test methods can be obtained from the appropriate ASTM test methods or in Reference 12. The ratings for the 12 systems exposed to the cyclic test procedure are given in Table A-1.

Deterioration of the paint systems subjected to the wet-and-dry-cycle test occurred only in or adjacent to the scribe. Thus, the rating factors included in Table A-1 indicate the deterioration of the scribe. These factors are general protection, tuberculation, rusting, undercutting, and blistering. The general protection rating is more fully discussed in Reference 12.

When the general protection rating assigned was 7 or less, the coating system was considered to have failed; and the panel was removed from the test. At this point the endurance given in Table A-1 was assigned. The endurance in this case is the number of cycles required to cause paint failure (a protection rating of 7) divided by 10, with minor adjustments to differentiate between systems failing at approximately the same time.

^c Sometimes the designations VL and VF were used for very light or very few and intermediate severities were indicated by combining letters, such as LM.

Table A-1. Wet-and-Dry-Cycle Test Results

System	Number of Cycles	General Protection		Tuberculation		Rusting on Scribe		Undercutting		Blistering on Scribe		Remarks
		1	2	1	2	1	2	1	2	1	2	
125. Mica-filled asphalt emulsion	8	10	10	10	10	4/L	5-/L	10	10	10	10	Cycle 8, Panel 1: Rust on bottom 2/3 of scribe Cycle 16, Panel 2: Rust on bottom of scribe Endurance: Panel 1-165 ^a Panel 2-155 ^a
	16	10	10	10	10	2/L	4/L	10	10	10	10	
	20	10	10	10	10-	1/L	2/L	10	10	10	10	
	29	10	10	10	10-	0/L	2/L	10	10	10	10	
	54	10	10	10	10-V/L	0/L	0/L	10	10	10	10	
	95	10	10	10	10	0/L	0/L	10	10	10	10	
	145	10	10	8/L	8/L	0/L	0/L	10	10	10	10	
	182	10	10	10	10	0/L	0/L	10	10	10	10	
	240	10	10	9+/L	10	0/L	0/L	10	10	10	10	
	303	10	10	9/L	9/L	0/L	0/L	10	10	10	10	
	350	10	10	9/L	9/L	0/L	0/L	10	10	10	10	
	402	10	10	9/L	9/L	0/V/L	J/V/L	10	10	10	10	
	453	10	10	7/L	8/L	0/L	0/L	9/L	10	10	10	
	508	9+	9+	8/M	9/M	0/L	0/L	9/L	10	10	10	
	539	9+	9	8/M	8/M	0/L	0/L	9/L	9/L	10	10	
	577	9+	9+	9/M	9/M	0/L	0/L	9/L	9/L	10	10	
	636	9+	9+	9/L	9/L	0/L	0/L	9+/L	9+/L	10	10	
	741	9	9	9/M	9/M	0/L	0/L	9/L	9/L	10	10	
	860	9	9-	9/M	9/M	0/L	0/L	9/L	9-/L	10	10	
	974	9	9-	9/L	9/M	0/L	0/L	9/L	8+/L	10	10	
1,089	9	9-	9/L	9/M	0/L	0/L	9/L	9-/L	10	10		
1,245	9	8	9/L	8+/M	0/L	0/L	9/L	8+/L	10	10		
1,419	9	8	9/L	8/M	0/L	0/L	9/L	8/L	10	2/F		

continued

Table A-1. Continued

System	Number of Cycles	General Protection		Tuberculation		Rusting on Scribe		Undercutting		Blistering on Scribe		Remarks
		1	2	1	2	1	2	1	2	1	2	
111. Epoxy-phenolic	8	10	10	10	10	4/L	3/L	10	10	10	10	Cycle 16, Panel 2: Pin point rusting in upper left of panel Cycle 303, Panel 1: Small rust spot on backside of panel Endurance: Panel 1-142 Panel 2-142
	16	10	10	10	10	2/L	0/L	10	10	10	10	
	20	10	10	10	8/M	1/L	0/L-M	10	10	10	10	
	29	10	10	9+/L	9+/L	0/L	0/L-M	10	10	10	10	
	54	10	10	9+/L	9+/L	0/L	0/L	10	10	10	10	
	95	10	10	6/L	10	0/L	0/L	10	9+/L	10	8/VF	
	145	10	9+	6/M	8/L	0/M	0/L	10	9/L	10	10	
	182	10	9+	9/M	9/M	0/M	0/M	9/L	6/L	10	10	
	240	10	10	10	10	0/L	0/L	10	10	8/F	8/F	
	303	9+	9+	8/M	9/M	0/M	0/M	9/L	9/L	10	4/F	
	350	9	9+	9/M	9/M	0/M	0/M	8/M	9+/L	2/M	4/F	
	402	8	8	7/H	8/H	0/M	0/H	5/H	9/L	4/M	4/M	
	453	8	8	8/H	8/H	0/M	0/M	5/H	7/M	2/M	2/M	
	508	8	8	7/H	7/H	0/H	0/H	5/H	5/H	2/MD	2/M	
	539	8	8	8/H	8/H	0/M	0/M	5/H	5/M	2/M	2/M	
	577	8	8	7/H	7/H	0/M	0/M	6/H	6/H	2/MD	2/MD	
	636	8	8	8/H	8/M	0/M	0/M	8/L	8/L	2/M	2/M	
	741	8	8	8/H	8/M	0/M	0/M	8/M	8/M	2/M	2/M	
	860	8	8	8/H	8/H	0/M	0/M	8/M	8/M	2/M	2/M	
	974	8	8	7/H	8/H	0/M	0/M	7/H	8/H	2/M	2/M	
1,082	8	8	7/H	8/H	0/M	0/M	7/H	8/H	2/M	2/M		
1,245	8	8	5/H	6/H	0/H	0/H	5/H	6/H	2/MD	2/M		
1,419	7	7	5/H	6/H	0/M	0/M	6/H	7/H	2/MD	2/MD		

