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Technical Report

CORROSION OF MATERIALS IN HYDROSPACE

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NAVAL FACILITIES ENGINEERING COMMAND

U. S. NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California

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CORROSION OF MATERIALS IN HYDROSPACE

Technical Report R-504

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by

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ABSTRACT

A total of 1,590 specimens of 107 different alloys were exposed by the Naval Civil Engineering Laboratory at depths of 2,340, 5,300, and 5,640 feet at two sites in the Pacific Ocean for 197, 1,064, and 123 days to determine the effects of deep ocean environments on the corrosion of materials.

The corrosion rates, pit depths, types of corrosion, changes in mechanical properties, and analyses of corrosion products of the alloys are presented.

Titanium alloys and two nickel base alloys (Ni-Fe-Cr-825 and Ni-Mo-Cr-"C") were immune to corrosion. The corrosion rates of copper alloys and steels decreased with a decrease in the oxygen concentration of the seawater and with increasing time of exposure at a nominal depth of 5,500 feet. The corrosion rates of most of the aluminum alloys increased with increasing time of exposure and with decreasing oxygen concentration of seawater. Muntz metal, and nickel-manganese bronze were attacked by dezincification and aluminum bronze by dealuminification. All the stainless steels except types 316 and 316L, 20-Cb and 17 Cr - 7 Ni - 0.7 Ti - 0.2 Al were attacked by pitting corrosion. Only two precipitation hardened stainless steels were susceptible to stress corrosion cracking. The oceanographic parameters varied with depth. Changes in temperature and oxygen concentration exerted the most influence on the corrosion of the alloys.

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The Laboratory invites comment on this report, particularly on the results obtained by those who have applied the information.

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PREFACE

The U. S. Naval Civil Engineering Laboratory is conducting a research program to determine the effects of the deep ocean environment on materials. It is expected that this research will establish the best materials to be used in deep ocean construction.

A Submersible Test Unit (STU) was designed, on which many test specimens can be mounted. The STU can be lowered to the ocean floor and left for long periods of exposure. Planned exposures range from 4 to 48 months at depths from 2,500 to 18,000 feet.

Thus far, two deep ocean test sites in the Pacific Ocean have been selected. Six STUs have been exposed and recovered. Test Site I (nominal depth of 6,000 feet) is approximately 81 nautical miles southwest of Port Hueneme, latitude 33°44'N and longitude 120°45'W. Test Site II (nominal depth of 2,500 feet) is 75 nautical miles west of Port Hueneme, latitude 34°06'N and longitude 120°42'W. Additional test sites at depths of 12,000 and 18,000 feet may be chosen.

Various reports concerning the deep ocean will deal with such subjects as (1) the causes and rates of corrosion of metals and alloys, the causes of changes in the mechanical properties of metals and alloys, and the degradation of nonmetallic materials; (2) the physical and chemical parameters of seawater; and (3) the biodeterioration of materials. In addition, techniques and equipment for emplacing, relocating, and retrieving STUs will be reported.

This report presents the results of the evaluations of the alloys on the first three structures recovered (STUs I-1, I-3, and II-1). Three of the four previous reports (TN-605, TN-695, and TN-793) on the corrosion of these materials presented only the results of the visual observations and the fourth report (TN-781) presented the corrosion rates and pit depths of eight selected alloys. Future reports will contain the results of the evaluations of the alloys on the last three structures recovered (STUs I-2, I-4, and II-2).

INTRODUCTION

Improvements in techniques and the development of new techniques pertaining to naval material has placed an emphasis on the deep ocean as an operating environment. Consequently, unprecedented constructions are necessary to support antisubmarine warfare systems, oceanographic research, and rescue missions in the abyssal areas of the oceans.

Since the Naval Facilities Engineering Command of the Office of Naval Material is charged with the responsibility for the construction of all fixed naval facilities, the construction and maintenance of naval structures at great ocean depths are additional facets of this responsibility.

To study the problems of construction in the deep ocean, project "Deep Ocean Studies" was established. Fundamental to the design, construction, and operation of structures, and their related facilities, is information on the deterioration of materials in deep ocean environments. This report is devoted to the portion of the project concerned with determining the effects of deep ocean environments on the corrosion of materials.

A test site was considered to be suitable if the circulation, sedimentation, and bottom conditions were representative of open ocean conditions: (1) the bottom should be reasonably flat, (2) the site should be open and not located in an area of restricted circulation such as a silled basin, (3) the site should be reasonably close to Port Hueneme for ship operations, and (4) the site should be within the operating range of the more precise navigating and locating techniques.

A nominal depth of 6,000 feet was chosen for the initial site because it was representative of an intermediate depth. The initial site was relatively flat in a broad submarine valley southwest of San Miguel Island; it was readily accessible to NCEL; and it was subject to the effects of the ocean currents. The location of this site in the Pacific Ocean in relation to Port Hueneme and the Channel Islands is shown in Figure 1 as Submersible Test Units (STUs) I-1, I-2, I-3, and I-4.

The environmental conditions at the bottom, a depth of 5,650 feet, at a location about 5 miles northwest of STU I-1 were reported to be as follows:[1]

1. Temperature, 2.53° C
2. Salinity, 34.58 ppt
3. Oxygen, 1.29 ml/l

The complete oceanographic data at this location on 12 January 1962, as reported by Scripps Institution of Oceanography is shown in Figure 2.

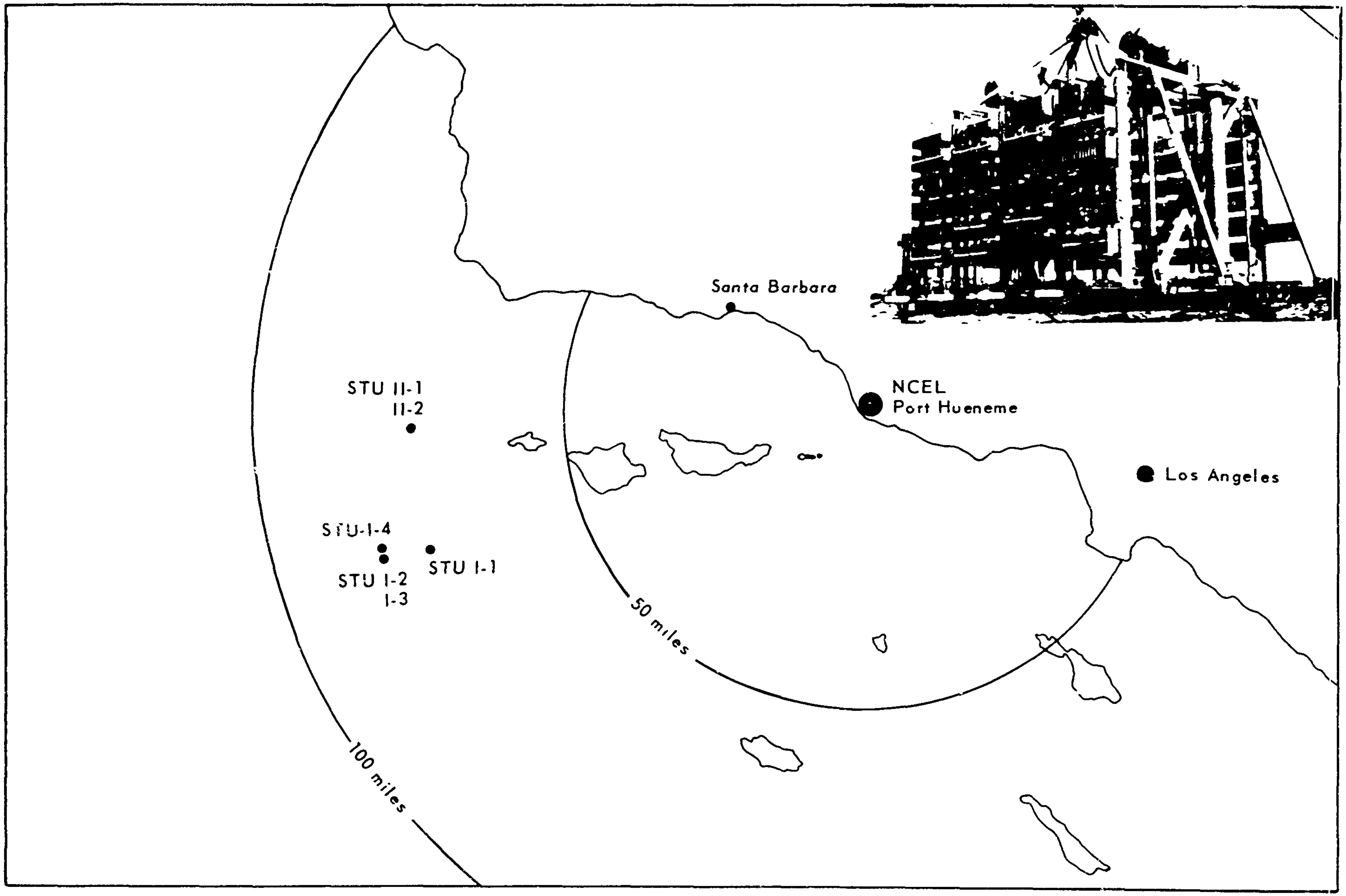

Figure 1. STU sites off Pacific Coast. STU shown in inset.

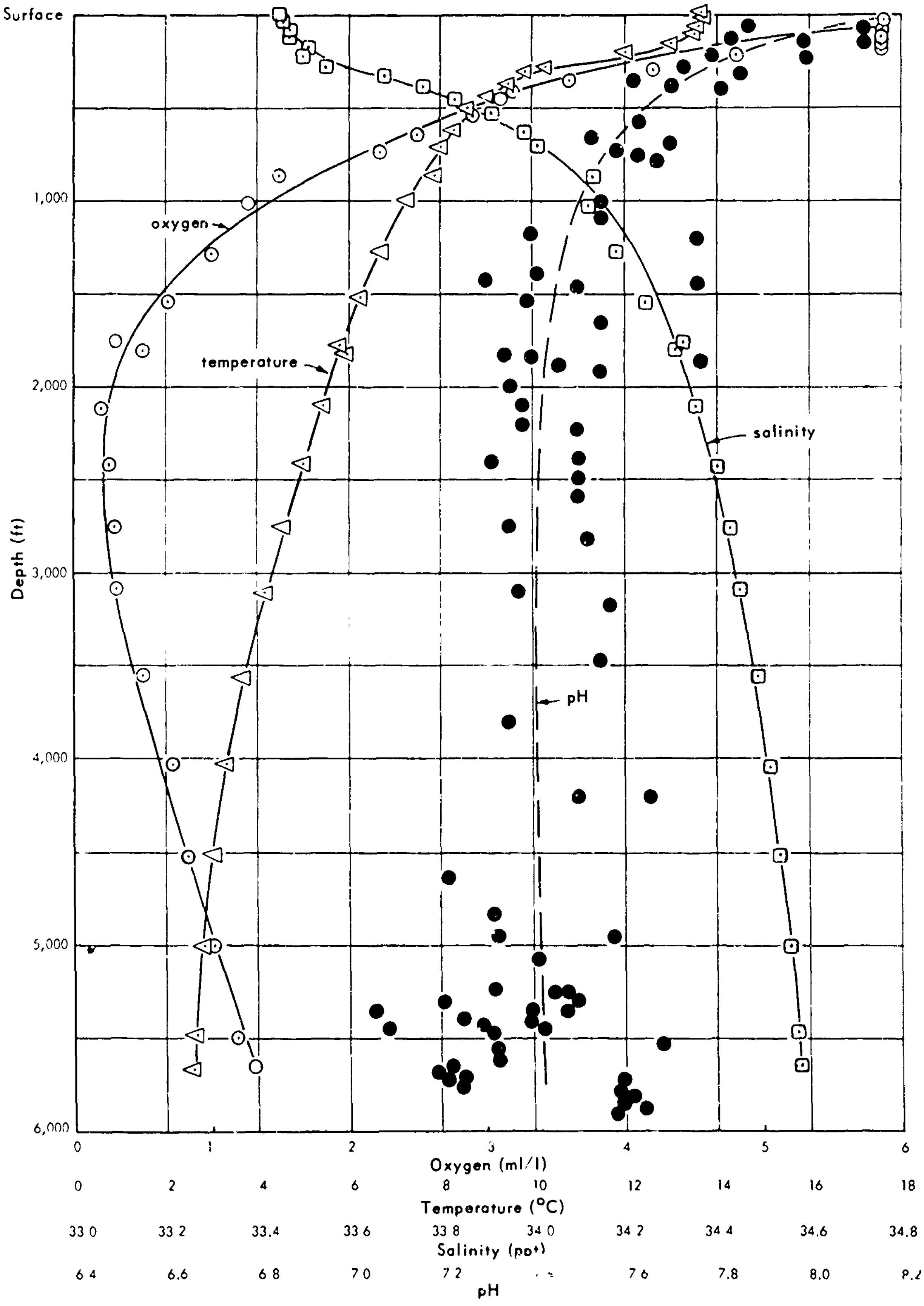

Figure 2. Oceanographic data from a location about 5 miles northwest of STU I-1 site (except for the pH curve, which represents data from the vicinity of STU I-1).

A summary of the characteristics of the bottom waters at the different exposure sites is given in Table 1.

The complete oceanographic data from the NCEL cruises made from 1961 to 1963 also showed the presence of an oxygen minimum zone (as shown in Figure 2) at depths of 2,000 to 3,000 feet. This minimum oxygen zone was present at all sites investigated when the ocean floor was at a depth of 2,000 to 13,000 feet.

Because of this oxygen minimum concentration zone it was decided to establish the second exposure site (STU II-1 and II-2) at a nominal depth of 2,500 feet. Because corrosion rates are affected by the concentration of oxygen in the environment it was decided that fruitful information would be obtained at this depth. This site is shown in Figure 1, and the characteristics of the bottom water are given in Table 1.

The NCEL oceanographic investigations also disclosed that the ocean floor at these sites was rather firm and was characterized as sandy, green cohesive mud (partially glauconite) with some rocks. The biological characteristics of this sediment are described in References 4 and 5. Some surface data and data from depth in the Atlantic Ocean, accumulated by other investigators, are included in this report for purposes of comparison.

PREPARATION OF SPECIMENS

The specimens for the first exposure (1,064 days) were measured for length, width, and thickness, and were then degreased in stabilized trichloroethylene vapor. After being degreased the specimens were placed in a room in which the relative humidity was maintained at 20% and were weighed. The weighed specimens were placed in the racks which were to be placed on the STU for exposure in the deep ocean environment.

The specimens for all subsequent exposures were treated as follows:

1. Length, width, and thickness were determined.
2. They were degreased with methyl-ethyl-ketone.
3. The different types of alloys were then cleaned as follows:
   a. Irons, steels, and alloy steels were sand-blasted to a white finish with silica sand conforming to the requirements of Military Specification 177-26A, Class 1, 21 May 1964.
   b. Martensitic, ferritic, austenitic, and precipitation hardening stainless steels, and titanium alloys, were cleaned in an ultrasonic tank containing 10%, by volume, nitric acid.
   c. Copper base and nickel base alloys were cleaned in 18%, by volume, hydrochloric acid.

    d. Aluminum alloys were cleaned in an ultrasonic tank containing concentrated nitric acid.

4. The cleaned specimens were stored in a room in which the relative humidity was maintained at 20% and were weighed.
5. The weighed specimens were then placed in the racks which were to be placed on the STU for exposure in the deep ocean environments at different depths for different periods of time.

After being treated, the specimens were assembled in racks of various types which were, in turn, fastened to an open-framework STU, shown in the inset in Figure 1. The details of the construction, emplacement, and retrieval of the STUs are given in References 6 through 9.

The 6 x 12-inch specimens were held in the type of rack shown in Figure 3. The specimens were held in place by four molded, grooved polyethylene insulators and were separated from each other by 1 inch. The specimens were thus electrically insulated from each other and from contact with all metallic parts of the rack and structure, thereby precluding the possibility of galvanic corrosion. The center dividers and end plates were either aluminum alloy 5086-H32 or titanium alloy 75-A. The rods through the insulators were nickel-copper alloy 400 fastened with nuts and washers of the same composition. In all cases polyvinyl chloride (PVC) washers were used between the metal washer and the end plates. The two longer rods (those on the sides) were used to fasten the racks on the STU structures.

The 1 x 6-inch specimens were fastened to the type of rack shown in Figure 4. The specimens were bolted to NEMA grade CE phenolic-resin-impregnated cotton fabric strips with nylon nuts and bolts. These strips were then fastened to the titanium end plates with nickel-copper alloy 400 machine screws to form a rack.

Some of the first stress corrosion specimens were stressed by machining them to lengths calculated to produce the desired stress on the convex side when sprung into a jig with slots 7.00 inches apart (Figure 5). The ends of the jigs and specimens were coated with a water-impervious compound to prevent galvanic corrosion between the jig and the ends of the specimens. This method was later found to be unsatisfactory because of the crevice corrosion of the specimens occurring at the edges of the coating.

An improved four-point loading method was adopted whereby the specimens were stressed by bowing them over anvils 2 inches apart. The four-point loading assembly with a capacity for 15 specimens is shown in Figure 6. The anvils were made of NEMA grade G-10 epoxy-impregnated laminated glass cloth. There was a 1/16-inch radius at the tops of the anvils. Two such anvils were bolted to slotted aluminum alloy 5086-H34 base plates so that their apexes were 2 inches ± 0.005 inch apart. The specimens were placed across the anvils, and the ends were tightened by means of bolts and nuts to the base plate until the calculated deflections across the anvils were obtained. The bolts were insulated from the specimens with shoulder grommets and from the base plates with plastic sleeves and PVC washers. Four of these jigs were then bolted to titanium end plates to form a rack (Figure 7).

Table 1. Characteristics of Bottom Waters1/

Site	Depth of STU (ft)	Sampling Water Depth (ft)	Pressure (psi)	Temperature (°F)	Oxygen (ml/l)	Salinity (ppt)
I-1	5,300	5,310	2,300	36.5	1.26	34.56
I-3	5,640	5,870	2,445	36.3	1.50	34.59
II-1	2,340	2,425	1,015	40.8	0.39	34.39
Surface2/	—	65	28	52-63	5.4-6.5	33.76

Site	pH	Current (knots avg)	Oxidation-Reduction Potential (mv)	Alkalinity (milli-equivalents)
I-1	7.44	0.03	+215	2.39
I-3	7.48	0.03	+215	2.53
II-1	7.49	0.06	+230	2.56
Surface2/	7.9-8.3	variable	+217	2.72

1/ Table derived from References 2 and 3.

2/ Off the Channel Islands.

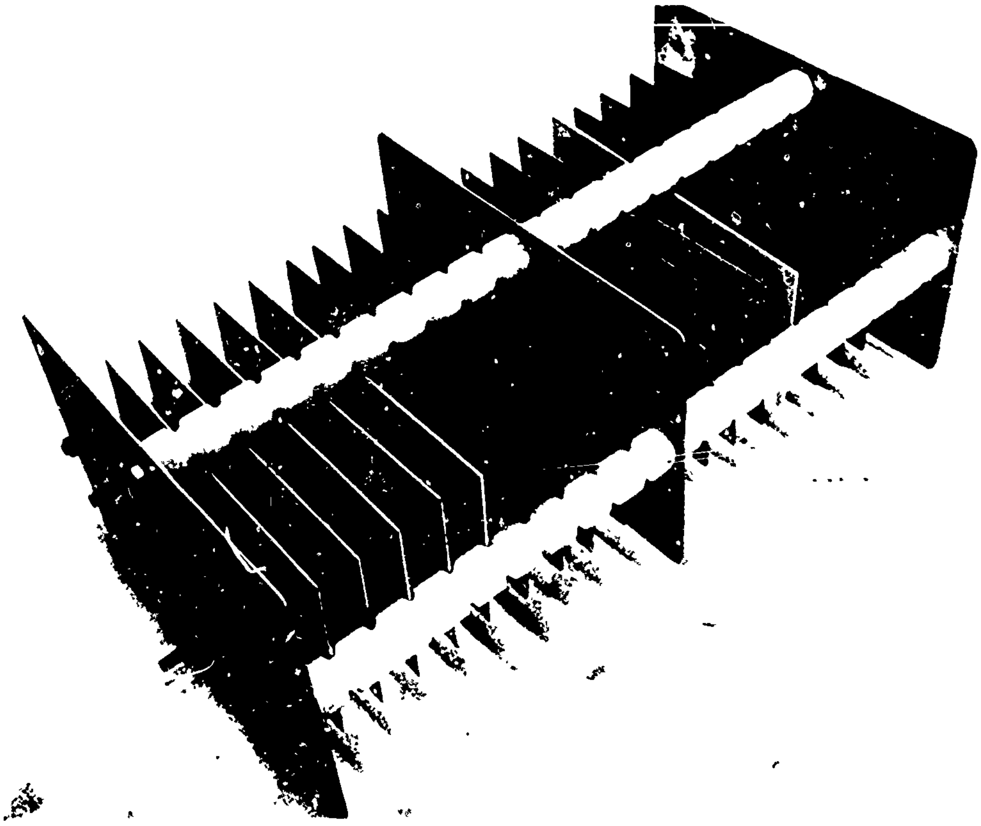

Figure 3. Exposure rack for 6 x 12-inch specimens.

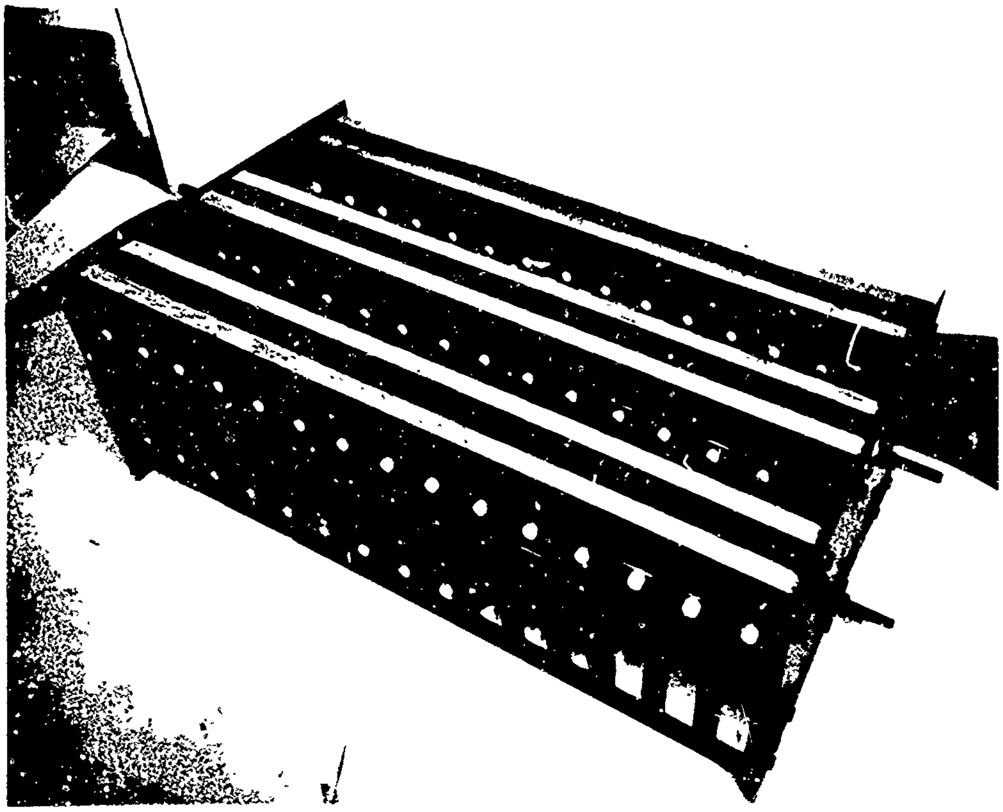

Figure 4. Exposure rack for 1 x 6-inch specimens.

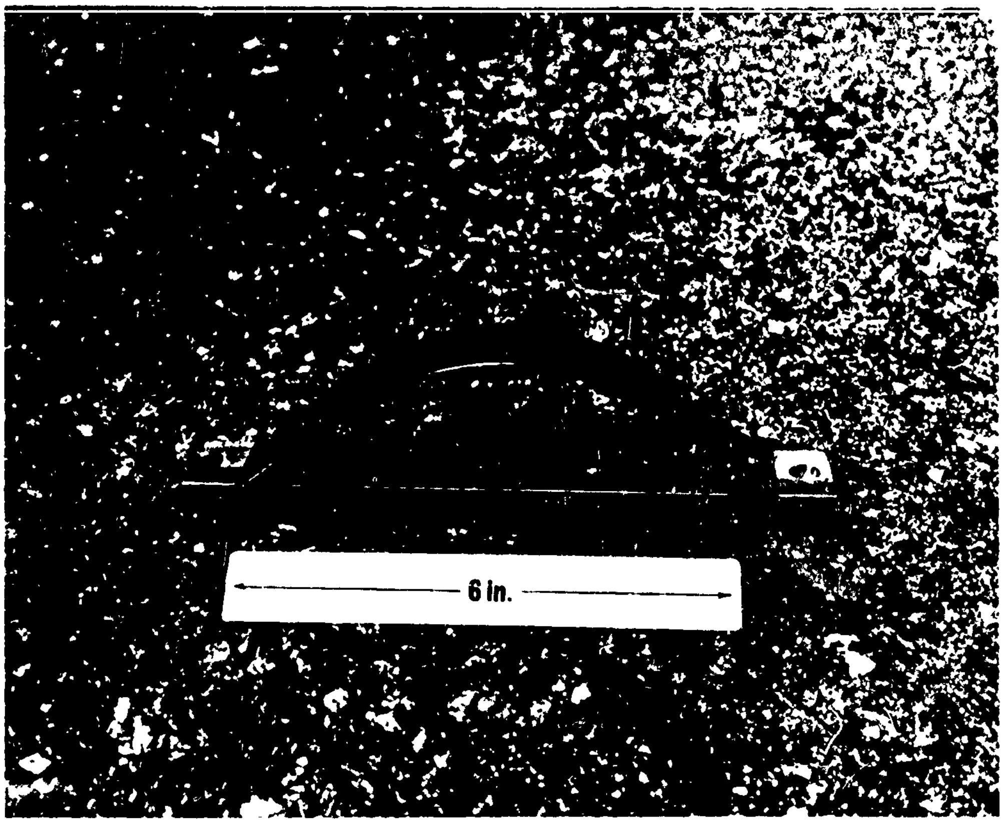

Figure 5. Jig for stress corrosion specimens.

