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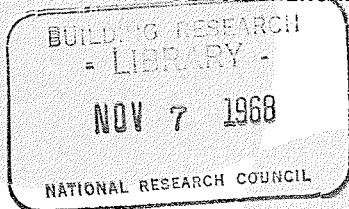
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MEASUREMENT OF ATMOSPHERIC FACTORS AFFECTING THE  
CORROSION OF METALS

BY

HERBERT GUTTMAN AND P. J. SEREDA

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## MESURE DES FACTEURS ATMOSPHERIQUES DETERMINANT LA CORROSION DES METAUX

### SOMMAIRE

Les auteurs ont mesuré les facteurs atmosphériques déterminant la corrosion de l'acier, du cuivre et du zinc dans trois stations littorales d'expérimentation en Amérique du Nord, et dans quatre autres stations à l'intérieur. Ils ont déterminé la durée pendant laquelle les panneaux métalliques en voie de corrosion restent mouillés, leur température, et les taux d'anhydride sulfureux et de chlorure de sodium atmosphériques. Les pertes pondérales des panneaux métalliques ont fortement varié selon la saison et le lieu d'exposition, bien que la durée des essais ait été uniforme. Les analyses statistiques montrent de façon concluante que les facteurs atmosphériques mesurés déterminent complètement les vitesses de corrosion à toutes les stations d'expérimentation tout au moins pendant le premier mois. Pour des périodes plus longues, la vitesse de corrosion dépend soit des facteurs atmosphériques ou des facteurs découlant des modifications superficielles résultant de l'accumulation des produits de corrosion et de corps étrangers. Aux endroits où les facteurs atmosphériques déterminent seuls la corrosion, les relations établies empiriquement permettent de calculer les pertes par corrosion de l'acier, du cuivre et du zinc. Ces relations permettent aussi de tenir compte des variations des pertes par corrosion observées sur des éprouvettes exposées à diverses saisons.



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## Measurement of Atmospheric Factors Affecting the Corrosion of Metals

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**REFERENCE:** Guttman, Herbert and Sereda, P. J., "Measurement of Atmospheric Factors Affecting the Corrosion of Metals," *Metal Corrosion in the Atmosphere, ASTM STP 435*, American Society for Testing and Materials, 1968, pp. 326-359.

**ABSTRACT:** Atmospheric factors, namely, time of wetness of corroding metal panels, panel temperature, and atmospheric sulfur dioxide and atmospheric chloride content, were measured at four inland and three coastal North American test sites while corrosion data for steel, copper, and zinc were being developed. Corrosion losses experienced by panels of these metals which were exposed at different times of the year for similar periods of time showed considerable variation at all sites.

Statistical analyses show conclusively that the atmospheric factors measured completely control the rates of corrosion at all sites for at least the initial month. For longer periods of time control of the corrosion process remains with the atmospheric factors in some cases, and in others it is gradually transferred to factors related to the changing surface conditions resulting from accumulation of corrosion products and foreign agents.

At the sites where the atmospheric factors control corrosion, the empirical equations developed enable one to predict the corrosion losses of steel, copper, and zinc from a knowledge of the atmospheric factors. They also now make it possible to account for variations in observed corrosion losses experienced by panels exposed at different times of the year.

**KEY WORDS:** atmospheric corrosion testing, steel, copper, zinc, time of panel wetness, sulfur dioxide, lead peroxide methods, atmospheric chlorides, wet-candle method

The literature abounds with data on weathering of metals at geographic locations throughout the world. These data serve a very useful purpose and have been the basis for selection of engineering materials of construction for many types of structures. The contributions to the fund of knowledge that has been developed over the years by the various ASTM

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technical committees, the British Non-Ferrous Metals Research Association, other societies and associations, and individuals are notable.

Wide variations in corrosion rates have been observed not only from location to location, but from exposure date to exposure date at any given location. Many investigators have attempted to measure the factors responsible for the variations and to define their effects on the corrosion of metals. It is recognized that atmospheric sulfur dioxide, atmospheric chlorides, and factors relating to the time of wetness of a corroding surface exert critical effects on the corrosivity of an atmosphere.

Considerable work has been done on the measurement of sulfur dioxide in the atmosphere. Volumetric methods have been developed [1,2]<sup>3</sup> which give instantaneous or frequent periodic indications of the actual concentration of sulfur dioxide. These methods require fairly costly instrumentation.

The lead peroxide method developed in the United Kingdom [3] and the Liesegang bell method developed in Germany and as discussed by Schikorr [4] present an integrated measure of the sulfur dioxide "activity" during a period of exposure. Both of these are well suited to measuring the relative levels of sulfur dioxide at corrosion test sites during the time when metals are under test. Correlations between the lead peroxide method and the volumetric methods have been established [5,6]. The results of work on steel and zinc carried out by Hudson and Stanners [7] and by the National Research Council in a Canadian program [8] indicate a close relationship between the severity of corrosion and the atmospheric sulfur dioxide concentration.

The most extensive work reported on the measurement of atmospheric chlorides is that by Ambler and Bain [9] as part of a study of the corrosion of metals in Nigeria. Their results show a relationship between corrosion and atmospheric salinity. Their "wet candle" technique and other methods of chloride measurement are discussed by Foran et al [5]. Compton [10] reported on increased corrosion due to airborne chlorides in tropical and desert areas.

Moisture plays an important, if not the most important role in the corrosion of metals and the deterioration of other materials. Copson [11] postulated from his extensive work that the corrosion rate of steel depends on the quality and quantity of water reaching the steel surfaces. Dearden [12] attempted to correlate the corrosion of steel with the hours of rainfall registered by a recording rain gage. Ellis [13] determined the wetness factor by means of a device that recorded the presence of moisture on a glass plate exposed during his zinc exposure program. Larrabee [14] showed the effect of rain in washing contaminants such as sulfur

<sup>3</sup> The italic numbers in brackets refer to the list of references appended to this paper.

compounds from the skyward surface of an exposed steel specimen and the effect of precipitation such as dew on the groundward side. These programs made valuable contributions in the area of the effects of moisture on corrosion, but they were not successful in developing methods of detecting and recording the time when a corroding specimen is wet.

In a recent program, Oma et al [15] investigated the effects of temperature, relative humidity, precipitation, sulfur dioxide, chlorides, and several types of particulate pollutants on the corrosion of steel specimens exposed for one month periods in an industrial area of Tokyo. They developed an empirical equation which accounts for practically all of the month-to-month variations in corrosion rate which were observed. As a matter of interest, the observed rates varied from a low of less than 5 milligrams per square decimeter per day (mdd) to a high of approximately 100 mdd.

A Task Group on Measurement of Atmospheric Factors (of Subcommittee VII) of ASTM Committee B-3 on Corrosion of Non-Ferrous Metals and Alloys was formed in 1956, and at its first meeting decided to study the effects of surface moisture on the corrosion of metals. An instrument capable of measuring and recording the time of wetness of exposed metal specimens was developed and proven to be effective by extensive studies carried out in Ottawa [16-18]. The operation of the so-called "dew-detector" involves the measurement of a potential developed between a corroding metal specimen and a platinum electrode placed in its immediate vicinity. Surface moisture due either to precipitation or condensation serves as the cell electrolyte. Studies of relative humidity data extracted from meteorological records for several Canadian cities and time of wetness values measured by the dew-detector indicate that it should be possible to estimate wetness time from meteorological records. This is based on the fact that the measured time of wetness at two inland sites and two marine sites corresponds to the time that the relative humidity is in excess of 83 and 87 per cent, respectively.

In 1959 the Task Group decided to undertake an exposure program to measure atmospheric factors that affect the corrosion of metals at a number of test sites and to correlate metal weight losses due to corrosion with those factors. This program was transferred to Subcommittee IV of Committee G-1 upon its organization. Pertinent details and findings are dealt with in this report.

### **Experimental Procedure**

The program was carried out in two phases, Phase 1 during the period January 1961 to March 1963, and Phase 2 during the period December 1963 to March 1966. Participating test sites at Cleveland, Ohio, the 80- and 800-ft sites at Kure Beach, N. C., Ottawa, Ont., the Fort Sherman field site in the Panama Canal Zone (Phase 2 only), South Bend, Pa., and

Trail, B. C. (Phase 1 only), were equipped to measure the following factors of interest:

1. Time of panel wetness on skyward and groundward surfaces using the "dew-detector" developed by the Task Group—all sites.
2. Panel temperature and ambient temperature during time of panel wetness—all sites.
3. Atmospheric sulfur dioxide activity as determined by the lead peroxide candle method during time of panel wetness and during total exposure period—all sites, excepting those at Kure Beach and the Panama Canal Zone. Instrumentation for exposing the lead peroxide cylinder during time of wetness has been discussed elsewhere [17].
4. Atmospheric sulfur dioxide activity during total exposure period—Kure Beach 800-ft and Panama Canal Zone sites.
5. Atmospheric chloride content as determined by the wet-candle method—the Kure Beach sites during the latter stages of Phase 1; Kure Beach and Panama Canal Zone sites during Phase 2.

Monthly records of these factors were developed for each site.

During Phase 1 of the program, sets of 4 by 6-in. panels of steel, copper, and zinc were exposed for one- and twelve-month periods according to the schedule shown in Table 1. There were some exceptions to this, and these will become apparent on examination of the data tables to be presented later.

During Phase 2, similar sets of panels were exposed for 3, 6, 9, and 18-month periods, according to the schedule shown in Table 2. The only exception to this schedule was at the Panama Canal Zone site.

The composition of the metals tested are given in Table 3.

In all cases, the panels were degreased and weighed before exposure. On withdrawal they were chemically cleaned to remove corrosion products and re-weighed. The steel panels were cleaned in a sodium hydride-sodium hydroxide solution, the copper panels in sulfuric acid, and the zinc panels in ammonium hydroxide.

### Phase 1 Results

The atmospheric factor and corrosion data developed for the one and twelve-month exposure periods at each site are appended as Appendix I, Tables 16 to 21.<sup>4</sup> Comments regarding these tabulations are as follows:

1. The total time of wetness is the average of the skyward and groundward times of wetness. The unit shown (days) is defined as the average time of wetness (hours) divided by 24.
2. The average panel temperatures shown are the averages during the time the panels were wet.

<sup>4</sup>Tables 16, 22, 23, 24, 25, and 26 have been selected from the Appendices to indicate the nature of the contained material. Complete sets of the tabulated data are available from University Microfilms, Inc., 300 N. Zeeb Road, Ann Arbor, Mich., 48106, at \$3.00 per copy.

3. The average sulfur dioxide concentration is that during the time of panel wetness. The sulfur dioxide activity values have been converted to parts per million using an autometer-lead peroxide cylinder relationship<sup>5</sup> which is a modification of that previously reported [5].

TABLE 1--Phase 1 exposure and withdrawal schedule.

	1961												1962												1963			
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A
<i>Exposures:</i>																												
1-month panels	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
12-month panels	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
<i>Withdrawals:</i>																												
1-month panels	-	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
12-month panels	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	

TABLE 2--Phase 2 exposure and withdrawal schedule.

