Corrosion of Metals in Tropical Environments:

Part 10, Final Report of 16-Year Exposures

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A comprehensive long-term investigation of corrosion of 52 metals immersed in seawater and in fresh water, suspended at mean-tide level, and exposed to marine and inland tropical atmospheres has been completed for exposure periods of up to 16 years. A series of reports on specific metal groups has already been published. This is a final report on the project; it presents tabulated results for all metal-environment combinations included in the study, both for simple plates and bimetallic couples. Many of these are previously unreported data. Time-corrosion curves for all single-metal exposures not previously reported on to completion are included; these

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are for 16 wrought and cast ferrous metals in two atmospheres and 7 nonferrous metals in all five environments. Because of their basic value for comparing corrosiveness of environments and for evaluating effectiveness of alloys, curves for all the commercially pure metals are presented for all five environments. The final steady-state corrosion rate is a most useful value for estimating expected metal life; this value (R_c) has been established for most metals in each environment and is included with all curves and tabulated data.

CONTENTS

CORROSION OF METALS IN TROPICAL ENVIRONMENTS: Part 10, Final Report of Sixteen-Year Exposures

INTRODUCTION

Just before World War II, construction was started on a third set of locks for the Panama Canal. During the design and early stages of this project the engineers were confronted with the problem of selecting materials that would perform satisfactorily in the extreme tropical environments of the area.

At that time practically no information was available on the natural corrosion of metals in tropical environments; even for temperate climates, very little worthwhile data had been published for underwater exposures. A few short-term rates had been obtained from aqueous exposures and some attempts at collecting longer-term data were under way. These were compromised by the serious flaw of reexposing samples after cleaning, a procedure leading only to a repetition of the short-term corrosion results.

The dearth of information was so critical for the Canal project that a crash corrosion investigation was undertaken in tropical seawater in Panama. Shortly thereafter, because of enemy submarine action and shifting priorities, the Third Locks Project was halted, and completion was postponed until after the war. During the late 1940's the work was renewed, but it was then decided to further postpone the Third Locks Project and to undertake the design of a sea-level canal incorporating tidal locks to control the high tides on the Pacific side of the Isthmus of Panama.

The sea-level construction was to be an undertaking of much greater magnitude than the original project, and the engineers once again needed corrosion data for many metallic materials. This time, however, there was more time available to investigate the problem. The earlier crash program had been completed, but its results showed only one definite conclusion: that this was not the way to evaluate natural corrosion. The number of samples and short-term exposures were inadequate for establishing reliable corrosion rates. Furthermore, the number of metals and metallic combinations tried was only a fraction of those that had to be considered.

At this point it was decided to begin a comprehensive study of metallic corrosion in natural tropical environments, both aqueous and atmospheric.

As a first step, well-known authorities in the field of corrosion were contacted and requested to submit their ideas on selection of metals, methods of exposure and cleaning, and evaluation of results. Their suggestions were incorporated into the investigation wherever feasible; as a result, the study was more scientifically organized, and more metals of general interest were included. Also as a result of these consultations, the schedule for removal of test samples was adjusted to a log scale and extended to 16 years.

Note: Manuscript submitted October 11, 1974

The long-term study was begun by the Special Engineering Division of the Panama Canal, which was the sole operator of the project during the early stages. In 1953, when the Panama Canal was reorganized as a private company, the Special Engineering Division was scheduled for disbandment, and the corrosion investigation was to be abandoned. At that point, however, the Naval Research Laboratory took over the project. The corrosion scientists at NRL were aware of the uniqueness and importance of the work and of the cost and effort that had gone into preliminary collection of materials, fabrication of test samples, construction of test piers and atmospheric sites and supporting structures, preexposure cleaning and testing, etc. By enlisting joint financial support from the Army, the Navy, and the Panama Canal Company, the Naval Research Laboratory was able to continue the project uninterrupted. An act of Congress transferred control of the Panama Canal Corrosion Laboratory and its environs to the Naval Research Laboratory in 1952.

During the course of this study more than 13,000 individual specimens were exposed and 168,000 data measurements were made. Additional exposures were made until 1958. All tests have now been completed, in most cases through the originally planned 16 years.

As Naval Research Laboratory scientists collected the long-range results of these investigations, studied the data, and compared them with information gathered by other workers in this field, the importance of the work became increasingly evident. The results obtained at logarithmic time intervals could usually be plotted into precise corrosion curves. From these it was possible to establish steady-state corrosion rates for most metals, values which provide a new dimension for corrosion engineers by permitting more accurate predictions of expected metal life in natural environments. The completed curves also showed how misleading the earlier results, obtained by short-term testing, would have been.

Comparison with data taken in temperate climates was made whenever possible. It was found that the curves are usually similar in shape, but the tropical curves are slightly higher [1,2], indicating that the latter usually represents an upper limit for corrosion in uncontaminated natural environments.

Collection of long-term corrosion data for natural seawater and fresh water is much more difficult than evaluation of atmospheric corrosion. Specimens must be larger, with heavy holding racks; supporting structures that can resist severe wave action are required, as well as heavy-duty cranes and handling equipment. All contribute to make such exposures a very costly proposition. Also, over long periods of exposure, many things can happen to ruin the tests (hurricanes, pollution, harbor construction, or changes in project objectives that cause loss of interest or funding).

Only a few water-immersion studies have been undertaken anywhere, and most of the earlier ones suffered from serious design or procedural flaws such as sand blasting exposed samples to remove fouling and then reexposing them [3] or exposing single samples to be cleaned, weighed, and then reexposed [4]. The most useful of these early studies were the exposures made by the London Institute of Civil Engineering, which conducted 15-year tests at four sites around the world [5], but only one specimen was removed at 5-year intervals, and only two metals, wrought iron and carbon steel, were included. French researchers started a comprehensive investigtation in the late 1930's

[6], but their work was interrupted by the war, and little information was obtained. Most recently, Russian researchers have obtained 6-year curves for carbon and low-alloy steels [7]. At the U.S. Navy Civil Engineering Laboratory at Port Hueneme corrosion rates of a number of metals in the deep ocean have been determined, but the comparative surface-water tests of similar metals were destroyed by a severe storm after only 2 years' exposure [8]. The paucity of properly collected corrosion information causes the results of this series of reports to represent the bulk of the world's knowledge on natural corrosion in tidal and surface-water exposures.

This will be the final report of this study. A number of other reports have been published, each dealing with a specific group of metals or a particular phase of the investigation [9-17]. A considerable part of the total information, however, has not been previously published; this is particularly true with regard to galvanic couples, both under water and in the atmosphere. In addition, a few nonferrous single metals in all environments, and ferrous metals in marine and inland atmospheres, are reported here completely for the first time.

In all cases where previous reports have not covered the complete corrosion-time relation for an individual metal or alloy, the curves have been plotted and are presented here. The bimetallic galvanic data, which are voluminous, have been summarized in Appendix A, with tabulations showing the average corrosion at 1, 8, and 16 years for each of the couple components. In order for the galvanic losses to have full significance, it is necessary to have comparative corrosion losses of each metal in single-plate exposures; summary tabulations of all the single-plate exposures are therefore included in Appendix B, which thus encompasses the final results for all metal exposures included in the entire investigation.

EXPERIMENTAL CONDITIONS

Exposure Environments

Exposure sites representing five distinct environments were selected for the corrosion studies. Locations and photographs of these sites appear in Fig. 1.

Most of the metals were exposed in all five environments, providing comparison of environmental effects on a single metal, as well as the more obvious comparison of different metals in each environment. Immersion exposures were made from two piers constructed especially for the program: one a freshwater site in Gatun Lake (Fig. 1c) and the other a seawater site in the Pacific Ocean at Naos Island, off the Fort Amador causeway (Fig. 1d). Gatun Lake is a large, calm body of soft (50 ppm), clear water. There are no measurable currents at this exposure site. Water depth is about 30 ft. Samples were continuously immersed at an average depth of 6 ft. Seawater exposures at Naos Island were made at two elevations. The upper rack was placed at mean-tide level for intermittent immersion, and the lower rack was just below minimum low tide, for continuous immersion. At this site the average water depth is about 40 ft, the average tidal range is 13 ft, and maximum currents measure less than 1 ft/s.

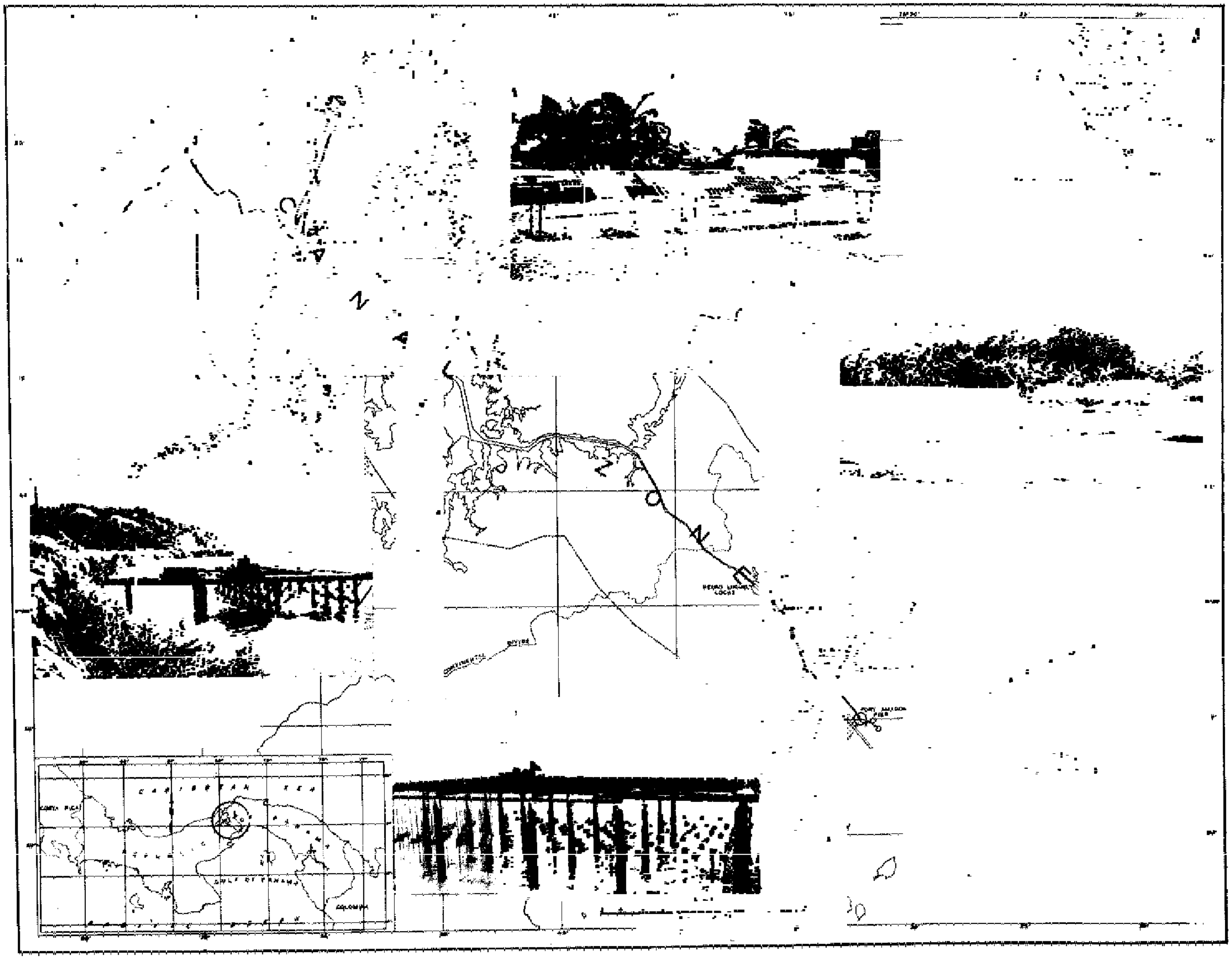

Fig. 1 — Locations of test sites

The two atmospheric sites were located on opposite sides of the Isthmus of Panama. The marine atmospheric exposure site was on the roof of the Washington Hotel by the shore of Limon Bay, an arm of the Caribbean Sea (Fig. 1a). The rooftop elevation is 55 ft above sea level. The prevailing wind is landward, and breakers on a seawall about 1 mi. offshore generally provide some salinity in the atmosphere. The other site was open and inland; although it was only 5 mi. from the Pacific Ocean, at the Miraflores Locks of the Panama Canal (Fig. 1b) the prevailing wind is from the land. This site can best be classified as inland, tropical, and semirural. Analyses of the test environments and a summary of Canal Zone climatic conditions during a 20-year period are presented in Tables 1 and 2 and Fig. 2.

Metals Tested

Fifty-two different metals and alloys were included in the study. Most were exposed in all five environments. The metals included nine cast metals, six commercially pure metals, and four nonferrous coated steels. The rest were structural alloys, practically all of which are still in general use. The low-alloy steels, the α and $\alpha\beta$ brasses, the bronzes, the nickel-copper and copper-nickel, and the austenitic stainless steels are all high-priority materials on today's market. Tables 3-6 identify the metals tested and show the chemical composition, specific gravity, and original specification numbers for each. All sampling and testing for these data were done by personnel of the Canal Zone Corrosion Laboratory with the exception of the 20-year meteorological summary, which was supplied by the Panama Canal Company.

Methods of Exposure

All specimens for each environment were exposed simultaneously. Each set consisted of ten replicates of simple panels or bimetallic couples. Duplicate specimens were removed at 1, 2, 4, 8, and 16 years. No clean-and-return methods were used; removal of a pair in no way disturbed the remaining specimens. Before exposure all samples were vapor-degreased with trichloroethylene, and for most of the ferrous panels, rolling scale was first removed by pickling.

The simple plate specimens for seawater, fresh water, and sea mean-tide exposures were 9 × 9 × 1/4 in. The bimetallic couples in these environments consisted of strips 2 × 9 × 1/4 in. attached to plates 9 × 9 × 1/4 in. Both simple and coupled plates were mounted in racks and supported by ceramic insulators. Couple strips were oriented vertically. An exploded view of an underwater coupled specimen is shown in Fig. 3. Figure 4 shows a typical underwater rack with samples in place. Each rack held eight panels and five glass dividers; the dividers were used to reduce the possibility of stray current effects.

Single-metal exposures in the atmosphere were made with panels 4 × 8 × 1/16 in. These were supported by ceramic insulators on racks, as shown in Fig. 5. Panels were all angled 30° from horizontal and faced toward the sea (north) at the marine site, and south at the inland location.

Table 1
Summary of Individual Analyses of Water Samples Obtained at the Immersion Test Sites

Constituent or Property Determined	Fresh Water Gatun Lake at Gatun			Seawater, Pacific Ocean at Fort Amador					
				Upper Rack Level Elevation 0.0 ft			Lower Rack Level Elevation 14.0 ft		
	Maximum	Minimum	Av.	Maximum	Minimum	Av.	Maximum	Minimum	Av.
Elec. conductivity (mhos × 10^{-3} at 81° F)	0.12	0.091	0.11	51.7	21.3	42.2	51.7	35.4	45.4
Total dissolved solids (ppm)	165	69	113	42,776	22,613	35,832	41,480	26,390	35,735
Total suspended solids (ppm)	23	0.0	7.6	220	0	64	173	0	49
Turbidity (ppm)	<5	<5	<5	20	<5	<5	25	<5	<5
Oxygen saturation (percent)	98	78	90	105	62	90	103	64	87
Oxygen consumed (ppm)	2.4	0.7	1.4	2.5	0.6	1.6	2.6	0.4	1.6
Biochemical oxygen demand (ppm)	2.2	0.1	1.0	3.4	0.2	1.6	2.3	0.0	1.5
pH (colorimetric)	8.0	6.9	7.5	8.4	7.8	8.2	8.4	7.8	8.1
Organic and volatile matter (ppm)	65	6.6	34	10,379	2,150	6,226	10,632	2,759	6,236
Sulfate (ppm)	7.2	0.0	2.6	3,240	1,590	2,431	3,177	1,837	2,473
Chloride (ppm)	12.5	0.0	7.0	20,098	11,300	17,415	19,949	10,379	17,357
Nitrate (ppm)	Trace	0.0	Trace	0.01	0.00	Trace	0.01	0.00	Trace

Table 2
Summary of Individual Analyses of Air Samples Obtained at the Atmospheric Test Sites

Constituent (determined in mg per 100 cu ft)	Cristobal Test Site			Miraflores Test Site		
	Maximum	Minimum	Av.	Maximum	Minimum	Av.
Total dissolved solids	5.48	0.30	0.70	2.58	0.15	0.86
Organic and volatile matter	1.72	0.16	0.74	0.69	0.11	0.34
Sulfate	0.64	0.030	0.20	1.13	0.011	0.25
Chloride	0.42	0.035	0.23	0.16	0.013	0.055
Nitrate	0.11	0.00	0.031	0.12	0.00	0.040

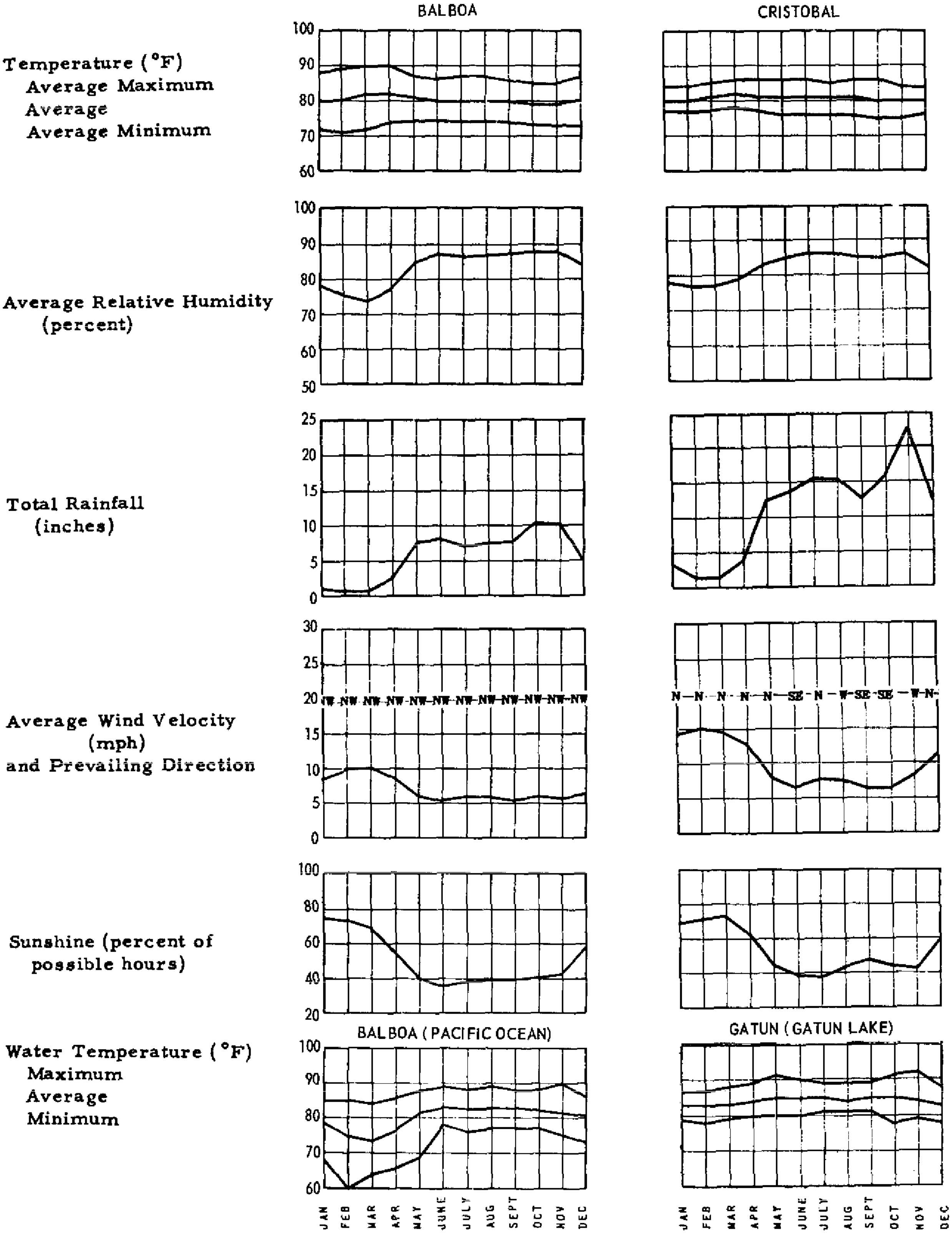

Fig. 2 — Canal Zone climatic conditions (average records, 20 years minimum)

