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Corrosion of Metals in Tropical Environments

Part 9 - Structural Ferrous Metals - Sixteen Years' Exposure to Sea and Fresh Water

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PREVIOUS REPORTS IN THIS SERIES

"Part 1 – Test Methods Used and Results Obtained for Pure Metals anda Structural Steel," A. L. Alexander, B. W. Forgeson, H. W. Mundt, C. R. Southwell, and L. J. Thompson, NRL Report 4929, June 1957

"Part 2 – Atmospheric Corrosion of Ten Structural Steels," C. R. Southwell, B. W. Forgeson, and A. L. Alexander, NRL Report 5002, Dec. 1957

"Part 3 – Underwater Corrosion of Ten Structural Steels," B. W. Forgeson, C. R. Southwell, and A. L. Alexander, NRL Report 5153, Aug. 1958

"Part 4 – Wrought Iron," C. R. Southwell, B. W. Forgeson, and A. L. Alexander, NRL report 5370, Oct. 1959

"Part 5 – Stainless Steels," B. W. Forgeson, C. R. Southwell, and A. L. Alexander, NRL Report 5517, Sept. 1960

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"Part 7 – Copper znd Copper Alloys - 16 Years' Exposure," C. R. Southwell, C. W. Hummer, Jr., and A. L. Alexander, NRL Report 6452, Oct. 1966

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ABSTRACT

Effects of corrosion on 20 structural ferrous metals immersed in seawater and fresh water and exposed at mean-tide elevation have been measured at various intervals during 16 years. Corrosion rates and time-corrosion curves derived from both weight loss and pitting have been established. A brief state-of-the-knowledge review for seawater corrosion of ferrous metals reveals the paucity of adequate long-term data in the corrosion literature. Between 2 and 16 years' exposure, corrosion rates of most ferrous metals stabilized to constant values. These final constant rates provide the most significant data for comparing the corrosion resistance of the different metals in the various environments and for estimating service life over more extended periods. Based on this evaluation, the general corrosion rates of steels in seawater and fresh water are appreciably less than usually reported, and the long-term pitting rate of structural steel in seawater is only 1/3 to 1/5 of that normally reported for these metals.

The corrosion of various low-alloy steels has been compared during 16 years of seawater exposure. Of the alloying elements considered, none was found which improves the corrosion resistance of the metals in the sea, while chromium and nickel seemed to cause increased general corrosion or pitting during the longer periods of marine exposure. Aston-process wrought iron and various cast irons and steels have been evaluated for long-term seawater exposure. Only the 18% nickel cast iron shows any definite advantage over carbon steel. Steel corrosion losses in tropical and temperate latitude seawaters have been compared. Results indicate similar corrosion-time relations for the different latitudes but slightly higher final rates for the tropical sea. Useful upper-limit corrosion rates are thus provided by the tropical seawater studies.

PROBLEM STATUS

This is an interim report; work on the problem is continuing.

AUTHORIZATION

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CORROSION OF METALS IN TROPICAL ENVIRONMENTS

PART 9 - STRUCTURAL FERROUS METALS–SIXTEEN YEARS' EXPOSURE TO SEA AND FRESH WATER

INTRODUCTION

Recently increased interest in structures to be immersed in the sea for extended periods has focused attention on studies designed to establish the stability of structural materials in the ocean. Whereas floating designs, such as ships, can be drydocked periodically to inspect and repair the effects of corrosive degradation, this is not possible with fixed structures which must remain in place over extended periods. Prerequisite to intelligent decisions on the need for, and design of, protective procedures for these structures is a reasonable knowledge of the magnitude and direction of the normal corrosion-time relations for the structural metals involved.

The literature describing long-term corrosive effects of both seawater and fresh water has been relatively meager. In two instances in the last several decades when large permanent structures were being planned for construction in the sea, long-term corrosion programs were initiated to obtain data on which reliable specifications could be based. These two projects were the Passamaquoddy tidal power development in Maine and an alternate route for a lock or sea-level canal in Panama. Neither has yet advanced beyond the design stage, but for both projects the corrosion studies were continued to completion.

The comprehensive long-term corrosion investigation, begun when preliminary designs were being made for the Panama Canal modifications, now provides valuable data which should be applicable to these and many related projects presently in the offing. The tropical study provided for the evaluation of 52 metals and alloys in five natural environments for exposure periods of 1, 2, 4, 8, and 16 years. Both single plates and bimetallic couples were included. A total of more than 13,000 samples was exposed. This report, ninth in a series (1 - 8) and the fourth describing the final results from the Panama investigation, includes the complete 16-year data obtained for underwater corrosion of wrought and cast structual ferrous metals.

PREVIOUS STUDIES

Greater effort has been put into the study of iron and steel in underwater environments than for most other metals, but even so relatively little adequate long-term data have been published. To appreciate more fully the extent and scope of the experiments to be described, a brief look at the state of knowledge of the corrosion of iron and steel in natural seawater appears warranted.

As early as 1916, the American Society for Testing Materials, Committee A-5, initiated studies to compare the corrosion rates of mild steel and copper steel exposed to the atmosphere. In 1920 this committee exposed the same metals in estuarine water at Annapolis, Maryland, and in 1927 a study of the corrosive effects of seawater on these same metals was initiated in tanks of flowing seawater at Portsmouth, N.H., and at Key West, Florida. In each of these early efforts, evaluations were based solely on time to perforation. Since pitting of the metal occurs from two sides and perforation depends to

a large degree on the random location of opposite pits, the observed results varied considerably. Another incongruity resulted from the masking of penetration by the attachment of marine fouling. In fact, fouling became so serious it was necessary to sandblast samples before they could be inspected. The final report issued in 1950 (9) acknowledged the shortcomings of the methods employed and provided very little unqualified data on the corrosion rates of ferrous metals in seawater.

Corrosion studies were started for the Passamaquoddy tidal project in 1936 (10). A large number of metals were included, and arrangements were made to examine the specimens at four intervals throughout an 8-year period. While some good comparative data were obtained, the number of replicates involved and the methods of exposure could not yield reliable corrosion-time curves. Although three samples of each metal were exposed, one in the atmosphere, one at mean tide, and one in the sea, no replicates to provide for periodic removal were included in any of these environments. Moreover, each steel sample represented three different surface conditions, namely, mill scale, roughly machined, and smoothly machined, thus almost assuring some galvanic effects between adjacent surfaces. As each sample was removed, it was cleaned, inspected, and weighed, and then returned to its environment for the remaining exposure intervals. This periodic cleaning procedure removes any protective scale that has formed and, in effect, starts a new period of accelerated and changing corrosion rates.

Other comparative studies of ferrous metals in seawater have been made by several organizations in the United States, but in most instances the duration of exposure and/or number of replicates involved was insufficient to provide significant corrosion-time relationships. Predominant among such tests were single-panel exposures continued for many years on a clean-and-return basis, thus repeating the error alluded to above. One of the more useful evaluations of seawater corrosion of steel was made by the U.S. Steel Corporation at the International Nickel company's exposure facility at Kure Beach, N.C. (11). Five structural steels were immersed in quiet seawater for periods up to 8-1/2 years; however, only four panels per metal were exposed, providing for single panels to be removed at 1.5-, 2.5-, 4.5-, and 8.5-year intervals. Corrosion damage was measured by weight loss.

Meanwhile, underwater corrosion studies were being conducted in Europe, where, beginning in 1921, the London Institute of Civil Engineering started investigations of carbon steels and wrought irons exposed in seawater at four locations around the world (12). These studies were allowed to continue over a 15-year period. This was an excellent start for natural water corrosion studies, and some good comparative results were obtained for the few samples exposed without millscale.* However, here also too few specimens were included; only one sample of each metal was removed at 5-year inspection intervals. Also, the bar samples used, with their high edge-to-surface ratio, generally showed greater losses than the plate samples preferred by later investigators. In 1937, the British Iron and Steel Research Association (13) initiated comparative tests at Gosport, England, using ten plate replicates of each material, all of which were removed after 1.2 years of exposure. The single time points thus obtained were highly accurate, but single points were inadequate for establishing corrosion rates or extrapolating to longer terms. Similar comparative tests at other locations were made by BISRA, but again only for single time periods.

Comprehensive exposure studies were started in France and Germany in the late 30's but were interrupted by World War II. The French, however, reported on some 3- and 4-year exposures to seawater and fresh water (14).

*Corrosion testing of ferrous metals with cathodic rolling scale does not evaluate the metal but rather the integrity and quality of the scale.

In recent years the Russian Academy of Physical Chemistry exposed four structural steels for 6 years in the Barents Sea. Most of the samples were tested with rolling scale surfaces, but one set with shotblasted surfaces was included and provides some useful corrosion data for far northern seawater (15).

The subject study in Panama is apparently the only major investigation of metallic corrosion in natural waters that has been conducted in the last 25 years, and it seems to be by far the most comprehensive and thorough that has ever been undertaken.

EXPERIMENTAL CONDITIONS

Metals

Of the 52 metals included in the Panama program, 26 were ferrous base, and most of these were structural types generally containing less than 5% alloying elements. The results from the exposure of these structural ferrous metals in underwater environments provide the subject of this report. The metals included are identified in Table 1. Varied compositions are represented, and in some instances different initial surface conditions are included. Complete chemical compositions and physical properties of the samples are given in Tables A1 and A2 in the Appendix.

Exposure Environments

The five environments included fresh water, seawater, seawater mean tide, and marine and inland atmospheres. Immersion studies require much larger plates and more massive supporting racks than those done in the atmosphere. In addition, large overwater pier structures or floating platforms are required from which specimens can be suspended. Therefore, underwater studies become very costly and time consuming. Undoubtedly, this is the reason, at least in part, for the extreme shortage of information available concerning the seawater and fresh-water corrosion of metals. In the present instance a majority of the time and expense of the program was devoted to the three underwater exposures.