	1963	1964				1965				
	Dec	Mar	June	Sept	Dec	Mar	June	Sept	Dec	
<i>Exposures:</i>										
3-month panels		x	x	x	x	x	x	x	x	-
6-month panels		x	x	x	x	x	x	x	-	-
9-month panels		x	x	x	x	x	x	-	-	-
18-month panels		x	x	x	-	-	-	-	-	-
<i>Withdrawals:</i>										
3-month panels	-	x	x	x	x	x	x	x	x	x
6-month panels	-	-	x	x	x	x	x	x	x	x
9-month panels	-	-	-	x	x	x	x	x	x	x
18-month panels	-	-	-	-	-	-	x	x	x	x

NOTE--Program commenced in March 1964 and terminated in March 1966 at Panama Canal Zone site.

TABLE 3--Analysis of metals tested, per cent.

	Cu	Mn	Mo	Cr	C	P	Ni	S
Steel	0.024	0.34	0.012	0.034	0.039	0.007	0.02	0.018
	Cu	S						
Copper	99.940	0.003						
	Cu	Fe	Mg	Pb	Cd	Zn		
Zinc	0.003	0.006	<0.001	0.10	0.005	99.89		

4. The corrosion losses shown are the averages of three panels in the case of the one-month exposures, and of two panels in the case of the twelve-month exposures.

The atmospheric factor data show that the sites vary significantly from one another in atmospheric sulfur dioxide concentration, panel tempera-

<sup>5</sup> See p. 223.



ture and panel time of wetness. These differences become apparent when twelve-month data are considered as shown in Fig. 1. It is important to note that the average sulfur dioxide and total time of wetness values for twelve-month periods beginning with different months vary significantly at all of the sites. The average temperatures at any specific site do not show the same degree of variation. The fact that the panels were wet for approximately 35 per cent of the time at Ottawa and approximately 70 per cent of the time at the Kure Beach 80-ft site is of interest. Values for the other sites lie between these extremes.

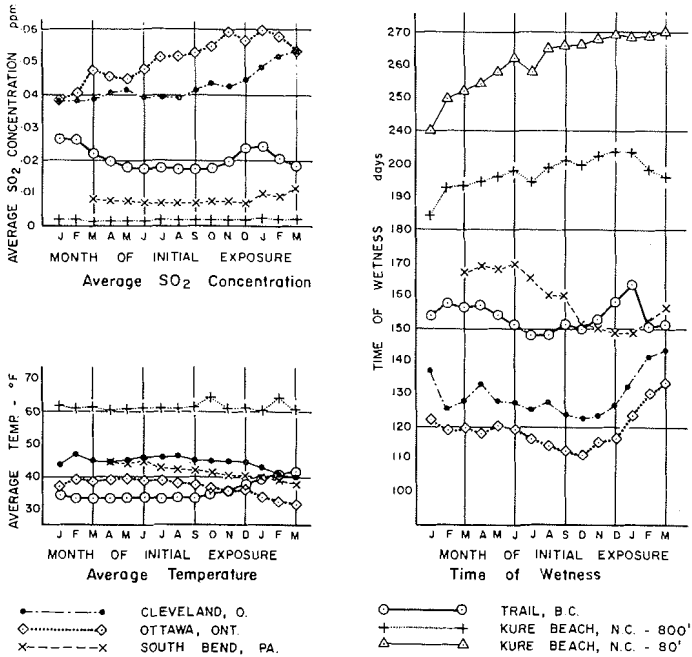


FIG. 1—Phase I twelve-month atmospheric factor data.

The corrosion loss data for the three metals also show considerable variation from site to site and from specimen to specimen at any one site. When a 4 by 6-in. panel is exposed for a period of twelve months, a 1-g weight loss is equivalent to a corrosion rate of 0.155 mils per year (mpy) for steel, 0.136 mpy for copper, and 0.170 mpy for zinc. Table 4 shows the minimum and maximum corrosion rates experienced by the twelve-month panels at each of the sites. The tabulation indicates the extremes in the variations encountered. As will become evident later, these variations can be accounted for in most cases by variations in the atmospheric factor data for twelve-month periods beginning with different months as shown in Fig. 1.

It is not possible to sort out the effects of the various atmospheric fac-

tors on corrosion by cursory examination of the data. This fact is illustrated in Table 5, which qualitatively ranks all sites except the Kure Beach 80-ft with respect to corrosivity (as determined from corrosion losses of the twelve-month specimens of steel, copper, and zinc), time of wetness, atmospheric sulfur dioxide and temperature. In the table, a rating of 1 denotes the highest corrosivity, 5 the lowest; 1 the most time of wetness, 5 the least; and so on.

The atmospheric factor and corrosion data for each metal were subjected to regression analyses using a quadratic equation in three variables. As a first approach data for the one-month and twelve-month exposures were included in the analyses. Agreement between observed corrosion losses and those calculated from the empirical equations which were developed was fair for the monthly losses and poor for the twelve-month losses. The one-month data only were then subjected to analyses and equations were developed for each metal when considering each of the test sites separately and for each metal when considering Cleveland, Ottawa, South Bend, and Trail as one group. The equations were of the form:

$$y = b_0 + b_1A + b_2B + b_3C + b_{11}A^2 + b_{22}B^2 + b_{33}C^2 + b_{12}AB + b_{13}AC + b_{23}BC$$

where:

$y$  = corrosion loss of steel, copper, or zinc in g/panel,

$b_i$  = regression coefficients,

$A$  = (time of wetness, days - 14.3)/5.0,

$B$  = (temperature, °F - 5.25)/15.0, and

$C$  = (SO<sub>2</sub>, ppm - 0.0202)/0.024.

The results of the analyses are given in Table 6. As an example of how this table is used, consider the case of steel at Ottawa. The equation developed is:

$$y = -0.572 + 1.696B + 0.215C - 0.268B^2 + 0.174AB.$$

Figures 2, 3, and 4 show the observed one and twelve-month weight losses experienced by the steel, copper, and zinc panels, respectively, and the estimated monthly losses as calculated from the correlation equations which were developed. Agreement between the observed and estimated losses is generally good, except in the cases where the four-site equations have been applied to the data from the Kure Beach sites. In other words, the equations account for most of the month-to-month weight loss variations at any one site and most of the site-to-site variations when considering Cleveland, Ottawa, South Bend, and Trail.

The equations developed do not enable one to identify the atmospheric factor which exerts the most critical effect on corrosion, or to observe how the others modify this effect. Phase 2 of the program was designed

to investigate this matter more fully and, if possible, to develop correlations between the atmospheric factors and the longer term corrosion losses.

## Phase 2 Results

Tables summarizing the monthly atmospheric data for the six participating sites are appended as Appendix II, Tables 22 to 25.<sup>4</sup> Each table lists the values obtained for a specific factor at each of the test sites. Comments regarding these tabulations are as follows:

TABLE 4—Corrosion rates experienced by twelve-month panels (mpy).

Site	Steel		Copper		Zinc	
	Min	Max	Min	Max	Min	Max
Cleveland	1.349	2.333	0.046	0.067	0.076	0.133
Ottawa	1.270	1.711	0.034	0.065	0.091	0.129
South Bend	1.253	1.654	0.056	0.082	0.050	0.114
Trail	1.124	1.848	0.063	0.099	0.054	0.069
Kure Beach 800	1.253	1.558	0.099	0.128	0.077	0.140
Kure Beach 80	3.349	5.525	0.092	0.153	0.178	0.266

TABLE 5—Corrosivity and atmospheric factor rankings.

Site	Corrosivity			Atmospheric Factors		
	Fe	Cu	Zn	Time of Wetness	SO <sub>2</sub> Concentration	Temperature
Cleveland	1	4	3	4	2	2
Ottawa	2	5	2	5	1	4
Trail	3	2	5	3	3	5
South Bend	4	3	4	2	4	3
Kure Beach 800	5	1	1	1	5	1

NOTE—Rankings are based on the averages of the twelve-month exposure data.

1. The time of wetness values are the averages of the skyward and groundward surface values.

2. Temperatures were not measured at the Panama Canal Zone site. The value of 79 F shown is based on prior meteorological data.

3. The lead peroxide candles used for measuring atmospheric sulfur dioxide activity were exposed each month during the times when panels were wet at Cleveland, Ottawa, and South Bend. At the other sites they were exposed for full calendar months.

Time of wetness values for the skyward and groundward surfaces as such are not shown. Some comment regarding these is warranted. Studies during the development stages of the dew-detector [16,17] and experience during the first year of Phase 1 indicated that the groundward surface is wet more often and for longer periods of time than the skyward, particularly at the inland sites. This was not necessarily the case during Phase 2.

TABLE 6—Phase I regression analyses results.

Metal Considered	Regression Coefficient	Test Site <sup>a</sup>							
		1	2.	3	4	5	6	7	
Steel.....	$b_0$	0.711	-0.572	0.967	0.836	-2.522	-7.116	0.386	
	$b_1$	0.463	.....	-0.595	0.411	.....	.....	.....	
	$b_2$	.....	1.696	.....	0.213	1.958	4.623	0.481	
	$b_3$	.....	0.215	.....	.....	.....	.....	0.317	
	$b_{11}$	-0.425	.....	.....	.....	.....	.....	-0.128	
	$b_{22}$	.....	-0.268	.....	.....	-0.249	-0.553	.....	
	$b_{33}$	.....	.....	.....	.....	.....	.....	-0.104	
	$b_{12}$	.....	0.174	0.185	.....	0.0838	0.138	0.0823	
	$b_{13}$	.....	.....	-0.433	.....	.....	.....	.....	
	$b_{23}$	0.0730	.....	.....	0.154	.....	.....	0.107	
	$b_0$	0.0523	0.0421	-0.0125	0.00816	0.220	0.0673	-0.0666	
	Copper.....	$b_1$	.....	.....	.....	0.0124	.....	.....	0.0794
		$b_2$	.....	.....	.....	.....	.....	.....	.....
$b_3$		.....	.....	.....	.....	.....	0.242	.....	
$b_{11}$		.....	.....	.....	-0.0128	-0.0933	.....	-0.00596	
$b_{22}$		.....	0.00584	0.0103	0.00904	.....	.....	-0.0105	
$b_{33}$		.....	.....	0.0584	.....	.....	.....	0.00925	
$b_{12}$		0.00202	0.0134	.....	.....	.....	.....	0.00651	
$b_{13}$		.....	-0.00499	.....	.....	.....	.....	.....	
$b_{23}$		-0.00188	.....	.....	.....	.....	-0.123	-0.00657	
Zinc.....		$b_0$	0.0638	0.0361	0.0392	0.0691	-0.0782	-0.1903	0.0572
		$b_1$	.....	.....	.....	0.0297	.....	.....	.....
		$b_2$	.....	0.0237	.....	.....	0.0699	0.127	.....
		$b_3$	.....	0.0208	.....	.....	.....	.....	.....
	$b_{11}$	.....	-0.0196	.....	.....	.....	.....	.....	
	$b_{22}$	0.00494	.....	.....	.....	.....	.....	0.00599	
	$b_{33}$	.....	.....	0.175	0.00895	.....	.....	0.00649	
	$b_{12}$	0.0117	.....	0.0147	.....	.....	.....	0.0146	
	$b_{13}$	.....	.....	.....	0.0109	.....	.....	.....	