Table 3
Composition of Nonferrous Metals Exposed in Aqueous Environments

Metal	Specification*	Ident. No.	Specific Gravity	Composition (Percent by Weight)																
				C	Mn	P	S	Si	Cr	Ni	Cu	As	Fe	Zn	Al	Sn	Pb	Cd	Co	Mg
Aluminum (1100)	QQ-A-561, Type 3	1	2.71		0.015			0.16			0.18		0.47	0.16	99.0					
Aluminum (6061T)	QQ-A-327, Cond. T	2	2.70		0.01			0.55	0.30		0.23		0.15	0.015	97.9					
Magnesium (AZ31X)	ASTM B-90-41T, Type 18X, Cond. A	5	1.77		0.38			0.004			0.02		0.001	1.25	2.90					95.4
Muntz brass	ASTM B-171-42, w/.2% AS	10	8.36								59.98	0.19	0.048	39.4		0.022	0.41	0.19		
Naval brass	QQ-B-636, Amend 3, Class A, ½hard	12	8.39								59.87		0.05	39.4		0.58	0.09			
Manganese brass	QQ-B-721a, Amend 1, Class A, ½hard	17	8.38		0.09						57.32		1.12	40.8	0.10	0.50	0.10			
Cartridge brass	QQ-B-611a, Amend 3, Comp. E, ½hard	13	8.53								70.07		0.04	29.9			none			
Low brass	ASTM B-36-43T, Alloy No. No. 4, ½hard	14	8.66								80.00		0.04	19.9			0.049			
Commercial bronze	ASTM B-36-41T, No. 2, ½hard	15	8.80								90.50		0.007	9.5			0.030			
Aluminum bronze	QQ-B-666, Type IV, Grade A, Amend 3, Hard	16	8.20								94.84		0.08	0.01	5.1					
Phosphor bronze	QQ-B-746, Grade A, Am. 2, Type IV, ½hard	18	8.90			0.25					95.54		0.010	0.30		4.21	0.048			
Silicon bronze	QQ-C-591a, Class A, Amend. 1, ½hard	19	8.58		none			2.64		none	96.30		0.04	0.98			trace			
Copper	QQ-C-501a, Amend. 2, Class A, soft	40	8.91				0.001				99.92		0.002					0.004		
Copper-nickel	*Navy 46C6, Type III, soft*	46	8.92		0.91					30.03	68.75		0.31	0.42		0.015	0.056			
Monel	Navy, 46M7f, Class A, cold rolled, annealed	47	8.84	0.15	0.91		0.008	0.14		66.59	30.37		1.83		trace					
Nickel	ASTM B-162-41T, cold rolled, annealed	49	8.87	0.07	0.20		*0.01*	*0.037*		*98.46*	*0.02*		0.34						0.90	
Lead	QQ-L-201, Amend. 1, Grade A	80	11.31								0.058	0.0001	0.002	0.001		0.0018	99.9	0.0001	0.0046	
Zinc	QQ-Z-301A, Type III	7	7.13										0.0062	99.5	trace		*0.492*	*0.0472*		
Cast bronze (ounce metal)	Navy 46B23d (Oz-c)	60	8.42			0.013				0.31	84.16		0.04	5.6		4.76	5.14			
Cast bronze (valve metal)	Navy 46B8g Comp M	67	8.36			0.016				0.53	87.88		0.05	3.8		6.04	1.73			
Cast tin bronze	*Navy 46M6g Comp G*	68	8.31			0.020				0.36	87.49		0.04	4.2		7.94	none			
Cast nickel-tin bronze	Navy 46M6h Comp G-A	69	8.60			0.019				6.23	88.70		0.03	1.90		3.19	0.01			

*Surface condition of all nonferrous metals was "as received" — all were degreased before exposure.

Table 4
Composition of Ferrous Metals Exposed
in Aqueous Environments

Metal	Initial Surface Condition*	Specification	Ident. No.	Specific Gravity	Composition (Percent by Weight)								
					C	Mn	P	S	Si	Cr	Ni	Cu	Mo
Carbon steel	Pickled		35										
Carbon steel	Machined	QQ-S-741, IIA1	36	7.85	0.24	0.48	0.040	0.027	0.008	0.03	0.051	0.080	0
Carbon steel	Millscale		34										
Carbon steel 0.3% Cu	Pickled	QQ-S-741, IIA2	37	7.85	0.22	0.44	0.019	0.033	0.009	Trace	0.14	0.35	0
2% Nickel steel	Pickled	RR-3A	20	7.84	0.20	0.54	0.012	0.023	0.18	0.15	1.94	0.63	0
5% Nickel steel	Pickled	SAE 2515	23	7.85	0.13	0.49	0.010	0.014	0.16	0.10	5.51	0.062	0
3% Chromium steel	Pickled	Proprietary	24	7.82	0.08	0.44	0.010	0.017	0.13	3.16	0.16	0.11	0.02
5% Chromium steel	Pickled	AISI Type 501D	25	7.81	0.08	0.41	0.020	0.019	0.20	5.06	0.11	0.062	0.52
Low-alloy steel	Pickled	Proprietary "Yoloy"	26	7.86	0.08	0.47	0.007	0.026	0.060	0.00	1.54	0.87	0
Low-alloy steel	Pickled	Proprietary "Corten"	27	7.82	0.15	0.45	0.113	0.026	0.47	0.68	0.49	0.42	0
Low-alloy steel	Pickled	Proprietary "HT-50"	28	7.85	0.078	0.75	0.058	0.022	0.04	Trace	0.72	0.61	0.13
Low-alloy steel	Pickled	Proprietary "Mayari R"	29	7.84	0.13	0.60	0.089	0.021	0.15	0.55	0.30	0.61	0.059
Cast steel	Machined	QQ-S-6816, 1	70	7.82	0.27	0.68	0.028	0.028	0.41	0.12	0.22	0.10	0
Gray cast iron	Machined	QQ-I-652, 30	78	7.08	3.18	0.80	0.162	0.103	1.98	0.57	0.31	0.08	0
Austenitic cast iron	Machined	INCO 18-22 Ni	79	7.11	2.66	0.94	0.24	0.104	3.17	2.29	17.9	0.80	0
Wrought iron	Machined	Aston process	290	7.76	0.04	0.038	0.141	0.018	0.098	Trace	0.006	0.020	0
Wrought iron	Millscale	ASTM A42-39	190										
410 Stainless steel (13% Cr)	As received	47-5-20 INT Grade 3A	50	7.72	0.07	0.48	0.016	0.021	0.29	13.15	0.23	0.08	0
302 Stainless steel (18 – 8)	As received	QQ-S-776 Grade 1C	57	7.89	0.09	1.15	0.034	0.018	0.56	17.79	8.88	0.072	0
316 Stainless steel (18 – 13 + Mo)	As received	QQ-S-766 Grade 1H	58	7.95	0.11	1.67	0.019	0.023	0.54	17.93	12.08	0.084	2.32
321 Stainless steel (17 – 10 + Ti)	As received	QQ-S-766 Grade II	59	7.89	0.08	1.11	0.013	0.030	0.44	17.63	10.33	0.13	0.50(Ti)

*All metals were degreased before exposure.

Table 5
Composition of Nonferrous Metals Exposed in Atmospheric Environments

Metal	Specification*	Ident. No.	Specific Gravity	Composition (Percent by Weight) C	Mn	P	S	Si	Cr	Ni	Cu	As	Fe	Zn	Al	Sn	Pb	Cd	Co	Mg
Aluminum (1100)	QQ-A-561, Type 1, ½hard	1	2.71		0.01			0.18			0.20		0.75	0.005	98.85					0.003
Aluminum (6061T)	QQ-A-327 Cond. T	2	2.70		0.053			0.57			0.26		0.30	0.003	97.64					0.87
Aluminum (2024T)	QQ-A-362 Cond. T	3	2.70		0.45			0.14			4.15		0.57	0.031	92.96					1.72
Magnesium (AZ31X)	ASTM-B-90, Type 18X, Cond. A	5	1.77		0.24			0.029		0.001	0.01		0.003	1.51	3.01					98.21
Magnesium (AZ61X)	ASTM-B-90, Type 8X, Cond. A	6	1.80		0.29			0.026		0.001			0.003	0.47	6.86					99.21
Muntz brass	ASTM-B-171 (0.2% As)	10	8.40								59.95	0.19	0.01	38.87		0.022	0.76			
Naval brass	QQ-B-636, Class A, ½hard	12	8.41								60.08		0.04	39.02		0.84	0.02			
Manganese bronze	QQ-B-721 A, Class A, ½hard	17	8.37								57.86		1.04	40.25	0.12	0.85	0.02			
Cartridge brass	QQ-B-611 A, Comp. E, ¼hard	13	8.52								70.00		0.02	29.96			0.024			
Low brass	ASTM-B-36, No. 4, ½hard	14	8.65								80.06		0.03	19.90			0.016			
Commercial bronze	ASTM-B-36, No. 2, ½hard	15	8.79								89.68		0.007	10.31			0.004			
Aluminum bronze	QQ-B-666, Grade A, Type V	16	8.36							0.05	95.68		0.03		3.77		0.01			
Phospher bronze	QQ-B-746, Grade A, S.T. V	18	8.89		0.07	0.36					95.10		0.04			4.38				
Silicon bronze	QQ-C-591a, Class A, ½hard	19	8.56		0.08			2.90			96.14		0.05	0.54						
Copper	QQ-C-501a, Class A, soft	40	8.91								99.9									
Nickel silver	ASTM-B-122 No. 2, ½hard	45	8.76		0.34					18.49	64.06		0.05	17.33		0.004				
Copper nickel	Navy 46C6A, Type IV, soft	46	8.93		0.56					29.28	69.74		0.09	0.20		0.10	0.03			
Monel	Navy 46M7, Class A, cold-rolled, annealed	47	8.85	0.06	0.40		0.15	0.03		67.43	28.68		2.38							
Nickel	ASTM-B-162 cold-rolled	49	8.88	0.07	0.14		0.002	0.05		99.24	0.16		0.14							
Lead	QQ-L-201, Amend-1, Grade A	80	11.29								0.072		0.002			0.001	99.9	0.002	0.007	0.011
Zinc	QQ-Z-301a, Type 2	7	7.14								0.02	0.01	0.02	99.7			0.22	0.06		
Cast bronze (ounce metal)	Navy 46B23d (Oz-c)	60	8.42			0.013				0.31	84.16		0.04	5.6		4.76	5.14			
Cast bronze (valve metal)	Navy 46B8g Comp. M	67	8.36			0.016				0.53	87.88		0.05	3.8		6.04	1.73			
Cast tin bronze	Navy 46M6g Comp. G	68	8.31			0.020				0.36	87.49		0.04	4.2		7.94	0.00			
Cast nickel-tin bronze	Navy 46M6h Comp. G-H	69	8.60			0.019				6.23	88.70		0.08			5.19	0.01			
Galvanized steel	QQ-I-716, Am2, C. Base 1015	8		0.16	0.50	0.016	0.047	0.005	0.03	0.029	0.30									
Zinc-sprayed steel	t ≈ 10 mils, Base 1020	9		0.22	0.45	0.033	0.030	0.005	0.01	0.026	0.028									
Lead-coated steel	t ≈ 10 mils, Base 1017	89		0.19	0.46	0.006	0.048	0.006	0.02	0.008	0.011									
Aluminum-sprayed steel	t ≈ 10 mils, Base 1020	4		0.21	0.47	0.004	0.025	0.002	0.012	0.002	0.022									

*Surface condition of all nonferrous metals was "as-received" — all were degreased before exposure.

Table 6
Composition of Ferrous Metals Exposed
in Atmospheric Environments

Metal	Surface Condition*	Specification	Ident. No.	Specific Gravity	Composition (Percent by Weight)								
					C	Mn	P	S	Si	Cr	Ni	Cu	Mo
Carbon steel	Pickled		35										
Carbon steel	Machined	QQ-S-741, Type II Grade A, Class 1	36	7.85	0.25	0.46	0.083	0.014	0.004	0.025	0.035	0.020	—
Carbon steel	Millscale		34										
Carbon steel 0.3 Cu	Pickled	QQ-S-741 Class 2	37	7.84	0.22	0.41	0.004	0.030	0.008	0.015	0.10	0.24	—
2% Nickel steel	Pickled	RR-SPECS-3-A	20	7.84	0.18	0.52	0.036	0.024	0.19	0.14	2.06	0.61	—
5% Nickel steel	Pickled	SAE-2515	23	7.83	0.10	0.50	0.01	0.021	0.20	0.07	4.55	0.054	0.074
3% Chromium steel	Pickled	Max. 0.10% C Hot Rolled	24	7.80	0.07	0.54	0.008	0.016	0.14	3.24	0.13	0.11	0.032
5% Chromium steel	Pickled	Mo 1/2% AISI Type 501D	25	7.80	0.12	0.58	0.020	0.014	0.32	5.20	0.060	0.036	0.41
Low-alloy steel	Pickled	Proprietary Yoloy	26	7.85	0.13	0.41	0.007	0.026	0.048	—	1.70	0.90	—
Low-alloy steel	Pickled	Proprietary Corten	27	7.82	0.12	0.41	0.084	0.026	0.50	0.60	0.63	0.43	—
Low-alloy steel	Pickled	Proprietary HT-50	28	7.83	0.087	0.73	0.65	0.018	0.067	0.03	0.82	0.59	0.19
Low-alloy steel	Pickled	Proprietary Mayari R	29	7.85	0.11	0.54	0.086	0.029	0.18	0.50	0.40	0.57	—
ASTM "K" iron	Pickled	R-35869	38	7.82	0.08	0.45	0.076	0.030	0.003	0.10	0.013	0.26	—
Ingot iron	Pickled	Low copper	30	7.84	0.03	0.04	0.004	0.002	0.002	0.00	0.007	0.008	—
Wrought iron	Pickled		90										
Wrought iron	Machined	Aston process ASTM A162-39	190	7.74	0.02	0.024	0.117	0.015	0.095	0.01	0.007	0.018	—
Wrought iron	Millscale		290										
410 Stainless steel (13% Cr)	As received	QQ-S-766a Class 32	50	7.71	0.08	0.44	0.017	0.02	0.35	14.42	0.52	0.078	—
430 Stainless steel (17% Cr)	As received	ASTM A176-94 Grade 4, Fin. 1	56	7.68	0.10	0.34	0.014	0.008	0.29	17.22	0.12	0.024	—
301 Stainless steel (17 Cr - 7 Ni)	As received	QQ-S-766a C4, Cond. 2,F.1	57	7.88	0.10	1.13	0.012	0.021	0.39	18.12	7.62	0.030	—
316 Stainless steel (18 - 13 + Mo)	As received	QQ-S-766a C5, Cond. 2	58	7.95	0.08	1.50	0.031	0.016	0.43	17.08	11.96	0.078	2.12
321 Stainless steel (17 - 10 + Ti)	As received	QQ-S-766a C6, Cond. a	59	7.87	0.09	1.00	0.011	0.018	0.53	17.76	9.92	0.13	0.54(Ti)
Cast steel	Machined	QQ-S-6816, 1	70	7.82	0.27	0.68	0.028	0.028	0.41	0.12	0.22	0.10	—
Gray cast iron	Machined	QQ-I-652, 30	78	7.08	3.18	0.80	0.162	0.103	1.98	0.57	0.31	0.08	—
Austenitic cast iron (18% Ni)	Machined	INCO 18-22 Ni	79	7.11	2.66	0.94	0.24	0.104	3.17	2.92	17.9	0.80	—

*All metals were degreased before exposure.

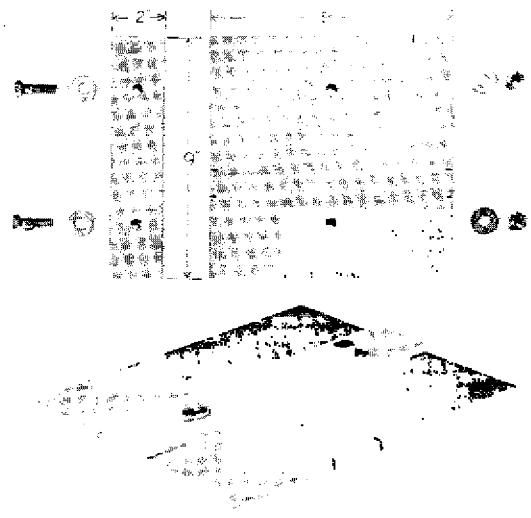

Fig. 3 — Galvanic couple samples used for aqueous exposure

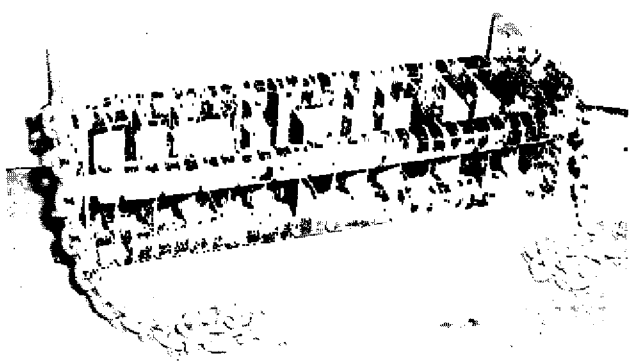

Fig. 4 — Preexposure view of rack for aqueous exposures, with specimen panels and glass separators installed

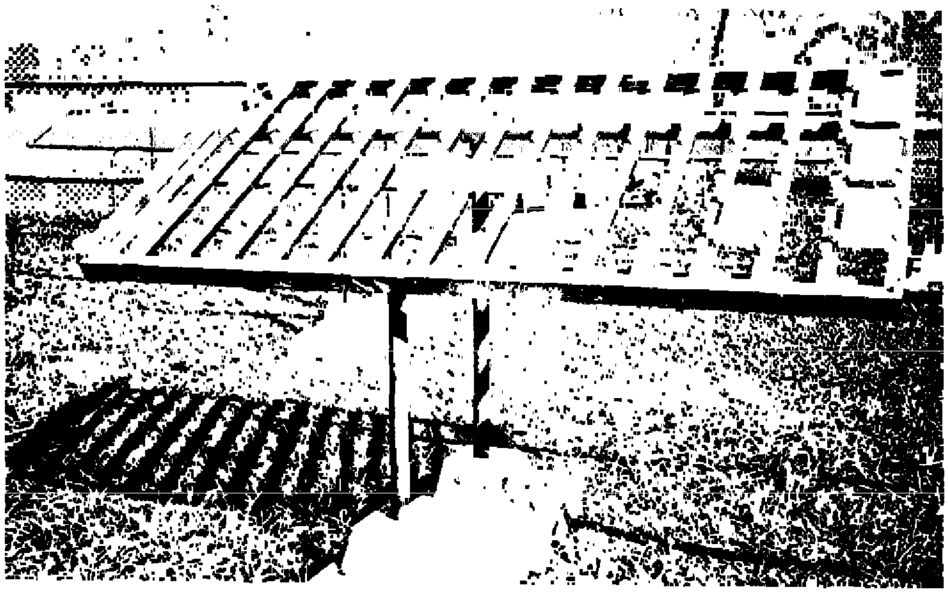

Fig. 5 — Typical atmospheric exposure frame for uncoupled panels showing four panels installed

Bimetallic exposures in the atmosphere were made with the ASTM-type coupled disc array. Figure 6 shows an assembled and disassembled view of the coupled specimen. Equal areas are exposed on each disc, and each of the two center discs is sandwiched between pieces of the other metal. Only the two center pieces were measured for corrosion loss.