Immersion studies were made from two piers designed especially for the project. One is a tropical fresh-water site in Gatun Lake, which is shown in Fig. 1. Samples at this pier were suspended at an average depth of 6 feet in 30 feet of water, about 50 feet out from the natural shoreline. No significant current flow was found at the fresh-water site. The other pier shown in Fig. 2 is for marine exposures in the Pacific Ocean. It is located off the Fort Amador causeway at Naos Island, 1-1/2 miles from the mainland. The ocean exposures were made at two elevations 14 feet apart. Upper racks were at half-tide level, and the lower racks were just below minimum low tide. Average water depth is about 25 feet, average tidal range is 13 feet, and maximum currents measure less than 1 foot per second.

Chemical composition of the fresh water and seawater at the test sites and a 20-year record of water temperatures are shown in Table A3 and Fig. A1 in the Appendix.

Procedures

The details of exposure and the methods by which the specimens were cleaned, measured, and examined are described in earlier reports (1 - 8). The underwater samples were 9- by 9- by 1/4-inch plates. These were supported in the test racks by ceramic insulators as shown in Fig. 3. Ten replicates for each metal-environment

Table 1
Structural Ferrous Metals Tested

Key	Metals	Initial Surface Condition	Specification
A	Mild steel	Pickled	QQ-S-741, type II, grade A, class 1
B	Mild steel	Machined	QQ-S-741, type II, grade A, class 1
C	Mild steel	As received	QQ-S-741, type II, grade A, class 1
D	Mild steel (0.31% Cu)	Pickled	QQ-S-741, type II, grade A, class 2
E	2% Ni steel	Pickled	RR-3A
F	5% Ni steel	Pickled	SAE 2515
G	3% cr steel	Pickled	Max 0.10% C
H	5% cr steel	Pickled	AISI type 501D
I	Low-alloy steel	Pickled	Proprietary Cu-Ni
J	Low-alloy steel	Pickled	Proprietary Cu-Cr-Si
K	Low-alloy steel	Pickled	Proprietary Cu-Ni-Mn-Mo
L	Low-alloy steel	Pickled	Proprietary Cr-Ni-Mn
M	Cast steel	Machined	QQ-S-6816 class 1
N	Cast steel	As received	
O	Gray cast iron	Machined	QQ-I-652 class 30
P	Gray cast iron	As received	
Q	Austenitic cast iron	Machined	INCO 18-22 Ni
R	Austenitic cast iron	As received	
S	Wrought iron	Machined	Aston process
T	Wrought iron	As received	ASTM A42-39

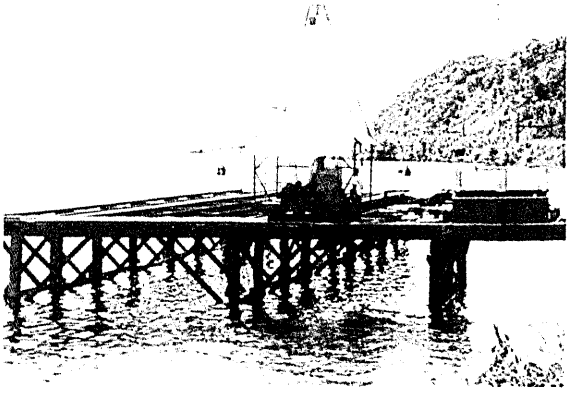

Fig. 1 - Pier for fresh-water immersion in Gatun Lake

combination were included so that duplicate specimens of each could be removed at 1-, 2-, 4-, 8-, and 16-year time intervals. Weight loss and depth of pitting were measured to evaluate the extent of corrosion; subsequently, strips were cut from the cleaned plates and used to determine changes in tensile strength.

Since the amount of data collected throughout the 16-year period is quite massive, some discussion of possible methods of presentation of these data is in order. First reference is made to the solid-line curve in Fig. 4a, which is a hypothetical corrosion-time curve but very similar to the curve pattern to be expected for mild steel corroding underwater in nonfouling conditions. The relation shows that the corrosion rate was very unstable during the first few years,

changing from a 7.4-mpy average during the first year to a final constant rate after 4 years of only 1.0 mpy. Corrosion rates determined during the period of changing slope have very limited significance. The steady final rate R_c, on the other hand, is the most useful and fundamental corrosion rate obtainable for a metal in a corrosive environment, but it can only be determined from exposures over an extended period with an adequate number of properly spaced measurements.

The method most commonly used for reporting corrosion rates is to make a single measurement of corrosion loss, divide by the time elapsed, and call the quotient the corrosion rate. The considerable deviation from the true rate inherent in this method becomes apparent when results are compared with the actual plot of corrosion loss vs time in Fig. 4a. Such comparisons are shown by the dashed lines for single interval rates of 1 and 8 years. The 1-year secant rate R_1 is 7.4 times the final slope of the curve R_c, and even the 8-year single-interval rate R_8 is double the actual final rate R_c.

Often corrosion rates are plotted as a function of time. Two methods of accomplishing this are illustrated in Fig. 4b

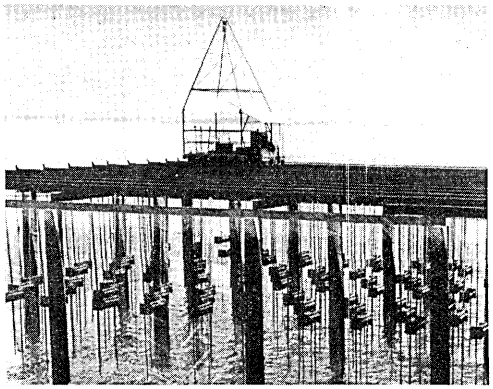

Fig. 2 - Seawater specimens in place at Fort Amador pier (view at low tide)

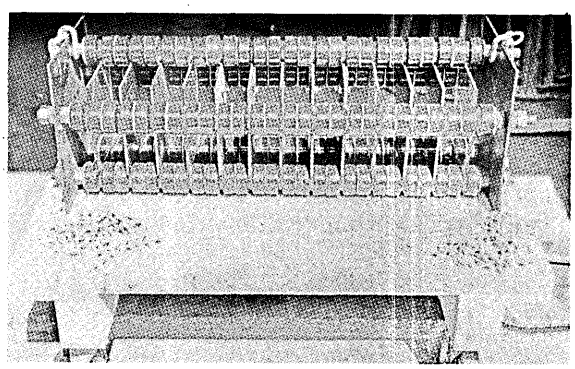

Fig. 3 - Typical immersion rack with specimens in place

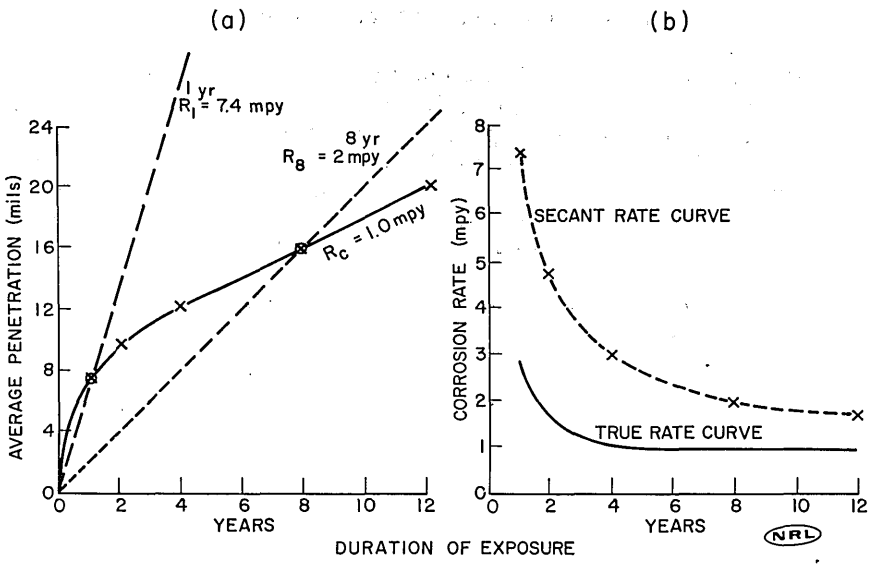

Fig. 4 - Corrosion rate data — methods of presentation

for the same data given in Fig. 4a. The first, shown by the broken line, is obtained by plotting the single-interval rates (secant rates) vs time. This makes a smooth curve but, as is evident in this example, can be quite misleading. The rate here is shown as decreasing over 12 years, while the actual corrosion rate was constant for the last 7 years shown. The solid line in Fig. 4b is a plot of the true rate, which provides the correct reading of rates and rate changes; but it is difficult to obtain unless a mathematical equation of the corrosion-time relation is available, and it does not permit easy reading of corrosion losses. The direct corrosion-time curve in Fig. 4a shows most clearly the progression of corrosion and, when linear, represents a constant rate. This latter method is used for reporting the 16-year corrosion data to follow.

RESULTS

Comprehensive Tabulations

Tables 2, 3, and 4 present comprehensive summaries of the corrosion results for all 20 ferrous metal variations in the three underwater environments. To conform to general corrosion terminology, weight loss is shown in grams per square decimeter, and penetration values are shown in mils. Pitting represents the average of the five deepest pits on each surface of duplicate panels.

Stabilized corrosion rates in the tables were determined from the time-corrosion curves for each metal-environment combination and is the slope of the final tangent or final linear portion of the curves. Such a value approaches or equals the final steady rate and gives one of the best evaluations of the different metals and/or environments. Also, extrapolation of this value to longer exposure periods is quite simple by using

$$\bar{P}_t = \bar{P}_{16} + R_c\ (t - 16),$$

where

$\bar{P}_t$ = average penetration at time t ($t > 16$),

$\bar{P}_{16}$ = average penetration at 16 years,

and

R_c = stabilized (constant) corrosion rate.

