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US ARMY
MATERIEL COMMAND

METHODOLOGY INVESTIGATION

FINAL REPORT

COMPARATIVE CORROSION EVALUATION; FORT SHERMAN, PANAMA, AND KURE BEACH, NORTH CAROLINA

GEORGE F. DOWNS III

EARL. A. BAKER

MATERIEL TEST DIVISION

UNITED STATES ARMY TROPIC TEST CENTER

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OCTOBER 1989

Prepared for:
Commander, U.S. Army Test and Evaluation Command, ATTN: AMSTE-TC-M, Aberdeen Proving Ground, MD 21005-5055

U.S. Army Test and Evaluation Command, Aberdeen Proving Ground, MD 21005-5055

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SUBJECT: Methodology Investigation Final Report: Comparative Corrosion Evaluation; Fort Sherman, Panama and Kure Beach, North Carolina

1. Subject report is approved.

2. Point of contact at this headquarters is Mr. Roger L. Williamson, AMSTE-TC-M, amstetcm@apg-emh4.apg.army.mil, AUTOVON 298-3677/2170.

FOR THE COMMANDER:

GROVER H. SHELTON
Chief, Meth Imprv Div
Directorate for Technology

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The US Army Tropic Test Center initiated a project in early 1986 to furnish quantitative data relating the severities of atmospheric corrosion of steel and iron at Tropic Test Center exposure sites to those of the well-known sites at Kure Beach, North Carolina, operated by LaQue Center for Corrosion Technology. All samples were analyzed at the LaQue Center laboratories to ensure uniform treatment of samples and identical analytical methods.

Samples of mild steel and ingot iron were exposed for durations of three and twelve months on a quarterly basis for a total of four 3-month and five 12-month exposures at four sites in or near Fort Sherman, Panama and two sites at Kure Beach, North Carolina.

Results indicate that the Fort Sherman Breakwater and Coastal Sites are substantially more aggressive toward steel and iron than either of the Kure Beach Sites, and that the Fort Sherman Open and Forest are somewhat less aggressive than either Kure Beach Site. Relative

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severities varied from season to season, but for an average of all seasons, 12-month exposure of mild steel shows the Breakwater to be about 10 times as aggressive as the Kure Beach 25-meter lot, and the Coastal Site to be 5 times as aggressive as the 25-meter lot. The Kure Beach 250-meter lot was about two-thirds as aggressive as the 25-meter lot. The Sherman Open Site was about half as aggressive as the 25-meter lot, while the Forest (Skunk Hollow) Site was about 40 percent as aggressive.

It has long been recognized that chamber corrosion tests (e.g. salt spray and salt fog) are beneficial as a quality control tool, but are less valid as predictors of service life. For this reason, there have been many efforts to develop accelerated corrosion test methods without losing the advantages of testing in natural environments. Results of this project indicate a potential for reduced-duration corrosion tests while still retaining the validity of natural environment exposure.

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FOREWORD

The U.S. Army Tropic Test Center (TTC) was responsible for planning, executing and reporting this project. George F. Downs III was the project officer. Under contract with Tropic Test Center, LaQue Center for Corrosion Technology (LCCT) furnished the exposure specimens, exposed and retrieved specimens at the two Kure Beach sites, and evaluated the retrieved specimens for all sites. Earl A. Baker managed the project for LCCT. The Atmospheric Sciences Laboratory (ASL) Meteorological (Met) Team (Panama) and the National Oceanic and Atmospheric Administration (NOAA) office at Wilmington, NC, provided meteorological support during the project.

During the exposures reported herein, the corrosion community was saddened by the death of Frank LaQue, the founder of the LaQue Center for Corrosion Technology and the sites used in this project at Kure Beach, North Carolina. It is hoped that this report will contribute to his memory.

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SECTION 1. SUMMARY

1.1 BACKGROUND

Because a large number of the world's trouble spots are located in the humid tropics, it is important that U.S. Army military equipment be tested in that environment. Atmospheric corrosion is one of the primary degrading factors which affect materiel in hot, humid climates. Recently the Department of the Army has established an active Corrosion Prevention and Control (CPC) program to fight corrosion problems that degrade readiness and operational performance.

1.2 PROBLEM

Some of the most severe sites in the world for corrosion testing are located in the Republic of Panama under the control of the U.S. Army Tropic Test Center. Atmospheric corrosion tests have been conducted both in the Panama Canal Area and at Kure Beach, North Carolina for over 45 years. Although at least one comparative corrosion investigation (reference 1) has been conducted which compared Kure Beach sites with sites in Panama, most of the Panama sites used have been abandoned for a number of years. They have been replaced by sites which are generally more aggressive as well as more representative of the range of humid tropic environments to which military equipment may be exposed. This project compares four atmospheric corrosion sites currently in use at Fort Sherman, Panama, with the two atmospheric exposure sites at Kure Beach, North Carolina.

1.3 OBJECTIVES

a. To provide a direct comparison of the atmospheric corrosion sites currently in use by Tropic Test Center with internationally known corrosion sites.

b. To provide guidance in selection of sites and seasons for short-term exposures at more aggressive sites.

1.4 PROCEDURES

a. Samples of mild steel and ingot iron were exposed at four sites in/near Fort Sherman, Panama, and two LaQue Center sites at Kure Beach, North Carolina. Panama sites included Fort Sherman Breakwater Exposure Site at Toro Point, Fort Sherman Coastal Exposure Site, Fort Sherman Open (Sunfield) Exposure Site, and Fort Sherman Forest (Skunk Hollow) Exposure Site. Kure Beach Sites included one 25 meters from the water's edge at mean tide (the 25 meter lot) and another 250 meters from the water's edge (the 250 meter lot). Historical data concerning these sites can be found in Appendix B for TTC sites and Appendix C for LaQue Center sites. Geographical and terrain descriptions for TTC and LaQue Center sites are in Appendix D.

b. Mild steel was chosen as most representative of both military and civilian metal structures and hardware, and is rapidly attacked by corrosive environmental conditions when unprotected. Additionally, it is familiar to investigators worldwide, so that data from this study can be compared with data from many other investigations, both current and past. Ingot iron was chosen because it is, along with mild steel, used in the LaOue Center's ongoing site calibration program. Data from this study can be compared to long term corrosion results from the Kure Beach sites which include varying exposure parameters, such as angle of inclination, height, and different terrain configurations between the sites and the water. Ingot iron responds somewhat differently to corrosive environments than does steel, but is also rapidly corroded when unprotected, and thus yields valid corrosion data in a relatively short time. Specific information on these two materials is given in Appendix E.

c. Metal panels were exposed boldly on racks inclined 30° to the horizontal, facing the water at both marine and inland sites. The panels were mounted on ceramic insulators to eliminate galvanic effects and to reduce insofar as possible the retention of moisture at mounting points, in accordance with ANSI/ASTM G50-76 (reference 2), Standard Recommended Practice for Conducting Atmospheric Corrosion Tests on Metals.

d. There were two series of exposures in this project, one of 3 months duration, and one of 12 months duration. Both series began on 1 July 1986, and quarterly thereafter until 31 March 1987 for 3-month exposures, and 1 July 1987 for 12-month exposures. A schedule of actual exposure and retrieval dates is shown in Appendix F, which also gives the number of exposure days for each phase.

e. All samples were analyzed in the LaQue Center laboratories to assure uniform treatment of samples and identical analytical techniques. The cleaning and evaluation of panels was done in basic accordance with ANSI/ASTM G1-72, Standard Recommended Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens (reference 2), with the exception that a single solution of hydrochloric acid (specific gravity: 1.19) inhibited with 20 grams per liter of antimony trioxide was used for pickling the panels. A report was furnished by LaQue Center for each group of panels giving the following information for each panel: site, panel identification code, mass (original, final, and loss), mass loss per unit area (gm/m^2), corrosion rate (mm/year), characterization of surface attack (general/depth of localized attack).

f. Following the exposure and retrieval of each group of panels, those from Tropic Test Center sites were brought to the Tropic Test Center Materials Laboratory where they were rinsed in hot water to remove superficial salt, rinsed in alcohol to enhance rapid drying, and dried in the air-conditioned laboratory in a dish drainer to minimize further corrosion. They were then photographed and shipped to LaQue Center for laboratory evaluation.

g. Meteorological data for the sites were furnished by the Atmospheric Sciences Laboratory Meteorological Team, Panamá, for Tropic Test Center sites, and by the National Oceanic and Atmospheric Administration office in Wilmington, North Carolina, for LaQue Center sites. Additionally, atmospheric saltfall data for the sites were collected by both centers for their sites using the wet candle method, and data on atmospheric oxides of sulfur and nitrogen were collected using plates furnished by National Environmental Testing, Incorporated, of Cedar Falls, Iowa, who also did the analysis of the plates.

1.5 RESULTS

a. Discussions of corrosion results are based on primarily on corrosion rates--in millimeters per year. Many technical articles use microns per year; however, on the basis of the extreme corrosion rates observed, millimeters per year were the most appropriate unit. Trends and rank orders were virtually identical for mass loss and corrosion rate results. In addition, corrosion rate results for exposure periods of differing lengths can be directly compared.

b. Complete corrosion data are presented in Appendices G (ingot iron) and H (steel).

c. Meteorological data for the various exposure sites are presented in Appendix I. Atmospheric contaminant data are in Appendix J. Some of these data seemed to lend themselves better to graphic presentations. These graphs are presented in Appendix K.

d. Corrosion rates, by site, for steel and iron are presented in table 1. Mass loss, by site, for steel and iron are presented in table 2. Table 3 is a comparison of the corrosion rates at all sites to those at the the Kure Beach 25-meter lot.

(1) The average steel corrosion rates (mm/yr), for all 3-month exposure phases, at the different sites in order of site severity were: Fort Sherman Breakwater, 0.7; Fort Sherman Coastal, 0.20; Kure Beach 25-meter lot, 0.13; Kure Beach 250-meter lot, 0.07; Fort Sherman Open, 0.045; and Fort Sherman Forest, 0.028.

(2) The average of corrosion rates for all phases, 12-month exposures, ranged from slightly less to about a third less than the 3-month rates at all sites, except for the Coastal site. The Fort Sherman Coastal Exposure Site corrosion rates, for both mild steel and ingot iron, were about 50 percent greater for the 12-month exposures than for the 3-month exposures. It should be noted that although this is a general trend between averages of all phases, in both the most aggressive and least aggressive phases, cases abound where the short-term corrosion rate is lower than the long-term rate.

(3) During the 12-month exposures in phase 5 at all sites, the corrosion rates for ingot iron were unusually high--in some cases, more than twice the corrosion rate of the next most aggressive phase for the same site. The abnormally high saltfall at the end of phase 5 could partially explain the Fort Sherman sites' results; however, it would not explain the difference at the Kure Beach sites. Specimens were cleaned and weighed using standard techniques; no abnormalities were noted in the lab. There were two differences that might have had an effect: the ingot iron used in the fifth phase was from a different heat; it also was somewhat thicker than that used in earlier phases. Some samples were perforated during 12-month exposures which would make corrosion rates for phases 1 through 4 artificially low; however this effect was noted at all sites and perforation only occurred at the Breakwater and Coastal sites. We can only conclude that some unknown phenomenon affected all the iron samples for phase 5.

(4) The data for 12-month exposure of ingot iron are tabulated both with and without the phase 5 data in tables 1 and 2. With the phase 5 data included, the most aggressive phase was always phase 5, and averages of all phases ranged from 10 to 60 percent higher than without the phase 5 data. For this reason, future discussions of ingot iron results will ignore the phase 5 results.

e. Generally, the sites, for both materials and all phases, ranked as follows, from most aggressive to least aggressive:

Fort Sherman Breakwater Exposure Site
Fort Sherman Coastal Exposure Site
Kure Beach 25-meter Lot
Kure Beach 250-meter Lot
Fort Sherman Open Exposure Site
Fort Sherman Forest Exposure Site (Skunk Hollow)

Ranking by sites and phases was variable and precluded any hard-and-fast generalizations; however, a graphic presentation of the data by sites and phases helped make the trends clearer. Graphs comparing sites in most aggressive phase, least aggressive phase, and average of all phases are presented in Appendix L. Graphs of corrosion rates and mass losses, by phases, for each site are presented in Appendix M.

TABLE 1. CORROSION RATES (mm/year), BY SITE

Variable	Fort Sherman Breakwater	Fort Sherman Coastal	Fort Sherman Open	Skunk Hollow	Kure Beach 25m Lot	Kure Beach 250m Lot
Part A. Steel						
3-month Exposure						
Most Aggressive Phase	(4) .898	(3) .396	(1) .048	(3) .051	(2) .178	(2) .086
Average All Phases	.713	.199	.045	.028	.127	.070
Least Aggressive Phase	(2) .320	(1) .115	(2) .044	(2) .016	(3) .089	(4) .059
12-month Exposure						
Most Aggressive Phase	(1) .603	(2) .351	(3) .033	(3) .029	(2) .074	(2) .043
Average All Phases	.571	.299	.031	.025	.059	.038
Least Aggressive Phase	(2) .516	(4) .207	(2) .028	(5) .020	(5) .048	(1) .035
Part B. Iron						
3-month Exposure						
Most Aggressive Phase	(4) 1.12	(3) .588	(1) .058	(4) .046	(2) .214	(2) .087
Average All Phases	.833	.327	.055	.034	.159	.079
Least Aggressive Phase	(2) .463	(2) .196	(4) .052	(1) .025	(3) .107	(4) .068
12-month Exposure (Phase 5 excluded)						
Most Aggressive Phase	(4) .648	(1) .563	(4) .041	(1) .036	(1) .158	(2) .052
Average All Phases	.573	.472	.037	.030	.113	.046
Least Aggressive Phase	(2) .522	(4) .326	(3) .035	(2) .026	(3) .073	(4) .041
12-month Exposure (Phase 5 included)						
Most Aggressive Phase	(5) .767	(5) .765	(5) .073	(5) .087	(5) .504	(5) .118
Average All Phases	.612	.531	.046	.041	.191	.060

Numbers in parentheses are phases.

TABLE 2. MASS LOSS (g/m^2), BY SITE

Part A. Steel

Variable	Fort Sherman: Breakwater	Fort Sherman: Coastal	Fort Sherman: Open	Fort Sherman: Skunk Hollow	Kure Beach: 25m Lot	Kure Beach: 250m Lot
3-month Exposure						
Most Aggressive Phase	(4) 178	(3) 77.6	(1) 9.9	(3) 10.0	(2) 34.8	(2) 13.5
Average All Phases	141	38.9	9.0	5.5	24.8	10.9
Least Aggressive Phase	(2) 61.3	(1) 23.0	(2) 8.4	(2) 3.0	(3) 16.0	(2) 5.7
12-month Exposure						
Most Aggressive Phase	(1) 475	(2) 276	(3) 25.9	(3) 22.9	(2) 59.3	(2) 34.2
Average All Phases	446	229	24.0	19.2	47.2	26.2
Least Aggressive Phase	(2) 406	(4) 157	(2/4) 22.3	(4/5) 16.1	(5) 37.4	(1) 9.5

Part B. Iron

Variable	Fort Sherman: Breakwater	Fort Sherman: Coastal	Fort Sherman: Open	Fort Sherman: Skunk Hollow	Kure Beach: 25m Lot	Kure Beach: 250m Lot
3-month Exposure						
Most Aggressive Phase	(4) 222	(3) 116	(1) 11.7	(4) 9.0	(2) 41.9	(1/2) 17.1
Average All Phases	165	64.5	10.8	6.6	31.6	15.7
Least Aggressive Phase	(2) 88.9	(2) 37.7	(4) 10.2	(1) 5.1	(3) 20.7	(4) 14.1
12-month Exposure (Phase 5 excluded)						
Most Aggressive Phase	(4) 485	(1) 443	(4) 31.1	(1) 28.1	(1) 126	(2) 41.1
Average All Phases	444	369	29.1	23.1	89.4	35.8
Least Aggressive Phase	(2) 410	(4) 248	(3) 27.6	(2) 20.3	(3) 58.3	(4) 32.2
12-month (Phase 5 included)						
Most Aggressive Phase	(5) 604	(5) 603	(5) 57.5	(5) 68.5	(5) 395	(5) 92.3
Average All Phases	476	416	34.8	32.1	151	47.1

Numbers in parentheses are phases. Where two numbers are shown, phases showed equal loss.

TABLE 3. SEVERITY RATINGS, BY EXPOSURE SITE

(by corrosion rate)
Based on Kure Beach 25-meter Lot = 1.0
(Numbers in parentheses are corrosion rates on which ratings were based.)

Part A. Average of All Phases
(Phase 5 excluded for iron)

Site	Steel 3-month	Steel 12-month	Iron 3-month	Iron 12-month
Breakwater	5.6	9.7	5.2	5.1
Sherman Coastal	1.6	5.1	2.1	4.2
Kure Beach 25m	1.0 (.127)	1.0 (.059)	1.0 (.159)	1.0 (.113)
Kure Beach 250m	.55	.64	.50	.41
Sherman Open	.35	.53	.35	.33
Sherman Forest	.22	.42	.21	.27

Part B. Most Aggressive Phase
(Phase 5 excluded for iron)

Site	Steel 3-month	Steel 12-month	Iron 3-month	Iron 12-month
Breakwater	5.0	8.1	5.2	4.1
Sherman Coastal	2.2	4.7	2.7	3.6
Kure Beach 25m	1.0 (.178)	1.0 (.074)	1.0 (.214)	1.0 (.158)
Kure Beach 250m	.48	.58	.41	.33
Sherman Open	.27	.45	.27	.26
Sherman Forest	.29	.39	.21	.23

Part C. Least Aggressive Phase

Site	Steel 3-month	Steel 12-month	Iron 3-month	Iron 12-month
Breakwater	3.6	10.8	4.3	7.2
Sherman Coastal	1.3	4.3	1.8	4.5
Kure Beach 25m	1.0 (.089)	1.0 (.048)	1.0 (.107)	1.0 (.073)
Kure Beach 250m	.66	.73	.64	.56
Sherman Open	.49	.58	.49	.48
Sherman Forest	.18	.42	.23	.36

1.6 ANALYSIS

a. Results indicated that the Fort Sherman Breakwater and Coastal Exposure Sites were substantially more aggressive toward steel and iron than either Kure Beach site. Furthermore, the Fort Sherman Open and Forest (Skunk Hollow) Exposure Sites were somewhat less aggressive than either Kure Beach site. Relative severities varied from season to season. For an average of all phases, the 12-month exposure results for mild steel showed that the Breakwater site was about ten times as aggressive than the Kure Beach 25-meter lot, and the Coastal site was more than four times as aggressive as the Kure Beach 25-meter lot. The Kure Beach 250-meter lot was about two-thirds as aggressive as the 25-meter lot. The Fort Sherman Open Exposure Site was about half as aggressive as the 25-meter lot, while the Forest (Skunk Hollow) site was about 40 percent as aggressive. These data are gross simplifications for convenience and brevity. Complete data are presented in tabular and graphic form in the body and appendices of this report.

b. In spite of considerable variability between the two metals and the various phases, the sites used in this project formed a continuum of severities: from the highly aggressive Fort Sherman Breakwater Exposure Site to the relatively benign Fort Sherman Open and Forest (Skunk Hollow) Exposure Sites, with the Kure Beach Sites an intermediate severity. The total range of severities is a factor of about 20.

c. Although these tests were conducted using unprotected ferrous metals, as opposed to coated, plated, or otherwise protected materials, the results of this investigation still apply, by extension, to the majority of Army mechanical equipment, structures, and many other items. Nearly all ferrous corrosion problems occur as a result of defects and failures in protective coatings; in spite of considerable care and effort, corrosion problems still abound. Testing in a more aggressive environment generally means that problems that will occur eventually will surface more quickly, thus reducing the time required to obtain a valid test, without resorting to artificial environments, elevated temperatures, and acidified solutions which can invalidate results by changing failure modes.

d. This project showed that exposure times can be shortened substantially by using a more aggressive environment; however, seasonal variations must be taken into account when using short exposure periods because great variability can occur among seasons. This variability is reduced substantially at less aggressive sites, which are more uniform from one season to another; variability also is reduced over longer periods where a succession of seasons is experienced by the test item or sample. Data in paragraph 2.1 and Appendix L of this report can be used as a guideline to give the tester a feel for which seasons are more aggressive for tests that are conducted for short periods, e.g. April through July at the Breakwater Site, and during the dry season (January through March) at the Coastal Site.

1.7 CONCLUSIONS

a. The data in this report quantify atmospheric corrosion severity of steel and iron at four TTC sites in the Republic of Panama and two well-known sites at Kure Beach, North Carolina, demonstrating that there is a continuum of severities with the Kure Beach sites intermediate among the Fort Sherman sites. Publication of this report will assist in making these assets better known among the corrosion and materiel developer communities.

b. Tabular and graphic data in this report provide a basis for comparison of data gathered from the sites used in this project, so that estimates could be made of exposure test durations depending on which site is chosen and what degree of severity is desired. These data also provide a basis for comparison between these sites and other sites, whether currently in use, previously used, or candidates for future site locations.

c. Project results indicate a potential for reduced-duration (accelerated) corrosion tests while still retaining the validity of natural environment exposure, thereby reducing the required exposure duration.

1.8 RECOMMENDATIONS

a. Where practicable, exposure time in corrosion testing should be reduced by exposing test items or samples at a more aggressive exposure site, consistent with the anticipated end use of the item, security requirements, and other applicable constraints.

b. The U.S. should retain access to the Fort Sherman exposure sites as long as possible because of their wide range of environmental characteristics and their considerable history. If relocation to another area is necessary, another series of studies similar to this one will be required. These studies would be required, not only for metals, but also for a range of other materials, including representative fabrics, polymeric materials, composites, and possibly even wood.

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SECTION 2. DETAILS OF INVESTIGATION

2.1 PHASE RELATIONSHIPS FOR 3-MONTH EXPOSURES

2.1.1 General

The 3-month exposures encompassed different seasons; hence, great variations were observed among phases at most sites. The most prominent exception to this was the Fort Sherman Open Exposure Site, where all phases were within 7 percent of the average corrosion rate for both iron and steel. The Kure Beach 250-meter lot also was relatively consistent; all 3-month corrosion rates fell within 15 percent of the average. At the other sites, variations among phases ranged upward to factors of 3 or more. In general, the same phases showed the highest corrosion rates for iron and steel at each site. The following paragraphs present exposure results, by site. Tables 4 through 9 show corrosion rates, along with atmospheric contaminant and meteorological data, by phase, for each site. A brief discussion of the characteristics for the different phases also is included.

2.1.2 Fort Sherman Breakwater Exposure Site

TABLE 4. RESULTS AND CONDITIONS AT FORT SHERMAN BREAKWATER EXPOSURE SITE

	Corrosion Rate (mm/year)		Total			Mean		Total
Phase	Steel	Iron	Saltfall (g/m^2)	SO_2 (g/m^2)	NO_x (m_g/m^2)	Temp (°F)	RH (%)	Rainfall (inches)
1	.861	1.08	76.5	3.65	9.6	79	95	30.8
2	.320	.463	65.9	4.06	17.3	76.3	96	30.7
3	.774	.670	150	5.62	18.6	80.7	87.3	2.0
4	.898	1.12	39.3	5.38	16.2	82	87.3	45.8

No clear pattern emerged regarding the interrelationship of dominant factors in corrosivity. One would normally think of saltfall as a dominant factor; however, the phase with the highest saltfall, while showing extreme corrosion rates, did not show the highest corrosion rates. In this case, the phase with the greatest rainfall was the most aggressive at this site. One theory is that saltfall reached what might be called a "saturation point"; i.e., a point where its effect in accelerating corrosion was hindered by its drying or protective effect. This protective effect could prevent the oxygen required to continue the corrosion process from reaching the surface of the metal. When the wet season began (end of phase 3, beginning of phase 4), the corrosion proceeded faster because more oxygen-laden water reached the metal surface.

2.1.3 Fort Sherman Coastal Exposure Site

TABLE 5. RESULTS AND CONDITIONS AT FORT SHERMAN COASTAL EXPOSURE SITE

Phase	Corrosion Rate (mm/year) Steel	Corrosion Rate (mm/year) Iron	Total Saltfall (g/m^2)	Total SO_2 (g/m^2)	Total NO_x (m_g/m^2)	Mean Temp (°F)	Mean RH (%)	Total Rainfall (inches)
1	.115	.233	15.9	3.77	8.2	79	95	30.8
2	.129	.196	47.9	3.87	12.2	76.3	96	30.7
3	.396	.588	108	5.22	13.5	80.7	87.3	2.0
4	.155	.291	25.0	5.23	13.3	82	87.3	45.8

At this site (which could be considered a more conventional marine site than the Breakwater), a more expected pattern emerged. The most rapid corrosion occurred during the dry season (phase 3), which had the highest saltfall and the lowest rainfall. Other contaminants were high during both phases 3 and 4, which indicates they had relatively little effect because there were large differences between phase 3 and 4 corrosion rates. It appears that the rainfall during phase 4 reduced the corrosion rate by washing away some of the atmospheric salt and other contaminants; however, enough salt remained to cause higher corrosion rates than in phases 1 and 2.