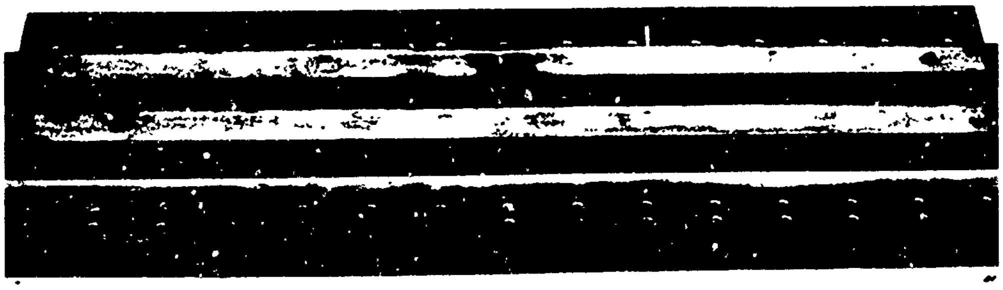

Figure 6. Four-point jig for stress corrosion specimens.

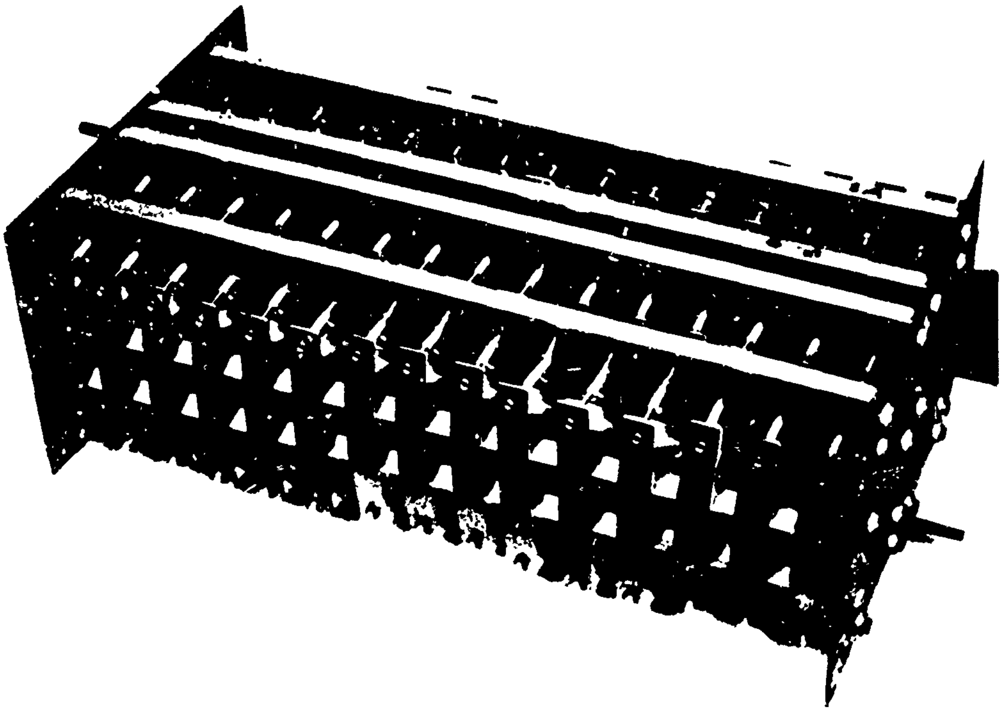

Figure 7. Stress corrosion rack.

The 6 x 12-inch specimens were exposed in either quadruplicate or triplicate both on the sides and in the base of the STU. Those on the sides were 1-1/2 to 6 feet above the ocean bottom and were subjected only to the seawater, but those in the base were subjected to both the bottom sediment and the seawater. To one specimen of each group of three of four in each environment (water or mud) was bolted a 1-square-inch piece of the same material with a plastic nut and bolt, to evaluate the material's susceptibility to crevice corrosion.

The 1 x 6-inch specimens were exposed in either quintuplicate or triplicate.

The locations of the various STUs, and the number of days they were exposed in the Pacific Ocean are given in Table 2.

Table 2. STU Data

STU	Latitude (North)	Longitude (West)	Depth of STU (ft)	Number of Specimens[1]	Number of Materials	Exposure (days)
I-1	33°46'	120°37'	5,300	1,409	396	1,064
I-3	33°44'	120°45'	5,640	1,371	398	123
II-1	34°06'	120°42'	2,340	2,389	603	197

[1] Including specimens for other sponsors.

METHODS USED TO EVALUATE MATERIALS

After retrieval the specimens were examined visually for gross corrosion damage, and representative specimens were photographed in color and in black and white. The corrosion products were then removed from the specimens in appropriate chemical solutions as follows:

1. Steels and low-alloy steels were treated in an ultrasonically vibrated tank containing 10%, by weight, ammonium citrate solution heated to 150°F; they were then washed in hot water, scrubbed with a fiber bristle brush, again washed in hot water, dipped into distilled water, rinsed in absolute ethyl alcohol, and dried in a current of warm air.
2. Martensitic, ferritic, austenitic, precipitation hardening stainless steels, and titanium alloys, were treated in an ultrasonically vibrated tank containing 10%, by volume, nitric acid solution heated to 150°F; they were then washed in hot water, scrubbed with a fiber bristle brush, again washed in hot water, dipped into distilled water, rinsed in absolute ethyl alcohol, and dried in a current of warm air.
3. Aluminum alloys were treated in an ultrasonically vibrated tank containing concentrated nitric acid at room temperature; they were then washed in hot water, scrubbed with a fiber bristle brush, again washed in hot water, dipped into distilled water, rinsed in absolute ethyl alcohol, and dried in a current of warm air.
4. Copper base alloys and nickel base alloys were immersed in an 18%, by volume, hydrochloric acid solution at room temperature; they were then washed in hot water, scrubbed with a fiber bristle brush, again washed in hot water, dipped into distilled water, rinsed in absolute ethyl alcohol, and dried in a current of warm air.

An exposed control specimen of each alloy was also cleaned with each group of companion specimens.

The cleaned specimens were weighed and the weight losses determined. From these weight losses were calculated the corrosion rates in milligrams per square decimeter per day (MDD) and mils penetration per year (MPY). A survey was made of each specimen for the types of corrosion and the depths of the pits, where appropriate. The depth of the deepest pit, the average depth of the 10 deepest pits, and the pitting frequency (average number of pits per square inch) were determined. Areas of cleaned specimens showing different types of attack were photographed. The tensile strength, yield strength (0.2% offset), and percent elongation were determined on specimens machined from the corroded specimens. Chemical analyses were made of the corrosion products removed from some alloys. Specimens of the alloys were examined metallographically for types of corrosion other than the uniform and the pitting types.

RESULTS AND DISCUSSION

The results of the evaluations will be discussed according to the different groups of alloys.

Steels

The chemical compositions of the iron and steel alloys are given in Table 3 and the surface conditions in Table 4. The corrosion rates and types of corrosion are given in Table 5, and the corrosion rates are shown graphically in Figures 8 through 11.

Water in the open sea is quite uniform in its composition throughout the oceans;[14] therefore, the corrosion rates of steels exposed under similar conditions in clean seawater should be comparable. The results of many investigations on the corrosion rates of structural steels in surface seawater at many locations throughout the world show that after a short period of exposure the rates are constant and amount to between 3 and 5 mils per year.[11, 15, 16] Factors which may cause differences in corrosion rates outside these limits are variations in marine fouling, contamination of the seawater near the shorelines, variations in velocity, and differences in the surface-water temperature.

Figure 8 shows a comparison of the corrosion rates of low-carbon steels immersed in the surface of the Atlantic Ocean at Harbor Island, North Carolina and in the Pacific Ocean at Fort Amador, Panama Canal Zone, with those at depths of from 5,300 feet to 5,640 feet (nominal 5,500 feet) in the Pacific Ocean and at depths of 4,500 feet and 5,600 feet in the Atlantic Ocean (Tongue-of-the-Ocean, Bahamas). The corrosion rates of steels at the surface in both the Atlantic and Pacific Oceans decrease rather rapidly with time and become constant after about 2 to 3 years of uninterrupted exposure. The fact that the initial corrosion rate after 1 year of exposure for the steel at Fort Amador is higher than that at Harbor Island is attributed to the difference in the average temperatures (27°C versus 21°C). (Theoretically, an increase of 10°C should cause the rate of a chemical reaction to be doubled.)

The corrosion rates of the steels (C1010 and A36) exposed at a nominal depth of 5,500 feet in the Pacific Ocean also decreased with time of exposure and were consistently lower than the surface corrosion rates. The corrosion rates at a depth of 5,500 feet in the Pacific Ocean were about one-third the rate of the steels at Harbor Island after about 3 years of exposure.

This difference in the corrosion rates cannot be attributed solely to the difference between the average temperatures (21°C versus 2.4°C) at the two sites. Other variables which can influence corrosion rates are current, oxygen concentration, and pH. The current at the surface was variable but slight, being due to normal tidal action, and at depth in the Pacific Ocean there was practically no current; hence, there was probably very little effect due to differences in current. The oxygen concentrations were quite different (5.2 ml/l versus 1.4 ml/l); the lower concentration of oxygen is conducive to lower corrosion rates for steels. The lower pH (7.5) at depth, however, should be conducive to an increase in corrosion rate over environments of higher pH (8.1) such as at the surface at Harbor Island.

Considering the differences in all the above variables at the two locations, i is probable that the steels should corrode at depth at slower rates than at the surface.

The corrosion rates for a C1010 steel exposed by NCEL for the International Nickel Company, Inc. (INCO), at depth in the Pacific Ocean are in excellent agreement with the results for NCEL steels (C1010 and A36).

The corrosion rates for a C1010 steel obtained by the Naval Research Laboratory (NRL) at a depth of 5,600 feet in the Tongue-of-the-Ocean were slightly higher than those obtained by NCEL at a nominal depth of 5,500 feet in the Pacific Ocean. NRL oceanographic data for the Tongue-of-the-Ocean were not available for depths greater than 4,967 feet[17] (at a depth of 4,967 feet: 4.18°C, 5.73 ml/l of oxygen), which was 600 feet higher than the location of the specimens; hence, it cannot be assumed that these oceanographic data represent the environment of the specimens. However, it is possible to postulate that the oxygen concentration in the Tongue-of-the-Ocean was greater than that on the bottom of the Pacific Ocean, and therefore, higher corrosion rates would be expected.

The corrosion rates for a C1010 steel exposed for 90 days (6.0 MPY) and 180 days (5.75 MPY) in the Tongue-of-the-Ocean at a depth of 4,500 feet by the Naval Applied Science Laboratory (NASL) were considerably higher than all other rates obtained at depth. Since these tests were conducted in the vicinity of the NRL tests, the same oceanographic data probably would apply. However, in this case the specimens were approximately 500 feet above the lowest recorded oceanographic data, and again, it cannot be assumed that they represent the environment of the specimens. But from the data in Table 1 of Reference 17 it is known that the oxygen concentration was between 4.96 and 5.73 ml/l, which would be greater than that at the surface. It would be expected, therefore, that the corrosion rates would be within the range of those at the surface; they do, in fact, agree with the 1-year surface data from Fort Amador.

Wrought iron corroded at depth at about the same rate as the carbon steels. When wrought iron was completely immersed at the surface in the Pacific Ocean at the Panama Canal Zone, its corrosion rate was also the same as that for carbon steel. From these data it can be concluded that wrought iron, at depth and at the surface, corrodes at the same rates as the carbon steels.

The corrosion rates of the low-alloy steels at a nominal depth of 5,500 feet, shown in Figure 9, compare very favorably with those of the carbon steels. Although there is a difference of about 2 MPY after 123 days of exposure, there is only a difference of 0.5 MPY after 1,064 days of exposure. For practical purposes, it can be stated that carbon steels, high-strength low-alloy steels, and low-alloy steels, after a short initial period of exposure, corrode at the same rate at a depth of about 5,500 feet at this particular site (STU I area) in the Pacific Ocean.

Table 3. Chemical Composition of Iron and Steels, Percent by Weight

Alloy	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	V	B	Ti	Other
Wrought iron	0.02	0.06	0.13	0.01	0.13	-	-	-	-	-	-	-	2.5 slag
AISI C1010	0.12	0.50	0.004	0.023	0.060	-	-	-	-	-	-	-	-
AISI C1010	0.11	0.52	0.016	0.024	0.048	-	-	-	-	-	-	-	-
ASTM A36	0.24	0.70	0.011	0.027	0.055	-	-	-	-	-	-	-	-
ASTM A36	0.20	0.55	0.010	0.020	0.064	-	-	-	-	-	-	-	-
ASTM A387, grade D	0.06	0.49	0.013	0.021	0.24	-	2.20	1.02	-	-	-	-	-
HSLA No. 1 1/	0.18	0.86	0.014	0.023	0.28	0.05	0.64	0.18	-	0.047	0.0028	0.020	-
HSLA No. 2	0.12	0.30	0.015	0.025	0.27	2.34	1.25	0.20	0.17	-	-	-	-
HSLA No. 3	0.17	0.28	0.020	0.018	0.20	2.96	1.76	0.40	-	-	-	-	-
HSLA No. 3	0.10	0.28	0.014	0.010	0.25	2.91	1.59	0.52	-	-	-	-	-
HSLA No. 4	0.07	0.38	0.11	0.025	0.54	0.31	0.88	-	0.28	-	-	-	-
HSLA No. 5	0.14	0.78	0.020	0.025	0.23	0.74	0.56	0.42	0.22	0.36	0.0041	-	-
AISI 4340	0.43	0.73	0.013	0.014	0.27	1.77	0.82	0.24	-	-	-	-	-
AISI type 502	0.06	0.48	0.020	0.010	0.33	-	4.75	0.55	-	-	-	-	-

1/ High-strength, low-alloy steel.

Table 4. Condition of the Irons and Steels

Alloy	Surface and Metallurgical Conditions
Wrought iron	As fabricated pipe
C1010	Hot rolled (mill) and pickled (laboratory)
C1010	Hot rolled (mill) and pickled (laboratory)
ASTM A36	Hot rolled (mill) and pickled (laboratory)
ASTM A36	Hot rolled (mill) and pickled (laboratory)
ASTM A387, grade D	Hot rolled (mill) and pickled (laboratory)
HSLA No. 1[1]	Water-quenched from 1,650° to 1,750°F and tempered at 1,100° to 1,275°F (mill), blast-cleaned (laboratory)
HSLA No. 2	Hot rolled and pickled
HSLA No. 3	Water-quenched from 1,650°F and tempered at 1,150° to 1,200°F (mill), blast-cleaned (laboratory)
HSLA No. 3	Water-quenched from 1,650°F and tempered at 1,150° to 1,200°F (mill), blast-cleaned (laboratory)
HSLA No. 4	Hot rolled (mill) and pickled (laboratory)
HSLA No. 5	Water-quenched from 1,650° to 1,750°F and tempered at 1,150° to 1,275°F (mill), blast-cleaned (laboratory)
AISI 4340 (200 ksi)	Oil-quenched from 1,550°F, tempered for 1 hour at 750°F, blast-cleaned (laboratory)
AISI 4340 (150 ksi)	Oil-quenched from 1,550°F, tempered for 1 hour at 1,050°F, blast-cleaned (laboratory)
AISI type 502	Annealed and pickled, No. 1 sheet finish (mill)

[1] High-strength, low-alloy steel.

Table 5. Corrosion Rates of Irons and Steels

Alloy	Environment[1]	Exposure (days)	Depth (ft)	Corrosion Rates[2]				Type of Corrosion
				MDD	MPY	Crevice		
						MDD	MPY	
Wrought iron[3]	W	1,064	5,300	3.10[4]	0.6	-	-	Uniform corrosion, slight crevice corrosion
Wrought iron[3]	W	123	5,640	14.1	2.6	-	-	Uniform corrosion
Wrought iron[3]	W	197	2,340	10.5	2.0	-	-	Uniform corrosion
Wrought iron[3]	M	197	2,340	6.5	1.2	-	-	Uniform corrosion
C1010[3]	W	1,064	5,300	4.5	0.8	-	-	Uniform corrosion
C1010	W	1,064	5,300	5.9	1.1	2.9	0.5	Uniform corrosion
C1010	M	1,064	5,300	5.2	1.0	4.5	0.8	Uniform corrosion
C1010	W	123	5,640	16.6	3.0	16.3	3.0	Uniform corrosion, slight crevice corrosion
C1010	M	123	5,640	12.2	2.2	11.9	2.2	Uniform corrosion, slight crevice corrosion
C1010	W	197	2,340	8.1	1.5	8.4	1.5	Uniform corrosion
C1010	M	197	2,340	9.3	1.7	8.9	1.6	Uniform corrosion
ASTM-A36[3]	W	1,064	5,300	3.2	0.6	-	-	Uniform corrosion
ASTM-A36	W	123	5,640	16.9	3.1	16.2	3.0	Uniform corrosion, slight crevice corrosion
ASTM-A36	M	123	5,640	12.9	2.4	11.5	2.1	Uniform corrosion, slight crevice corrosion
ASTM-A36	W	197	2,340	9.4	1.7	9.2	1.7	Uniform corrosion
ASTM-A36	M	197	2,340	9.5	1.7	9.1	1.7	Uniform corrosion
ASTM-A387, grade D	W	123	5,640	16.1	3.0	16.4	3.0	Uniform corrosion, slight crevice corrosion
ASTM-A387, grade D	M	123	5,640	12.7	2.3	14.3	2.6	Uniform corrosion, slight crevice corrosion
ASTM-A387, grade D	W	197	2,340	9.9	1.8	11.4	2.1	Uniform corrosion
ASTM-A387, grade D	M	197	2,340	10.7	2.0	9.9	1.8	Uniform corrosion

Continued

Table 5. Continued.

Alloy	Environment[1]	Exposure (days)	Depth (ft)	Corrosion Rates[2]				Type of Corrosion
				MDD	MPY	Crevice		
						MDD	MPY	
HSLA No. 1[3], [5]	W	1,064	5,300	3.3	0.6	-	-	Uniform corrosion
HSLA No. 1	W	1,064	5,300	3.3	0.6	3.1	0.6	Uniform corrosion
HSLA No. 1	M	1,064	5,300	4.0	0.7	3.1	0.6	Uniform corrosion
HSLA No. 1	W	123	5,640	15.7	2.9	14.7	2.7	Uniform corrosion
HSLA No. 1	M	123	5,640	11.9	2.2	10.1	1.9	Uniform corrosion
HSLA No. 1	W	197	2,340	7.7	1.4	7.3	1.3	Uniform corrosion
HSLA No. 1	M	197	2,340	7.5	1.4	7.7	1.4	Uniform corrosion
HSLA No. 2[3]	W	1,064	5,300	2.5	0.5	-	-	Uniform corrosion
HSLA No. 2	W	123	5,640	25.2	4.7	24.7	4.6	Uniform corrosion, slight crevice corrosion
HSLA No. 2	M	123	5,640	23.0	4.3	23.7	4.4	Uniform corrosion, slight crevice corrosion
HSLA No. 2	W	197	2,340	7.7	1.4	7.9	1.5	Uniform corrosion
HSLA No. 2	M	197	2,340	7.2	1.4	8.2	1.5	Uniform corrosion
HSLA No. 3[3]	W	1,064	5,300	3.6	0.7	-	-	Uniform corrosion, slight crevice corrosion
HSLA No. 4	W	1,064	5,300	6.0	1.1	3.6	0.7	Uniform corrosion
HSLA No. 4[3]	W	1,064	5,300	1.4	0.3	-	-	Uniform corrosion
HSLA No. 4[3]	W	123	5,640	19.9	3.6	-	-	Uniform corrosion
HSLA No. 4[3]	W	197	2,340	8.0	1.5	-	-	Uniform corrosion
HSLA No. 4[3]	M	197	2,340	5.0	0.9	-	-	Uniform corrosion

Continued

Table 5. Continued.

Alloy	Environment[1]	Exposure (days)	Depth (ft)	Corrosion Rates[2]				Type of Corrosion
				MDD	MPY	Crevice		
						MDD	MPY	
HSLA No. 5[3]	W	1,064	5,300	4.7	0.9	-	-	Uniform corrosion
HSLA No. 5	W	1,064	5,300	3.9	0.7	4.5	0.8	Uniform corrosion
HSLA No. 5	M	1,064	5,300	5.6	1.0	5.0	0.9	Uniform corrosion
HSLA No. 5	M	123	5,640	17.1	3.1	11.4	2.1	Uniform corrosion, slight crevice corrosion
HSLA No. 5	M	123	5,640	8.6	1.6	6.0	1.1	Uniform corrosion, slight crevice corrosion
HSLA No. 5	W	197	2,340	7.5	1.4	7.9	1.4	Uniform corrosion
HSLA No. 5	M	197	2,340	8.2	1.5	7.5	1.4	Uniform corrosion
AISI 4340(200 ksi)[3]	W	123	5,640	15.1	2.8	-	-	Uniform corrosion
AISI 4340(200 ksi)[3]	W	197	2,340	7.8	1.4	-	-	Uniform corrosion
AISI 4340(200 ksi)[3]	M	197	2,340	7.6	1.4	-	-	Uniform corrosion
AISI 4340(150 ksi)	W	123	5,640	14.8	2.7	-	-	Uniform corrosion
AISI 4340(150 ksi)	W	197	2,340	10.2	1.9	-	-	Uniform corrosion
AISI 4340(150 ksi)	M	197	2,340	7.0	1.3	-	-	Uniform corrosion
AISI type 502[3]	W	1,064	5,300	14.1	2.6	-	-	Pitting corrosion
AISI type 502	W	1,064	5,300	10.4	1.9	8.7	1.6	Pitting corrosion, deepest pit 40 mils, average depth 32 mils, frequency 1.3/sq in.
AISI type 502	M	1,064	5,300	9.1	1.7	9.6	1.8	Pitting corrosion, deepest pit 44 mils, average depth 40 mils, frequency 1.0/sq in.
AISI type 502	W	123	5,640	32.1	5.9	18.7	3.5	Pitting corrosion, deepest pit 24 mils, average depth 22 mils, frequency 1/2 sq in., crevice corrosion to 24 mils

Continued

Table 5. Continued.

Alloy	Environment[1]	Exposure (days)	Depth (ft)	Corrosion Rates[2]				Type of Corrosion
				MDD	MPY	Crevice		
						MDD	MPY	
AISI type 502	M	123	5,640	23.1	4.3	18.9	3.4	Pitting corrosion, deepest pit 22 mils, average depth 18 mils, frequency 1/2 sq in., crevice corrosion to 22 mils
AISI type 502	W	197	2,340	7.7	1.4	3.3	0.6	Pitting corrosion, deepest pit 20 mils, average depth 16 mils, crevice corrosion to 13 mils, frequency 1/1.7 sq in.
AISI type 502	M	197	2,340	6.7	1.2	5.4	1.0	Pitting corrosion, deepest pit 20 mils, average depth 18 mils, frequency 1/2 sq in., crevice corrosion to 23 mils

[1] W = specimens exposed on sides of STU in water; M = specimens exposed in base of STU, partially embedded in bottom sediment.

[2] MDD = milligrams per square decimeter per day; MPY = mils penetration per year.

[3] Specimen size, 1 x 6 inches, all others, 6 x 12 inches.

[4] Supplied by Chemistry Division of NCEL.

[5] HSLA = high-strength, low-alloy steel.

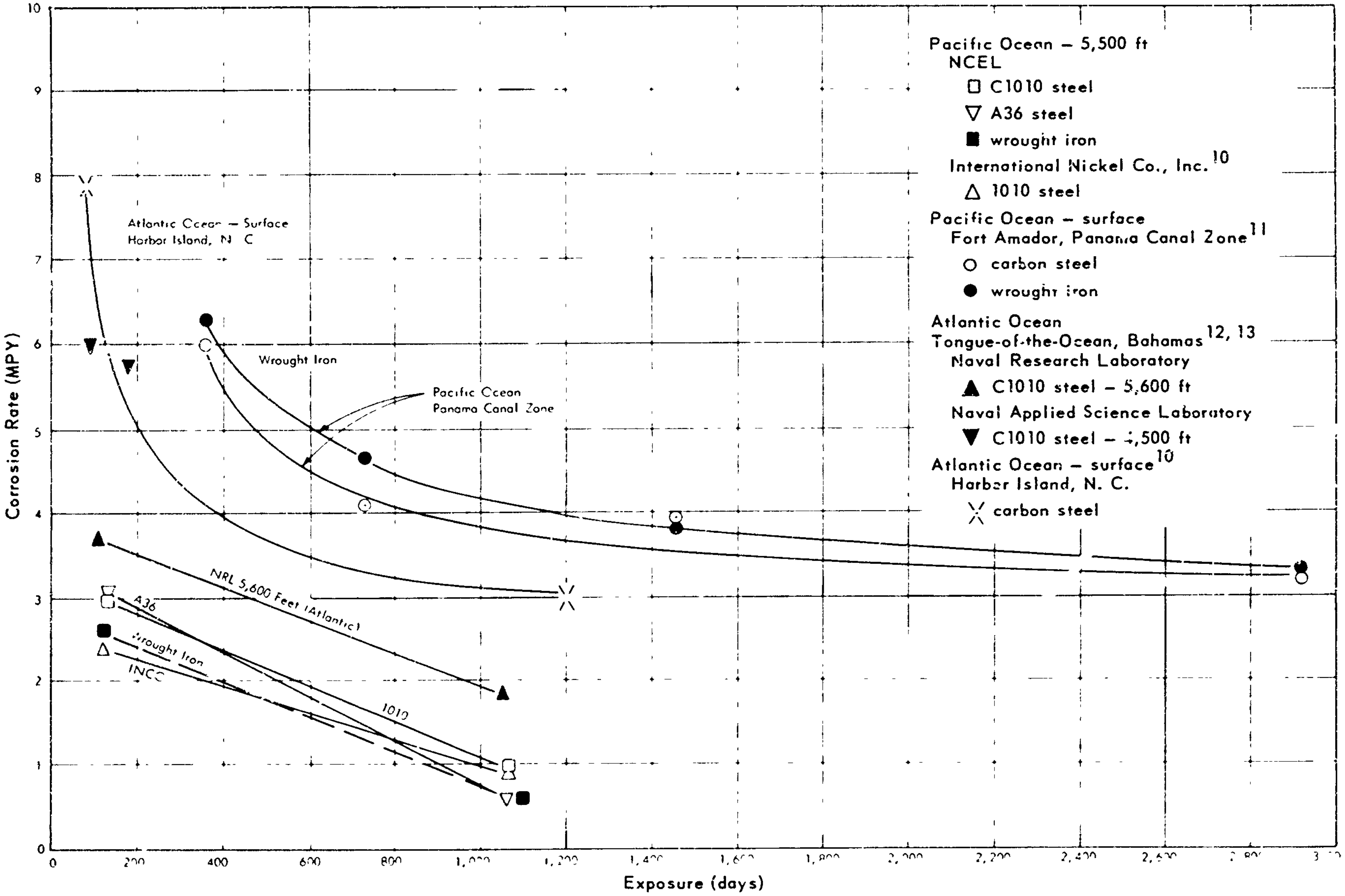

Figure 8. Corrosion rates of carbon steels in the Atlantic and Pacific Oceans at various depths.