<sup>a</sup> Test site identification: 1—Cleveland, 2—Ottawa, 3—South Bend, 4—Trail, 5—Kure Beach 800-ft, 6—Kure Beach 80-ft, 7—all sites excepting those at Kure Beach.

Table 7 briefly summarizes the situation. Shown are the monthly averages of the values for the skyward and groundward times of wetness, the number of readings considered in calculating the averages, and the number of cases where the skyward readings were greater than the groundward.

Tables 26 to 31, Appendix II, show totals or averages of the atmospheric factor data for periods of time corresponding in length to those periods during which corrosion specimens were exposed, and the cor-

TABLE 7—Monthly averages time of panel wetness during Phase 2.

Site	Average T of W, Days		No. of Readings	No. of Reading Where S > G
	Sky (S)	Ground (G)		
Kure Beach 80 ft.....	23.6	21.7	25	21
Kure Beach 800 ft.....	17.5	15.4	25	18
Panama.....	16.8	15.2	21	14
South Bend.....	13.2	13.8	24	4
Cleveland.....	10.5	11.1	18	9
Ottawa.....	8.8	10.1	24	12

TABLE 8—Corrosion rates experienced by 9- and 18-month panels (mpy).

Months	Site	Steel		Copper		Zinc	
		Min	Max	Min	Max	Min	Max
9 months....	Cleveland	1.516	2.475	0.056	0.073	0.067	0.112
	Ottawa	1.110	1.387	0.032	0.048	0.052	0.093
	South Bend	1.241	2.261	0.077	0.106	0.047	0.096
	Panama	1.181	1.552	0.102	0.156	0.085	0.145
	Kure Beach 800 ft	1.343	1.931	0.106	0.150	0.102	0.233
	Kure Beach 80 ft	2.430	10.357	0.149	0.173	0.179	0.424
18 months....	Cleveland	...	1.461	...	0.055	...	0.098
	Ottawa	...	1.039	...	0.043	...	0.079
	South Bend	...	1.450	...	0.095	...	0.076
	Kure Beach 800 ft	...	1.515	...	0.106	...	0.129
	Kure Beach 80 ft	...	10.216	...	0.147	...	0.236

rosion data for steel, copper, and zinc for each of the six test sites. Note that the sulfur dioxide activity values have been converted to equivalent ppm sulfur dioxide (SO<sub>2</sub>).

Experience during Phase 2 was similar to Phase 1 with respect to variations encountered in time of panel wetness, temperature, and atmospheric sulfur dioxide at the different sites. Atmospheric chloride data collected at the three marine sites show considerable month-to-month variations. The average values for the longer periods were slightly higher at Panama than at the Kure Beach 800-ft site. The averages at the Kure Beach 80-ft site were approximately eight times those at the other two.

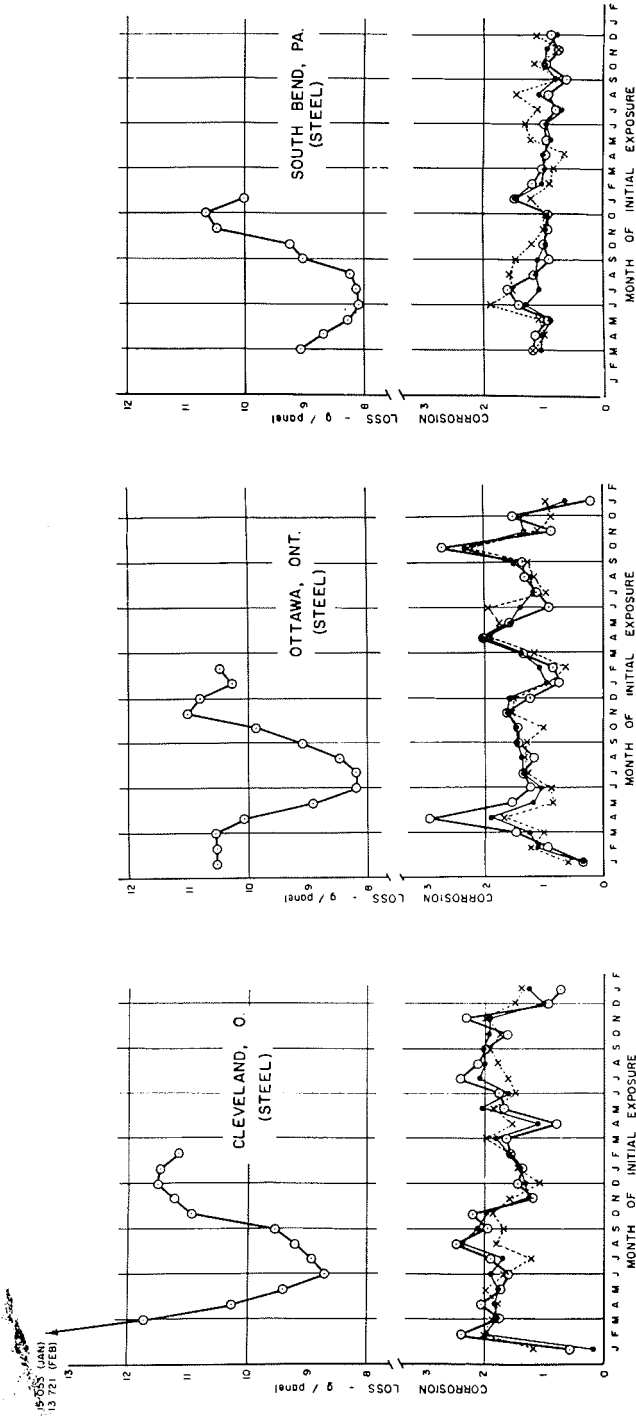
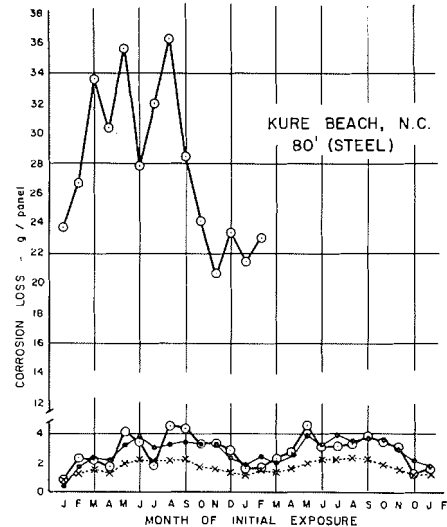
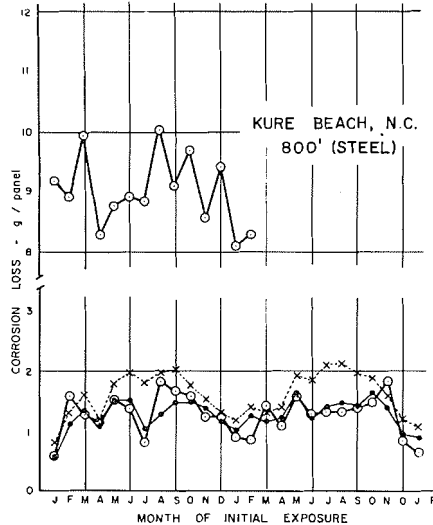
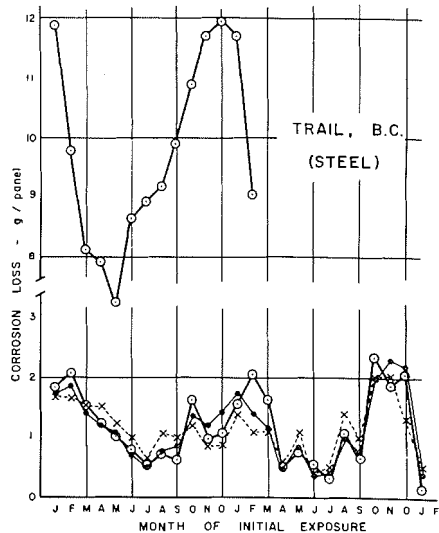


FIG. 2—Phase I steel corrosion data.



○—○ OBSERVED

x-----x ESTIMATED (4 SITE EQUATION)

●—● ESTIMATED (INDIVIDUAL SITE EQUATION)

FIG. 2—Continued.