continued

Table A-1. Continued

System	Number of Cycles	General Protection		Tuberculation		Rusting on Scribe		Undercutting		Blistering on Scribe		Remarks
		1	2	1	2	1	2	1	2	1	2	
113. Epoxy	8	10	10	10	10	4/L	1/L	10	10	10	10	Cycle 8, Panels 1, 2: Pin point rusting very light along scribe Cycle 95, Panel 1: Solid blistering on bottom of scribe Endurance: Panel 1-24 Panel 2-24
	16	10	10	10	10	0/L	0/L	10	10	10	10	
	20	10	10	10	7/H	0/L	0/L-M	10	10	10	10	
	29	10	10	10	8	0/L	0/M	10	10	10	10	
	54	9+	10-	10	9+/L	0/L	0/L	10	10	8/D	8/F-M	
	95	9	9+	4/L	9/L	0/L	0/L	9+/L	9+/L	8/D	8/F-M	
	145	8	8	6/M	8/L	0/M	0/L	2/L	4/L	6/D	6/D	
	182	8	8	3/M	4/H	0/M	0-A	5/L	3/M	6/MD	4/MD	
	240	7	7	10	10	0/M	0/M	3/M	3/M	4/MD	4/MD	

continued

Table A-1. Continued

System	Number of Cycles	General Protection		Tuberculation		Rusting on Scribe		Undercutting		Blistering on Scribe		Remarks
		1	2	1	2	1	2	1	2	1	2	
115. Epoxy	8	10	10	10	10	6/L	8/L	10	10	10	10	Cycle 16, Panels 1, 2: Pin point rusting along scribe Cycle 240, Panel 2: Rust spots on back Cycle 303, Panel 2: One rust spot on back Cycle 350, Panel 2: One rust spot on back Cycle 577, Panel 2: Re-moved from test Endurance: Panel 1-97 Panel: 2-54
	16	10	10	10	10	4/L	5/L	10	10	10	10	
	20	10	10	10	9/M	3/L	3/M	10	10	10	8/F/M	
	29	10	10	10	9/M	0/L	2/L	10	10	10	8/F	
	54	9+	10-	9+/L	9/M	0/L	0/L-M	9+	10	10	8/F	
	95	9	9-	6/M	9/M	0/L	0/M	9/L	9/L	6/M	6/D	
	145	9	9	4/H	4/H	0/M	0/M	8/L	8/L	8/M	8/M/D	
	182	9	9	7/M	6/M	0/M	0/M	8/L	5/L	10	6/F	
	240	9	9	7/L	8/M	0/M	0/M	8/L	6/L	8/M/D	6/M	
	303	8	8	6/H	4/H	0/H	0/H	6/L-M	5/L	6/M/D	6/M/D	
	350	8	8	6/H	5/H	0/H	0/H	6/M	5/M	2/M/D	2/M/D	
	402	8	8	5/H	6/H	0/M	0/M	4/M	3/M	4/M/D	4/D	
	453	8	8	4/H	4/H	0/H	0/H	5/M	4/M	2/M/D	2/D	
	501	8	8	7/H	5/H	0/H	0/H	6/H	4/H	2/M/D	2/M/D	
	577	8	7	4/H	4/H	0/H	0/H	5/H	5/H	10	2/D	
		8	8	5/H	5/H	0/H	0/H	4/H	4/H	2/M/D	2/D	
		8	8	7/M	7/M	0/M	0/M	7/M	7/M	2/M/D	2/M/D	
		8	8	8/M	8/M	0/M	0/M	7/M	7/M	2/M/D	2/M/D	
		860	8	8	8/M	0/M	0/M	6/M	6/M	2/M/D	2/M/D	
		974	7	7	7/M	0/M	0/M	6/M	6/M	2/M/D	2/M/D	