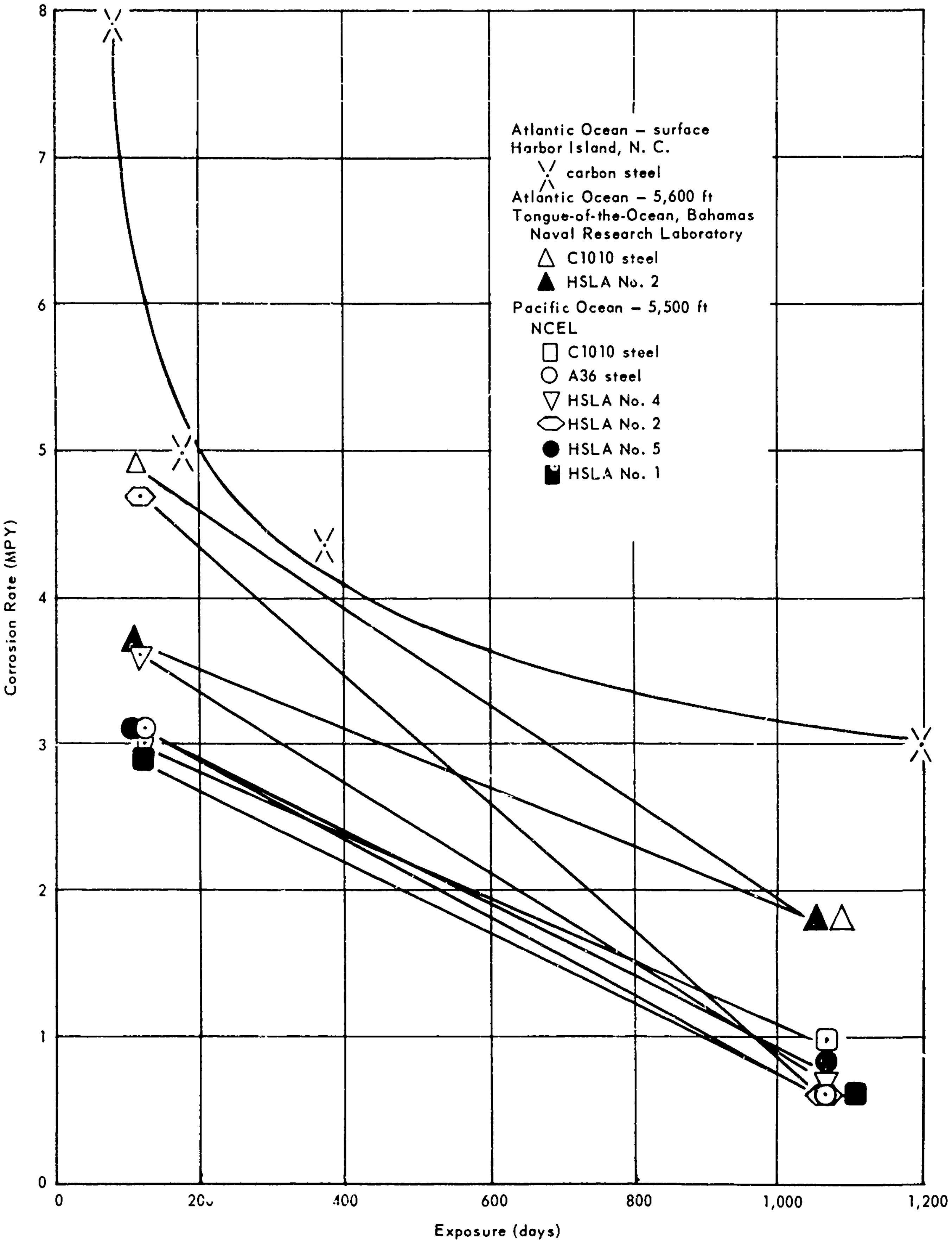

Figure 9. Corrosion rates of low alloy steels.

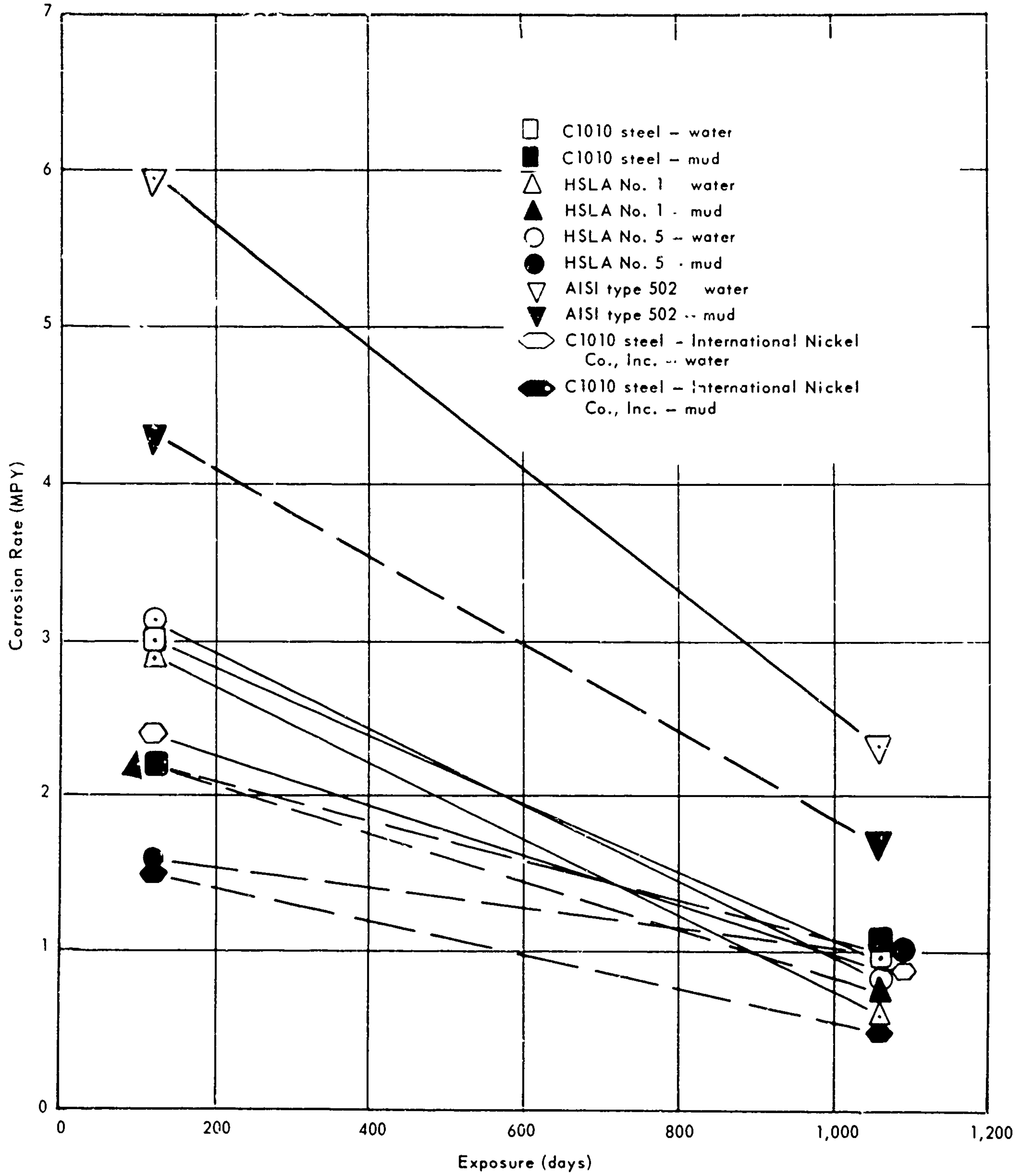

Figure 10. Corrosion of steels in water and partially embedded in bottom sediment.

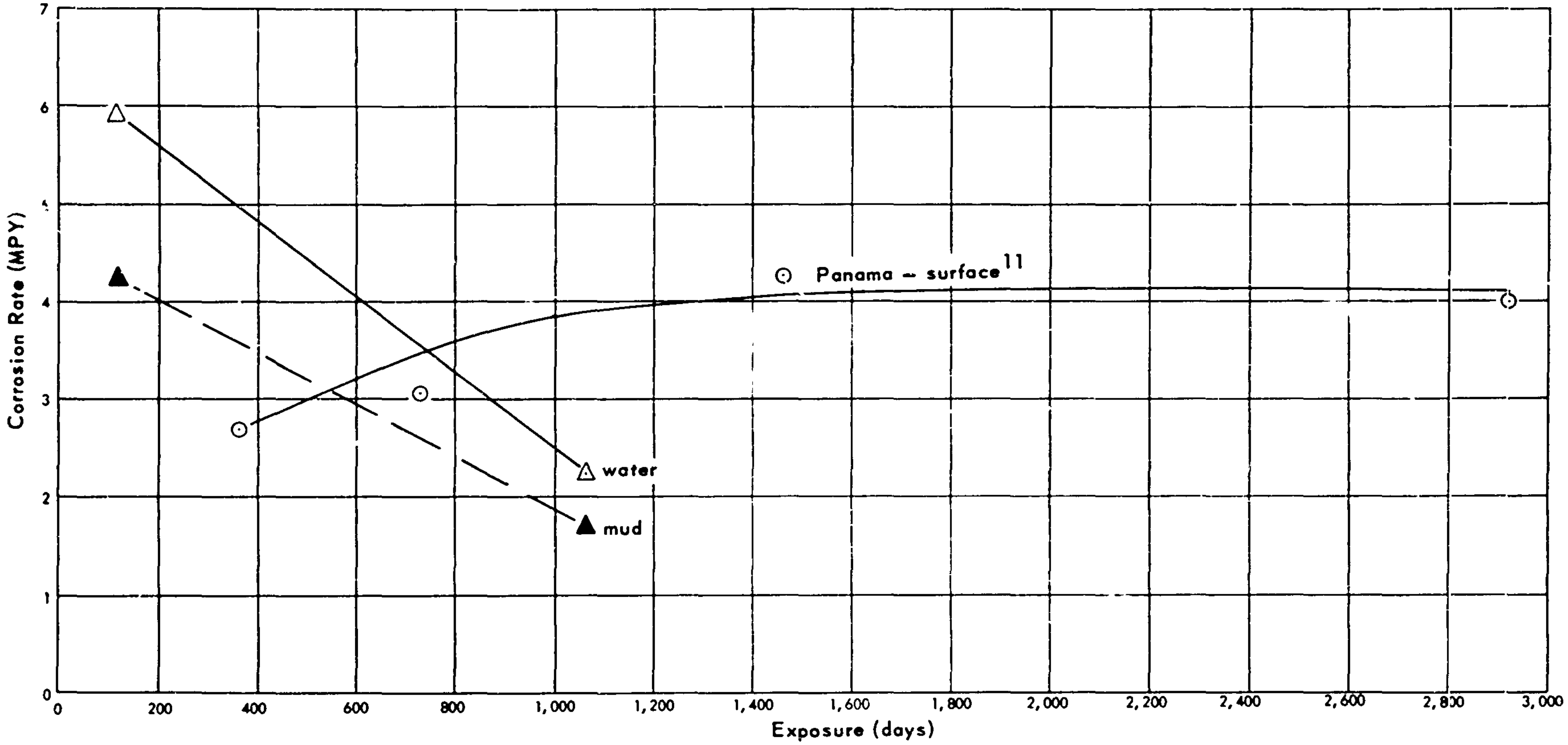

Figure 11. Comparison of corrosion of type 502 steel at a depth of 5,500 feet and at the surface of the Pacific Ocean.

The data from a depth of 5,600 feet in the Atlantic Ocean[13] are also plotted in Figure 9 for purposes of comparison. The corrosion rates of these two steels are also the same after 1,050 days of exposure, but are slightly higher than those in the Pacific Ocean.

In Figure 10 are shown the corrosion rate curves for the steels exposed both in the water portions (water specimens) of the STUs and in the base (mud specimens) of the STUs. Portions of the specimens in the bases of the structures were either partially embedded in the bottom sediments or about 1 inch above it. After 123 days of exposure the corrosion rates of the mud specimens were slightly lower than their companion specimens in the water. However, after 1,064 days of exposure the corrosion rates were the same.

The only exception was a type 502 alloy steel containing 4.75% chromium and 0.55% molybdenum. The corrosion rates for this steel were higher than those of the other steels in both environments. These higher rates are attributed to the pitting type of corrosion to which it was susceptible (see Table 5).

A comparison of the corrosion rates of type 502 alloy steel at a depth of 5,500 feet in the Pacific Ocean and at the surface of the Pacific Ocean, Panama Canal Zone, is shown in Figure 11. No explanation is given for the slight increase in corrosion rate of the type 502 alloy in the Pacific Ocean at the Panama Canal Zone. On the other hand, the corrosion rates at a depth of 5,500 feet decreased with time. Also the type of corrosion was chiefly broad pits.

The data under "Crevice" in Table 5 show that there were no significant changes in corrosion rates in these alloys due to crevice corrosion. Although slight crevice corrosion was found in a few cases, the intensity was not great enough to significantly change the corrosion rate of that particular alloy.

As can be seen in Table 5 the corrosion rates of the steels at a depth of 2,340 feet for 197 days were, in general, less than their rates at 5,640 feet for 123 days. In one instance the corrosion rate at a depth of 2,340 feet was about one-fourth of the rate at a depth of 5,640 feet; in the remaining instances the corrosion rates at a depth of 2,340 feet were about one-half those at a depth of 5,640 feet. The average of all steels was 1.6 MPY for 197 days at a depth of 2,340 feet as compared to 3.2 for 123 days at a depth of 5,640 feet. These lower corrosion rates are attributed to the lower oxygen concentration of the seawater at 2,340 feet: 0.39 ml/l versus 1.26-1.50 ml/l (Table 1).

Mechanical Properties. The percent change in the mechanical properties of the exposed steels is given in Table 6. There were no significant changes in the mechanical properties except in the type 502 steel after 1,064 days of exposure at a depth of 5,300 feet. The 33% and 45% losses in elongation in the type 502 steel were significant and were caused by pitting corrosion. The average pit depths were 32 and 40 mils as shown in Table 5.

Stress Corrosion. The steels which were stressed at 35, 50, and 75% of their respective yield strengths, and their susceptibility to stress corrosion cracking at depths of 2,340 feet and 5,640 feet, are given in Table 7. None of these steels were susceptible to stress corrosion cracking during the periods of time of exposure and at the depths exposed.

Corrosion Products. The corrosion products from some of the steels were analyzed by X-ray diffraction, spectrographic analysis, quantitative chemical analysis, and infrared spectrophotometry. The results of the analyses were as follows:

Source of Products	Compounds Found
Carbon steel (C1010)	Alpha iron oxide ($\alpha Fe_2O_3 \cdot H_2O$), iron hydroxide, $Fe(OH)_2$, Fe, traces of Mn and Mo, light chlorides, 1.62% sulfate ion, significant amount of phosphate ion
AISI 4340 steel	Alpha iron oxide ($\alpha Fe_2O_3 \cdot H_2O$), Beta iron (111) oxide hydroxide (β-FeOOH), iron (11) hydroxide $Fe(OH)_2$, Fe, Ni, Ca, Si, Mn, 2.17% chloride ion, 3.75% sulfate ion, significant amount of phosphate ion
HSLA No. 5	Iron oxide hydrate ($Fe_2O_3 \cdot H_2O$), iron hydroxide, $Fe(OH)_2$, Fe, Cu, Ni, Si, Mo, Cr, Mn, trace B, 1.86% chloride ion, 1.41% sulfate ion, significant amount of phosphate ion

Anchor Chains. Two types of anchor chain, 3/4-inch Dilok and 3/4-inch welded stud link, were exposed for 123 days at a depth of 5,640 feet, for 1,064 days at 5,300 feet, and for 197 days at 2,340 feet. At the end of each exposure period the chain links were covered with layers of flaky red rust. Destructive testing of the exposed chains showed that for these periods of exposure there were no significant changes in the breaking loads, hence no impairment of the properties of the chains. The Dilok chains all failed at the bottoms of the sockets, and there was rust in these sockets, indicating that seawater had penetrated the forged connection.

Table 6. Percent Changes in Mechanical Properties of Iron a

Alloy	Environment[1]	Original Properties							
					123 Days at 5,640 Feet			197 Days	
		Tensile Strength (ksi)	Yield Strength (ksi)	Elongation (%)	Tensile Strength	Yield Strength	Elongation	Tensile Strength	Yi Stren
C1010	W	54.1	36.3	42.3	-	-	-	+0.9	+
	M	-	-	-	-0.9	-0.3	+1.2	+3.2	+
ASTM A36 steel	W	66.9	38.1	38.5	-1.9	+2.4	+18.2	-	
	M	-	-	-	-	-	-	-	
ASTM A36 steel	W	64.4	40.3	39.5	-	-	-	+2.0	+
	M	-	-	-	0	+0.7	-0.8	+1.6	+
ASTM A387-D	W	76.3	48.6	31.5	-	-	-	+3.0	-
	M	-	-	-	+3.3	+3.9	-5.4	+5.0	+
HSLA No. 1[2]	W	121.4	109.7	12.2	-	-	-	+2.0	+
	M	-	-	-	+0.2	+0.7	+41.8	+1.7	+
HSLA No. 2	W	100.1	88.9	27.7	+1.3	-2.0	-12.3	-	
	M	-	-	-	-	-	-	-	
HSLA No. 3	W	106.7	87.5	30.0	-	-	-	-	
	M	-	-	-	-	-	-	-	
HSLA No. 4	W	70.2	52.4	32.3	+4.8	-46.2	+23.8	+5.3	
	M	-	-	-	-	-	-	+5.7	-
HSLA No. 5	W	125.4	117.9	15.7	-	-	-	+3.4	+
	M	-	-	-	+1.0	+1.5	-1.3	+1.2	-
4340(200 ksi)	W	200.9	184.9	7.7	+4.4	+4.7	+42.9	+3.3	
	M	-	-	-	-	-	-	+2.8	-
4340(200 ksi)	W	209.0	189.6	8.0	-	-	-	-3.3	-
	M	-	-	-	-	-	-	-0.8	-
4340(150 ksi)	W	143.1	131.8	13.3	+3.4	+3.9	+27.8	+3.9	
	M	-	-	-	-	-	-	+5.1	-
4340(150 ksi)	W	147.4	135.8	14.0	-	-	-	-0.1	-
	M	-	-	-	-	-	-	+0.3	-
AISI type 502	W	59.2	35.7	33.2	-	-	-	+0.5	-
	M	-	-	-	-2.0	+5.3	-33.6	-1.7	-

[1] W = specimens exposed on sides of STU in water; M = specimens exposed in base of STU, partially embedded in

[2] HSLA = high-strength, low-alloy steel.

cal Properties of Iron and Steel Alloys Due to Corrosion

Percent Change After —									
Feet	197 Days at 2,340 Feet			1,064 Days at 5,300 Feet (1 x 6-in. specimens)			1,064 Days at 5,300 Feet (6 x 12-in. specimens)		
longation	Tensile Strength	Yield Strength	Elongation	Tensile Strength	Yield Strength	Elongation	Tensile Strength	Yield Strength	Elongation
-	+0.9	+1.9	-3.6	+8.5	+7.2	+8.7	+4.6	+5.8	-13.2
+1.2	+3.2	+5.5	-5.0	-	-	-	+4.3	+9.6	-10.2
+18.2	-	-	-	+4.2	+3.9	+13.5	-	-	-
-	-	-	-	-	-	-	-	-	-
-	+2.0	+3.7	-1.3	-	-	-	-	-	-
-0.8	+1.6	+4.5	-1.3	-	-	-	-	-	-
-	+3.0	-4.1	-10.2	-	-	-	-	-	-
-5.4	+5.0	+1.2	-10.5	-	-	-	-	-	-
-	+2.0	+2.6	+39.3	+4.0	+4.7	+77.9	+3.0	+3.33	+28.7
+41.8	+1.7	+0.6	+39.3	-	-	-	+1.8	+2.1	+35.2
-12.3	-	-	-	+6.3	+3.6	+41.9	+3.6	+2.6	-6.5
-	-	-	-	-	-	-	+3.4	+1.7	-10.5
-	-	-	-	+9.6	+4.0	+33.3	-	-	-
-	-	-	-	-	-	-	-	-	-
+23.8	+5.3	+7.3	+39.3	+5.4	+5.7	+42.4	+3.7	+5.3	-3.4
-	+5.7	+8.2	+31.6	-	-	-	-	-	-
-	+3.4	+3.4	+3.2	+8.6	+8.5	+10.2	+4.7	+4.7	-6.4
-1.3	+1.2	+1.2	0	-	-	-	+3.9	+4.0	-8.9
+42.9	+3.3	+6.2	+55.8	-	-	-	-	-	-
-	+2.8	+4.5	+42.9	-	-	-	-	-	-
-	-3.3	-1.9	+8.8	-	-	-	-	-	-
-	-0.8	+0.4	+12.5	-	-	-	-	-	-
+27.8	+3.9	+2.4	+30.1	-	-	-	-	-	-
-	+5.1	+5.4	+27.8	-	-	-	-	-	-
-	-0.1	-1.1	-7.1	-	-	-	-	-	-
-	+0.3	+0.4	+2.1	-	-	-	-	-	-
-	+0.5	-3.9	-3.0	+11.1	+18.8	+2.4	-9.1	-12.9	-33.1
-33.6	-1.7	-4.2	-1.5	-	-	-	-7.9	+0.8	-44.9

, partially embedded in bottom sediment.

Table 7. Stress Corrosion of Steels

Alloy	Stress (ksi)	Percent of Yield Strength	Exposure (days)	Depth (ft)	Number of Specimens	Number Failed
4340(150 ksi)	46.1	35	123	5,640	3	0
	46.1	35	197	2,340	3	0
	65.9	50	123	5,640	3	0
	65.9	50	197	2,340	3	0
	98.9	75	123	5,640	3	0
	98.9	75	197	2,340	3	0
4340(200 ksi)	64.7	35	123	5,640	3	0
	64.7	35	197	2,340	3	0
	92.5	50	123	5,640	3	0
	92.5	50	197	2,340	3	0
	138.7	75	123	5,640	3	0
	138.7	75	197	2,340	3	0
HSLA No. 5	41.4	35	197	2,340	3	0
	59.1	50	197	2,340	3	0
	88.7	75	197	2,340	3	0
HSLA No. 1	38.4	35	197	2,340	3	0
	54.8	50	197	2,340	3	0
	82.3	75	197	2,340	3	0
AISI type 502	17.8	50	197	2,340	3	0
	26.7	75	197	2,340	3	0

Wire Rope. Data on the stressed and unstressed wire ropes exposed at various depths for different periods of time are given in Table 8.

The first eight wires were stressed in tension to values equivalent to approximately 20% of their original breaking strengths. After 1,064 days of exposure at a depth of 5,300 feet there were no stress corrosion failures of any of these wire ropes. However, the breaking strength of the type 316 stainless steel rope was decreased 40% and that of the galvanized plow steel was decreased 17% by crevice corrosion of the internal wires; the breaking strengths of the other six ropes were unaffected.

The zinc coatings on the lubricated galvanized and electrogalvanized wire ropes were not completely corroded after 1,064 days of exposure. But the thicker electrogalvanized zinc coating corroded faster than the thinner hot-dipped coating. The aluminum coating on the unlubricated aluminized steel wire rope was about 50% gone on the outside surfaces.

Specimens of 0.875-inch diameter plow steel wire rope were exposed as follows: lubricated and greased (as received), degreased, and degreased and wrapped with 10-mil-thick polyethylene tape. The breaking strengths of these ropes were the same after 123 days of exposure at a depth of 5,640 feet and were in agreement with the nominal values for this type of rope. There was light rust and a few bright spots on the inside strands of the degreased rope, but the inside strands of the rope in the "as received" condition were entirely bright. On the taped rope rust had formed on the outside surfaces, underneath the tape, for a distance of about 3 feet from the ends of the tape, and about 50% of the surfaces of the inside wires were bright at the break in the rope.

After 197 days of exposure at a depth of 2,340 feet there was no decrease in the breaking strengths of the last 12 wire ropes shown in Table 8. In all cases the inside wires were uncorroded. The outside surfaces of the two smallest galvanized cables were completely rusted, but those of the others had turned dark grey. This dark grey color indicated that there was still some protective zinc present. A few spots of rust were present on only the 0.094-, 0.187-, and 0.375-inch-diameter stainless steel cables.

Stainless Steels

The chemical compositions of the stainless steels are given in Table 9 and the metallurgical and surface conditions in Table 10. The corrosion rates and types of corrosion are given in Table 11.

Because of the propensity of stainless steels for pitting in seawater, corrosion rates are inconsequential in the majority of cases. Generally, the 400 series and the precipitation hardening stainless steels are more susceptible to pitting than the 300 series or modified 300 series stainless steels. Usually, the pits are few in number, randomly oriented, and deep. Since there are usually few but deep pits (perforations in many cases), the weight losses and the corresponding corrosion rates are small.

The corrosion of the stainless steels was manifested as either the crevice, the edge, or the tunneling type. Illustrations of these types are shown in Figures 12 to 25. Crevice corrosion which occurred underneath a lap joint is shown in Figure 12 and that which occurred underneath the head of a nylon bolt is shown in Figure 13. The lap joint shown in Figure 12 was created by bolting with a nylon bolt and nut a 1-in.-sq piece of 15-7 AMV-RH950 precipitation hardening stainless steel to a 6x 12-inch specimen of the same material. The crevice corrosion on the type 302 stainless steel specimen shown in Figure 13 was caused by the crevice created between the specimen and the head of a nylon bolt. These two illustrations of crevice corrosion are actually oxygen concentration cell (differential aeration cell) corrosion in which there develops a local difference in the dissolved oxygen concentration of the seawater inside and outside the crevices. The oxygen in the crevice is soon consumed because of the slow replacement rate of seawater, and this deficiency of oxygen creates an anodic area. This area soon loses its passivity, and a potential difference is generated between it and the large surrounding unshielded area (cathodic area). The resultant high current density thus promotes a high corrosion rate within the crevice.

That crevice corrosion of stainless steels is very aggressive is attested to by the fact that the thickness of the specimen in Figure 12 was 0.048 inch thick and was perforated within 123 days of exposure.

Pitting corrosion originated both at the edges of the specimens and, less frequently, on the flat surfaces of the panels. Pitting corrosion which started at the edges of the specimens was manifested in different ways: The pits enlarged to areas of considerable size and were filled with black iron oxide corrosion products covered on both surfaces with thin films of uncorroded metal (this is designated tunnel corrosion in this report). Figure 14 shows the corrosion products in place after the film of uncorroded metal was stripped from the surface of the specimen of 15-7 AMV precipitation hardening stainless steel. When the corrosion products were removed from these tunnels the corrosive attack was seen to be a variable rate process, as shown in Figure 15.

Tunneling corrosion which had started at the lower end of a specimen of type 410 stainless steel had a lacework appearance, as shown in Figure 16. This end of the specimen was about 2 inches above the bottom sediment and had been exposed for 123 days at a depth of 5,640 feet. Since this was the bottom end of the specimen, the path of the corrosive attack was upward.