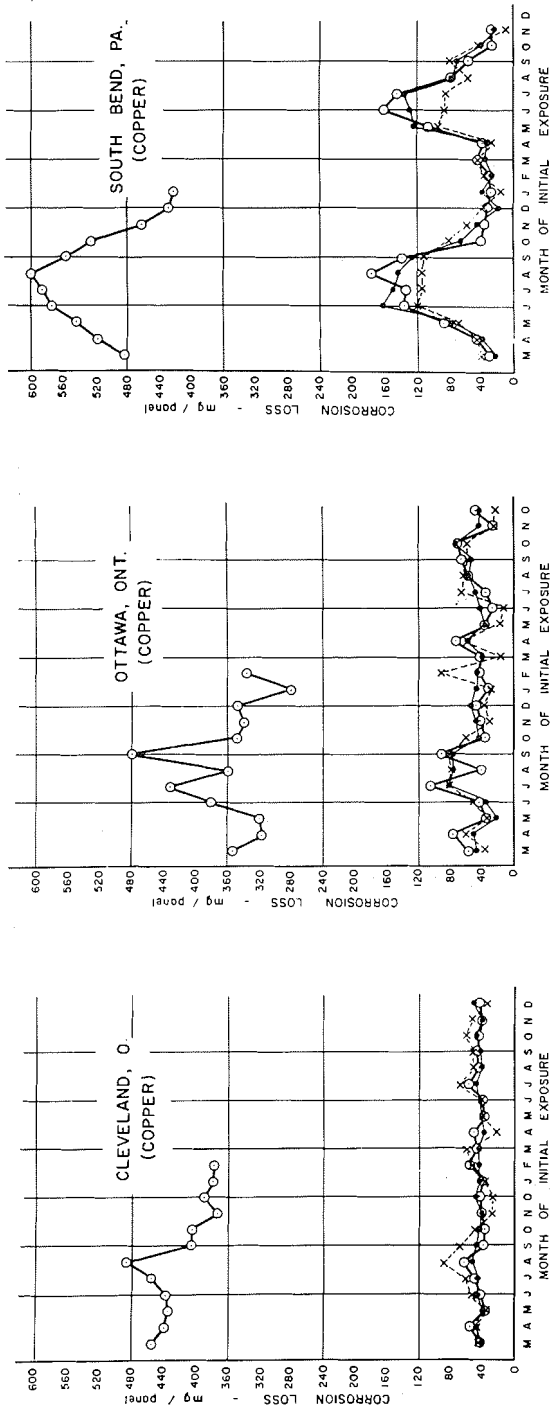
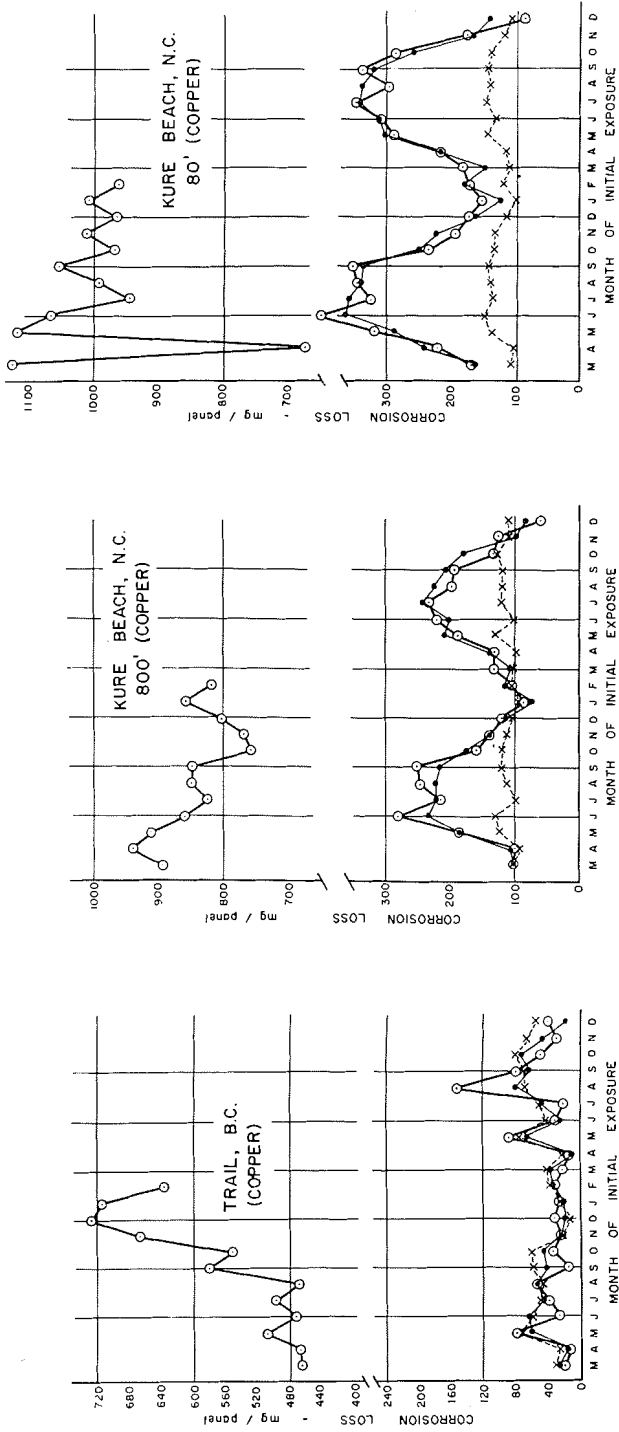


FIG. 3—Phase 1 copper corrosion data.





ESTIMATED (INDIVIDUAL SITE EQUATION)

ESTIMATED (4 SITE EQUATION)

OBSERVED

FIG. 3—Continued.

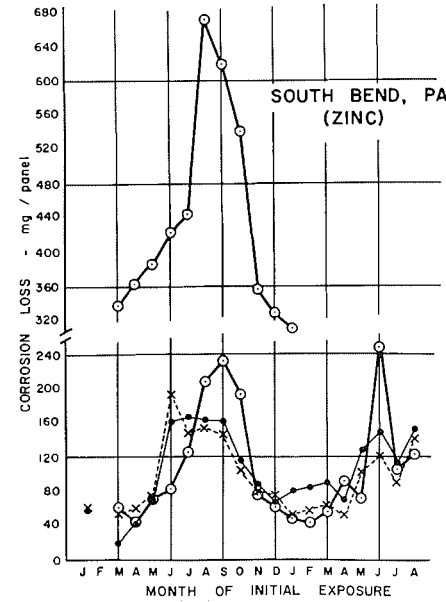
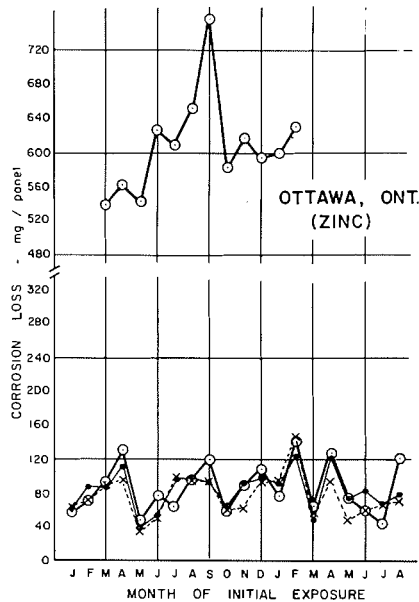
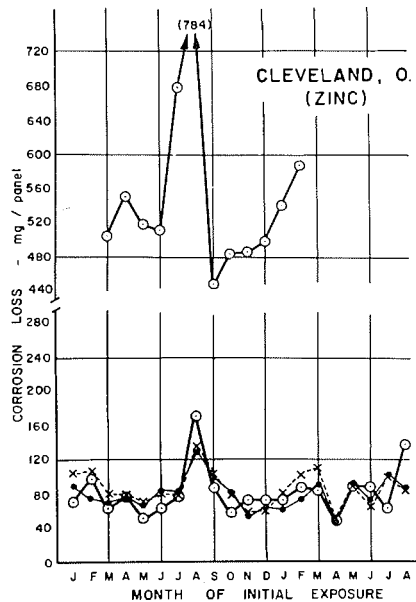


FIG. 4—Phase 1 zinc corrosion data.

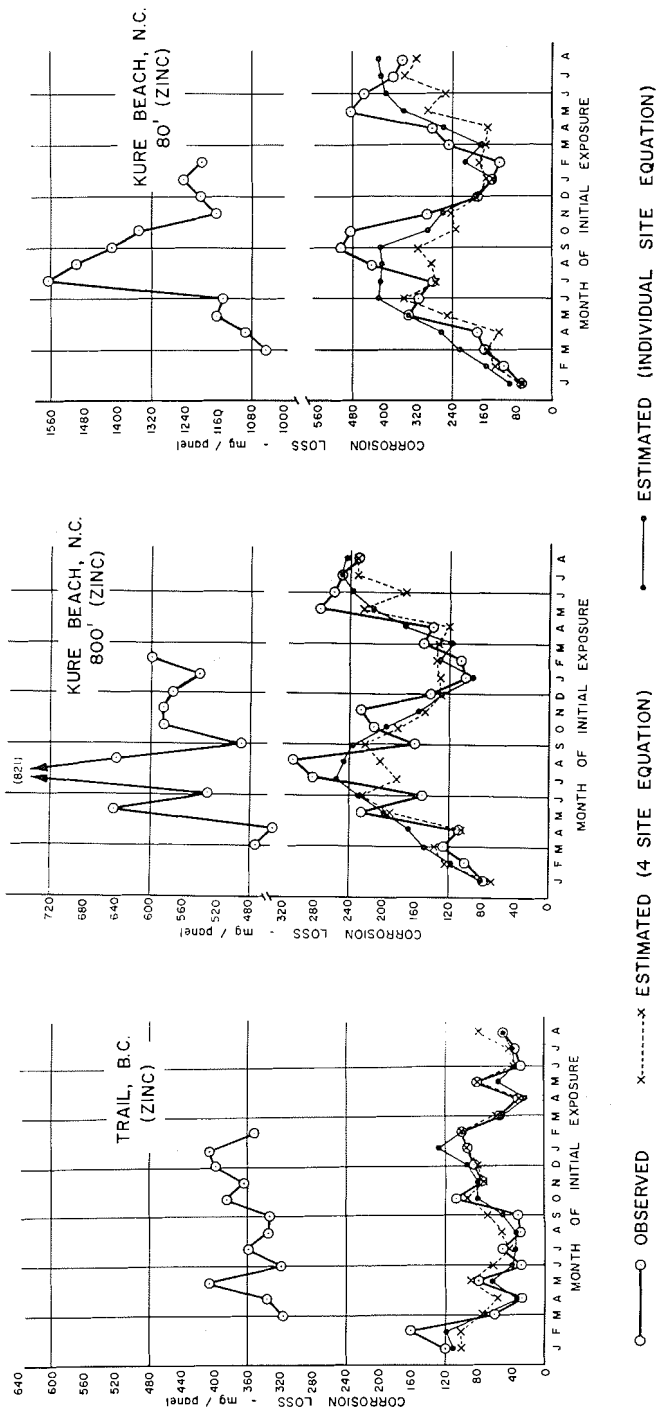


FIG. 4—Continued.

Variations in corrosion losses were again appreciable. These variations are due mainly to variations in atmospheric factors during periods of time which commenced at different months. Table 8 shows the minimum and maximum corrosion rates (mpy) experienced by the three metals at each site for the nine-month exposures and the maxima for the 18-month exposures.

This table is intended only to indicate the variations in corrosion rates. The initial exposure dates for panels whose rates are shown in the "maxi-

TABLE 9—Phase 2 regression analyses results inland sites.

Metal Considered	Regression Coefficient	Test Site		
		Cleveland	Ottawa	South Bend
Steel.....	$b_0$	7.4836	6.4199	5.2257
	$b_1$	5.2254	4.5330	4.1342
	$b_3$	...	0.1986	...
	$b_{11}$	-1.3807	-0.7191	-0.6345
	$b_{22}$	...	-0.2020	...
	$b_{33}$	0.3208	...	...
	$b_{12}$	-0.6440	...	...
	$b_{23}$	0.5430	...	...
Copper.....	$b_0$	0.2807	0.2382	0.2764
	$b_1$	0.2294	0.1975	0.2232
	$b_2$	0.0493	0.0278	0.0709
	$b_{11}$	-0.0234	...	...
	$b_{12}$	0.0478	0.0276	0.0353
Zinc.....	$b_0$	0.3324	0.3157	0.2328
	$b_1$	0.2790	0.2520	0.1425
	$b_2$	...	-0.0660	...
	$b_{12}$	...	-0.0644	-0.0294

NOTE—Basic equation is:

$$y = b_0 + b_1A + b_2B + b_3C + b_{11}A^2 + b_{22}B^2 + b_{33}C^2 + b_{12}AB + b_{13}AC + b_{23}BC$$

where:

$y$  = corrosion loss, g,

$A$  = (time of wetness, days-75)/70,

$B$  = (panel temperature, deg F-45)/12, and

$C$  = (SO<sub>2</sub>, ppm-0.02)/0.02.

imum" columns for the two sets of data were not the same. For this reason the tabulation cannot be used to indicate whether or not corrosion rates attain constant values with time.