2.1.4 Fort Sherman Open Exposure Site

TABLE 6. RESULTS AND CONDITIONS AT FORT SHERMAN OPEN EXPOSURE SITE

Phase	Corrosion Rate (mm/year) Steel	Corrosion Rate (mm/year) Iron	Total Saltfall (g/m^2)	Total SO_2 (g/m^2)	Total NO_x (m_g/m^2)	Mean Temp (°F)	Mean RH (%)	Total Rainfall (inches)
1	.0482	.0584	.861	3.74	8.1	80	89.3	36.2
2	.0439	.0558	1.60	3.53	11.5	80	89.3	31.5
3	.0444	.0540	3.38	5.0	9.9	82.3	84.3	2.1
4	.0445	.0515	1.58	5.32	11.0	80.3	87.7	47.0

Corrosion rates were remarkably uniform at this site--less than 15 percent difference among phases for iron and within 10 percent for steel. There were substantial differences among phases for rainfall and atmospheric saltfall, with almost an inverse relationship between the two. It appears that rainfall and atmospheric saltfall balanced each other in the levels present at this site. Because the corrosion rates were more similar among phases than the levels of individual contaminants, it cannot be said that any one was dominant.

2.1.5 Fort Sherman Forest (Skunk Hollow) Exposure Site

TABLE 7. RESULTS AND CONDITIONS AT FORT SHERMAN FOREST EXPOSURE SITE

Phase	Corrosion Rate (mm/year) Steel	Iron	Total Saltfall (g/m^2)	SO_2 (g/m^2)	NO_x (m_g/m^2)	Mean Temp (°F)	RH (%)	Total Rainfall (inches)
1	.0208	.0254	.321	3.96	12.8	76.7	92.5	37.4
2	.0158	.0273	.558	3.53	11.9	75.3	96.7	30.0
3	.0512	.0369	1.52	4.47	21.1	78.3	93.3	2.6
4	.0249	.0455	.574	5.39	15.0	78.3	94.3	37.4

a. For steel, atmospheric saltfall appeared to be the dominant factor because the corrosion rate for phase 3 was over twice that for any other phase. Phase 3 also was the only phase with very little rainfall at this site (2.55 inches compared to more than 30 inches for all other phases). However, because the relative humidity averaged well over 90 percent at this site for all phases, the samples were not dry. More than likely, the dew acted as a vehicle to soak atmospheric contaminants into the surface of the corrosion product, but there was little or no rain to wash contaminants off the surface.

b. For ingot iron, phase 4 was about 25 percent more aggressive than phase 3. Given the large variation in rainfall and atmospheric saltfall between these two phases, there is no clear rationale for the difference. Because the phases with highest and lowest rainfall were more aggressive than the phases with intermediate rainfall, rainfall apparently was not a dominant factor (assuming that the samples were frequently wet even without rainfall).

c. In the forest, leaves and other vegetation, along with atmospheric particulates and organic aerosols, fall continuously. Some of this falling material is known to render corrosion products relatively water-soluble. In forested areas, these materials can have a considerable impact in reducing the protective effect of accumulated corrosion products. It is impractical to classify microenvironments under each species of tree in tropical moist forests because there is a great diversity of vegetation and few pure stands or even predominant species. The variant results observed serve to demonstrate the complexity of the tropic forest environment and the futility of trying to duplicate it.

2.1.6 Kure Beach 25-meter Lot

TABLE 8. RESULTS AND CONDITIONS AT KURE BEACH 25-METER LOT

Phase	Corrosion Rate (mm/year) Steel	Iron	Total Saltfall (g/m^2)	SO_2 (g/m^2)	NO_x (m$_g$/m^2)	Mean Temp (°F)	RH (%)	Total Rainfall (inches)
1	.122	.169	38	4.11	33.9	80	77.3	19.8
2	.178	.214	59	4.20	52.7	59	80	9.6
3	.089	.107	34	4.28	30.6	48	68.7	13.6
4	.117	.145	12.5	5.78	19.0	70	74.7	9.2

At the 25-meter lot, the most aggressive corrosion was associated with high saltfall and humidity, low rainfall, but not with the highest temperatures. Atmospheric nitrogen oxides were at their highest levels when the corrosion was most rapid, although their effect was probably less than that of atmospheric sulfur dioxide, which were highest when corrosion was lowest. Saltfall and relative humidity apparently were the key factors.

2.1.7 Kure Beach 250-meter Lot

TABLE 9. RESULTS AND CONDITIONS AT KURE BEACH 250-METER LOT

Phase	Corrosion Rate (mm/year) Steel	Iron	Total Saltfall (g/m^2)	SO_2 (g/m^2)	NO_x (m$_g$/m^2)	Mean Temp (°F)	RH (%)	Total Rainfall (inches)
1	.0679	.0862	8.7	3.74	34.4	80	77.3	19.8
2	.0855	.0872	9.9	4.03	60.0	59	80	9.6
3	.0672	.0743	11.3	4.20	28.0	48	68.7	13.6
4	.0587	.0677	3.6	5.32	14.6	70	74.7	9.2

The 250-meter lot, like the Fort Sherman Open Exposure Site, was more consistent between phases than most other sites. The most aggressive corrosion was associated with fairly warm temperatures, high saltfall, the highest humidity, the lowest rainfall, and the highest atmospheric nitrogen oxides. As with the 25-meter lot, nitrogen and sulfur oxides probably were not very important factors in the corrosion rates observed, although they may have balanced each other and contributed to uniformity between phases.

2.2 PHASE RELATIONSHIPS FOR 12-MONTH EXPOSURES

2.2.1 General

Variability in corrosion rates between 12-month exposure phases at a given site was much less than that observed during the 3-month exposures. This reduced variability is due to the fact that samples were exposed to all seasons of the year. There were two principal influences which could lead to differences between phases: the effect of the order in which the climatic and environmental variables were presented to the samples, and the variation of climatic and environmental variables from year to year. Unfortunately, these two influences were somewhat difficult to separate, and the situation was compounded by anomalous results for ingot iron at all sites during phase 5. Phases 1 and 5 were the only ones in which the samples were exposed to the same seasons, in the same order, for two different years. The following paragraphs present exposure results, by site. Tables 10 through 15 show corrosion rates, along with atmospheric contaminant and meteorological data, by phase, for each site. A brief discussion of the characteristics for the different phases is included.

2.2.2 Fort Sherman Breakwater Exposure Site

TABLE 10. RESULTS AND CONDITIONS AT FORT SHERMAN BREAKWATER EXPOSURE SITE

	Corrosion Rate (mm/year)		Total			Mean		Total
Phase	Steel	Iron	Saltfall (g/m^2)	SO_2 (g/m^2)	NO_x (m_g/m^2)	Temp (°F)	RH (%)	Rainfall (inches)
1	.603	.563	348	18.7	61.6	79.5	90.4	109.4
2	.516	.522	315	18.9	61.8	80.1	88.9	131.2
3	.566	.561	317	19.2	58.7	81.0	88.3	161.2
4	.590	>.648	559	22.4	45.7	81.1	87.1	160.3
5	.578	(.767)	625	19.3	41.8	80.9	87.2	138.1

For steel, the difference in corrosion rates between phases 1, 4 and 5 was small, although saltfall was much greater in phases 4 and 5. Atmospheric sulfur dioxide did not vary enough among phases to be a factor in changing corrosion rates, and the effect of nitrogen oxides, if any, was slight. Lower rainfall may have been a contributing factor to making phase 1 slightly more aggressive for steel than phases 4 and 5.

2.2.3 Fort Sherman Coastal Exposure Site

TABLE 11. RESULTS AND CONDITIONS AT FORT SHERMAN COASTAL EXPOSURE SITE

	Corrosion Rate (mm/year)		Total			Mean		Total
Phase	Steel	Iron	Saltfall (g/m^2)	SO_2 (g/m^2)	NO_x (m_g/m^2)	Temp (°F)	RH (%)	Rainfall (inches)
1	.306	.563	196	18.1	47.1	79.5	90.4	109.4
2	.351	.527	188	18.2	46.6	80.1	88.9	131.2
3	.259	.472	171	18.0	42.5	81.0	88.3	161.2
4	.207	.326	191	16.8	34.0	81.1	87.1	160.3
5	.339	(.765)	198	13.8	33.0	80.9	87.2	138.1

The only apparent correlation at this site was a slight inverse relationship with rainfall, probably because the rain washes the salt from the exposed samples. Salt and moisture were sufficient to cause rapid corrosion; contaminant levels did not vary enough to contribute to the large changes in corrosion rate.

2.2.4 Fort Sherman Open Exposure Site

TABLE 12. RESULTS AND CONDITIONS AT FORT SHERMAN OPEN EXPOSURE SITE

	Corrosion Rate (mm/year)		Total			Mean		Total
Phase	Steel	Iron	Saltfall (g/m^2)	SO_2 (g/m^2)	NO_x (m_g/m^2)	Temp (°F)	RH (%)	Rainfall (inches)
1	.0328	.0373	7.43	17.6	40.8	80.7	87.7	116.7
2	.0283	.0360	7.68	17.8	43.3	80.4	88.5	148.3
3	.0331	.0351	7.88	18.3	44.0	80.3	88.9	178.9
4	.0294	.0411	8.14	19.2	38.4	80.0	87.9	179.6
5	.0299	(.0729)	9.01	16.2	38.1	80.3	87.4	151.6

As with the 3-month exposures, corrosion rates were uniform at this site: ±5 percent among phases for steel, and ±8 percent for iron, which is about as accurately as one can expect to measure corrosion rates. One hundred sixteen inches of rain were recorded during the phase with the lowest rainfall--a greater amount probably would make little difference. Saltfall, the key parameter usually considered in atmospheric corrosion, was quite uniform at this site, as were the levels of other contaminants.

2.2.5 Fort Sherman Forest (Skunk Hollow) Exposure Site

TABLE 13. RESULTS AND CONDITIONS AT FORT SHERMAN FOREST EXPOSURE SITE

Phase	Corrosion Rate (mm/year) Steel	Iron	Total Saltfall (g/m^2)	SO_2 (g/m^2)	NO_x (m_g/m^2)	Mean Temp (°F)	RH (%)	Total Rainfall (inches)
1	.0284	.0358	2.98	17.3	60.9	77.2	94.4	107.4
2	.0239	.0258	3.04	17.4	58.2	77.6	95.1	130.3
3	.0292	.0296	3.11	19.0	52.6	78.4	95.6	159.2
4	.0210	.0273	2.58	18.0	53.2	78.6	94.0	160.0
5	.0204	(.0869)	3.17	14.9	55.2	78.3	93.5	141.2

The differences observed among the 3-month phases at this site were not observed during the 12-month exposures. While this site was less uniform than the Fort Sherman Open Exposure Site, the variability among phases was only about ±17 percent for both metals. Because the samples were wet most of the time, the limiting factor may have been diffusion of oxygen through the water film and corrosion products on the surface. Another factor, at least for steel, may have been materials (forest litter, atmospheric particulates, and aerosols) accumulated during the dry season (first quarter of phase 3) and not washed off by rain. These materials accumulate moisture, prevent drying, and are somewhat acidic (either as deposited or from decomposition). These accumulated materials may affect a clean surface more than one that is already rusty by reducing the protective nature of the corrosion product formed, making it either more porous or more water-soluble. Phase 1, the second most aggressive phase for steel and the most aggressive phase for iron, also began with a period of somewhat reduced rainfall, thereby increasing the presence of accumulated materials on the surface of the samples.

2.2.6 Kure Beach 25-meter Lot

TABLE 14. RESULTS AND CONDITIONS AT KURE BEACH 25-METER LOT

Phase	Corrosion Rate (mm/year) Steel	Iron	Total Saltfall (g/m^2)	SO_2 (g/m^2)	NO_x (m_g/m^2)	Mean Temp (°F)	RH (%)	Total Rainfall (inches)
1	.0659	.158	143	18.4	136	64.3	75.2	52.1
2	.0739	.118	131	18.2	119	63.8	76.2	53.3
3	.0552	.0732	93.2	19.1	100	63.0	74.5	51.3
4	.0543	.1026	85.0	18.4	81.3	63.2	67.6	49.1
5	.0475	(.504)	92.6	15.0	78.1	62.8	74.1	54.0

The data from this site show no clear patterns. Differences in corrosion rates among phases were larger than the environmental parameters would seem to indicate. Possibly the time of year that the exposure starts is a factor in these differences.

2.2.7 Kure Beach 250-meter Lot

TABLE 15. RESULTS AND CONDITIONS AT KURE BEACH 250-METER LOT

Phase	Corrosion Rate (mm/year) Steel	Iron	Total Saltfall (g/m^2)	SO_2 (g/m^2)	NO_x (m_g/m^2)	Mean Temp (°F)	RH (%)	Total Rainfall (inches)
1	.0348	.0458	33.4	17.3	128	64.3	75.2	52.1
2	.0434	.0523	32.7	17.5	105	63.8	76.2	53.3
3	.0365	.0443	29.3	18.5	77.2	63.0	74.5	51.3
4	.0386	.0411	25.1	17.8	57.6	63.2	67.6	49.10
5	.0352	(.118)	28.9	15.1	55.0	62.8	74.1	53.98

Like the 25-meter lot, the data from this site show no clear pattern. When the phase 5 results for iron were excluded, corrosion rates became quite uniform, varying less than ±13 percent among phases for both metals. This site and the Fort Sherman Open Exposure Site were the two most uniform sites from phase to phase.

APPENDIX A. METHODOLOGY INVESTIGATION PROPOSAL AND DIRECTIVE

Not required (reference 3)

APPENDIX B. HISTORICAL DATA FOR TROPIC TEST CENTER SITES

This appendix provides a brief history of materials exposure work conducted by the United States in the Republic of Panama.

1. The initial requirements for materials exposure facilities in the humid tropics were associated with the Panama Canal. In the late 1930s it was recognized that the Panama Canal would soon be inadequate to handle the increasing number of ship transits. A decision was made to increase its capacity by either building a sea-level canal or a third set of locks. Congress authorized a feasibility study of these alternatives. The feasibility study resulted in the decision to construct a third set of locks, which the Special Engineering Division of the Panama Canal was organized to construct. The study also noted that the only available long-term service and performance data (for guidance in design and selection of materials) for such a vast project applied solely to domestic, temperate zone environments and were totally inadequate for a project of this magnitude in the humid tropics.

2. A carefully controlled study of construction materials in the actual environments in which they would be used was required. This view was reinforced by a literature search which revealed little or no quantitative information on the ratios of the rate of local environmental aggression to that observed in temperate latitudes. Therefore, a two-phase program was designed; one phase to yield indicative results in a period of 2 to 5 years, and a more comprehensive effort extending through a period of 16 years--data sufficiently complete to either confirm or augment the data derived from the initial phase. The Canal Zone General Materials Laboratory (reference 4) was established in 1940 to undertake these and other investigations for the Special Engineering Division of the Panama Canal.

3. Facilities were provided to expose a variety of metals and alloys to seven different environments. Samples were exposed in sufficient numbers that duplicate samples could be removed periodically for study and evaluation. Thus, critical properties (e.g., tensile strength, weight loss, pit depth, and dimensional changes) could be established in sufficient detail to predict their performance authoritatively in the actual structures themselves. Of corollary interest to corrosion engineers, in general, was comparing the changes in designated properties to studies of similar alloys in domestic environments.

4. The severe military equipment failures in the Southwest Pacific during World War II, attributed to humid tropic climatic conditions, added to the interest in materials exposure facilities in the humid tropics.

5. In February 1944, the National Defense Research Committee (NDRC) formed a committee on Tropical Deterioration. By June 1944, the University of Pennsylvania, under contract with the Tropical Deterioration Administrative Committee of the NDRC, had established an exposure station on Barro Colorado Island in the Panama Canal Zone. This island (artificially formed during canal construction) was used, primarily by the Naval Research Laboratory (NRL), since 1923 for plant and animal studies.

6. NRL interest in equipment/materials deterioration caused by the tropic environment was stimulated initially by the premature failure of electronic and communications equipment in tropic climates early in World War II. Equipment, normally trouble-free in temperate climates, either was inoperative on arrival or deteriorated rapidly thereafter. As the impact of such failures became apparent, the importance of "crash" programs to improve equipment reliability increased. Stop-gap measures were evolved to protect the equipment, or at least retard its rate of deterioration. At the same time, detailed studies began which would yield more fundamental design information and enable manufacturers to build more efficient equipment that would be more resistant to deterioration.

7. Because one of the original NRL missions was to develop and improve electronic communications equipment, it was their job to find solutions to the problems experienced in the tropics. However, the electronics experts were not familiar with the mechanisms of materials degradation by humidity, microbial growth. or corrosion, and recognized that additional expertise was necessary. The Microbiological Section was formed to develop techniques which would ensure that electronic equipment remained functional in the humid tropics. This section, working closely with the Laboratory's Electronics Divisions, progressed greatly toward extending the service life of electronic components.

8. In late 1944, a Frankford Arsenal survey team decided that the Barro Colorado location, excellent though it might be for biological studies, was particularly unsuitable for studies on military items. The survey team chose an alternate site in Fort Sherman, later known as Skunk Hollow. The site was surrounded by tropic forest but contained open areas and buildings which had been used as an antiaircraft battery.

9. In February 1945, Frankford Arsenal's Fire Control Design Division and the Laboratory Division established a Tropical Testing Station at the Fort Sherman Reservation. This site was used primarily to test ordnance material and materiel. Sample exposures and observations continued until the end of November. From May through November 1945, Dr. Leonard Teitell of Frankford Arsenal recorded meteorological data (rainfall, temperature, and relative humidity) at Skunk Hollow (reference 4).

10. The Canal Zone General Materials Laboratory 5-year exposure program, completed in 1945, showed the need for a second exposure program of greater duration and detail. In planning these experiments, suggestions and recommendations were obtained from some of the country's most prominent corrosion engineers. Executing the details became the responsibility of the laboratory staff--a well-balanced group of about 25 employees operating under the engineer in charge.

11. The end of World War II in 1945 had a significant impact on materials exposure work in Panama. The atomic bombs used at Hiroshima and Nagasaki not only ended World War II, but forced a reversal in the decision to increase Panama Canal capacity by constructing a third set of locks. Because a lake-and-lock canal would be highly vulnerable to atomic weapons, the third locks excavation was terminated, and a sea-level canal concept was adopted. Nonetheless, the Canal Special Engineering Division recognized the potential application of materials exposure results to Canal maintenance problems, and permitted the Canal Zone General Materials Laboratory to continue its program. The 16-year corrosion study began in 1947.

12. With the end of the third locks excavation came the decreased need for exposure testing. In November 1945, the Frankford Arsenal Tropical Testing Station at Skunk Hollow ceased operations; personnel returned to the States, and most of the equipment and materiel test specimens were removed from the site. However, the corrosion, lubrication, and mycological studies in progress remained; plans were made for observations/examinations to be conducted at intervals of several months. This began a series of TDY trips from Frankford Arsenal, and later Picatinny Arsenal (when Frankford closed), which continued until about 1980. These exposure results appear in various Frankford and Picatinny reports.

13. The conclusion of hostilities in 1945 also jeopardized the exposure sites at Barro Colorado Island and Fort Sherman. Believing that such sites had an essential function in post-war research and development, the Office of Naval Research was convinced that at least one such facility, accessible to the U.S. armed forces, should be maintained. On 1 December 1945, the Office of Naval Research assumed responsibility for the Barro Colorado Island operation. This filled an imminent gap and provided experimental facilities for the NRL. In 1946, after the NDRC withdrew support for the tropical deterioration program, the Office of Naval Research called together representatives of several Navy material bureaus and Army technical corps (including the Air Force) to determine the future course of their individual efforts in the field of tropical deterioration and to devise some means of coordinating such efforts. It was decided that the NRL would continue to manage, maintain, and operate a tropical exposure site for use by all Department of Defenses technical service branches. The tropical exposure site was relocated from Barro Colorado Island to the Fort Sherman site vacated by Frankford Arsenal.

14. Meanwhile, in cooperation with NRL and the Department of Agriculture, Frankford Arsenal used the Skunk Hollow site at Fort Sherman from 1952 to 1956 for an extensive test on fungus-proofing for wooden packing boxes.

15. In 1952, the Panama Canal Company decided to discontinue the Canal Zone General Materials Laboratory operation. To preclude losing all work accomplished on the long-term program (in long-term corrosion projects, the most valuable data are from the longest exposures), the Secretaries of the Army and Navy, and the Governor of the Canal Zone, executed an operational agreement permitting project completion. Results were to be presented in reports available to all interested government agencies and their contractors, as well as for publication in engineering journals. The NRL assumed responsibility for the Laboratory, and renamed it the Canal Zone Corrosion Laboratory. It was funded jointly by the Army Corps of Engineers, the Panama Canal, and the Navy. In 1953, the Canal Zone Corrosion Laboratory was designated as headquarters over all NRL efforts in the Canal Zone. The Army Engineer Research, and Development Laboratory (AERDL) based a tropic test team nearby, and the Army Chemical Corps used the Corrosion Laboratory's chemical facilities for several years.

16. Pressure to re-establish an Army "tropic test station" began in 1952. The prime mover in the station's planning was the late Dr. Paul Siple, renowned Antarctic explorer and internationally famous Army scientist. At the time, Dr. Siple worked in the Environmental Sciences element of the Office of the Army Chief of Staff (OACS), G-4 for Research and Development (R&D).

a. The OACS for R&D was concerned over both the narrowness of the tropic static exposure efforts and the loose-knit and uncoordinated efforts of the Army Technical Services in the Canal Zone. A preliminary site survey, made in late 1952 by AERDL personnel, recommended several preliminary sites for the station, and confirmed that the Canal Zone was the appropriate place for the station. The proposed new facility was designed to augment and expand, not replace, the NRL operations at the Corrosion Laboratory and the tropic exposure site.

b. Next, the OACS for R&D surveyed the Department of the Army (DA) staff, the Technical Services, and the U.S. Army, Caribbean (USARCARIB), for tropic testing requirements. The responses from the DA staff and the Technical Services were enthusiastic in support of the proposed tropic test station. The projected requirements were much broader than the static exposure tests which represented the sole effort up to that time. For example, the Surgeon General projected requirements for "tropical skin disease research, effects of humidity on wound healing, and the ecology of insects"; the Transportation Corps projected requirements for testing the "inland waterways feet, rail equipment, and construction equipment"; the Quartermaster Corps projected requirements for "physiological and psychological studies of man's response to wet-heat" and "evaluation of food, clothing and equipment under operational conditions."

c. USARCARIB's response was equally enthusiastic; their reply to the DA query stated that, "the Canal Zone is the optimum site for establishment of a Tropical Testing Station, and such establishment at an early date is strongly recommended." In December 1952, the DA Environmental Control Committee concluded that a requirement existed and recommended that the OACS, G-4 for R&D proceed to implement the station.

17. In early 1953, a second site survey team (from AERDL) recommended that the tropic test station headquarters be collocated with the NRL Corrosion Lab at Miraflores, but that equipment end items be given engineering and service tests at Fort Sherman. The team projected a permanent staff of approximately 45 people, augmented by approximately 170 TDY personnel. In coordination with USARCARIB, complete cost estimates were made with respect to renovating barracks, as well as constructing power lines, access roads, trails, and new test facilities.

a. In May 1953, the USARCARIB G-4 notified OACS G-4 that the total cost estimate for implementing the AERDL recommendation was approximately $537,000, and that USARCARIB had neither funds nor personnel to divert for such purposes. USARCARIB further stated that their headquarters did not want to assume direct administrative and technical supervision of the station.

b. The early plan for a tropic test station died in July 1953. DA notified USARCARIB that "unanticipated cuts" in the fiscal year 1954 R&D budget made it impossible for the Army to establish a tropic test station "at the time."

c. Although the plan for a tropic test station died in 1953, the requirement did not. In 1959, the Army Scientific Advisory Panel would again make a strong recommendation for a tropic test and research facility.

18. During 1953, the NRL tropic exposure site was moved from its original location on Fort Sherman to a more accessible area just off Galeta Point Road near the Fort Randolph military reservation at Coco Solo. This area, which retained most of the natural environments existing at Fort Sherman, was more amenable to surveillance by security police, and the buildings were of permanent construction. The site's facilities were available for use by all military services. It was managed locally by a scientist-in-charge, who, beginning in 1953, reported to the Chief of the Canal Zone Corrosion Laboratory at Miraflores. Although the buildings were demolished about 1955, the Fort Sherman (Skunk Hollow) site continued to be used because it had some advantages over the Galeta forest site.