continued

Table A-1. Continued

System	Number of Cycles	General Protection		Tuberculation		Rusting on Scribe		Undercutting		Blistering on Scribe		Remarks
		1	2	1	2	1	2	1	2	1	2	
118. Vinyl	8	10	10	10	10	0/L	3/L	10	10	10	10	Cycle 16, Panels 1, 2: Heavy rust stain along scribe Endurance: Panel 1-86 Panel 2-86
	16	10	10	10	10	0/L	0/L	9+/L	8/L	10	10	
	20	10	10	4/H	9	0/M	0/L	9	10	6/D	10	
	29	10	10	8/M	10	0/LM	0/LM	9	10	8/VF	10	
	54	9+	9+	2/H	2/M	0/M	0/M	9+/L	9+/L	6/F	10	
	95	9-	9-	2/H	2/H	0/H	0/H	9/L	9/L	6/M	6/M	
	145	9	9	2/H	2/H	0/H	0/H	9+/L	9+/L	8/M	4/F	
	182	8	9	5/H	5/H	0/M	0/H	10	10	8/F	10	
	240	8	9	6/H	6/H	0/H	0/M	8/L	9/L	4/F	4/F	
	303	8	9	5/H	5/H	0/H	0/H	8/L	9/L	4/M	6/F	
	350	8	9	4/H	4/H	0/H	0/H	8/L	9/L	2/M	6/F	
	402	8	8	6/H	4/H	0/H	0/H	8/H	5/M	4/L	4/MD	
	453	8	8	7/H	4/H	0/H	0/H	8/H	5/M	4/M	6/MD	
	508	8	8	5/H	5/H	0/H	0/H	5/M	5/M	4/MD	4/MD	
	539	8	8	7/H	4/H	0/H	0/H	8/H	5/H	4/MD	4/MD	
	577	8	8	7/H	5/H	0/H	0/H	7/H	4/H	2/MD	4/M	
	636	8	8	6/H	5/H	0/H	0/H	7/H	7/H	2/MD	2/M	
	741	8	8	4/H	2/H	0/H	0/H	4/M	3/M	2/M	2/M	
	860	7	7	2/H	2/H	0/H	0/H	4/M	4/M	2/MD	2/MD	

continued

Table A-1. Continued

System	Number of Cycles	General Protection		Tuberculation		Rusting on Scribe		Undercutting		Blistering on Scribe		Remarks
		1	2	1	2	1	2	1	2	1	2	
Epoxy	8	10	10	10	10	3/L	3/L	10	10	10	10	Cycle 1,245, Panel 1: Re-moved from test Endurance: Panel 1-125 Panel 2-147
	16	10	10	10	10	0/L	0/L	10	10	10	10	
	20	10	10	9/L	8/H	0/L	0/L	10	10	10	10	
	29	10	10	7/M	7/M	0/M	0/M	10	10	10	10	
	54	10	10	6/H	6/H	0/M	0/L	9	10	8/F	10	
	95	9	9	4/H	9/H	0/M	0/M	9/L	9/L	6/M	6/M	
	145	8	9	4/H	6/H	0/H	0/H	8/L	9/L	8/M	8/F	
	182	8	9	5/H	8/H	0/M	0/M	8/L	10	6/F	6/F	
	240	8	9	4/H	6/M	0/H	0/M	8/L	9/L	8/M	5/F	
	303	8	9	4/H	6/M	0/H	0/M	8/L	9/L	8/M	8/F	
	350	8	9	4/F	8/M	0/H	0/M	8/L	9/L	6/M	8/F	
	402	8	9	6/H	8/L	0/H	0/M	8/L	8/L	4/L	4/L	
	453	8	8	8/H	3/L	0/H	0/H	7/M	5/L	4/M	8/M	
	508	8	8	7/H	7/H	0/H	0/H	7/H	8/M	2/M	6/M	
	539	8	8	5/H	5/L	0/H	0/H	6/H	5/L	4/D	6/M	
	577	8	8	5/H	5/L	0/H	0/M	5/H	6/L	4/D	6/M	
	636	8	8	6/M	9/L	0/M	0/L	7/M	9/L	2/M	6/F	
	741	8	8	6/M	9/L	0/M	0/L	7/M	9/L	2/M	6/F	
	860	8	8	6/M	8/M	0/M	0/M	6/M	8/L	2/M	6/F	
	974	8	8	8/M	9/M	0/M	0/M	7/H	8/L	2/M	6/M	
1,089	8	8	7/M	9/M	0/M	0/M	6/H	8/L	2/D	6/M		
1,245	7	8	6/M	9/M	0/M	0/M	6/H	9/L	10	8/D		
1,419	8	8	8/M	8/M	0/M	0/M	8/L	8/L	8/D	8/D		