Tunneling corrosion traversed the width of a specimen of type 405 stainless steel, as shown in Figure 17. The bottom of this specimen had been embedded in the bottom sediment (end completely corroded) at a depth of 5,300 feet for 1,064 days. The path of the corrosive attack traversing the center of the specimen was downward at an angle of about 15 degrees and was above the water-bottom interface.

Table 8. Wire Rope Tests Rop

Alloy	Condition	Diameter (in.)	Stress on Rope (lb)	Exposure (days)	Depos (Day
Bright plow steel	Lubricated	0.325	2,100	1,064	5,3[illegible],06
Bright monitor steel	Lubricated	0.326	2,900	1,064	5,3[illegible],06
Galvanized plow steel	Lubricated - 0.83 oz Zn	0.340	2,100	1,064	5,3[illegible],06
Electrogalvanized	Lubricated - 1.50 oz Zn	0.335	2,200	1,064	5,3[illegible],06
Aluminized steel	Unlubricated - 0.38 oz Al	0.335	1,400	1,064	5,3[illegible],06
Type 316 stainless steel	Lubricated, 7 x 7	0.135	350	1,064	5,3[illegible],06
18 Cr - 14 Mn stainless steel	Unlubricated, 7 x 19	0.395	2,500	1,064	5,3[illegible],06
PVC coated Amgal	0.17 oz Zn	0.125	250	1,064	5,3[illegible],06
Plow steel	Lubricated and coated, 7 x 19	0.875	0	123	5,[illegible] 12
Plow steel	Degreased, 7 x 19	0.875	0	123	5,[illegible] 12
Plow steel	Degreased, covered with 10-mil polyethylene tape, 7 x 19	0.875	0	123	5,[illegible] 12
Galvanized aircraft cable	Lubricated, 7 x 7	0.094	0	197	2,[illegible] 19
Galvanized aircraft cable	Lubricated, 7 x 19	0.125	0	197	2,[illegible] 19

ope Tests

posure (days)	Depth (ft)	Breaking Load, (lb)		Remarks
		Original	Final	
,064	5,300	10,700	11,500	Outside, 100% rusted; inside, bright, cup and cone fracture
,064	5,300	14,300	15,300	Outside, 100% rusted; inside, bright, cup and cone fracture
,064	5,300	10,400	8,600	Outside, 80% yellow - 20% rust; inside, bright, cup and cone fracture
,064	5,300	10,900	11,600	Outside, 5% yellow - 95% rust; inside, bright, cup and cone fracture
,064	5,300	6,900	6,500	Outside, white corrosion products, 50% rust; inside, 95% bright - 5% light rust stain, cup and cone fracture
,064	5,300	1,700	1,000	50% rust stains; broke at corrosion pits on internal wires
,064	5,300	12,400	12,500	Outside, considerable rust and broken wires; inside, some broken wires in all strands, 45-deg fracture
,064	5,300	1,300	1,100	PVC dull inside, some rust on wires, dull grey, cup and cone and brittle fractures
123	5,640	-	48,200	Rusted on outside surfaces of wires, inside bright, 45-deg and cup and cone fracture
123	5,640	-	48,200	Completely rusted, inside few bright spots, 45-deg and cup and cone fracture
123	5,640	-	48,900	Rust at eyes and underneath tape for about 3 feet from eyes, inside, 50% bright surfaces, 45-deg and cup and cone fracture
197	2,340	1,100	1,000	Outside, 100% rust; inside, bright, cup and cone fracture
197	2,340	2,000	1,800	Outside, 100% rust; inside, bright, cup and cone fracture

Continued

Table 8. Con ble

Alloy	Condition	Diameter (in.)	Stress on Rope (lb)	Expo (da	Str n R (Ib
Galvanized aircraft cable	Lubricated, 7 x 19	0.187	0	1	(
Galvanized aircraft cable	Lubricated, 7 x 19	0.250	0	1	(
Galvanized ASTM-A-475	Class A coating 0.5 oz Zn 1 x 7	0.187	0	1	(
Galvanized ASTM-A-475	Class A coating 0.85 oz Zn 1 x 7	0.250	0	1	(
Stainless steel	Lubricated, 7 x 7	0.094	0	1	(
Stainless steel	Lubricated, 7 x 19	0.125	0	1	(
Stainless steel	Lubricated, 7 x 19	0.187	0	1	(
Stainless steel	Lubricated, 7 x 19	0.250	0	1	(
Stainless steel	Lubricated, 7 x 19	0.313	0	1	(
Stainless steel	Lubricated, 7 x 19	0.375	0	1	(

ble 8. Continued.

Stress n Rope (lb)	Exposure (days)	Depth (ft)	Breaking Load, (lb)		Remarks
			Original	Final	
0	197	2,340	3,500	3,700	Outside, dark grey; inside, bright, cup and cone fracture
0	197	2,340	6,100	6,200	Outside, dark grey; inside, bright, cup and cone fracture
0	197	2,340	2,600	2,500	Outside, dark grey with few yellow spots; inside, bright, cup and cone fracture
0	197	2,340	5,900	5,300	Outside, dark grey with few yellow spots; inside, bright, cup and cone fracture
0	197	2,340	800	800	Outside; few rust spots, balance metallic sheen; inside, bright metallic sheen, cup and cone fracture
0	197	2,340	1,600	1,800	Outside, bright metallic sheen; inside, bright metallic sheen, cup and cone fracture
0	197	2,340	2,700	2,800	Outside, few rust spots, balance bright metallic sheen; inside, bright metallic sheen, cup and cone fracture
0	197	2,340	5,100	5,100	Outside, bright metallic sheen; inside, bright metallic sheen, cup and cone fracture
0	197	2,340	7,100	7,000	Outside, bright metallic sheen; inside, bright metallic sheen, cup and cone fracture
0	197	2,340	11,900	11,600	Outside, few red stains, balance bright metallic sheen; inside, bright metallic sheen, cup and cone fracture

Table 9. Chemical Composition of Stainless Steels, Percent by Weight

Alloy	C	Mn	P	S	Si	Ni	Cr	Mo	Al	V	Ti	N_2	Cu	Other
AISI type 405	0.06	0.41	0.025	0.019	0.56	-	12.6	-	0.26	-	-	-	-	-
AISI type 405	0.05	0.65	0.017	0.015	0.57	-	12.46	-	0.21	-	-	-	-	-
AISI type 405	0.05	0.62	0.014	0.011	0.27	-	14.5	-	0.27	-	-	-	-	-
AISI type 410	0.13	0.43	0.019	0.005	0.45	0.10	12.30	-	-	-	-	-	-	-
AISI type 430	0.07	0.47	0.029	0.011	0.36	-	16.4	-	-	-	-	-	-	-
AISI type 430	0.05	0.46	0.012	0.010	0.36	0.12	16.50	-	-	-	-	-	-	-
AISI type 301	0.11	1.17	0.025	0.021	0.34	6.73	17.4	-	-	-	-	-	-	-
AISI type 302	0.06	1.05	0.020	0.013	0.60	9.33	18.21	-	-	-	-	-	-	-
AISI type 304	0.06	1.73	0.024	0.013	0.43	10.00	18.8	-	-	-	-	-	-	-
AISI type 304	0.05	1.56	0.020	0.012	0.52	9.55	19.2	0.18	-	-	-	-	-	-
AISI type 304L	0.03	1.24	0.028	0.023	0.68	10.20	18.7	-	-	-	-	-	-	-
AISI type 316	0.06	1.61	0.021	0.016	0.40	13.60	18.3	2.41	-	-	-	-	-	-
AISI type 316L	0.03	1.29	0.015	0.019	0.51	13.10	17.5	2.32	-	-	-	-	-	-
AISI type 316L	0.02	1.31	0.013	0.015	0.47	13.70	17.9	2.76	-	-	-	-	-	-
18 Cr - 14 Mn - 0.5 N	0.07	14.3	0.021	0.003	0.67	0.27	18.4	-	-	-	-	0.48	-	-
20 - CB	0.04	0.79	0.018	0.004	0.67	28.38	19.80	2.06	-	-	-	-	3.11	Co + Ta 0.77
20 - CB	0.05	0.82	-	-	0.70	28.43	20.09	2.32	-	-	-	-	3.37	Co + Ta 0.83
15 - 7 AMV	0.27	0.67	0.020	0.012	0.84	7.40	15.0	2.42	1.55	0.16	-	-	-	-
17 - 4 PH - sheet	0.03	0.24	0.017	0.011	0.59	4.17	15.92	-	-	-	-	-	3.23	Cb 0.24
17 - 4 PH - weldwire	0.03	0.50	0.021	0.011	0.42	4.98	16.81	-	-	-	-	-	3.40	-
17 - 7 PH - sheet	0.07	0.48	0.017	0.018	0.42	7.42	17.12	-	1.19	-	-	-	-	-
17 - 7 PH - weldwire	0.06	0.22	0.009	0.013	0.26	7.44	16.53	-	1.04	-	-	-	-	-
PH 15 - 7 Mo - sheet	0.07	0.50	0.016	0.016	0.28	7.19	15.05	2.19	1.11	-	-	-	-	-
PH 15 - 7 Mo - weldwire	0.07	0.21	0.009	0.017	0.25	7.44	14.60	2.14	0.79	-	-	-	-	-
PH 14 - 8 Mo - sheet	0.04	0.36	0.004	0.002	0.34	8.12	14.71	2.25	1.21	-	-	-	-	-
PH 14 - 8 Mo - weldwire	0.04	-	0.002	0.003	0.016	8.42	12.73	2.20	0.98	-	-	-	-	-
AM 355	0.12	0.77	0.021	0.009	0.34	4.62	15.35	2.73	-	-	-	0.095	-	-
17 Cr - 7 Ni - 0.7 Ti - 0.2 Al	0.05	0.54	0.011	0.006	0.57	6.89	16.8	-	0.14	-	0.64	-	-	-
17 Cr - 7 Ni - 0.7 Ti - 0.2 Al	0.05	0.56	0.026	0.009	0.74	6.80	16.8	-	0.09	-	0.79	-	-	-

Table 10. Condition of the Stainless Steels

Alloy	Surface and Metallurgical Conditions
AISI type 405	Annealed and pickled, No. 2B sheet finish (mill)
AISI type 405	Annealed and pickled, No. 2B sheet finish (mill)
AISI type 405	Annealed and pickled, No. 1 sheet finish (mill)
AISI type 410	No. 2D sheet finish (mill)
AISI type 430	No. 2B sheet finish (mill)
AISI type 430	Annealed and pickled, No. 2B sheet finish (mill)
AISI type 301	Annealed, pickled, cold-rolled (about 22% cold reduction) (1/2 H) (mill)
AISI type 302	No. 2B sheet finish
AISI type 304	Annealed and pickled, No. 1 sheet finish (mill)
AISI type 304	Annealed and pickled, No. 1 sheet finish (mill)
AISI type 304L	Annealed and pickled, No. 2B sheet finish (mill)
AISI type 316	Annealed and pickled, No. 1 sheet finish (mill)
AISI type 316L	Annealed and pickled, No. 2B sheet finish (mill)
AISI type 316L	Annealed and pickled, No. 2B sheet finish (mill)
18 Cr - 14 Mn - 0.5 N	Annealed and pickled, No. 2B sheet finish (mill)
20 - Cb	Annealed and pickled, No. 2B sheet finish (mill)
20 - Cb	Annealed and pickled, No. 2B sheet finish (mill)
15 - 7 AMV - annealed	Annealed and pickled (laboratory)
15 - 7 AMV - RH 1150	Conditioned at 1,800°F for 15 minutes, air-cooled, refrigerated for 16 hours at -100°F, then aged at 1,150°F for 1 hour, pickled (laboratory)
15 - 7 AMV - RH 950	Conditioned at 1,800°F for 15 minutes, air-cooled, refrigerated for 16 hours at -100°F, then aged at 950°F for 2 hours, pickled (laboratory)

Continued

Table 10. Continued.

Alloy	Surface and Metallurgical Conditions
17-4PH-H 925	Conditioned at 1,900°F for 30 minutes, air-cooled, heated to 925°F for 4 hours, air-cooled, wet grit blast-cleaned
17-7 PH-TH 1050	Annealed at 1,950°F for 30 minutes, air-cooled, heated at 1,400°F for 90 minutes, cooled to 60°F within 1 hour, held for 30 minutes, heated at 1,050°F for 90 minutes, air-cooled to room temperature, wet grit blast-cleaned
17-7 PH-RH 1050	Annealed at 1,950°F for 30 minutes, air-cooled, heated at 1,750°F for 10 minutes, air-cooled to room temperature, within 1 hour started cooling to-100°F, held for 8 hours, air-warmed to room temperature, heated at 1,050°F for 60 minutes, air-cooled to room temperature, wet grit blast-cleaned
PH 15-7 Mo-RH 1100	Annealed at 1,950°F for 30 minutes, air-cooled, heated at 1,750°F for 10 minutes, air-cooled to room temperature, within 1 hour started cooling to-100°F, held for 8 hours, air-warmed to room temperature, heated at 1,100°F for 60 minutes, air-cooled to room temperature, wet grit blast-cleaned
PH 14-8 Mo-SRH 950	Annealed at 1,825°F for 30 minutes, air-cooled, heated at 1,700°F for 1 hour, air-cooled and within 1 hour cooled to-100°F, held 8 hours, air-warmed to room temperature, aged 1 hour at 950°F, air-cooled, wet grit blast-cleaned
AM 355-CRT	Cold-rolled 30 to 33%, tempered at 950°F in hot caustic for 3 minutes
17 Cr-7 Ni-0.7 Ti-0.2 Al	Annealed at 1,950°F, air-cooled, aged at 1,000°F for 30 minutes, air-cooled, pickled (laboratory)

Table 11. Corrosion Rates of Stainless Steels

Alloy	Thickness (in.)	Environment[1]	Exposure (days)	Depth (ft)	Corrosion Rates[2]		Crevice Corrosion, Depth (mils)	Type of Corrosion
					MDD	MPY		
AISI type 405[3]	0.123	W	1,064	5,300	9.0	1.7	perforated	Edge, tunnel to perforation
AISI type 405	0.123	W	1,064	5,300	6.4	1.2	47	Edge, tunnel to perforation
AISI type 405	0.123	M	1,064	5,300	5.8	1.1	perforated	Edge, tunnel to perforation
AISI type 405	0.262	W	123	5,640	12.7	2.4	0	Edge, tunnel
AISI type 405	0.262	M	123	5,640	10.8	2.0	0	Edge, tunnel
AISI type 405	0.262	W	197	2,340	11.1	2.1	0	Edge, tunnel
AISI type 405	0.262	M	197	2,340	7.8	1.4	0	Edge, tunnel
AISI type 410	0.040	W	123	5,640	1.0	0.2	slight	Tunnel to perforation
AISI type 410	0.040	M	123	5,640	2.8	0.5	slight	Tunnel to perforation
AISI type 410	0.040	W	197	2,340	1.0	0.2	10	Edge, tunnel
AISI type 410	0.040	M	197	2,340	1.2	0.2	15	Edge, tunnel
AISI type 430[3]	0.137	W	1,064	5,300	7.2	1.3	97	Edge, tunnel to perforation
AISI type 430	0.137	W	1,064	5,300	2.7	0.5	25	Tunnel to perforation
AISI type 430	0.137	M	1,064	5,300	3.9	0.7	40	Tunnel, one end gone
AISI type 430	0.137	W	123	5,640	2.6	0.5	10	Edge, tunnel
AISI type 430	0.137	M	123	5,640	0.9	0.2	10	Edge, tunnel
AISI type 430	0.137	W	123	2,500	0.0	0.0	0	Slight edge attack
AISI type 430	0.050	W	123	5,640	0.0	0.0	0	No visible corrosion
AISI type 430	0.050	M	123	5,640	0.0	0.0	0	No visible corrosion
AISI type 430	0.137	W	197	2,340	1.6	0.3	17	Tunnel
AISI type 430	0.137	M	197	2,340	2.1	0.4	19	Tunnel
AISI type 301	0.103	W	1,064	5,300	2.4	0.4	0	Tunnel to perforation
AISI type 301	0.103	M	1,064	5,300	5.4	1.0	0	Edge, tunnel to perforation

Continued

AISI type 301	0.103	W	123	5,640	1.8	0.3	slight	Tunnel
AISI type 301	0.103	M	123	5,640	3.7	0.7	slight	Tunnel
AISI type 301	0.103	W	197	2,340	1.7	0.3	slight	Tunnel
AISI type 301	0.103	M	197	2,340	1.5	0.3	slight	Tunnel
AISI type 302	0.050	W	123	5,640	0.0	0.0	slight	No visible corrosion
AISI type 302	0.050	M	123	5,640	0.0	0.0	slight	No visible corrosion
AISI type 302	0.050	W	197	2,340	0.0	0.0	perforated, pin hole	Slight tunnel
AISI type 302	0.050	M	197	2,340	0.0	0.0	20	Slight tunnel
AISI type 304[3]	0.195	W	1,064	5,300	0.06	0.01	18	No visible corrosion
AISI type 304	0.195	W	1,064	5,300	0.19	0.03	74	Edge
AISI type 304	0.195	M	1,064	5,300	0.01	0.001	0	Edge, slight tunnel
AISI type 304[3]	0.214	W	1,064	5,300	0.06	0.01	0	13 mils max pit depth on one specimen of five
AISI type 304	0.214	W	1,064	5,300	0.22	0.04	21	No visible corrosion
AISI type 304	0.214	M	1,064	5,300	0.16	0.03	29	Tunnel
AISI type 304	0.214	W	123	5,640	0.25	0.04	0	Tunnel
AISI type 304	0.214	M	123	5,640	0.04	0.01	0	Tunnel
AISI type 304	0.214	W	197	2,340	1.3	0.24	11	Edge tunnel
AISI type 304	0.214	M	197	2,340	0.16	0.03	slight	Edge tunnel
AISI type 304L[3]	0.117	W	1,064	5,300	0.5	0.09	perforated	Edge tunnel
AISI type 304L	0.117	W	1,064	5,300	1.4	0.25	27	Tunnel to perforation
AISI type 304L	0.117	M	1,064	5,300	0.5	0.09	0	Tunnel to perforation
AISI type 304L	0.117	W	123	5,640	1.0	0.18	slight	Tunnel
AISI type 304L	0.117	M	123	5,640	0.25	0.05	slight	Tunnel
AISI type 304L	0.117	W	123	2,500	0.00	0.00	0	No visible corrosion
AISI type 304L	0.117	W	197	2,340	1.3	0.23	8	Tunnel
AISI type 304L	0.117	M	197	2,340	0.42	0.08	18	Tunnel

Continued

Table 11. Continued.

Alloy	Thickness (in.)	Environment[1]	Exposure (days)	Depth (ft)	Corrosion Rates[2]		Crevice Corrosion, Depth (mils)	Type of Corrosion
					MDD	MPY		
AISI type 316[3]	0.230	W	1,064	5,300	0.13	0.02	21	No visible corrosion
AISI type 316	0.230	W	1,064	5,300	0.00	0.00	12	No visible corrosion
AISI type 316	0.230	M	1,064	5,300	0.01	0.001	0	No visible corrosion
AISI type 316	0.230	W	123	5,640	0.21	0.04	0	Slight edge
AISI type 316	0.230	M	123	5,640	0.12	0.02	0	Slight edge
AISI type 316	0.230	W	197	2,340	0.38	0.07	0	No visible corrosion
AISI type 316	0.230	M	197	2,340	0.08	0.01	0	No visible corrosion
AISI type 316L[3]	0.121	W	1,064	5,300	0.20	0.03	25	No visible corrosion
AISI type 316L	0.121	W	1,064	5,300	0.003	0.001	8	No visible corrosion
AISI type 316L	0.121	M	1,064	5,300	0.000	0.000	20	No visible corrosion
AISI type 316L	0.121	W	123	5,640	0.000	0.000	slight	No visible corrosion
AISI type 316L	0.121	M	123	5,640	0.000	0.000	slight	No visible corrosion
AISI type 316L	0.121	W	123	2,500	0.000	0.000	0	No visible corrosion
AISI type 316L	0.121	W	197	2,340	0.000	0.000	18	No visible corrosion
AISI type 316L	0.121	M	197	2,340	0.000	0.000	12	No visible corrosion
18 Cr - 14 Mn - 0.5 N[3]	0.115	W	1,064	5,300	0.9	0.2	0	No visible corrosion
18 Cr - 14 Mn - 0.5 N	0.115	W	1,064	5,300	0.7	0.1	0	Tunnel to perforation
18 Cr - 14 Mn - 0.5 N	0.115	M	1,064	5,300	2.2	0.4	0	Tunnel to perforation
18 Cr - 14 Mn - 0.5 N	0.115	W	123	5,640	0.00	0.00	0	No visible corrosion
18 Cr - 14 Mn - 0.5 N	0.115	M	123	5,640	2.1	0.4	perforated	Tunnel
18 Cr - 14 Mn - 0.5 N	0.115	W	197	2,340	3.8	0.7	109	Tunnel
18 Cr - 14 Mn - 0.5 N	0.115	M	197	2,340	3.5	0.7	21	Tunnel
20 - Cb	0.123	W	1,064	5,300	0.00	0.00	0	No visible corrosion

Continued

20-Cb	0.123	W	123	5,640	0.00	0.00	0	No visible corrosion
20-Cb	0.123	M	123	5,640	0.00	0.00	0	No visible corrosion
20-Cb	0.123	W	197	2,340	0.05	0.01	slight	No visible corrosion, crevice corrosion at wall of bolt hole
20-Cb	0.123	M	197	2,340	0.84	0.15	slight	No visible corrosion, crevice corrosion at wall of bolt hole
17 Cr-7 Ni-0.7 Ti-0.2 Al[3]	0.115	W	1,064	5,300	0.13	0.02	50	No visible corrosion
17 Cr-7 Ni-0.7 Ti-0.2 Al	0.115	W	1,064	5,300	0.000	0.000	16	No visible corrosion
17 Cr-7 Ni-0.7 Ti-0.2 Al	0.115	M	1,064	5,300	0.000	0.000	0	No visible corrosion
17 Cr-7 Ni-0.7 Ti-0.2 Al	0.275	W	123	5,640	0.000	0.000	slight	No visible corrosion
17 Cr-7 Ni-0.7 Ti-0.2 Al	0.275	M	123	5,640	0.000	0.000	0	No visible corrosion
17 Cr-7 Ni-0.7 Ti-0.2 Al	0.275	W	197	2,340	0.000	0.000	0	No visible corrosion
17 Cr-7 Ni-0.7 Ti-0.2 Al	0.275	M	197	2,340	0.000	0.000	0	No visible corrosion
15-7 AMV-annealed	0.048	W	123	5,640	0.11	0.02	perforated	Tunnel to perforation
15-7 AMV-annealed	0.048	M	123	5,640	2.7	0.5	perforated	Tunnel to perforation
15-7 AMV-annealed	0.048	W	197	2,340	2.1	0.4	perforated	Edge, tunnel to perforation, parts of specimens missing
15-7 AMV-annealed	0.048	M	197	2,340	1.8	0.3	perforated	Edge, tunnel to perforation, parts of specimens missing
15-7 AMV-RH 1150[3]	0.045	W	1,064	5,300	6.2	1.2	perforated	Tunnel to perforation
15-7 AMV-RH 1150	0.045	W	1,064	5,300	6.4	1.2	perforated	Tunnel to perforation 11-sq-in. hole
15-7 AMV-RH 1150	0.045	M	1,064	5,300	4.2	0.8	perforated	Tunnel to perforation, 12-sq-in. hole
15-7 AMV-RH 1150	0.045	W	123	5,640	0.5	0.1	perforated	Tunnel to perforation
15-7 AMV-RH 1150	0.045	M	123	5,640	0.6	0.1	perforated	Tunnel to perforation
15-7 AMV-RH 1150	0.045	W	197	2,340	2.1	0.4	perforated	Tunnel to perforation, parts of specimens missing

Continued

Table 11. Continued.

Alloy	Thickness (in.)	Environment[1]	Exposure (days)	Depth (ft)	Corrosion Rates[2]		Crevice Corrosion, Depth (mils)	Type of Corrosion
					MDD	MPY		
15-7 AMV - RH 1150	0.045	M	197	2,340	1.8	0.3	perforated	Tunnel to perforation, parts of specimens missing
15-7 AMV - RH 950[3]	0.048	W	1,064	5,300	10.5	2.0	perforated	Tunnel to perforation
15-7 AMV - RH 950	0.048	W	1,064	5,300	4.9	0.9	perforated	Tunnel to perforation. stress corrosion cracks at drilled hole
15-7 AMV - RH 950	0.048	M	1,064	5,300	4.7	0.9	perforated	Tunnel to perforation
15-7 AMV - RH 950	0.048	W	123	5,640	2.1	0.4	perforated	Tunnel, pitting
15-7 AMV - RH 950	0.048	M	123	5,640	5.4	1.0	perforated	Parts of specimens missing
15-7 AMV - RH 950	0.048	W	123	2,500	3.4	0.7	slight	Pitting
15-7 AMV - RH 950	0.048	W	197	2,340	3.2	0.6	perforated	Edge, tunnel to perforation
15-7 AMV - RH 950	0.048	M	197	2,340	2.5	0.5	perforated	Edge, tunnel to perforation
AM 355 - CRT[3]	0.040	W	123	5,640	0.04	0.007	0	No visible corrosion
AM 355 - CRT[3]	0.040	W	197	2,340	1.2	0.2	slight	Pitting
AM 355 - CRT[3]	0.040	M	197	2,340	0.4	0.08	0	Slight pitting
17-4 PH - H 925, C weld[4]	0.112	W	197	2,340	0.05	0.01	-	No visible corrosion
17-4 PH - H 925, C weld	0.112	M	197	2,340	1.1	0.2	-	Weld bead attack
17-4 PH - H 925, B weld	0.112	W	197	2,340	0.11	0.02	-	No visible corrosion
17-4 PH - H 925, B weld	0.112	M	197	2,340	0.90	0.2	-	Tunnel 1-1/2 in. long
17-7 PH - TH 1050, C weld	0.126	W	197	2,340	2.0	0.4	-	Crevice corrosion and tunneling at separator contact
17-7 PH - TH 1050, C weld	0.126	M	197	2,340	1.5	0.3	-	Crevice corrosion and tunneling at separator contact

Continued

17-7 PH-TH 1050, B weld	0.126	W	197	2,340	0.8	0.2	-	Crevice corrosion and tunneling at separator contact
17-7 PH-TH 1050, B weld	0.126	M	197	2,340	0.4	0.07	-	Many pits in one area, 0.5 in. diameter
17-7 PH-RH 1050, C weld	0.126	W	197	2,340	1.7	0.3	-	Stress corrosion cracked in heat-affected zone
17-7 PH-RH 1050, C weld	0.126	M	197	2,340	3.4	0.6	-	Crevice corrosion and tunneling at separator contact
17-7 PH-RH 1050, B weld	0.126	W	197	2,340	3.1	0.6	-	Tunnel 1-1/2 in. long 1/2 in. from and parallel to weld bead
17-7 PH-RH 1050, B weld	0.126	M	197	2,340	1.5	0.3	-	Tunnel starting at edge 1 in. long x 1/2 in. wide
PH 15-7 Mo-RH 1100, C weld	0.124	W	197	2,340	3.0	0.6	-	Crevice corrosion and tunneling at separator contact
PH 15-7 Mo-RH 1100, C weld	0.124	M	197	2,340	2.4	0.5	-	Tunnel starting at edge 1 in. long x 3/4 in. wide
PH 15-7 Mo-RH 1100, B weld	0.124	W	197	2,340	1.0	0.2	-	Tunneling at one corner
PH 15-7 Mo-RH 1100, B weld	0.124	M	197	2,340	1.6	0.3	-	Tunneling at one corner
PH 14-8 Mo-SRH 950, C weld	0.120	W	197	2,340	1.9	0.4	-	Crevice corrosion at separator contact and tunneling on one edge
PH 14-8 Mo-SRH 950, C weld	0.120	M	197	2,340	0.21	0.04	-	No visible corrosion
PH 14-8 Mo-SRH 950, B weld	0.120	W	197	2,340	0.11	0.02	-	Incipient pits and tunneling
PH 14-8 Mo-SRH 950, B weld	0.120	M	197	2,340	0.05	0.01	-	No visible corrosion

[1] W = specimens exposed on sides of STU in water; M = specimens exposed in base of STU, partially embedded in bottom sediment.