19. On 11 July 1955, Alexander and Forgeson of NRL published a report entitled "Field Facilities for Environmental Research in the Canal Zone" (NRL Report 4557, reference 5). It described the Corrosion Laboratory at Miraflores, various associated atmospheric and water immersion sites, as well as the tropic exposure sites and laboratory at Galeta Island.

20. In 1961, Frankford Arsenal began planning an extensive series of studies about the effects of the humid tropic environment on materials (reference 6). This involved participation by other Army laboratories engaged in materials research. As a result of the Army Scientific Advisory Panel's recommendation, the U.S. Army Research and Development Office, Panama, was created in late 1962, and all local tropic materials studies were coordinated with that office.

21. A 1962 Canal Zone facilities survey indicated that exposure sites and laboratory facilities at Fort Sherman would be the most suitable for Army materials testing. However, the sites would have to be constructed and would not be ready in time for the first group of material specimens. Arrangements were made to use the NRL site at Galeta Island for the first group of Army Research Laboratories (ARL) material specimens, and they were placed on exposure in February 1963. Subsequent materials exposures were conducted at the four sites constructed in Fort Sherman: open, marine, tree-shaded, and rain forest areas.

a. By March 1963, the Fort Sherman Breakwater Exposure Site on Toro Point was completed, and the first samples were emplaced. This marine site (with a very high atmospheric salt content) was chosen primarily to expose metals and painted and deposited coatings on metals for corrosion studies. The site is a narrow strip of land extending from Toro Point, with the Caribbean Sea to the north and Limon Bay to the south. This extension is a wall of large rocks forming the western half of the breakwater that quiets the waters of Limon Bay for ships transiting the canal. The specimen racks, enclosed by an aluminum protective fence, are on a narrow strip of land preceding the rocks. Panels emplaced on the racks face north to the prevailing and the Caribbean Sea. Atmospheric salt content is measured at the site; other meteorological variables are collected at the Fort Sherman Coastal Exposure Site. The saltfall for 1 year has been calculated by Brierly to be 829 kilograms/hectare; TTC measurements range from 350 to over 600 grams/square meter, equivalent to 1 1/2 to 3 tons/ hectare. Southwell and Bultman (reference 7), in their comparison of this site to other worldwide tropic and temperate exposure sites, showed that it produced the highest corrosion rate ever reported on 1-year steel panels.

b. By August 1963, the Fort Sherman Open (Sunfield) Exposure Site (at the intersection of Chagres and Wenburg Roads) was completed, and the first samples were emplaced there. This site is a cleared, level, fenced area, surrounded by open spaces on three sides. There are some trees on one side, across Chagres Road. The specimen racks face either south, east, or toward the Caribbean Sea. These racks are at angles of 30 or 45 degrees, depending on the type of specimens and exposure desired. A full range of meteorological measurements are made at this site; electricity and water also are available.

c. In May 1977, the Fort Sherman Coastal and McKenzie Forest Exposure Sites were established to replace the Galeta Point Marine Site, as well as the Galeta Limited and Coco Solo Forest Sites. The Coastal site provided a true marine site somewhat less aggressive than the Breakwater site.

22. In March 1964, the U.S. Army Research and Development Office, Panama, was redesignated as the U.S. Army Tropic Test Center, under the newly established U.S. Army Testat Miraflores to the TTC headquarters
at Corozal. The Chemical, Biological, and Soils Laboratories stayed at Miraflores until October 1975, when they also moved to Corozal.

c. In April 1975, TTC's Atlantic Test Branch, Galeta Laboratory, and Coco Solo Tank Farm were closed, and the Coco Solo/Galeta sites were abandoned. Personnel were transferred to TTC headquarters at Corozal.

23. In 1977, when Frankford Arsenal closed, Teitell's tropic exposure efforts were moved to the U.S. Army Armament Research and Development Command (ARRADCOM), now U.S. Army Armament Research, Development and Engineering Center (ARDEC), under U.S. Army Armament, Munitions and Chemical Command (AMCCOM), Picatinny Arsenal, Dover, New Jersey. He continued in charge of those studies until his death in 1981.

24. There are many other names that could be mentioned in this history, and a multitude of details that could be added. The name of Leonard Teitell could hardly be left out because he personally selected three of the four Panama sites used in this study, and visited them regularly until shortly before his death.

25. In July 1989, U.S. Army Tropic Test Center was redesignated the U.S. Army Tropic Test Site (TTS) under U.S. Army Dugway Proving Ground's (DPG) Natural Environment Test Branch. Exposure testing will continue at the present sites and the Materials Laboratory will continue to operate. Technical tests will be conducted by safari test teams from DPG.

APPENDIX C. HISTORICAL DATA FOR LaQUE CENTER SITES

1. In the fall of 1935, Francis (Frank) L. LaQue, a corrosion specialist with the International Nickel Company (INCO), convinced several professional associates from other industries to join him in establishing a corrosion testing project at Kure Beach on the North Carolina coast.

a. The Kure Beach site was established on Ethyl-Dow Chemical Company property. In 1934, this company built a plant to extract bromine from seawater to manufacture ethylene dibromide, a sterilizing agent and gasoline additive.

b. LaQue's initial effort compared marine corrosion attack of carbon and low-alloy steel plates for ship hulls. The process consisted of immersing the plates in a "hydraulic jump" supplied with seawater through an intake channel from the ocean.

2. From this highly successful beginning effort, the world's leading marine corrosion laboratory developed. In 1940, again as a cooperative effort, the Kure Beach site added atmospheric exposure facilities. INCO acquired the Kure Beach site after the Ethyl-Dow plant closed in 1945. The plant was dismantled, which left INCO with access to the uncluttered and uncontaminated land--an ideal site for marine atmospheric corrosion exposure sites.

3. In 1950, the marine immersion corrosion test facility became part of INCO's research organization, and was relocated to an area on Banks Channel, between the mainland and Wrightsville Beach. The move was necessary because the beach site was quite vulnerable to storms. LaQue, in typical fashion, located a small two-story building facing the channel and the road, and made a down payment on it before asking INCO for an appropriation.

4. Throughout the beginning years, people involved in the various corrosion tests at Kure Beach met regularly, though informally, to exchange ideas. The original meetings were held in a hotel near the site; the first recorded general meeting was in 1939. In a few years, participation increased and a larger meeting place was required--a movie theater in Wrightsville Beach. In 1950, these forums became known as the "Seahorse Institute." Dow, one of the partners in the original project, provided space for a small control laboratory in the bromine plant. This is where the LaQue Center's marine corrosion museum started. Plates from the original test are still part of the museum's collection.

5. The Laboratory has grown and diversified steadily over the past 54 years, accumulating valuable corrosion data which are accessible to the scientific and industrial communities. The LaQue Center for Corrosion Technology, Inc., a wholly owned subsidiary of INCO, Ltd., continues to operate both the Kure Beach sites and the Wrightsville Beach Laboratory and Center. Earl A. Baker, who has been with the LaQue Center for over 30 years, and has been in charge of marine atmospheric corrosion testing at Kure Beach since 1972, is a coauthor of this report.

APPENDIX D. GEOGRAPHICAL AND TERRAIN DESCRIPTIONS

Fort Sherman (Toro Point) Breakwater Exposure Site

The Fort Sherman Breakwater Exposure Site (discussed in references 6 and 7) is located on the base of the breakwater extending into the Caribbean Sea from Toro Point on Fort Sherman, Panamá. The breakwater separates Limon Bay from the Caribbean Sea and provides smooth water for the Atlantic entrance to the Panamá Canal. The latitude and longitude of the site are 9° 22′ 21" North, 79° 56′ 48" West. The site was established in the early 1960s and first used in 1963 (see Appendix B). It was originally provided with an aluminum chain link fence and a combination of monel and steel racks for exposure samples. Most of the original fence is in good condition, as are the monel racks; the steel racks have long since rusted away. Prevailing northerly winds maintain a continuous wave action against the breakwater, providing abundant salt spray and an exceptionally high atmospheric saltfall, particularly in the dry season (December to April). The samples, as exposed on racks, are approximately 12 feet above mean tide level, at an angle of 30 degrees to the horizontal facing the water. Tidal variation is approximately 18 inches. Humidity is high most of the year, and yearly rainfall (from April through December) is about 130 inches. From December until April, only occasional rains fall. Because of the proximity of this site to the Fort Sherman Coastal Exposure Site, which collects detailed meteorological data, only atmospheric saltfall, sulfation, and nitration data were collected at this site.

Fort Sherman Coastal Exposure Site

The Coastal site was established in about 1977 to replace the marine site at Galeta Island which was abandoned when the Tropic Test Center Atlantic Test Branch closed in 1975. This site is similar to the Galeta site in that it is close to the shore but protected from wave action by a coral reef. Although it is outside the breakwater, it is within sight of the Breakwater site, at an elevation of about 2 feet above mean high tide level, and about 165 feet from the water's edge. The latitude and longitude of the site are 9° 22′ 15" North, 79° 57′ 1" West. The site is provided with aluminum chain link fence (installed in 1985) and aluminum racks. Panels are exposed on racks at an angle of 30 degrees to the horizontal, facing the water. Meteorological data (including temperature, humidity, windspeed and direction and rainfall) are monitored at this site. These parameters are considered to be the same at the Breakwater site because of its close proximity.

Fort Sherman Open (Sunfield) Exposure Site

This site (discussed in reference 6) is located about 1.3 kilometers inland from the breakwater, at the corner of Wenburg and Chagres Roads on Fort Sherman. It was established about the same time as the Breakwater site, and first used in 1963. It has been used widely to expose fabrics, plastics, and rubber, as well as most other materials. A number of corrosion exposures also have been performed at this site because of its somewhat elevated atmospheric saltfall. The latitude and longitude of the site are 9° 21′ 42" North, 79° 57′ 17" West.

During the wet season, the water table is at ground level, assuring continuous high humidity. In spite of the heavy rainfall on the Atlantic side of the Isthmus, this site gets as much solar radiation as the Pacific open sites, probably because it rains more suddenly on the Atlantic side and the sky is not overcast as much of the time. In addition to the meteorological parameters monitored at the Coastal site, solar radiation is monitored at this site.

Fort Sherman Forest (Skunk Hollow) Exposure Site

This is the oldest continually available exposure site on the Isthmus of Panamá (discussed in references 4, 5, and 6). It is probably best characterized as a mature tropical wet lowland forest. Many types of materials have been exposed here to determine resistance to fungus, humidity, insect attack, and chemical effects of atmospheric particulates, as well as corrosion. It was established in 1944 by a team from Frankford Arsenal. Rainfall is slightly higher here than at other Atlantic side sites. Because this site is in a hollow between two ridges, wind generally is light and variable. Exposure racks are made of Monel, mounted on aluminum stands, and fitted with ceramic insulators. Latitude and longitude of this site are 9° 19′42" North, 79° 57′ 25" West. The same meteorological parameters are monitored here as at the Coastal site. Normally, samples are emplaced in the densest shade available. Corrosion response is different at this site for the following reasons: because the samples are shaded and remain wet much of the time, because the water wetting the samples picks up a variety of organic contaminants from the tree canopy through which it falls, and because the atmospheric saltfall is much lower than most other Atlantic sites.

Kure Beach 25-meter Lot

This site is located in Southeastern North Carolina, on the road from Wilmington to Fort Fisher, just north of the town of Kure Beach. The exposure site is situated between the road and the water's edge, with samples facing the water 25 meters back from mean tide level. Latitude and longitude of the site are 34° 00′ 20" North, 77° 54′ 13" West. This site has been used since 1940 for atmospheric corrosion exposures.

Kure Beach 250-meter Lot

This site is located across the road from the 25-meter lot, at a distance of 250 meters from the mean tide level. This increased distance from tide level substantially reduces atmospheric saltfall. Racks at this site face south. Latitude and longitude of the site are 34° 00′ 25" North, 77° 54′ 21" West. This site has been used since 1940 for atmospheric corrosion exposures.

APPENDIX E. DESCRIPTION OF EXPOSED MATERIALS

Mild Steel

ASTM A414 grade A (reference 2)

Samples were furnished in drill-coded panels, 4 by 6 by 1/4 inches.

Composition: K01501--Carbon, 0.046%; Manganese, 0.32%; Phosphorus, 0.006%; Sulfur, 0.009%; Silicon, 0.003%; Copper, 0.019%; Chromium, 0.020%; Molybdenum, 0.011%; Nickel, 0.019%.

Ingot Iron

Samples were furnished in drill-coded coupons, 2 by 4 by 1/16 inches (Heat 023AD), or 2 by 4 by 5/32 inches (Heat 023AG).

Composition:

a. Heat 023AD--Carbon, 0.020%; Manganese, 0.040%; Phosphorus, 0.005%; Sulfur, 0.028%; Silicon, 0.010%, Copper, 0.050%, Chromium, 0.006%; Molybdenum, 0.010%.

b. Heat 023AG--Carbon, 0.010%; Manganese, 0.012%; Phosphorus, 0.006%, Sulfur, 0.021%; Silicon, 0.004%; Copper, 0.039%.

APPENDIX F. EXPOSURE SCHEDULE

	3-month		12-month	
PHASE	DATES	DAYS	DATES	DAYS
1 P	7/1/86-10/2/86	93	7/1/86-7/1/87	365
1 NC	7/1/86-10/1/86	92	7/1/86-7/7/87	371
2 P	10/2/86-12/30/86	89	10/1/86-10/1/87	365
2 NC	10/1/86-12/31/86	91	10/1/86-10/1/87	365
3 P	12/30/86-3/31/87	91	1/1/87-12/29/87	364
3 NC	12/31/86-4/1/87	90	1/1/87-1/5/88	369
4 P	3/31/87-7/1/87	92	4/13/87-3/30/88	352
4 NC	4/1/87-7/7/87	97	4/1/87-3/31/88	364
5 P	*		7/1/87-7/1/88	366
5 NC	*		7/7/87-7/6/88	365

Legend:

Exposure period designations:
1 = exposure beginning approximately 1 July 1986
2 = exposure beginning approximately 1 October 1986
3 = exposure beginning approximately 31 December 1986
4 = exposure beginning approximately 1 April 1987
5 = exposure beginning approximately 1 July 1987
P = schedule for Panamá sites at Fort Sherman
NC = schedule for North Carolina sites at Kure Beach.

* There was no phase 5 for the 3-month exposure

APPENDIX G. TABULATED CORROSION DATA--INGOT IRON

Sites used were as follows:

BW= Fort Sherman Breakwater Exposure Site (Toro Point), Panamá
SC= Fort Sherman Coastal Exposure Site (near Toro Point), Panamá
SO= Fort Sherman Open Exposure Site (Sunfield), Panamá
SH= Fort Sherman Forest Exposure Site (Skunk Hollow), Panamá
KB25= Kure Beach 25-meter Lot, Kure Beach, North Carolina
KB250= Kure Beach 250-meter Lot, Kure Beach, North Carolina

INGOT IRON (3 MONTHS)

Site	Dates	Days	Corrosion Rate* (mm/year)		Mass Loss* (g/m^2)		Surface Attack (mm)
BW-1	7/1/86-10/2/86	93	1.06/1.10	1.08	212/220	216	0.40-0.48
SC-1	7/1/86-10/2/86	93	.228/.238	.233	45.4/47.6	46.5	0.03-0.0[illegible]
SO-1	7/1/86-10/2/86	93	.0588/.0580	.0584	11.7/11.6	11.7	general
SH-1	7/1/86-10/2/86	93	.0240/.0267	.0254	4.78/5.32	5.05	general
KB25-1	7/1/86-10/1/86	92	.164/.174	.169	32.4/34.5	33.5	general
KB250-1	7/1/86-10/1/86	92	.0872/.0851	.0862	17.3/16.9	17.1	general
BW-2	10/2/86-12/30/86	89	.395/.530	.463	75.8/102	88.9	0.09-0.17
SC-2	10/2/86-12/30/86	89	.198/.194	.196	38.1/37.2	37.7	0.17-0.19
SO-2	10/2/86-12/30/86	89	.0551/.0563	.0558	10.6/10.8	10.7	general
SH-2	10/2/86-12/30/86	89	.0250/.0295	.0273	4.80/5.67	5.24	general
KB25-2	10/1/86-12/31/86	91	.211/.217	.214	41.3/42.4	41.9	general
KB250-2	10/1/86-12/31/86	91	.0834/.0909	.0872	16.3/17.8	17.1	general
BW-3	12/30/86-3/31/87	91	.699/.640	.670	125/137	131	0.40-0.42
SC-3	12/30/86-3/31/87	91	.525/.650	.588	103/128	116	0.60-0.68
SO-3	12/30/86-3/31/87	91	.0535/.0544	.0540	10.5/10.7	10.6	general
SH-3	12/30/86-3/31/87	91	.0377/.0361	.0369	7.08/7.39	7.24	general
KB25-3	12/31/86-4/1/87	90	.105/.109	.107	20.3/21.1	20.7	general
KB250-3	12/31/86-4/1/87	90	.0760/.0726	.0743	14.7/14.1	14.4	general
BW-4	3/31/87-7/1/87	92	1.10/1.13	1.12	219/225	222	0.15-0.20
SC-4	3/31/87-7/1/87	92	.302/.280	.291	55.4/59.8	57.6	0.20-0.30
SO-4	3/31/87-7/1/87	92	.0533/.0496	.0515	9.82/10.6	10.21	general
SH-4	3/31/87-7/1/87	92	.0434/.0475	.0455	8.61/9.41	9.01	general
KB25-4	4/1/87-7/7/87	97	.148/.141	.145	29.4/30.9	30.2	general
KB250-4	4/1/87-7/7/87	97	.0667/.0686	.0677	13.9/14.3	14.1	general

* Shows readings from duplicate samples and their average.

RANK ORDER--INGOT IRON (3 MONTHS)

Site	Dates	Days	Corrosion Rate* (mm/year)		Mass Loss* (g/m^2)		Surface Attack (mm)
BW-4	3/31/87-7/1/87	92	1.10/1.13	1.12	219/225	222	0.15-0.20
BW-1	7/1/86-10/2/86	93	1.06/1.10	1.08	212/220	216	0.40-0.48
BW-3	12/30/86-3/31/87	91	.699/.640	.670	125/137	131	0.40-0.42
SC-3	12/30/86-3/31/87	91	.525/.650	.588	103/128	116	0.60-0.68
BW-2	10/2/86-12/30/86	89	.395/.530	.463	75.8/102	88.9	0.09-0.17
SC-4	3/31/87-7/1/87	92	.302/.280	.291	55.4/59.8	57.6	0.20-0.30
SC-1	7/1/86-10/2/86	93	.228/.238	.233	45.4/47.6	46.5	0.03-0.05
KB25-2	10/1/86-12/31/86	91	.211/.217	.214	41.3/42.4	41.9	general
SC-2	10/2/86-12/30/86	89	.198/.194	.196	38.1/37.2	37.7	0.17-0.19
KB25-1	7/1/86-10/1/86	92	.164/.174	.169	32.4/34.5	33.5	general
KB25-4	4/1/87-7/7/87	97	.148/.141	.145	29.4/30.9	30.2	general
KB25-3	12/31/86-4/1/87	90	.105/.109	.107	20.3/21.1	20.7	general
KB250-2	10/1/86-12/31/86	91	.0834/.0909	.0872	16.3/17.8	17.1	general
KB250-1	7/1/86-10/1/86	92	.0872/.0851	.0862	17.3/16.9	17.1	general
KB250-3	12/31/86-4/1/87	90	.0760/.0726	.0743	14.7/14.1	14.4	general
KB250-4	4/1/87-7/7/87	97	.0667/.0686	.0677	13.9/14.3	14.1	general
SO-1	7/1/86-10/2/86	93	.0588/.0580	.0584	11.7/11.6	11.7	general
SO-2	10/2/86-12/30/86	89	.0551/.0563	.0558	10.6/10.8	10.7	general
SO-3	12/30/86-3/31/87	91	.0535/.0544	.0540	10.5/10.7	10.6	general
SO-4	3/31/87-7/1/87	92	.0533/.0496	.0515	9.82/10.6	10.21	general
SH-4	3/31/87-7/1/87	92	.0434/.0475	.0455	8.61/9.41	9.01	general
SH-3	12/30/86-3/31/87	91	.0377/.0361	.0369	7.08/7.39	7.24	general
SH-2	10/2/86-12/30/86	89	.0250/.0295	.0273	4.80/5.67	5.24	general
SH-1	7/1/86-10/2/86	93	.0240/.0267	.0254	4.78/5.32	5.05	general

* Shows readings from duplicate samples and their average.

INGOT IRON (12 MONTHS)

Site	Dates	Days	Corrosion Rate* (mm/year)		Mass Loss* (g/m^2)		Surface Attack (mm)
BW-I	7/1/86-7/1/87	365	.528/.597	.563	415/469	442	>1.53(perf)
SC-I	7/1/86-7/1/87	365	.562/.564	.563	441/444	443	>1.53(perf)
SO-I	7/1/86-7/1/87	365	.0375/.0370	.0373	29.0/29.5	29.3	0.08-0.10
SH-I	7/1/86-7/1/87	365	.0470/.0245	.0358	19.2/36.9	28.1	general
KB25-I	7/1/86-7/7/87	371	.157/.159	.158	125/127	126	0.10-0.20
KB250-I	7/1/86-7/7/87	371	.0454/.0461	.0458	36.3/36.8	36.6	general
BW-II	10/1/86-10/1/87	365	.548/.495	.5215	389/431	410	>1.53(perf)
SC-II	10/1/86-10/1/87	365	.526/.528	.527	413/415	414	>1.53(perf)
SO-II	10/1/86-10/1/87	365	.0347/.0373	.036	27.2/29.3	28.3	0.06-0.07
SH-II	10/1/86-10/1/87	365	.0231/.0286	.0258	18.1/22.5	20.3	nil
KB25-II	10/1/86-10/1/87	365	.119/.117	.118	92.4/93.3	92.9	0.05-0.15
KB250-II	10/1/86-10/1/87	365	.0527/.0518	.0523	41.4/40.7	41.1	0.01
BW-III	1/1/87-12/29/87	364	.533/.588	.561	417/461	439	>1.53(perf)
SC-III	1/1/87-12/29/87	364	.505/.438	.472	343/396	370	>1.53(perf)
SO-III	1/1/87-12/29/87	364	.0331/.0371	.0351	26.0/29.1	27.6	0.02-0.03
SH-III	1/1/87-12/29/87	364	.0277/.0315	.0296	21.7/24.6	23.2	general
KB25-III	1/1/87-1/5/88	369	.0709/.0755	.0732	56.5/60.1	58.3	0.12-0.16
KB250-III	1/1/87-1/5/88	369	.0407/.0479	.0443	32.4/34.0	33.2	general
BW-IV	4/13/87-3/30/88	352	>.632/>.648	>.648	479/491	485	>1.53(perf)
SC-IV	4/13/87-3/30/88	352	.335/.318	.326	241/254	248	>1.53(perf)
SO-IV	4/13/87-3/30/88	352	.0392/.0429	.0411	29.7/32.5	31.1	0.08-0.10
SH-IV	4/13/87-3/30/88	352	.0229/.0316	.0273	17.3-23.9	20.6	0.03
KB25-IV	4/1/87-3/31/88	364	.1037/.1015	.1026	79.5/81.2	80.4	0.35-0.36
KB250-IV	4/1/87-3/31/88	364	.0403/.0418	.0411	31.6/32.8	32.2	0.10
BW-V	7/1/87-7/1/88	366	.758/.775	.767	597/611	604	uniform
SC-V	7/1/87-7/1/88	366	.754/.776	.765	594/612	603	0.85-0.95
SO-V	7/1/87-7/1/88	366	.0713/.0745	.0729	56.2/58.7	57.5	0.30-0.32
SH-V	7/1/87-7/1/88	366	.0828/.0910	.0869	65.2/71.7	68.5	0.30-0.65
KB25-V	7/7/87-7/6/88	365	.469/.539	.504	367/422	395	0.35-0.38
KB250-V	7/7/87-7/6/88	365	.117/.118	.118	91.9/92.7	92.3	0.37

* Shows readings from duplicate samples and their average.