continued

Table A-1. Continued

System	Number of Cycles	General Protection		Tuberculation		Rusting on Scribe		Undercutting		Blistering on Scribe		Remarks
		1	2	1	2	1	2	1	2	1	2	
120. Vinyl mastic	8	10	10	10	10	6/L	3/L	10	10	10	10	Cycle 16, Panel 2: Rusting in bottom of scribe mark Endurance: Panel 1-155 Panel 2-142
	16	10	10	10	10	2/L	4/L	10	10	10	10	
	20	10	10	9+	10	2/M	0/L	10	10	10	10	
	29	10	10	10	10	1/L	0/L	10	10	10	10	
	54	10	10	10	10-V/L	0/L	0/L	10	10	10	10	
	95	10	10	10	10	0/L	0/L	10	10	10	10	
	145	10	10	8/M	4/M	0/L	0/L	10	10	10	10	
	182	10	10	10	10/10	0/L	0/L	10	10	10	10	
	240	10	10	8/L	6/M	0/L	0/L	10	10	10	10	
	303	10	10-	9/L	6/H	0/L	0/H	10	9/L	10	10	
	350	10	9	9/L	4/H	0/L	0/H	10	9/L	10	10	
	402	10	9	9/L	5/H	0/L	0/L	10	5/M	10	4/M	
	453	9	8	7/M	5/H	0/L	0/H	10	7/L	10	6/M	
	508	9	8	9/M	5/H	0/L	0/M	10	5/M	10	4/M	
	539	9	8	8/M	5/H	0/L	0/H	10	7/H	10	4/MD	
	577	9	8	9/L	5/H	0/L	0/H	10	9/L	10	4/MD	
	636	9	8	9/M	5/H	0/M	0/H	10	9+/L	10	2/F	
	741	9	8	9/M	8+/H	0/M	0/MH	10	9+/L	10	2/F	
860	9	8	9/H	8/H	0/M	0/M	10	9/L	10	2/M		
974	9	8	9/H	6/H	0/L	0/M	10	9/L	10	2/M		
1,089	9	8	9/H	6/H	0/L	0/M	10	9/L	10	2/M		
1,245	9-	8	9/H	4/H	0/L	0/H	10	9/L	10	2/MD		
1,419	9-	7	9/H	4/H	0/L	0/H	10	9/M	10	2/MD		

continued

Table A-1. Continued

System	Number of Cycles	General Protection		Tuberculation		Rusting on Scribe		Undercutting		Blistering on Scribe		Remarks
		1	2	1	2	1	2	1	2	1	2	
122. Aluminum vinyl	8	10	10	10	10	4/L	3/L	10	10	10	10	Cycle 95, Panels 1, 2: Size 8 blister on right side of panel Cycle 303, Panels 1, 2: Blisters filled with white solution Cycle 577, Panel 1: Blister filled with water Endurance: Panel 1-144 ^d Panel 2-144 ^d
	16	10	10	10	10	0/L	1/L	10	10	10	10	
	20	10	10	8/M	10	0/L	0/L	9+	10	10	10	
	29	10	10	9-/M	10	0/L	0/L	10	10	10	10	
	54	10	10	7/H	9/M	0/M	0/M	10	10	10	10	
	95	10	10-	4/M	3/M	0/M	0/M	10	9+/L	10	10-/L	
	145	9-	9	4/H	3/H	0/H	0/M	9/L	9/L	8/M	8/M	
	182	9-	9+	8/H	5/H	0/M	0/H	9/L	9/L	6/F	6/M	
	240	9-	9-	6/M	2/M	0/M	0/H	7/L	9/L	6/M	6/M	
	303	9-	9-	6/M	6/M	0/H	0/H	7/L	6/L	6/M	6/MD	
	350	9-	8	6/M	6/H	0/H	0/H	7/L	7/L	8/MD	4/MD	
	402	8	8	6/H	4/H	0/H	0/H	8/L	4/L	8/MD	8/MD	
	453	8	8	5/H	5/H	0/H	0/H	9/M	9/L	8/MD	8/MD	
	508	8	8	5/H	5/H	0/H	0/H	8/M	8/L	8/MD	8/MD	
	539	8	8	8/M	8/M	0/H	0/H	8/L	8/L	6/MD	6/MD	
	577	8	8	6/M	6/M	0/H	0/H	8/L	8/L	6/MD	6/MD	
	636	8	8	5/M	5/M	0/H	0/H	8/L	8/L	6/MD	6/MD	
	741	8	8	5/M	5/M	0/H	0/H	7/L	7/L	6/MD	6/MD	
	860	8	8	5/M	5/M	0/H	0/H	7/L	7/L	6/MD	6/MD	
	974	8	8	5/H	7/H	0/H	0/H	7/M	7/M	6/D	6/D	
	1,089	8	8	5/H	5/H	0/H	0/H	6/L	7/L	6/D	6/D	
	1,245	8	8	6/H	5/H	0/H	0/H	6/L	6/L	6/D	6/D	
	1,419	8	8	6/H	5/H	0/H	0/H	6/L	6/L	6/D	6/D	