No tensile data have been included in these tables, as it has been shown previously by Hudson (16) and by Alexander, et al, (1), that for structural steels reduction in tensile strength is essentially equal to average penetration determined from weight loss. Weight loss gives far less variable results than mechanical tests for heavily corroded samples of iron and steel and is therefore a more precise evaluation of loss in tensile strength. Most panels were approximately 1/4 inch thick, and for these a 25-mil reduction in thickness would be approximately equivalent to a 10% reduction in tensile strength.

While complete data for all metal-environment combinations are presented in the three tabulations, the following discussion will be focused on mild carbon steel in all three environments and on the alloy steels, cast irons, and wrought irons immersed in seawater.

Structural Carbon Steel

Carbon steel was exposed with millscale, machined, and pickled surfaces. Additional samples of mild copper-bearing carbon steel (0.31% copper) were exposed with pickled surfaces. Of the four variations of mild steel, only that with millscale surfaces

Table 2
Comprehensive Tabulation of Corrosion Damage
Structural Ferrous Metals Continuously Immersed in Fresh Water
(Gatun Lake—Panama Canal Zone)

Metals				General Corrosion											Pitting Penetration								
Class	Key	Type	Surface Condition	Weight Loss (g/dm²)					Average Penetration (mils)*					Stabilized Corrosion Rate† (mpy)	Average 20 Deepest Pits‡ (mils)			Deepest Pit (mils)			Pitting Factor§		
				1 yr	2 yr	4 yr	8 yr	16 yr	1 yr	2 yr	4 yr	8 yr	16 yr		1 yr	8 yr	16 yr	1 yr	8 yr	16 yr	1 yr	8 yr	16 yr
wrought	A	C steel	Pickled	15.2	23.7	34.0	43.7	56.2	7.7	12	17	22	28	0.7	20	58	72	24	71	93	3	3	3
	B	C steel	Machined	15.0	23.2	31.8	40.3	48.8	7.5	12	16	20	25	0.6	22	60	65	26	88	94	3	4	4
	C	C steel	Millscale	12.6	19.0	27.2	37.7	50.7	6.3	9.5	14	19	25	0.7	29	48	66	40	74	91	6	4	4
	D	C steel, 0.3% Cu	Pickled	15.7	24.2	35.2	46.4	57.1	7.9	12	18	23	29	0.7	22	64	64	34	82	89	4	4	3
	E	2% Ni steel	Pickled	14.7	25.3	34.7	40.2	43.6	7.4	13	17	20	22	0.3	19	63	66	29	89	87	4	4	4
	F	5% Ni steel	Pickled	13.1	24.6	35.5	46.8	59.4	6.6	12	18	24	29	0.8	18	69	71	33	100	99	9	7	3
	G	3% Cr steel	Pickled	4.84	7.29	10.8	19.3	29.3	2.4	3.7	5.4	9.7	15	0.7	24	54	77	28	63	98	12	6	6
	H	5% Cr steel	Pickled	3.80	4.49	7.09	17.1	26.7	1.9	2.3	3.6	8.6	13	0.6	23	52	67	29	58	96	15	7	7
	I	Low-alloy steel	Pickled	12.1	19.7	26.0	32.6	43.9	6.0	9.9	13	16	22	0.7	17	67	75	31	85	110	5	5	5
	J	Low-alloy steel	Pickled	11.3	17.2	23.6	33.1	48.4	5.7	8.6	12	17	24	0.9	40	79	88	56	93	112	10	6	5
	K	Low-alloy steel	Pickled	14.5	22.6	31.7	44.6	62.1	7.3	11	16	22	31	1.1	24	81	101	32	120	124	5	5	5
	L	Low-alloy steel	Pickled	10.7	16.3	25.3	31.1	53.4	5.4	8.2	13	16	27	1.2	40	111	113	47	146	141	9	9	9
	S	Wrought iron	Machined	15.0	23.1	28.3	28.9	¶	7.6	12	14	15	¶	¶	27	50	¶	32	89	¶	4	6	¶
	T	Wrought iron	As received	14.6	22.4	29.5	37.2	¶	7.4	11	15	19	¶	¶	18	54	¶	23	80	¶	3	4	¶
cast	M	Cast steel	Machined	16.2	23.7	28.7	38.2	52.4	8.2	12	14	19	26	0.9	30	67	98	38	92	140	4	5	5
	N	Cast steel	Cast (as rec.)	13.7	21.7	29.0	**	**	7.6	12	16	**	**	**	62	**	**	116	**	**	15	**	**
	O	Gray cast iron	Machined	12.5	21.0	27.0	41.4	59.1	7.0	12	15	23	33	1.2	52	106	108	68	131	††	10	6	††
	P	Gray cast iron	Cast (as rec.)	14.2	23.3	29.8	**	**	7.9	13	17	**	**	**	72	**	**	150	**	**	19	**	**
	Q	Ni cast iron	Machined	1.64	2.88	5.12	7.60	14.5	0.9	1.6	2.8	4.2	8.0	0.4	9	27	37	11	36	61	12	9	8
	R	Ni cast iron	Cast (as rec.)	¶	¶	¶	¶	¶	¶	¶	¶	¶	¶	¶	¶	¶	¶	¶	¶	¶	¶	¶	¶

*$\overline{P}$ = 393.7 W/AD, where $\overline{P}$ = average penetration (mils), W = weight loss (g), A = exposed area (cm²), and D = density (g/cc).
†Slope of time-corrosion curve at t = 16 yr.
‡Five deepest on each surface of duplicate panels.
§Ratio: deepest pit/average penetration.
¶No samples exposed.
**Not determined.
††Perforation of panel prevents obtaining an accurate value.

Table 3
Comprehensive Tabulation of Corrosion Damage
Structural Ferrous Metals Continuously Immersed in Sea Water
(Pacific Ocean—Panama Canal Zone)

Metals				General Corrosion											Pitting Penetration								
Class	Key	Type	Surface Condition	Weight Loss (g/dm²)					Average Penetration (mils)*					Stabilized Corrosion Rate† (mpy)	Average 20 Deepest Pits‡ (mils)			Deepest Pit (mils)			Pitting Factor§		
				1 yr	2 yr	4 yr	8 yr	16 yr	1 yr	2 yr	4 yr	8 yr	16 yr		1 yr	8 yr	16 yr	1 yr	8 yr	16 yr	1 yr	8 yr	16 yr
	A	C steel	Pickled	11.8	16.5	31.4	50.9	90.8	5.9	8.3	16	26	46	2.5	41	66	90	62	86	155	11	3	3
	B	C steel	Machined	11.0	18.0	29.8	53.9	98.7	5.5	9.0	15	27	49	2.7	38	58	¶	64	157	¶	12	6	¶
	C	C steel	Millscale	8.38	15.5	30.1	46.5	¶	4.2	7.8	15	23	¶	¶	55	¶	¶	104	¶	¶	25	¶	¶
w	D	C steel, 0.3% Cu	Pickled	11.8	18.3	29.1	55.3	98.1	5.9	9.2	15	28	49	2.7	36	63	85	61	108	124	10	4	3
r	E	2% Ni steel	Pickled	14.8	18.3	34.1	63.0	104	7.4	9.2	17	32	52	2.7	33	94	¶	51	179	¶	7	6	¶
o	F	5% Ni steel	Pickled	12.5	20.0	33.2	63.7	103	6.3	10	17	32	52	2.7	29	117	¶	57	214	¶	9	7	¶
u	G	3% Cr steel	Pickled	4.13	10.9	35.6	80.4	140	2.1	5.5	18	40	70	3.8	11	65	93	20	78	109	10	2	2
g	H	5% Cr steel	Pickled	5.34	12.1	33.6	63.5	119	2.7	6.1	17	32	56	3.5	27	63	69	91	90	100	34	3	2
h	I	Low-alloy steel	Pickled	11.7	16.9	41.2	52.6	96.7	5.9	8.5	21	26	48	2.7	54	82	¶	65	152	¶	11	6	¶
t	J	Low-alloy steel	Pickled	13.6	22.3	37.5	85.7	160	6.9	11	19	43	80	4.8	31	80	¶	46	175	¶	7	4	¶
	K	Low-alloy steel	Pickled	12.8	19.1	30.2	50.9	89.8	6.4	9.6	15	25	45	2.5	27	56	71	47	139	110	7	5	2
	L	Low-alloy steel	Pickled	12.6	21.9	41.2	87.4	167	6.3	11	21	44	84	5.0	26	¶	¶	36	¶	¶	6	¶	¶
	S	Wrought iron	Machined	12.7	15.1	28.2	43.8	**	6.5	7.7	14	22	**	**	34	63	**	51	138	**	8	6	**
	T	Wrought iron	As received	12.5	18.4	29.9	51.5	86.4	6.3	9.3	15	26	44	2.5	46	¶	127	73	¶	200	7	¶	3
	M	Cast steel	Machined	14.7	18.7	29.9	55.2	86.1	7.4	9.4	15	28	43	2.5	56	84	103	84	135	146	11	5	3
c	N	Cast steel	Cast (as rec.)	12.6	11.9	15.8	††	††	6.3	6.0	7.9	††	††	††	65	††	††	131	††	††	21	††	††
a	O	Gray cast iron	Machined	17.8	27.5	39.6	104	170	9.9	16	22	58	95	5.8	42	97	††	58	160	††	6	3	††
s	P	Gray cast iron	Cast (as rec.)	11.3	14.1	26.7	††	††	6.3	7.9	15	††	††	††	69	††	††	204	††	††	32	††	††
t	Q	Ni cast iron	Machined	5.98	8.98	14.5	27.3	41.2	3.3	5.0	8.0	15	23	1.1	<5	42	67	<5	114	116	<2	8	5
	R	Ni cast iron	Cast (as rec.)	4.51	4.00	††	††	††	2.5	2.2	††	††	††	††	<5	††	††	<5	††	††	<2	††	††

*$\overline{P}$ = 393.7 W/AD, where $\overline{P}$ = average penetration (mils), W = weight loss (g), A = exposed area (cm²), and D = density (g/cc).
†Slope of time-corrosion curve at t = 16 yr.
‡Five deepest on each surface of duplicate panels.
§Ratio: deepest pit/average penetration.
¶Perforation of panel prevents obtaining an accurate value.
**No samples exposed.
††Not determined.