RANK ORDER--INGOT IRON (12 MONTHS)

Site	Dates	Days	Corrosion Rate* (mm/year)		Mass Loss* (g/m^2)		Surface Attack (mm)
BW-V	7/1/87-7/1/88	366	.758/.775	.767	597/611	604	uniform
SC-V	7/1/87-7/1/88	366	.754/.776	.765	594/612	603	0.85-0.95
BW-IV	4/13/87-3/30/88	352	>.632/>.648	>.648	479/491	485	>1.53(perf)
BW-I	7/1/86-7/1/87	365	.528/.597	.563	415/469	442	>1.53(perf)
SC-I	7/1/86-7/1/87	365	.562/.564	.563	441/444	443	>1.53(perf)
BW-III	1/1/87-12/29/87	364	.533/.588	.561	417/461	439	>1.53(perf)
SC-II	10/1/86-10/1/87	365	.526/.528	.527	413/415	414	>1.53(perf)
BW-II	10/1/86-10/1/87	365	.548/.495	.5215	389/431	410	>1.53(perf)
KB25-V	7/7/87-7/6/88	365	.469/.539	.504	367/422	395	0.35-0.38
SC-III	1/1/87-12/29/87	364	.505/.438	.472	343/396	370	>1.53(perf)
SC-IV	4/13/87-3/30/88	352	.335/.318	.326	241/254	248	>1.53(perf)
KB25-I	7/1/86-7/7/87	371	.157/.159	.158	125/127	126	0.10-0.20
KB25-II	10/1/86-10/1/87	365	.119/.117	.118	92.4/93.3	92.9	0.05-0.15
KB250-V	7/7/87-7/6/88	365	.117/.118	.118	91.9/92.7	92.3	0.37
KB25-IV	4/1/87-3/31/88	364	.1037/.1015	.1026	79.5/81.2	80.4	0.35-0.36
SH-V	7/1/87-7/1/88	366	.0828/.0910	.0869	65.2/71.7	68.5	0.30-0.65
KB25-III	1/1/87-1/5/88	369	.0709/.0755	.0732	56.5/60.1	58.3	0.12-0.16
SO-V	7/1/87-7/1/88	366	.0713/.0745	.0729	56.2/58.7	57.5	0.30-0.32
KB250-II	10/1/86-10/1/87	365	.0527/.0518	.0523	41.4/40.7	41.1	0.01
KB250-I	7/1/86-7/7/87	371	.0454/.0461	.0458	36.3/36.8	36.6	general
KB250-III	1/1/87-1/5/88	369	.0407/.0479	.0443	32.4-34.0	33.2	general
SO-IV	4/13/87-3/30/88	352	.0392/.0429	.0411	29.7/32.5	31.1	0.08-0.10
KB250-IV	4/1/87-3/31/88	364	.0403/.0418	.0411	31.6/32.8	32.2	0.10
SO-I	7/1/86-7/1/87	365	.0375/.0370	.0373	29.0/29.5	29.3	0.08-0.10
SO-II	10/1/86-10/1/87	365	.0347/.0373	.0360	27.2/29.3	28.3	0.06-0.07
SH-I	7/1/86-7/1/87	365	.0470/.0245	.0358	19.2/36.9	28.1	general
SO-III	1/1/87-12/29/87	364	.0331/.0371	.0351	26.0/29.1	27.6	0.02-0.03
SH-III	1/1/87-12/29/87	364	.0277/.0315	.0296	21.7/24.6	23.2	general
SH-IV	4/13/87-3/30/88	352	.0229/.0316	.0273	17.3-23.9	20.6	0.03
SH-II	10/1/86-10/1/87	365	.0231/.0286	.0258	18.1/22.5	20.3	general

* Shows readings from duplicate samples and their average.

APPENDIX H. TABULATED CORROSION DATA--MILD STEEL

Sites used were as follows:

BW= Fort Sherman Breakwater Exposure Site (Toro Point), Panamá
SC= Fort Sherman Coastal Exposure Site (near Toro Point), Panamá
SO= Fort Sherman Open Exposure Site (Sunfield), Panamá
SH= Fort Sherman Forest Exposure Site (Skunk Hollow), Panamá
KB25= Kure Beach 25-meter Lot, Kure Beach, North Carolina
KB250= Kure Beach 250-meter Lot, Kure Beach, North Carolina

MILD STEEL (3 MONTHS)

Site	Dates	Days	Corrosion Rate* (mm/year)		Mass Loss* (g/m^2)		Surface Attack (mm)
BW-1	7/1/86-10/2/86	93	.980/.741	.861	196/149	173	0.30-0.38
SC-1	7/1/86-10/2/86	93	.112/.117	.115	22.4/23.5	23.0	0.03-0.05
SO-1	7/1/86-10/2/86	93	.0474/.0510	.0482	9.5-10.2	9.9	general
SH-1	7/1/86-10/2/86	93	.0256/.0159	.0208	3.20/5.13	4.17	general
KB25-1	7/1/86-10/1/86	92	.124/.119	.122	23.6/24.7	24.1	general
KB250-1	7/1/86-10/1/86	92	.0674/.0684	.0679	13.4/13.6	13.5	general
BW-2	10/2/86-12/30/86	89	.298/.341	.320	57.1/65.4	61.3	0.16-0.17
SC-2	10/2/86-12/30/86	89	.132/.127	.129	23.1/25.3	24.2	0.12
SO-2	10/2/86-12/30/86	89	.0422/.0455	.0439	8.09/8.74	8.42	general
SH-2	10/2/86-12/30/86	89	.0136/.0179	.0158	2.61/3.43	3.02	general
KB25-2	10/1/86-12/31/86	91	.177/.178	.178	34.7/34.8	34.8	general
KB250-2	10/1/86-12/31/86	91	.0868/.0841	.0855	16.5/17.0	16.8	general
BW-3	12/30/86-3/31/87	91	.763/.784	.774	150/154	152	0.41-0.52
SC-3	12/30/86-3/31/87	91	.411/.380	.396	74.5/80.7	77.6	0.41-0.44
SO-3	12/30/86-3/31/87	91	.0435/.0453	.0444	8.53/8.89	8.71	general
SH-3	12/30/86-3/31/87	91	.0487/.0536	.0512	9.56/10.5	10.03	general
KB25-3	12/31/86-4/1/87	90	.0892/.0887	.0890	15.9/16.0	16.0	general
KB250-3	12/31/86-4/1/87	90	.0677/.0666	.0672	11.9/12.1	12.0	general
BW-4	3/31/87-7/1/87	92	.917/.878	.898	174/182	178	0.02-0.09
SC-4	3/31/87-7/1/87	92	.144/.165	.155	28.6/32.7	30.7	general
SO-4	3/31/87-7/1/87	92	.0455/.0435	.0445	8.62/9.03	8.83	general
SH-4	3/31/87-7/1/87	92	.0223/.0275	.0249	4.43/5.45	4.94	general
KB25-4	4/1/87-7/7/87	97	.115/.118	.117	24.1/24.6	24.4	general
KB250-4	4/1/87-7/7/87	97	.0587/.0587	.0587	12.3/12.3	12.3	general

* Shows readings from duplicate samples and their average.

RANK ORDER--MILD STEEL (3 MONTHS)

Site	Dates	Days	Corrosion Rate* (mm/year)		Mass Loss* (g/m^2)		Surface Attack (mm)
BW-4	3/31/87-7/1/87	92	.917/.878	.898	174/182	178	0.02-0.09
BW-1	7/1/86-10/2/86	93	.980/.741	.861	196/149	173	0.30-0.38
BW-3	12/30/86-3/31/87	91	.763/.784	.774	150/154	152	0.41-0.52
SC-3	12/30/86-3/31/87	91	.411/.380	.396	74.5/80.7	77.6	0.41-0.44
BW-2	10/2/86-12/30/86	89	.298/.341	.320	57.1/65.4	61.3	0.16-0.17
KB25-2	10/1/86-12/31/86	91	.177/.178	.178	34.7/34.8	34.8	general
SC-4	3/31/87-7/1/87	92	.144/.165	.155	28.6/32.7	30.7	general
SC-2	10/2/86-12/30/86	89	.132/.127	.129	23.1/25.3	24.2	0.12
KB25-1	7/1/86-10/1/86	92	.124/.119	.122	23.6/24.7	24.1	general
KB25-4	4/1/87-7/7/87	97	.115/.118	.117	24.1/24.6	24.4	general
SC-1	7/1/86-10/2/86	93	.112/.117	.115	22.4/23.5	23.0	0.03-0.05
KB25-3	12/31/86-4/1/87	90	.0892/.0887	.0890	15.9/16.0	16.0	general
KB250-2	10/1/86-12/31/86	91	.0868/.0841	.0855	16.5/17.0	16.8	general
KB250-1	7/1/86-10/1/86	92	.0674/.0684	.0679	13.4/13.6	13.5	general
KB250-3	12/31/86-4/1/87	90	.0677/.0666	.0672	11.9/12.1	12.0	general
KB250-4	4/1/87-7/7/87	97	.0587/.0587	.0587	12.3/12.3	12.3	general
SH-3	12/30/86-3/31/87	91	.0487/.0536	.0512	9.56/10.5	10.03	general
SO-1	7/1/86-10/2/86	93	.0474/.0510	.0482	9.5-10.2	9.9	general
SO-4	3/31/87-7/1/87	92	.0455/.0435	.0445	8.62/9.03	8.83	general
SO-3	12/30/86-3/31/87	91	.0435/.0453	.0444	8.53/8.89	8.71	general
SO-2	10/2/86-12/30/86	89	.0422/.0455	.0439	8.09/8.74	8.42	general
SH-4	3/31/87-7/1/87	92	.0223/.0275	.0249	4.43/5.45	4.94	general
SH-1	7/1/86-10/2/86	93	.0256/.0159	.0208	3.20/5.13	4.17	general
SH-2	10/2/86-12/30/86	89	.0136/.0179	.0158	2.61/3.43	3.02	general

* Shows readings from duplicate samples and their average.

MILD STEEL (12 MONTHS)

Site	Dates	Days	Corrosion Rate* (mm/year)		Mass Loss* (g/m^2)		Surface Attack (mm)
BW-I	7/1/86-7/1/87	365	.593/.613	.603	467/483	475	0.55-0.88
SC-I	7/1/86-7/1/87	365	.286/.325	.306	225/256	241	0.40-0.70
SO-I	7/1/86-7/1/87	365	.0316/.0339	.0328	24.9/26.7	25.8	general
SH-I	7/1/86-7/1/87	365	.0295/.0272	.0284	21.4/23.2	22.3	general
KB25-I	7/1/86-7/7/87	371	.0677/.0640	.0659	51.2/54.2	52.7	general
KB250-I	7/1/86-7/7/87	371	.0350/.0345	.0348	27.6/27.9	27.8	general
BW-II	10/1/86-10/1/87	365	.517/.515	.516	405/407	406	1.2-1.3
SC-II	10/1/86-10/1/87	365	.357/.344	.351	271/281	276	0.7
SO-II	10/1/86-10/1/87	365	.0290/.0276	.0283	21.8/22.8	22.3	general
SH-II	10/1/86-10/1/87	365	.0282/.0196	.0239	15.4/22.2	18.8	general
KB25-II	10/1/86-10/1/87	365	.0743/.0734	.0739	58.5/60.1	59.3	0.01-0.05
KB250-II	10/1/86-10/1/87	365	.0435/.0433	.0434	34.1/34.3	34.2	general
BW-III	1/1/87-12/29/87	364	.559/.573	.566	438/449	444	0.9-1.1
SC-III	1/1/87-12/29/87	364	.268/.250	.259	196/210	203	0.02-0.4
SO-III	1/1/87-12/29/87	364	.0322/.0339	.0331	25.2/26.6	25.9	general
SH-III	1/1/87-12/29/87	364	.0299/.0285	.0292	22.3/23.5	22.9	general
KB25-III	1/1/87-1/5/88	369	.0564/.0540	.0552	42.9/44.8	43.9	general
KB250-III	1/1/87-1/5/88	369	.0363/.0366	.0365	28.8/29.1	29.0	general
BW-IV	4/13/87-3/30/88	352	.602/.577	.590	438/457	448	0.69-0.78
SC-IV	4/13/87-3/30/88	352	.220/.194	.207	147/167	157	0.51-0.73
SO-IV	4/13/87-3/30/88	352	.0300/.0288	.0294	21.8/22.8	22.3	0.02-0.03
SH-IV	4/13/87-3/30/88	352	.0201/.0219	.0210	15.6/16.6	16.1	general
KB25-IV	4/1/87-3/31/88	364	.0551/.0535	.0543	42.1/43.4	42.8	0.12-0.14
KB250-IV	4/1/87-3/31/88	364	.0386/.0385	.0386	30.3/30.4	30.4	general
BW-V	7/1/87-7/1/88	366	.555/.601	.578	438/474	456	0.82-0.84
SC-V	7/1/87-7/1/88	366	.335/.343	.339	264/271	268	0.63
SO-V	7/1/87-7/1/88	366	.0295/.0302	.0299	23.3/23.8	23.6	general
SH-V	7/1/87-7/1/88	366	.0208/.0201	.0204	15.8/16.4	16.1	general
KB25-V	7/7/87-7/6/88	365	.0469/.0481	.0475	37.0/37.8	37.4	0.09-0.10
KB250-V	7/7/87-7/6/88	365	.0350/.0354	.0352	27.6/27.9	27.8	0.04-0.05

* Shows readings from duplicate samples and their average.

RANK ORDER--MILD STEEL (12 MONTHS)

Site	Dates	Days	Corrosion Rate* (mm/year)		Mass Loss* (g/m^2)		Surface Attack (mm)
BW-I	7/1/86-7/1/87	365	.593/.613	.603	467/483	475	0.55-0.88
BW-IV	4/13/87-3/30/88	352	.602/.577	.590	438/457	448	0.69-0.78
BW-V	7/1/87-7/1/88	366	.555/.601	.578	438/474	456	0.82-0.84
BW-III	1/1/87-12/29/87	364	.559/.573	.566	438/449	444	0.9-1.1
BW-II	10/1/86-10/1/87	365	.517/.515	.516	405/407	406	1.2-1.3
SC-II	10/1/86-10/1/87	365	.357/.344	.351	271/281	276	0.7
SC-V	7/1/87-7/1/88	366	.335/.343	.339	264/271	268	0.63
SC-I	7/1/86-7/1/87	365	.286/.325	.306	225/256	241	0.40-0.70
SC-III	1/1/87-12/29/87	364	.268/.250	.259	196/210	203	0.02-0.4
SC-IV	4/13/87-3/30/88	352	.220/.194	.207	147/167	157	0.51-0.73
KB25-II	10/1/86-10/1/87	365	.0743/.0734	.0739	58.5/60.1	59.3	0.01-0.05
KB25-I	7/1/86-7/7/87	371	.0677/.0640	.0659	51.2/54.2	52.7	general
KB25-III	1/1/87-1/5/88	369	.0564/.0540	.0552	42.9/44.8	43.9	general
KB25-IV	4/1/87-3/31/88	364	.0551/.0535	.0543	42.1/43.4	42.8	0.12-0.14
KB25-V	7/7/87-7/6/88	365	.0469/.0481	.0475	37.0/37.8	37.4	0.09-0.10
KB250-II	10/1/86-10/1/87	365	.0435/.0433	.0434	34.1/34.3	34.2	general
KB250-IV	4/1/87-3/31/88	364	.0386/.0385	.0386	30.3/30.4	30.4	general
KB250-III	1/1/87-1/5/88	369	.0363/.0366	.0365	28.8/29.1	29.0	general
KB250-V	7/7/87-7/6/88	365	.0350/.0354	.0352	27.6/27.9	27.8	0.04-0.05
KB250-I	7/1/86-7/7/87	371	.0350/.0345	.0348	27.6/27.9	27.8	general
SO-III	1/1/87-12/29/87	364	.0322/.0339	.0331	25.2/26.6	25.9	general
SO-I	7/1/86-7/1/87	365	.0316/.0339	.0328	24.9/26.7	25.8	general
SO-V	7/1/87-7/1/88	366	.0295/.0302	.0299	23.3/23.8	23.6	general
SO-IV	4/13/87-3/30/88	352	.0300/.0288	.0294	21.8/22.8	22.3	0.02-0.03
SH-III	1/1/87-12/29/87	364	.0299/.0285	.0292	22.3/23.5	22.9	general
SH-I	7/1/86-7/1/87	365	.0295/.0272	.0284	21.4/23.2	22.3	general
SO-II	10/1/86-10/1/87	365	.0290/.0276	.0283	21.8/22.8	22.3	general
SH-II	10/1/86-10/1/87	365	.0282/.0196	.0239	15.4/22.2	18.8	general
SH-IV	4/13/87-3/30/88	352	.0201/.0219	.0210	15.6/16.6	16.1	general
SH-V	7/1/87-7/1/88	366	.0208/.0201	.0204	15.8/16.4	16.1	general

* Shows readings from duplicate samples and their average.

APPENDIX I. METEOROLOGICAL DATA

Fort Sherman Coastal and Breakwater Exposure Sites

Month	Temperature (°F)		Relative Humidity (%)		Rainfall	Windspeed
	Mean	Extremes	Mean	Extremes	(in)	(mph)
7/86	79	71/90	94	84/97	5.36	6
8/86	81	73/90	94	76/98	12.93	4
9/86	77	70/87	96	72/100	12.50	4
10/86	75	70/85	96	74/100	13.26	2
11/86	77	69/85		80/96	13.57	5
12/86	77	70/84			3.82	8
1/87	79	72/86	88	79/92	1.09	10
2/87	81	72/86	89	78/99	0.74	10
3/87	82	74/94	85	61/94	0.15	8
4/87	82	75/87	85	69/98	11.42	8
5/87	82	74/88	88	70/99	20.18	5
6/87	82	75/90	89	74/99	14.15	4
7/87	82	73/90	90	71/100	16.87	3
8/87	82	73/90	90	74/100	27.52	5
9/87	80	74/88	89	67/99	18.41	3
10/87	79	73/89	90	63/100	30.38	3
11/87	80	72/86	89	73/100	18.24	5
12/87	81	73/88	87	70/100	2.01	7
1/88	81	77/85	81	69/92	0.80	11
2/88	81	75/86	84	73/98	0.90	12
3/88	81	74/85	83	69/98	0.21	11
4/88	82	70/90	84	64/99	0.40	8
5/88	82	73/94	90	56/100	9.50	5
6/88	80	72/91	89	56/100	12.88	4

(Meteorological data given in this table are all that were furnished; where no value appears, data were not furnished.)

Fort Sherman Open Exposure Site

Month	Temperature (°F) Mean	Temperature (°F) Extremes	Relative Humidity (%) Mean	Relative Humidity (%) Extremes	Rainfall (in)	Windspeed (mph)	Solar Rad Avg	Solar Rad Total
7/86	81	72/90	87	63/100	7.54	3	366	11346
8/86	80	72/89	90	66/100	14.85	2	365	11315
9/86	79	72/81	91	62/100	13.76	2	355	10650
10/86	78	72/89	94	64/100	13.93	1	320	9920
11/86	81	72/90	88	65/100	13.29	2	366	10980
12/86	81	72/90	86	61/100	4.26	4	403	12491
1/87	82	75/88	83	68/100	1.10	3	399	12356
2/87	82	70/90	87	69/100	0.82	3	424	11869
3/87	83	74/98	83	64/99	0.19	3	504	15610
4/87	81	73/90	81	61/100	12.86	3	386	11585
5/87	80	70/89	90	62/100	20.84	2	388	12026
6/87	80	72/89	92	71/100	13.25	1	305	9162
7/87	79	72/89	93	69/100	21.23	2	302	9373
8/87	79	73/88	92	72/100	27.85	2	331	10268
9/87	79	72/89	93	67/100	19.69	1	343	10300
10/87	78	73/94	93	64/100	27.17	1	328	10167
11/87	79	71/97	93	69/100	18.86	2	326	9794
12/87	81	72/88	87	65/100	15.00	4	377	13575
1/88	81	73/87	80	61/97	0.79	5	465	14411
2/88	81	75/87	82	66/99	1.96	4	446	11597
3/88	82	75/89	79	62/100	0.12	4	423	16201
4/88	82	72/91	80	1/100	0.32	3	551	16528
5/88	82	74/94	88	61/100	6.59	2	389	12055
6/88	80	72/91	89	62/100	12.05	2	379	11417

Fort Sherman Forest Exposure (Skunk Hollow) Site

Month	Temperature (°F)		Relative Humidity (%)		Rainfall (in)	Windspeed (mph)
	Mean	Extremes	Mean	Extremes		
7/86	77	70/84			8.08	
8/86	77	70/86	95	70/100	15.22	
9/86	76	70/80	90	68/99	14.13	
10/86	76	71/81	95	86/96	14.47	
11/86	75	72/81	96	85/100	12.21	
12/86	75	71/80	99	90/100	3.32	
1/87	76	70/81	97	78/100	1.50	
2/87	79	73/85	93	84/99	0.88	
3/87	80	74/91	90	67/98	0.17	
4/87	79	72/85	90	69/100	10.19	
5/87	78	72/84	95	78/100	17.26	
6/87	78	71/83	98	83/100	9.92	
7/87	77	71/83	98	86/100	16.28	
8/87	79	73/86	98	84/100	26.29	
9/87	79	74/85	98	81/100	17.79	
10/87	78	73/86	99	79/100	25.45	
11/87	79	73/84	99	86/100	17.80	
12/87	79	71/84	92	71/100	15.71	
1/88	78	73/83	86	67/100	0.65	
2/88	78	73/92	89	73/100	2.47	
3/88	79	73/85	86	64/100	0.22	
4/88	79	74/86	87	67/100	0.37	
5/88	77	71/87	94	61/100	8.86	
6/88	78	72/87	96	66/100	9.31	

Kure Beach Sites

Month	Temperature (°F) Mean	Temperature (°F) Extremes	Relative Humidity (%) Mean	Relative Humidity (%) Extremes	Rainfall (in)	Windspeed (mph)	Sky Cover
7/86	84	66/100	77	59/89	7.44	8	.5
8/86	79	57/95	77	70/91	6.64	9	.7
9/86	77	54/95	78	57/90	5.71	7	.6
10/86	67	38/95	79	57/88	2.97	8	.5
11/86	60	28/84	83	70/90	3.19	8	.8
12/86	50	27/76	78	58/86	3.43	8	.7
1/87	45	24/73	73	56/84	6.49	10	.6
2/87	46	26/72	62	52/76	4.42	10	.7
3/87	53	28/79	71	51/86	2.70	9	.6
4/87	60	32/90	70	50/83	2.96	10	.5
5/87	71	43/89	76	56/92	0.95	8	.5
6/87	79	60/93	78	59/92	5.24	9	.6
7/87	82	60/100	77	58/90	5.19	8	.5
8/87	76	68/96	83	64/93	9.35	8	.6
9/87	77	55/91	84	61/95	6.42	6	.6
10/87	59	36/81	73	48/85	0.51	7	.4
11/87	58	27/81	73	51/85	5.67	7	.5
12/87	50	26/75	74	51/82	1.35	8	.6
1/88	46		71		5.41		
2/88	46		67		2.00		
3/88	54		68		4.05		
4/88	62		70		3.56		
5/88	69		76		7.54		
6/88	74		73		2.93		

Note: All data available at time of writing are shown in this table.