continued

Table A-1. Continued

System	Number of Cycles	General Protection		Tuberculation		Rusting on Scribe		Undercutting		Blistering on Scribe		Remarks
		1	2	1	2	1	2	1	2	1	2	
124. Epoxy	8	10	10	10	10	6/L	4/L	10	10	10	10	Cycle 16, Panels 1, 2: Pin point rusting in scribe
	16	10	10	10	10	4/L	2/L	10	10	10	10	
	20	10	10	8/M	9+	4/M	1/L	10	10	10	10	
	29	10	10	9/L	9+V/L	1/L	0/L	10	10	10	10	
	54	10	10	9/L	9/L	0/L	0/L	10	10	10	10	
	95	10	10	8/M	6/L	0/L	0/M	10	9+L	10	10	
	145	10	10	2/M	2/M	0/M	0/M	10	10	10	10	
	182	9	9	5/H	5/H	0/M	0/M	10	10	6/F	6/F	
	240	9+	9	9/L	9/L	0/M	0/L	9/L	9/L	6/F	6/F	
	303	9	9-	6/M	9/L	0/M	0/M	8/L	8/L	6/F	6/F	
	350	9-	9	6/H	7/H	0/H	0/H	7/M	8/M	4/M	6/F	
	402	8	8	7/H	7/H	0/H	0/H	7/M	6/M	6/M	6/M	
	453	8	8	4/H	7/H	0/H	0/H	7/H	6/H	4/M	4/M	
	508	8	8	5/H	6/H	0/H	0/M	5/H	8/H	2/M	2/M	
	539	8	8	5/H	6/H	0/H	0/H	7/H	7/H	4/M	2/M	
	577	8	8	6/H	7/H	0/H	0/H	7/H	8/H	2/M	2/M	
	636	8	8	5/H	7/H	0/H	0/H	6/H	7/H	2/M	2/M	
	741	8	8	6/H	7/H	0/H	0/H	6/H	7/H	2/M	2/M	
	860	8	8	6/H	7/H	0/H	0/H	6/H	7/H	2/M	2/M	
	974	8	8	6/H	7/H	0/H	0/H	5/M	6/M	2/M	2/M	
1,089	7	7	6/H	7/H	0/H	0/H	4/M	6/M	2/M	2/M		
1,245	7	7	6/H	6/H	0/H	0/H	6/M	6/M	2/M	2/M		

continued

Table A-1. Continued

System	Number of Cycles	General Protection		Tuberculation		Rusting on Scribe		Undercutting		Blistering on Scribe		Remarks
		1	2	1	2	1	2	1	2	1	2	
126. Epoxy	8	10	10	10	10	2/L	0/L	10	10	10	10	Cycle 16, Panel 2: Slight blisters Cycle 240, Panel 1: One rust spot on back Cycle 303, Panel 1: One rust spot on back Cycle 741, Panel 1: Removed from test Endurance: Panel 1-75 Panel 2-84
	16	10	10	10	10	0/L/L	0/L	10	10	10	10	
	20	10	10	10	7/L	0/L	0/L	10	8	10	2/D	
	29	10	9+	10	9+	0/L	0/L	10	9+	10	10	
	54	10	9+	9+/L	9/L	0/L	0/L	10	9+/L	8/F	10	
	95	10	9+	8/L	9/L	0/L	0/L	10	9/L	10	6/M	
	145	10	9	8/L	8/M	0/L	0/M	9+/L	10	8/F	10	
	182	10	9	10	8/H	0/L	0/M	10	8/L	10	10	
	240	9+	9	10	9/L	0/L	0/L	10	9/L	8/F	6/F	
	303	9	9-	9/L	9/L	0/M	0/M	9/L	8/L	6/F	8/F	
	350	9-	9	8/M	10	0/M	0/M	9/L	9/L	2/M	2/F	
	402	8	8	8/M	5/H	0/M	0/M	6/M	5/L	4/M/D	4/M	
	453	8	8	4/H	8/L	0/M	0/M	5/M	8/L	6/D	6/M/D	
	508	8	8	5/L	7/H	0/M	0/M	5/H	5/M	2/M/D	4/M	
	539	8	8	4/H	6/M	0/H	0/H	4/M	6/M	10	10	
	577	8	8	4/H	6/H	0/H	0/H	4/H	6/M	2/M/D	2/M/D	
	636	8	8	5/H	8/M	0/H	0/M	6/H	8/H	2/M/D	2/M	
	741	7	8	9/M	9/M	0/M	0/M	4/H	6/M	2/M/D	2/M	
	860	7	7	5/H	5/H	0/M	0/M	5/H	5/H	2/M/D	2/M/D	