Only three sets of each metal were exposed at the test sites for the 18-month period. This was not a large enough number to establish the specimen-to-specimen fluctuation trend exhibited by the 3, 6, and 9-month sets. It was felt that this long-term data deficiency would tend to bias studies of the data. Accordingly, a decision was made to incorporate Phase 1 and Phase 2 results into the statistical analyses which were carried out.

TABLE 10—Phase 2 regression analyses results marine sites.

Metal Considered	Regression Coefficient	Test Site		
		Panama	Kure Beach 800 ft	Kure Beach 80 ft
Steel . . . . .	$b_0$	1.5822	3.0545	4.3846
	$b_2$	...	1.1802	...
	$b_4$	4.8443	...	...
	$b_{11}$	...	-0.2199	2.2186
	$b_{33}$	2.8720	...	...
	$b_{44}$	...	...	0.0219
	$b_{12}$	...	1.2222	...
	$b_{13}$	-3.0575	-2.2820	...
	$b_{14}$	...	...	0.5433
	$b_{34}$	5.2295	...	...
Copper . . . . .	$b_0$	-3.9404	0.3047	0.5026
	$b_1$	...	0.3051	0.1562
	$b_2$	3.0296	0.5613	...
	$b_3$	10.8608	...	...
	$b_4$	-0.5068	...	...
	$b_{11}$	-0.0265	-0.0308	...
	$b_{33}$	6.8921	...	...
	$b_{13}$	-0.3113	...	...
	$b_{14}$	0.0882	...	0.0039
	$b_{23}$	...	0.5109	...
$b_{34}$	-0.6393	...	...	
Zinc . . . . .	$b_0$	0.3462	0.1859	0.5092
	$b_1$	...	...	0.2499
	$b_2$	...	0.1690	...
	$b_{44}$	...	...	0.0012
	$b_{12}$	0.0552	0.1422	...
	$b_{24}$	0.0162	...	...

NOTE—Basic equation is:

$$y = b_0 + b_1A + b_2B + b_3C + b_4D + b_{11}A^2 + b_{22}B^2 + b_{33}C^2 + b_{44}D^2 + b_{12}AB + b_{13}AC + b_{14}AD + b_{23}BC + b_{24}BD + b_{34}CD$$

where:

- $y$  = corrosion loss, g,  
 $A$  = (time of wetness, days-75)/70,  
 $B$  = (panel temperature, deg F-45)/12,  
 $C$  = (SO<sub>2</sub>, ppm-0.02)/0.02, and  
 $D$  = (Cl<sup>-</sup>, mg-18)/10.

The atmospheric factor and corrosion data were analyzed by the following techniques:

1. Regression analysis using a quadratic equation with time of wetness, temperature, and sulfur dioxide concentration as the variables for Cleveland, Ottawa, and South Bend and with time of wetness, temperature, sulfur dioxide concentration, and atmospheric chloride count as the variables for Panama and the two Kure Beach sites.

2. Curve-fitting where: (a) time of wetness and sulfur dioxide data

TABLE 11—Phase 2 curve-fitting results (time of wetness, SO<sub>2</sub>) inland sites.

Metal Considered	Equation Parameters	Test Site		
		Cleveland	Ottawa	South Bend
Steel.....	<i>a</i>	-0.64740	0.16058	0.37320
	<i>b</i>	0.67690	0.70625	0.74617
	<i>c</i>	-0.67920	1.78100	0.53610
Copper.....	<i>a</i>	-0.03715	-0.01006	0.00889
	<i>b</i>	0.83210	0.83044	0.90105
	<i>c</i>	-0.24575	-0.68078	0.64302
Zinc.....	<i>a</i>	-0.00538	0.03700	-0.06925
	<i>b</i>	0.88530	0.87681	0.61940
	<i>c</i>	-1.43100	0.17027	-0.26910

NOTE—Basic equation is:

$$y = aA^b(B + c)$$

where:

- y* = corrosion loss, g,
- A* = time of wetness, days, and
- B* = SO<sub>2</sub>, ppm.

TABLE 12—Phase 2 curve-fitting results (time of wetness, temperature) inland sites.

Metal Considered	Equation Parameters	Test Site		
		Cleveland	Ottawa	South Bend
Steel.....	<i>a</i>	0.004056	0.0003879	-0.0008599
	<i>b</i>	0.67179	0.78691	0.66471
	<i>c</i>	50.80235	511.03597	-417.42447
Copper.....	<i>a</i>	0.0001082	0.0000608	0.00014
	<i>b</i>	0.83934	0.83634	0.86331
	<i>c</i>	23.48773	63.67978	3.08855
Zinc.....	<i>a</i>	-0.0000205	-0.0001054	-0.0000592
	<i>b</i>	0.96095	0.87290	0.62648
	<i>c</i>	-294.76500	-116.92762	-333.56933

NOTE—Basic equation is:

$$y = aA^b (B + c)$$

where:

- y* = corrosion loss, g,
- A* = time of wetness, days, and
- B* = temperature, deg F.

and time of wetness and temperature data for Cleveland, Ottawa, and South Bend, (*b*) time of wetness and atmospheric chloride data for Panama and the Kure Beach sites, and (*c*) time of wetness and temperature data for the Kure Beach sites were fitted to an equation of the type  $y = aA^b (B + c)$ .

The results of the analyses are given in Tables 9 to 14.

Corrosion losses were calculated using these equations. In some cases, agreement between the observed and estimated losses was good. In others

TABLE 13—Phase 2 curve-fitting results (time of wetness, chloride count) marine sites.

Metal Considered	Equation Parameters	Test Site		
		Panama	Kure Beach 800 ft	Kure Beach 80 ft
Steel.....	<i>a</i>	0.0003483	0.0035165	0.0000518
	<i>b</i>	0.88041	0.78426	1.59073
	<i>c</i>	217.73130	28.09492	-13.87083
Copper.....	<i>a</i>	0.0003872	0.0004197	0.0000369
	<i>b</i>	0.60414	0.65947	0.57322
	<i>c</i>	71.47727	47.82301	1041.73840
Zinc.....	<i>a</i>	0.0003314	0.0014100	0.0002840
	<i>b</i>	0.61475	0.54618	0.54616
	<i>c</i>	55.75238	12.51736	104.00458

NOTE—Basic equation is:

$$y = aA^b (B + c)$$

where:

- y* = corrosion loss, g,
- A* = time of wetness, days, and
- B* = chloride count, mg Cl<sup>-</sup>/m<sup>2</sup>/d.

TABLE 14—Phase 2 curve-fitting results (time of wetness, temperature) marine sites.

Metal Considered	Equation Parameters	Test Site		
		Panama	Kure Beach 800 ft	Kure Beach 80 ft
Steel.....	<i>a</i>	...	0.0038132	0.0000211
	<i>b</i>	...	0.76757	1.61733
	<i>c</i>	...	-15.75565	170.29125
Copper.....	<i>a</i>	...	0.0006275	0.0001075
	<i>b</i>	...	0.63901	0.63394
	<i>c</i>	...	-14.37599	220.36306
Zinc.....	<i>a</i>	...	0.0015016	0.0008234
	<i>b</i>	...	0.57610	0.52104
	<i>c</i>	...	-37.16710	24.84405

NOTE—Basic equation is:

$$y = aA^b (B + c)$$

where:

- y* = corrosion loss, g,
- A* = time of wetness, days, and
- B* = temperature, deg F.

it was fair to good, fair or poor. The different equations for a specific metal at a specific site usually gave similar results, there being a few exceptions to this. Table 15 shows a qualitative assessment of the degree of agreement between the observed and estimated losses.

Figures 5 to 10 show the observed weight losses and the estimated losses which are in "best" agreement with the observed losses for steel, copper, and zinc at each site. It is seen that in some cases "best" agreement is still "poor." Indications are that a reasonable degree of correla-

TABLE 15—Agreement between observed and calculated corrosion losses.<sup>a</sup>

Analytical Method	Cleveland			Ottawa			South Bend			Panama			Kure Beach 800 ft			Kure Beach 80 ft				
	Fe	Cu	Zn	Fe	Cu	Zn	Fe	Cu	Zn	Fe	Cu	Zn	Fe	Cu	Zn	Fe	Cu	Zn		
	Regression analyses...	P	P	F-G	F <sup>b</sup>	P	F-G	P	F-G	P	P	P	P	G	G	F	F	P-F <sup>c</sup>	P-F	
<i>Curve-fitting:</i>																				
T of W and SO <sub>2</sub> .....	P	P	F-G	F <sup>b</sup>	P	F-G	P	F-G	P	P	P	P	G	F-G	F	F	P-F <sup>c</sup>	P	P	
T of W and temperature.....	P	P	F-G	F <sup>b</sup>	P	F-G	P	F-G	P	P	P	P	F-G	F-G	F	F	P-F <sup>c</sup>	P	P	
T of W and Cl <sup>-</sup> .....	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

<sup>a</sup> G = good, F = fair, P = poor.  
<sup>b</sup> Agreement best for 3- and 6-month exposures.  
<sup>c</sup> Agreement best for 9-month exposures.



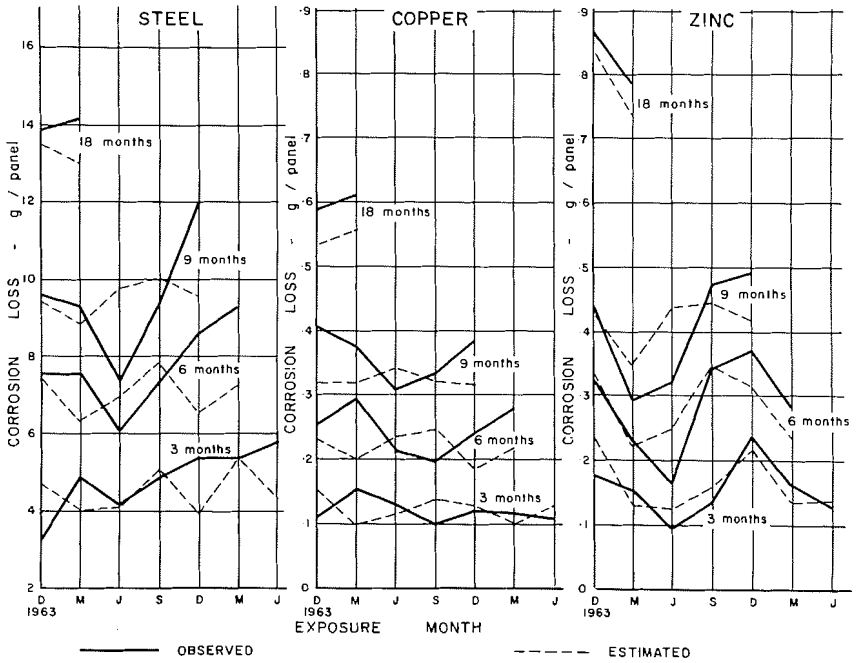


FIG. 5—Phase 2 corrosion data for Cleveland.