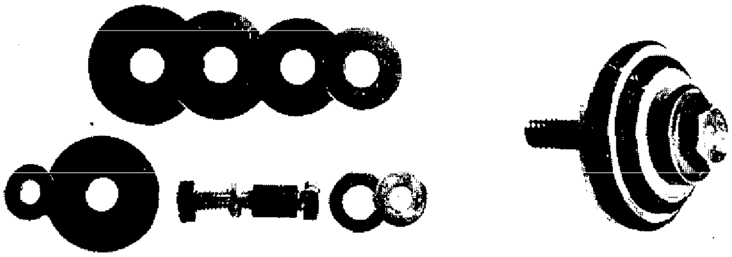

Fig. 6 — Exploded and assembled views of galvanic corrosion specimen for atmospheric exposures

METHODS OF EVALUATION

Upon removal from exposure, test panels were field-cleaned with scrapers to remove as much of the corrosion products and fouling as possible. After removal to the laboratory, specimens were given a final cleaning by timed immersions in suitably inhibited chemical cleaning solutions and thorough scrubbing with bristle brushes.

Considerable effort was spent in determining the proper cleaning procedures. These have been presented in more detail in Part 1 [9] of this series. Cleaning losses were determined on blanks of all metals and adjustments were made as required. After cleaning, corrosion damage was evaluated by determining weight loss, pitting penetration, and changes in mechanical properties.

Weight Loss

Panels were weighed and check-weighed before exposure, and the process was repeated after exposure and final cleaning. Precision of weighing was normally to 0.01 g for immersion panels and 0.001 g for atmospheric panels and discs. Corrosion weight was expressed as grams per square decimeter and as average penetration of the surface in mils. The latter value is more useful when metals of various densities are to be compared. The conversion from grams per square decimeter to mils is

$$\frac{3.937}{\text{sp gr}} \times \text{g/dm}^2 = \text{mils.}$$

Weight loss is the most useful and the most precise of the three evaluation methods. The precision and reproducibility of weight loss results permits plotting reliable time-corrosion curves from which steady-state corrosion rates can be determined. With most metals, weight loss is a better indicator of decreased structural strength than tensile testing of corroded specimens.

Only for those metals subject to dealloying, such as the $\alpha\beta$ brasses, and for those with deep and scattered pitting, such as austenitic stainless steels in seawater, was the weight loss of questionable value. Even for these, though, some information was gained by determining weight loss, as the volume of metal corroded was indicated. This permits comparing relative dealloying in the brasses, and in the case of austenitic stainless steels in seawater, the extensive subsurface pitting could be estimated from the weight-loss determination.

Pitting

Pitting is a most useful value in expressing corrosion damage. It is particularly necessary for metals where scattered pitting constitutes the major damage, and where specific requirements, such as for containers, make perforation a first consideration.

Pitting is used here to mean the deeper points of corrosion penetration, whether they be true pits which are deep and narrow, or only wide, shallow depressions. Pit depths are expressed in mils of penetration. As the corrosion becomes more uniform, the pitting penetration approaches the value of the average penetration determined from weight loss. Measurement of pitting was not as clear-cut and precise as the weight loss. For one thing, since it is not practical to measure all pits, some number must be selected; this introduces the possibility of judgment errors. Another factor is the difficulty in accurately measuring penetration for metals where no original, uncorroded surface remains. In such cases pits had to be measured from the corroded surface, and a correction (half the measured reduction in thickness) was added to the measured penetration. For submerged metals this method was usually satisfactory, but some of the atmospheric panels appeared to corrode more heavily from the bottom surface, so that some error was inherent in the correction. Only pits of 5 mils or greater were considered.

The most important pit is the deepest, but it is such a variable quantity, dependent on chance, the area exposed, and proper selection, that determination of pitting trends could not be made with this value alone. For this study the five deepest pits on each surface of the duplicate panels were measured at each removal; these values were then averaged to obtain a mean of the 20 deepest pits. This 20-pit average was found to be a much more useful value for expressing pitting vs time relations. However, in all presentations of pitting data the deepest pit is also included.

Change in Mechanical Properties

The tensile test for measuring corrosion damage was a frequently prescribed method at the time this investigation was started, and on the advise of corrosion experts it was decided to perform this test on all the noncoupled specimens. This required determination of mechanical properties (proportional limit, yield strength, ultimate strength, elongation, and reduction in area) of all original metals as well as of the aged control specimens and the corroded panels at each time period. After removal from exposure, cleaning, measuring, and weighing, corroded specimens were cut into strips sufficient to provide two tensile specimens from each panel. These strips were milled into standard 1/2-in.-wide tensile blanks and then loaded to failure. The results of the four tests were then averaged, and the change in mechanical properties between this average and the average of three unexposed but aged control samples was reported as the corrosion effect. This worked reasonably well on most of the atmospheric metals, where corrosion was usually uniform; but on immersed panels, many of which became irregular in cross section, the tensile tests were less than satisfactory. The major drawbacks were the high sensitivity to notch effect and to the rate of straining, which could not be controlled for specimens with heavily corroded surfaces. Another factor of uncertainty was the effect of aging of the laboratory controls compared with aging of the field-exposed specimens. These factors all tend to minimize the reliability of the mechanical-properties tests.

In an attempt to salvage some reliable tensile data from the underwater exposures, two additional 2-in.-wide specimens were cut and tested. These provided more representative cross-sections, and somewhat more reliable ultimate tensile-strength results were obtained.

With the tensile test it was hoped to pinpoint intergranular corrosion, selective dealloying, and subsurface pitting. None of the metals showed any serious intergranular corrosion. Only the copper-zinc brasses and gray cast iron were selectively dealloyed, and subsurface pitting occurred only for pure nickel and nickel stainless steels in seawater. Tensile data for these have been previously reported [13,15,16]. For other metals, the tensile-strength losses were directly proportional to weight loss, which was a much more precise measurement. For these reasons, no additional tensile strength data are included in these final summaries of the corrosion data.

RESULTS

As stated previously, for this final report a detailed discussion of results will not be undertaken; rather, we have tried to present adequately all of the remaining unreported data in Figs. 7-10 and to include a comprehensive summary of results from the entire study in Appendix A, Tables A1-A6. Wherever data need explaining, or are considered to be of special significance, a small amount of discussion is included.

Single-Panel Exposures, Nonferrous Metals

The single-panel exposures have for the most part been completely or partially reported. Only the cast bronzes have not been formally reported for any exposure. Figure 7 presents the curves for the four cast bronzes in all five exposure environments. As noted on the curves, the origins have been offset so that each curve stands alone, allowing comparisons of magnitude and rate. In general, corrosion resistance increases from left to right in this figure. The final steady-state corrosion rate is given for each. This value is the slope of the linear or approximately linear part of the curve and represents the rate that can be used for extrapolating corrosion losses to longer periods of time.

As with most metal groups, superior performance in one environment does not necessarily carry over to others. As can be seen from the cast bronze curves, the order of resistance varied for the different environments.

Relative to other metals, exceptionally low corrosion losses at mean tide and in the lake water were exhibited by the four cast bronzes. With most metals these two environments would be considerably more corrosive than either of the atmospheric exposures. Pitting of the cast bronzes was very low for all conditions of exposure, about the same as for wrought bronze containing 10% zinc (Metal No. 15). Pitting results for 1, 8, and 16 years are included in Tables A1 and A2 in Appendix A.

Commercially pure metals are of considerable interest because they serve as a basis of comparison for the different metal alloy groups; also, since their composition is not subject to change, they are the best suited for comparing corrosivity of different environments. Some of the results for the commercially pure metals have been reported previously but either incompletely or scattered throughout the reports [9,14-16]. In Figs. 8 and 9, complete 16-year curves are presented for all the nonferrous pure metals (lead, nickel, copper, zinc, and aluminum) exposed in the five environments. Using these curves, intermetallic and interenvironmental comparisons can be made.

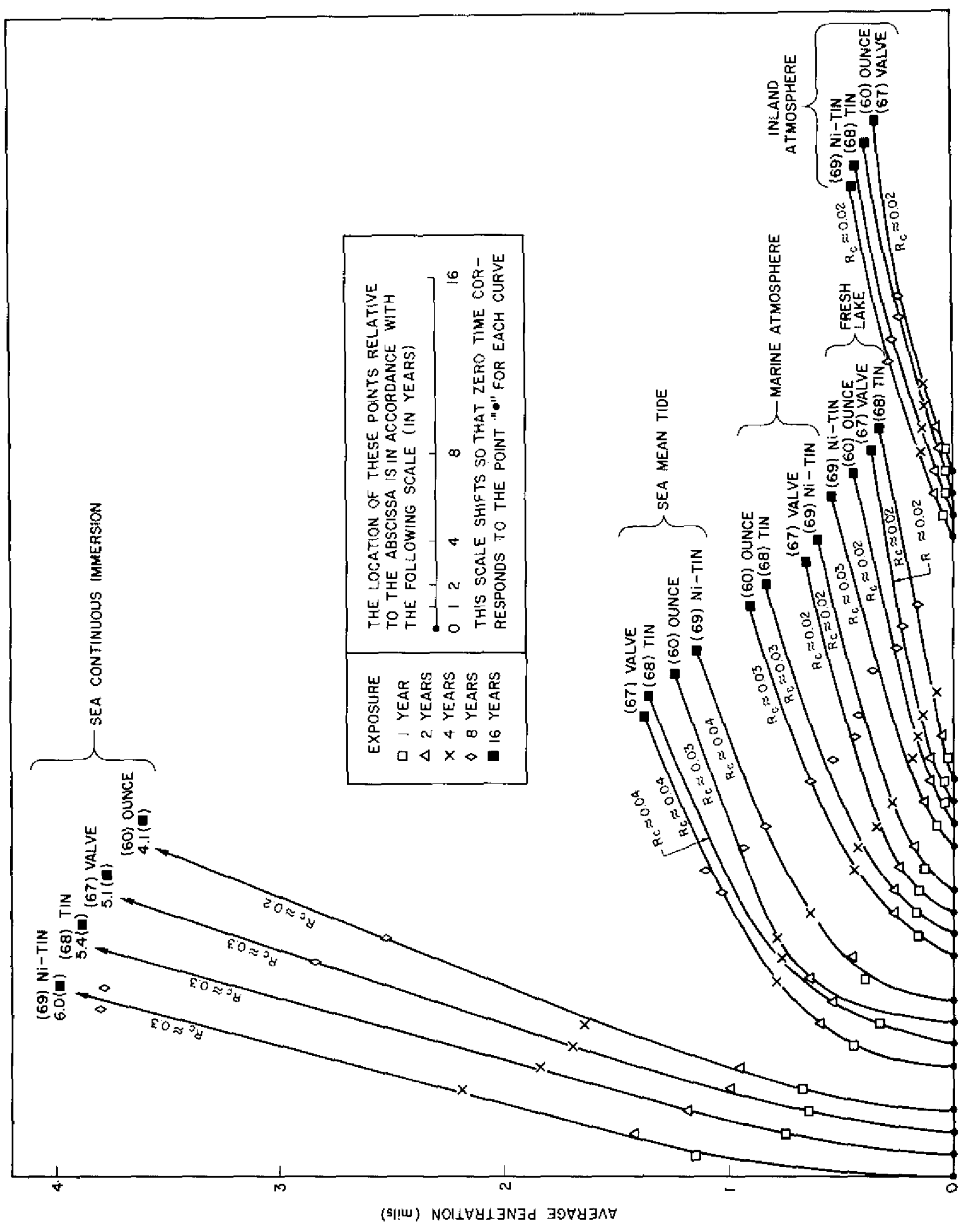

Fig. 7 — Time-corrosion curves for cast bronzes exposed in five different natural environments

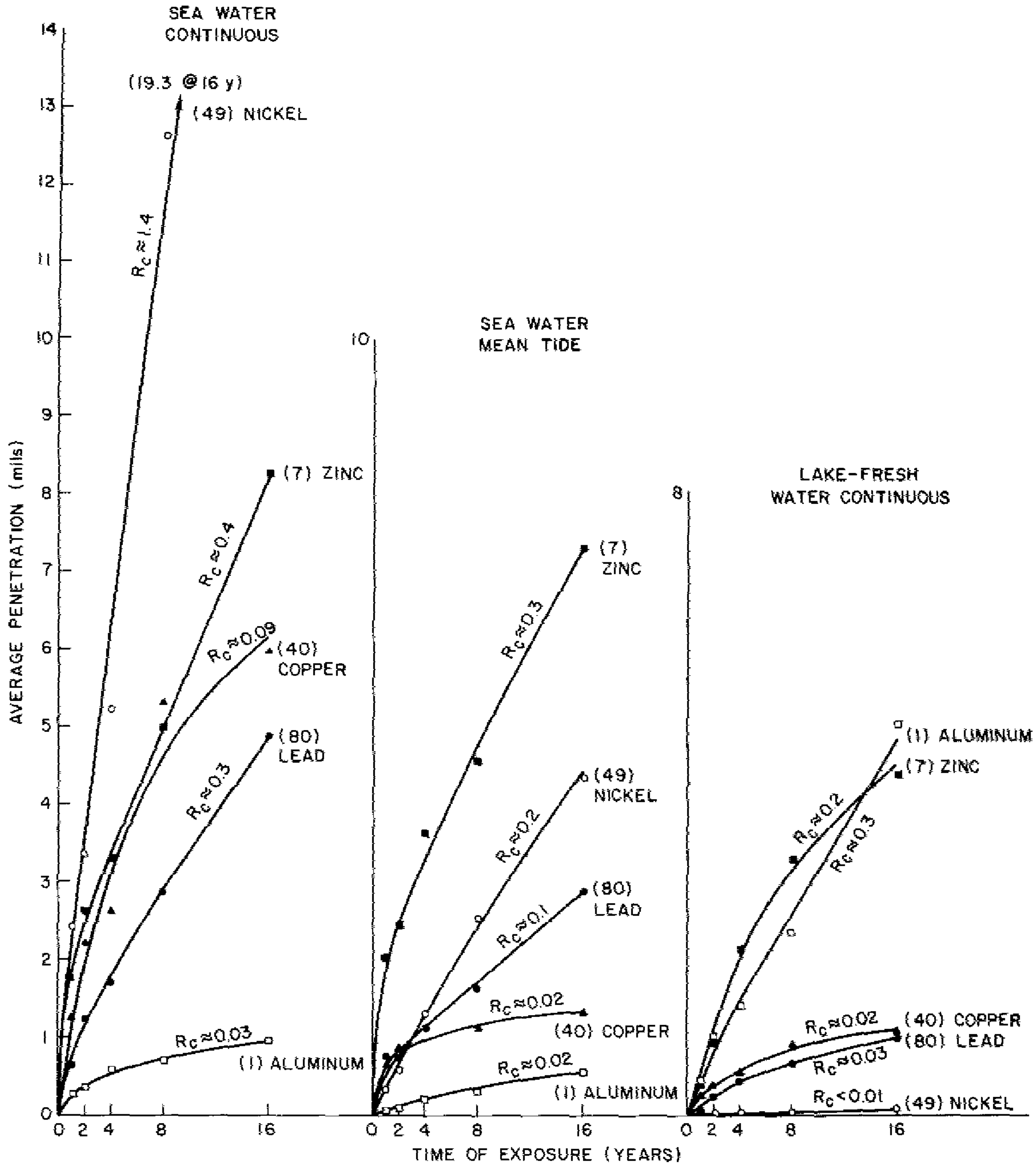

Fig. 8 — Time-corrosion curves for commercially pure metals exposed in three different aqueous environments

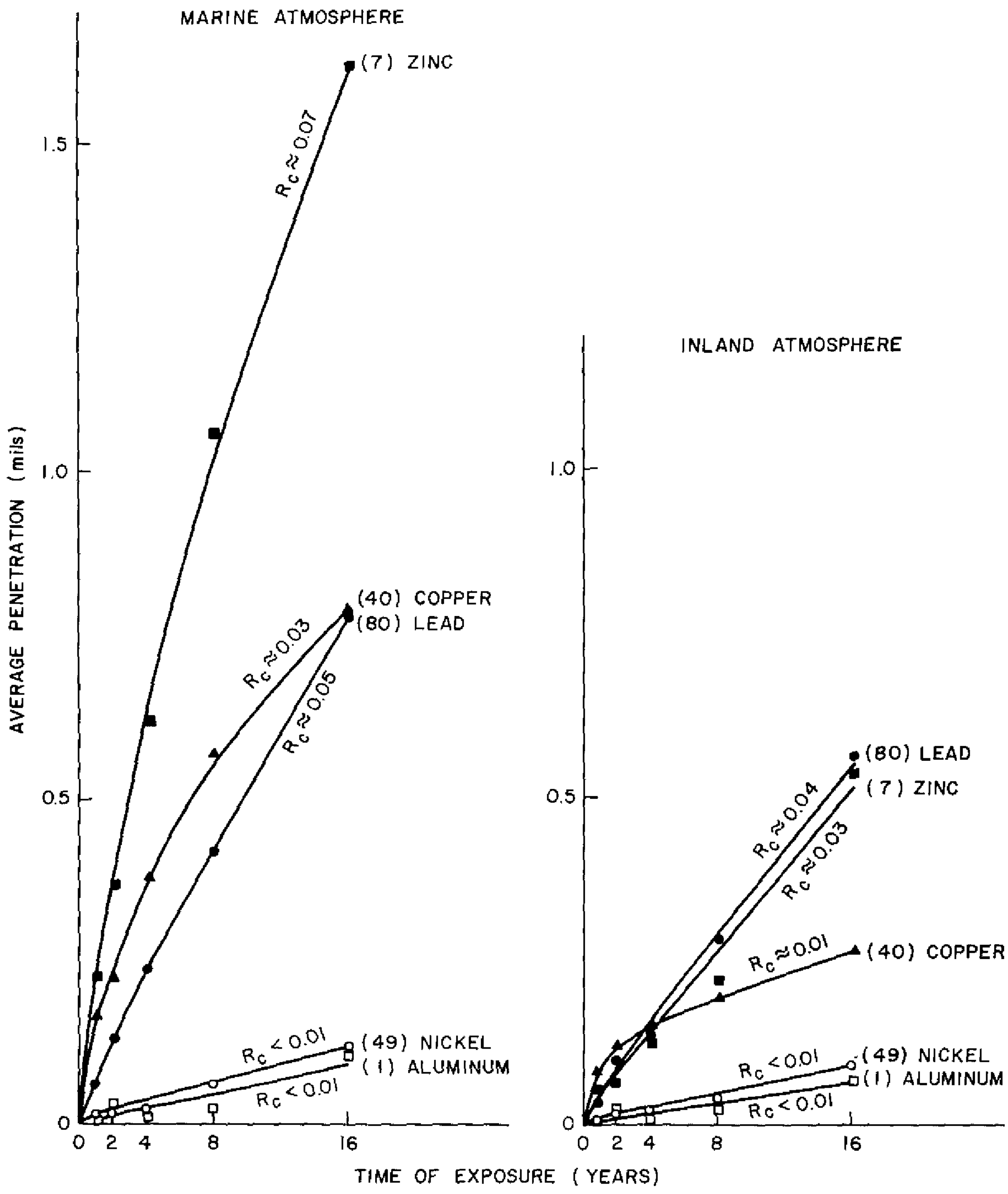

Fig. 9 — Time-corrosion curves for commercially pure metals exposed in two tropical atmospheric environments