[2] MDD = milligrams per square decimeter per day; MPY = mils penetration per year.

[3] Specimen size, 1 x 6 inches; all others 6 x 12 inches.

[4] C weld = 3-inch-diameter weld ring in center of 6 x 12-inch specimens; B weld = transverse butt weld 6 inches long in 6 x 12-inch specimens.

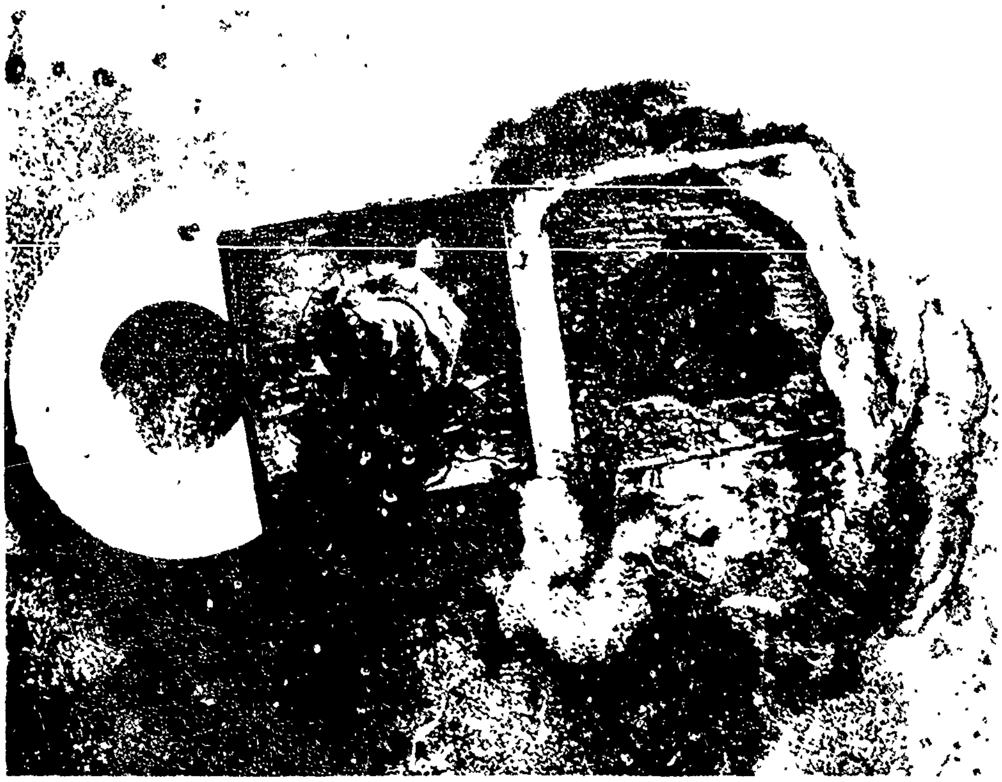

Figure 12. Crevice corrosion at the faying surfaces of two pieces of 15-7 AMV stainless steel bolted together (123 days at 5,640 feet).

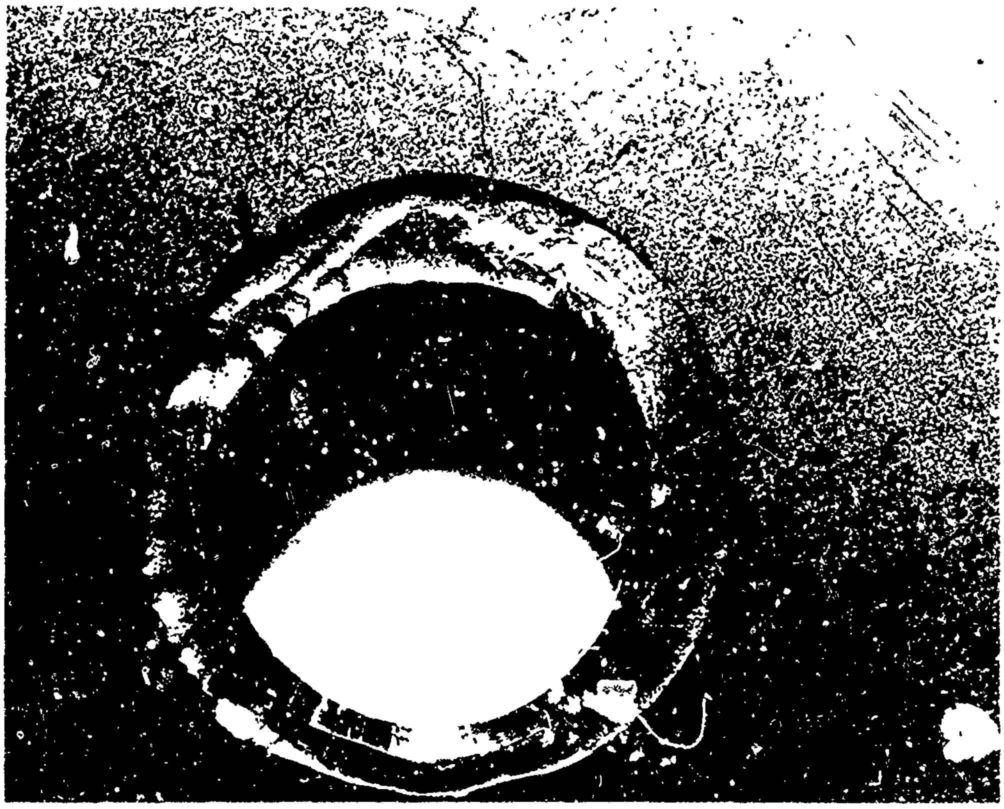

Figure 13 Crevice corrosion underneath head of nylon bolt on type 302 stainless steel (123 days at 5,640 feet).

Figure 14. Tunnel corrosion with corrosion products in place.

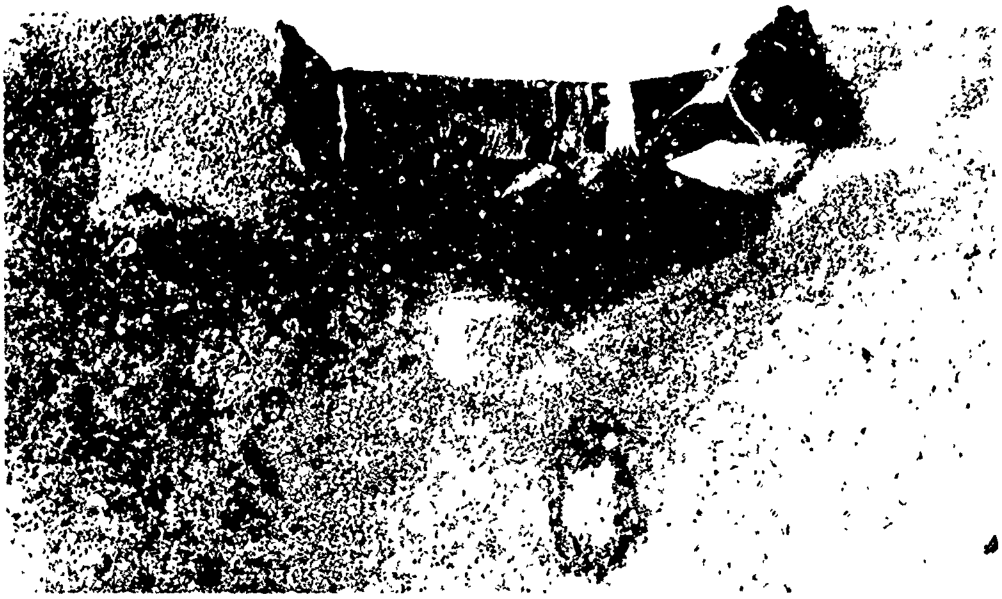

Figure 15. Tunnel walls showing that the attack was a variable rate process.

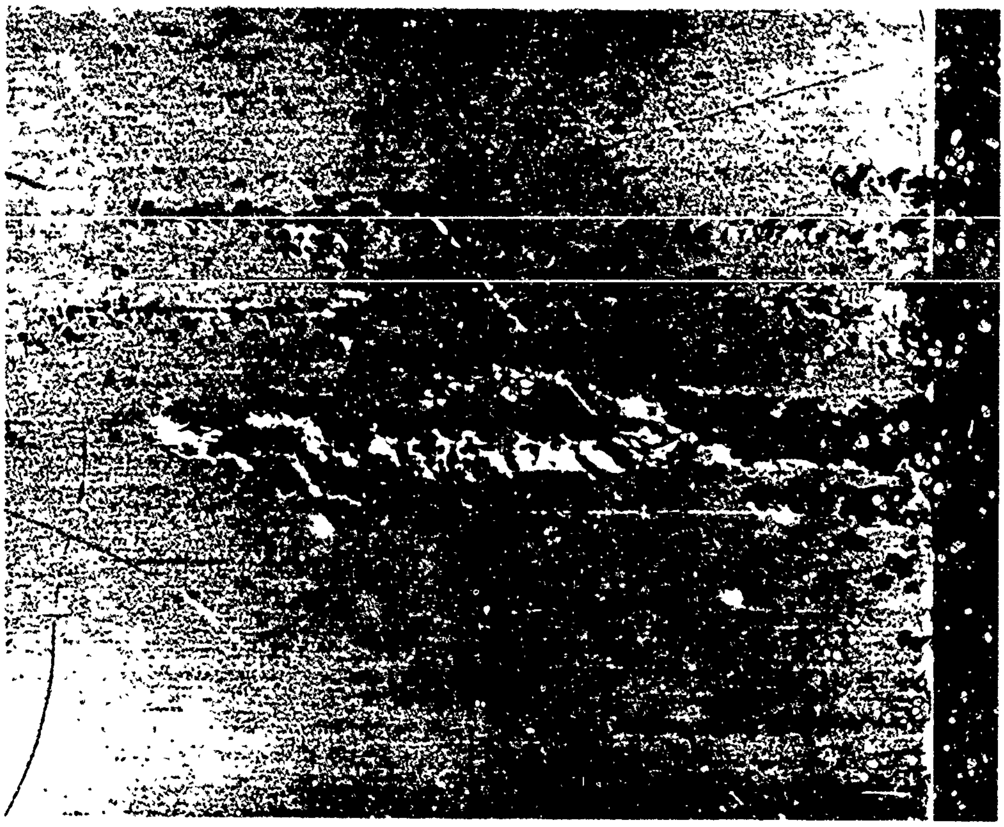

Figure 16. Lacework appearance of tunnel corrosion in type 410 stainless steel (123 days at 5,640 feet). Bottom of specimen at right.

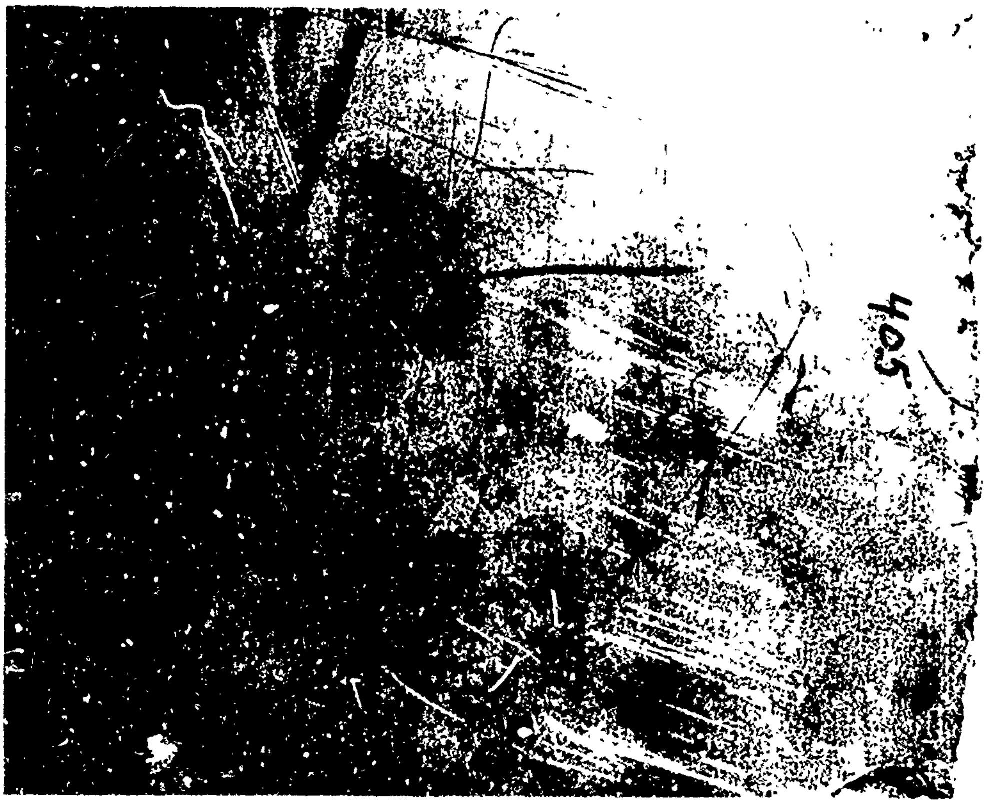

Figure 17. Tunnel corrosion across width of specimen of type 405 stainless steel (1,064 days at 5,300 feet). Top of specimen at right.

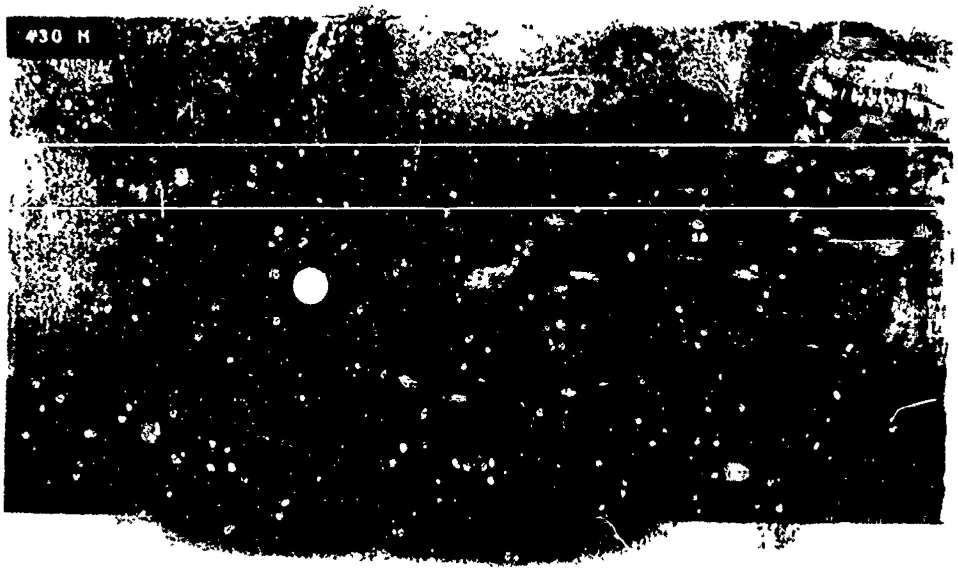

Figure 18. Tunnel corrosion in specimen of type 430 stainless steel (1,064 days in mud at 5,300 feet). Bottom at right. Path was upward to waterline, then laterally parallel to water-sediment interface.

Figure 19. Portion of specimen shown in Figure 18 after cleaning.

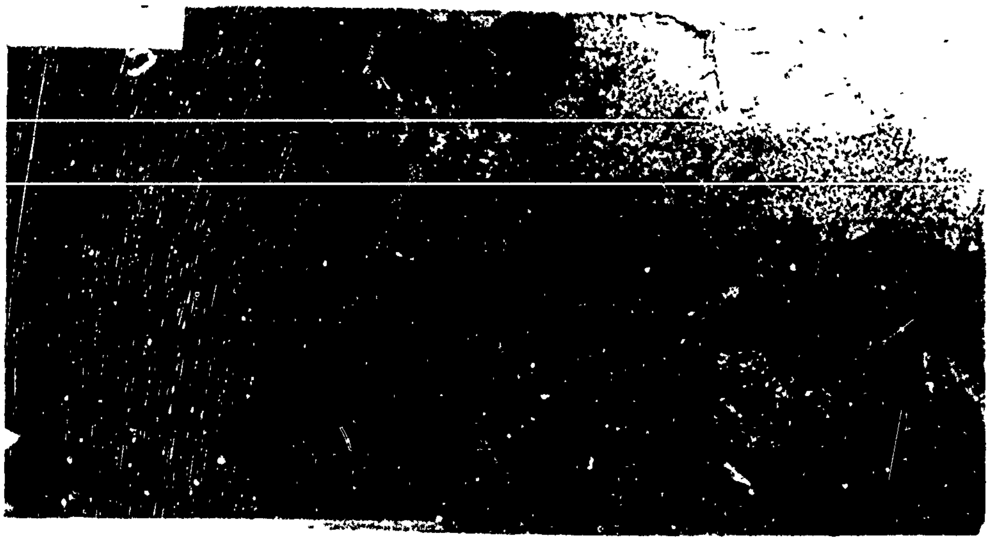

Figure 20. Tunnel corrosion across almost the entire length of a specimen of type 301 stainless steel (1,064 days at 5,300 feet). Top of specimen at left.

Figure 21. Tunnel corrosion in type 304L stainless steel (1,064 days at 5,300 feet). After cleaning.

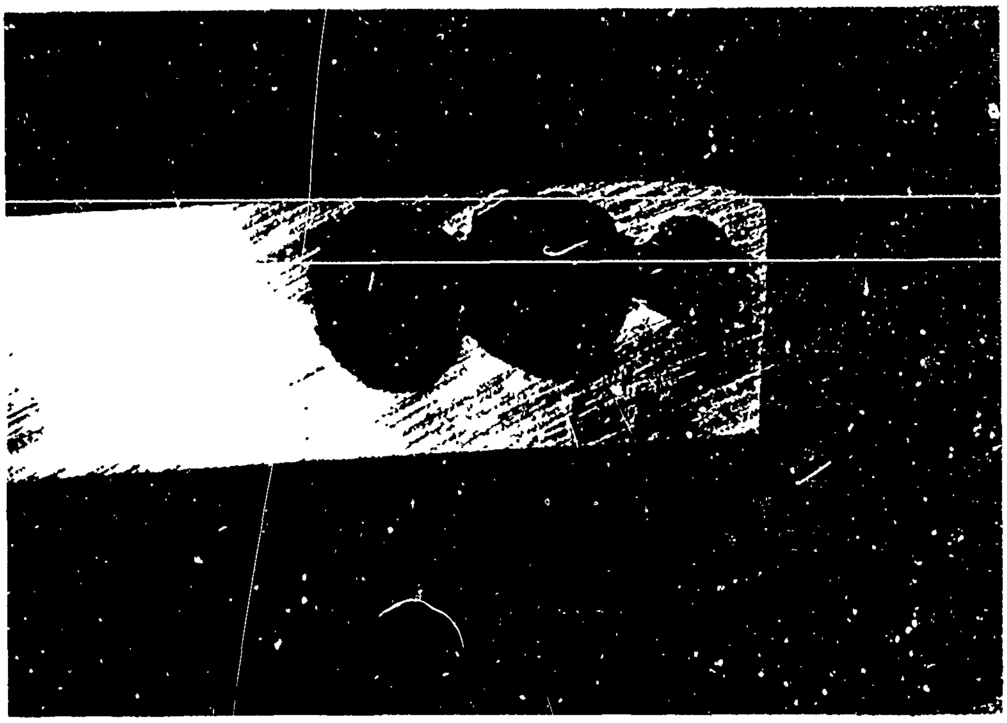

Figure 22. Section through tunnel in type 304L stainless steel. Note hole at top. Section mounted in bakelite and polished; X4.

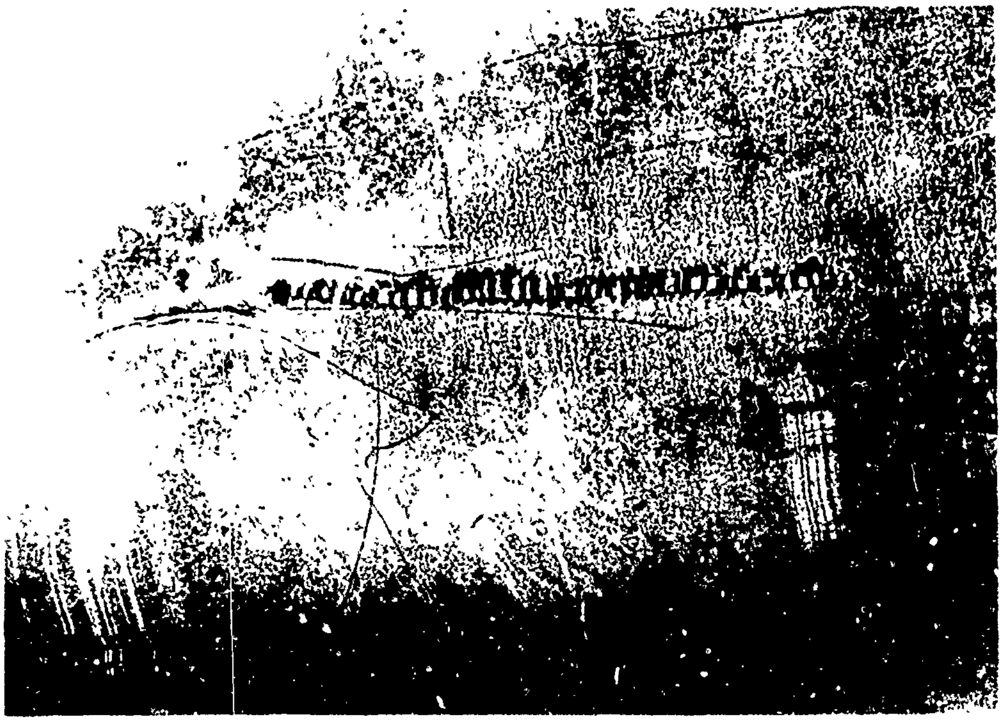

Figure 23. Origin of tunnel corrosion at left in center of specimen of type 430 stainless steel (123 days at 5,640 feet). Top of specimen at left.

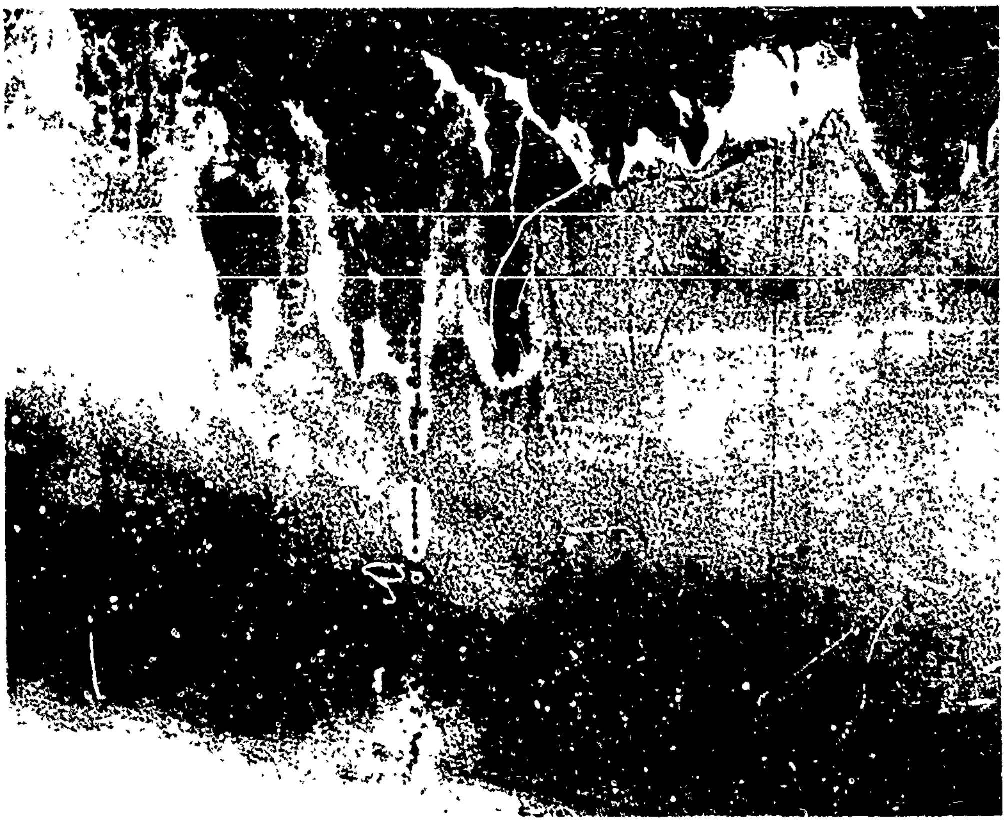

Figure 24. End of type 410 stainless steel specimen which had been embedded in bottom sediment for 197 days at 2,340 feet.