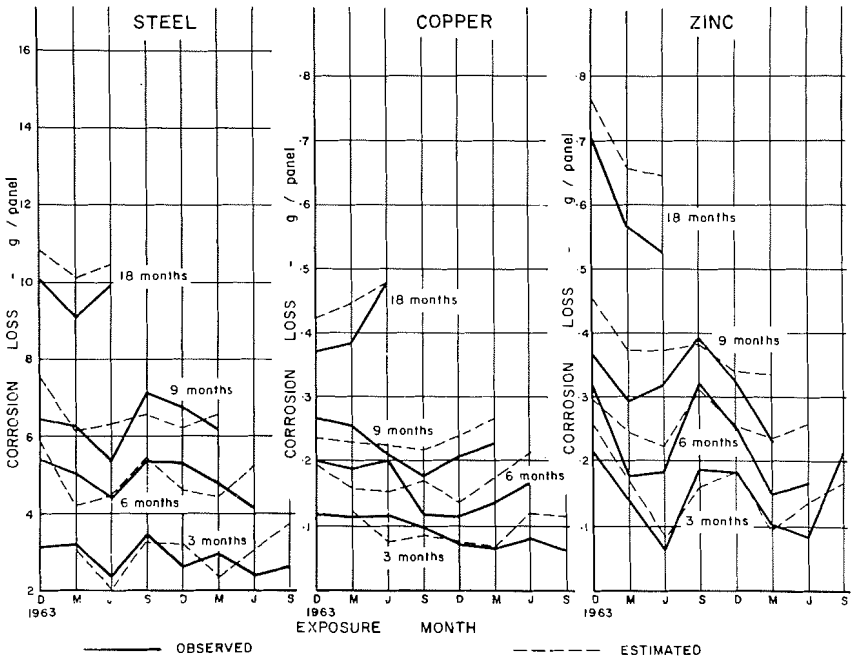


FIG. 6—Phase 2 corrosion data for Ottawa.

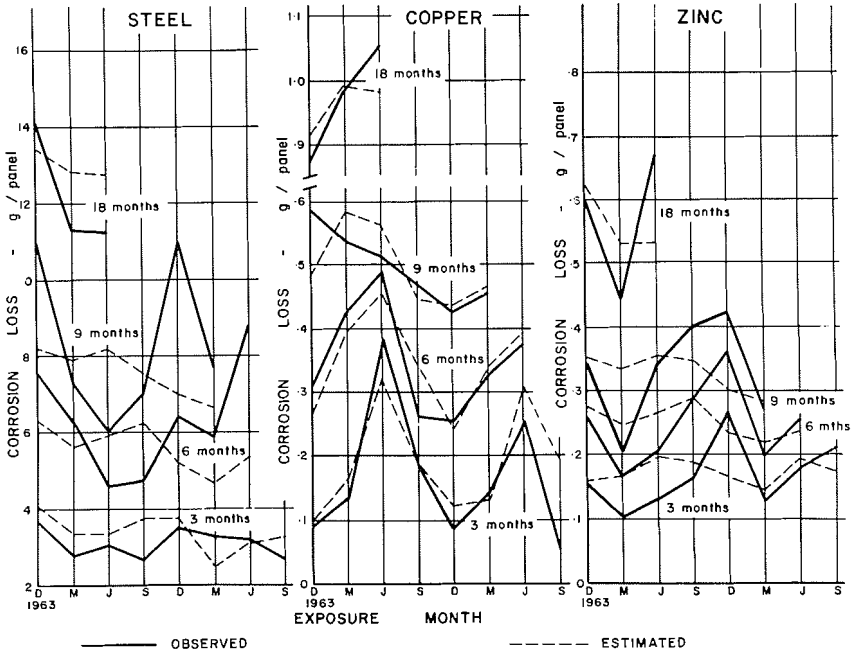


FIG. 7—Phase 2 corrosion data for South Bend.

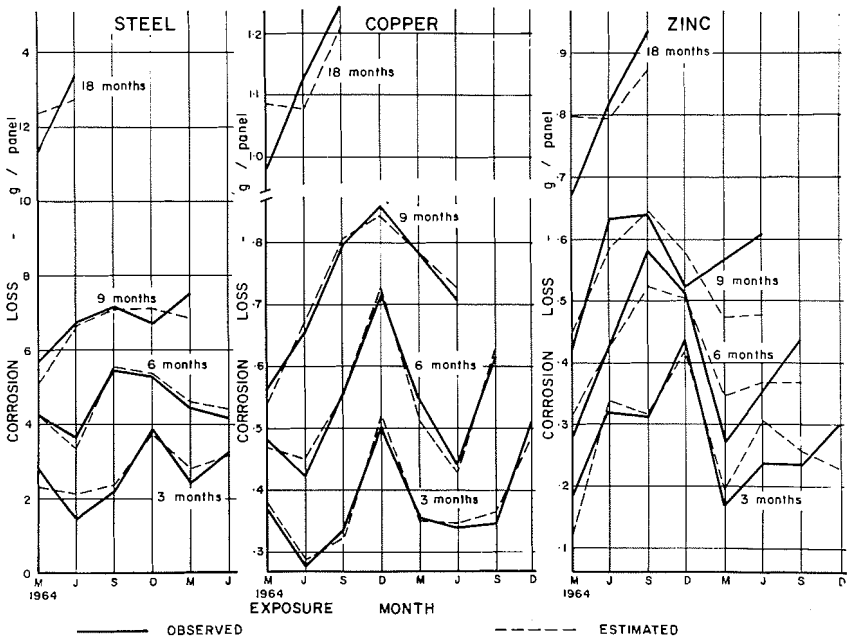


FIG. 8—Phase 2 corrosion data for Panama.

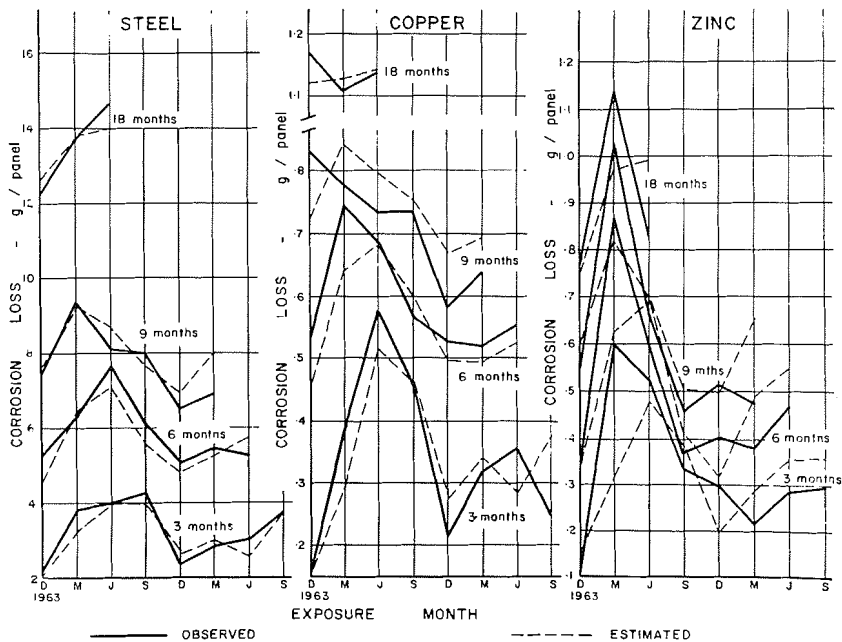


FIG. 9—Phase 2 corrosion data for Kure Beach 800 ft.

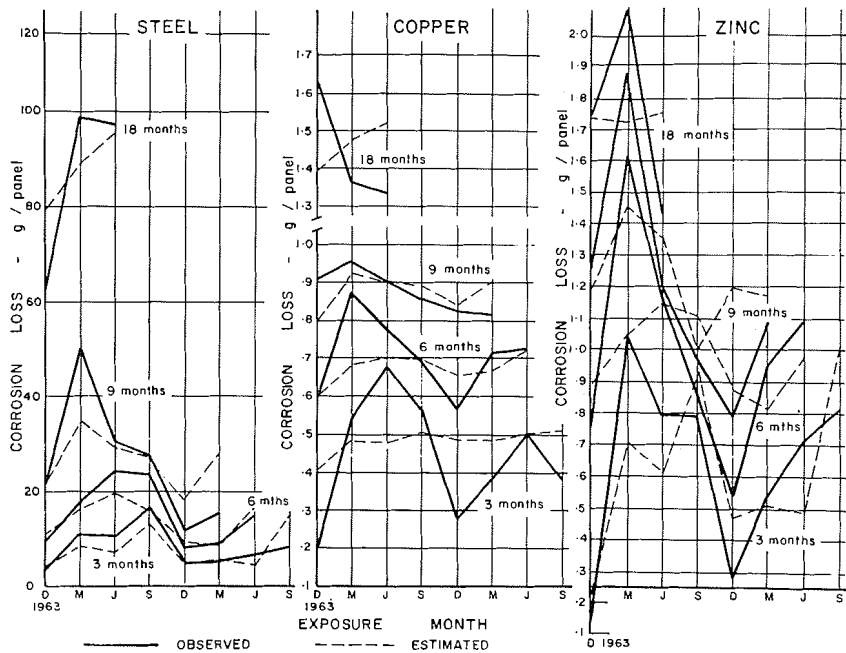


FIG. 10—Phase 2 corrosion data for Kure Beach 80 ft.

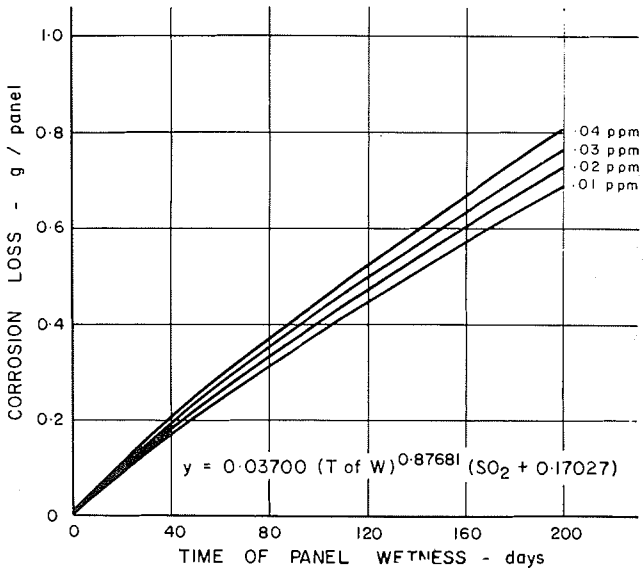


FIG. 11—Empirical relationship between corrosion of zinc and time of wetness and sulfur dioxide at Ottawa.