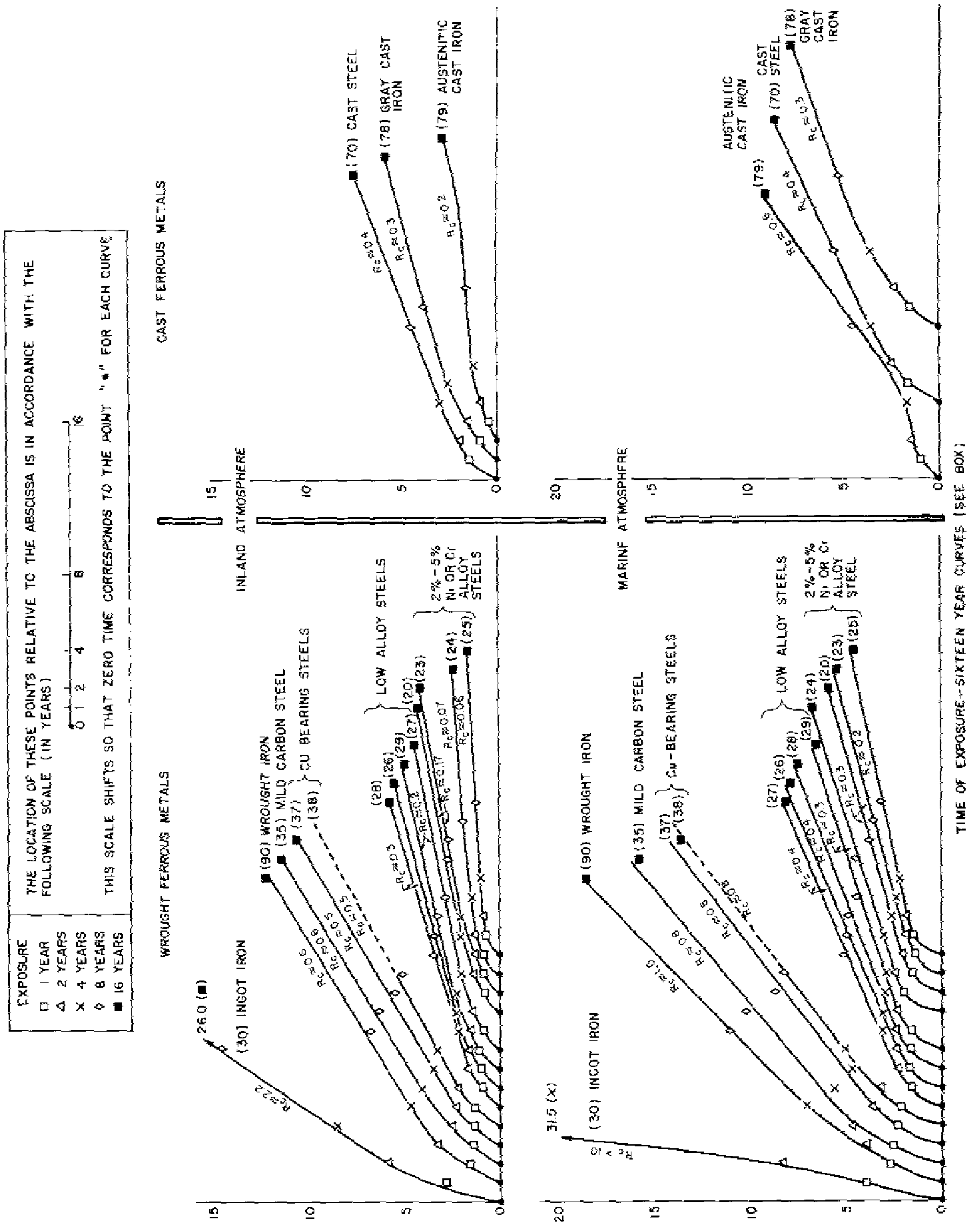

Fig. 10 — Time-corrosion curves for 16 ferrous metals exposed in marine and inland tropical atmospheric environments

As with closely related alloys, such as the group of cast bronzes previously discussed, the very different pure metals also showed appreciable variation in relative corrosion resistance from one environment to the next. For example, nickel had the highest corrosion in seawater but was by far the most resistant metal in fresh water, and aluminum was excellent in four of the five environments but was the most heavily corroded pure metal in fresh water.

Single-Panel Exposures, Ferrous Metals

Structural ferrous metals were among the most thoroughly represented of any group in the study; 12 wrought and 3 cast ferrous metals were included. Of these, 13 metals were exposed in the three aqueous environments and all 15 metals in the two atmospheric exposures. All of the 13 metals in the seawater immersion, seawater meantide, and fresh water immersion exposures have been completely reported [17]. Of the atmospheric exposures, none have been previously reported in full, and no atmospheric results whatsoever have been published on the cast metals (Nos. 70, 78, and 79), ingot iron (No. 30), or carbon steel (No. 38). Because of the continuously increasing use of some of these ferrous metals in the unpainted condition, especially the low-alloy "weathering" steels, the long-term atmospheric results are of paramount interest. Figure 10 presents the 16-year time-corrosion curves for all of these structural ferrous metals in both the inland and marine atmospheres. As with Fig. 7 for cast bronzes, the origin of each curve has been offset so each stands alone, yet all can be plotted in one figure. By having all curves together and at the same scale, easy comparison of magnitude and direction can be made. Pitting data for all these metals for periods of 1, 8, and 16 years can be found in Tables A3 and A4 in Appendix A.

From the 16-year curves for these structural ferrous metals a number of observations can be made. For instance, the base metal in this group, the plain mild carbon steel (No. 35) corroded at about a third higher rate in the marine than in the inland environment, and similar increases prevailed for most of the wrought steels. There was no practical advantage for the two copper-bearing steels (Nos. 37, 38) over the plain carbon steel; all three corroded at about the same rate. The Aston process wrought iron (No. 90) has been marketed at a premium as a corrosion-resistant material, but it actually showed slightly less resistance in the atmospheric exposures than carbon steel. The low-copper ingot iron (No. 30) had much lower corrosion resistance than carbon steel; in the marine atmosphere this commercially pure iron corroded at the phenomenally high rate of 10 mils per year (mpy), more than 12 times the rate of carbon steel.

The low-alloy weathering steels were significantly more resistant than plain carbon steels, with steady-state rates approximately half as high in both marine and inland exposures. The 2% to 5% nickel chromium-alloy steels generally had even lower rates. The best in both environments was the 5% chromium alloy with 1/2% molybdenum; its corrosion rate in the marine atmosphere was one-fourth that of plain carbon steel, while in the inland atmosphere it had an exceptionally low rate of 0.06 mpy, which was about one-tenth that of carbon steel. This chromium-molybdenum steel may well be worth the added cost when an exceptionally resistant weathering steel is needed. It should be mentioned that this high resistance does not necessarily carry over to all other environments; in seawater this metal corroded at an appreciably higher rate than carbon steel.

The cast ferrous metals on the right half of Fig. 10 provided some unexpected results. The nickel austenitic cast iron (No. 79) had very low corrosion rates up to about 2 mils average penetration; then, in both environments, the curves started turning up. At the end of 16 years in the marine atmosphere, the final rate was appreciably higher than that of the other two cast metals. The reason for the change in rate has not been established. As can be seen in Table A3, this nickel cast iron was extremely resistant in all three aqueous environments.

For all of the wrought metals, the marine atmosphere caused greater corrosion than the inland, but for two of the cast metals, cast steel (No. 70) and gray cast iron (No. 78), there was practically no difference in the final rates between the marine and inland atmospheric exposures.

Bimetallic Couples, General

The large volume of galvanic corrosion data is presented in tabular form only; no attempt has been made to plot curves from the results. The information has been summarized sufficiently to keep it within the bounds of a single report, but enough detail is presented to satisfy the interest of the reader in any specific metal or environment.

There are 1,275 possible bimetallic combinations for the 51 metals included in the galvanic study; with duplicate samples, five environments, five time periods, and reverse area relations, it would have taken an impractically large number of samples to test every possible combination. Carbon steel (No. 35) was the metal exposed in combination with most of the other metals. Phosphorus bronze (No. 19) was also used in a large number of couples; however, many interesting combinations of metals were necessarily omitted. Study of the bimetallic corrosion tables will reveal many significant findings relating to specific metal combinations, groups of metals, and environmental influences. A few of these will be mentioned briefly.

Bimetallic Couples, Aqueous Exposures

Some of the galvanic couple data for underwater exposures have been previously reported [13,15,16], but much is reported here for the first time. Table A5 shows results for 1, 8, and 16 years for all couple combinations exposed to the seawater and freshwater environments. These are for the strips 2 $\times$ 9 $\times$ 1/4 in. attached to plates 9 $\times$ 9 $\times$ 1/4 in. In this table the metal numbers are shown in brackets, and the area relation of the couple is shown by the symbols $<$ (less than) or $>$ (greater than). For example, (58) $<$ (35) represents a couple consisting of a strip (21.9 sq in. exposed) of metal 58, coupled to a plate (151 sq in. exposed) of metal 35.

The data given are weight-loss results averaged from duplicate specimens and converted to average penetration to facilitate comparison of different-density metals. Results are given for all three aqueous environments: seawater continuous immersion, seawater mean tide, and lake water continuous immersion. The value in parantheses for each set of data is the value of normal corrosion of the uncoupled metal at the time period indicated. This permits rapid assessment of the galvanic effects of coupling.

In the seawater exposure it was found that carbon steel is a very effective anode for protecting more noble metals such as stainless steels, nickel-copper alloys, brass, etc. As expected, steel plates were protected by zinc and aluminum strips. With most of the combinations such as these, which had large differences in potential, the strip anodes, at the 1:6.7 anode/cathode area ratios, provided very effective protection through 8 years. At 8 years they were 50% to 70% consumed; and by 16 years the anodic strips were usually completely gone. The highest rate of anode loss was for steel attached to pure copper plates.

At mean tide a surprisingly high degree of cathodic protection was evident throughout the 8 years, and while protection of most cathodes was only slightly less effective than that obtained for submerged samples, the rate of anode loss on most of these couples was appreciably lower than the rate for the same combinations continuously immersed. Photographs showing comparative loss of zinc anodes coupled to steel plates for 8 years in the three underwater environments are presented in Fig. 11.

In the fresh lake water there was a lesser but still definite galvanic effect. Cathodic protection of plates with strip anodes was usually not very effective in fresh water, but corrosion of smaller-area anodic materials was sometimes found to be destructively high.

Most of the couples were made up of metals with large potential differences, but a few were of similar metals with small differences in potential, and these resulted in an unexpectedly high galvanic effect. Such couples as wrought iron $\lesseqgtr$ carbon steel and 2% nickel steel $<$ carbon steel showed some definite galvanic action. The corrosion of wrought iron strips coupled to carbon steel plates was almost doubled in seawater and increased 60% in fresh water. Two percent nickel steel plates increased the corrosion of the contacting carbon steel strips by 30% in both sea and fresh water. The couples phosphorus bronze $<$ 316 stainless steel and phosphorus bronze $<$ Monel also resulted in a surprising amount of galvanic corrosion. In both seawater and fresh water, contact with Monel caused greater galvanic corrosion in phosphorus bronze than any other metal it was coupled with including 316 stainless steel. The corrosion rates of bronze strips contacting Monel plates were increased from 0.5 to 10.0 mpy for marine and 0.05 to 0.9 mpy for lake exposure.

Bimetallic Couples, Atmospheric Exposure

Table A6 gives the 1-year, 4-year, and 16-year results for the atmospheric coupled discs (8-year results were not determined). These are all approximately equal-area couples, with 1.2 to 1.3 sq in. exposed. The coupling is indicated by the "approximately equal" symbol ($\approx$). For example, (58) $\approx$ (35) indicates a disc couple with metal 58 attached to an approximately equal exposed area of metal 35. Each value represents the average of duplicate couples. With these specimens much of the corrosion is on the edges of the discs, and corrosion from such exposures is unrelated to average penetration, so values are given in weight loss as grams per square decimeter (g/dm^2); however, if comparisons of metals of different densities are desired, use of the specific gravities shown in Tables 3 to 6 and the conversion equation on page 14 will put them on a volume-of-metal-lost basis. Also, with the atmospheric disc couples no normal corrosion values are provided; this is because the great difference in size and shape between the coupled discs and the uncoupled panels does not afford a good basis for comparison. The best evaluation can be obtained by relating to the self-coupling data determined for the more important metals in the study.

(a) Continuous immersion in tropical seawater (Pacific Ocean, Canal Zone; weight loss, 353 g)

(b) Alternate immersion in tropical seawater, mean tide exposure (Pacific Ocean, Canal Zone; weight loss, 214 g)

(c) Continuous immersion in tropical fresh water (Gatun Lake, Canal Zone; weight loss, 63 g)

Fig. 11 — Comparative loss of zinc-strip anodes coupled to 2% nickel steel plates for 8 years of exposure in three different underwater environments

In the atmospheric studies, the tropical marine exposures generally resulted in about four to eight times as much galvanic corrosion as at the tropical inland location. In regard to the effects on less noble metals, the position of austenitic 316 stainless steel (No. 58) and Monel (No. 47) changed from their ranking in seawater, where Monel was somewhat more aggressive. In the atmosphere, of all the noble metals tested the 316 alloy caused the greatest amount of galvanic corrosion, almost double the amounts with Monel cathodes. The effect of 301 stainless was almost equal to that of 316.

As can be seen from the foregoing underwater and atmospheric data, the extremely noble position in the galvanic series for the austenitic stainless steels and the nickel-copper alloy makes these materials hazardous for use in unfavorable area ratios with almost any other construction metal. In simple exposures these noble metals are very resistant in most natural environments, except in stagnant or slowly moving seawater, where they are susceptible to heavy pitting. However, when they are used in structures where they are in contact with other metals, they are galvanically protected and can survive undamaged for years in seawater. Inspection of such bimetallic or polymetallic structures can often lead to misjudgment of the true corrosion resistance of the metals involved and to misapplication in other metallic structures for sea immersion.

The above is only one example of corrosion mistakes that can arise from an insufficient understanding of galvanic effects. It is hoped that the considerable amount of galvanic test data presented in this report will prove of value in establishing guidelines for selection of materials for exposure in natural environments.

SUMMARY

This final report on corrosion of metals in natural environments provides 16-year time-corrosion curves for all metals that have not been previously reported in full: cast bronzes, wrought pure metals, and cast and wrought ferrous metals. Further, tabulated summaries of results cover the above and all other metals and bimetallic couples exposed in all five environments: seawater, mean tide, fresh water, and marine and inland atmospheres.

Cast bronzes are frequently used in naval applications; curves for five of these cast alloys show that they have very good long-term resistance to corrosion in all exposures and exceptionally high resistance at mean tide and in fresh water.

Commercially pure metals are best suited for evaluating alloys and the corrosiveness of environments. The lead, nickel, copper, zinc, and aluminum curves show a considerable variation in order of resistance in the different environments. Aluminum had the lowest corrosion rate in all exposures except lake water immersion.

Curves for 15 structural ferrous metals in the marine and inland atmosphere show a considerable advantage for the low-alloy "weathering" steels over plain carbon steels. A 5% chromium steel with 1/2% molybdenum showed even higher resistance and should make a most excellent material for use in unpainted structures.

Copper-bearing steels are no more resistant than plain carbon steel in either atmospheric environment. Aston process wrought iron was equal to carbon steel in the marine atmosphere but was slightly less resistant in the inland atmosphere.

The marine atmosphere was about 1.3 times more corrosive to wrought steels than the inland location, but for cast iron and steel there was little difference.

A very large amount of bimetallic corrosion information, most of which has not been previously reported, is presented in tabular summaries. From these results it was found that carbon steel is a very effective anode for more noble metals; strips of steel effectively protected stainless steels, etc., for periods in excess of 8 years in seawater, and through 16 years at mean tide. In fresh water, cathodic protection was not very effective. However, when the anodes were smaller than the cathodes, the anodes were significantly damaged by galvanic action in this medium.

Bimetallic corrosion results for the atmospheric exposures reveal that the marine atmosphere caused 4 to 8 times more galvanic corrosion than the inland atmosphere.

The above are only a few general results from the large amount of data included. The significance of this final report is not in the few conclusions presented, but rather in that all the results from this very extensive study have been condensed here into a single report where one may study the results of particular interest, whether it be individual metals, groups of alloys, general corrosion, pitting, environmental effects, or galvanic corrosion.

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Appendix A

SUMMARY OF RESULTS FOR ALL EXPOSURES

Tables A1 through A6 give detailed data on corrosion loss, average penetration, pitting, etc., for all metals in various conditions of exposure — seawater and lake water immersion, and mean-tide seawater immersion.