Table 4
Comprehensive Tabulation of Corrosion Damage
Structural Ferrous Metals Exposed at Mean-Tide Elevation
(Pacific Ocean—Panama Canal Zone)

Metals				General Corrosion											Pitting Penetration								
Class	Key	Type	Surface Condition	Weight Loss (g/dm²)					Average Penetration (mils)*					Stabilized Corrosion Rate† (mpy)	Average 20 Deepest Pits‡ (mils)			Deepest Pit (mils)			Pitting Factor§		
				1 yr	2 yr	4 yr	8 yr	16 yr	1 yr	2 yr	4 yr	8 yr	16 yr		1 yr	8 yr	16 yr	1 yr	8 yr	16 yr	1 yr	8 yr	16 yr
wrought	A	C steel	Pickled	18.8	18.5	25.4	46.3	94.5	9.5	9.3	13	23	47	2.9	16	40	66	27	65	98	3	3	2
	B	C steel	Machined	21.0	21.7	30.5	49.5	83.5	11	11	15	25	42	2.5	21	45	52	46	124	73	4	5	2
	C	C steel	Millscale	18.4	22.5	26.3	36.9	87.0	9.3	11	13	18	44	2.8	18	43	54	24	75	102	2	4	2
	D	C steel, 0.3% Cu	Pickled	22.4	22.6	23.0	48.3	92.1	11	11	12	24	46	2.8	24	45	51	38	63	67	3	3	1.5
	E	2% Ni steel	Pickled	17.7	17.9	27.5	45.6	110	8.9	9.0	14	23	55	3.7	22	39	70	39	50	83	4	2	1.5
	F	5% Ni steel	Pickled	15.6	17.2	25.4	39.8	107	7.8	8.7	13	20	54	3.7	¶	39	62	¶	75	91	¶	4	1.7
	G	3% Cr steel	Pickled	22.1	23.6	29.1	51.1	95.7	11	12	15	25	48	3.5	23	82	**	32	93	**	3	4	**
	H	5% Cr steel	Pickled	23.3	22.6	24.9	48.6	94.1	12	12	13	25	47	2.6	28	88	**	37	99	**	3	4	**
	I	Low-alloy steel	Pickled	23.7	26.0	30.0	79.3	98.0	12	13	15	40	49	3.3	¶	70	58	¶	134	93	¶	3	1.7
	J	Low-alloy steel	Pickled	21.4	19.5	24.2	41.9	98.0	11	10	12	21	49	3.4	20	47	60	27	54	72	3	3	1.5
	K	Low-alloy steel	Pickled	21.6	30.3	37.3	49.3	122	11	15	19	25	61	3.6	24	40	59	32	94	147	2	4	2
	L	Low-alloy steel	Pickled	18.2	18.0	21.5	40.9	91.3	9.1	9.0	11	21	46	2.9	19	39	61	27	50	93	2	2	2
	S	Wrought iron	Machined	14.3	15.6	23.9	32.3	††	7.3	7.9	12	16	††	2.4	17	35	††	27	49	††	3	3	††
	T	Wrought iron	As received	11.9	12.3	16.1	33.9	71.2	6.1	6.2	8.2	17	36	††	17	35	¶	23	41	¶	4	2	¶
cast	M	Cast steel	Machined	15.8	15.2	21.8	42.3	97.5	7.9	7.7	11	21	49	3.4	35	53	91	77	76	159	10	4	3
	N	Cast steel	Cast (as rec.)	10.6	13.6	19.2	¶	¶	5.3	6.8	9.6	¶	¶	¶	65	¶	¶	256	¶	¶	48	¶	¶
	O	Gray cast iron	Machined	46.0	52.6	55.2	81.8	157	26	29	31	46	87	4.9	55	**	**	80	**	¶	3	**	¶
	P	Gray cast iron	Cast (as rec.)	12.1	16.6	16.8	¶	¶	6.7	9.2	9.3	¶	¶	¶	58	¶	¶	125	¶	¶	10	¶	¶
	Q	Ni cast iron	Machined	2.96	3.71	5.38	7.04	13.2	1.6	2.1	3.0	3.9	7.3	1.3	¶	42	67	¶	114	116	¶	29	16
	R	Ni cast iron	Cast (as rec.)	1.39	1.17	2.14	¶	¶	0.8	0.6	1.2	¶	¶	¶	¶	¶	¶	¶	¶	¶	¶	¶	¶

*$\overline{P}$ = 393.7 W/AD, where $\overline{P}$ = average penetration (mils), W = weight loss (g), A = exposed area (cm²), and D = density (g/cc).
†Slope of time-corrosion curve at t = 16 yr.
‡Five deepest on each surface of duplicate panels.
§Ratio: deepest pit/average penetration.
¶Not determined.
**Perforation of panel prevents obtaining an accurate value.
††No samples exposed.

showed any significant difference in underwater corrosion, and then only in continuous seawater immersion was the difference appreciable. Under seawater the millscale surfaces sustained much deeper pitting than the others. This is evident from the pit depth data in Table 3. Any supposition that millscale surfaces will be rapidly removed by corrosion is strongly disputed by the long-term data. Much of the scaled area remained relatively unattacked through the first 8 years of exposure.

The results for the pickled, machined, and copper-bearing carbon steels are so similar that average curves for the three probably most precisely represent the relation of corrosion to time for mild carbon steel. The data from the three have been combined to obtain more accurate curves for structural carbon steel in fresh water, in seawater, and at mean tide.

The average results for carbon steels continuously immersed in fresh water are shown in Fig. 5. Weight loss, which measures general corrosion and loss in strength, is plotted as the smooth line in the lower curve, while average pitting penetration is shown by the point-to-point curve above. The maximum pit depth (94 mils) occurred after 16 years. The weight loss shows that there is a very smooth, almost parabolic relation with time. The corrosion rate decreases from 7.5 mpy average for 1 year to a final, practically constant, rate of less than or equal to 0.7 mpy. Average pitting depths increased rapidly during the first few years but leveled off at a rate approaching that of general corrosion. The maximum pit depth measured during the 16 years was 94 mils, which gives a pitting factor of 3.4.

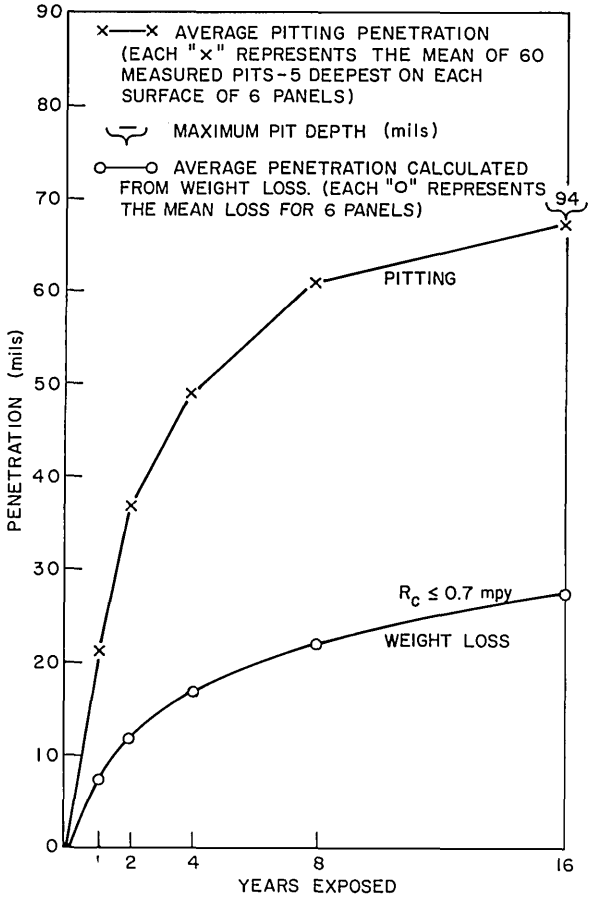

Fig. 5 - Corrosion of carbon steel continuously immersed in fresh water

Seawater immersion is undoubtedly the most important environment investigated in this study. Curves for structural carbon steel corroding in this medium are presented in Fig. 6. General corrosion loss becomes almost linear with time after the first year or two of immersion. However, during this initial period, there is a considerable rate change, which should not be discounted. The 1-year average rate is 5.8 mpy, while the final steady-state rate is less than one-half of this, at 2.7 mpy. This steady-state rate is considerably lower than rates usually reported for mild steel in seawater, even in temperate latitudes. This is probably because tests are usually short-term and initial rate changes are always included in averages. Larrabee (17), studying 23-year-old H beams from a seawater structure in California, also concluded that the usual corrosion rates reported for carbon steel in seawater were much higher than actual long-term rates.

Pitting rates of steels in seawater are generally reported to be several

times higher than average penetration. Fink (18) reports values of 10 to 15 mpy. Early data from this study would more than exceed these values (about 40 mils the first year). However, the completed long-term pitting curve shows a substantial decrease in pitting rate after the first 2 to 4 years; ultimately, the pitting curve almost parallels that based on weight loss, indicating that average pitting penetration over more extended periods would probably continue at only about 3 mils per year.

The curves for cast steel, to be discussed later, are quite similar to those for carbon steel, and the pitting rate also decreased to an eventual value approximating the general corrosion rate. In fresh water and mean tide average pitting also followed this same pattern. The maximum pit depth for continuous immersion in seawater was 157 mils, which provides a 16-year pitting factor of 3.2.

Results from the Panama mean-tide experiments are shown in Fig. 7. It should be emphasized, however, that mean-tide data have somewhat limited applicability. Corrosion at mean tide may be influenced by wind velocity and direction, wave height, tidal range, fouling attachment, and splash zone and atmospheric conditions. As a result, its magnitude may show considerable variation with location.