APPENDIX J. ATMOSPHERIC CONTAMINANT DATA

Fort Sherman Breakwater Exposure Site

Month	Saltfall (mg/m^2) Daily	Saltfall (mg/m^2) Total	Sulfur Dioxide (mg/m^2) Daily	Sulfur Dioxide (mg/m^2) Total	Nitrogen Oxides (ug/m^2) Daily	Nitrogen Oxides (ug/m^2) Total
7/86	1002	31062	39	1209	92	2852
8/86	841	26071	40	1240	148	4588
9/86	644	19320	40	1200	72	2160
10/86	167	5177	37	1147	118	3658
11/86	520	15600	37	1110	80	2400
12/86	1455	45105	58	1798	361	11191
1/87	1428	44268	53	1643	309	9579
2/87	2500	70000	39	1092	148	4144
3/87	1150	35650	93	2883	157	4867
4/87	589	17670	85	2550	108	3240
5/87	514	15934	42	1302	245	7595
6/87	720	21600	51	1530	178	5340
7/87	604	18724	52	1612	148	4588
8/87	444	13764	36	1116	83	2573
9/87	370	11100	38	1140	89	2670
10/87	270	8370	40	1240	144	3534
11/87	309	9270	63	1890	45	1350
12/87	1617	50127	40	1240	297	9207
1/88	4256	131936	34	1054	46	1380
2/88	4676	135604	89	2581	67	1943
3/88	4051	125581	167	5177	73	2263
4/88	2814	84420	<39	<1170	171	5130
5/88	947	28410				
6/88	263	7890	<37	<1110	118	3540

Fort Sherman Coastal Exposure Site

Month	Saltfall (mg/m^2) Daily	Saltfall (mg/m^2) Total	Sulfur Dioxide (mg/m^2) Daily	Sulfur Dioxide (mg/m^2) Total	Nitrogen Oxides (ug/m^2) Daily	Nitrogen Oxides (ug/m^2) Total
7/86	416	12896	40	1240	110	3410
8/86	46	1435	43	1333	95	2945
9/86	52	1560	40	1200	60	1800
10/86	45	1392	48	1488	64	1984
11/86	306	9180	37	1110	42	1260
12/86	1203	37293	41	1271	289	8959
1/87	997	30907	50	1550	190	5890
2/87	1915	53620	36	1008	103	2884
3/87	747	23157	86	2666	153	4743
4/87	574	17220	82	2460	157	4710
5/87	127	3937	42	1302	137	4247
6/87	129	3870	49	1470	143	4290
7/87	71	2201	52	1612	100	3100
8/87	71	2201	36	1116	61	1891
9/87	112	3360	37	1110	87	2610
10/87	29	911	40	1240	54	1674
11/87	159	4770	40	1200	45	1350
12/87	790	24490	40	1240	164	5084
1/88	1478	45818	34	1054	38	1178
2/88	1421	41209	60	1740	42	1218
3/88	1314	40734	<40	<1240	84	2604
4/88	723	21690	<39	<1170	199	5970
5/88	302	9362				
6/88	45	1350	<37	<1110	118	3540

Fort Sherman Open Exposure Site

Month	Saltfall (mg/m²) Daily	Saltfall (mg/m²) Total	Sulfur Dioxide (mg/m²) Daily	Sulfur Dioxide (mg/m²) Total	Nitrogen Oxides (ug/m²) Daily	Nitrogen Oxides (ug/m²) Total
7/86	16.2	502	41	1271	88	2728
8/86	8.0	248	41	1271	116	3596
9/86	3.7	111	40	1200	58	1740
10/86	14.1	437	37	1147	90	2790
11/86	12.8	384	37	1110	44	1320
12/86	25.2	781	41	1271	239	7409
1/87	35.1	1088	41	1271	115	3565
2/87	40.8	1142	30	840	86	2408
3/87	37.2	1153	93	2883	128	3968
4/87	20.8	624	85	2550	123	3690
5/87	17.9	555	42	1302	117	3627
6/87	13.3	399	49	1470	131	3930
7/87	14.9	462	55	1705	184	5704
8/87	9.0	279	36	1116	61	1891
9/87	12.6	378	37	1110	99	2970
10/87	7.8	242	47	1457	54	1674
11/87	11.2	336	46	1380	155	4650
12/87	39.4	1221	40	1240	192	5952
1/88	43.6	1352	34	1054	31	961
2/88	43.1	1250	125	3625	40	1160
3/88	33.5	1039	<40	<1240	71	2201
4/88	27.8	834	<39	<1170	120	3600
5/88	32.6	1011				
6/88	20.1	603	<37	<1110	138	4140

Fort Sherman Forest (Skunk Hollow) Exposure Site

	Saltfall (mg/m^2)		Sulfur Dioxide (mg/m^2)		Nitrogen Oxides (ug/m^2)	
Month	Daily	Total	Daily	Total	Daily	Total
7/86	3.5	109	41	1271	179	5549
8/86	5.4	167	48	1488	154	4774
9/86	1.5	45	40	1200	84	2520
10/86	4.3	133	37	1147	122	3782
11/86	2.7	81	37	1110	110	3300
12/86	11.1	344	41	1271	154	4774
1/87	12.0	372	35	1085	180	5580
2/87	13.6	381	30	840	185	5180
3/87	24.8	769	82	2542	334	10354
4/87	4.6	138	82	2460	153	4590
5/87	6.9	214	48	1488	199	6169
6/87	7.4	222	48	1440	143	4290
7/87	3.9	121	50	1550	82	2542
8/87	2.5	78	36	1116	89	2759
9/87	6.3	189	46	1380	163	4890
10/87	2.8	87	49	1519	61	1891
11/87	6.6	198	79	2370	146	4380
12/87	10.9	338	40	1240	361	11191
1/88	6.9	214	34	1054	87	2697
2/88	11.6	336	<40	<1160	88	2552
3/88	14.4	446	<40	<1240	170	5270
4/88	15.3	459	<39	<1170	190	5700
5/88	10.8	335				
6/88	12.3	369	<37	<1110	222	6660

Kure Beach 25-meter Lot

	Saltfall (mg/m^2)		Sulfur Dioxide (mg/m^2)		Nitrogen Oxides (ug/m^2)	
Month	**Daily**	**Total**	**Daily**	**Total**	**Daily**	**Total**
7/86	408	12648	48	1488	272	8432
8/86	535	16585	42	1302	265	8215
9/86	293	8790	44	1320	576	17280
10/86	286	8866	44	1364	131	4061
11/86	1106	33180	46	1380	507	15210
12/86	541	16771	47	1457	1077	33387
1/87	201	6231	43	1333	547	16957
2/87	780	21840	41	1148	311	8708
3/87	191	5921	58	1798	159	4929
4/87	152	4560	95	2850	193	5790
5/87	156	4836	48	1488	229	7099
6/87	102	3060	48	1440	203	6090
7/87	123	3813	41	1271	178	5518
8/87	313	9703	48	1488	148	4588
9/87	411	12330	39	1170	215	6450
10/87	362	11222	46	1426	350	10850
11/87	194	5820	85	2550	408	12240
12/87	125	3875	37	1147	363	11253
1/88	297	9207	37	1147	120	3720
2/88	145	4205	<41	<1189	150	4350
3/88	399	12369	<39	<1209	108	3348
4/88	257	7710	41	1230	204	6120
5/88	197	6107				
6/88	209	6270	<39	<1170	101	3030

Kure Beach 250-meter Lot

Month	Saltfall (mg/m^2) Daily	Saltfall (mg/m^2) Total	Sulfur Dioxide (mg/m^2) Daily	Sulfur Dioxide (mg/m^2) Total	Nitrogen Oxides (ug/m^2) Daily	Nitrogen Oxides (ug/m^2) Total
7/86	144	4464	46	1426	417	12927
8/86	77	2387	36	1116	57	1767
9/86	61	1830	40	1200	656	19680
10/86	73	2263	48	1488		
11/86	127	3810	36	1080	472	14160
12/86	123	3813	47	1457	833	25823
1/87	152	4712	43	1333	513	15903
2/87	191	5348	35	980	244	6832
3/87	41	1271	61	1891	169	5239
4/87	44	1335	88	2640	155	4650
5/87	34	1073	42	1302	147	4557
6/87	38	1143	46	1380	180	5400
7/87	55	1705	47	1457	164	5084
8/87	84	2604	44	1364	136	4216
9/87	121	3630	39	1170	154	4620
10/87	108	3348	53	1643	189	5859
11/87	61	1830	73	2190	298	8940
12/87	42	1290	37	1147	191	5921
1/88	83	2573	37	1147	84	2604
2/88	53	1537	<41	<1189	88	2552
3/88	98	3038	<39	<1209	104	3224
4/88	109	3270	46	1380	156	4680
5/88	66	2046				
6/88	68	2040	39	<1170	88	2640

APPENDIX K. METEOROLOGICAL AND ATMOSPHERIC CONTAMINANT GRAPHIC DATA

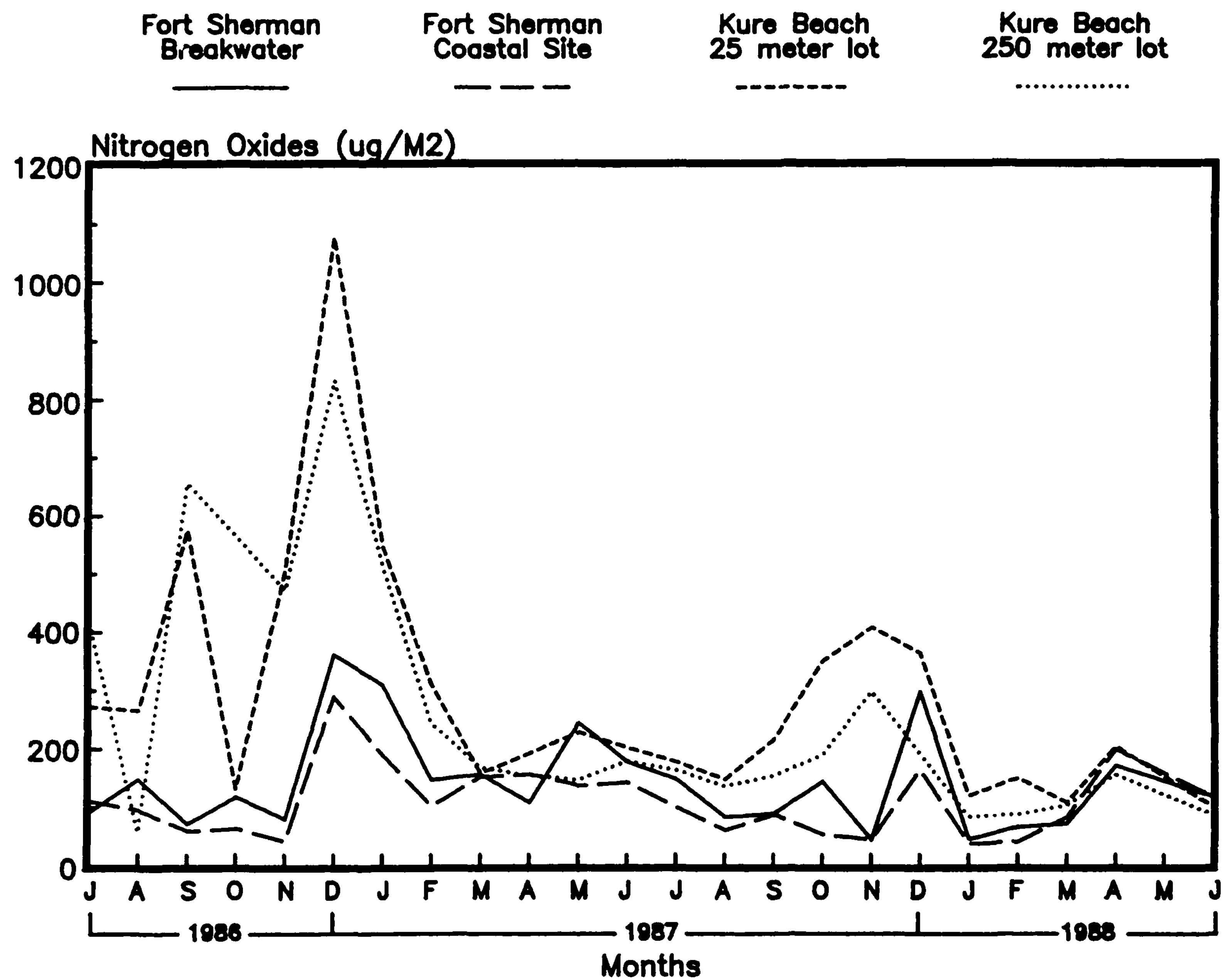

Figure K-1. Nitrogen Oxides (ug/m^2) at Fort Sherman Breakwater, Fort Sherman Coastal, Kure Beach 25-meter, and Kure Beach 250-meter Sites.

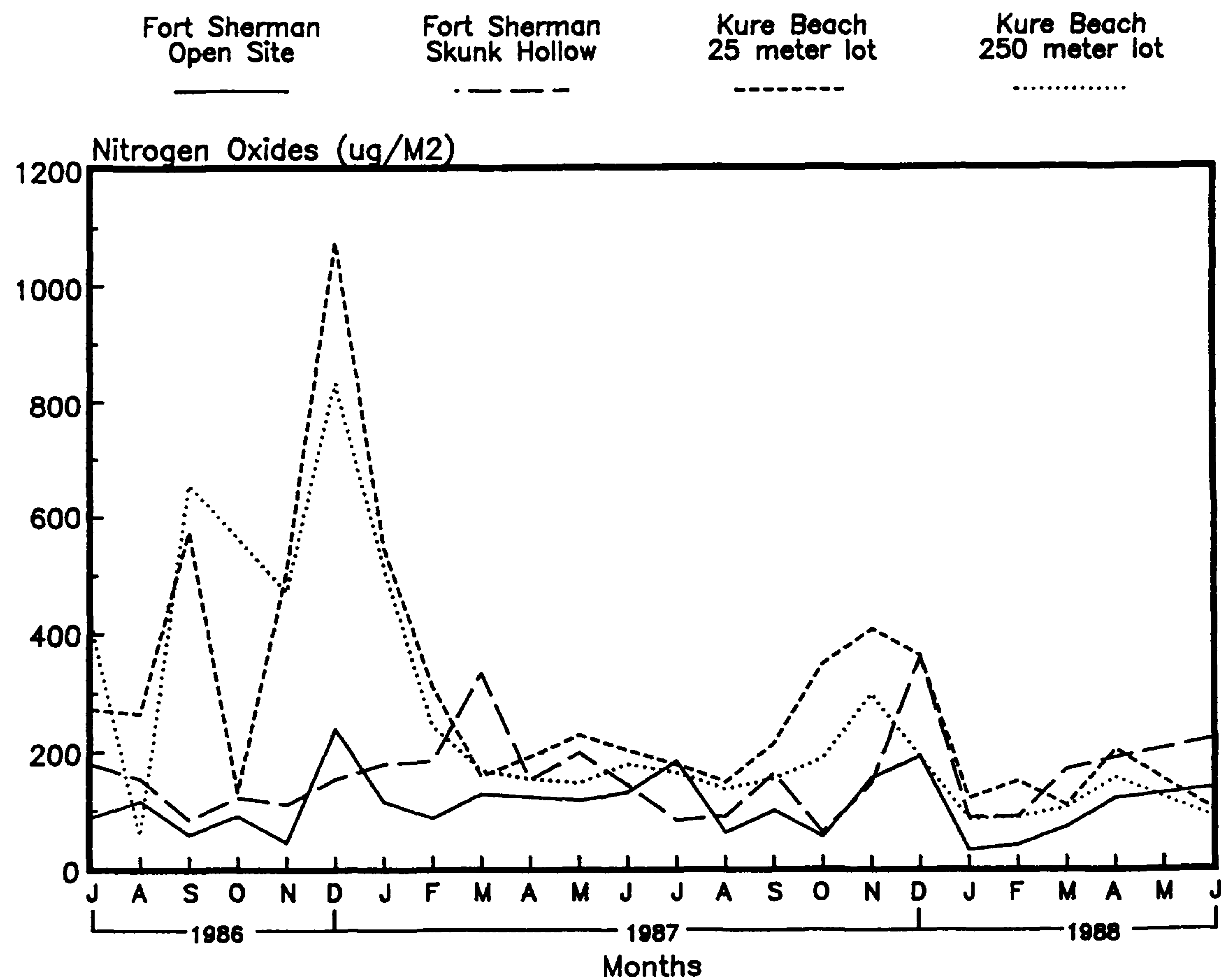

Figure K-2. Nitrogen Oxides (ug/m^2) at Fort Sherman Open, Fort Sherman Forest (Skunk Hollow), Kure Beach 25-meter, and Kure Beach 250-meter Sites.

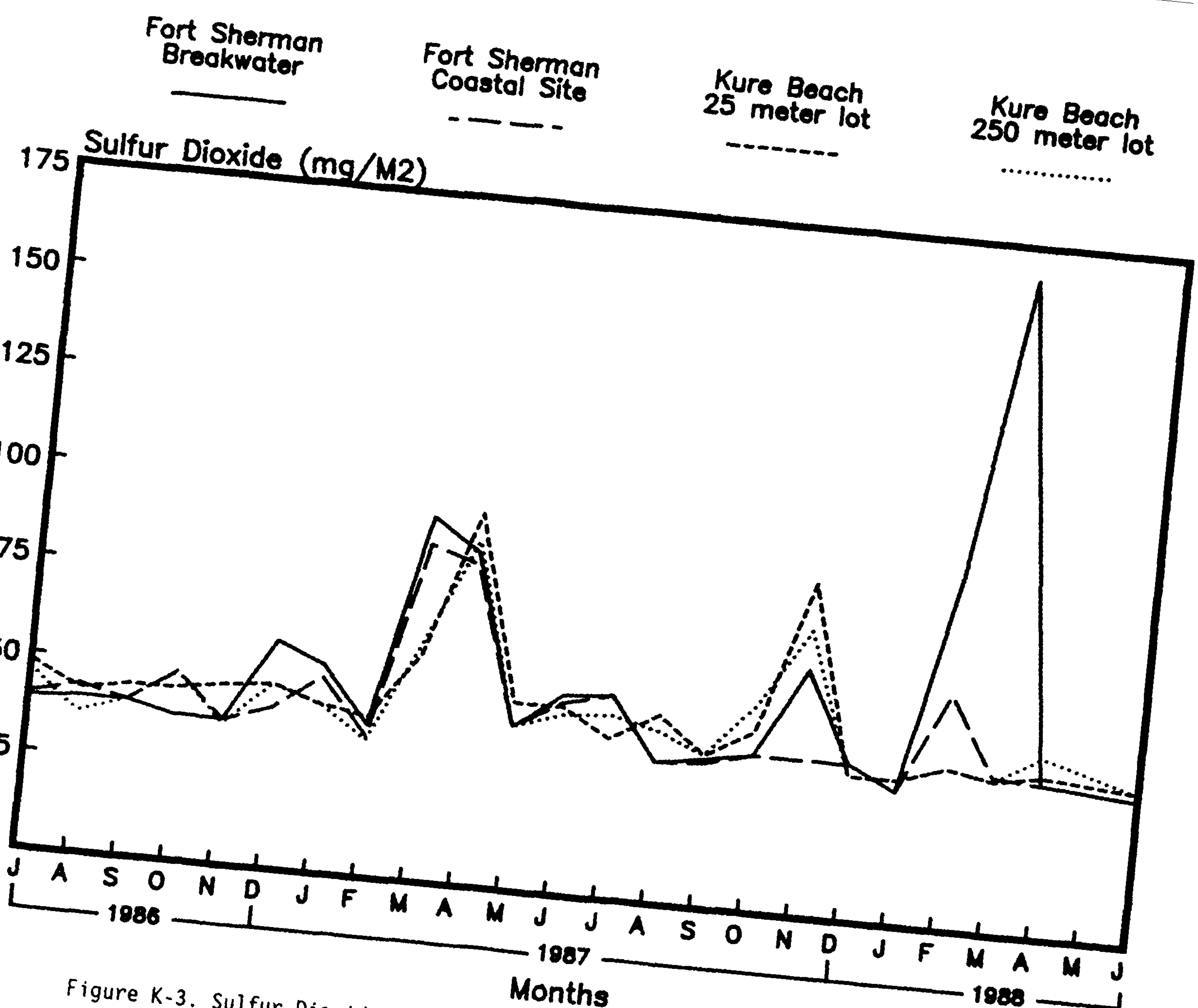

Figure K-3. Sulfur Dioxide (mg/m^2) at Fort Sherman Breakwater, Fort Sherman Coastal, Kure Beach 25-meter, and Kure Beach 250-meter Sites.

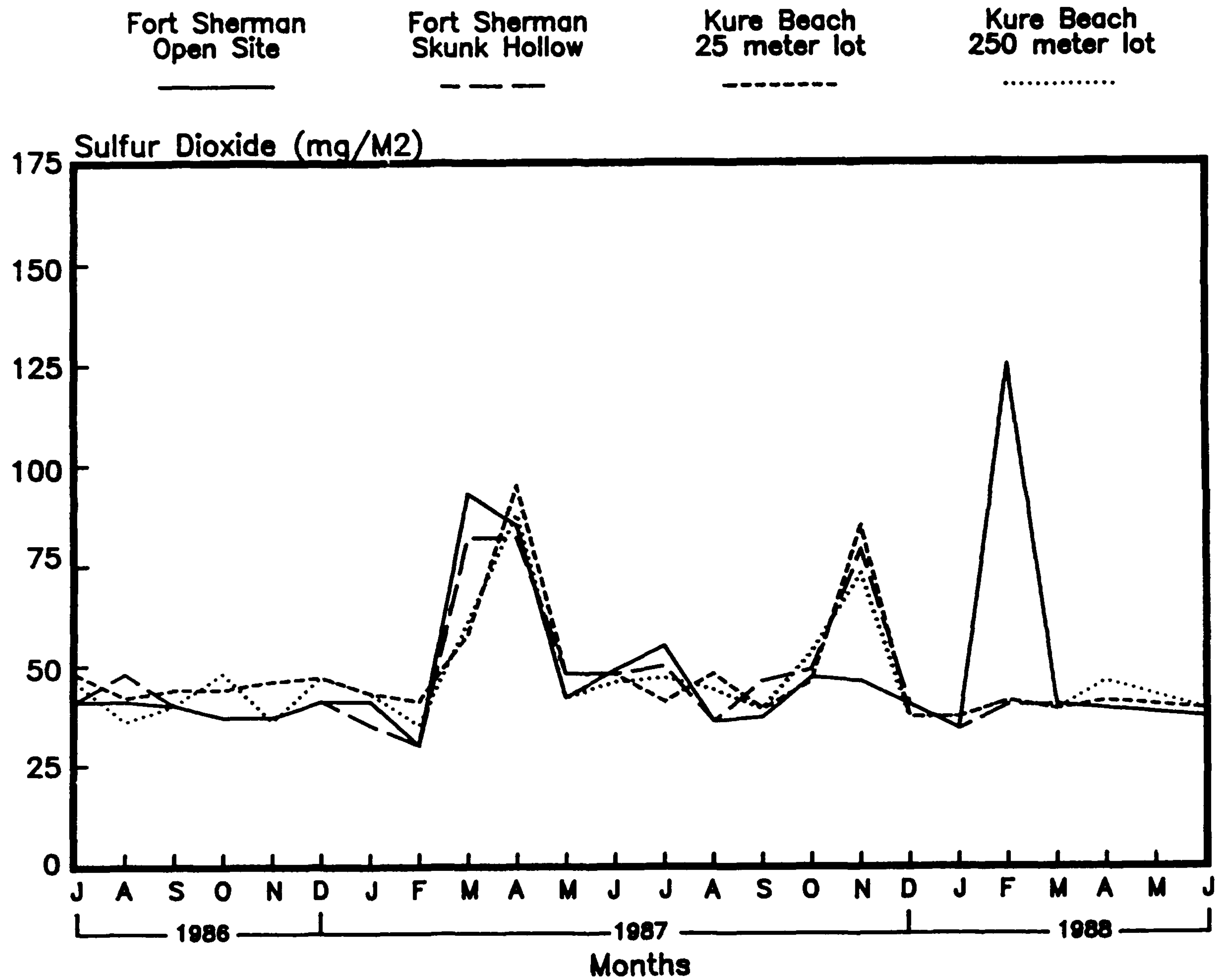

Figure K-4. Sulfur Dioxide (mg/m^2) at Fort Sherman Open, Fort Sherman Forest (Skunk Hollow), Kure Beach 25-meter, and Kure Beach 250-meter Sites.