Table A1
Corrosion Damage for Nonferrous Metals Exposed as Simple Plates in Aqueous Environments

Metals: Type	Metals: Surface Condition*	Metals: Ident. No.	Exposure S=Seawater Immersion M=Seawater Mean Tide L=Lake Water Immersion	General Corrosion: Weight Loss (g/dm^2)			General Corrosion: Average Penetration (mils)			General Corrosion: Steady-State Rate† (mpy)	Pitting Penetration (mils) (20-pit average)‡		
				1 yr	8 yr	16 yr	1 yr	8 yr	16 yr		1 yr	8 yr	16 yr
Lead (99.9% Pb)	As received	80	S	1.7	8.2	14.0	0.6	2.9	4.9	0.3	<5	23	28(48)
			M	2.3	4.7	8.3	0.8	1.6	2.9	0.1	<5	20	24(34)
			L	0.1	1.9	3.3	0.0	0.7	1.1	0.03	<5	<5	8(28)
Nickel (99% Ni)	As received	49	S	5.4	28.4	43.4	2.4‖	13.0‖	19.0‖	1.4‖	125	120	192(P)
			M	0.8	5.8	9.9	0.4	2.6	4.4	0.2	<5	65	61(121)
			L	0.0	0.0	0.1	0.0	0.0	0.0	0.01	<5	<5	<5
Nickel-copper (Monel: 70Ni-30Cu, cold rolled)	As received	47	S	3.7	14.2	19.5	1.6	6.3	8.7	0.3	17	40	34(55)
			M	0.2	3.0	6.0	0.1	1.3	2.7	0.2	<5	14	14(24)
			L	0.0	0.3	1.4	0.0	0.1	0.6	0.04	<5	12	17(53)
Nickel-copper (Monel: 70Ni-30Cu, hot rolled)	As received	48	S	4.7	14.4	18.7	2.1	6.4	8.4	0.3	43	50	56(82)
			M	0.3	3.1	5.7	0.1	1.4	2.6	0.2	<5	17	24(36)
			L	—¶	—	—	—	—	—	—	—	—	—
Copper-nickel (70Cu-30Ni)	As received	46	S	1.2	3.4	5.1	0.5	1.5	2.3	0.1	<5	<5	<5(37)
			M	0.2	1.0	1.7	0.1	0.4	0.8	0.04	<5	<5	<5(<5)
			L	0.4	2.2	3.0	0.2	1.0	1.3	0.04	<5	<5	<5(<5)
Copper (99.9% Cu)	As received	40	S	2.7	12.0	13.6	1.2	5.3	6.0	0.09	20	28	31(57)
			M	1.5	2.5	3.0	0.7	1.1	1.3	0.02	<5	10	<5(23)
			L	0.5	1.9	2.3	0.2	0.8	1.0	0.02	<5	<5	<5
Silicon bronze (2.5% Si)	As received	19	S	3.4	11.9	12.8	1.6	5.4	5.9	0.2	14	20	18(80)
			M	1.6	3.4	4.5	0.7	1.5	2.0	0.1	<5	13	14(65)
			L	0.7	2.2	2.4	0.3	1.0	1.2	0.02	<5	<5	<5(9)
Phosphor bronze (4Sn-0.25P)	As received	18	S	2.4	9.1	12.4	1.1	4.0	5.5	0.2	<5	<5	19(35)
			M	1.1	4.6	7.9	0.5	2.1	3.5	0.2	<5	<5	<5(11)
			L	0.3	1.0	1.6	0.1	0.5	0.7	0.04	<5	<5	<5(<5)
Aluminum bronze (5%Al)	As received	16	S	0.4	1.6	2.6	0.2	0.8	1.3	0.1	<5	<5	<5(21)
			M	0.2	0.8	1.2	0.1	0.4	0.6	0.02	<5	<5	<5(<5)
			L	0.1	0.6	0.9	0.1	0.3	0.4	0.02	<5	<5	<5(<5)
Commercial bronze (10%Zn)	As received	15	S	2.0	10.6	11.0	0.9	4.7	4.9	0.1	—	25	33(51)
			M	0.9	1.6	2.3	0.4	0.7	1.0	0.04	<5	<5	<5(11)
			L	0.5	2.3	3.0	0.2	1.0	1.3	0.05	<5	<5	<5(<5)
Low brass (20%Zn)	As received	14	S	1.4	6.5	8.2	0.7	3.0	3.7	0.1	<5	33	22(53)
			M	0.7	1.1	1.4	0.3	0.5	0.7	0.1	<5	<5	<5(<5)
			L	0.6	2.5	3.6	0.3	1.2	1.7	0.06	<5	<5	<5(<5)
Cartridge brass (30%Zn)	As received	13	S	1.0	5.3	7.8	>0.5**	>2.4**	>3.6**	**	**	**	**
			M	0.4	0.8	1.9	>0.2**	>0.4**	>0.9**	**	**	**	**
			L	0.8	2.8	3.9	0.3	1.3	1.8	0.1	<5	<5	<5(<5)
Naval brass (39Zn+1Sn)	As received	12	S	6.3	15.0	26.5	>2.9**	>7.0**	>12.4**	**	**	**	**
			M	2.0	8.6	12.7	>1.0**	>4.0**	>6.0**	**	**	**	**
			L	0.7	3.3	4.0	>0.3**	>1.6**	>1.9**	**	**	**	**
Muntz brass (40Zn-0.25As)	As received	10	S	2.4	9.1	17.3	>1.1**	>4.3**	>8.2**	**	**	**	**
			M	1.7	7.7	12.0	>0.8**	>3.6**	>5.7**	**	**	**	**
			L	1.2	5.0	7.4	>0.5**	>2.4**	>3.5**	**	**	**	**
Manganese brass (41Zn+Sn+Fe)	As received	17	S	6.5	25.0	36.6	>3.0**	>11.0**	>17.2**	**	**	**	**
			M	2.1	8.2	16.0	>1.0**	>3.8**	>7.5**	**	**	**	**
			L	0.4	1.3	2.0	0.2	0.6	0.9	0.04	<5	<5	<5(<5)
Cast bronze (Ounce metal)	Machined	60	S	1.5	5.4	8.4	0.7	2.5	4.1	0.2	<5	20	21(33)
			M	1.1	2.0	2.7	0.5	0.9	1.2	0.03	<5	<5	<5(<5)
			L	0.1	0.5	0.9	<0.1	0.3	0.4	0.02	<5	<5	<5(<5)
Cast bronze (Valve metal)	Machined	67	S	1.4	6.1	10.9	0.7	2.8	5.2	0.3	6	18	16(44)
			M	1.0	2.2	2.9	0.5	1.0	1.4	0.04	<5	8	9(18)
			L	0.1	0.5	0.8	<0.1	0.2	0.4	0.02	<5	<5	<5(<5)
Cast tin bronze (9%Sn)	Machined	68	S	1.6	8.0	11.3	0.8	3.8	5.4	0.2	16	21	24(50)
			M	0.7	2.3	2.9	0.3	1.1	1.4	0.04	<5	<5	<5(<5)
			L	0.1	0.3	0.7	<0.2	0.1	0.3	0.02	<5	<5	<5(<5)
Cast nickel-tin bronze (6Ni-3Sn)	Machined	69	S	2.5	8.3	13.0	1.2	3.8	6.0	0.3	9	14	23(37)
			M	0.9	1.8	2.5	0.4	0.8	1.2	0.04	<5	<5	<5(13)
			L	0.2	0.8	1.2	0.1	0.4	0.5	0.02	<5	<5	<5(<5)
Zinc (99.5%Zn)	As received	7	S	3.2	9.1	14.9	1.8	5.0	8.2	0.4	14	53	62(107)
			M	3.7	8.2	13.2	2.1	4.6	7.3	0.3	11	24	29(41)
			L	0.7	5.6	7.9	0.4	3.3	4.4	0.1	<5	13	18(33)
Aluminum (6061T)	As received	2	S	0.2	0.5	0.6	0.3	0.7	0.9	0.03	<5	23	14(79)
			M	<0.1	<0.1	0.2	<0.1	0.1	0.3	0.02	<5	<5	17(41)
			L	<0.1	0.5	1.0	0.1	0.8‖	1.5‖	0.3‖	11	59	96(107)
Aluminum (1100: 99% Al)	As received	1	S	0.2	0.5	0.7	0.3	0.7	1.0	0.03	6	11	17(33)
			M	0.0	0.2	0.4	0.1	0.3	0.5	0.02	10	14	39(67)
			L	0.3	1.6	3.5	0.4	2.3‖	5.0‖	0.3‖	24	61	98(109)
Magnesium (AZ31X: 3Al-1Zn)	As received	5	S	3.2	13.8	—	7.2	31.3	—	‖	193	P(P)	—
			M	6.0	17.6	—	13.1	39.3	—	‖	102	P(P)	—
			L	1.7	5.5	—	3.8	7.6	—	1.0	<5	24(35)	—

* All samples were degreased before exposure.
† Slope of linear portion of time-corrosion curve or, if nonlinear, the slope of the tangent at 16 years.
‡ Twenty-pit average is determined from the five deepest pits on each surface of duplicate panels. The deepest pit during the 16 years' exposure is shown in parentheses. Perforation is shown by a "P".
‖ Deep local-action pitting; average penetration values not appropriate.
¶ Dash indicates value not determined.
** Selective dealloying prevents determination of a precise value.

Table A2
Corrosion Damage for Nonferrous Metals Exposed as Simple Plates in Atmospheric Environments

Metals			Exposure Environments K=Marine M=Inland	General Corrosion							Pitting Penetration (mils) (20-pit average)‡		
				Weight Loss (g/dm^2)			Average Penetration (mils)			Steady-State Rate† (mpy)			
Type	Surface Condition*	Ident. No.		1 yr	8 yr	16 yr	1 yr	8 yr	16 yr		1 yr	8 yr	16 yr
Lead (99.9% Pb)	As received	80	K	0.17	1.22	2.28	0.06	0.42	0.79	0.05	<5	<5	<5(<5)
			M	0.09	0.69	1.61	0.03	0.24	0.56	0.04	<5	<5	<5(<5)
Lead-coated steel	As received	89	K	0.23	1.02	—‖	0.08	0.36	—	—	<5	<5(<5)	—
			M	0.14	0.79	—	—	—	—	—	<5	<5(<5)	—
Nickel (99% Ni)	As received	49	K	0.02	0.13	0.26	0.01	0.06	0.11	<0.01	<5	<5	<5(<5)
			M	0.01	0.09	0.21	0.01	0.04	0.10	<0.01	<5	<5	<5(<5)
Nickel-copper (Monel: 70 Ni - 30 Cu, cold rolled	As received	47	K	0.10	0.26	0.49	0.04	0.12	0.22	0.01	<5	<5	<5(<5)
			M	0.02	0.14	0.30	0.01	0.06	0.14	<0.01	<5	<5	<5(<5)
Nickel silver	As received	45	K	0.09	0.49	0.83	0.08	0.44	0.74	0.02	<5	<5	<5(<5)
			M	0.04	0.29	0.63	0.02	0.13	0.28	0.02	<5	<5	<5(<5)
Copper nickel (70 Cu - 30 Ni)	As received	46	K	0.08	0.52	0.93	0.03	0.23	0.41	0.02	<5	<5	<5(<5)
			M	0.04	0.30	0.62	0.02	0.13	0.28	0.02	<5	<5	<5(<5)
Copper (99.9% Cu)	As received	40	K	0.37	1.29	1.73	0.17	0.57	0.76	0.03	<5	<5	<5(<5)
			M	0.18	0.43	0.60	0.08	0.19	0.26	0.01	<5	<5	<5(<5)
Silicon bronze (2.5 Si - 1 Zn)	As received	19	K	0.67	2.36	4.06	0.31	1.08	1.86	0.09	<5	<5	<5(<5)
			M	0.35	0.82	1.33	0.16	0.38	0.61	0.03	<5	<5	<5(<5)
Phosphor bronze (4 Sn - 0.25P)	As received	18	K	0.44	1.37	2.16	0.19	0.61	0.96	0.04	<5	<5	<5(<5)
			M	0.13	0.56	0.81	0.06	0.25	0.36	0.01	<5	<5	<5(<5)
Aluminum bronze (5% Al)	As received	16	K	0.18	0.47	0.84	0.09	0.22	0.39	0.02	<5	<5	<5(<5)
			M	0.10	0.28	0.52	0.04	0.13	0.25	0.01	<5	<5	<5(<5)
Commercial bronze (10% Zn)	As received	15	K	0.25	0.67	0.10	0.11	0.30	0.50	0.02	<5	<5	<5(<5)
			M	0.11	0.42	0.71	0.05	0.19	0.32	0.01	<5	<5	<5(<5)
Low brass (20% Zn)	As received	14	K	0.18	0.49	0.81	0.08	0.22	0.37	0.02	<5	<5	<5(5)
			M	0.08	0.35	0.65	0.04	0.16	0.29	0.02	<5	<5	<5(<5)
Cartridge brass (30% Zn)	As received	13	K	0.11	0.39	0.72	0.05	0.18	0.33	0.02	<5	<5	<5(<5)
			M	0.05	0.26	0.54	0.02	0.12	0.25	0.01	<5	<5	<5(<5)
Naval brass (39 Zn - 1 Sn)	As received	12	K	0.13	0.44	0.81	0.06	0.20	0.38	0.02	<5	<5	<5(8)
			M	0.07	0.30	0.61	0.03	0.14	0.28	0.01	<5	<5	<5(5)
Muntz brass (40 Zm- 0.25 As)	As received	10	K	0.14	0.48	0.97	0.06	0.14	0.27	0.03	<5	<5	<5(5)
			M	0.09	0.34	0.68	0.04	0.16	0.32	0.01	<5	<5	<5(<5)
Manganese brass (41 Zn + Sn + Fe)	Machined	17	K	0.38	0.70	1.26	0.18	0.33	0.60	0.03	<5	<5	<5(<5)
			M	0.33	0.45	1.07	0.15	0.21	0.50	0.02	<5	<5	<5(<5)
Cast bronze (Ounce metal)	Machined	60	K	0.37	1.36	1.94	0.18	0.63	0.90	0.02	<5	<5	<5(6)
			M	0.11	0.52	0.84	0.05	0.25	0.39	0.01	<5	<5	<5(33)
Cast bronze (Valve Metal)	Machined	67	K	0.36	0.94	1.41	0.17	0.44	0.66	0.03	<5	<5	<5(<5)
			M	0.13	0.51	0.75	0.06	0.24	0.35	<0.01	<5	16	<5(84)
Cast tin bronze (9% Sn)	Machined	68	K	0.38	1.13	1.77	0.18	0.53	0.84	0.04	<5	<5	<5(6)
			M	0.11	0.61	0.91	0.05	0.29	0.43	<0.01	—	<5	<5(<5)
Cast nickel tin bronze (6 Ni - 3 Sn)	Machined	69	K	0.29	0.91	1.34	0.13	0.42	0.61	0.02	<5	<5	<5(<5)
			M	0.12	0.63	0.95	0.05	0.29	0.43	<0.01	<5	<5	<5(<5)
Zinc (99.5% Zn)	As received	7	K	0.43	1.91	2.94	0.23	1.05	1.62	0.07	<5	9(15)	<5(<5)
			M	0.09	0.38	0.98	0.05	0.21	0.54	0.03	<5	<5	<5(<5)
Galvanized steel	As received	8	K	0.47	1.72	—	0.26	0.95	—	—	<5	<5(<5)	—
			M	0.05	0.39	—	0.06	0.66	—	—	<5	<5(<5)	—
Zinc-sprayed steel	As received	9	K	0.09	1.20	—	—	—	—	—	<5	6(7)	—
			M	0.16	0.73	—	—	—	—	—	<5	<5(6)	—
Aluminum (6061T)	As received	2	K	0.02	0.02	0.08	0.02	0.02	0.09	<0.01	<5	<5	<5(<5)
			M	0.01	0.01	0.06	0.01	0.02	0.06	<0.01	<5	<5	<5(<5)
Aluminum (1100:99% Al)	As received	1	K	0.01	0.01	0.08	0.01	0.01	0.60	<0.01	<5	<5	<5(<5)
			M	0.01	0.02	0.05	0.01	0.02	0.04	<0.01	<5	<5	<5(<5)
Alclad (2400T)	As received	3	K	0.02	0.01	0.09	0.02	0.02	0.13	<0.01	<5	<5	<5(<5)
			M	0.01	0.00	0.05	0.01	0.00	0.07	<0.01	<5	<5	<5(<5)
Aluminum-sprayed steel	As received	4	K	0.01	0.00	—	0.00	0.00	—	—	<5	<5	<5(<5)
			M	0.05	0.00	—	0.04	0.00	—	—	<5	<5	<5(<5)
Magnesium (AZ61X)	As received	6	K	0.22	2.84	5.35	0.48	6.21	11.22	0.75	7	10	16 (20)
			M	0.17	1.48	3.52	0.36	3.24	7.71	0.56	<5	1	11 (20)
Magnesium (AZ31X)	As received	5	K	0.48	3.54	6.78	1.06	7.82	15.05	0.94	7	20	22 (34)
			M	0.27	2.05	4.23	0.60	4.55	9.39	0.60	<5	9	15 (20)

*All samples were degreased before exposure.
†Slope of linear portion of *time-corrosion* curve or, if nonlinear, the slope of the tangent at 16 years.
‡Twenty-pit average is determined from the five deepest pits on each surface of duplicate panels.
The deepest pit during the 16 years exposure is shown in parentheses. Perforation is shown by a "P."
‖Dash indicates value not determined.