continued

Table A-1. Continued

System	Number of Cycles	General Protection		Tuberculation		Rusting on Scribe		Undercutting		Blistering on Scribe		Remarks
		1	2	1	2	1	2	1	2	1	2	
127. Vinylalkyd	8	10	10	10	10	2/L	1/L	10	10	10	10	Cycle 20, Panel 2: Slight blistering on bottom of panel Cycle 860, Panel 2: Removed from test Endurance: Panel 1-109 Panel 2-74
	16	10	10	10	10	1/L	0/L	10	10	10	10	
	20	10	10	10	10	2/LM	0/VL	10	10	10	10	
	29	10	10	10	10	0/LM	0/L	10	10	10	10	
	54	10	10	10	10	0/L	0/L	10	10	10	10	
	95	10	10	8/M	4/M	0/L	0/M	10	9+/L	10	8/F	
	145	10-	9-	4/M	4/H	0/M	0/H	9+/L	9/L	8/F	8/M	
	182	9	9	8/M	4/H	0/L	9/MH	6/M	10	6/M	6/D	
	240	9-	8	9/M	4/H	0/M	0/H	7/L	5/L	6/M	6/MD	
	303	8-	8	8/M	4/H	0/M	0/H	6/L	5/L	6/MD	6/MD	
	350	8	8	7/M	6/H	0/H	0/H	6/L	4/M	6/M	2/D	
	402	8	8	8/H	6/H	0/M	0/H	4/L	2/H	6/MD	6/D	
	453	8	8	8/H	6/H	0/M	0/H	4/L	4/M	4/MD	6/MD	
	508	8	8	8/H	7/H	0/M	0/H	3/L	4/M	4/MD	4/MD	
	539	8	8	7/H	6/H	0/M	0/M	3/H	4/M	4/MD	4/MD	
	577	8	8	5/M	4/M	4/M	0/M	3/M	3/M	4/MD	2/MD	
	636	8	8	7/M	5/H	0/M	0/H	7/LM	5/M	2/MD	2/MD	
	741	8	7	8/M	7/M	0/M	0/M	7/M	6/M	2/MD	2/D	
	860	8	8	7/M	6/M	0/M	0/M	7/M	2/M	2/M		
	974	8	8	6/M	6/M	0/M	0/M	6/H	2/M	2/M		
	1,089	7	7	7/M	7/M	0/M	0/M	6/H	2/D	2/D		

continued

Table A-1 Continued

System	Number of Cycles	General Protection		Fuberculation		Rusting on Scribe		Undercutting		Blistering on Scribe		Remarks
		1	2	1	2	1	2	1	2	1	2	
128. Vinyl-alkyd	8	10	10	10	10	8/L	5/L	10	10	10	10	Cycle 8, Panels 1, 2: Pin point rust in scribe
	16	10	10	10	10	7/L	3/L	10	10	10	10	Cycle 16, Panels 1, 2: Pin point rust in scribe
	20	10	10	9+	9+/L	7/L	4/L	10	10	10	10	Cycle 20, Panels 1, 2: Pin point rust in scribe
	29	10	10	9+/L	8/N/L	5/L	1/L	10	10	10	10	Cycle 20, Panels 1, 2: Pin point rust in scribe
	54	10+	10+	5/M	3/H	0/LM	0/M	10	10	10	10	
	95	10+	9+	2/M	4/M	0/M	0/M	9/L	9/L	8/F	8/MD	
	145	9+	9-	1/H	1/H	0/H	0/H	9/L	8/L	8/M	8/MD	
	182	8	8	4/H	4/H	0/M	0/H	8/L	9/H	6/F	6/MD	
	240	8	8	5/H	5/H	0/H	0/H	4/L	5/L	6/MD	6/MD	
	303	8	8	4/H	4/H	0/H	0/H	4/M	4/M	6/D	4/MD	
	350	8	8	5/H	4/H	0/H	0/H	4/M	4/M	6/D	2/MD	
	402	8	8	5/H	3/H	0/H	0/H	4/M	3/M	4/MD	4/D	
	453	8	8	4/H	2/H	0/H	0/H	8/L	4/M	6/M	6/D	
	508	8	8	4/H	3/H	0/H	0/H	3/M	1/M	4/D	4/D	
	534	8	8	3/H	2/H	0/H	0/H	5/M	4/H	4/D	4/D	
	577	7	7	4/H	4/H	0/H	0/H	3/M	3/M	2/D	2/D	Endurance: Panel 1-58 Panel 2-58

^d Panels had not failed. Endurance values were estimated.

Appendix B

LINEAR REGRESSION ANALYSIS

by

W. C. Ingold

Regression is the estimation or prediction of unknown values of one variable from known values of another variable. An example in the case of paints might be the prediction of the life of a paint from known or measurable properties such as electrical properties, moisture permeability, and accelerated test results. The life of the paint, being the unknown, would be the dependent variable y , while the measurable properties would be the independent variables x_1, x_2, x_3 , etc.

Four valuable results that can be obtained from a linear regression analysis are: (1) a prediction equation, empirical in nature, (2) correlation coefficients, (3) a multiple correlation coefficient, and (4) confidence limits.

The empirical equation answers the question: "What weight should be assigned each of the predictor or estimator variables in order to obtain the best criterion variable?" This weighting factor, in linear regression, will take the form of numerical coefficients of the independent variables.

The prediction equation is developed by the method of least squares, in which the sum of the squares of the distances from the predicted to the observed is kept as small as possible. An equation with one independent variable will take the following form:

$$\hat{y} = \bar{y} + A(x - \bar{x})$$

where

\hat{y} = the predicted dependent variable

\bar{y} = the mean of the known dependent variables

x = the observed independent variable

\bar{x} = the mean of the known independent variables

A = the regression coefficient or weighting factor

While this equation may be used to interpolate for intermediate values, one should be cautioned against extrapolation beyond the domain of the data on which it was developed.