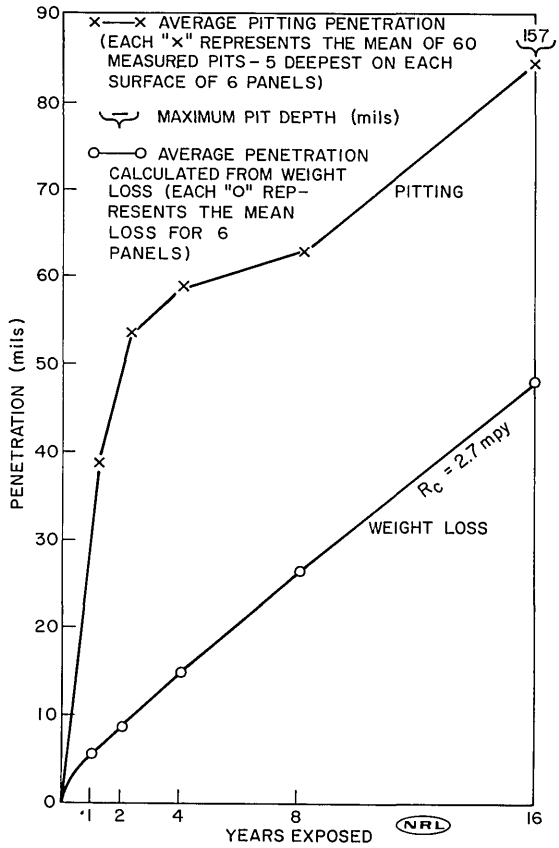

Fig. 6 - Corrosion of carbon steel continuously immersed in seawater

This variation can be best appreciated by considering the ratio of seawater to mean-tide corrosion for 10 years' exposure at several locations around the world (12), Table 5.

In the Panama mean-tide experiments, initial corrosion was quite high, 10-mil average penetration for the first year; but between 1 and 3 years almost no increase was apparent, and the rate was very low. Subsequently, the rate increased until finally, after 4 years, it stabilized at a relatively constant value of 2.7 mpy. This was the same final rate obtained for seawater immersion.

This mean-tide corrosion behavior of carbon steel is an interesting phenomenon. More or less similar time relations were found for most of the other structural steels exposed at mean tide, but such was not found for carbon steel immersed in either fresh or seawater nor for most of the nonferrous metals, even at mean tide.

It is possible that stabilization at mean tide comes more slowly because of the different type and rate of fouling at the immersed and mean-tide elevations. After stabilization, steel corrosion in both seawater environments may be controlled by anaerobic bacteria thriving under a heavy self-repairing fouling cover.

Early pitting at mean tide was not as great as for immersed samples, but, again, pitting eventually roughly paralleled weight loss. The maximum pit of 98 mils was about equal to the maximum in fresh water but 40% less than under seawater. The pitting factor at 16 years is 2.2 for mean-tide exposure.

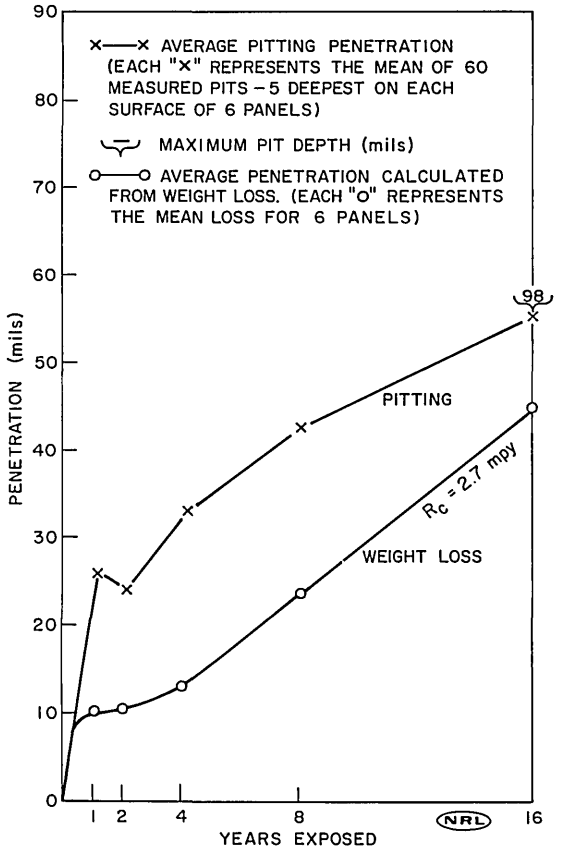

Fig. 7 - Corrosion of carbon steel at mean-tide elevation

A comparison of corrosion rates of carbon steel in waters of different salinity is shown in Fig. 8. These waters include Gatun Lake with an average salinity of 0.007 ppt, Miraflores Lake brackish water at an average salinity of 0.4 ppt, and seawater at Fort Amador at an average 17.4 ppt. The data from brackish water were obtained from a preliminary study. They are less significant because the experiments were conducted with fewer panels and less precise control, and the environmental conditions, which probably varied considerably in salinity and oxygen content, were not determined. The results do show, however, that at similar temperature and velocity corrosion of ferrous metals in brackish water can be considerably higher than in either fresh water or seawater. This higher loss in brackish water could result from higher oxygen content, but the absence of heavy protective fouling, which did not develop at this low salinity, probably contributed also to the higher initial corrosion rate. With just two points, establishing the slope of the curve or any sort of final corrosion rate is not feasible. Without heavy fouling protection, however, a decreasing rate similar to that found in fresh water is probable.

A comparison of the solid curves for fresh water and seawater in Fig. 8 points to the inherent dangers in extrapolating long-term corrosion rates from short-term data. After 1, 2, and 4 years of immersion in Gatun Lake, the average corrosion loss of steel was higher than in seawater. Only after 8 years' immersion did the two assume their relative steady-state positions. Examination of the 16-year curves shows that the final steady-state rates were 2.7 mpy for seawater and ≤ 0.7 mpy for fresh water.

Table 5
Variability of Mean-Tide Corrosion

Location	Corrosion Ratio (seawater/mean tide)
Nova Scotia	2.5
New Zealand	2.0
Panama Pacific	1.1
England	0.8
Ceylon	0.6

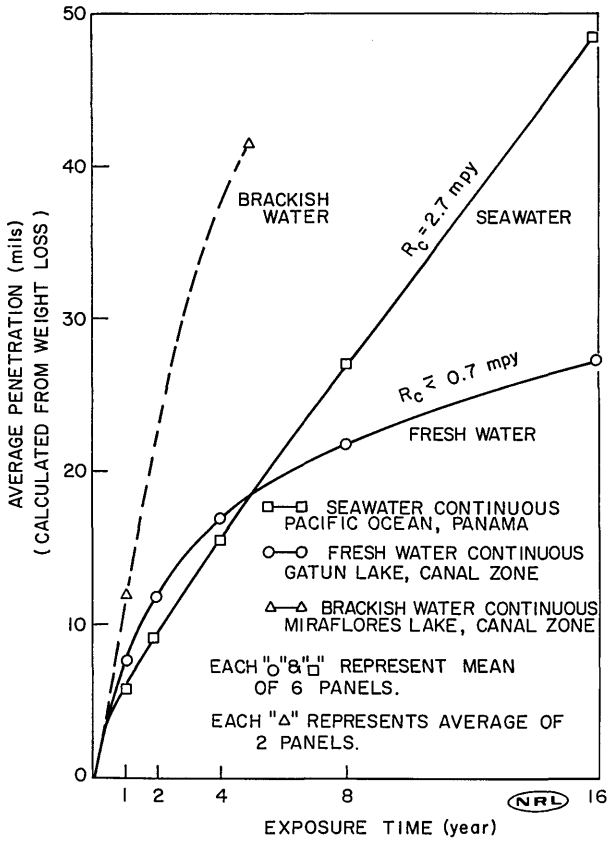

Fig. 8 - Comparative weight losses of carbon steel in different salinity waters

Crennell (19) states that "data from the Canal Zone gave the surprising information that steel corrodes at about the same rate in fresh water as in seawater." This conclusion was reached from average rates and partial data that were available at the time of publication. With the completed 16-year exposures, it is now apparent that corrosion rates of metals in natural waters change considerably with time, in some instances over periods of many years. Only the final steady-state rate or one approaching this rate has any real significance. Based on the steady-state rate evaluations from this study, seawater eventually will be about four times more corrosive to steel than fresh water.

Alloy Steels

A systematic study of different alloying elements in steel was not an objective of the investigation; however, a representative group of the low-alloy metals in commercial production at the time this study was initiated was exposed to the different environments. These metals included a copper-bearing steel, four proprietary low-alloy steels, 2% and 5% nickel steels, and 3% and 5% chromium steels.

Other investigators have studied similar metals in seawater but for considerably shorter periods and with fewer specimens. Generally, their results have shown that, with the exception of chromium, alloying additions of 5% or less have very little effect on the seawater corrosion of steels. With chromium, however, there is some controversy; some have reported up to a 50% reduction in corrosion rates in seawater with 2 to 5%

chromium (13,20,21). Chaudron (14), however, reported that chromium increased corrosion. The NRL's 16-year data permit for the first time an evaluation of the long-term steady-state corrosion rates of the low-alloy steels in quiet seawater. Some of these data, presented in the next three figures, provide some rather surprising results.

Corrosion losses in seawater of 2% and 5% nickel steels are compared with carbon steel in Fig. 9. It is apparent from these curves that weight losses for the two nickel steels were about equal, and both were only slightly higher than for mild carbon steel. The final steady-state rates were approximately equal for all three at 2.7 mpy.