Table A3
Corrosion Damage for Ferrous Metals Exposed As Simple Plates in Aqueous Environment

Metals: Type	Metals: Surface Condition*	Metals: Ident. No.	Exposure (S=Seawater Immersion, M=Seawater Mean Tide, L=Lake Water Immersion)	General Corrosion: Weight Loss (g/dm^2) 1 yr	Weight Loss 8 yr	Weight Loss 16 yr	Average Penetration (mils) 1 yr	Average Penetration 8 yr	Average Penetration 16 yr	Steady-State Rate† (mpy)	Pitting Penetration (mils) (20-pit average)‡ 1 yr	Pitting 8 yr	Pitting 16 yr
Carbon steel (0 24% C)	Pickled	35	S	11.8	50.9	90.8	5.9	25.5	48.1	2.7	41	66	90(155)
			M	18.8	46.3	94.5	9.5	23.2	45.2	2.7	16	40	66(98)
			L	15.2	43.7	56.2	7.7	21.9	26.0	0.7	20	58	72(93)
Carbon steel (0.24% C)	Machined	36	S	11.0	53.9	98.7	5.5	27.1	49.5	2.7	38	58	102(P)
			M	21.0	49.5	83.5	10.5	24.9	41.9	2.5	21	45	52(124)
			L	15.0	40.3	48.8	7.5	20.2	24.5	0.6	22	60	65(94)
Carbon steel (0.24% C)	Millscale	34	S	8.4	46.5	123.9	4.2	23.3	62.2	¶	55	167	240(P)
			M	18.4	36.9	87.0	9.3	18.5	43.7	2.8	18	43	54(109)
			L	12.6	37.7	50.7	6.3	18.9	25.4	0.7	29	48	66(91)
Carbon steel (Copper-bearing: 0.31 Cu - 0.22 C)	Pickled	37	S	11.8	55.3	98.1	5.9	27.7	49.3	2.7	36	63	85(124)
			M	22.4	48.3	92.1	11.2	24.3	46.2	2.8	24	45	51(67)
			L	15.7	46.4	57.1	7.9	23.3	28.7	0.7	22	64	64(89)
Low-alloy steel (Cu - Ni)	Pickled	26	S	11.7	52.6	96.7	5.9	26.4	48.4	2.7	54	82	130(P)
			M	23.7	79.3	98.0	11.8	39.7	49.1	3.3	—¶	70	68(134)
			L	12.1	32.6	43.9	6.0	16.3	22.0	0.7	17	67	75(110)
Low-alloy steel (Cu - Cr - Si)	Pickled	27	S	13.6	85.7	160.4	6.9	43.1	80.5	4.8	31	80	99(P)
			M	21.4	41.9	98.0	10.8	21.1	49.3	3.4	20	47	60(72)
			L	11.3	33.1	48.4	5.7	16.7	24.4	0.9	40	79	88(112)
Low-alloy steel (Cu - Ni- Mn - Mo)	Pickled	28	S	12.8	50.9	89.8	6.4	25.5	45.1	2.5	27	56	71(139)
			M	21.6	49.3	122.6	10.8	24.8	61.5	3.6	23	40	59(147)
			L	14.5	44.6	62.1	7.3	22.4	31.2	1.1	24	81	101(124)
Low-alloy steel (Cr - Ni- Mn)	Pickled	29	S	12.6	87.4	167.5	6.3	43.9	84.0	5.0	26	96	237(P)
			M	18.2	40.9	91.3	9.1	20.5	45.8	2.9	19	39	61(93)
			L	10.7	31.1	53.4	5.4	16	26.5	1.2	40	111	113(146)
Nickel steel (2% Ni)	Pickled	20	S	14.8	63.0	104.1	7.4	31.7	52.0	2.7	33	94	139(P)
			M	17.7	45.6	110.1	8.9	22.9	55.3	3.7	22	39	70(83)
			L	14.7	40.2	43.6	7.4	20.2	22.0	0.3	19	63	66(89)
Nickel steel (5% Ni)	Pickled	23	S	12.5	63.7	102.7	6.3	32.0	51.6	2.7	29	117	115(P)
			M	15.6	39.8	107.6	7.8	20.0	54.0	3.7	<15	39	62(91)
			L	13.1	46.8	59.4	6.6	24.0	29.8	0.8	18	69	71(100)
Chromium steel (3% Cr)	Pickled	24	S	4.1	80.4	140.0	2.1	40.4	70.4	3.8	11	65	93(109)
			M	22.1	51.1	95.7	11.1	25.7	48.2	3.5	24	82	192(P)
			L	4.8	19.3	29.3	2.4	9.7	14.7	0.7	24	54	77(98)
Chromium steel (5% Cr)	Pickled	25	S	5.3	63.5	118.9	2.7	32.0	60.0	3.5	27	63	69(100)
			M	23.3	48.6	94.1	11.7	24.5	47.4	3.6	28	88	153(P)
			L	3.8	17.1	26.7	1.9	8.6	13	0.6	23	52	67(96)
Wrought Iron (Aston Process)	Machined	290	S	12.7	43.8	—	6.5	22.2	—	—	34	63(138)	—
			M	14.3	32.3	—	7.3	16.4	—	—	17	35(49)	—
			L	15.0	28.9	—	7.6	14.6	—	—	27	50(89)	—
Wrought Iron (Aston Process)	Millscale	190	S	12.5	51.5	86.4	6.3	26.1	43.8	2.5	46	83	127(P)
			M	11.9	33.9	71.2	6.1	17.2	36.1	2.4	17	35(41)	—
			L	14.6	37.2	—	7.4	18.9	—	—	18	54(80)	—
Cast steel (0.27% C)	Machined	70	S	14.7	55.2	86.1	7.4	27.8	43.3	2.5	56	84	103(146)
			M	15.9	42.3	97.5	7.9	21.3	49.1	3.4	35	53	91(159)
			L	16.2	38.2	52.4	8.2	19.2	26.3	0.9	30	67	98(140)
Gray cast iron (3.2%C)	Machined	78	S	17.8	103.5	170.1	9.9	57.6	94.6	5.8	42	97(160)	—
			M	46.0	81.8	156.6	25.6	45.5	87.1	4.9	55	100(P)	—
			L	12.5	41.4	59.1	7.0	23.0	32.9	1.2	52	106	108(P)
Austenitic cast iron (18% Ni)	Machined	79	S	6.0	27.3	41.2	3.3	15.1	22.8	1.1	<5	42	67(116)
			M	3.0	7.0	13.3	1.6	3.9	7.3	1.3	<5	17	30(40)
			L	1.6	7.6	14.5	0.9	4.2	8.0	0.4	9	27	37(61)
410 Stainless steel (13% Cr)	As received	50	S	6.0	28.1	46.8	3.1‖	14.3‖	23.9‖	‖	61(P)	161(P)	212(P)
			M	1.0	6.7	12.6	0.5	3.4‖	6.4‖	‖	46	67	107(P)
			L	0.0	1.1	1.8	0.0	0.5	0.9‖	‖	<5	<5	94(P)
302 Stainless steel (18 Cr - 8 Ni)	As received	57	S	2.9	11.0	18.7	1.5‖	5.5‖	9.5‖	‖	70(P)	140	151(P)
			M	0.4	1.8	3.3	0.2	0.9	1.6	‖	6	58	50(110)
			L	0.0	0.0	0.0	0.0	0.0	0.0	0.0	<5	<5	<5(<5)
316 Stainless steel (18 - 13 + Mo)	As received	58	S	1.2	4.1	1.6	0.6‖	2.0‖	0.8‖	‖	45(P)	156(P)	95(P)
			M	0.1	0.4	0.2	0.1	0.2	0.1	‖	5	16	13(36)
			L	0.0	0.0	0.0	0.0	0.0	0.0	0.0	<5	<5	<5(<5)
321 Stainless steel (17 - 10 + Ti)	As received	59	S	2.3	10.0	14.6	1.2‖	5.0‖	7.3‖	‖	64	193(P)	237(P)
			M	0.3	1.3	2.3	0.1	0.7	1.1	‖	7	56	55(93)
			L	0.0	0.0	0.0	0.0	0.0	0.0	0.0	<5	<5	<5(<5)

* All samples were degreased before exposure.
† Slope of linear protion of time-corrosion curve or, if nonlinear, the slope of the tangent at 16 years.
‡ Twenty-pit average is determined from the five deepest pits on each surface of duplicate panels.
The deepest pit during the 16 years' exposure is shown in parentheses. Perforation is shown by a "P".
‖ Deep local action pitting—average penetration not appropriate.
¶ Dash indicates value not determined.

Table A4
Corrosion Damage for Ferrous Metals Exposed as Simple Plates in Atmospheric Environments

Metals: Type	Metals: Surface Condition*	Metals: Ident. No.	Exposure Environment K=Marine M=Inland	General Corrosion: Weight Loss (g/dm^2) 1 yr	Weight Loss 8 yr	Weight Loss 16 yr	Average Penetration (mils) 1 yr	Average Penetration 8 yr	Average Penetration 16 yr	Steady-State Rate† (mpy)	Pitting Penetration (mils) (20-pit average)‡ 1 yr	Pitting 8 yr	Pitting 16 yr
Ingot iron (Low Cu)	Pickled	30	K	7.87	‖	‖	3.96	‖	‖	—¶	16	‖	‖
			M	5.71	29.53	51.86	2.86	14.82	26.03	2.2	<5	35	46(74)
Wrought iron (Aston process)	Pickled	90	K	5.41	21.76	36.73	2.75	11.07	18.70	0.95	12	29	53(61)
			M	3.35	13.56	23.98	1.76	6.90	12.21	0.62	<5	16	22(37)
Wrought iron (Aston process)	Millscale	190	K	5.34	21.78	31.17	2.72	11.08	15.86	—	<5	41	49(61)
			M	3.27	14.07	23.47	1.66	7.16	11.94	—	8	20	40(59)
Carbon steel (0.24% C)	Pickled	35	K	5.02	20.28	31.49	2.52	10.18	15.81	0.84	11	34	51(123)
			M	2.73	12.58	22.77	1.37	6.31	11.43	0.60	<5	17	22(33)
Carbon steel (0.24% C)	Millscale	34	K	5.16	21.83	31.52	2.59	10.95	15.82	—	10	37	52(123)
			M	2.98	12.79	23.87	1.50	6.42	11.98	—	<5	17	27(45)
Carbon steel (0.24% C)	Machined	36	K	3.92	13.52	21.19	1.97	6.79	10.64	0.47	<5	14	18(39)
			M	2.75	10.05	17.14	1.38	5.04	8.60	0.43	<5	14	19(26)
ASTM "K" iron (0.26 Cu - 0.08 C)	Pickled	38	K	4.10	16.47	—	2.06	8.28	—	0.76	14	30	—
			M	2.57	10.06	—	1.29	5.06	—	0.53	<5	13	—
Copper-bearing steel (0.24 Cu – 0.27 C)	Pickled	37	K	4.34	17.46	27.10	2.18	8.76	13.60	0.76	10	31	30(66)
			M	2.75	10.96	18.63	1.38	5.50	9.35	0.57			
Cast steel (0.27% C)	Machined	70	K	3.47	10.97	16.97	1.75	5.52	8.53	0.43	<5	14	17(36)
			M	2.46	8.88	14.95	1.24	4.46	7.52	0.38	<5	15	18(31)
Low-alloy steel (Cu - Ni)	Pickled	26	K	3.43	10.01	16.45	1.72	5.02	7.80	0.41	6	12	14(17)
			M	2.24	6.84	11.29	1.12	3.43	5.67	0.26	<5	11	17(22)
Low-alloy steel (Cu - Cr - Si)	Pickled	27	K	3.38	10.16	15.96	1.70	5.11	8.03	0.41	10	12	18(35)
			M	1.97	5.77	8.51	0.99	2.90	4.28	0.18	<5	10	17(27)
Low-alloy steel (Cu - Ni - Mn - Mo)	Pickled	28	K	3.43	9.74	14.69	1.72	4.90	7.39	0.38	8	12	16(36)
			M	2.10	6.86	11.39	1.05	3.45	5.73	0.27	<5	12	15(21)
Low-alloy steel (Cr - Ni - Mn)	Pickled	29	K	3.33	8.98	12.56	1.67	4.51	6.30	0.31	<5	12	13(29)
			M	2.29	6.36	9.99	1.15	3.19	5.03	0.22	<5	12	14(20)
Nickel steel (2% Ni)	Pickled	20	K	3.07	7.48	11.41	1.54	3.75	5.73	0.26	<5	11	13(19)
			M	1.85	5.65	8.46	0.93	2.83	4.25	0.17	<5	11	15(21)
Nickel steel (5% Ni)	Pickled	23	K	2.67	7.07	10.62	1.34	3.55	5.34	0.25	8	12	12(15)
			M	1.99	5.32	8.32	1.00	2.67	4.19	0.17	<5	10	14(21)
Chromium steel (3% Cr)	Pickled	24	K	3.93	9.04	13.19	1.98	4.56	6.66	0.31	11	18	24(63)
			M	2.06	3.71	4.50	1.04	1.87	2.28	0.07	8	10	13(17)
Chromium steel (5% Cr)	Pickled	25	K	3.21	6.05	8.81	1.62	3.56	4.45	0.20	11	11	13(19)
			M	1.58	2.29	2.73	0.80	1.15	1.38	0.06	<5	<5	<5(9)
Gray cast iron (3.2% C)	Machined	78	K	2.74	9.41	13.86	1.62	5.23	7.70	0.32	<5	14	18(37)
			M	1.76	7.03	10.67	0.98	3.91	5.98	0.26	<5	15	22(37)
Austenitic cast iron (18% Ni)	Machined	79	K	1.77	8.00	16.60	0.98	4.43	9.19	0.60	<5	22	41(59)
			M	0.96	3.08	5.30	0.53	1.70	2.90	0.23	<5	6	<5(9)
410 Stainless steel (13% Cr)	As received	50	K	0.08	0.08	0.35	0.04	0.04	0.18	<0.01	<5	<5	<5(<5)
			M	0.01	0.00	0.02	0.00	0.00	0.01	0.00	<5	<5	<5(<5)
430 Stainless steel (17% Cr)	As received	56	K	0.05	0.07	0.17	0.02	0.04	0.08	<0.01	<5	<5	<5(<5)
			M	0.00	0.13	0.02	0.00	0.07	0.01	0.00	<5	<5	<5(<5)
301 Stainless steel (17 Cr - 7 Ni)	As received	57	K	0.01	0.01	0.03	0.01	0.01	0.02	<0.01	<5	<5	<5(<5)
			M	0.00	0.01	0.00	0.00	0.00	0.00	0.00	<5	<5	<5(<5)
321 Stainless steel (17 - 10 + Ti)	As received	59	K	0.01	0.02	0.05	0.00	0.01	0.02	0.00	<5	<5	<5(<5)
			M	0.00	0.00	0.00	0.00	0.00	0.00	0.00	<5	<5	<5(<5)
316 Stainless steel (18 - 13 + Mo)	As received	58	K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	<5	<5	<5(<5)
			M	0.00	0.00	0.00	0.00	0.00	0.00	0.00	<5	<5	<5(<5)

*All samples were degreased before exposure.
†Slope of linear portion of time-corrosion curve or, if nonlinear, the slope of the tangent at 16 years.
‡Twenty-pit average is determined from the five deepest pits on each surface of duplicate panels. The deepest pit during the 16 years' exposure is shown in parentheses. Perforation of a panel is shown by a "P."
¶Dash indicates value not determined.
‖Panels completely corroded.

Table A5
Corrosion Damage for Metals Exposed as Bimetallic Couples in Aqueous Environments