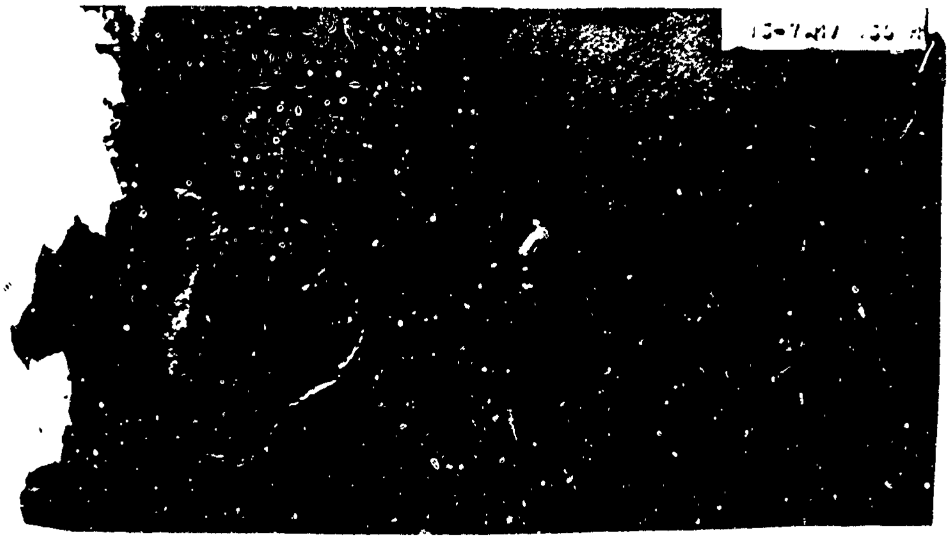

Figure 25. Left end of 15-7 AMV-RH1050 specimen which had been embedded in bottom sediment for 1,064 days at 5,300 feet.

Tunneling corrosion started at the bottom of a specimen of type 430 stainless steel which had been embedded in the bottom sediment. Its path was upward toward the water-bottom interface in a nearly vertical direction to just below the waterline, where the path of attack changed about 90 degrees and traversed the specimen parallel to the water-bottom interface. The uncleaned specimen is shown in Figure 18, and the corroded portion, after cleaning, is shown in Figure 19.

Some of the type 300 series stainless steels were also attacked by this type of corrosion. Figure 20 shows a specimen of type 301 stainless steel in which the tunneling had traversed almost the entire length of the specimen in 1,064 days of exposure at a depth of 5,300 feet. The same type of attack is shown in Figure 21 on a cleaned specimen of type 304L stainless steel after 1,064 days of exposure. A section through a specimen of type 304L stainless steel to show the mode of the tunneling corrosion is shown in Figure 22.

The origin of this type of attack in the different types of stainless steels is not confined to the edges of the specimens or to crevices between two pieces of metal or between a piece of metal and a piece of nonmetal, but can be anywhere. In some cases the origin of this type of corrosion was on the flat surface of a specimen, as shown in Figure 23. A pit originated a little to the left of center and progressed downward in a stepwise fashion.

All the stainless steels in environments containing appreciable concentrations of chloride ions tend to corrode at specific areas, forming deep pits. Pits usually develop first as a result of differential aeration cells, which subsequently convert into passive-active cells. Hence, any situation where there is a difference in the degree of aeration will cause a pit to initiate in the area of lesser aeration. It is here that oxygen or any other depolarizer is first completely depleted, the deficiency of oxygen creating an anodic area. This anodic area is small in relation to the remaining cathodic area. Loss of passivity in this region soon follows, accounting for a potential difference with respect to a large surrounding cathodic area of from 0.5 to 1.0 volt. The resultant high current density of the passive-active cell accompanies a high corrosion rate of the anode, and at the same time cathodically protects the alloy area immediately surrounding the anode. Consequently, other pits are prevented from initiating nearby. This action also firmly fixes the anode in place, accounting for deep penetration of the metal in a short period of time.[18]

Through flow of current, chloride ions transfer into the pit and form concentrated solutions of ferric, nickel, and chromic chlorides. The high chloride ion concentration ensures that the pit surface remains active. At the same time, the high specific gravity of such corrosion products causes leakage out of the pit in the direction of gravity, inducing breakdown of passivity wherever the products come in contact with the alloy surface. This accounts for the shape of pits elongated in the direction of gravity, often observed in practice.[18]

The lines of pits as shown in Figures 20 and 23 can be accounted for on the basis of gravity.

The paths of the lines of pits in Figures 17 and 21 were at a slightly downward angle of about 15 degrees from the horizontal. In these two instances the corrosion products did not move in the exact direction of gravity but nearly horizontal to it. It is possible that the hydrostatic pressure, combined with a very small current, could have influenced the direction of progress of the pitting.

The progress of pitting shown in Figures 16, 18, and 19 defies the laws of gravity in that the progress was upward from the bottom of the specimens. In Figures 18 and 19 the pitting or tunneling changed direction at the water-bottom interface to move across the specimen.

Thus, it is evident that all the tunneling corrosion cannot be explained on the basis of the corrosion products moving in the direction of gravity.

In some cases the entire ends of the specimens which had been embedded in the bottom sediments were removed by corrosion, as shown in Figures 24 and 25. Figure 24 shows the corroded end of a specimen of type 410 stainless steel which had been embedded in the bottom sediment for 197 days at a depth of 2,340 feet. Alloy 15-7 AMV-RH 1050 was also severely corroded when embedded in the bottom sediment for 1,064 days of exposure at a depth of 5,300 feet, as shown in Figure 25.

There was crevice corrosion in varying degrees of severity, from slight to the point where it resulted in perforation, at crevices formed at the contacting surfaces where two pieces of the same material had been bolted together with a nylon bolt and nut on all types of stainless steels. Those least susceptible were types 316 and 316L, 20-Cb, and 17 Cr-7 Ni-0.7 Ti-0.2 Al alloys. These same alloys were also the least susceptible to pitting attack; some were completely unattacked (except for the crevice type) after 1,064 days of exposure at a depth of 5,300 feet.

Mechanical Properties. The percent change in the mechanical properties of the exposed stainless steels is given in Table 12.

As expected, because of the few localized pits in these alloys, there are few instances where there was any significant change in the mechanical properties. After 1,064 days of exposure in the bottom sediment the percent elongation of type 430 stainless steel had decreased by 42%, but there was essentially no change in its tensile and yield strengths. Other significant changes in the mechanical properties occurred in type 304L steel after 1,064 days of exposure in the water at a depth of 5,300 feet and in 18 Cr-14 Mn-0.5 N alloy after 1,064 days of exposure partially embedded in the bottom sediment at a depth of 5,300 feet.

Stress Corrosion. The stainless steels which were stressed at 35, 50, and 75% of their respective yield strengths, and their susceptibility to stress corrosion cracking at depths of 2,340 and 5,640 feet, are shown in Table 13.

Only the precipitation hardening stainless steel 15-7 AMV, heat-treated to the RH 1150 and RH 950 conditions, was susceptible to stress corrosion cracking.

Table 12. Percent Changes in Mechanical Properties of Stainless Steels Due to

Alloy	Environment[1/]	Original Properties			Percent Chang						
					123 Days at 5,640 Feet			197 Days at 2,340 Feet			
		Tensile Strength (ksi)	Yield Strength (ksi)	Elongation (%)	Tensile Strength	Yield Strength	Elongation	Tensile Strength	Yield Strength	Elongation	T St
AISI type 405	W	72.7	57.2	23.8	-	-	-	-	-	-	
	M	-	-	-	-	-	-	-	-	-	
AISI type 405	W	-	-	-	-	-	-	-	-	-	
	M	-	-	-	-	-	-	-	-	-	
AISI type 405	W	77.0	50.5	24.7	-	-	-	+2.2	-0.7	-0.8	
	M	-	-	-	+0.6	-2.4	+3.2	+2.0	-2.4	-2.0	
AISI type 410-2D	W	79.5	48.8	30.5	-	-	-	+0.8	-3.5	-2.6	
	M	-	-	-	0	-3.1	+8.3	+0.6	-2.5	-2.6	
AISI type 430	W	71.8	53.9	29.3	+4.7	-3.5	-5.5	+4.1	+1.3	-8.0	-
	M	-	-	-	-	-	-	+5.6	+3.3	-14.7	
AISI type 430-2B	W	72.5	55.1	27.8	-1.2	-2.0	-1.1	-	-	-	
	M	-	-	-	-	-	-	-	-	-	
AISI type 301-1/2 H	W	174.7	124.9	27.0	-	-	-	-0.6	-7.1	-15.6	
	M	-	-	-	+1.3	+7.0	+18.5	+0.7	-8.1	-3.7	
AISI type 302-2B	W	93.3	43.5	54.2	-	-	-	-3.3	-10.1	-2.8	
	M	-	-	-	+3.7	-3.7	+4.2	-3.5	-9.9	-1.9	
AISI type 304	W	86.1	36.0	59.5	+2.4	+0.6	+8.0	+0.6	+7.0	-4.2	
	M	-	-	-	-	-	-	+0.5	+4.0	-3.4	
AISI type 304	W	-	-	-	-	-	-	-	-	-	
	M	-	-	-	-	-	-	-	-	-	
AISI type 304L	W	80.5	40.0	56.3	-	-	-	+1.0	+2.5	-3.7	-
	M	-	-	-	+4.7	+5.0	+8.4	-2.0	-9.3	+1.6	
AISI type 316	W	81.6	36.5	55.3	-	-	-	+0.1	+12.6	-3.8	-
	M	-	-	-	+0.4	0	-0.2	+2.6	+8.8	-2.4	
AISI type 316L	W	81.1	47.5	51.7	-	-	-	-	-	-	-
	M	-	-	-	-	-	-	-	-	-	
AISI type 316L	W	86.1	48.0	48.3	-	-	-	+0.9	-2.5	+2.1	
	M	-	-	-	-0.7	-1.7	+2.1	+0.8	-2.3	+1.0	
18 Cr-14 Mn-0.5 N	W	126.1	81.1	52.0	-	-	-	-1.6	+4.8	-3.9	-
	M	-	-	-	0	-2.6	+5.8	-0.7	+3.1	+1.9	
20-CB	W	91.5	46.9	40.0	-	-	-	-1.0	-1.1	+3.8	
	M	-	-	-	+5.0	+18.7	-4.5	+0.1	+0.8	-4.5	
15-7 AMV-annealed	W	93.1	59.6	18.5	-	-	-	-	-	-	
	M	-	-	-	-	-	-	-	-	-	
15-7 AMV-annealed	W	129.4	57.4	26.8	-8.2	+3.0	-49.6	+0.2	-10.1	+39.2	
	M	-	-	-	-	-	-	+0.2	-9.8	+42.9	

A

Changes in Mechanical Properties of Stainless Steels Due to Corrosion

	Percent Change After —											
	123 Days at 5,640 Feet			197 Days at 2,340 Feet			1,064 Days at 5,300 Feet (1 x 6-in. specimens)			1,064 Days at 5,300 Feet (6 x 12-in. specimens)		
ation)	Tensile Strength	Yield Strength	Elongation	Tensile Strength	Yield Strength	Elongation	Tensile Strength	Yield Strength	Elongation	Tensile Strength	Yield Strength	Elongation
.8	-	-	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-	-	-
.7	-	-	-	+2.2	-0.7	-0.8	-	-	-	-	-	-
	+0.6	-2.4	+3.2	+2.0	-2.4	-2.0	-	-	-	-	-	-
5	-	-	-	+0.8	-3.5	-2.6	-	-	-	-	-	-
	0	-3.1	+8.3	+0.6	-2.5	-2.6	-	-	-	-	-	-
3	+4.7	-3.5	-5.5	+4.1	+1.3	-8.0	-1.1	-4.8	+19.5	+9.9	+3.7	-15.7
	-	-	-	+5.6	+3.3	-14.7	-	-	-	-3.9	+0.4	-42.0
8	-1.2	-2.0	-1.1	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-	-	-
0	-	-	-	-0.6	-7.1	-15.6	-	-	-	-3.0	-1.8	-10.0
	+1.3	+7.0	+18.5	+0.7	-8.1	-3.7	-	-	-	+0.5	+9.0	-15.9
.2	-	-	-	-3.3	-10.1	-2.8	-	-	-	-	-	-
	+3.7	-3.7	+4.2	-3.5	-9.9	-1.9	-	-	-	-	-	-
.5	+2.4	+0.6	+8.0	+0.6	+7.0	-4.2	+1.0	+6.4	+5.9	-0.1	+2.5	-5.4
	-	-	-	+0.5	+4.0	-3.4	-	-	-	-0.7	+1.7	-6.2
	-	-	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-	-	-
.3	-	-	-	+1.0	+2.5	-3.7	+3.9	+3.5	+1.8	-31.8	-30.2	-34.6
	+4.7	+5.0	+8.4	-2.0	-2.3	+1.6	-	-	-	+3.1	+7.8	-5.5
.3	-	-	-	+0.1	+12.6	-3.8	+3.3	+7.1	-3.6	+1.7	+8.8	-5.4
	+0.4	0	-0.2	+2.6	+8.8	-2.4	-	-	-	+1.7	+7.4	-7.4
.7	-	-	-	-	-	-	+1.8	-6.5	+5.0	+0.9	-9.3	-4.6
	-	-	-	-	-	-	-	-	-	+0.9	-11.2	0
3	-	-	-	+0.9	-2.5	+2.1	-	-	-	-	-	-
	-0.7	-1.7	+2.1	+0.8	-2.3	+1.0	-	-	-	-	-	-
.0	-	-	-	-1.6	+4.8	-3.9	-0.6	-10.7	+1.9	-1.9	+4.4	-3.8
-	0	-2.6	+5.8	-0.7	+3.1	+1.9	-	-	-	-27.1	-30.5	-36.0
.0	-	-	-	-1.0	-1.1	+3.8	-	-	-	-	-	-
-	+5.0	+18.7	-4.5	+0.1	+0.8	-4.5	-	-	-	+3.7	+9.2	-2.5
.5	-	-	-	-	-	-	-	-	-	-	-	-
	-	-	-	-	-	-	-	-	-	-	-	-
8	-8.2	+3.0	-49.6	+0.2	-10.1	+39.2	-	-	-	-	-	-
-	-	-	-	+0.2	-9.8	+42.9	-	-	-	-	-	-

Continued

Table 12. Continued.

Alloy	Environment[1]	Original Properties			123 Days at 5,640 Feet			197 Days at 2,:		ys at 5,6
		Tensile Strength (ksi)	Yield Strength (ksi)	Elongation (%)	Tensile Strength	Yield Strength	Elongation	Tensile Strength	Yield Strength	eld ength
15-7 AMV-RH 1150	W	195.8	165.9	8.0	-	-	-	-	-	-
	M	-	-	-	-	-	-	-	-	-
15-7 AMV-RH 1150	W	190.0	158.2	8.3	-	-	-	+1.7	+2.8	-
	M	-	-	-	-2.2	+1.4	-15.7	+1.8	+4.7	+1.4
15-7 AMV-RH 950	W	247.9	220.0	2.2	-	-	-	-3.4	-0.4	-
	M	-	-	-	-19.3	-	-4.1	-2.0	+2.2	-
17-4 PH-H 925, C weld[2]	W	-	-	-	-	-	-	-	-	-
	M	-	-	-	-	-	-	-	-	-
17-4 PH-H 925, B weld	W	191.9	185.4	3.0	-	-	-	-	-	-
	M	-	-	-	-	-	-	-	-	-
17-7 PH-TH 1050, C weld	W	-	-	-	-	-	-	-	-	-
	M	-	-	-	-	-	-	-	-	-
17-7 PH-TH 1050, B weld	W	196.8	188.1	3.0	-	-	-	-	-	-
	M	-	-	-	-	-	-	-	-	-
17-7 PH-RH 1050, C weld	W	-	-	-	-	-	-	-	-	-
	M	-	-	-	-	-	-	-	-	-
17-7 PH-RH 1050, B weld	W	206.7	196.7	4.6	-	-	-	-	-	-
	M	-	-	-	-	-	-	-	-	-
PH 15-7 Mo RH 1100, C weld	W	-	-	-	-	-	-	-	-	-
	M	-	-	-	-	-	-	-	-	-
PH 15-7 Mo RH 1100, B weld	W	191.6	183.2	3.0	-	-	-	-	-	-
	M	-	-	-	-	-	-	-	-	-
PH 14-8 Mo SRH 950, C weld	W	-	-	-	-	-	-	-	-	-
	M	-	-	-	-	-	-	-	-	-
PH 14-8 Mo SRH 950, B weld	W	229.0	214.1	2.0	-	-	-	-	-	-
	M	-	-	-	-	-	-	-	-	-
AM 355-CRT	W	229.0	215.3	19.2	+4.0	-10.5	-1.0	+3.1	-10.8	·10.5
	M	-	-	-	-	-	-	+2.7	-8.8	-
17 Cr-7 Ni-0.7 Ti-0.2 Al	W	198.9	193.2	8.5	-	-	-	-	-	-
	M	-	-	-	-	-	-	-	-	-
17 Cr-7 Ni-0.7 Ti-0.2 Al	W	191.1	184.0	14.2	+10.9	+11.4	+7.0	+1.3	+2.3	·11.4
	M	-	-	-	-	-	-	+2.3	+3.5	-

[1] W = specimens exposed on sides of STU in water, M = specimens exposed in base of STU, partially embedded in bottom sediment

[2] C weld = 3-inch-diameter weld ring in center of 6 x 12-inch specimens, B weld - transverse butt weld 6 inches long in 6 x 12-inch

le 12. Continued.

Percent Change After —										
at 5,640 Feet		197 Days at 2,340 Feet			1,064 Days at 5,300 Feet (1 x 6-in. specimens)			1,064 Days at 5,300 Feet (6 x 12-in. specimens)		
eld ngth	Elongation	Tensile Strength	Yield Strength	Elongation	Tensile Strength	Yield Strength	Elongation	Tensile Strength	Yield Strength	Elongation
-	-	-	-	-	-	-	-	+1.6	+1.9	-10.0
-	-	-	-	-	-	-	-	+1.6	+3.3	-2.5
-	-	+1.7	+2.8	-1.2	-	-	-	-	-	-
1.4	-15.7	+1.8	+4.7	-9.6	-	-	-	-	-	-
-	-	-3.4	-0.4	-18.2	-	-	-	-	-	-
-	-4.1	-2.0	+2.2	-18.2	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
10.5	-1.0	+3.1	-10.8	+4.2	-	-	-	-		-
-	-	+2.7	-8.8	+4.2	-	-	-	-	-	-
-	-	-	-	-	+4.0	+4.4	+61.2	+1.7	+2.0	-25.9
-	-	-	-	-	-	-	-	+4.1	+4.7	-23.5
11.4	+7.0	+1.3	+2.3	-18.3	-	-	-	-	-	-
-	-	+2.3	+3.5	-20.4	-	-	-	-	-	-

tially embedded in bottom sediment.
butt weld 6 inches long in 6 x 12-inch specimens.

Table 13. Stress Corrosion of Stainless Steels

Alloy	Stress (ksi)	Percent of Yield Strength	Exposure (days)	Depth (ft)	Number of Specimens	Number Failed
AISI type 405	20.0	35	197	2,340	3	0
AISI type 405	28.6	50	197	2,340	3	0
AISI type 405	42.9	75	197	2,340	3	0
AISI type 304L	20.0	50	197	2,340	3	0
AISI type 304L	30.0	75	197	2,340	3	0
AISI type 304L	14.0	35	123	5,640	3	0
AISI type 304L	20.0	50	123	5,640	3	0
AISI type 304L	30.0	75	123	5,640	3	0
AISI type 316L	16.8	35	197	2,340	3	0
AISI type 316L	24.0	50	197	2,340	3	0
AISI type 316L	36.0	75	197	2,340	3	0
AISI type 316L	16.8	35	123	5,640	3	0
AISI type 316L	24.0	50	123	5,640	3	0
AISI type 316L	36.0	75	123	5,640	3	0
20-Cb	23.5	50	197	2,340	3	0
20-Cb	35.2	75	197	2,340	3	0

Continued

Table 13. Continued.

Alloy	Stress (ksi)	Percent of Yield Strength	Exposure (days)	Depth (ft)	Number of Specimens	Number Failed
20 - Cb	16.4	35	123	5,640	3	0
20 - Cb	23.5	50	123	5,640	3	0
20 - Cb	35.2	75	123	5,640	3	0
15 - 7 AMV, annealed	20.9	35	197	2,340	3	0
15 - 7 AMV, annealed	29.8	50	197	2,340	3	0
15 - 7 AMV, annealed	44.7	75	197	2,340	3	0
15 - 7 AMV, RH 1150	79.1	50	197	2,340	3	2
15 - 7 AMV, RH 1150	118.7	75	197	2,340	3	3
15 - 7 AMV, RH 1150	45.4	35	123	5,640	3	0
15 - 7 AMV, RH 1150	79.1	50	123	5,640	3	0
15 - 7 AMV, RH 1150	118.7	75	123	5,640	3	0
15 - 7 AMV, RH 950	77.0	35	197	2,340	3	0
15 - 7 AMV, RH 950	110.0	50	197	2,340	3	2[1]
15 - 7 AMV, RH 950	165.0	75	197	2,340	3	2
15 - 7 AMV, RH 950	77.0	35	123	5,640	3	1[2]
15 - 7 AMV, RH 950	110.0	50	123	5,640	3	3

Continued

15-7 AMV, RH 950	165.0	75	123	5,640	3	3[3]
17-4 PH, H 925, welded[4]	64.9	35	197	2,340	2	0
17-4 PH, H 925, welded	92.7	50	197	2,340	2	0
17-4 PH, H 925, welded	139.1	75	197	2,340	2	0
17-7 PH, TH 1050, welded	65.8	35	197	2,340	2	0
17-7 PH, TH 1050, welded	94.1	50	197	2,340	2	0
17-7 PH, TH 1050, welded	141.1	75	197	2,340	2	0
17-7 PH, RH 1050, welded	68.8	35	197	2,340	2	0
17-7 PH, RH 1050, welded	98.4	50	197	2,340	2	0
17-7 PH, RH 1050, welded	147.5	75	197	2,340	2	0
PH 15-7 Mo, RH 1100, welded	64.1	35	197	2,340	2	0
PH 15-7 Mo, RH 1100, welded	91.6	50	197	2,340	2	0
PH 15-7 Mo, RH 1100, welded	137.4	75	197	2,340	2	0
PH 14-8 Mo, SRH 950, welded	74.9	35	197	2,340	2	0
PH 14-8 Mo, SRH 950, welded	107.1	50	197	2,340	2	0
PH 14-8 Mo, SRH 950, welded	160.6	75	197	2,340	2	0
17 Cr-7 Ni-0.7 Ti-0.2 Al	67.6	35	197	2,340	3	0
17 Cr-7 Ni-0.7 Ti-0.2 Al	96.6	50	197	2,340	3	0
17 Cr-7 Ni-0.7 Ti-0.2 Al	144.9	75	197	2,340	3	0

[1] Incipient crack in one specimen.
[2] Incipient crack.
[3] One specimen broke before being submerged.
[4] Transverse butt weld at apex of bend in the specimen.

Two cases of stress corrosion cracking were found in 6 x 12-inch specimens where the magnitudes and distribution of the tensile stresses were unknown. Stress corrosion cracks originated at a drilled hole in a specimen of 15-7 AMV-RH 1150 precipitation hardening stainless steel which had been exposed in the water for 1,064 days at a depth of 5,300 feet, as shown in Figure 26. The direction of propagation of one crack is 90 degrees from the direction of the other two, which indicates that residual multiaxial tensile stresses were present in the area of the hole. These stresses were undoubtedly concentrated in the area of the hole as the result of the drilling operation. Note the rim of rolled metal around the circumference of the hole, which indicates poor drilling practice.

The other failure was of a welded specimen of 17-7 PH-RH 1050 precipitation hardening stainless steel after 197 days of exposure at a depth of 2,340 feet, as shown in Figure 27. This specimen had been heat-treated to the RH 1050 condition; then a weld bead was deposited by the gas-shielded tungsten-arc process to form a 3-inch-diameter circle in the center of the specimen. By means of this welding procedure a maximum of residual welding stresses are "locked-up" in a specimen. The stress crack originated in the heat-affected zone on the outer periphery of the weld bead.

Figure 26. Stress corrosion cracks which originated at drilled hole in specimen of 15-7 AMV-RH1150 (1,064 days at 5,300 feet).

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Figure 26. Stress corrosion cracks which originated at drilled hole in specimen of 15-7 AMV-RH1150 (1,064 days at 5,300 feet).

Figure 27. Stress corrosion crack which originated in heat-affected zone of welded 17-7 PH-RH1050 (197 days at 2,340 feet).

Metallurgical Condition. Polished and polished-and-etched sections from all the stainless steels were examined metallographically at magnifications between 100 and 1,000 for any metallurgical or microstructural conditions which might affect the corrosion behavior of the alloys.

Intergranular corrosion was found in the type 405, annealed and pickled, ferritic, nonhardenable, stainless steel. The type of edge penetration and corrosion that outline the grains after 123 days of exposure at a depth of 5,640 feet in the Pacific Ocean is shown in Figure 28. After the specimen was etched to delineate the grain boundaries, metallographic examinations showed that the corrosion was confined to the grain boundaries and to the stringers of austenite decomposition products, as shown in Figure 29.

Corrosion Products. The corrosion products taken from one of the corrosion tunnels in type 430 stainless steel were analyzed by X-ray diffraction, spectrographic analysis, quantitative chemical analysis, and infrared spectrophotometry and were found to be amorphous ferric oxide ($Fe_2O_3 \cdot XH_2O$), Fe, Cr, Mn, Si, trace of Ni, 1.41% chloride ion, 2.12% sulfate ion, significant amount of phosphate ion.

Aluminum Alloys

The chemical compositions of the aluminum alloys are given in Table 14. The corrosion rates and types of corrosion are given in Table 15, and corrosion rates are shown graphically in Figures 30 to 32.

Figure 28. Edge corrosion in type 405 stainless steel showing corrosion at grain boundaries. Unetched; X100.

Figure 29. A portion of the area in Figure 28 showing that corrosion was along the grain boundaries and in the stringers of austenite decomposition product. Electrolytic oxalic acid etch; X500.

Table 14. Chemical Composition of Aluminum Alloys, Percent by W

Alloy	Si	Fe	Cu	Mn	Mg	Cr	
2219-T81	0.20	0.30	5.8-6.8	0.20-0.40	0.02	-	[illegible]
3003-H14	0.60	0.70	0.20	1.0-1.5	-	-	[illegible]
Alclad 3003-H12							
Core	0.60	0.70	0.20	1.0-1.5	-	-	[illegible]
Cladding	0.70	-2/	0.10	0.10	0.10	-	[illegible]
5052, welding rod	0.45	-2/	0.10	0.10	2.2-2.8	0.15-0.35	[illegible]
5454-H32	0.40	-2/	0.10	0.50-1.0	2.4-3.0	0.05-0.20	[illegible]
5456-H343 and H321	0.40	-2/	0.10	0.50-1.0	4.7-5.5	0.05-0.20	[illegible]
5083-H113	0.40	0.40	0.10	0.30-1.0	4.0-4.9	0.05-0.25	[illegible]
5086-H34	0.40	0.50	0.10	0.20-0.70	3.5-4.5	0.05-0.25	[illegible]
6061-T6	0.40-0.80	0.70	0.15-0.40	0.15	0.8-1.2	0.15-0.35	[illegible]
7039-T6 1/	0.11	0.17	trace	0.22	2.80	0.21	[illegible]
7079-T6 1/	0.14	0.12	0.64	.20	3.50	0.16	[illegible]
7178-T6	0.50	0.70	1.6-2.4	0.30	2.4-3.1	0.18-0.40	[illegible]

1/ Composition as furnished by producer, all others are Aluminum Association composition limits

2/ The percent of Si and Fe combined cannot exceed the value given for Si.