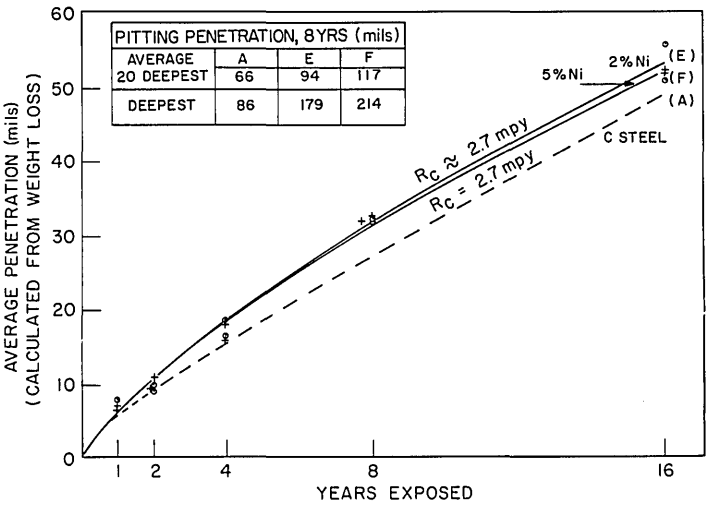

Fig. 9 - Corrosion of 2% and 5% nickel steels continuously immersed in seawater

On the other hand, pitting after long immersion periods was considerably higher for the nickel steels, with the 5% alloy showing greater average pit depth than the 2% alloy. Short-term data gave the misleading impression that pitting resistance was improved with increased nickel content. The first year showed pit depths to average 25% and 30% less for 2% and 5% nickel steel, respectively, than for carbon steel. By 8 years, however, this pitting relationship was completely reversed, with 2% and 5% nickel steels showing 42% and 77% deeper pits than carbon steel. At 16 years, perforations of the nickel steel panels prevented accurate evaluation of final pit depths.

In comparing 2% and 5% chromium steels with mild steel, the weight losses were more surprising. The long-term general corrosion data plotted in Fig. 10 reveal a considerable disadvantage for chromium steels compared to mild carbon steel. The curves show the corrosion of both 3% and 5% chromium steels to have started slowly. After the first year the loss was less than 1/2 that of carbon steel. Between 2 and 4 years, however, there was a sharp increase in the corrosion rates of the chromium steels. After 4 years, the high corrosion rates decreased gradually and seemed to reach a steady rate of about 3.5 to 3.8 mpy, compared to 2.7 for the carbon steel. Sixteen-year losses were respectively 22% and 45% higher for the 5% and 3% chromium steels than for carbon steel.

Pitting penetration after 1 year was also much lower for the chromium steels, but subsequent data showed that by 8 and 16 years, the average pit depth for 2% chromium steel was approximately equal to that of mild carbon steel. The 5% chromium alloy,

although having a higher incidence of pitting, continued to exhibit slightly shallower penetrations throughout the exposure periods.

Chromium steels have been reputed to be superior to carbon steel in resisting general corrosion in seawater. If compared on the basis of short-term data only, this would indeed appear to be true. Also, if the reported superiority of chromium steels was established on the basis of the cumulative loss of repeatedly cleaned and reexposed samples, the relative advantage could erroneously appear to be considerable and might seem to continue so indefinitely.

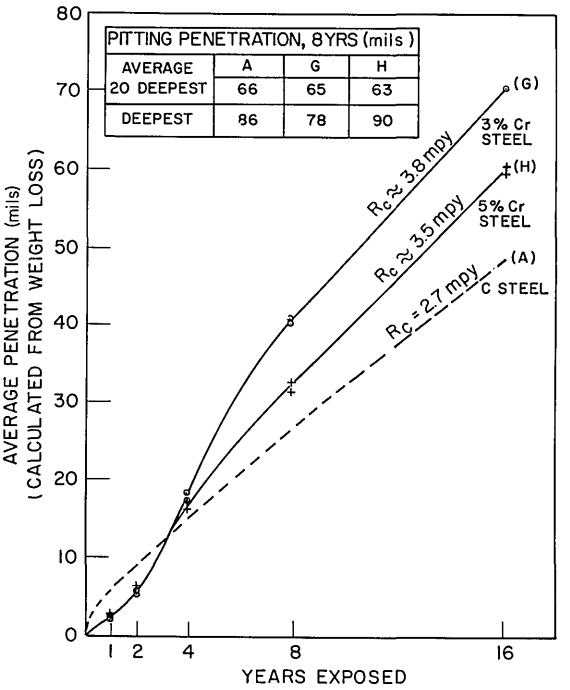

Fig. 10 - Corrosion of 3% and 5% chromium steels continuously immersed in seawater

We next consider the results for four proprietary low-alloy steels. Metals of this class have proved extremely resistant to atmospheric corrosion. In fact, following collection of long-term atmospheric data by the manufacturers, it was realized that films of corrosion product became so protective after several years that the use of these steels in many atmospheres without the application of protective coatings or additional maintenance was feasible. On the basis of this high atmospheric resistance, some of these metals have been assumed also to possess superior corrosion resistance to seawater, but the present study has shown repeatedly that such environmental extrapolation is very unreliable. The 16-year data in Fig. 11 show the long-term effects of seawater on four of these proprietary metals.

A comparison of the curve for mild carbon steel (broken line, Fig. 11) with those for the low-alloy steels shows that general corrosion rates for metals (I) and (K) are very similar to mild steel (A). The other two metals (L) and (J) corrode significantly faster. The constant rate for (J) leveled out at approximately 4.8 mpy and for (L) at 5.0 mpy vs. 2.7 for mild steel. Chromium is common to both of these alloys of lower resistance. Alloys (L) and (J) contained 0.6% and 0.7% chromium, respectively, while the others contained only traces. And, of course, as just shown in the preceding Fig. 10, 3% and 5% chromium also resulted in higher general corrosion losses.

Based on pitting data the low-alloy steels show little or no advantage over mild carbon steel; slightly deeper long-term pitting was measured for alloys (I), (J), and (L) but somewhat lower pitting for (K).

Wrought Iron

The corrosion of Aston-process wrought iron in seawater is compared with mild steel in Fig. 12. Data for the comparison of steel and clean wrought iron are available only thru the 8-year period. Machined wrought iron was included to 8 years only because of insufficient samples. Weight losses for the two surface conditions were reasonably similar through 8 years. In all probability, the curve obtained with the millscale

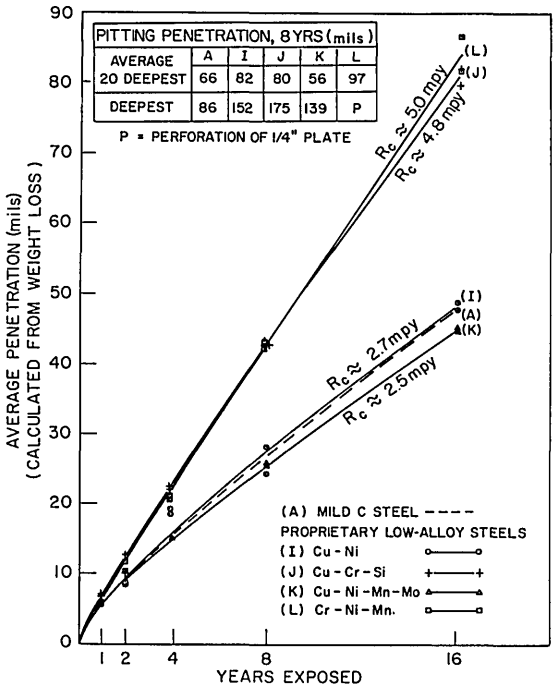

Fig. 11 - Corrosion of proprietary low-alloy steels continuously immersed in seawater

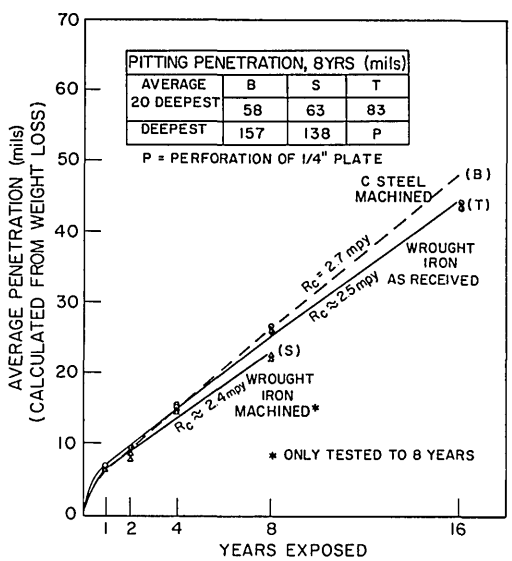

Fig. 12 - Corrosion of Aston-process wrought iron continuously immersed in seawater

surface (T) fairly represents the corrosion rate of wrought iron over extended periods. A slight advantage in favor of Aston wrought iron is indicated by the weight-loss data. Comparison of depth of pitting of steel and wrought iron can be made only to 8 years between initially cleaned materials, because the millscale surface does adversely affect pitting resistance. At 8 years, the pitting penetration in seawater was essentially equal for the machined wrought iron and machined carbon steel.

Cast Ferrous Metals

Weight loss and pitting for the cast ferrous metals are shown in Fig. 13. The curves are for 1/4-inch-thick plates with machined surfaces exposed to continuous immersion in seawater. The corrosion of cast steel, shown in Fig. 13a, is quite similar to that of wrought carbon steel as judged from both weight loss and pitting. Average pitting was rapid at first, but after 4 years parallels the slope of the weight-loss curve at approximately 2 to 3 mpy. The 16-year pitting factor equals 3.3, which was also about the same as for wrought steel.

Gray cast iron, shown in Fig. 13b, was heavily graphitized; after 16 years in seawater only about 1/5 of the original metal remained as a small center core. The graphite layer remained in place, and the panels appeared, on the surface, to be in almost the original condition. This graphitized material was mechanically removed before cleaning. Apparently the porous graphite offered no protection to the uncorroded metal; in fact, it probably accelerated corrosion by galvanic action. Underlying metal corroded at a higher rate than any other ferrous metal studied. The steady-state rate approximated 6 mpy. Pitting was not serious. The pitting factor was 3.1 at 8 years.