The correlation coefficient answers the question: "How good is a factor as a predictor of an unknown?" It is calculated with the following formula using the data available:

$$r = \frac{\sum (x - \bar{x})(y - \bar{y})}{\sqrt{(\sum (x - \bar{x})^2) (\sum (y - \bar{y})^2)}}$$

where

- r = coefficient of correlation
- x = independent variable
- \bar{x} = mean of independent variables
- y = dependent variable
- \bar{y} = mean of dependent variables

The value r is a measure of the accuracy of the estimate of an unknown y from a known x. If r is zero, there is no indication of any accuracy. A value of r near +1 or -1 indicates a high degree of accuracy in predicting y, given an x.

One measure of how well the predicting equation will fit the data if there is more than one independent variable is the multiple correlation coefficient. Possibly no single factor or independent variable taken alone would give a good estimate of the dependent variable, yet quite frequently some combination will give a good estimate. The multiple correlation coefficient is used to investigate this fit.

$$R^2 = \frac{\left[\sum y \tilde{y} - \frac{(\sum y)^2}{N} \right]^2}{\left[\sum y^2 - \frac{(\sum y)^2}{N} \right] \left[\sum \tilde{y}^2 - \frac{(\sum \tilde{y})^2}{N} \right]}$$

where

- R^2 = multiple correlation coefficient
- y = observed dependent variable
- \tilde{y} = predicted dependent variable
- N = number of cases

An R^2 value near 1 indicates the equation will be highly effective in predicting dependent variables from given independent variables. Quite frequently with sufficient and good data an R^2 of 0.99 is achieved.

To estimate the range in which a predicted y will fall when given the value for $x_1, x_2, \text{etc.}$, a confidence interval is computed. Given values A and B, the inequality $A < \tilde{y} < B$ expresses mathematically that the predicted y will lie between those two values, known as confidence limits. $B-A$ is the confidence interval. Because one can never be absolutely sure that this will be true, some qualification must be included, indicating with what degree of certainty the statement can be made. This qualification is the confidence coefficient--usually a value between 0.90 and 1.00. A value quite commonly used is 0.95. If this restriction is applied to the above inequality it would then be translated: in 95 out of 100 cases y will lie between the values A and B. It is desirable to keep the confidence interval as narrow as possible while keeping the confidence coefficient at a predetermined acceptably high level.

Appendix C

CORRELATION OF LABORATORY AND FIELD RESULTS

When field exposure results of all paints were correlated with results from each of the laboratory tests individually (runs 1, 2, and 3), the highest multiple correlation coefficient (R^2) was obtained with the cyclic test procedure versus scribed panels exposed at Kaneohe ($R^2 = 0.6182$). All other R^2 values in runs for these three tests were 0.55 or less, as shown in Table 3. This suggests that, when comparing paints of different generic types, none of these test methods individually give results that can be used to predict paint performance with any degree of accuracy.

When correlations were made between data from the individual tests and the performance of the epoxy paints (runs 8, 9, and 10) or the vinyl paints (runs 16, 17, and 18), somewhat better results were obtained. Thus, a comparison of results from the wet-and-dry-cycle test and scribed panels at Kaneohe gave an R^2 of 0.8960 (run 10). Similarly, a comparison of results from the electrical tests for vinyl paints and their exposure on scribed panels at Kaneohe gave an R^2 of 0.8392 (run 16) and from permeability tests for epoxy paints and their exposure on plain panels at Kwajalein gave an R^2 of 0.8237 (run 9). Although these three multiple correlation coefficients were higher for the epoxy or the vinyl paints than for all 12 paints considered together, the greatest majority of R^2 values for the individual tests (runs 1 to 3, 8 to 10, and 16 to 18) were 0.4 or less. No one test method gave consistently high R^2 values; instead each of the tests exhibited only one relatively good correlation as indicated above. This lack of a consistently good fit of the independent variables (laboratory test results) and dependent variables (field performance data) to the linear regression curve suggests that the individual tests cannot be considered good predictors of field performance for paints.

Better correlations were obtained when data from all three test methods were compared to field exposure results using linear regression analysis. When all 12 paints were considered (runs 4 to 7), the best R^2 was obtained by correlating independent variables x_2 , x_4 , x_6 , and x_8 to x_{11} with results from scribed panels at Kaneohe (y_3 , $R^2 = 0.8426$). However, the majority of multiple correlation coefficients in this group ranged from 0.5 to 0.8.

The best correlations were obtained when comparisons were made between laboratory and field exposure results on paints grouped according to generic types. For epoxy paints (runs 11 to 15) and for vinyl paints (runs 19 to 22), a number of multiple correlation coefficients exceeding 0.9 were obtained. The best correlation obtained for the epoxy paints compared the AC resistance (x_4) and capacitance (x_6) after 10 days exposure, permeability constant (x_9), and wet-and-dry-cycle test (x_{11}) results with results from the field exposure of scribed