Chemical Composition of Aluminum Alloys, Percent by Weight

Cu	Mn	Mg	Cr	Zn	Ti	Other	Al
5.8-6.8	0.20-0.40	0.02	-	0.10	0.02-0.10	V,0.05-0.15 Zr,0.10-0.25	remainder
0.20	1.0-1.5	-	-	0.10	-	-	
0.20	1.0-1.5	-	-	0.10	-	-	
0.10	0.10	0.10	-	0.8-1.3	-	-	
0.10	0.10	2.2-2.8	0.15-0.35	0.10	-	Be,0.0008	
0.10	0.50-1.0	2.4-3.0	0.05-0.20	0.25	0.20	-	
0.10	0.50-1.0	4.7-5.5	0.05-0.20	0.25	0.20	-	
0.10	0.30-1.0	4.0-4.9	0.05-0.25	0.25	0.15	-	
0.10	0.20-0.70	3.5-4.5	0.05-0.25	0.25	0.15	-	
0.15-0.40	0.15	0.8-1.2	0.15-0.35	0.25	0.15	-	
trace	0.22	2.80	0.21	4.00	0.02	-	
0.64	0.20	3.50	0.16	4.30	0.03	-	
1.6-2.4	0.30	2.4-3.1	0.18-0.40	6.3-7.3	0.10	-	▼

others are Aluminum Association composition limits; single values are maximum.

ot exceed the value given for Si.

Table 15. Corrosion Rates, Pit Depths, and Pitting Frequency of Aluminum Allo

Alloy	Environment[1]	Exposure (days)	Depth (ft)	Corrosion Rate[2]		Pit Depth (mils)		Pitting Frequency (no. sq in.)	
				MDD	MPY	Max	Avg		
2219-T81[3]	W	1,064	5,300	3.16	1.60	26.0	19.2	5	Edge attack and cre
2219-T81	W	1,064	5,300	2.75	1.39	35.0	22.9	11.4	General pitting
2219-T81	M	1,064	5,300	2.98	1.51	48.0	25.0	9.3	General pitting
2219-T81	W	123	5,640	3.98	2.01	15.5	12.1	9.0	General pitting and
2219-T81	M	123	5,640	3.78	1.91	19.5	15.8	7.0	General pitting and
2219-T81	W	197	2,340	5.11	2.58	25.0	19.8	33.4	General pitting, slig
2219-T81	M	197	2,340	4.05	2.05	32.0	16.3	18.5	General pitting, slig
3003-H14[3]	W	1,064	5,300	3.94	2.07	29.0	12.1	0.5	Some edge attack, se
3003-H14	W	1,064	5,300	4.18	2.20	P[4]	84.9	1.4	Extensive edge attac
3003-H14	M	1,064	5,300	3.65	1.92	P	70.4	1.5	Extensive edge attac
3003-H14	W	123	5,640	0.87	0.46	18.0	11.8	4.8	Few scattered pits
3003-H14	M	123	5,640	3.31	1.74	55.0	50.4	4.7	Edge attack, few dee
3003-H14	W	197	2,340	4.48	2.38	48.0	16.0	0.3	Severe edge attack,
3003-H14	M	197	2,340	3.14	1.65	P	27.7	0.49	Edge attack, crevice
Alclad 3003-H12[3]	W	1,064	5,300	1.39	0.73	15.0	14.8	-	Few large areas of cl 1 x 2.5 in.
Alclad 3003-H12	W	1,064	5,300	0.58	0.31	20.0	16.5	0.4	Cladding removed in
Alclad 3003-H12	M	1,064	5,300	1.47	0.77	18.0	15.6	0.6	Cladding removed in
Alclad 3003-H12	W	123	5,640	0.36	0.19	18.0	14.6	0.1	Slight edge attack, b crevice corrosion
Alclad 3003-H12	M	123	5,640	5.33	2.80	19.5	14.5	13.5	Slight edge attack, b cladding gone, crevic
Alclad 3003-H12	W	197	2,340	4.14	2.18	17.0	16.0	1.6	Cladding gone in mar
Alclad 3003-H12	M	197	2,340	2.10	1.11	14.0	12.5	1.0	One area, 7 sq in., cl
5454-H32	W	197	2,340	1.28	0.69	24.0	9.0	1	Slight edge attack, fe
5454-H32	M	197	2,340	1.10	0.59	16.0	8.1	0.5	Slight edge attack, fe
5454-H32, welded[5]	W	123	5,640	0.13	0.07	7.0	2.9	6 pits (total)	No weld zone attack
5454-H32, welded	M	123	5,640	2.25	1.21	49.0	45.6	23.0	Few deep pits, no wel
5454-H32, welded	W	197	2,340	0.64	0.34	41.0	28.0	15.8	Edge attack, some atta zone, scattered pits in
5454-H32, welded	M	197	2,340	1.04	0.56	49.0	31.6	13.2	Edge attack, some atta zone, scattered pits in corrosion

ion Rates, Pit Depths, and Pitting Frequency of Aluminum Alloys

epth (ft)	Corrosion Rate[2]		Pit Depth (mils)		Pitting Frequency (no. sq in.)	Remarks
	MDD	MPY	Max	Avg		
,300	3.16	1.60	26.0	19.2	5	Edge attack and crevice corrosion, 47 mils deep
,300	2.75	1.39	35.0	22.9	11.4	General pitting
,300	2.98	1.51	48.0	25.0	9.3	General pitting
,640	3.98	2.01	15.5	12.1	9.0	General pitting and crevice corrosion
,640	3.78	1.91	19.5	15.8	7.0	General pitting and crevice corrosion
,340	5.11	2.58	25.0	18.8	33.4	General pitting, slight edge attack
,340	4.05	2.05	32.0	16.3	18.5	General pitting, slight edge attack
,300	3.94	2.07	29.0	12.1	0.5	Some edge attack, severe crevice corrosion
,300	4.18	2.20	P[4]	84.9	1.4	Extensive edge attack, scattered deep pits
,300	3.65	1.92	P	70.4	1.5	Extensive edge attack, scattered deep pits
,640	0.87	0.46	18.0	11.8	4.8	Few scattered pits
,640	3.31	1.74	55.0	50.4	4.7	Edge attack, few deep pits, crevice corrosion
,340	4.48	2.38	48.0	16.0	0.3	Severe edge attack, few pits
2,340	3.14	1.65	P	27.7	0.49	Edge attack, crevice corrosion, severe surface attack
5,300	1.39	0.73	15.0	14.8	-	Few large areas of cladding removed, some 1 x 2.5 in.
5,300	0.58	0.31	20.0	16.5	0.4	Cladding removed in many areas, crevice corrosion
5,300	1.47	0.77	18.0	15.6	0.6	Cladding removed in many areas, crevice corrosion
5,640	0.36	0.19	18.0	14.6	0.1	Slight edge attack, blistering, cladding penetrated crevice corrosion
5,640	5.33	2.80	19.5	14.5	13.5	Slight edge attack, blistering, large areas of cladding gone, crevice corrosion
2,340	4.14	2.18	17.0	16.0	1.6	Cladding gone in many large areas
2,340	2.10	1.11	14.0	12.5	1.0	One area, 7 sq in., cladding gone
2,340	1.28	0.69	24.0	9.0	1	Slight edge attack, few scattered pits
2,340	1.10	0.59	16.0	8.1	0.5	Slight edge attack, few scattered pits
5,640	0.13	0.07	7.0	2.9	6 pits (total)	No weld zone attack
5,640	2.25	1.21	49.0	45.6	23.0	Few deep pits, no weld zone attack
2,340	0.64	0.34	41.0	28.0	15.8	Edge attack, some attack at edge of heat-affected zone, scattered pits in plate
2,340	1.04	0.56	49.0	31.6	13.2	Edge attack, some attack at edge of heat-affected zone, scattered pits in plate, severe crevice corrosion

Continued

Table 15. Continued.

Alloy	Environment[1]	Exposure (days)	Depth (ft)	Corrosion Rate[2]		Pit Depth (mils)		Pitting Frequency (no. sq in.)	
				MDD	MPY	Max	Avg		
5456-H321[3]	W	1,064	5,300	1.04	0.56	-	-	-	Extensive edge
5456-H321	W	1,064	5,300	2.34	1.28	43.0	36.5	0.7	Extensive edge
5456-H321	M	1,064	5,300	2.69	1.46	36.0	33.0	1.5	Extensive edge
5456-H321	W	123	5,640	0.09	0.05	<1	-	-	Surface etchin
5456-H321	M	123	5,640	3.86	2.08	49.0	40.0	6.2	Few deep pits,
5456-H321	W	197	2,340	4.55	2.47	17.0	8.2	0.5	Edge attack, fe
5456-H321	M	197	2,340	4.00	2.17	41.0	7.3	0.3	Edge attack, se
5456-H343[3]	W	1,064	5,300	0.26	0.14	<1	-	-	Some edge atta
5456-H343	W	123	5,640	1.83	0.99	25.0	15.3	-	Crevice corro
5456-H343	W	197	2,340	0.79	0.43	-	-	-	Crevice corrosi
5456-H343	M	197	2,340	0.61	0.33	-	-	-	Crevice corrosi
5083-H113	W	197	2,340	1.00	0.54	23.0	23.0	1 pit (total)	Edge attack
5083-H113	M	197	2,340	1.10	0.59	14.0	12.5	2 pits (total)	Edge attack
5083-H113, welded[5]	W	123	5,640	0.00	0.00	27.5	17.1	2 pits (total)	Few deep pits
5083-H113, welded	M	123	5,640	1.74	0.94	65.0	53.7	5.5	Few deep pits
5083-H113, welded	W	197	2,340	0.46	0.25	72.0	48.0	1	Few pits in pla
5083-H113, welded	M	197	2,340	1.37	0.74	55.0	21.0	0.9	Few pits in plat
5086-H34[3]	W	1,064	5,300	1.52	0.82	<1	-	-	Severe edge at
5086-H34	W	1,064	5,300	1.70	0.92	67.0	54.0	0.2	Severe edge at
5086-H34	M	1,064	5,300	2.37	1.28	53.0	50.4	0.5	Severe edge at in mud large ar
5086-H34	W	123	5,640	0.17	0.09	<1	-	-	Scattered etche
5086-H34	M	123	5,640	2.55	1.38	13.0	7.8	3 pits (total)	Few pits, crevic
5086-H34	W	123	2,500	0.09	0.05	<1	-	-	Scattered etche
5086-H34	W	197	2,340	1.17	0.63	<1	-	-	Slight edge atta
5086-H34	M	197	2,340	2.06	1.11	29.0	15.8	-	Crevice corrosi attack in mud a deep
6061-T6,[3] Lot No. 1	W	1,064	5,300	1.94	1.03	59.0	33.4	0.5	Few deep pits,
6061-T6, Lot No. 1	W	1,064	5,300	1.09	0.58	77.0	63.8	0.4	Few deep pits,
6061-T6, Lot No. 1	M	1,064	5,300	1.86	0.99	77.0	64.0	0.7	Few deep pits,

A

Table 15. Continued.

sure ys)	Depth (ft)	Corrosion Rate[2]		Pit Depth (mils)		Pitting Frequency (no. sq in.)	Remarks
		MDD	MPY	Max	Avg		
64	5,300	1.04	0.56	-	-	-	Extensive edge attack, crevice corrosion
64	5,300	2.34	1.28	43.0	36.5	0.7	Extensive edge attack, scattered pits
64	5,300	2.69	1.46	36.0	33.0	1.5	Extensive edge attack, scattered pits
23	5,640	0.09	0.05	<1	-	-	Surface etching
23	5,640	3.86	2.08	49.0	40.0	6.2	Few deep pits, exfoliation, crevice corrosion
97	2,340	4.55	2.47	17.0	8.2	0.5	Edge attack, few shallow pits
97	2,340	4.00	2.17	41.0	7.3	0.3	Edge attack, severe surface attack of portion in mud
64	5,300	0.26	0.14	<1	-	-	Some edge attack, crevice corrosion
23	5,640	1.83	0.99	25.0	15.3	-	Crevice corrosion, scattered pits
97	2,340	0.79	0.43	-	-	-	Crevice corrosion, edge attack
97	2,340	0.61	0.33	-	-	-	Crevice corrosion, edge attack
97	2,340	1.00	0.54	23.0	23.0	1 pit (total)	Edge attack
97	2,340	1.10	0.59	14.0	12.5	2 pits (total)	Edge attack
23	5,640	0.00	0.00	27.5	17.1	2 pits (total)	Few deep pits
23	5,640	1.74	0.94	65.0	53.7	5.5	Few deep pits
97	2,340	0.46	0.25	72.0	48.0	1	Few pits in plate
97	2,340	1.37	0.74	55.0	21.0	0.9	Few pits in plate, one crack in weld bead
64	5,300	1.52	0.82	<1	-	-	Severe edge attack, crevice corrosion 90 mils deep
64	5,300	1.70	0.92	67.0	54.0	0.2	Severe edge attack, crevice corrosion 100 mils deep
64	5,300	2.37	1.28	53.0	50.4	0.5	Severe edge attack, severe crevice corrosion, portions in mud large areas 4 x 1-1 2 in. x 60 mils deep
23	5,640	0.17	0.09	<1	-	-	Scattered etched areas
23	5,640	2.55	1.38	13.0	7.8	3 pits (total)	Few pits, crevice corrosion 50 mils deep
23	2,500	0.09	0.05	<1	-	-	Scattered etched areas
197	2,340	1.17	0.63	<1	-	-	Slight edge attack, slight crevice corrosion
97	2,340	2.06	1.11	29.0	15.8	-	Crevice corrosion in water 38 mils deep, severe edge attack in mud and over large surface areas to 65 mils deep
64	5,300	1.94	1.03	59.0	33.4	0.5	Few deep pits, edge attack, crevice corrosion
64	5,300	1.09	0.58	77.0	63.8	0.4	Few deep pits, crevice corrosion
64	5,300	1.86	0.99	77.0	64.0	0.7	Few deep pits, edge attack

Continued

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Table 15. Continued.

Alloy	Environment[1]	Exposure (days)	Depth (ft)	Corrosion Rate[2]		Pit Depth (mils)		Pitting Frequency (no./sq in.)	
				MDD	MPY	Max	Avg		
6061-T6, Lot No. 1	W	123	5,640	0.11	0.06	<1	-	-	Few incipient pi
6061-T6, Lot No. 1	M	123	5,640	1.06	0.57	19.5	18.2	2.8	Crevice corrosio
6061-T6, Lot No. 2	W	123	5,640	0.00	0.00	<1	-	2 pits (total)	Few incipient pi
6061-T6, Lot No. 2	M	123	5,640	2.78	1.48	26.0	23.4	3.6	Crevice corrosio
6061-T6, Lot No. 1	W	197	2,340	1.99	1.06	47.0	42.3	2.2	Large deep pits c
6061-T6, Lot No. 1	M	197	2,340	2.36	1.26	54.0	43.0	2.0	Large deep pits c
7039-T6	W	123	5,640	0.16	0.08	3.0	1.5	2 pits (total)	Exfoliation, crev
7039-T6	M	123	5,640	4.17	2.14	38.0	33.8	0.3	Exfoliation, crev
7039-T6	W	197	2,340	3.27	1.68	27.0	18.5	0.1	Severe exfoliatic
7039-T6	M	197	2,340	3.92	2.01	61.0	25.0	0.2	Severe exfoliatic
7079-T6	W	123	5,640	9.93	5.21	P	56.5	6.8	Scattered pits, c
7079-T6	M	123	5,640	5.56	2.91	P	55.0	10.7	Scattered pits, c
7079-T6	W	197	2,340	8.64	4.53	P	46.8	3.3	Random pits, edg
7079-T6	M	197	2,340	5.77	3.03	49.0	36.3	2.0	Random pits, edg
7178-T6[3]	W	1,064	5,300	2.79	1.43	45.0	25.4	0.5	Severe edge atta
7178-T6	W	123	5,640	8.03	4.11	43.0	36.1	-	Few scattered de
7178-T6	W	197	2,340	6.25	3.20	-	-	-	Crevice corrosio
7178-T6	M	197	2,340	4.74	2.43	-	-	-	Crevice corrosio

[1] W = specimens exposed on sides of STU in water; M = specimens exposed in base of STU, partially embedded in bottom sedime

[2] MDD = milligrams per square decimeter per day; MPY = mils penetration per year.

[3] Specimen size, 1 x 6 inches; all others 6 x 12 inches.

[4] P = perforated.

[5] These specimens were welded with a 5052 rod.

Table 15. Continued.

Depth (ft)	Corrosion Rate[2]		Pit Depth (mils)		Pitting Frequency (no./sq in.)	Remarks
	MDD	MPY	Max	Avg		
5,640	0.11	0.06	<1	-	-	Few incipient pits
5,640	1.06	0.57	19.5	18.2	2.8	Crevice corrosion, few pits
5,640	0.00	0.00	<1	-	2 pits (total)	Few incipient pits
5,640	2.78	1.48	26.0	23.4	3.6	Crevice corrosion, few pits
2,340	1.99	1.06	47.0	42.3	2.2	Large deep pits and numerous small pits
2,340	2.36	1.26	54.0	43.0	2.0	Large deep pits and numerous small pits
5,640	0.16	0.08	3.0	1.5	2 pits (total)	Exfoliation, crevice corrosion
5,640	4.17	2.14	38.0	33.8	0.3	Exfoliation, crevice corrosion
2,340	3.27	1.68	27.0	18.5	0.1	Severe exfoliation, few pits
2,340	3.92	2.01	61.0	25.0	0.2	Severe exfoliation, few pits, crevice corrosion
5,640	9.93	5.21	P	56.5	6.8	Scattered pits, crevice corrosion, exfoliation
5,640	5.56	2.91	P	55.0	10.7	Scattered pits, crevice corrosion, exfoliation
2,340	8.64	4.53	P	46.8	3.3	Random pits, edge attack, exfoliation
2,340	5.77	3.03	49.0	36.3	2.0	Random pits, edge attack, exfoliation
5,300	2.79	1.43	45.0	25.4	0.5	Severe edge attack, crevice corrosion
5,640	8.03	4.11	43.0	36.1	-	Few scattered deep pits, crevice corrosion
2,340	6.25	3.20	-	-	-	Crevice corrosion
2,340	4.74	2.43	-	-	-	Crevice corrosion

ter; M = specimens exposed in base of STU, partially embedded in bottom sediment.

ay; MPY = mils penetration per year.

nches.

Corrosion Rate (MPY)

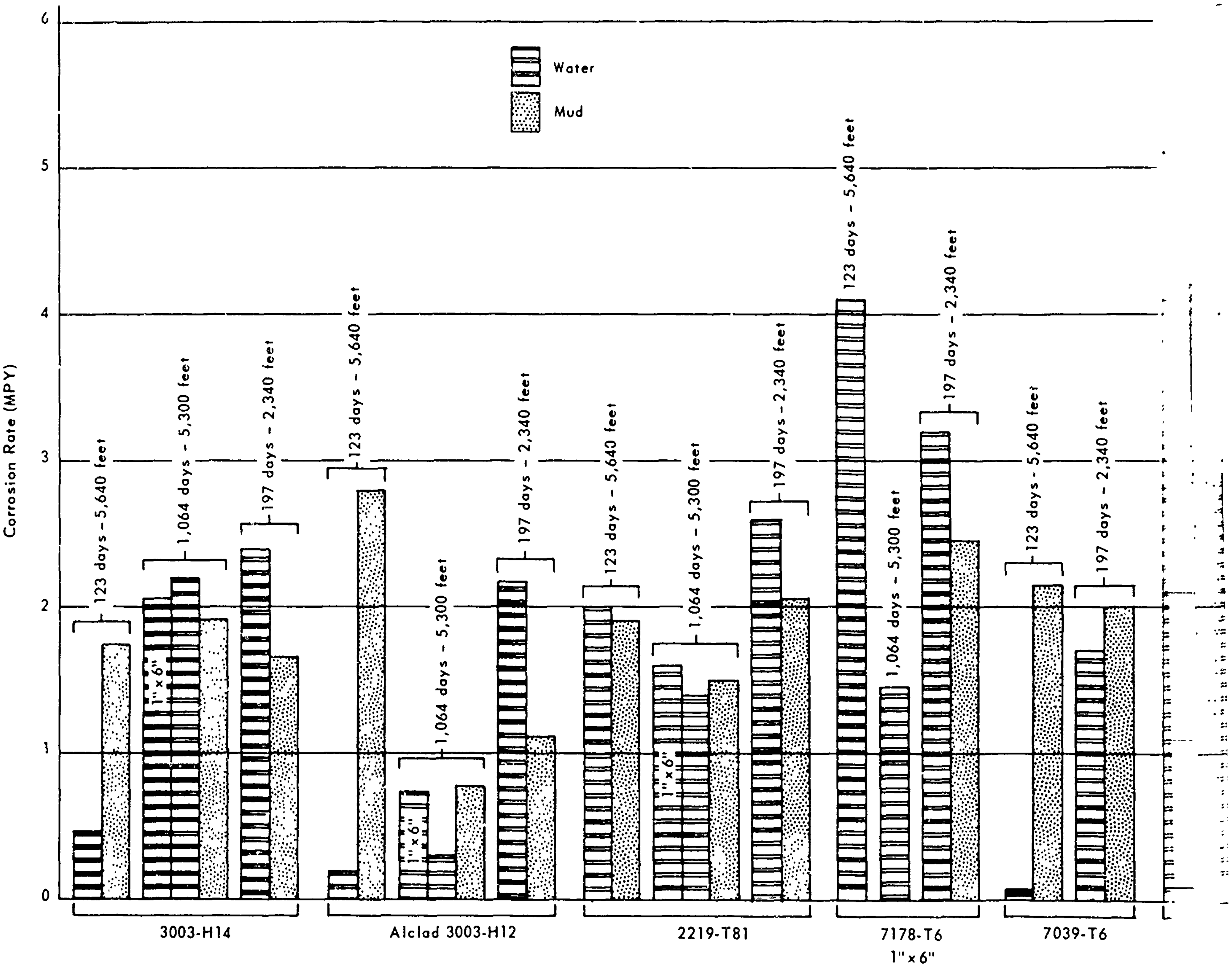

Figure 30. Corrosion rates of

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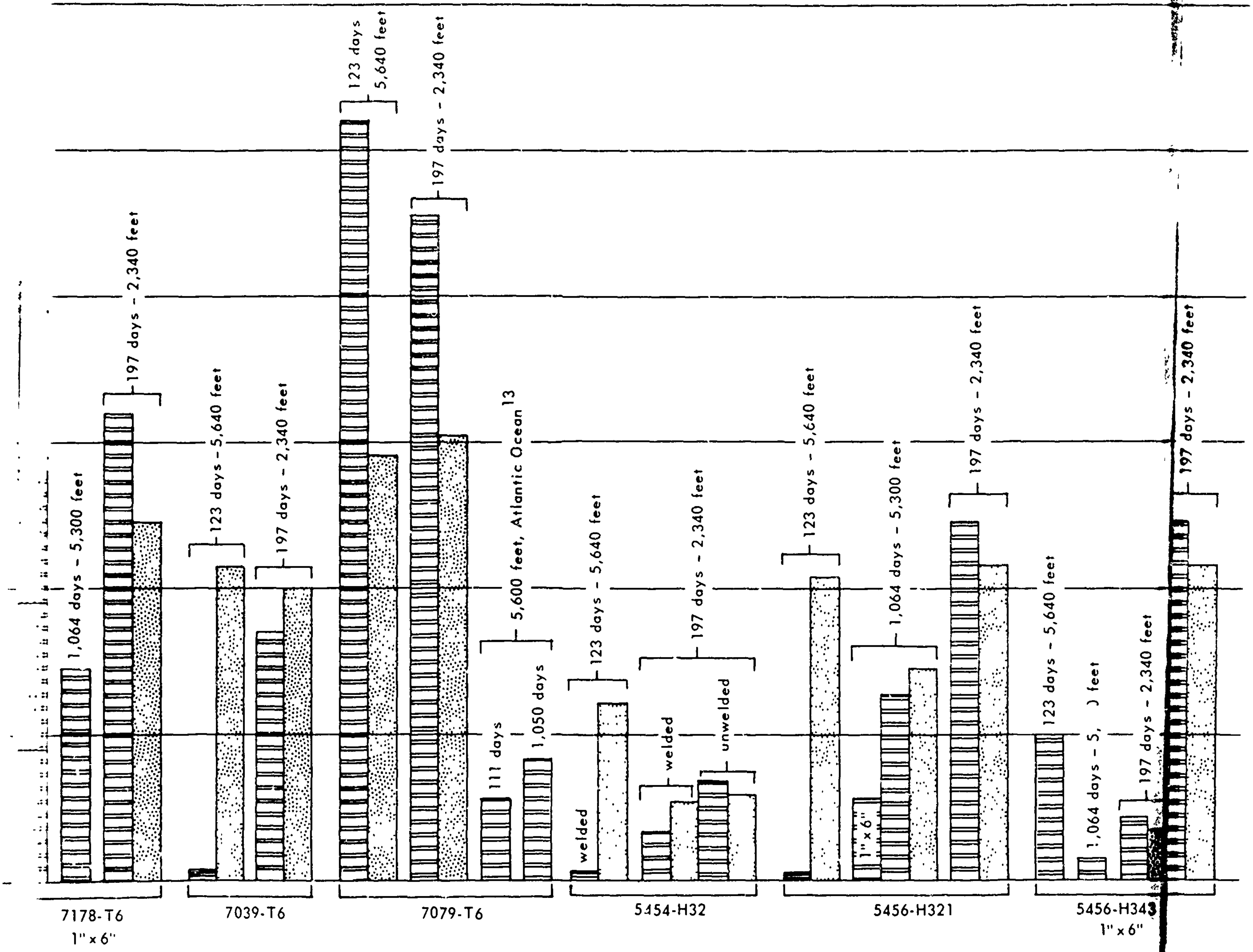
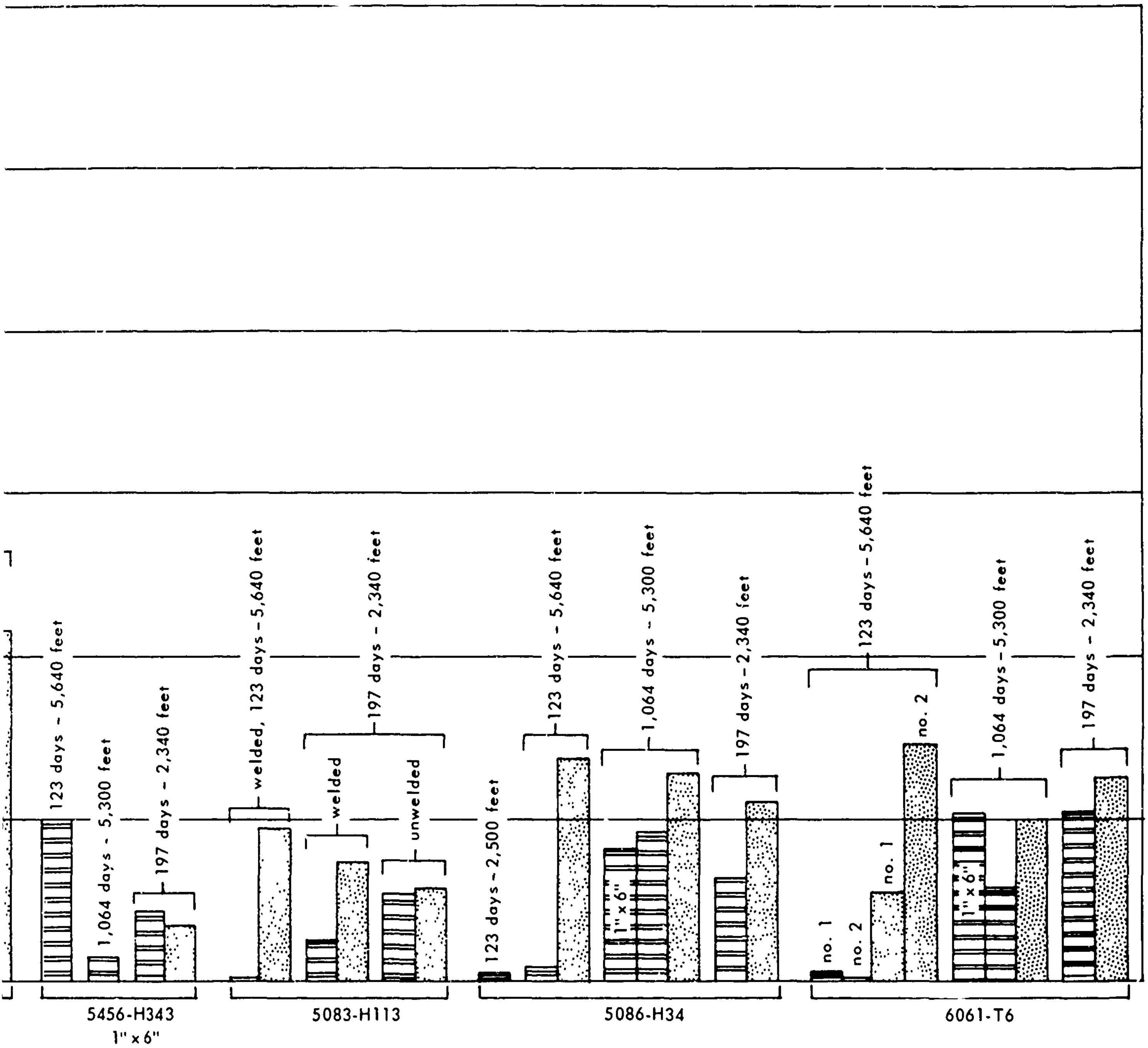