Austenitic cast iron, Fig. 13c, contained 18% nickel and was the most

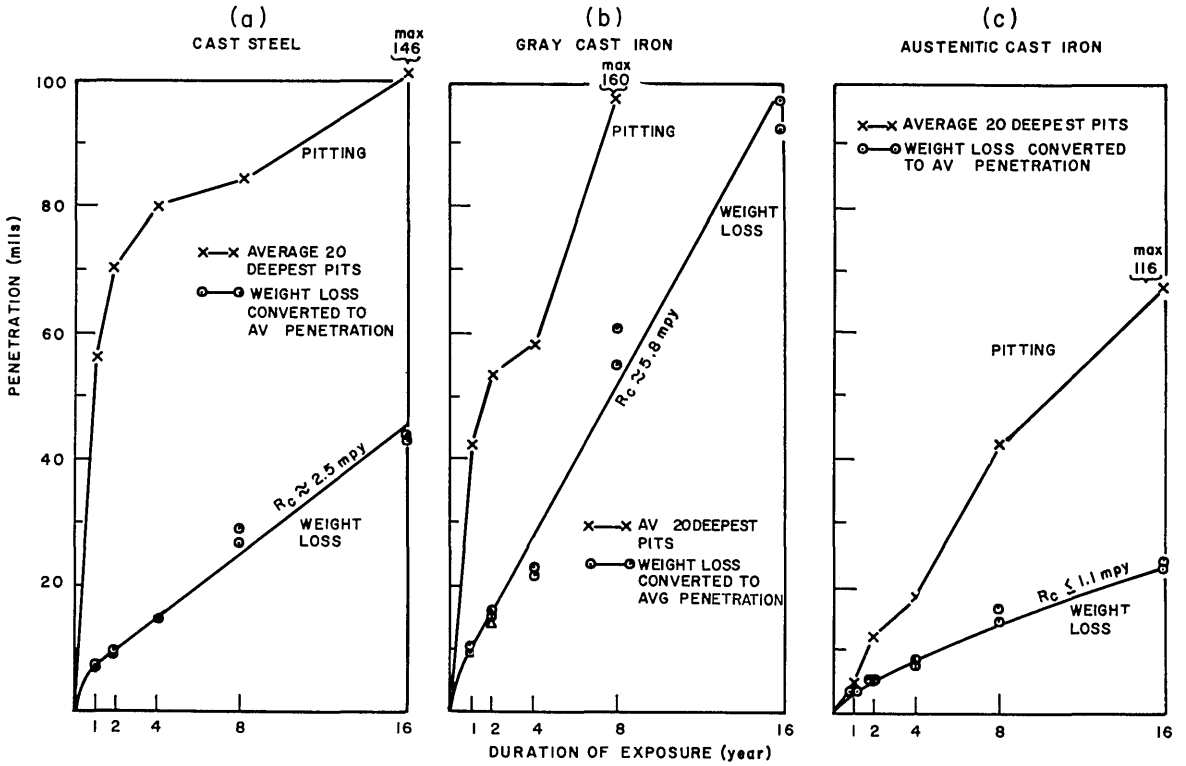

Fig. 13 - Corrosion of cast ferrous metals in seawater; (a) cast steel, (b) gray cast iron, and (c) austenitic cast iron

resistant to seawater corrosion of the metals included in this report. The final constant general corrosion rate was equal to or less than 1.1 mpy. This was about 1/5 that of gray cast iron. Average pitting of the austenitic iron seemed to increase steadily in depth at the rate of about 3 to 4 mpy. The pitting rate decrease noted for most of the other ferrous metals did not occur. The maximum pit depth at 16 years was 116 mils. Much less advantage for the high-nickel iron was shown on the basis of pitting than on weight loss. The pitting factor at 16 years was 5.1.

Results of the exposure of cast metals with as-cast surfaces for 2 and 4 years are included in Table 2. Examination of these data suggests that such surfaces corrode more erratically than machined surfaces. In all cases lower weight loss per unit area was observed than with machined surfaces. On the other hand, pitting penetration was usually deeper in the as-cast plates.

COMPARISON OF TROPICAL AND TEMPERATE LATITUDE CORROSION

With this large mass of ferrous metal corrosion data collected in tropical seawater, it is especially desirable to compare with ferrous corrosion in temperate seas. The usefulness of these results for structural design in other latitudes will depend on reasonably close agreement. Figure 14 shows the corrosion curve for mild carbon steel in

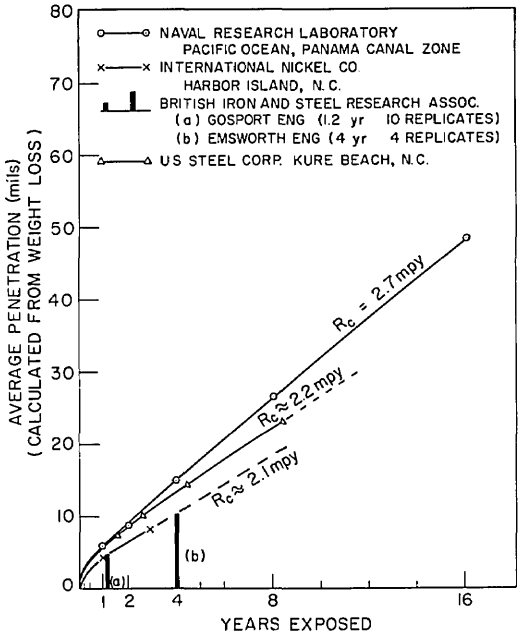

Fig. 14 - Comparative corrosion of structural carbon steel in tropical and temperate seawater

tropical seawater compared with similar data available from temperate latitudes. The Harbor Island experiment (22) extended for only 3 years, but it appears that a steady-state rate of approximately 2 mpy is probable. The two bits of data from England (13), shown by the bar graphs, were precisely established points from a large number of replicates, but as they represent single time points from two locations, the bars have not been connected. However, if corrosive conditions were equal for these two locations, a constant rate of about 2 mpy would also be indicated in the English seawater. The curve obtained over 8-1/2 years from Kure Beach (11) provides the most useful data from a temperate latitude for comparison with the tropical results. Initially, the two curves practically coincide, but slightly less downward curvature was obtained with the tropical data. The final Kure Beach rate stabilized at approximately 2.2 mpy vs 2.7 mpy in the Canal Zone.

In the far northern waters of the Barents sea, the Russian Academy of Physical Chemistry collected data on the corrosion of carbon steel during 6 years of immersion (15). Their results show corrosion rates becoming constant after 2 to 4 years at values of about 1.4 to 1.8 mpy.

Tropical corrosion rates appear to be sufficiently close to those from other latitudes so that practical design data are provided. The slightly higher losses in the tropics should represent a general upper limit for ferrous metal corrosion in uncontaminated natural seawater.

SUMMARY

Several attempts have been made to obtain corrosion rates for ferrous metals in seawater and fresh water. However, prior to these tropical studies, there has been very little published information that provides the necessary long-term relations.

Most of the corrosion rates of the metals in the tropical underwater environments stabilized to a steady-state after 1 to 8 years' exposure. This final constant rate provides the most significant value for comparing corrosion rates of different metals or extrapolating to more extended periods of exposure.

Fresh-water corrosion of carbon steel showed a smooth, almost parabolic relation with time. Rates changed from 7.4 mpy av for the first year to 0.7 mpy for the interval from 8 to 16 years. Pitting penetration revealed a much higher but similarly shaped curve that eventually decreased to a final rate approximately equal to that of general corrosion.

Seawater corrosion of carbon steel becomes linear with time within the first 1 to 2 years' exposure. The final constant rate for general corrosion was established as 2.7

mpy, a rate which is appreciably lower than has usually been reported even in temperate seas. Pitting rates for mild steel in tropical seawater changed from 25 to 35 mpy for the first 2 years to an eventual slope roughly parallel to that of average penetration at approximately 3 mpy.

The corrosion rate of carbon steel at mean tide did not become stabilized until after 4 years' exposure. The final constant rate was 2.7 mpy. This is the same final rate established within 1 or 2 years for continuous seawater immersion. After stabilization, corrosion rates in both environments may be controlled by anaerobic bacteria under heavy self-repairing fouling cover.

Two and 5% nickel alloy steels showed undersea general corrosion rates approximately equal to that of mild carbon steel. Pitting of the nickel steels was less than mild steel at 1 year, but after 8 to 16 years' exposure it was considerably deeper.

Three and 5% chromium steels had initial corrosion losses in seawater lower than those of carbon steel, but beyond 4 years the advantage was reversed. At 16 years the chromium steels showed 22 to 45% higher losses than ordinary steel.

Of four proprietary low-alloy steels immersed in seawater, two without chromium showed long-term corrosion rates approximately equal to carbon steel. The other two, containing small percentages of chromium, had substantially higher general corrosion losses after 8 and 16 years' exposure.

Aston-process wrought iron continuously immersed in seawater showed no advantage in pitting over mild steel in the same exposure and only a slight advantage in general corrosion resistance.

Gray cast iron in seawater had the highest corrosion rate of any of the metals tested; its final constant rate was more than double that for mild steel and over five times the constant rate for an austenitic cast iron.

Comparison of tropical corrosion losses with available temperate climate data indicates similar corrosion-time relations for the different latitudes but slightly higher final rates for the tropical seawater.

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Appendix

ANALYSES OF METALS AND ENVIRONMENTS

So that exact test conditions would be known, considerable effort was expended during the course of the investigation in analyzing the metals under study and the environments in which they were exposed. Tables A1 through A3 and Fig. A1 give summaries of the pertinent results of these tests.

All sampling and testing for the appendix 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.