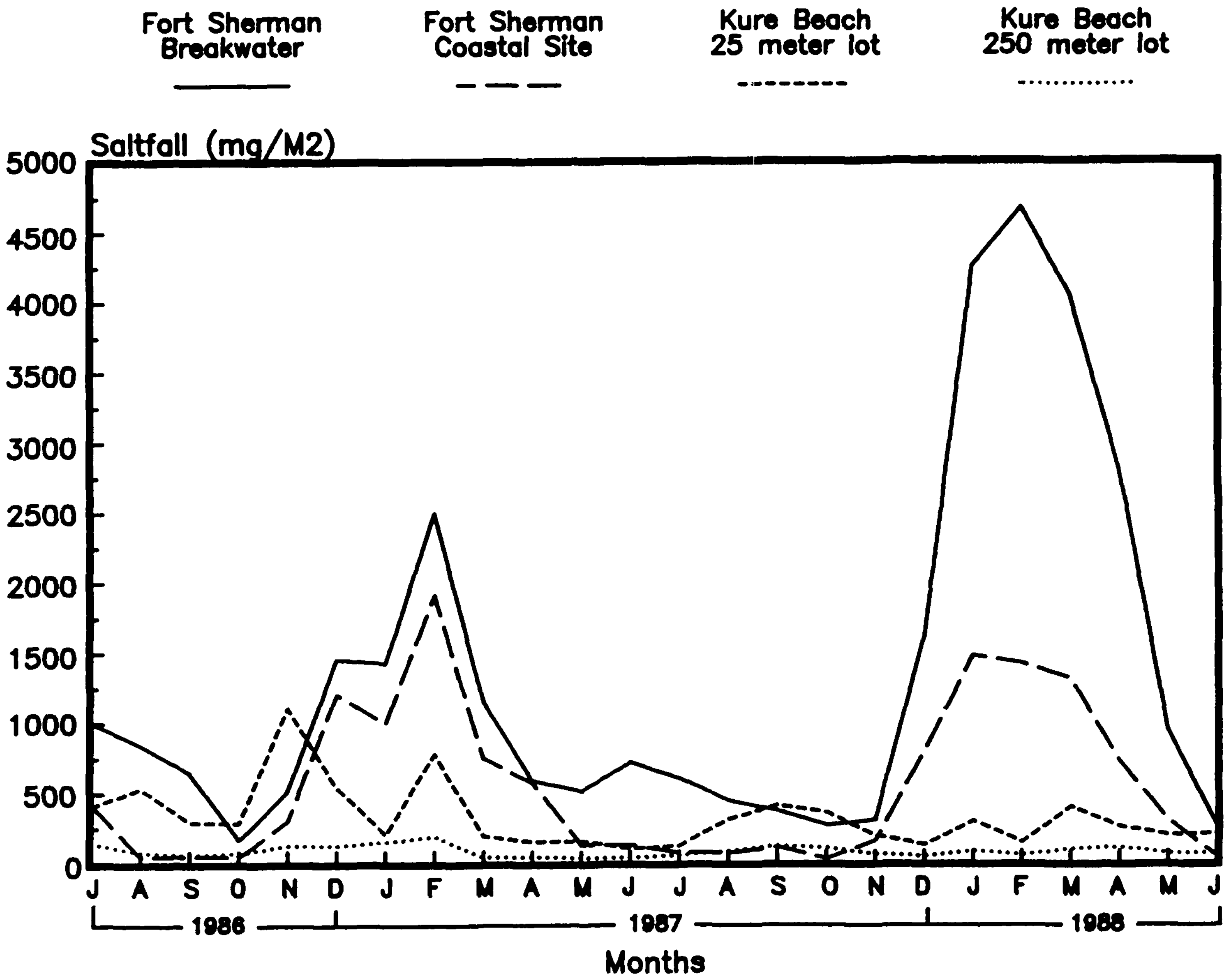

Figure K-5. Saltfall (mg/m^2) at Fort Sherman Breakwater, Fort Sherman Coastal, Kure Beach 25-meter, and Kure Beach 250-meter Sites

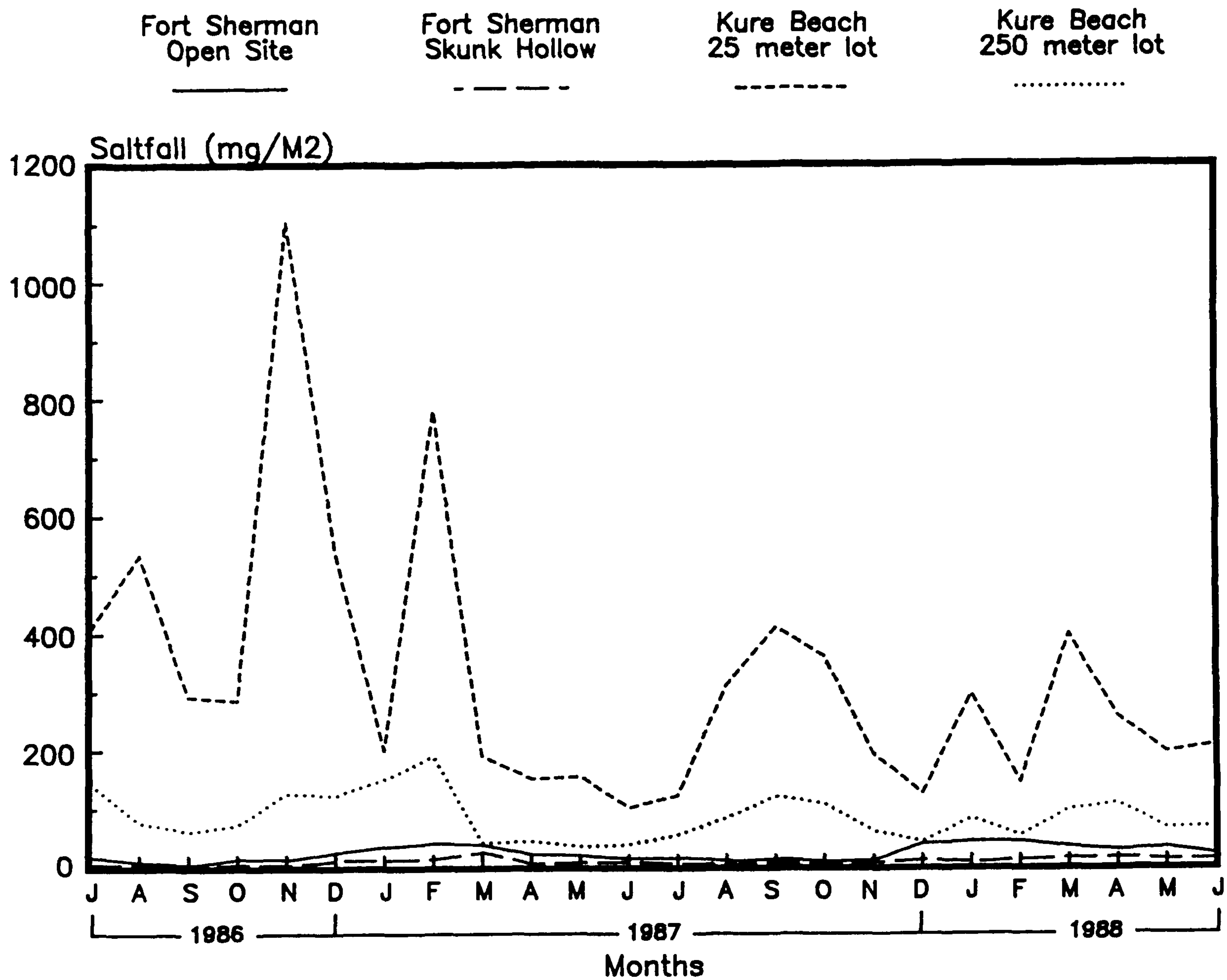

Figure K-6. Saltfall (mg/m^2) at Fort Sherman Open, Fort Sherman Forest (Skunk Hollow), Kure Beach 25-meter, and Kure Beach 250-meter Sites.
(note change in scale from figure K-5).

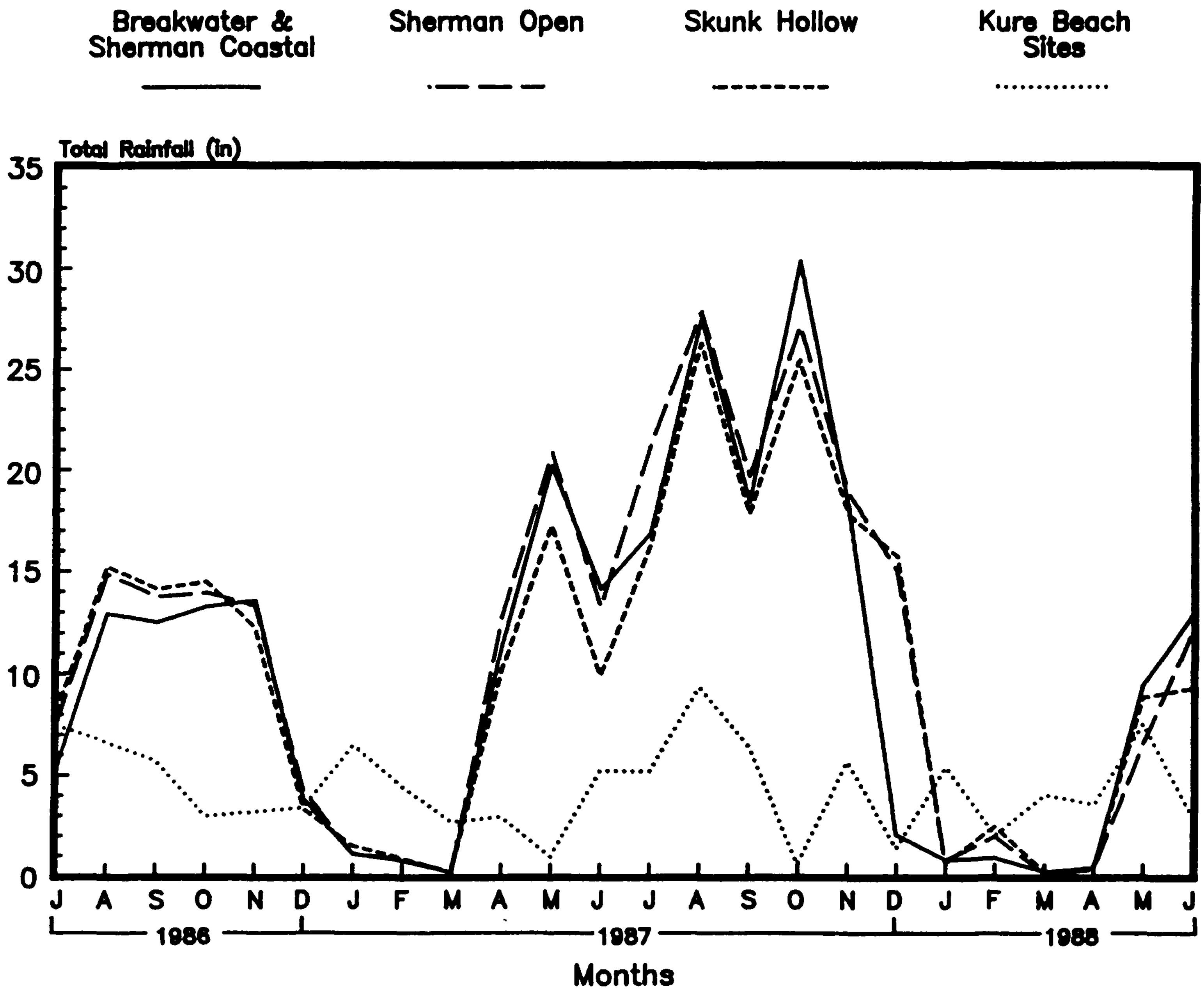

Figure K-7. Rainfall (inches) at all Sites.

APPENDIX L. GRAPHS OF CORROSION RATE

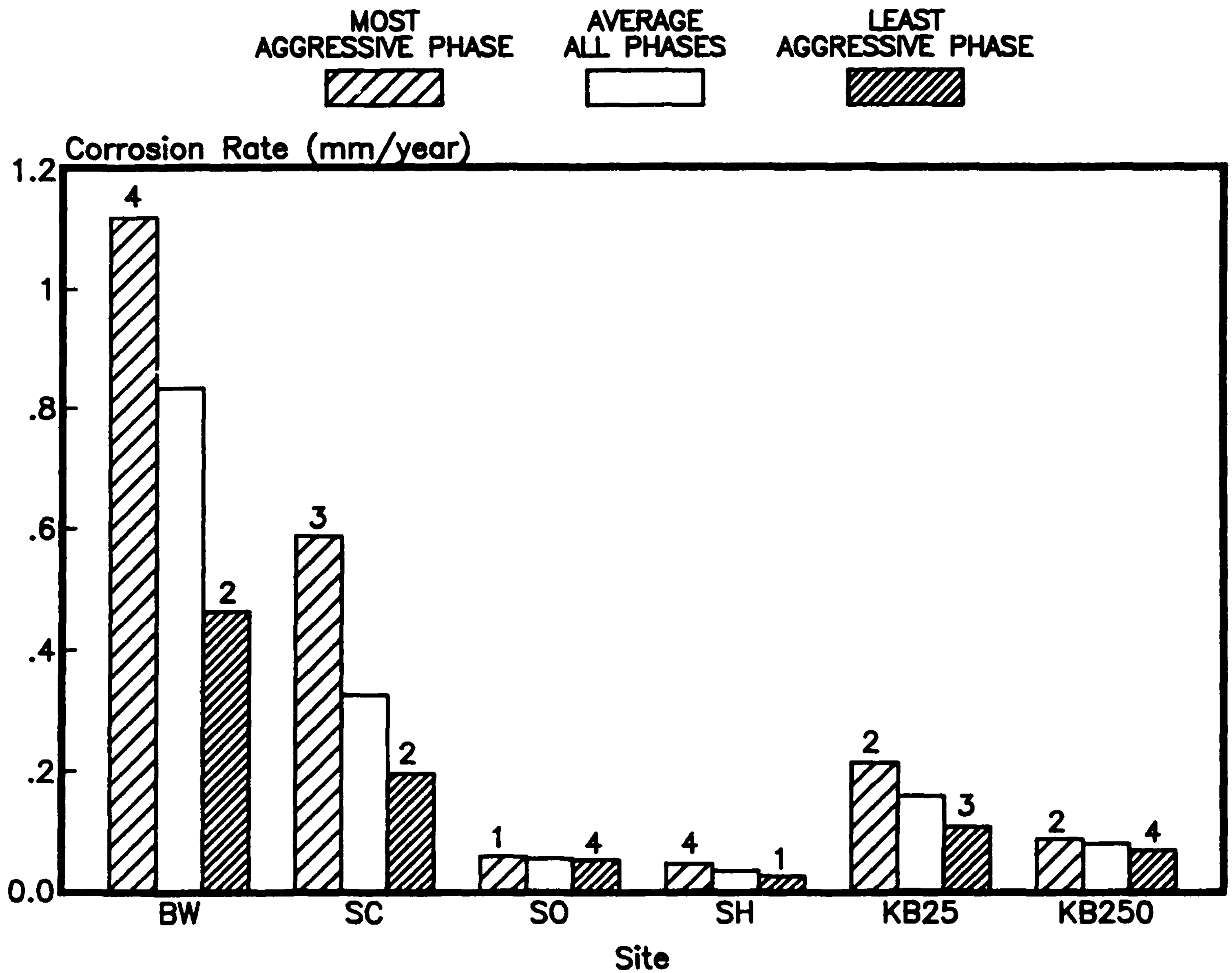

Figure L-1. Corrosion Rates at all Sites for 3-month Exposures of Iron. Numbers above bars identify phase that was most or least aggressive.

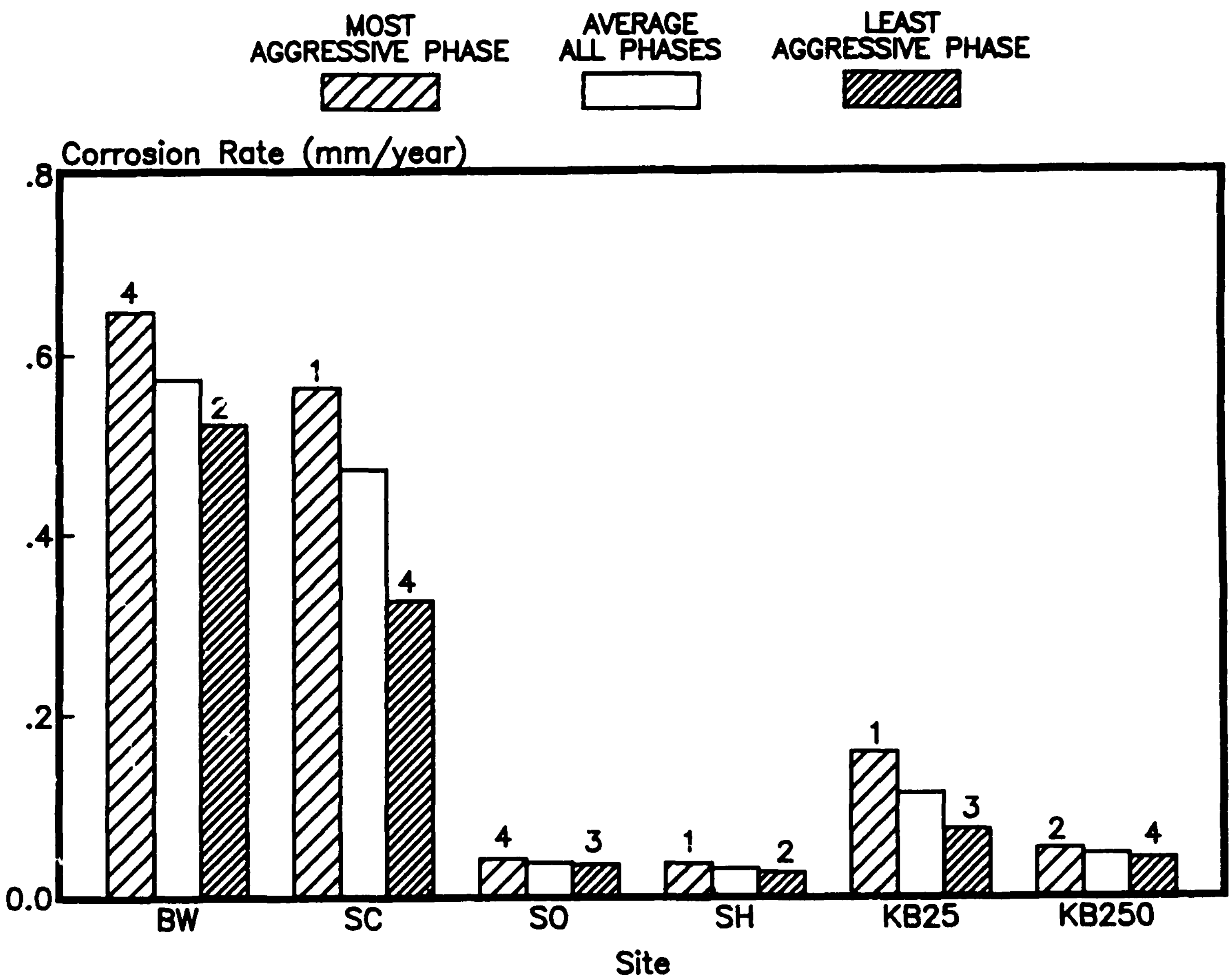

Figure L-2. Corrosion Rates at all Sites for 12-month Exposures of Iron (Phase 5 excluded). Numbers above bars identify phase that was most or least aggressive.

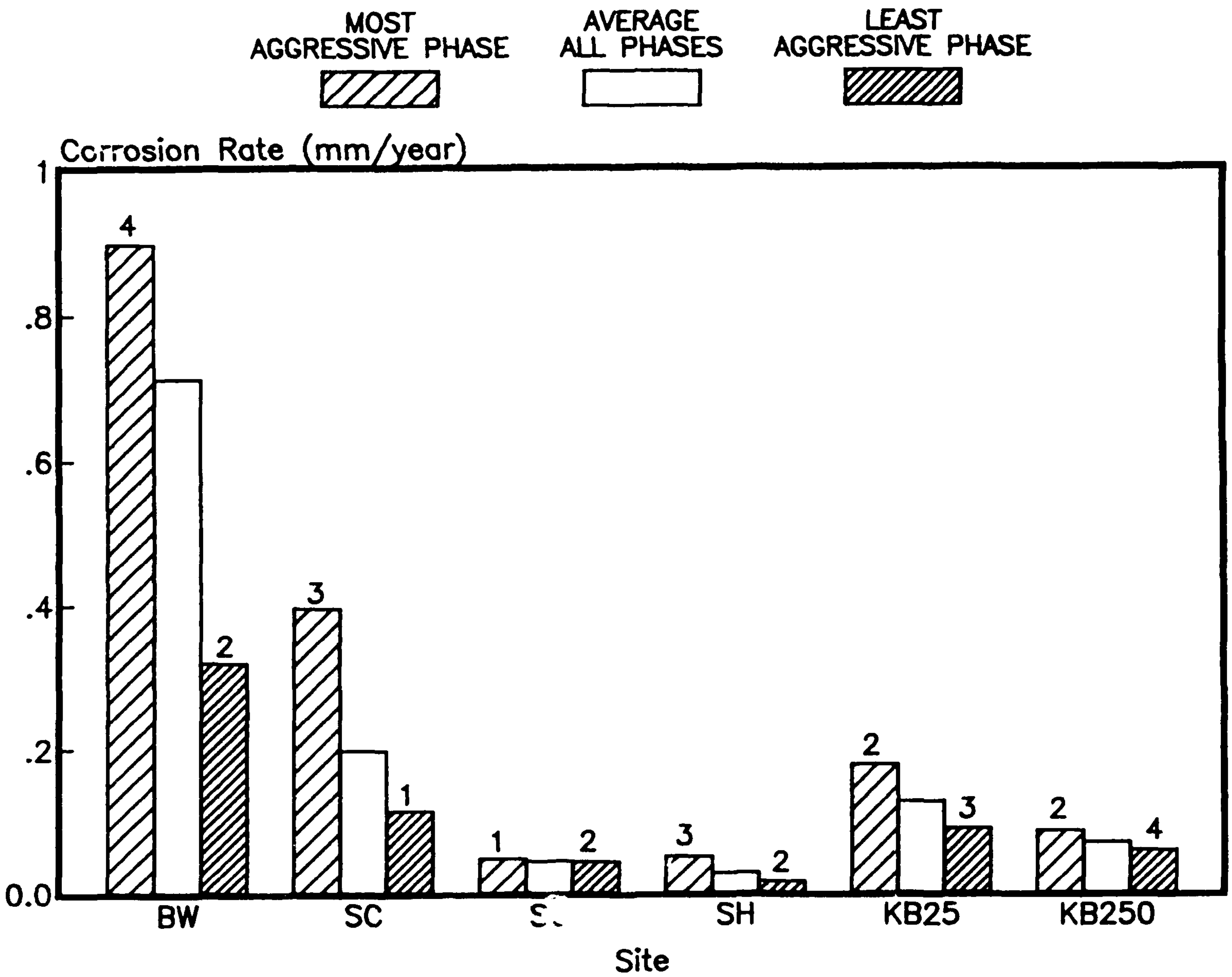

Figure L-3. Corrosion Rates at all Sites for 3-month Exposures of Steel. Numbers above bars identify phase that was most or least aggressive.

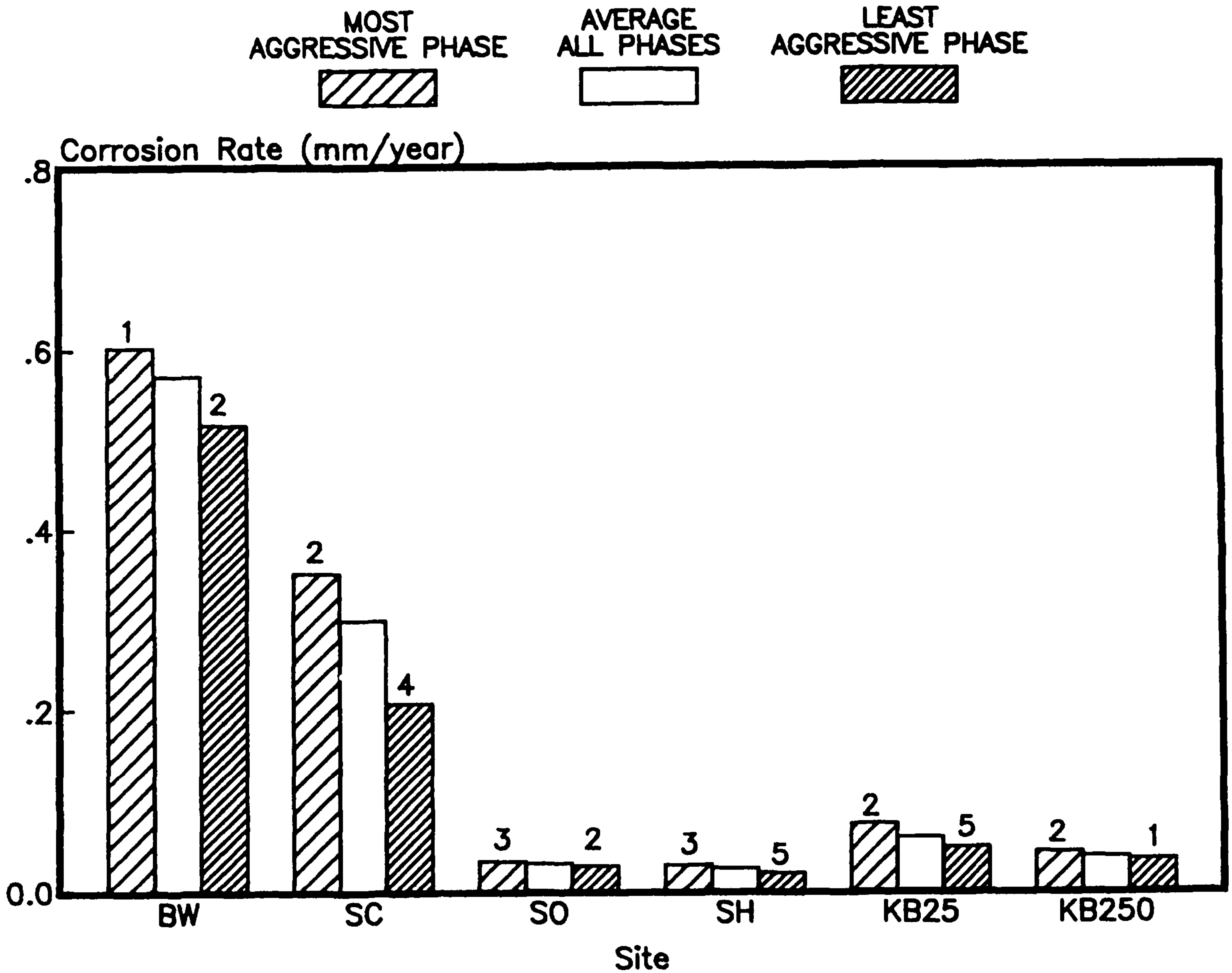

Figure L-4. Corrosion Rates at all Sites for 12-month Exposures of Steel. Numbers above bars identify phase that was most or least aggressive.