Couple: Strip (2 × 9 × 1/4 in.)	Couple	Couple: Plate (9 × 9 × 1/4 in.)	Strip Metal Average Penetration (mils): Seawater 1 yr	Strip Seawater 8 yr	Strip Seawater 16 yr	Strip Mean Tide 1 yr	Strip Mean Tide 8 yr	Strip Mean Tide 16 yr	Strip Fresh Water 1 yr	Strip Fresh Water 8 yr	Strip Fresh Water 16 yr	Plate Metal Average Penetration (mils): Seawater 1 yr	Plate Seawater 8 yr	Plate Seawater 16 yr	Plate Mean Tide 1 yr	Plate Mean Tide 8 yr	Plate Mean Tide 16 yr	Plate Fresh Water 1 yr	Plate Fresh Water 8 yr	Plate Fresh Water 16 yr
316 Stainless steel (18 - 13 + Mo)	[58] < [35]	Carbon steel (0.24% C)	0.0	0.0	0.1 (2.0)	0.1	0.0	0.1 (0.2)	0.0	0.0	0.0 (0.0)	7.9	28.3	49.5 (48.1)	12.2	24.7	43.7 (45.2)	8.0	25.1	32.4 (26.0)
316 Stainless steel (18 - 13 + Mo)	[58] < [12]	Naval brass (39 Zn - 1 Sn)	0.0	0.0	0.0 (2.0)	0.0	0.0	0.0 (0.2)	0.0	0.0	0.0 (0.0)	3.9	9.3	16.2 (12.4)	1.0	4.7	7.7 (6.0)	0.4	2.0	2.5 (1.9)
316 Stainless steel (18 - 13 + Mo)	[58] < [18]	Phosphor bronze (4 Sn - 0.25 P)	0.0	0.0	0.0 (2.0)	0.0	0.0	0.0 (0.2)	0.0	0.0	0.0 (0.0)	1.6	6.0	9.4 (5.5)	0.7	3.4	6.1 (3.5)	0.2	0.7	0.7 (0.7)
316 Stainless steel (18 - 13 + Mo)	[58] < [58]	316 Stainless steel (18 - 13 + Mo)	0.0	0.3	3.1 (2.0)	0.0	0.1	0.1 (0.2)	0.0	0.0	0.0 (0.0)	0.0	0.6	1.3 (2.0)	0.0	0.0	0.1 (0.2)	0.0	0.0	0.0 (0.0)
302 Stainless steel (18 Cr - 8 Ni)	[57] < [35]	Carbon steel (0.24% C)	0.0	0.0	0.2 (9.3)	0.1	0.0	0.1 (1.6)	0.0	0.0	0.0 (0.0)	7.5	27.3	50.6 (48.1)	11.7	23.0	47.2 (45.2)	8.1	25.0	31.7 (26.0)
302 Stainless steel (18 Cr - 8 Ni)	[57] < [57]	302 Stainless steel (18 Cr - 8 Ni)	0.1	5.7	8.2 (9.3)	0.2	0.5	1.3 (1.6)	0.0	0.1	0.1 (0.0)	0.3	4.5	7.6 (2.0)	0.1	0.7	1.2 (0.2)	0.0	0.0	0.0 (0.0)
Nickel (99% Ni)	[49] < [35]	Carbon steel (0.24% C)	0.0	0.0	0.1 (19.3)	0.0	0.0	0.1 (4.4)	0.0	0.0	0.0 (0.0)	7.7	29.9	50.8 (48.1)	12.0	21.4	42.3 (45.2)	7.7	23.7	29.1 (26.0)
Nickel-copper (Monel: 70 Ni - 30 Cu, cold rolled)	[47] < [35]	Carbon steel (0.24% C)	0.0	0.0	0.1 (8.7)	0.0	0.0	0.1 (2.7)	0.0	0.0	0.0 (0.6)	8.0	27.8	51.2 (48.1)	10.5	23.0	42.8 (45.2)	7.9	22.3	28.6 (26.0)
Nickel-copper (Monel: 70 Ni - 30 Cu, cold rolled)	[47] < [47]	Nickel-copper (Monel: 70 Ni - 30 Cu, cold rolled)	3.6	6.9	17.2 (8.7)	0.1	2.3	4.3 (8.7)	0.2	1.3	1.3 (0.6)	1.4	6.9	9.7 (8.7)	0.1	1.3	2.7 (2.7)	0.0	0.1	0.4 (0.6)
Copper-nickel (70 Cu - 30 Ni)	[46] < [35]	Carbon steel (0.24% C)	0.0	0.0	0.1 (2.3)	0.0	0.0	0.1 (0.8)	0.0	0.0	0.1 (1.3)	7.6	29.8	50.4 (48.1)	12.3	21.0	53.0 (45.2)	7.9	22.8	29.8 (26.0)
Phosphor bronze (4 Sn - 0.25 P)	[18] < [1]	Aluminum (1100: 99% Al)	0.2	0.3	0.7 (5.5)	0.1	0.2	0.4 (3.5)	0.0	0.0	0.1 (0.7)	1.7	3.6	6.5 (1.0)	1.3	2.3	6.0 (0.5)	1.5	6.6	12.4 (5.0)
Phosphor bronze (4 Sn - 0.25 P)	[18] < [8]	Galvanized steel	0.0	0.1 (4.0)	—†	0.1	0.1 (2.1)	—	0.0	0.0 (0.5)	—									
Phosphor bronze (4 Sn - 0.25 P)	[18] < [35]	Carbon steel (0.24% C)	0.1	0.2	0.4 (5.5)	0.2	0.1	0.4 (3.5)	0.1	0.1	0.1 (0.7)	7.5	29.6	55.1 (48.1)	11.3	22.3	46.4 (45.2)	8.7	24.5	28.9 (26.0)
Phosphor bronze (4 Sn - 0.25 P)	[18] < [37]	0.3% Cu steel	0.2	0.2 (4.0)	—	0.1	0.2 (2.1)	—	0.1	0.2 (0.5)	—	7.8	32.6 (49.3)	—	14.2	25.8 (46.2)	—	8.0	23.0 (28.7)	—
Phosphor bronze (4 Sn - 0.25 P)	[18] < [26]	Low-alloy steel (Cu - Ni)	0.1	0.1	0.5 (5.5)	0.1	0.1	0.4 (3.5)	0.0	0.1	0.1 (0.7)	7.4	28.8	53.3 (48.4)	13.1	34.5	56.0 (49.1)	6.7	18.0	23.0 (22.0)
Phosphor bronze (4 Sn - 0.25 P)	[18] < [27]	Low-alloy steel (Cu - Cr - Si)	0.2	0.3	0.5 (5.5)	0.1	0.1	0.3 (3.5)	0.1	0.1	0.2 (0.7)	8.1	43.9	78.5 (80.7)	10.8	25.9	59.8 (49.3)	6.2	18.1	24.1 (24.4)
Phosphor bronze (4 Sn - 0.25 P)	[18] < [28]	Low-alloy steel (Cu - Ni - Mn - Mo)	0.1	0.2	0.6 (5.5)	0.1	0.2	0.4 (3.5)	0.1	0.1	0.1 (0.7)	7.4	26.6	48.3 (45.1)	11.2	21.2	56.3 (61.0)	7.6	22.7	31.8 (31.2)
Phosphor bronze (4 Sn - 0.25 P)	[18] < [29]	Low-alloy steel (Cr - Ni - Mn)	0.1	0.2	0.5 (5.5)	0.1	0.1	0.3 (3.5)	0.1	0.1	0.1 (0.7)	8.0	45.0	99.6 (84.1)	9.9	24.3	65.2 (45.8)	6.0	16.4	25.6 (26.8)
Phosphor bronze (4 Sn - 0.25 P)	[18] < [20]	Nickel steel (2% Ni)	0.1	0.2	0.5 (5.5)	0.1	0.1	0.4 (3.5)	0.0	0.1	0.2 (0.7)	7.9	31.9	60.8 (52.0)	8.6	23.5	55.9 (55.0)	8.2	21.7	24.6 (21.1)
Phosphor bronze (4 Sn - 0.25 P)	[18] < [24]	Chromium steel (3% Cr)	0.2	0.3	0.6 (5.5)	0.2	0.3	0.4 (3.5)	0.1	0.1	0.2 (0.7)	2.2	43.4	86.5 (70.4)	10.9	29.7	57.2 (48.1)	3.0	11.2	16.2 (14.7)
Phosphor bronze (4 Sn - 0.25 P)	[18] < [70]	Cast steel (0.27% C)	0.1	0.2	0.3 (5.5)	0.1	0.1	0.3 (3.5)	0.1	0.2	0.1 (0.7)	8.3	29.8	51.6 (43.3)	10.0	22.6	48.5 (49.1)	8.2	18.2	30.1 (26.3)
Phosphor bronze (4 Sn - 0.25 P)	[18] < [78]	Gray cast iron (3.2% C)	0.1	0.2	0.3 (5.5)	0.0	0.2	0.3 (3.5)	0.0	0.2	0.1 (0.7)	10.0	59.4	104.7 (94.6)	19.4	51.8	76.2 (87.1)	5.2	23.5	33.3 (32.9)
Phosphor bronze (4 Sn - 0.25 P)	[18] < [79]	Austenitic cast iron (18% Ni)	0.1	0.1	0.3 (5.5)	0.1	0.1	0.2 (3.5)	0.6	0.2	0.0 (0.7)	4.2	15.1	27.3 (22.8)	1.9	5.0	10.2 (7.3)	1.3	7.0	13.3 (8.0)
Phosphor bronze (4 Sn - 0.25 P)	[18] < [46]	Copper-nickel (70 Cu - 30 Ni)	1.6	3.3	4.6 (5.5)	0.7	1.3	1.6 (3.5)	0.1	0.4	0.5 (0.7)	0.6	2.0	3.8 (2.3)	0.1	0.6	1.0 (0.8)	0.2	1.0	1.3 (1.3)
Phosphor bronze (4 Sn - 0.25 P)	[18] < [47]	Nickel-copper (Monel: 70 Ni - 30 Cu, cold rolled)	2.7	86.3	71.8 (5.5)	1.7	14.9	19.0 (3.5)	1.6	8.8	14.1 (0.7)	0.3	2.0	7.0 (8.7)	0.1	1.0	2.2 (2.7)	0.0	0.4	0.8 (0.6)
Phosphor bronze (4 Sn - 0.25 P)	[18] < [50]	410 Stainless steel (13% Cr)	0.5	0.4	0.7 (5.5)	0.4	0.6	0.7 (3.5)	0.2	0.7	0.9 (0.7)	3.5	14.7	24.7 (23.9)	0.6	4.2	8.8 (6.4)	0.1	1.4	3.3 (0.9)
Phosphor bronze (4 Sn - 0.25 P)	[18] < [57]	302 Stainless steel (18 Cr - 8 Ni)	7.8	16.3	21.9 (5.5)	1.1	8.5	13.7 (3.5)	0.5	4.1	3.8 (0.7)	0.0	3.8	6.3 (9.3)	0.1	0.4	1.0 (1.1)	0.0	0.0	0.0 (0.0)
Phosphor bronze (4 Sn - 0.25 P)	[18] < [58]	316 Stainless steel (18 - 13 + Mo)	22.8	37.4	41.3 (5.5)	3.2	21.9	29.8 (3.5)	0.3	1.7	1.8 (0.7)	0.0	0.2	0.2 (2.0)	0.0	0.0	0.0 (0.2)	0.0	0.0	0.0 (0.0)
Aluminum bronze (5% Al)	[16] < [35]	Carbon steel (0.24% C)	0.1	0.1	0.4 (1.3)	0.1	0.1	0.4 (0.6)	0.0	0.1	0.2 (0.4)	7.4	28.6	57.6 (48.1)	10.6	23.7	46.1 (45.2)	8.5	23.1	28.0 (26.0)
Low brass (80 Cu - 20 Zn)	[14] < [35]	Carbon steel (0.24% C)	0.1	0.1	0.4 (3.7)	0.1	0.1	0.5 (0.7)	0.1	0.2	0.2 (1.7)	7.4	29.2	54.4 (48.1)	12.0	20.0	44.3 (45.2)	8.6	24.9	29.4 (26.0)
Naval brass (39 Zn - 1 Sn)	[12] < [35]	Carbon steel (0.24% C)	0.1	0.1	0.2 (12.4)	0.2	0.1	0.3 (6.0)	0.1	0.1	0.2 (1.9)	7.2	29.7	54.4 (48.1)	13.4	22.8	45.1 (45.2)	8.6	23.8	28.0 (26.0)
Copper (99.9% Cu)	[40] < [35]	Carbon steel (0.24% C)	2.0	3.0	7.0 (6.0)	2.0	3.0	6.0 (1.3)	0.0	1.0	3.0 (1.0)	7.6	29.5	54.9 (48.1)	11.9	23.0	42.7 (45.2)	7.8	23.9	30.6 (26.0)
Lead (99.9% Pb)	[80] < [35]	Carbon Steel (0.24% C)	0.7	0.6	1.1 (14.0)	0.6	1.5	3.9 (8.3)	0.2	1.4	2.4 (3.3)	7.2	28.9	48.5 (48.1)	11.5	23.7	43.8 (45.2)	8.0	23.3	30.7 (26.0)
Nickel steel (5% Ni)	[23] < [35]	Carbon steel (0.24% C)	3.7	9.2	27.1 (51.6)	3.9	7.8	26.5 (54.0)	4.5	12.9	16.3 (29.8)	6.9	27.8	47.3 (48.1)	11.4	20.8	46.6 (45.2)	8.8	21.2	28.9 (26.0)
Carbon steel (0.24% C)	[35] < [1]	Aluminum (1100: 99% Al)	0.5	0.5	0.6 (48.1)	0.7	0.8	2.3 (45.2)	8.7	13.3	15.9 (26.0)	1.5	5.1	7.1 (1.0)	1.0	2.5	6.6 (0.5)	0.4	5.2	11.5 (5.0)
Carbon steel (0.24% C)	[35] < [2]	Aluminum (6061T)	0.5	0.8	1.6 (48.1)	0.7	1.2	2.5 (45.2)	9.1	15.9	17.0 (26.0)	1.8	7.1	7.8 (0.9)	1.0	2.3	5.5 (0.3)	0.2	4.3	9.4 (1.5)
Carbon steel (0.24% C)	[35] < [8]	Galvanized steel	0.3	10.2 (25.5)	—	1.3	7.3 (23.2)	—	3.5	10.9 (21.9)	—									
Carbon steel (0.24% C)	[35] < [90]	Wrought iron (Aston process)	5.3	17.1 (25.5)	—	8.0	17.2 (23.2)	—	8.0	18.4 (21.9)	—	7.4	24.7 (22.2)	—	7.0	18.1 (16.4)	—	8.4	19.8 (14.6)	—
Carbon steel (0.24% C)	[35] < [35]	Carbon steel (0.24% C)	7.6	26.4 (25.5)	60.0 (48.1)	7.8	16.7	47.2 (45.2)	8.5	20.1	25.9 (26.0)	6.8	24.0	44.0 (48.1)	9.8	17.9	42.2 (45.2)	8.4	20.5	26.4 (26.0)

Table A5 (Continued)
Corrosion Damage for Metals Exposed as Bimetallic Couples in Aqueous Environments

Couple			Strip Metal Average Penetration (mils)									Plate Metal Average Penetration (mils)								
Strip (2 × 9 × 1/4 in.)		Plate (9 × 9 × 1/4 in.)	Seawater			Mean Tide			Fresh Water			Seawater			Mean Tide			Fresh Water		
			1 yr	8 yr	16 yr	1 yr	8 yr	16 yr	1 yr	8 yr	16 yr	1 yr	8 yr	16 yr	1 yr	8 yr	16 yr	1 yr	8 yr	16 yr
Carbon steel (0.24% C)	[35] < [37]	0.3% Copper steel	8.0	22.9 (25.5)	40.7 (48.1)	9.8	16.6	34.2 (45.2)	7.3	20.7	23.7 (26.0)	6.5	25.8	41.9 (49.3)	10.5	23.6	45.3 (46.2)	7.5	20.8	25.1 (28.7)
Carbon steel (0.24% C)	[35] < [20]	Nickel steel (2% Ni)	10.7	33.2 (25.5)	63.1 (48.1)	18.8	23.2	49.9 (45.2)	9.8	28.7	33.9 (26.0)	5.5	24.8	48.2 (52.0)	7.0	20.4	47.0 (55.3)	7.6	16.6	19.1 (22.0)
Carbon steel (0.24% C)	[35] < [60]	Cast bronze (Ounce metal)	36.9	151.4 (25.5)	M[‖]	24.4	103.4 (23.2)	M	16.0	58.7	77.3 (26.0)	0.0	0.1	3.1 (4.1)	0.1	0.2	0.3 (1.2)	0.0	0.1	0.3 (0.4)
Carbon steel (0.24% C)	[35] < [67]	Cast bronze (Valve metal)	36.0	185.0 (25.5)	M	19.9	81.1 (23.2)	M	14.9	56.7	69.0 (26.0)	0.1	0.1	1.9 (2.2)	0.1	0.1	0.1 (1.4)	0.0	0.1	0.2 (0.4)
Carbon steel (0.24% C)	[35] < [68]	Cast tin bronze (9% Sn)	35.2	164.0 (25.5)	M	21.0	87.0 (23.2)	M	15.1	52.0	61.0 (26.0)	0.1	0.1	2.5 (5.4)	0.1	0.2	0.2 (1.4)	0.0	0.1	0.2 (0.3)
Carbon steel (0.24% C)	[35] < [89]	Cast nickel-tin bronze (6 Ni - 3 Sn)	36.4	180.8 (25.5)	M	21.0	97.3 (23.2)	M	14.6	49.1	59.8 (26.0)	0.0	0.1	1.6 (6.0)	0.0	0.1	0.2 (1.2)	0.0	0.2	0.3 (0.5)
Carbon steel (0.24% C)	[35] < [10]	Muntz brass (40 Zn - 0.25 As)	37.2	161.8 (25.5)	M	36.3	126.8 (23.2)	M	14.6	61.4	77.4 (26.0)	0.1	0.1	5.2 (8.2)	0.2	0.3	0.9 (5.7)	0.2	1.0	1.5 (3.5)
Carbon steel (0.24% C)	[35] < [17]	Manganese brass (41 Zn + Sn + Fe)	34.8	158.7 (25.5)	M	32.7	106.2 (23.2)	M	13.7	45.9	66.4 (26.0)	0.1	0.1	7.9 (17.2)	0.2	0.3	1.5 (7.5)	0.1	0.3	0.4 (0.9)
Carbon steel (0.24% C)	[35] < [12]	Naval brass (39 Zn - 1 Sn)	35.2	176.5 (25.5)	M	34.6	118.9 (23.2)	M	13.9	47.7	64.3 (26.0)	0.1	0.1	7.4 (12.4)	0.3	0.3	0.7 (6.0)	0.1	0.5	0.8 (1.9)
Carbon steel (0.24% C)	[35] < [13]	Cartridge brass (30% Zn)	36.1	162.3 (25.5)	M	38.4	116.8 (23.2)	M	14.9	57.0	79.6 (26.0)	0.0	0.0	3.1 (3.6)	0.1	0.1	0.3 (0.9)	0.1	0.3	0.4 (1.8)
Carbon steel (0.24% C)	[35] < [14]	Low brass (20% Zn)	38.8	152.0 (25.5)	M	28.2	104.6 (23.2)	M	15.5	50.8	63.4 (26.0)	0.1	0.1	2.4 (3.7)	0.1	0.1	0.3 (0.7)	0.1	0.2	0.3 (1.7)
Carbon steel (0.24% C)	[35] < [15]	Commercial bronze (10% Zn)	37.9	155.6 (25.5)	M	21.3	93.9 (23.2)	M	14.1	50.9	67.7 (26.0)	0.1	0.1	3.1 (4.9)	0.0	0.1	0.2 (1.0)	0.0	0.2	0.2 (1.3)
Carbon steel (0.24% C)	[35] < [16]	Aluminum bronze (5% Al)	34.9	169.9 (25.5)	M	24.0	102.7 (23.2)	M	14.6	56.9	70.8 (26.0)	0.0	0.0	4.0 (1.3)	0.0	0.1	0.2 (0.6)	0.0	0.1	0.2 (0.4)
Carbon steel (0.24% C)	[35] < [18]	Phosphor bronze (4 Sn - 0.25 P)	35.1	172.1 (25.5)	M	25.2	96.2 (23.2)	M	14.3	45.6	65.5 (26.0)	0.1	0.1	1.9 (5.5)	0.1	0.2	0.2 (3.5)	0.1	0.2	0.3 (0.7)
Carbon steel (0.24% C)	[35] < [19]	Silicon bronze (2.5% Si)	35.8	177.6 (25.5)	M	21.5	96.3 (23.2)	M	15.4	57.2	72.9 (26.0)	0.1	0.2	2.7 (5.9)	0.1	0.2	0.3 (2.0)	0.1	0.2	0.3 (1.2)
Carbon steel (0.24% C)	[35] < [40]	Copper (99.9% Cu)	36.5	191.5 (25.5)	M	17.6	84.2 (23.2)	M	14.2	56.3	77.7 (26.0)	0.1	0.1	2.9 (6.0)	0.1	0.1	0.5 (1.3)	0.1	0.1	0.2 (1.0)
Carbon steel (0.24% C)	[35] < [46]	Copper-nickel (70 Cu - 30 Ni)	37.5	168.8 (25.5)	M	23.2	96.7 (23.2)	M	13.9	50.0	68.6 (26.0)	0.0	0.1	1.6 (2.3)	0.0	0.1	0.1 (0.8)	0.0	0.2	0.3 (1.3)
Carbon steel (0.24% C)	[35] < [47]	Nickel-copper (Monel: 70 Ni - 30 Cu, cold rolled)	34.2	157.7 (25.5)	M	23.3	92.2	191.5 (45.2)	12.7	40.0	60.9 (26.0)	0.0	0.1	2.4 (6.7)	0.0	0.1	0.1 (2.7)	0.0	0.0	0.0 (0.8)
Carbon steel (0.24% C)	[35] < [49]	Nickel (99% Ni)	39.5	175.1 (25.5)	M	20.3	86.4	184.8 (45.2)	11.8	48.0	71.3 (26.0)	0.0	0.0	4.8 (19.0)	0.0	0.1	0.3 (4.4)	0.0	0.0	0.2 (0.0)
Carbon steel (0.24% C)	[35] < [50]	410 Stainless steel (13% Cr)	32.8	159.9 (25.5)	M	22.2	73.7	178.4 (45.2)	11.8	45.2	56.4 (26.0)	0.2	0.1	9.2 (23.9)	0.1	0.1	0.5 (6.4)	0.0	0.0	0.0 (0.9)
Carbon steel (0.24% C)	[35] < [57]	302 Stainless steel (18 Cr - 8 Ni)	34.7	146.4 (25.5)	M	22.7	88.9	175.6 (45.2)	11.8	41.1	52.7 (26.0)	0.0	0.0	0.8 (9.5)	0.0	0.0	0.0 (1.6)	0.0	0.0	0.0 (0.0)
Carbon steel (0.24% C)	[35] < [58]	316 Stainless steel (18 - 13 + Mo)	34.7	140.6 (25.5)	M	22.6	81.9	175.4 (45.2)	10.5	33.3	44.4 (26.0)	0.0	0.0	0.0 (0.8)	0.0	0.0	0.0 (0.1)	0.0	0.0	0.0 (0.0)
Wrought iron (Aston process)	[90] < [35]	Carbon steel (0.24% C)	11.8	40.2 (22.2)	72.6 (—)	9.2	17.4 (16.4)	44.3 (—)	7.9	23.0 (14.6)	30.0 (—)	6.2	21.9	37.0 (48.1)	10.0	19.7	43.0 (45.3)			
Zinc (99.5% Zn)	[7] < [35]	Carbon steel (0.24% C)	31.5	148.1	195.6 (14.9)	37.3	102.5	194.2 (13.2)	2.7	24.2	43.1 (7.9)	0.7	0.9	15.5 (48.1)	1.1	0.9	2.0 (45.2)	7.0	17.6	19.9 (26.0)
Zinc (99.5% Zn)	[7] < [37]	0.3% Copper steel	31.9	157.5 (9.1)	—	37.3	91.4 (8.2)	—	2.9	22.6 (5.6)	—	0.4	3.6 (49.3)	—	1.0	0.7 (46.2)	—	8.5	19.7 (28.7)	—
Zinc (99.5% Zn)	[7] < [20]	Nickel steel (2% Ni)	30.3	138.3 (9.1)	M	52.5	85.8	191.5 (13.2)	2.9	24.8	36.6 (7.9)	0.4	0.3	14.9 (52.0)	1.7	0.9	2.6 (55.3)	6.7	15.0	17.4 (22.8)
Zinc (99.5% Zn)	[7] < [70]	Cast steel (0.2% C)	30.7	145.4 (9.1)	197.5	52.1	118.7	194.0 (13.2)	2.7	22.9	45.6 (7.9)	0.4	0.4	11.4 (43.3)	1.5	1.0	5.1 (49.1)	7.4	16.6	21.9 (26.3)
Zinc (99.5% Zn)	[7] < [79]	Austenitic cast iron (18% Ni)	37.3	119.3 (9.1)	M	19.3	101.8	126.3 (13.2)	5.0	13.9	23.7 (7.9)	0.0	0.0	0.1 (22.8)	0.0	0.0	0.0 (7.3)	0.7	3.9	7.7 (8.0)
Aluminum (1100: 99% Al)	[1] < [35]	Carbon steel (0.24% C)	26.7	131.1 (1.0)	M	23.9	83.6 (0.5)	M	0.4	10.7	39.9 (5.0)	0.7	0.6	16.9 (48.1)	0.8	1.3	2.4 (45.2)	7.4	18.8	21.7 (26.0)

*[58] < [35]: Indicates a couple consisting of a strip of metal No. 58 with an exposed area of 21.9 in.^{2} attached to a plate of metal No. 35 with an exposed area of 151.4 in.^{2} (area ratio = 1:6.9).
†Values in parentheses show the normal uncoupled corrosion loss.
‡Dash indicates value not determined.
‖"M" indicates that strips were missing—probably completely corroded.