Table A1
Composition of Structural Ferrous Metals Tested

Key	Metals	Initial Surface Condition	Specification	Composition (Percent)								
				C	Mn	P	S	Si	Cr	Ni	Cu	Mo
A	C steel	Pickled	QQ-S-741, IIA1	0.24	0.48	0.040	0.027	0.008	0.03	0.051	0.080	—
B	C steel	Machined										
C	C steel	Millscale										
D	C steel—0.3% Cu	Pickled	QQ-S-741, IIA2	0.22	0.44	0.019	0.033	0.009	Trace	0.14	0.35	—
E	2% Ni steel	Pickled	RR-3A	0.20	0.54	0.012	0.023	0.18	0.15	1.94	0.63	—
F	5% Ni steel	Pickled	SAE 2515	0.13	0.49	0.010	0.014	0.16	0.10	5.51	0.062	—
G	3% Cr steel	Pickled	Proprietary	0.08	0.44	0.010	0.017	0.13	3.16	0.16	0.11	0.02
H	5% Cr steel	Pickled	AISI Type 501D	0.08	0.41	0.020	0.019	0.20	5.06	0.11	0.062	0.52
I	Low-alloy steel	Pickled	Proprietary	0.08	0.47	0.007	0.026	0.060	0.00	1.54	0.87	—
J	Low-alloy steel	Pickled	Proprietary	0.15	0.45	0.113	0.026	0.47	0.68	0.49	0.42	—
K	Low-alloy steel	Pickled	Proprietary	0.078	0.75	0.058	0.022	0.04	Trace	0.72	0.61	0.13
L	Low-alloy steel	Pickled	Proprietary	0.13	0.60	0.089	0.021	0.15	0.55	0.30	0.61	0.059
M	Cast steel	Machined	QQ-S-6816, 1	0.27	0.68	0.028	0.028	0.41	0.12	0.22	0.10	—
N	Cast steel	As received										
O	Gray cast iron	Machined	QQ-I-652, 30	3.18	0.80	0.162	0.103	1.98	0.57	0.31	0.08	—
P	Gray cast iron	As received										
Q	Austenitic cast iron	Machined	INCO 18-22 Ni	2.66	0.94	0.24	0.104	3.17	2.29	17.9	0.80	—
R	Austenitic cast iron	As received										
S	Wrought iron	Machined	Aston Process ASTM A42-39	0.04	0.038	0.141	0.018	0.098	Trace	0.006	0.020	—
T	Wrought iron	As received										

Table A2
Physical and Mechanical Properties of Test Metals

Key	Metals	Physical Properties			Mechanical Properties					
		Surface	Density (g/cc)	Grain Size (ASTM No.)	Ultimate Tensile (psi)	Yield Point (psi)	Elongation (% for 2 in.)	Hardness (BHN-1000 kg)	Free Bend	
									Elong. (%)	Final Condition
A	C steel	Pickled	7.85	8	70,930	44,230	31	129	50	o.k.
B	C steel	Machined								
C	C steel	Millscale								
D	C steel, 0.3% Cu	Pickled	7.85	8	65,000	47,300	31	123	*	o.k.
E	2% Ni steel	Pickled	7.84	8	77,330	58,700	28	145	50	o.k.
F	5% Ni steel	Pickled	7.85	8	91,400	77,130†	21	204‡	50	Checked
G	3% Cr steel	Pickled	7.82	7	115,500	84,370†	16	242‡	40	Checked
H	5% Cr steel	Pickled	7.81	7	144,400	108,000†	14	298‡	*	Cracked
I	Low-alloy steel	Pickled	7.86	6	57,730	45,330	36	112	50	o.k.
J	Low-alloy steel	Pickled	7.82	7	71,700	57,170	34	138	40	o.k.
K	Low-alloy steel	Pickled	7.85	8	74,300	64,100	31	148	40	o.k.
L	Low-alloy steel	Pickled	7.84	8	74,970	51,770	30	156‡	25	Cracked
M	Cast steel	Machined	7.82	7	64,400	43,100	18	133	40	Cracked
N	Cast steel	As rec'd								
O	Gray cast iron	Machined	7.08	*	33,900	*	0	198‡	0	Ruptured
P	Gray cast iron	As rec'd								
Q	Austenitic cast iron	Machined	7.11	7	24,300	*	2	116	3	Ruptured
R	Austenitic cast iron	As rec'd								
S	Wrought iron	Machined	7.76	6	49,300	*	28	108	33	Cracked
T	Wrought iron	As rec'd								

*Not determined.
†Yield strength, 0.2% offset.
‡3000-kg load.

Table A3
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 $\times 10^{-3}$ 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

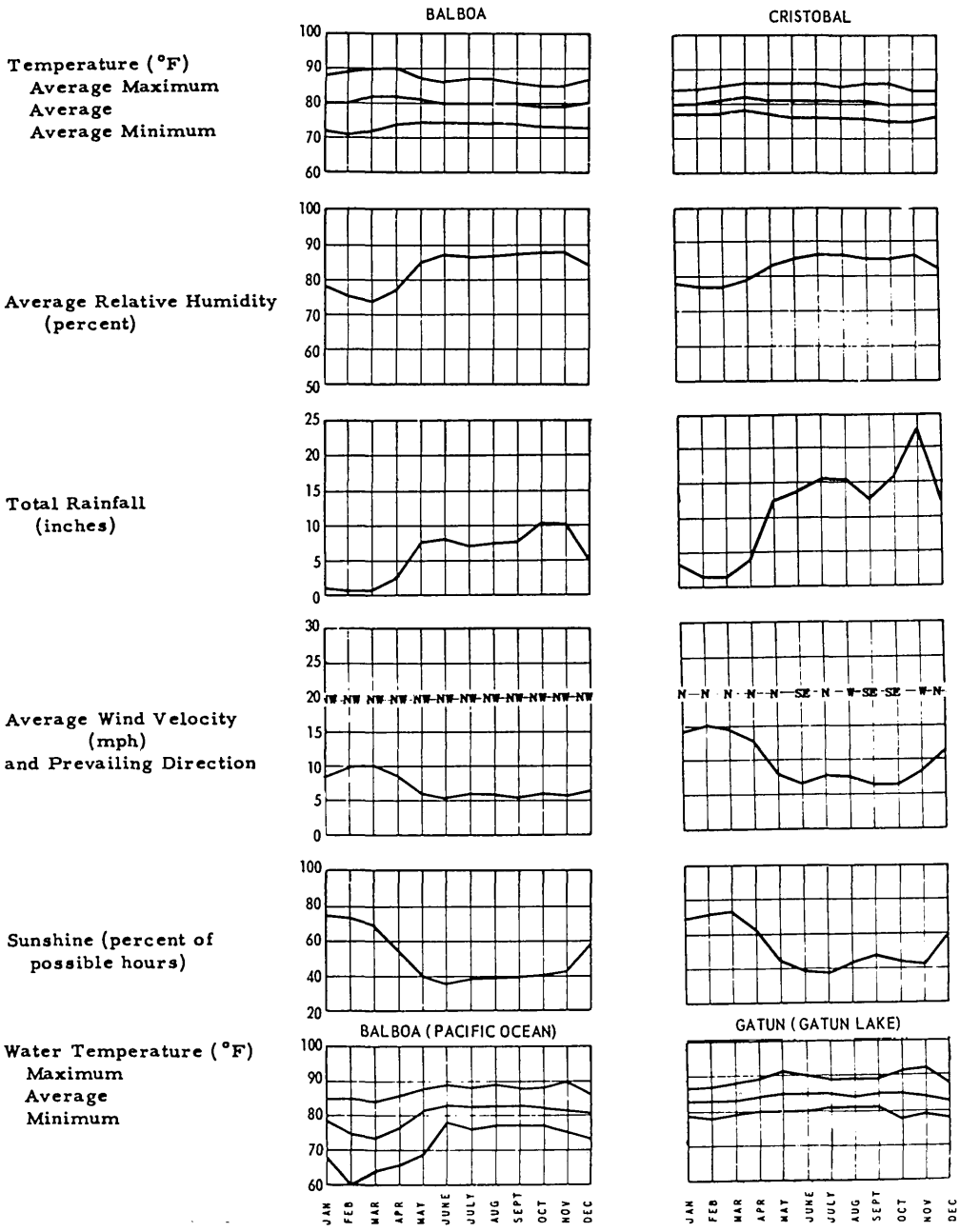

Fig. A1 - Canal Zone climatic conditions (average records, 20 years maximum)

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13. ABSTRACT

Effects of corrosion on 20 structural ferrous metals immersed in seawater and fresh water and exposed at mean-tide elevation have been measured at various intervals during 16 years. Corrosion rates and time-corrosion curves derived from both weight loss and pitting have been established. A brief state-of-the-knowledge review for seawater corrosion of ferrous metals reveals the paucity of adequate long-term data in the corrosion literature. Between 2 and 16 years' exposure, corrosion rates of most ferrous metals stabilized to constant values. These final constant rates provide the most significant data for comparing the corrosion resistance of the different metals in the various environments and for estimating service life over more extended periods. Based on this evaluation, the general corrosion rates of steels in seawater and fresh water are appreciably less than usually reported, and the long-term pitting rate of structural steel in seawater is only 1/3 to 1/5 of that normally reported for these metals.

The corrosion of various low-alloy steels has been compared during 16 years of seawater exposure. Of the alloying elements considered, none was found which improves the corrosion resistance of the metals in the sea, while chromium and nickel seemed to cause increased general corrosion or pitting during the longer periods of marine exposure. Aston-process wrought iron and various cast irons and steels have been evaluated for long-term seawater exposure. Only the 18% nickel cast iron shows any definite advantage over carbon steel. Steel corrosion losses in tropical and temperate latitude seawaters have been compared. Results indicate similar corrosion-time relations for the different latitudes but slightly higher final rates for the tropical sea. Useful upper-limit corrosion rates are thus provided by the tropical seawater studies.

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Low-alloy steel						
Wrought iron						
Cast iron						
Pitting						
General corrosion						
Time relation						
Stabilized rate						
Marine fouling						
Anaerobic bacteria						