APPENDIX M. GRAPHS COMPARING EXPOSURE PHASES VERSUS CORROSION RATE

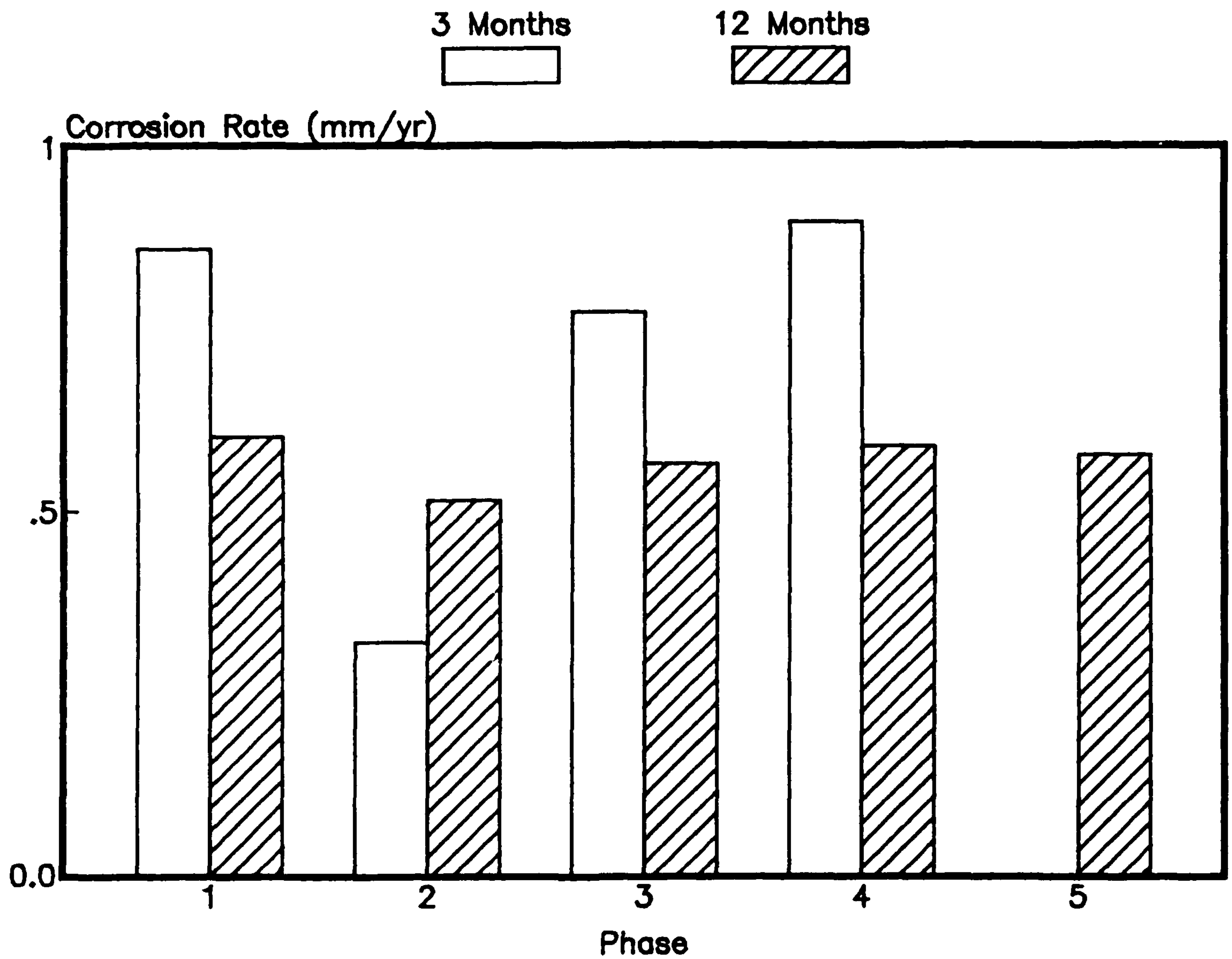

Figure M-1. Corrosion Rate for Steel at the Fort Sherman Breakwater Exposure Site, by Phase and Exposure Period.

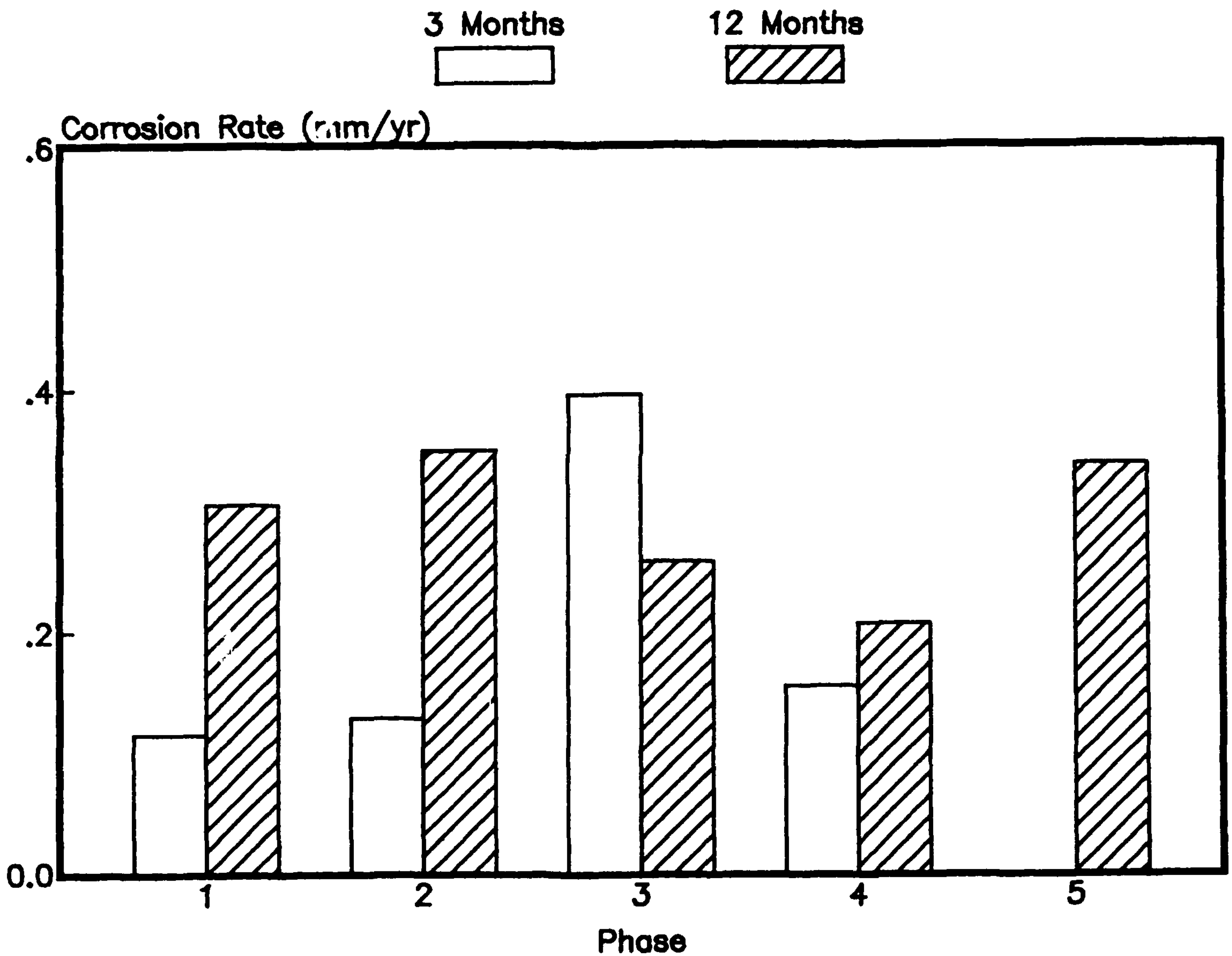

Figure M-2. Corrosion Rate for Steel at the Fort Sherman Coastal Exposure Site, by Phase and Exposure Period.

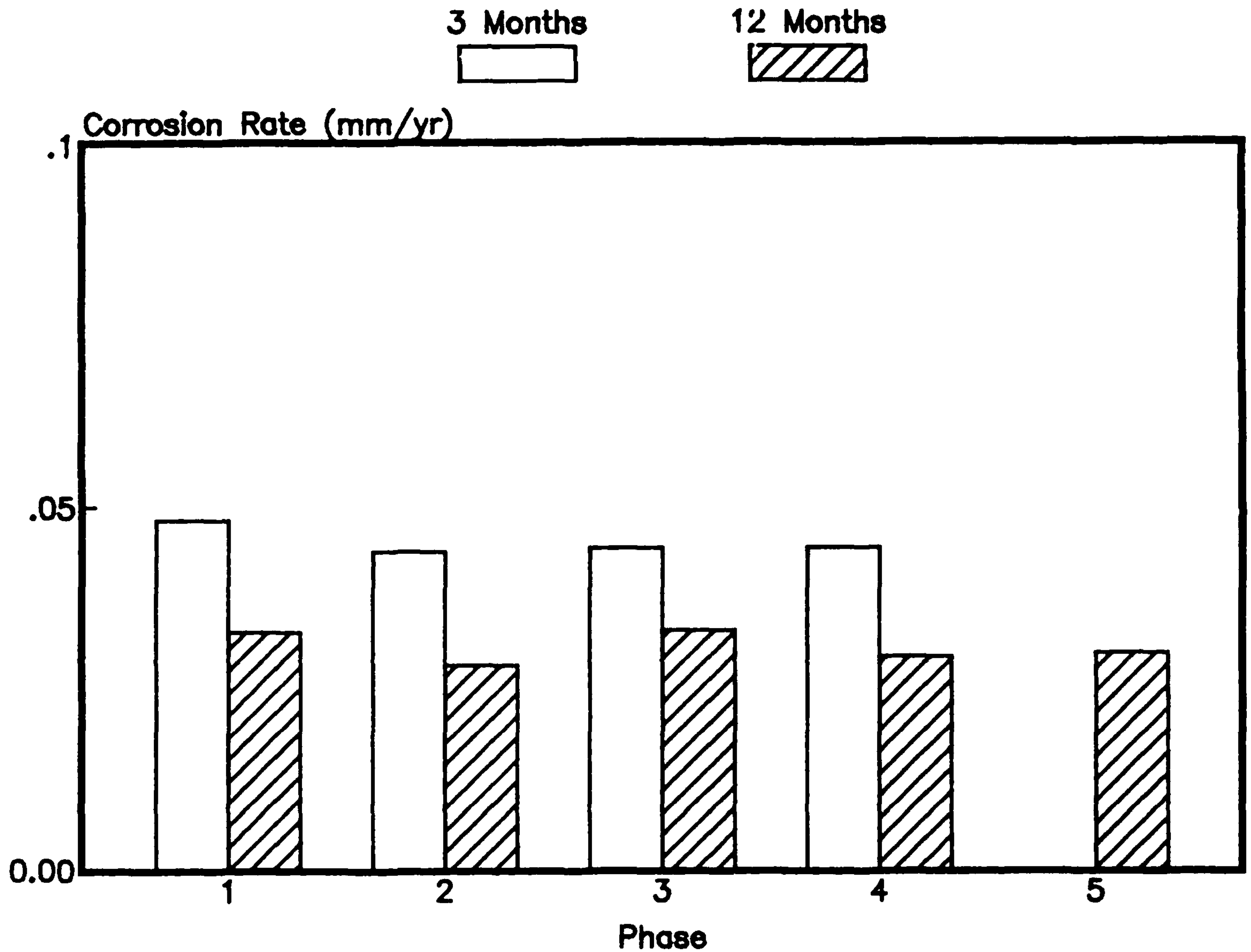

Figure M-3. Corrosion Rate for Steel at the Fort Sherman Open Exposure Site, by Phase and Exposure Period.

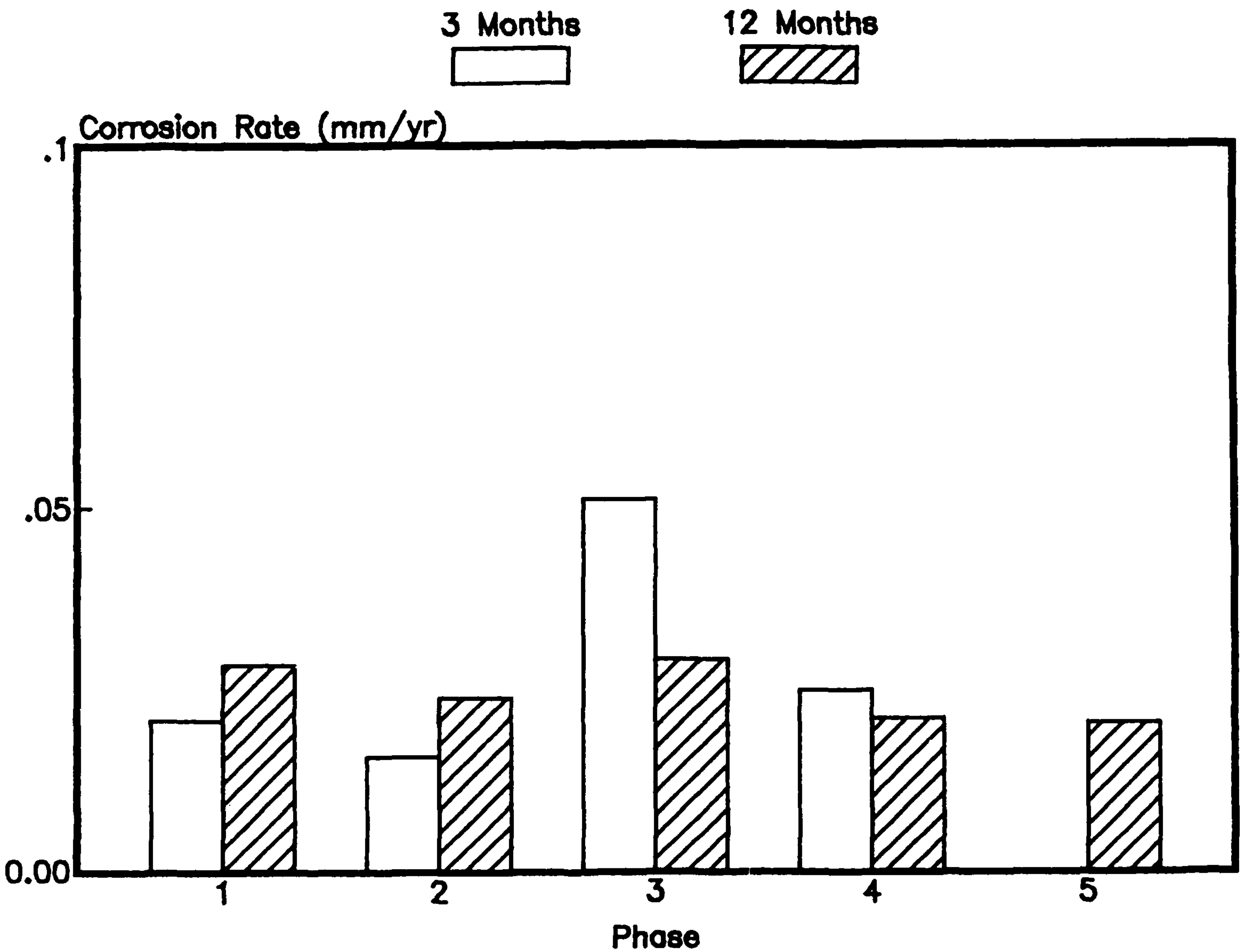

Figure M-4. Corrosion Rate for Steel at the Fort Sherman Forest (Skunk Hollow) Exposure Site, by Phase and Exposure Period.

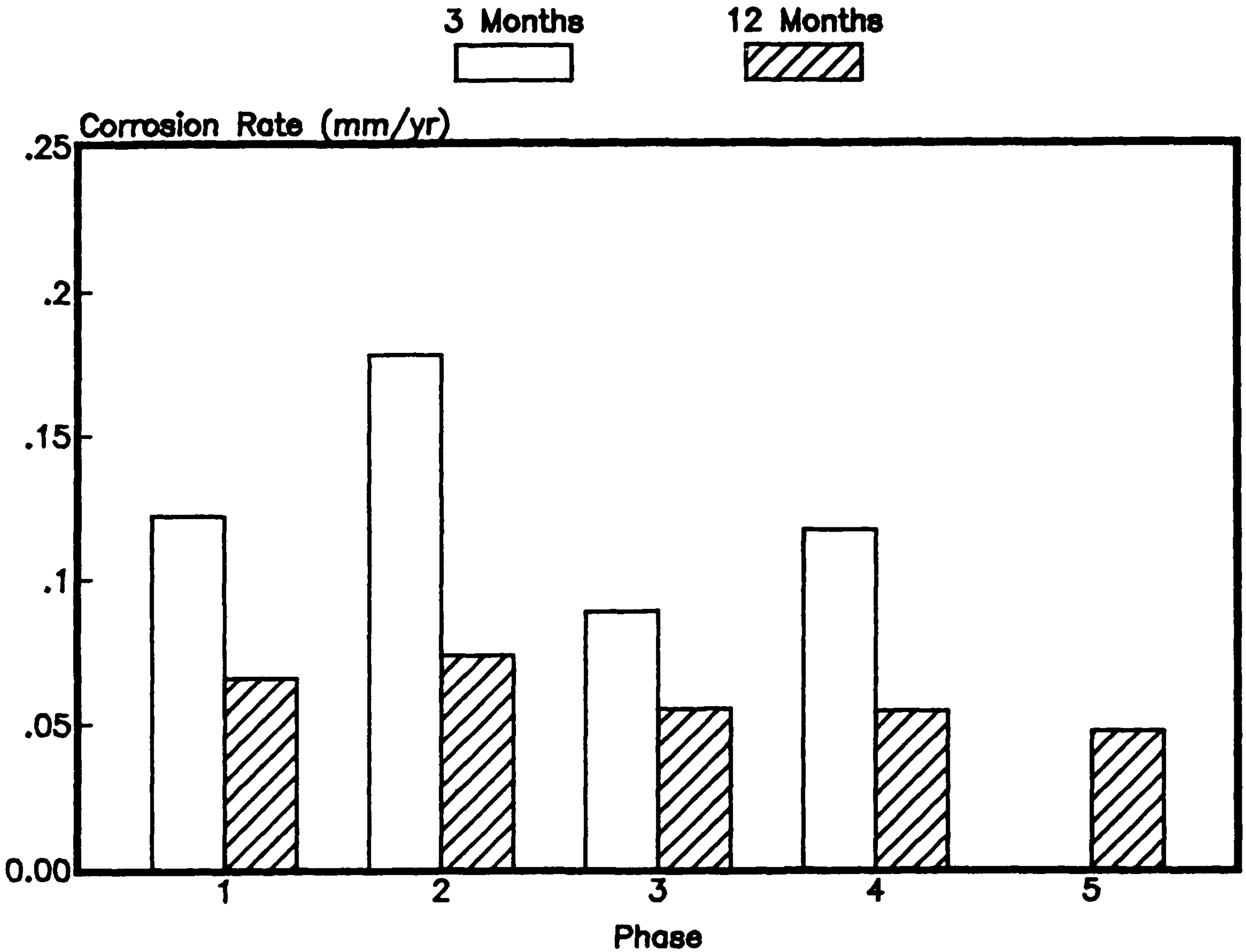

Figure M-5. Corrosion Rate for Steel at the Kure Beach 25-meter Lot, by Phase and Exposure Period.

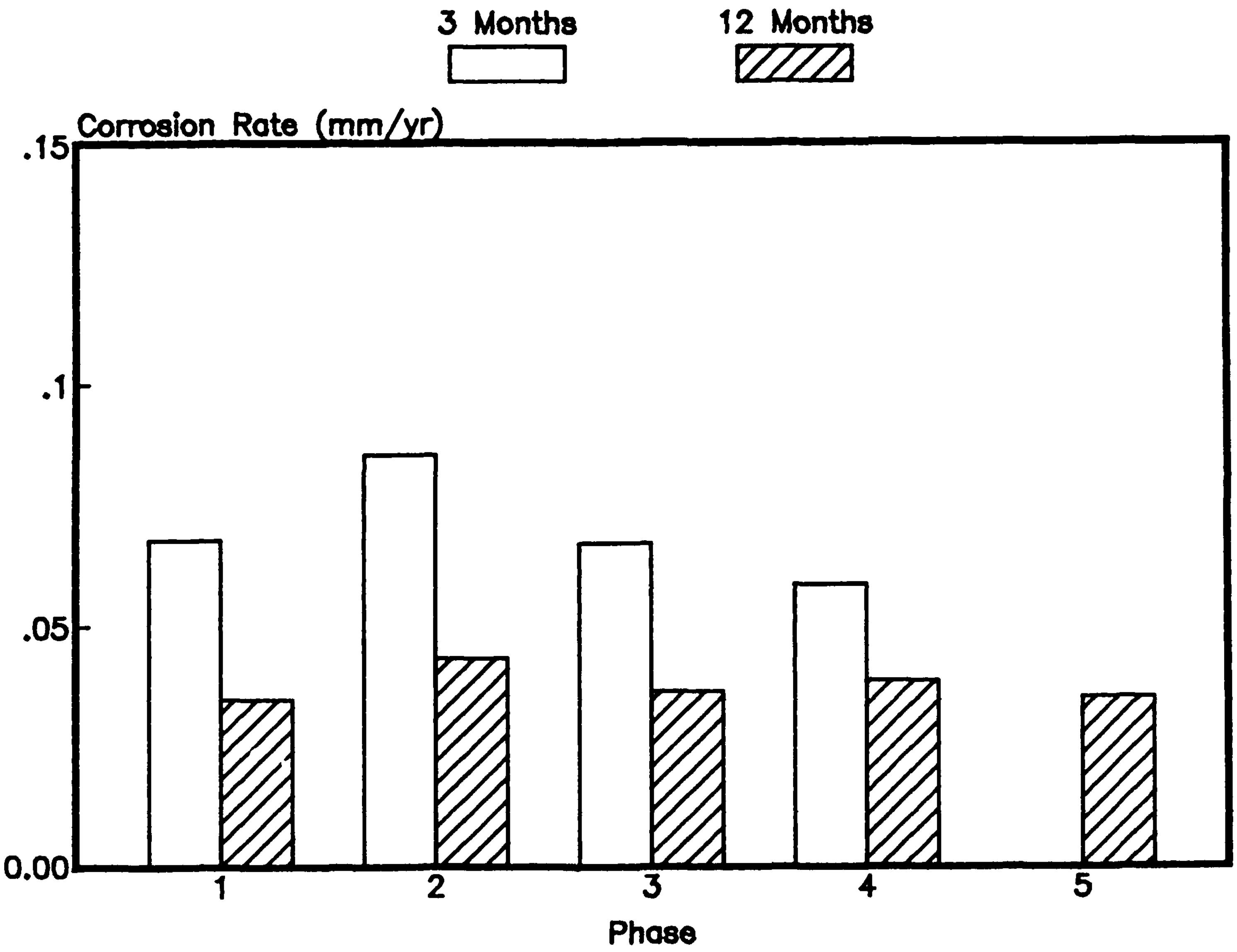

Figure M-6. Corrosion Rate for Steel at the Kure Beach 250-meter Lot, by Phase and Exposure Period.