panels at Kaneohe (y_3 , run 13, $R^2 = 0.9946$). These same laboratory data for the epoxy paints (run 13) also correlated well with performance results from the plain panels at Kwajalein (y_2 , $R^2 = 0.9735$). Similarly high R^2 values were obtained with these data where electrical properties obtained at zero exposure time were compared with results from scribed panels at Kaneohe (y_3 , run 11, $R^2 = 0.9904$), and after 1/4-day exposure time (run 12) with results from plain panels at Kwajalein (y_2 , $R^2 = 0.9511$) and scribed panels at Kaneohe (y_3 , $R^2 = 0.9769$). Although very good correlation was also obtained for epoxy paints when results from all three tests (run 15) were correlated with results from exposure of plain panels at Kwajalein (y_2 , $R^2 = 0.9893$), of scribed panels at Kaneohe (y_3 , $R^2 = 0.9923$) and of all panels at both sites (y_5 , $R^2 = 0.9341$), these results are questionable. In the latter cases, seven laboratory results (or independent variables) were correlated with field results from only six paint systems (or dependent variables). As mentioned earlier under the discussion of linear regression analysis, if there are equal numbers of dependent and independent variables, an accurate but meaningless fit of the variables to the linear regression equation can be obtained.

The highest multiple correlation coefficient or fit of the variables to the linear regression equation was obtained with the vinyl paints and results from the three laboratory tests (run 19). When data from the AC resistance (x_4) at zero exposure time, the permeability constant (x_9), and the wet-and-dry-cycle test (x_{11}) were correlated with exposure results for plain panels at Kaneohe (y_4), an R^2 of 1.000 was obtained. This indicates perfect correlation of dependent and independent variables. Good correlation was also obtained when x_4 , x_9 , x_{11} were compared to the performance of all panels at both sites (y_5 , run 19, $R^2 = 0.9748$) and when x_4 , after 1/4-day exposure time, x_9 , and x_{11} were compared with results from field exposure of plain panels at Kaneohe (y_4 , run 20, $R^2 = 0.9204$). Finally, good correlation was obtained when results from only two of the laboratory tests--the diffusion rate and the wet-and-dry-cycle test (x_8 and x_{10} , x_{11} , respectively, run 22)--were compared to results from scribed panels at Kwajalein (y_1 , $R^2 = 0.9990$), plain panels at Kwajalein (y_2 , $R^2 = 0.9822$) and scribed panels at Kaneohe (y_3 , $R^2 = 0.9470$).

Further study of Table 3 indicates that the technique shows more promise for predicting the performance of paints if the regression analysis is carried out by correlating laboratory and field performance of the paints that are grouped according to generic type; i.e., epoxies and vinyls. Although the increased correlation shown by the paints grouped in this manner might also be partially attributed to the fact that there are only half as many dependent variables in each group as there were when all 12 paints were considered together, the data suggests that the generic type is an important factor.

Thus with the epoxy paints, the results from the AC resistance, AC capacitance, permeability constant, and wet-and-dry-cycle test, as a group of independent variables, correlate well with field performance while results from the diffusion constant and wet-and-dry-cycle test

together show relatively poor correlation with the same dependent variables. For the vinyl paints, however, the results from the diffusion constant and the wet-and-dry-cycle tests together show very good correlation with field performance, while results from the AC resistance, permeability constant, and wet-and-dry-cycle test as a group of independent variables exhibited good, although not quite as consistently high, correlation with the independent variables.

For epoxy paints, consistently high correlation of independent and dependent variables is shown when the dependent variables are based on the performance data from scribed panels at Kaneohe. For vinyl paints, the dependent variables that consistently show the highest correlations are performance results from all panels exposed at both sites. Thus, when subjected to linear regression analysis, data from the epoxy and the vinyl paints with the consistently highest correlations were obtained using different combinations of dependent and independent variables.

The ultimate objective in correlating laboratory data and field results by means of linear regression analysis is to derive a linear equation which can be used to predict field performance from selected accelerated laboratory measuring or testing results. Using the accelerated laboratory test data for System 111 from Table 2, and the coefficients from Table 4 (run 13-3) the prediction equation would be as follows:

$$\begin{aligned}
 y_3 &= A_4x_4 + A_6x_6 + A_9x_9 + A_{11}x_{11} + C \\
 &= (-0.11)(510) + (-11,765.786)(0.0023) + (3.018)(1.253) \\
 &\quad + (0.404)(142) + 112.692 \\
 &= 90.6802
 \end{aligned}$$

Thus, the predicted protection ranking for this epoxy-phenolic paint exposed on scribed panels at Kaneohe is about 91 as compared to the experimental protection ranking of 90 listed in Table 2. This means that this paint system should perform up to approximately 9 years before failing when exposed on scribed panels at Kwajalein, which of course was the case. The protection rankings computed for all the epoxy paints using the coefficients in Table 4 derived in conjunction with the multiple correlation coefficient in run 13-3 are given below as an example along with the actual experimental protection rankings for these same systems from Table 2.

<u>System Number</u>	<u>Calculated Protection Ranking</u>	<u>Experimental Protection Ranking</u>
111	91	90
113	10	9
115	36	35
119	61	58
124	56	59
126	39	39

A comparison of the calculated and experimental protection rankings show very close agreement and are certainly within experimental error. This would, of course, be expected since the prediction equation was derived from these same dependent and independent variables. These results are included merely to illustrate the method.