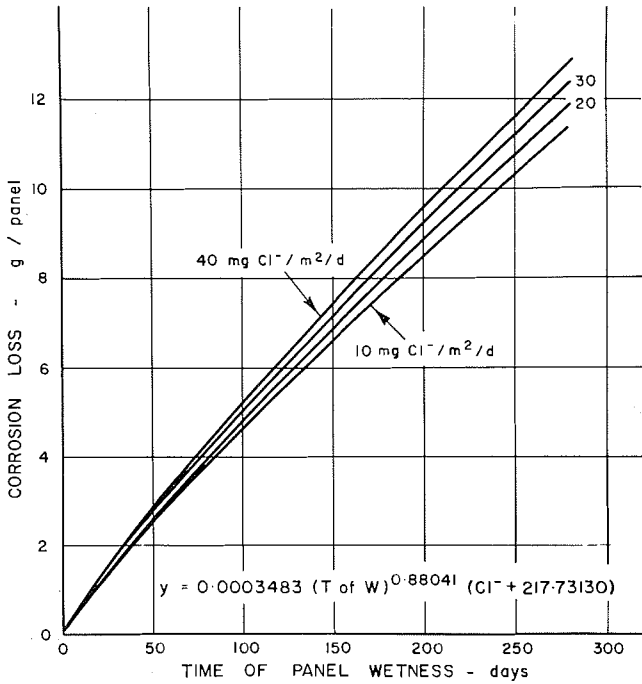


FIG. 12—Empirical relationship between corrosion of steel and time of wetness and atmospheric chlorides at Panama.

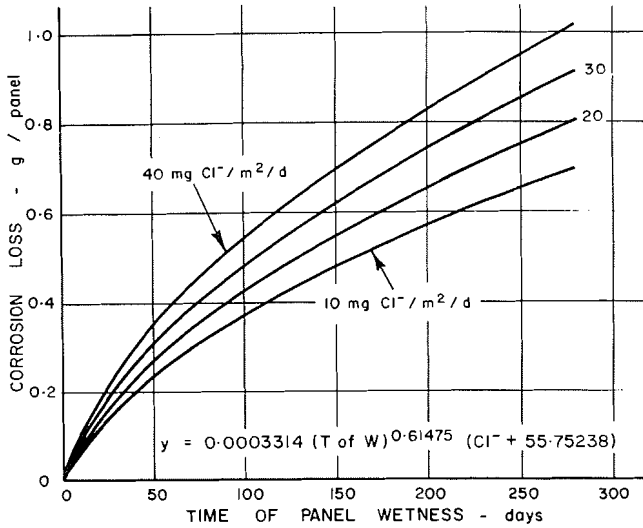


FIG. 13—Empirical relationship between corrosion of zinc and time of wetness and atmospheric chlorides at Panama.

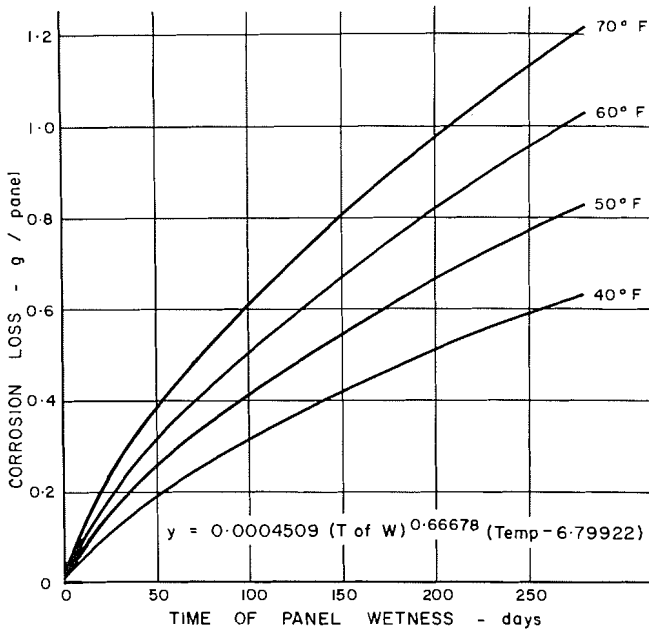


FIG. 14—Empirical relationship between corrosion of copper and time of wetness and temperature at Kure Beach 800-ft site.

tion exists between the corrosion losses and the measured atmospheric factors in the case of steel at all sites except Cleveland and South Bend; in the case of copper at all sites except Cleveland, Ottawa, and possibly Kure Beach 80 ft; and in the case of zinc at all sites except South Bend and possibly Kure Beach 80 ft.

The equations developed using the curve-fitting techniques are amenable to graphical presentation. Figures 11 to 14 show as examples relationships for zinc at Ottawa, steel at Panama, zinc at Panama, and copper at Kure Beach 800 ft. Some of the equations for the inland sites other than those shown present an anomalous picture in that they indicate that for a specific time of wetness, corrosion decreases as the temperature, or sulfur dioxide concentration increases. This is the case with zinc at Cleveland, Ottawa, and South Bend and steel at South Bend when temperature is the variable; and with steel at Cleveland, copper at Cleveland and Ottawa, and zinc at Cleveland and South Bend when sulfur dioxide is the variable. The apparent anomalies are due to the fact that in the specific cases mentioned interactions of meteorological factors are different than for the average conditions, as, for example, when snow on the panels is responsible for time of wetness.

The regression analyses equations also contain some apparent anomalies in that a sulfur dioxide term is significant only in the equations for steel at Cleveland, Ottawa, Panama, and Kure Beach 80 ft and for copper at Panama and Kure Beach 800 ft; a chloride term is not significant in any of the equations for Kure Beach 800 ft; a temperature term is absent from a number of equations where one would suspect it should be present; etc. No explanation is offered for these other than that they represent a shortcoming of the particular analytical technique used.

### Summary and Conclusions

A four-year program has been carried out wherein considerable corrosion data for steel, copper, and zinc were developed for seven North American test sites along with associated data for panel time of wetness, panel temperature, atmospheric sulfur dioxide, and atmospheric chloride content. This program has confirmed that the methods used for measuring the atmospheric factors are suitable for long term corrosion studies.

The results show conclusively that the atmospheric factors measured control completely the initial rate of corrosion of panels of steel, copper, and zinc. This control persists for these metals for at least one month. Evidence for this statement is obtained from the statistical analyses which indicate good correlation between the corrosion losses experienced during one-month exposure periods and the atmospheric factors.

For longer term exposures the atmospheric factors control the corrosion of zinc under most conditions investigated (all sites except South Bend) and of steel and copper at the marine sites. With steel and copper

at the inland sites it is assumed that control of the corrosion process is gradually transferred from the atmospheric factors to factors related to the changing surface condition resulting from accumulation of corrosion products and foreign agents. This appears to be true in all cases except steel at Ottawa and copper at South Bend.

A number of empirical equations have been developed which enable one to predict the corrosion losses for cases where atmospheric factors control the corrosion processes. These are for:

1. Steel at the Kure Beach 800 and 80-ft sites, Ottawa, and Panama.
2. Copper at the Kure Beach 800 and 80-ft sites, Panama, and South Bend.
3. Zinc at Cleveland, the Kure Beach 800 and 80-ft sites, Panama, and Ottawa.

(The relationships for copper and zinc at the Kure Beach 80-ft site are not as good as the others.)

Where these empirical equations are applicable, it is now possible to account for variations in observed corrosion losses experienced by panels exposed at different times of the year. It is important to note that corrosion data based on specimens exposed at one specific time of year should be used with caution. Such data should be supplemented with records of atmospheric conditions which prevail at the exposure site in order that a meaningful interpretation of the corrosion results can be made.

The results of this program indicate an area of future work concerned with the character of corrosion products which form on the surface of a corroding specimen and which modify the primary control of the atmospheric factors on the rate of corrosion of metals.

### *Acknowledgment*

Grateful acknowledgment is extended to the American Steel and Wire Div. and the Applied Research Laboratory of the United States Steel Corp., Armco Steel Corp., Bridgeport Brass Co., Cominco Ltd., The International Nickel Co. Inc., the National Research Council, Canada, and the United States Army Frankford Arsenal for their participation in this program. The following personnel of these companies and organizations, with the assistance of their associates, undertook various duties in connection with the program: B. V. Dolan, J. H. Rigo, T. P. May, S. K. Coburn, O. B. Ellis, A. Gallacio, R. V. Hall, H. H. Lawson, and J. R. Wellington. The part played by H. L. Williams, Cominco Ltd., in carrying out the statistical analyses deserves special mention.

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## APPENDIX I

TABLE 16—Phase 1 atmospheric factor and corrosion data (Site: Cleveland).

Month	Time of Wetness, days	Average Temperature, deg F	Average SO <sub>2</sub> , ppm	Weight Loss, g/panel		
				Fe	Zn	Cu
<i>1 month:</i>						
Jan. 61	22.6	22.4	0.0540	0.585	0.070	...
Feb.	12.5	36.9	0.0765	2.409	0.098	0.039
March	10.7	38.9	0.0590	1.745	0.062	0.043
April	12.1	40.0	0.0400	2.078	0.075	0.053
May	9.1	47.0	0.0520	1.793	0.050	0.038
June	9.3	58.8	0.0190	1.618	0.064	0.044
July	8.2	63.9	0.0060	1.922	0.077	0.051
Aug.	13.1	64.6	0.0095	2.488	0.171	0.063
Sept.	10.6	62.6	0.0130	1.958	0.086	0.038
Oct.	10.7	49.6	0.0340	2.214	0.057	0.037
Nov.	7.7	39.4	0.0545	1.191	0.073	0.041
Dec.	11.3	30.0	0.0225	1.451	0.073	0.043
Jan. 62	10.6	27.3	0.0700	1.380	0.073	0.039
Feb.	14.5	26.8	0.0755	1.575	0.088	0.057
March	16.0	34.4	0.0670	1.661	0.083	0.048
April	6.8	41.3	0.0550	0.797	0.046	0.049
May	8.4	67.5	0.0220	1.686	0.088	0.036
June	7.5	60.8	0.0190	1.768	0.088	0.039
July	10.2	64.0	0.0110	2.430	0.062	0.058
Aug.	9.2	61.4	0.0225	2.116	0.137	0.045
Sept.	10.0	53.9	0.0325	1.994	...	0.046
Oct.	11.5	48.7	0.0240	1.638	...	0.046
Nov.	10.9	39.3	0.0715	2.332	...	0.040
Dec.	19.1	24.8	0.0620	0.942	...	0.043
Jan. 63	17.8	22.6	0.0835	0.728	...	...
Feb.	16.2	19.5	0.0920	0.869	...	...
<i>12 months:</i>						
Jan. 61	137.9	43.5	0.0388	15.053	...	...
Feb.	125.9	46.4	0.0381	13.721	...	0.445
March	127.9	45.0	0.0387	11.739	0.504	0.456
April	133.2	44.1	0.0407	10.290	0.550	0.439
May	127.9	44.3	0.0415	9.415	0.516	0.435
June	127.2	45.8	0.0393	8.706	0.510	0.438
July	125.4	45.7	0.0396	8.940	0.678	0.456
Aug.	127.4	46.0	0.0395	9.243	0.784	0.489
Sept.	123.5	45.1	0.0414	9.572	0.446	0.406
Oct.	122.9	44.3	0.0432	10.951	0.483	0.405
Nov.	123.7	44.3	0.0422	11.227	0.484	0.371
Dec.	126.9	44.0	0.0444	11.522	0.496	0.388
Jan. 62	134.7	42.5	0.0489	11.493	0.541	0.378
Feb.	141.9	40.8	0.0520	11.184	0.588	0.377
March	143.6	39.9	0.0540	10.632	0.540	0.337