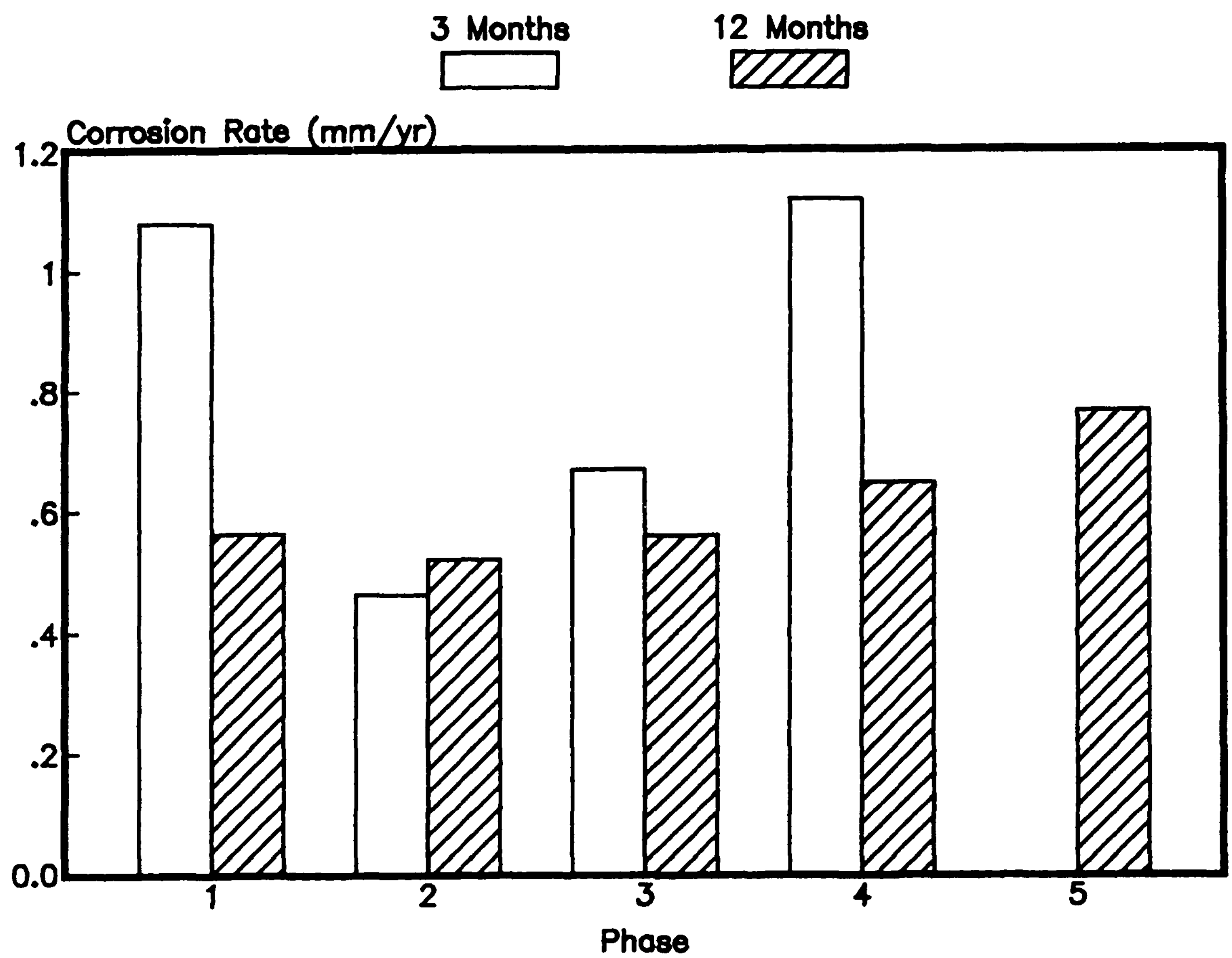

Figure M-7. Corrosion Rate for Iron at the Fort Sherman Breakwater Exposure Site, by Phase and Exposure Period.

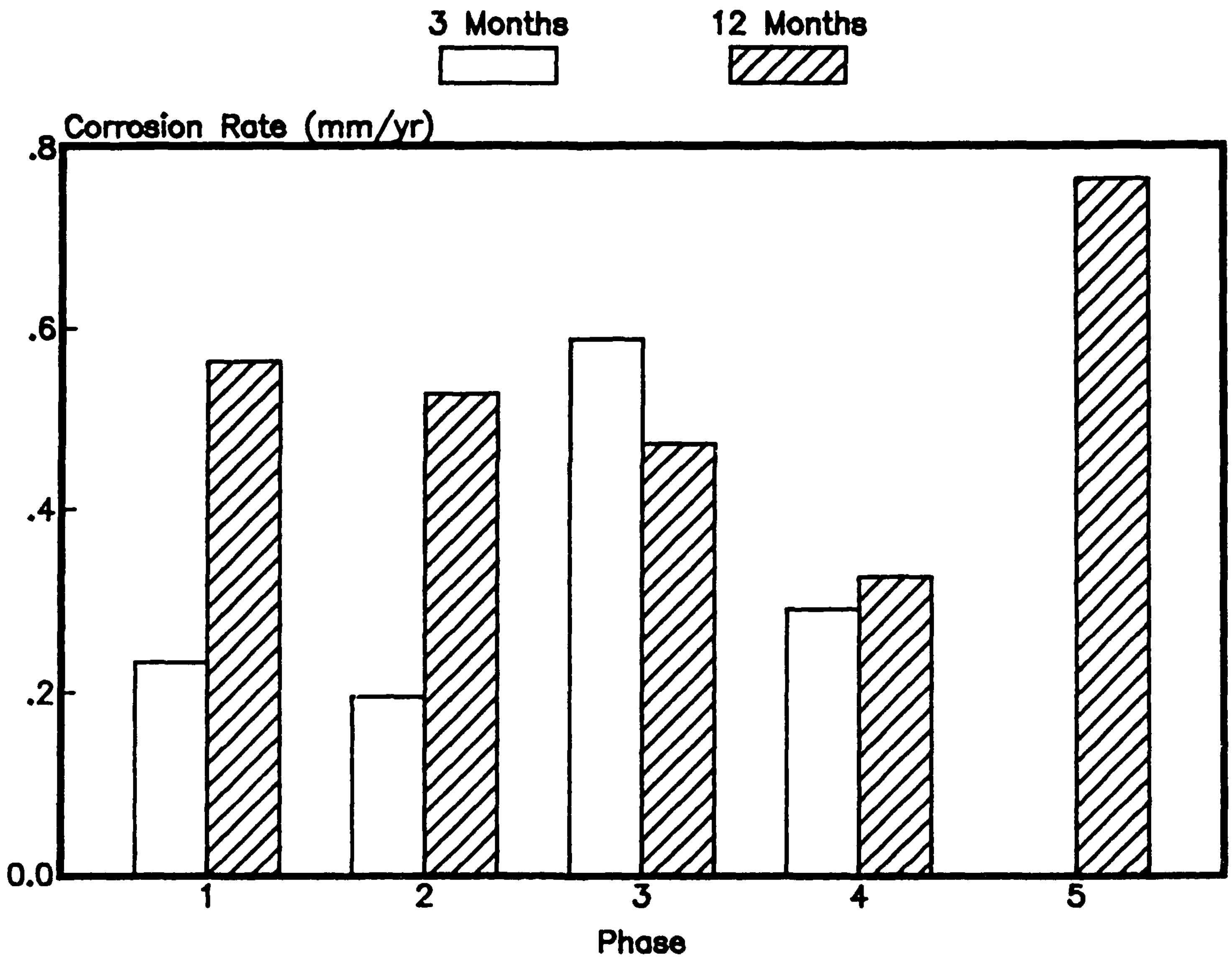

Figure M-8. Corrosion Rate for Iron at the Fort Sherman Coastal Exposure Site, by Phase and Exposure Period.

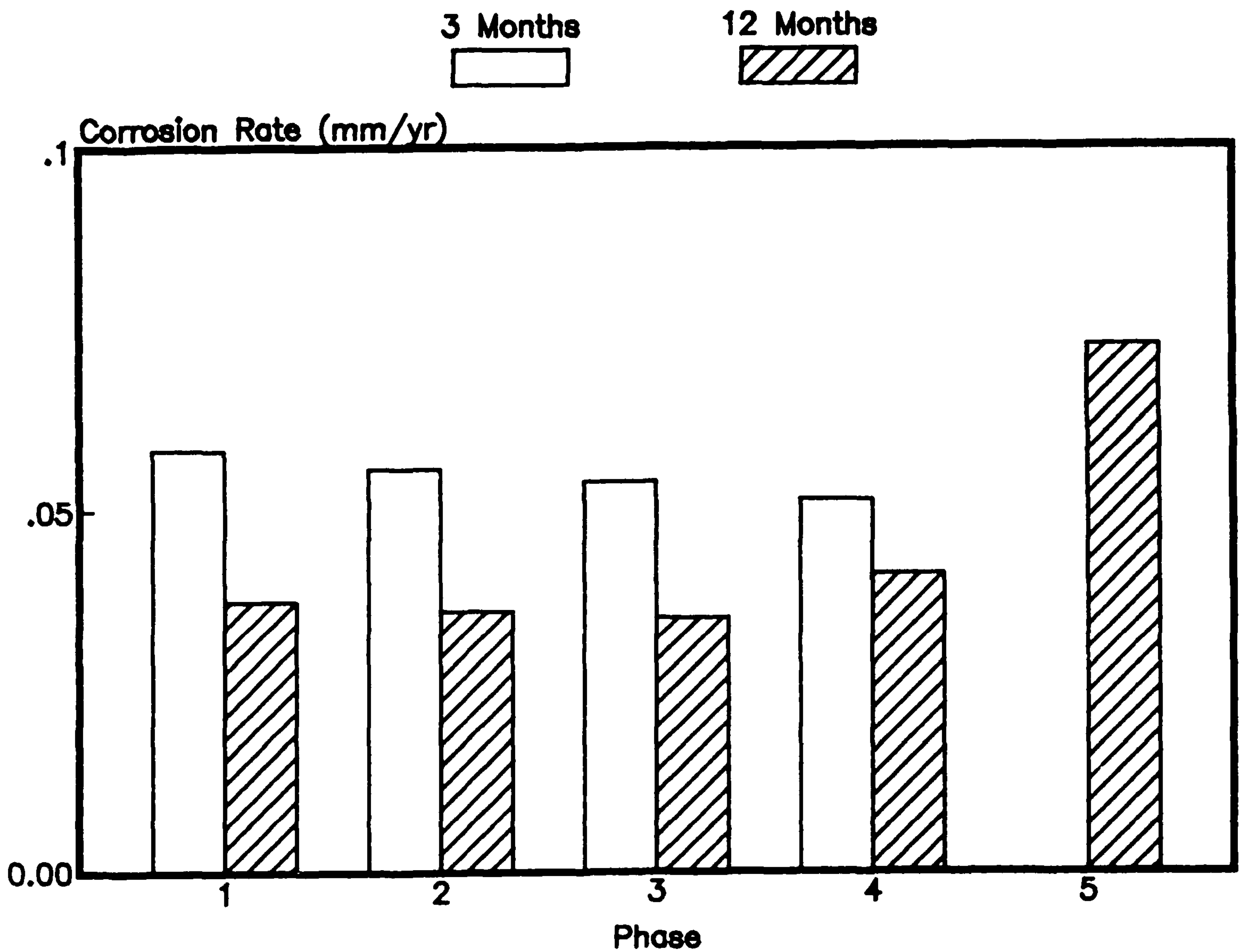

Figure M-9. Corrosion Rate for Iron at the Fort Sherman Open Exposure Site, by Phase and Exposure Period.

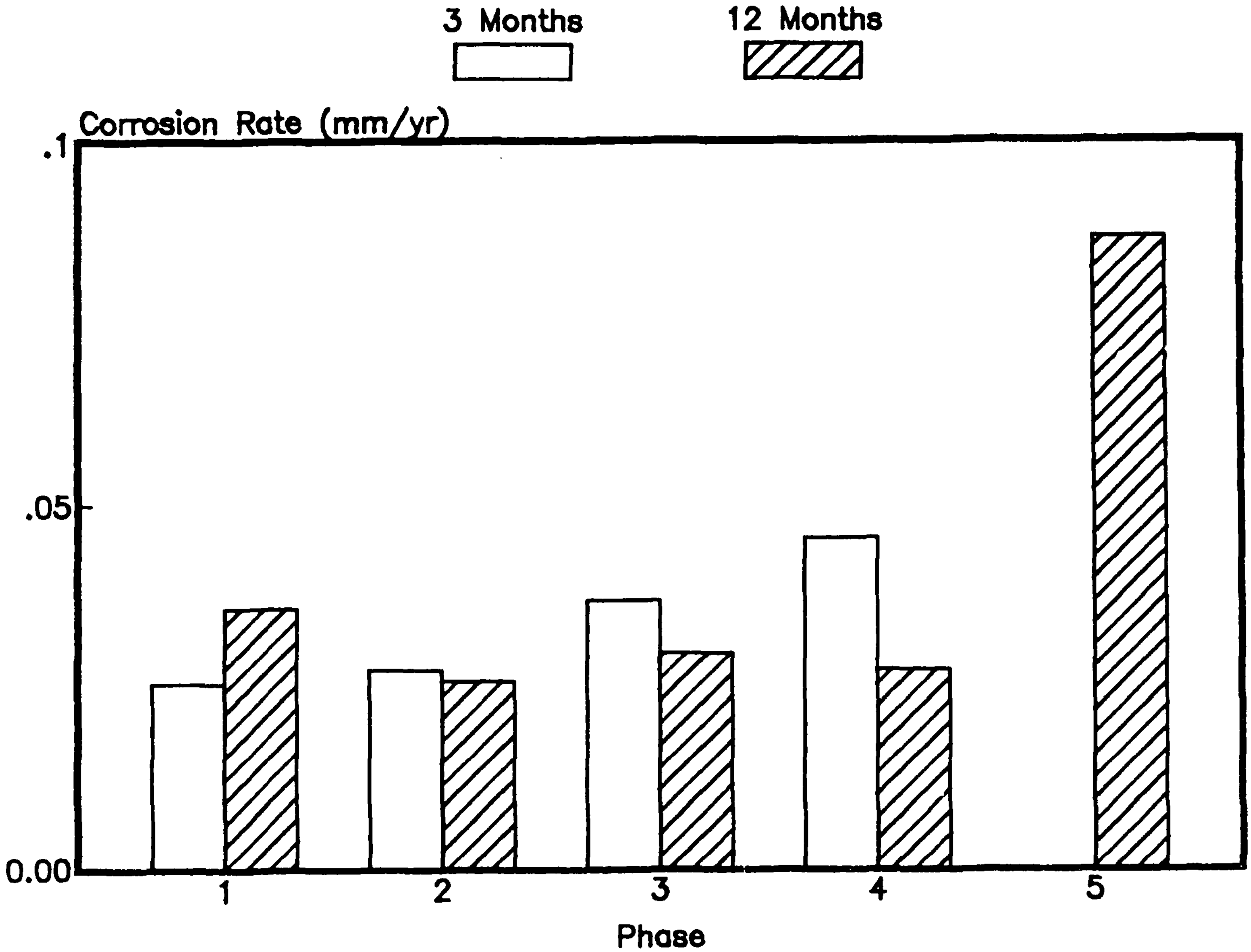

Figure M-10. Corrosion Rate for Iron at the Fort Sherman Forest (Skunk Hollow) Exposure Site, by Phase and Exposure Period.

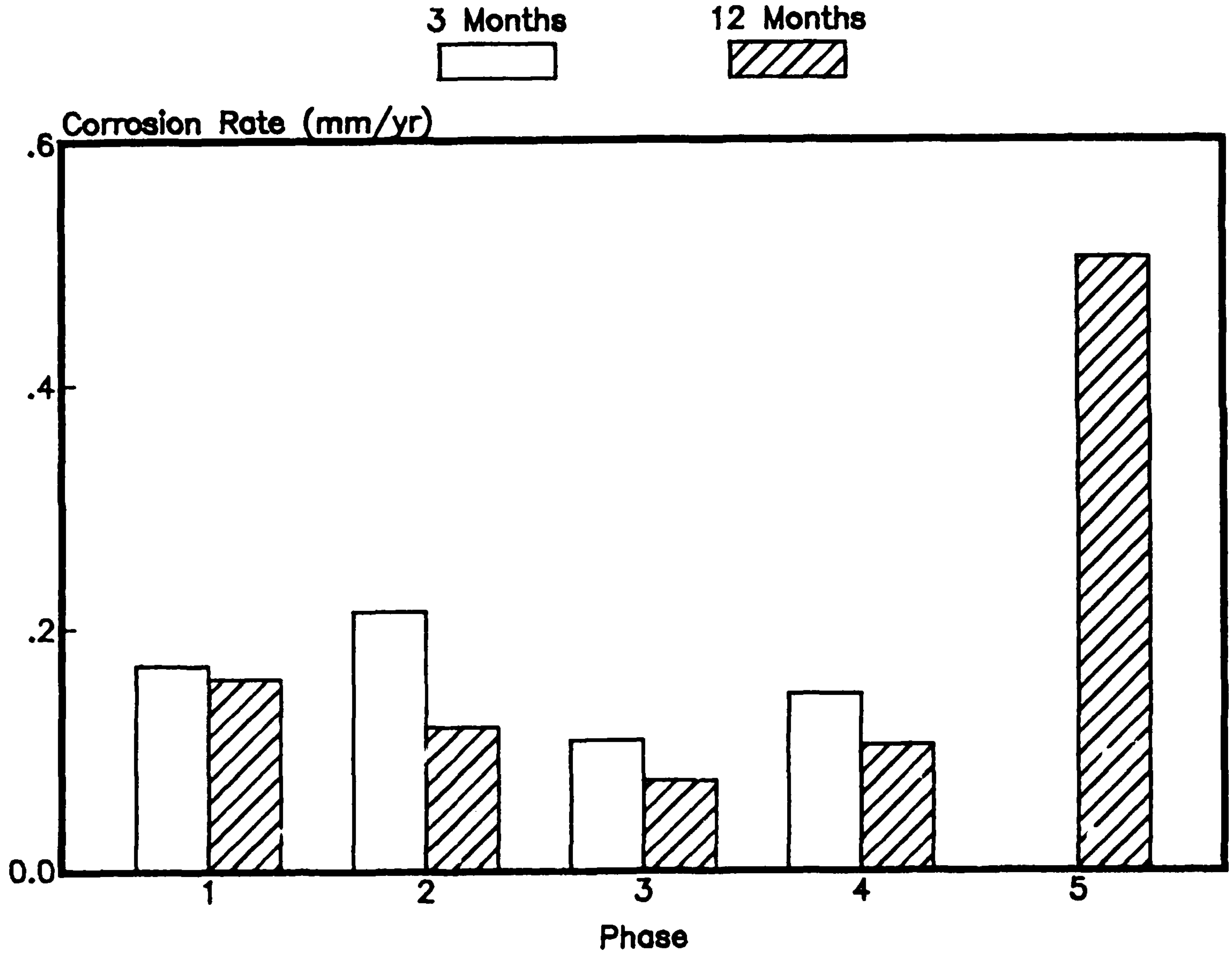

Figure M-11. Corrosion Rate for Iron at the Kure Beach 25-meter Lot, by Phase and Exposure Period.

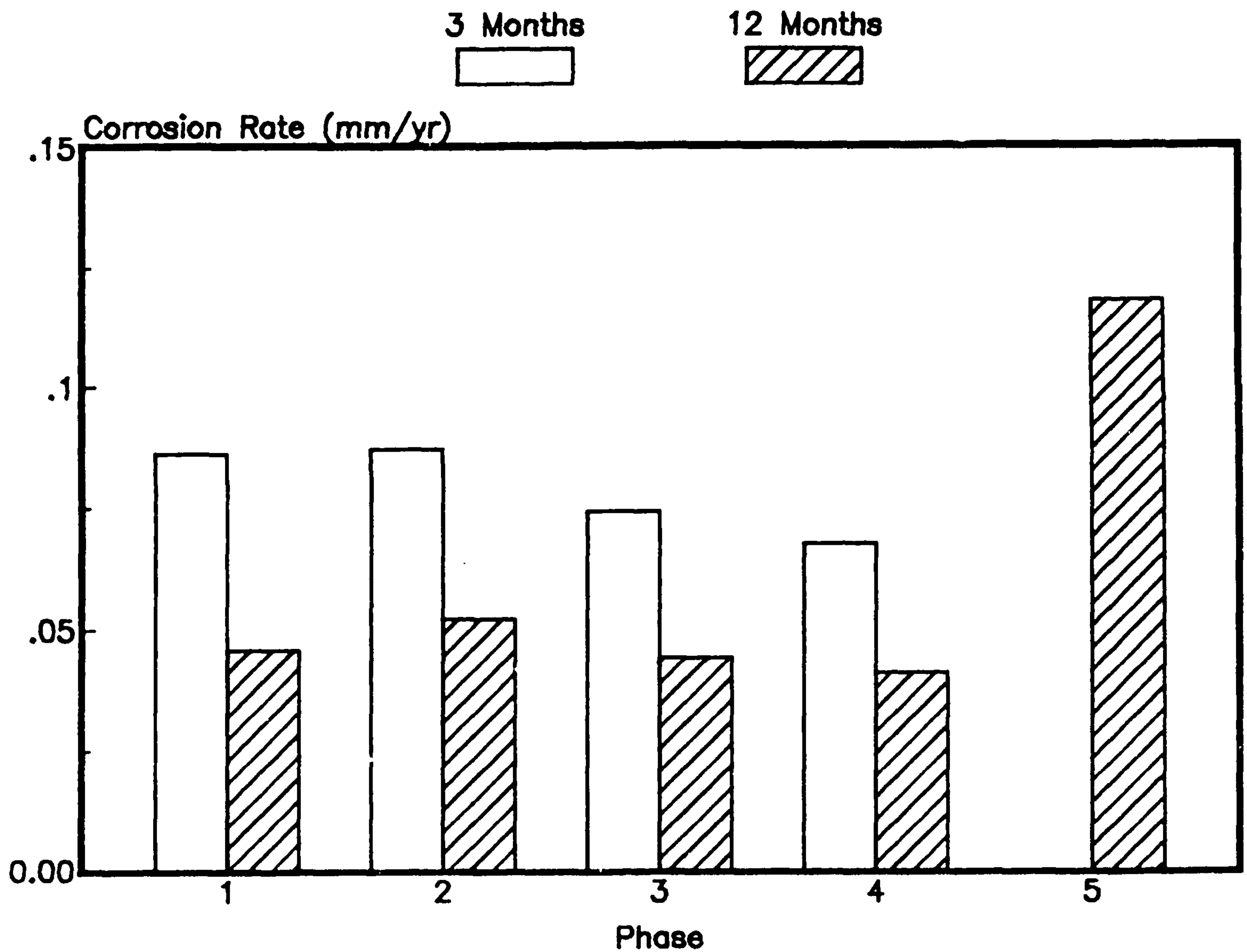

Figure M-12. Corrosion Rate for Iron at the Kure Beach 250-meter Lot, by Phase and Exposure Period.

APPENDIX N. REFERENCES

1. Corrosion of Metals in Tropical Environments, Part 1 - Test Methods Used and Results Obtained for Pure Metals and a Structural Steel, A. L. Alexander, B. W. Forgeson, H. W. Mundt, C. R. Southwell and L. J. Thompson, NRL Report 4929, Protective Coatings Branch, Chemistry Division, June 19, 1957, Naval Research Laboratory, Washington, D. C.

2. Annual Book of ASTM Standards, Issued annually, American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103

3. Letter, AMSTE-TC-M, HQ, TECOM, 11 September 1986, subject: FY87 RDTE Methodology Improvement Program Directive.

4. Weather at the Panama Canal Zone Tropical Testing Station, First Report, Frankford Arsenal Report R-742, Project 4/63, by L. Teitell, Ordnance Laboratory, Frankford Arsenal, Philadelphia, PA. October 1946

5. Field Facilities for Environmental Research of the Naval Research Laboratory, Allen L. Alexander and B. W. Forgeson, NRL Report 4557, Protective Coatings Branch, Chemistry Division, July 11, 1955, Naval Research Laboratory, Washington, D. C.

6. Studies of the Effects of Tropical Environments in Materials: I. Description of Exposure Sites, by Leonard Teitell, May 1968, Frankford Arsenal Report R-1888, Pitman-Dunn Research Laboratories, Frankford Arsenal, Philadelphia, Pennsylvania 19137

7. Atmospheric Corrosion Testing in the Tropics, C. R. Southwell and J. D. Bultman, Chapter 64 in Atmospheric Corrosion, edited by Dr. William H. Ailor, Copyright 1982 by John Wiley and Sons

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Charlottesville, VA 22901-5396	
U.S. Navy Surface Weapons Center	
ATTN: H31	1
Dahlgren, VA 22448	

Commander
U.S. Army Operations Test and Evaluation Agency
ATTN: CSTE-ZT 1
CSTE-CS 1
5600 Columbia Pike
Falls Church, VA 22041

Director
Marine Corps Operational Test and Evaluation Activity (MCOTEA)
ATTN: M&L 1
Quantico, VA 22134-5080

Deputy Commanding General
Marine Corps Research, Development
and Acquisition Command
ATTN: SSEC 1
Quantico, VA 22134-5080

Commander
U.S. Army Cold Regions Test Center
ATTN: STECR-TA 1
APO Seattle 98733-7850

Cortest Laboratories, Inc.
ATTN: R. Kane/D. Cuellar 1
11115 Mills Road, Siute 102
Cypress, TX 77429

Air Products and Chemicals Inc.
ATTN: S. W. Dean 1
7201 Hamilton Blvd.
Allentown, PA 18195-1501

Texas Instruments Inc.
ATTN: M/S 10/13 (Dr. Robert Baboian) 1
34 Forest Street
Attleboro, Massachusetts 02703

Commander
U.S. Army Dugway Proving Ground
ATTN: STEDP-MT 1
STEDP-MT-TM-N 5
STEDP-MT-TM-N-P 100
STEDP-SD-TA-F 5
STEDP-MT-AT 1
STEDP-MT-L 1
Dugway, UT 84022-5000