Table A6
Corrosion Damage for Metals Exposed as Bimetallic Couples in Atmospheric Environments

Couple			Metal A (g/dm^2)						Metal B (g/dm^2)					
Metal A		Metal B	Marine			Inland			Marine			Inland		
			1 yr	4 yr	16 yr	1 yr	4 yr	16 yr	1 yr	4 yr	16 yr	1 yr	4 yr	16 yr
316 Stainless steel (18 - 13 + Mo)	[58] ≈ [35]	Carbon steel* (0.24% C)	0.14	0.92	0.98	0.02	0.01	0.53	15.21	30.51	72.98	3.64	8.19	22.95
316 Stainless steel (18 - 13 + Mo)	[58] ≈ [18]	Phosphor bronze (4 Sn - 0.25 P)	0.00	0.01	0.49	0.00	0.00	0.53	1.96	5.10	13.42	0.16	0.77	1.95
316 Stainless steel (18 - 13 + Mo)	[58] ≈ [58]	316 Stainless steel (18 - 13 + Mo)	0.01	0.07	0.54	0.00	0.00	0.35	0.01	0.04	0.66	0.00	0.00	0.50
321 Stainless steel (17 - 10 + Ti)	[59] ≈ [35]	Carbon steel (0.24% C)	0.11	0.14	0.66	0.02	0.04	0.70	15.56	25.77	61.99	3.88	8.49	22.06
301 Stainless steel (17 Cr - 7 Ni)	[57] ≈ [35]	Carbon steel (0.24% C)	0.07	0.14	0.45	0.02	0.03	0.27	14.16	26.73	72.05	3.49	8.47	22.83
301 Stainless steel (17 Cr - 7 Ni)	[57] ≈ [18]	Phosphor bronze (4 Sn - 0.25 P)	0.00	0.03	0.23	0.00	0.01	0.21	1.74	4.21	13.87	0.18	0.66	1.82
301 Stainless steel (17 Cr - 7 Ni)	[57] ≈ [57]	301 Stainless steel (17 Cr - 7 Ni)	0.08	0.34	0.75	0.00	0.04	0.18	0.05	0.25	0.63	0.00	0.01	0.20
430 Stainless steel (17% Cr)	[56] ≈ [35]	Carbon steel (0.24% C)	0.12	0.29	1.60	0.02	0.04	1.31	13.08	25.54	55.48	3.75	8.62	22.89
430 Stainless steel (17% Cr)	[56] ≈ [18]	Phosphor bronze (4 Sn - 0.25 P)	0.10	1.04	1.47	0.01	0.02	1.41	1.32	3.32	6.44	0.17	0.81	1.96
410 Stainless steel (13% Cr)	[50] ≈ [35]	Carbon steel (0.24% C)	0.26	0.37	2.02	0.08	0.39	1.63	12.13	23.83	56.15	4.05	9.24	24.66
410 Stainless steel (13% Cr)	[50] ≈ [18]	Phosphor bronze (4 Sn - 0.25 P)	0.73	1.10	2.65	0.01	0.03	1.62	0.92	1.90	5.59	0.23	0.72	2.00
Nickel (99% Ni)	[49] ≈ [35]	Carbon steel (0.24% C)	0.13	0.35	0.77	0.02	0.08	0.35	10.87	20.29	52.04	3.15	7.59	18.54
Nickel-copper (Monel: 70 Ni - 30 Cu, cold rolled)	[47] ≈ [18]	Phosphor bronze (4 Sn - 0.25 P)	0.16	0.38	0.92	0.04	0.14	0.53	0.86	1.92	6.38	0.15	0.63	1.87
Nickel-copper (Monel: 70 Ni - 30 Cu, cold rolled)	[47] ≈ [35]	Carbon steel (0.24% C)	0.15	0.23	0.89	0.04	0.09	0.46	9.77	21.27	45.47	3.58	8.02	20.26
Nickel-copper (Monel: 70 Ni - 30 Cu, cold rolled)	[47] ≈ [47]	Nickel-copper (Monel: 70 Ni - 30 Cu, cold rolled)	0.12	0.23	0.48	0.03	0.10	0.66	0.15	0.51	0.92	0.03	0.09	0.50
Copper-nickel (70 Cu - 30 Ni)	[46] ≈ [35]	Carbon steel (0.24% C)	0.20	0.45	1.60	0.14	0.34	1.36	9.35	19.04	39.21	3.47	7.93	19.44
Copper-nickel (70 Cu - 30 Ni)	[46] ≈ [18]	Phosphor bronze (4 Sn - 0.25 P)	0.21	0.66	1.91	0.12	0.47	1.82	1.06	1.94	4.80	0.09	0.49	1.01
Nickel silver	[45] ≈ [35]	Carbon steel (0.24% C)	0.32	0.70	1.91	0.19	0.47	1.93	8.69	17.38	33.80	3.49	8.01	18.13
Copper (99.9% Cu)	[40] ≈ [35]	Carbon steel (0.24% C)	0.67	1.34	2.92	0.37	0.65	2.25	9.42	20.42	40.51	4.13	9.71	23.87
Silicon bronze (2.5 Si - 1 Zn)	[19] ≈ [35]	Carbon steel (0.24% C)	1.18	1.43	3.42	0.74	1.31	3.00	10.99	20.06	53.09	3.62	9.04	22.83
Phosphor bronze (4 Sn - 0.25 P)	[18] ≈ [6]	Magnesium (AZ61X)	0.17	0.93	1.98	0.06	0.09	0.37	3.03	10.13	30.97	1.44	5.50	11.32
Phosphor bronze (4 Sn - 0.25 P)	[18] ≈ [1]	Aluminum (1100: 99% Al)	0.29	0.64	0.87	0.14	0.41	0.79	0.95	6.16	11.55	0.18	0.85	1.60
Phosphor bronze (4 Sn - 0.25 P)	[18] ≈ [3]	Alclad (2024T)	0.31	1.17	2.84	0.16	0.33	1.30	3.39	5.46	10.03	0.44	4.11	5.65
Phosphor bronze (4 Sn - 0.25 P)	[18] ≈ [7]	Zinc (99.5% Zn)	0.34	0.73	1.15	0.15	0.33	0.69	2.12	5.47	11.34	0.76	1.75	4.35
Phosphor bronze (4 Sn - 0.25 P)	[18] ≈ [8]	Galvanized steel	0.31	0.64	1.82	0.09	0.27	0.69	4.01	7.92	—†	1.28	2.41	—
Phosphor bronze (4 Sn - 0.25 P)	[18] ≈ [35]	Carbon steel (0.24% C)	0.71	0.98	1.90	0.26	0.79	1.54	11.27	21.01	41.87	3.76	9.29	22.39
Phosphor bronze (4 Sn - 0.25 P)	[18] ≈ [26]	Low-alloy steel (Cu - Ni)	0.91	1.43	3.04	0.16	0.67	1.07	7.05	14.95	28.20	3.06	7.72	15.60
Phosphor bronze (4 Sn - 0.25 P)	[18] ≈ [27]	Low-alloy steel (Cu - Cr - Si)	0.81	1.76	3.48	0.28	0.42	1.32	7.02	15.10	27.21	2.76	6.41	14.81
Phosphor bronze (4 Sn - 0.25 P)	[18] ≈ [28]	Low-alloy steel (Cu - Ni - Mn - Mo)	0.80	1.97	4.48	0.24	0.61	1.64	6.71	15.18	36.44	2.91	7.30	17.50
Phosphor bronze (4 Sn - 0.25 P)	[18] ≈ [29]	Low-alloy steel (Cr - Ni - Mn)	0.72	1.65	2.92	0.25	0.54	1.28	7.49	16.01	26.86	2.68	7.23	15.06
Phosphor bronze (4 Sn - 0.25 P)	[18] ≈ [18]	Phosphor bronze (4 Sn - 0.25 P)	1.03	2.12	4.52	0.12	0.55	1.18	1.18	2.16	5.97	0.14	0.48	1.05
Aluminum bronze (5% Al)	[16] ≈ [35]	Carbon steel (0.24% C)	0.44	0.65	1.64	0.26	0.42	1.03	9.48	18.86	41.12	3.96	9.70	22.94
Commercial bronze (10% Zn)	[15] ≈ [35]	Carbon steel (0.24% C)	0.60	0.69	2.89	0.27	0.44	2.15	7.88	16.42	40.32	3.48	8.39	18.29
Low brass (20% Zn)	[14] ≈ [35]	Carbon steel (0.24% C)	0.54	0.80	2.92	0.24	0.57	2.24	8.88	16.68	41.10	3.48	8.39	18.29
Cartridge brass (30% Zn)	[13] ≈ [35]	Carbon steel (0.24% C)	0.55	1.07	3.12	0.21	0.63	1.98	6.85	13.36	31.42	3.46	7.40	16.21
Naval brass (39 Zn - 1 Sn)	[12] ≈ [35]	Carbon steel (0.24% C)	0.61	1.00	2.67	0.25	0.51	1.69	7.51	14.44	29.27	3.86	7.34	15.96
Muntz brass (40 Zn - 0.25 As)	[10] ≈ [35]	Carbon steel (0.24% C)	0.91	1.17	2.51	0.29	0.60	1.83	7.96	12.28	32.59	3.50	7.47	17.22
Manganese brass (41 Zn - 10 Fe)	[17] ≈ [35]	Carbon steel (0.24% C)	1.25	1.94	4.16	1.06	1.43	2.74	7.37	14.83	26.43	3.38	7.27	15.24
Cast bronze (Ounce metal)	[60] ≈ [35]	Carbon steel (0.24% C)	0.57	0.99	2.41	0.22	0.56	2.06	10.22	23.33	50.69	4.32	11.29	28.89

Table A6 (Continued)
Corrosion Damage for Metals Exposed as
Bimetallic Couples in Atmospheric Environments

Couple			Metal A (g/dm²)						Metal B (g/dm²)					
Metal A		Metal B	Marine			Inland			Marine			Inland		
			1 yr	4 yr	16 yr	1 yr	4 yr	16 yr	1 yr	4 yr	16 yr	1 yr	4 yr	16 yr
Cast bronze (Valve metal)	[67] ≈ [35]	Carbon steel (0.24% C)	0.59	0.99	2.05	0.22	0.49	1.74	13.73	25.19	53.29	4.99	11.26	29.50
Cast tin bronze (9% Sn)	[68] ≈ [35]	Carbon steel (0.24% C)	0.51	0.87	2.14	0.21	0.55	1.35	13.05	22.81	58.35	5.19	12.57	28.23
Cast nickel tin bronze (6 Ni - 3 Sn)	[69] ≈ [35]	Carbon steel (0.24% C)	0.49	1.09	2.23	0.25	0.61	1.51	11.61	24.83	48.78	4.69	11.39	27.84
Lead (99.9% Pb)	[80] ≈ [35]	Carbon steel (0.24% C)	3.64	7.98	32.90	2.15	4.05	11.26	3.84	5.17	7.39	1.87	3.99	8.31
Lead-coated steel	[89] ≈ [35]	Carbon steel (0.24% C)	5.27	11.02	–	2.51	20.35	–	4.86	8.29	19.58	2.47	4.59	11.03
Austenitic cast iron (18% Ni)	[79] ≈ [7]	Zinc (99.5% Zn)	0.66	0.89	1.29	0.65	1.10	1.33	1.91	5.07	13.11	0.75	1.83	5.28
Austenitic cast iron (18% Ni)	[79] ≈ [35]	Carbon steel (0.24% C)	2.40	4.79	31.62	1.18	2.99	6.42	7.46	17.53	39.49	3.75	7.75	17.07
Gray cast iron (3.2% C)	[78] ≈ [35]	Carbon steel (0.24% C)	4.47	8.65	19.18	2.20	3.88	9.55	6.83	19.95	66.59	3.28	8.59	23.49
Gray cast iron (3.2% C)	[78] ≈ [7]	Zinc (99.5% Zn)	1.64	1.55	3.72	1.44	2.06	3.51	2.06	5.55	12.59	0.81	2.32	5.74
Cast steel (0.27% C)	[70] ≈ [35]	Carbon steel (0.24% C)	6.86	12.09	26.71	3.49	7.11	13.75	6.99	14.60	30.29	2.90	6.82	18.78
Cast steel (0.27% C)	[70] ≈ [7]	Zinc (99.5% Zn)	1.82	2.18	2.81	1.76	2.80	3.44	2.30	5.73	12.15	0.85	2.32	5.98
Chromium steel (5% Cr)	[25] ≈ [35]	Carbon steel (0.24% C)	5.36	7.81	13.10	2.12	3.01	3.92	7.15	16.27	48.26	3.37	8.83	23.24
Chromium steel (3% Cr)	[24] ≈ [35]	Carbon steel (0.24% C)	7.81	8.92	13.73	2.52	3.42	5.11	8.38	16.72	43.02	3.36	9.16	21.13
Nickel steel (5% Ni)	[23] ≈ [35]	Carbon steel (0.24% C)	5.20	8.49	21.14	2.81	7.33	15.20	8.41	14.89	29.45	3.05	6.31	13.39
Nickel steel (2% Ni)	[20] ≈ [7]	Zinc (99.5% Zn)	1.75	2.36	1.87	1.11	1.18	1.36	2.41	6.44	12.79	0.94	2.03	4.80
Nickel steel (2% Ni)	[20] ≈ [35]	Carbon steel (0.24% C)	5.02	8.10	16.00	2.92	6.00	10.71	8.14	17.55	41.33	3.67	6.83	16.57
Low-alloy steel (Cu - Ni)	[26] ≈ [35]	Carbon steel (0.24% C)	5.25	7.56	15.10	2.03	5.40	9.43	8.13	15.72	37.39	3.03	6.34	18.33
Low-alloy steel (Cu - Cr - Si)	[27] ≈ [35]	Carbon steel (0.24% C)	5.76	6.05	12.03	2.62	2.96	6.33	8.83	17.15	43.93	3.22	7.42	20.38
Low-alloy steel (Cu - Ni - Mn - Mo)	[28] ≈ [35]	Carbon steel (0.24% C)	5.17	7.41	14.45	2.27	5.25	8.77	7.34	14.35	38.89	3.34	7.45	20.15
Low-alloy steel (Cr - Ni - Mn)	[29] ≈ [35]	Carbon steel (0.24% C)	5.30	8.18	13.02	2.11	4.52	5.67	8.78	18.07	49.78	3.24	8.05	22.83
Copper-bearing steel (0.24 Cu - 0.27 C)	[37] ≈ [35]	Carbon steel (0.24% C)	6.46	9.96	20.38	2.62	5.86	12.03	8.20	16.15	41.65	2.84	6.80	17.91
Wrought iron (Aston process)	[90] ≈ [35]	Carbon steel (0.24% C)	7.38	11.48	–	3.38	6.68	–	7.38	11.48	–	3.38	6.68	–
Millscale-coated carbon steel (0.24% C)	[34] ≈ [30]	Ingot iron (Low Cu)	6.41	11.96	30.30	3.24	6.96	13.72	14.63	37.91	75.60	6.83	14.09	43.33
Millscale-coated carbon steel (0.24% C)	[34] ≈ [35]	Carbon steel (0.24% C)	10.40	15.01	31.32	3.28	7.61	16.19	9.56	14.87	34.64	3.06	6.65	17.35
ASTM "K" iron (0.3% Cu)	[38] ≈ [35]	Carbon steel (0.24% C)	7.74	9.41	19.58	3.07	6.78	12.19	8.05	17.96	43.89	3.16	6.98	18.24
Carbon steel (0.24% C)	[35] ≈ [35]	Carbon steel (0.24% C)	6.31	15.43	33.93	3.06	6.91	17.16	5.35	14.38	30.72	2.78	6.37	16.26
Carbon steel (0.24% C)	[35] ≈ [5]	Magnesium (AZ31X: 3 Al - 1 Zn)	0.91	0.66	1.21	0.53	0.44	1.19	3.00	9.43	2.22	1.65	4.98	11.07
Carbon steel (0.24% C)	[35] ≈ [6]	Magnesium (AZ61X)	0.67	0.64	1.16	0.59	0.46	0.81	4.16	11.49	28.98	2.23	5.78	14.89
Carbon steel (0.24% C)	[35] ≈ [1]	Aluminum (1100: 99% Al)	2.28	1.92	2.76	3.68	4.69	6.09	1.84	6.68	16.52	0.28	0.98	1.89
Carbon steel (0.24% C)	[35] ≈ [2]	Aluminum (6061T)	2.54	2.20	2.93	3.94	4.88	6.29	1.44	5.12	14.42	0.28	0.89	2.02
Carbon steel (0.24% C)	[35] ≈ [3]	Alclad (2024T)	3.04	8.46	30.76	4.22	5.08	15.58	2.55	4.44	8.04	0.32	2.11	5.74
Carbon steel (0.24% C)	[35] ≈ [4]	Aluminum-sprayed steel	2.47	4.64	31.66	2.25	5.02	9.71	2.34	27.56	–	0.80	3.37	–
Carbon steel (0.24% C)	[35] ≈ [7]	Zinc (99.5% Zn)	1.79	1.79	2.63	1.31	1.24	2.12	2.56	5.94	13.17	1.12	2.25	5.57
Carbon steel (0.24% C)	[35] ≈ [8]	Galvanized steel	2.32	2.85	18.69	1.50	2.28	5.87	4.72	7.40	–	1.31	4.55	–
Carbon steel (0.24% C)	[35] ≈ [9]	Zinc-sprayed steel	1.96	2.06	3.15	1.63	1.89	2.50	2.39	5.79	14.39	1.17	3.13	9.43
Galvanized steel	[8] ≈ [8]	Galvanized steel	3.36	3.91	–	0.69	1.66	–	3.51	3.58	–	1.33	1.63	–
Aluminum (6061T)	[2] ≈ [6]	Magnesium (AZ61X)	0.10	0.36	0.15	0.01	0.10	0.12	0.95	3.93	11.04	0.63	2.17	5.72
Alclad (2024T)	[3] ≈ [6]	Magnesium (AZ61X)	0.48	1.13	1.21	0.01	0.17	0.58	1.24	5.60	13.83	0.69	2.67	6.42
Aluminum (1100: 99% Al)	[1] ≈ [6]	Magnesium (AZ61X)	0.07	0.35	0.39	0.03	0.17	0.35	0.98	4.81	11.62	0.59	2.36	6.54

*Indicates a couple consisting of metal discs with approximately equal exposed areas (0.54 in.²) (e.g., [58] ≈ [35]: Metal No. 58 coupled to Metal No. 35).
†Dash indicates value not determined.