## APPENDIX II

TABLE 22—*Monthly time of wetness, days.*

Month	Cleveland	Ottawa	South Bend	Kure Beach 80 ft	Kure Beach 800 ft	Panama
Dec. 63.....	17.8	18.5	22.8	12.9	10.7	...
Jan. 64.....	18.6	10.5	13.4	15.8	18.7	...
Feb. 64.....	15.2	12.1	14.0	11.2	11.4	...
March 64.....	9.1	10.1	11.9	17.8	15.1	...
April 64.....	8.6 <sup>a</sup>	11.8	20.8	21.7	18.9	10.8
May 64.....	6.9	4.7	9.5	29.5	13.5	11.5
June 64.....	7.3	4.5	11.4	21.2	16.4	13.7
July 64.....	8.3	5.9	16.0	17.9	11.4	14.6
Aug. 64.....	7.6	5.7	15.3 <sup>a</sup>	27.9	20.7	18.3
Sept. 64.....	10.4	6.4	19.9 <sup>a</sup>	27.3	21.0	17.7
Oct. 64.....	11.9	11.8	15.0	26.7	16.0	15.8
Nov. 64.....	9.3	12.8	12.1 <sup>a</sup>	22.3 <sup>a</sup>	17.5	18.6
Dec. 64.....	15.3	12.9	13.8	25.9	21.5	14.9
Jan. 65.....	13.8	8.5	14.4	23.4	19.7	21.5
Feb. 65.....	17.0 <sup>a</sup>	8.9	18.6	18.6	16.8	23.0
March 65.....	10.3 <sup>a</sup>	7.5	13.3	22.3	20.3	17.6
April 65.....	9.0	6.5	6.2	23.1	17.0	14.6
May 65.....	14.7	5.1	8.6	23.1	16.6	14.6
June 65.....	8.9	5.1	11.9	24.6	11.7 <sup>a</sup>	16.0
July 65.....	9.9	10.4	13.4	27.4	8.7	14.4
Aug. 65.....	7.0 <sup>a</sup>	11.9	13.2	22.3	14.1	16.1
Sept. 65.....	...	11.6	17.8	28.4	17.9	17.2
Oct. 65.....	...	9.1	13.8	25.0	18.4	13.7
Nov. 65.....	...	14.8	9.3	24.4	17.0	16.1

<sup>a</sup> Estimated.

TABLE 23—Average monthly panel temperature during time of wetness, deg F.

Month	Cleveland	Ottawa	South Bend	Kure Beach 80 ft	Kure Beach 800 ft	Panama
Dec. 63.....	23.7	9.05	20.0	44.0	43.8	...
Jan. 64.....	29.9	24.2	23.2	42.4	44.9	...
Feb. 64.....	27.1	17.7	20.7	44.9	44.7	...
March 64.....	38.4	27.9	33.3	51.8	52.3	...
April 64.....	40.8	38.8	48.1	60.7	60.3	80
May 64.....	50.3	51.6	65.4	65.8	67.2	79
June 64.....	54.8	55.0	71.4	76.0	75.1	79
July 64.....	62.8	62.2	76.2	76.0	76.2	79
Aug. 64.....	60.4	56.0	69.3	76.7	74.2	79
Sept. 64.....	58.9	50.1	63.3	75.4	72.5	79
Oct. 64.....	43.7	39.1	47.2	62.1	59.1	79
Nov. 64.....	44.2	31.5	42.3	58.1	56.6	79
Dec. 64.....	18.4 <sup>a</sup>	27.6	39.9	53.2	50.9	79
Jan. 65.....	22.0 <sup>a</sup>	21.1	27.5	44.8	44.1	79
Feb. 65.....	31.0 <sup>a</sup>	21.1	30.5	46.6	47.0	79
March 65.....	24.5 <sup>a</sup>	27.8	34.8	48.1	49.3	79
April 65.....	41.6	36.7	49.3	57.7	55.2	79
May 65.....	54.4	54.8	66.9	68.8	67.3	79
June 65.....	59.0 <sup>a</sup>	55.4	69.8	72.7	69.6	79
July 65.....	61.5 <sup>a</sup>	61.2	73.3	75.3	78.4	79
Aug. 65.....	60.0 <sup>a</sup>	61.6	72.9	74.5	73.7	79
Sept. 65.....	...	56.4	66.9	72.8	70.5	79
Oct. 65.....	...	44.1	46.1	61.8	59.2	79
Nov. 65.....	...	31.6	40.1	54.5	54.3	79
Dec. 65.....	...	...	...	45.0	42.7	79

<sup>a</sup> Estimated.

TABLE 24—Monthly sulfur dioxide activity, —mg SO<sub>2</sub>/dm<sup>2</sup>/day.

Month	Cleveland	Ottawa	South Bend	Kure Beach 80 ft	Kure Beach 800 ft	Panama
Dec. 63.....	1.38	2.29	1.29	0.22	0.22	...
Jan. 64.....	1.79	3.00	0.84	0.11	0.11	...
Feb. 64.....	0.88	1.50 <sup>a</sup>	2.51	0.07	0.07	...
March 64.....	2.26	4.38	0.51	0.12	0.12	...
April 64.....	1.43	1.23	0.86	0.10 <sup>a</sup>	0.10 <sup>a</sup>	0.04
May 64.....	0.97	1.62	0.35	0.10 <sup>a</sup>	0.10 <sup>a</sup>	0.12
June 64.....	1.09	1.20	0.11	0.09	0.09	0.08
July 64.....	0.98	0.69	0.48	0.12	0.12	0.00
Aug. 64.....	1.09	1.04	0.29	0.12	0.12	0.08
Sept. 64.....	1.18	0.98	0.74	0.15	0.15	0.10
Oct. 64.....	1.49	0.79	1.11	0.19	0.19	0.27
Nov. 64.....	1.82	1.81	1.00 <sup>a</sup>	0.09	0.09	0.10
Dec. 64.....	1.62	1.37	0.92	0.08	0.08	0.40
Jan. 65.....	1.47	1.64	1.17	0.17	0.17	0.20
Feb. 65.....	1.40 <sup>a</sup>	3.72	1.01	0.14	0.14	0.00
March 65.....	1.80 <sup>a</sup>	1.61	0.40 <sup>a</sup>	0.20	0.20	0.00
April 65.....	1.86	0.40	0.60	0.00	0.00	0.00
May 65.....	1.61	0.60	0.29	0.12	0.12	...
June 65.....	1.11	0.23	0.20	0.04	0.04	...
July 65.....	0.86	0.24	0.19	0.05 <sup>a</sup>	0.05 <sup>a</sup>	...
Aug. 65.....	...	0.41	0.41	0.05	0.05	0.07
Sept. 65.....	...	0.52	0.26	0.10	0.10	0.07
Oct. 65.....	...	0.70 <sup>a</sup>	0.37	0.15	0.15	0.08
Nov. 65.....	...	1.28	0.37	0.06	0.06	0.04
Dec. 65.....	...	1.68	0.37 <sup>a</sup>	0.21	0.21	...

<sup>a</sup> Estimated.

NOTE—Panama and Kure Beach sites activity values for total time of exposure. All others during time of wetness.

TABLE 25—Monthly chloride count, —mg Cl<sup>-</sup>/m<sup>2</sup> exposed gauze/day.

Month	Kure Beach 80 ft	Kure Beach 800 ft	Panama
Dec. 63.....	151.1	21.7	...
Jan. 64.....	35.5 <sup>a</sup>	8.3	...
Feb. 64.....	69.7	13.7	...
March 64.....	68.6	11.8	...
April 64.....	140.7	21.2	25.2
May 64.....	291.7	32.2	13.0
June 64.....	232.2	27.1	5.7
July 64.....	65.0	13.0	4.7
Aug. 64.....	127.4	22.2	1.8
Sept. 64.....	283.7	31.9	1.7
Oct. 64.....	253.8	24.4	16.0
Nov. 64.....	102.1	12.2	5.1
Dec. 64.....	53.3	6.5	32.2
Jan. 65.....	36.0	5.3	51.5
Feb. 65.....	122.2	15.0	36.6
March 65.....	169.3	21.2	36.1
April 65.....	74.6	10.8	96.7
May 65.....	33.8	4.4	4.5
June 65.....	44.9	10.6	6.6
July 65.....	29.9	12.2	9.5
Aug. 65.....	38.3	6.5	2.6
Sept. 65.....	256.0	23.0	5.0
Oct. 65.....	343.0	41.0	7.1
Nov. 65.....	93.3	10.6	5.6
Dec. 65.....	18.2	4.0	17.1

<sup>a</sup> Estimated.

TABLE 26—Phase 2 atmospheric factor and corrosion data (Site: Cleveland).

Exposure Date	Time of Wetness, days	Average Temperature, deg F	Average SO <sub>2</sub> , ppm	Weight Loss, g/panel		
				Fe	Zn	Cu
<i>3 months:</i>						
Dec. 63.....	51.6	27.0	0.049	3.170	0.177	0.110
March 64.....	24.5	42.4	0.062	4.853	0.153	0.153
June 64.....	23.2	59.9	0.034	4.187	0.095	0.129
Sept. 64.....	32.2	49.3	0.053	4.845	0.133	0.100
Dec. 64.....	46.1	23.8	0.054	5.356	0.235	0.120
March 65.....	25.0	41.9	0.080	5.341	0.162	0.118
June 65.....	25.8	60.3	0.034	5.744	0.129	0.113
<i>6 months:</i>						
Dec. 63.....	76.1	31.9	0.053	7.542	0.330	0.252
March 64.....	47.7	50.8	0.048	7.535	0.232	0.297
June 64.....	54.4	53.8	0.045	6.067	0.169	0.213
Sept. 64.....	78.3	34.9	0.052	7.317	0.340	0.197
Dec. 64.....	71.1	23.7	0.063	8.569	0.371	0.241
March 65.....	50.8	51.7	0.056	9.237	0.286	0.279
<i>9 months:</i>						
Dec. 63.....	99.3	38.2	0.049	9.600	0.443	0.404
March 64.....	79.7	50.2	0.050	9.330	0.296	0.379
June 64.....	101.5	41.1	0.049	7.356	0.321	0.309
Sept. 64.....	103.3	36.6	0.060	9.325	0.475	0.335
Dec. 64.....	96.9	38.9	0.055	12.009	0.492	0.388
<i>18 months:</i>						
Dec. 63.....	202.6	37.4	0.054	13.894	0.862	0.591
March 64.....	176.8	44.3	0.053	14.134	0.783	0.610