Figure 30. Corrosion rates of aluminum alloys in the deep ocean (the Pacific Ocean unless otherwise specifi otherv



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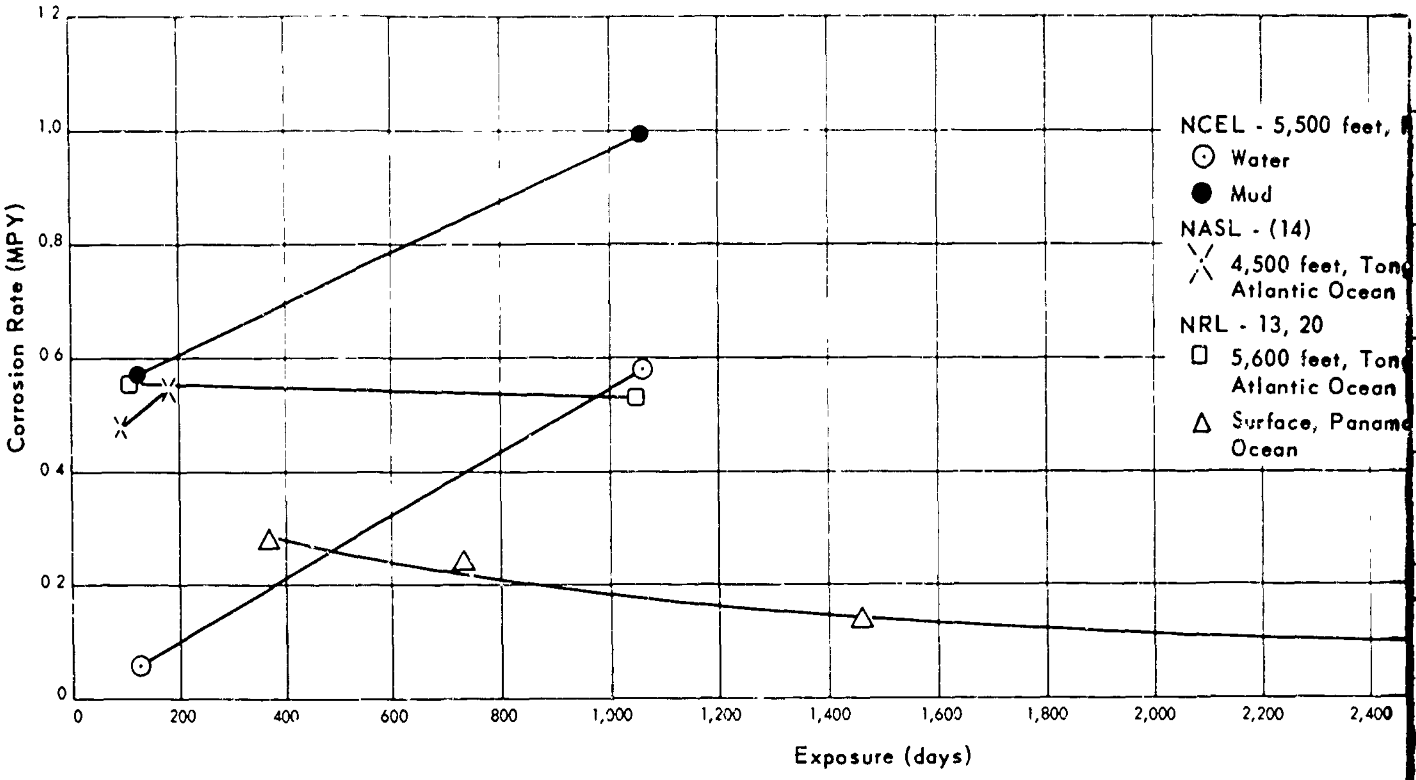
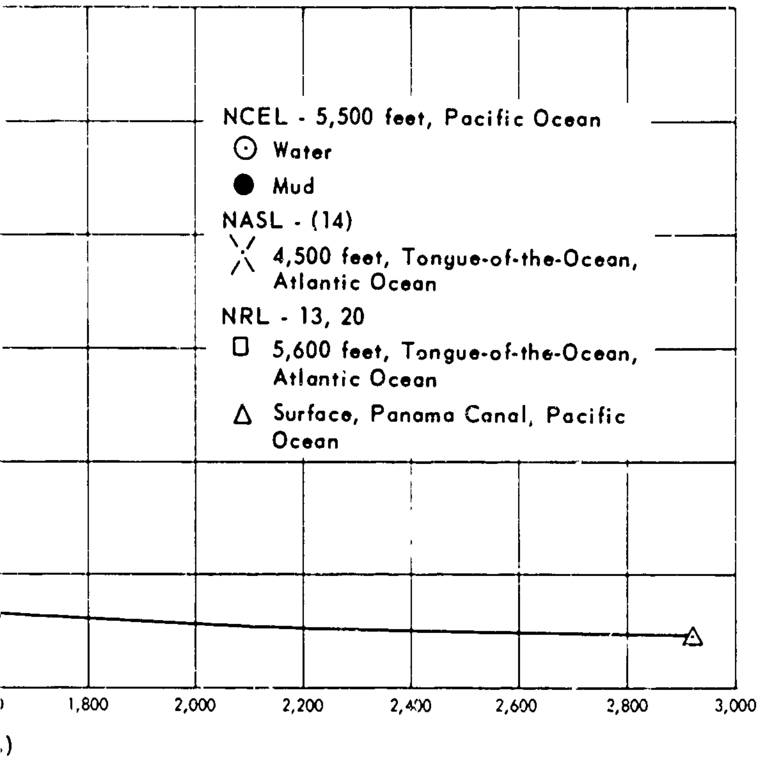


Figure 31. Corrosion of 6061-T6 in different localities.



in different localities.

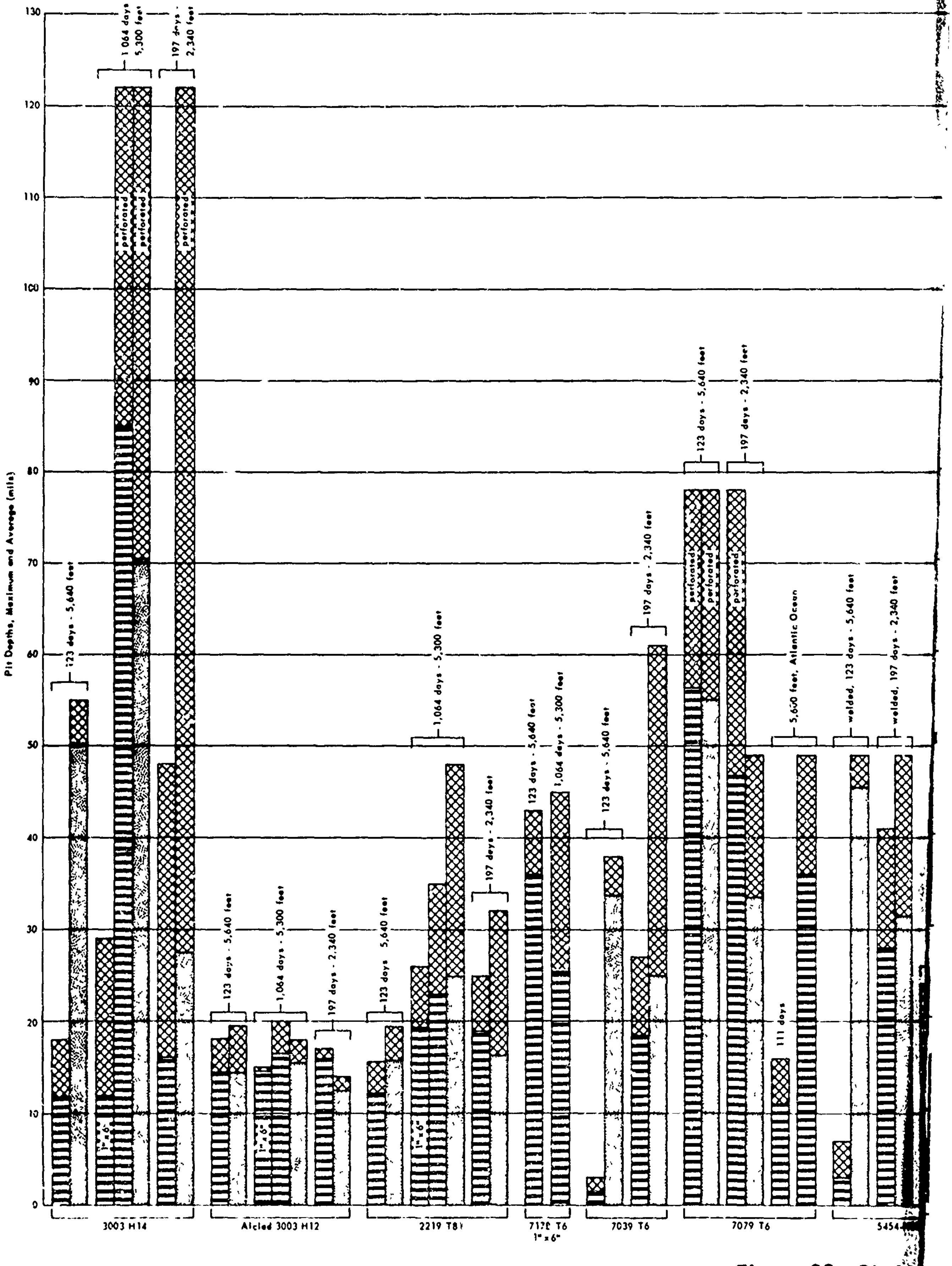


Figure 32. Pitti

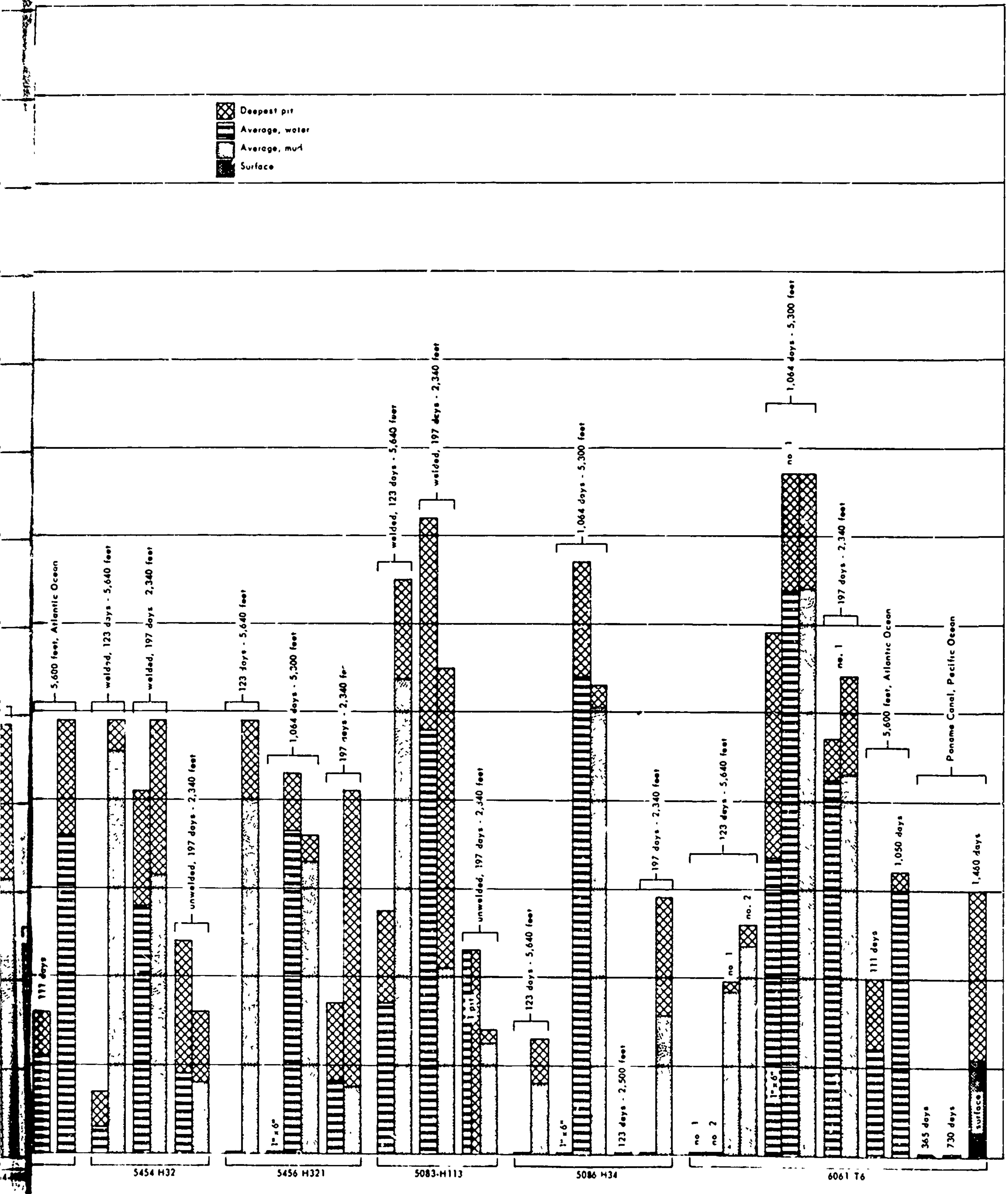


Figure 32. Pitting of aluminum alloys.

The corrosion rates of the alloys after different periods of exposure at depths of 2,340, 5,300, and 5,640 feet are shown in Figure 30. The corrosion rates of aluminum alloys 3003-H14, alclad 3003-H12, 5456-H321, 5086-H34, and 6061-T6 exposed in the water increased with time at a nominal depth of 5,500 feet, but those of alloys 2219-T81, 7178-T6, and 5456-H343 decreased with time. The corrosion rate of alloy 3003-H14 partially embedded in the bottom sediment increased with time, but the corrosion rates of 2219-T81, alclad 3003-H12, 5456-H321, 5456-H343, 5086-H34, 6061-T6, and 7178-T6 decreased with time.

Generally the corrosion rates of aluminum alloys decrease with time when exposed by surface immersion in the oceans.[19, 20] The corrosion rates for 6061-T6 aluminum alloy exposed at the surface in the Pacific Ocean at the Panama Canal Zone are plotted in Figure 31 to show this decrease with time.[20] Thus, the increase in corrosion rates with time of alloys 3003-H14, alclad 3003-H12, 5456-H321, 5086-H34, and 6061-T6 exposed in the water at a depth of 5,500 feet by NCEL, were contrary to the corrosion of aluminum alloys at the surface. In other exposures of aluminum alloys at a depth of 5,600 feet in the Atlantic Ocean by other investigators, the corrosion rates of 7079-T6 and 5086-H34 increased with time, but those of 1100 and 6061-T6 either decreased or remained constant.[13]

These increases in corrosion rates cannot be explained either on the basis of the lower temperatures at these two sites (one in the Pacific Ocean at a depth of 5,500 feet and the other in the Atlantic Ocean at a depth of 5,600 feet) or on the basis of differences in oxygen concentration between the surface and at depth. Corrosion rates decrease with a decrease in temperature. The oxygen concentration at a depth of 5,000 feet in the Atlantic Ocean was the same as at the surface,[17] but at a depth of 5,500 feet in the Pacific Ocean it was only about 0.2 of that at the surface. Two other variables, current and pressure, do not appear to be plausible explanations. Surface corrosion data for 6061-T6 aluminum alloy from the Panama Canal are included in Figure 31 to show that the corrosion rate of 6061-T6 decreases with time and that after 3 years of exposure it is considerably less than at a depth of 5,600 feet.[20]

The average depth of pitting after 3 years of continuous immersion in flowing seawater (1.25 ft/sec) at Kure Beach, N. C.,[21] was 0.5 mil, but it was 33.4 mils on 1 x 6-inch specimens and 65 mils on 6 x 12-inch specimens in the NCEL test. This increase in average pit depths by factors of 67 and 130 shows a considerably greater aggressiveness of seawater at a depth of 5,300 feet in the Pacific Ocean than that at the surface in the Atlantic Ocean.

The corrosion rates for 7079-T6 in the Pacific and Atlantic Oceans at depth are shown in Figure 30. The corrosion rates in the Pacific Ocean for 123 days and 197 days are from 9 to 10 times greater than in the Atlantic Ocean for 111 days.

The same comparison for 6061-T6 is also shown in Figure 30. In this case the corrosion rate for 123 days in the Pacific Ocean at a depth of 5,640 feet is about 1/10 of that in the Atlantic Ocean for 111 days at a depth of 5,600 feet, and the corrosion rate for 197 days of exposure at a depth of 2,340 feet in the Pacific Ocean is twice that in the Atlantic Ocean. In Figure 31 it can be seen that the corrosion rates for 6 x 12-inch specimens were the same after 3 years of exposure in both oceans at the same depth.

The corrosion rates for aluminum alloy 6061-T6 at different depths in the Atlantic Ocean and in the Pacific Ocean as well as for surface immersion are shown in Figure 31. Generally, the corrosion rates at depths in both oceans are higher than those totally immersed near the surface. The corrosion rates at the surface gradually decrease, becoming asymptotic with time. The corrosion rate at a depth of 5,600 feet in the Atlantic also decreases slightly with time, but at a depth of 4,500 feet in the Atlantic there is an increase in rate for the first 6 months of exposure. In the NCEL tests in the Pacific Ocean at a nominal depth of 5,500 feet, the corrosion rates increase with time.

The maximum and average depths of the pits in the aluminum alloys are shown in Figure 32. Except for the alclad 3003-H12, the average depths of the pits on the 6 x 12-inch specimens increased with time at a nominal depth of 5,500 feet. Where both 1 x 6-inch and 6 x 12-inch specimens were exposed at a depth of 5,300 feet for 1,064 days, the pitting on the 6 x 12-inch specimens was much more severe than that on the 1 x 6-inch specimens, except for the alclad 3003-H12 alloy. The great difference in performance between 1 x 6-inch and 6 x 12-inch specimens illustrates, very dramatically, the danger of using data obtained from small-size specimens for recommending the use of aluminum alloys for applications in seawater, especially where susceptibility to pitting is an important factor.

Only 1 x 6-inch specimens of alloys 7178-T6 and 5456-H343 were exposed at various depths, and for these two alloys the average depth of pits decreased with time.

In surface seawater exposures the depths of the pits also increase with time.[19,20]

As shown in Figure 32 the average depths of pits in 7079-T6 and 6061-T6 also increased with time when exposed at a depth of 5,600 feet in the Atlantic Ocean.[13] In this respect, the performance of these two alloys was similar in both deep ocean environments (NCEL tests in the Pacific Ocean and NRL tests in the Atlantic Ocean), except that the pits were deeper on the specimens exposed in the Pacific Ocean than in the Atlantic Ocean.

From the standpoint of depth of pitting, the bottom sediments were more aggressive than the adjacent seawater toward 3003-H14 after 123 and 197 days, 2219-T6 after 123 days, 7039-T6 after 123 days, welded 5454-H32 after 123 and 197 days, 5456-H321 after 123 days, welded 5083-H113 after 123 and 197 days, 5086-H34 after 123 and 197 days, and 6061-T6 after 123, 197, and 1,064 days of exposure. The bottom sediments were less aggressive or about the same as the adjacent seawater toward 3003-H14 after 1,064 days, 2219-T6 after 197 and 1,064 days, 7079-T6 after 123 and 197 days, unwelded 5454-H32 after 197 days, 5456-H321 after 1,064 days, 5083-H113 after 197 days, and 5086-H32 after 1,064 days of exposure.

The maximum and average depths of pits for 6061-T6 were greater after exposure for 1,064 days at a depth of 5,300 feet in the Pacific Ocean than after 1,460 days of exposure at the surface in the Pacific Ocean at the Panama Canal Zone.[20] Although the depths of pits in 6061-T6 increased with time of exposure at both locations, the rates were faster at a depth of 2,340 feet by a factor of four and at a depth of 5,300 feet by a factor of five than at the surface after 1,460 days of exposure.

Metallurgical Condition. Examinations of polished and polished-and-etched sections of the alloys on a metallurgical microscope at magnifications from 100 to 1,000 showed the presence of intergranular corrosion, as given in Table 16. The intergranular type of corrosion varied from traces in the 2219-T81 alloy to extensive areas of the exfoliation type in the 7039-T6, 7079-T6, and 7178-T6 alloys. Examples typical of the intergranular corrosion encountered are shown in Figures 33 to 36. Intergranular attack was found only in the heat-affected zones adjacent to the welds in 5454-H32 and 5083-H113. Although intergranular corrosion, or what appears to be intergranular corrosion because of the branching nature of its progress, was detected in 2219-T81 and 3003-H14, no intergranular precipitation could be detected at the grain boundaries at magnifications of 1,000. Examinations of replicas of etched surfaces with an electron microscope would be required to determine the presence or absence of intermetallic compounds at the grain boundaries.

The susceptibility of solid solution aluminum alloys to intergranular corrosion is due to the presence of narrow paths of an anodic material at the grain boundaries or along the slip planes in the alloy. The volume of this anodic material, distributed in narrow paths, is extremely small in comparison to the volume of the remaining cathodic material surrounding it. In a relationship such as this, these narrow anodic paths of material are corroded preferentially, hence the term intergranular corrosion. These narrow anodic paths are created by the selective precipitation of intermetallic constituents along grain boundaries during the solution heat treatment of the alloy. The precipitated constituents may be anodic to the surrounding solid solution, or the impoverished areas of solid solution from which the precipitated constituents are formed may be anodic to the other areas from which no precipitation has occurred. For example, in some of the 5,000-series alloys the combination of strain-hardening and a low-temperature stabilization treatment causes the intermetallic compound, beta Mg_2Al_3, to be precipitated in continuous paths along the grain boundaries of the alloy. This intermetallic compound is anodic to the solid solution alloy, hence the susceptibility to intergranular corrosion.

An illustration of the effect of strain-hardening and a low-temperature stabilization treatment on the corrosion behavior of a 5,000-series aluminum alloy (5086) is shown in Figure 37. The 1/2-inch rolled plate in the -H32 condition and the 1/8-inch rolled sheet in the -H34 condition, both of which had been strain-hardened and given a low-temperature stabilization treatment, were corroded by a combination of pitting and intergranular corrosion because of the precipitation of the beta Mg_2Al_3 constituent along the grain boundaries. The extruded angle which was in the -H112 condition had not been subjected to either a strain-hardening or a low-temperature stabilization treatment during its manufacturing process (that is, it was "as extruded") and was relatively free from corrosion except for some small incipient pits. The beta Mg_2Al_3 constituent was uniformly dispersed throughout the grains of the alloy in the extruded angle; hence, there were no anodic paths to foster intergranular attack.

Table 16. Intergranular Corrosion and Intergranular Precipitation in Aluminum Alloys

Alloy	Corrosive Environment	Intergranular Corrosion	Intergranular Precipitation
2219-T81	water	yes	no
	mud	yes	no
3003-H14	water	yes	no
	mud	yes	no
Alclad 3003-H12	water	no	no
	mud	no	no
5454-H32	water	no	no
	mud	no	no
5454-H32, welded	water	yes	no
	mud	yes	no
5456-H321	water	yes	yes
	mud	yes	yes
5456-H343	water	yes	yes
	mud	yes	yes
5083-H113	water	no	no
	mud	no	no
5083-H113, welded	water	yes	no
	mud	yes	no
5086-H34	water	yes	yes
	mud	yes	yes
6061-T6	water	yes	yes
	mud	yes	yes
7039-T6	water	yes	yes
	mud	yes	yes
7079-T6	water	yes	yes
	mud	yes	yes
7178-T6	water	yes	yes
	mud	yes	yes

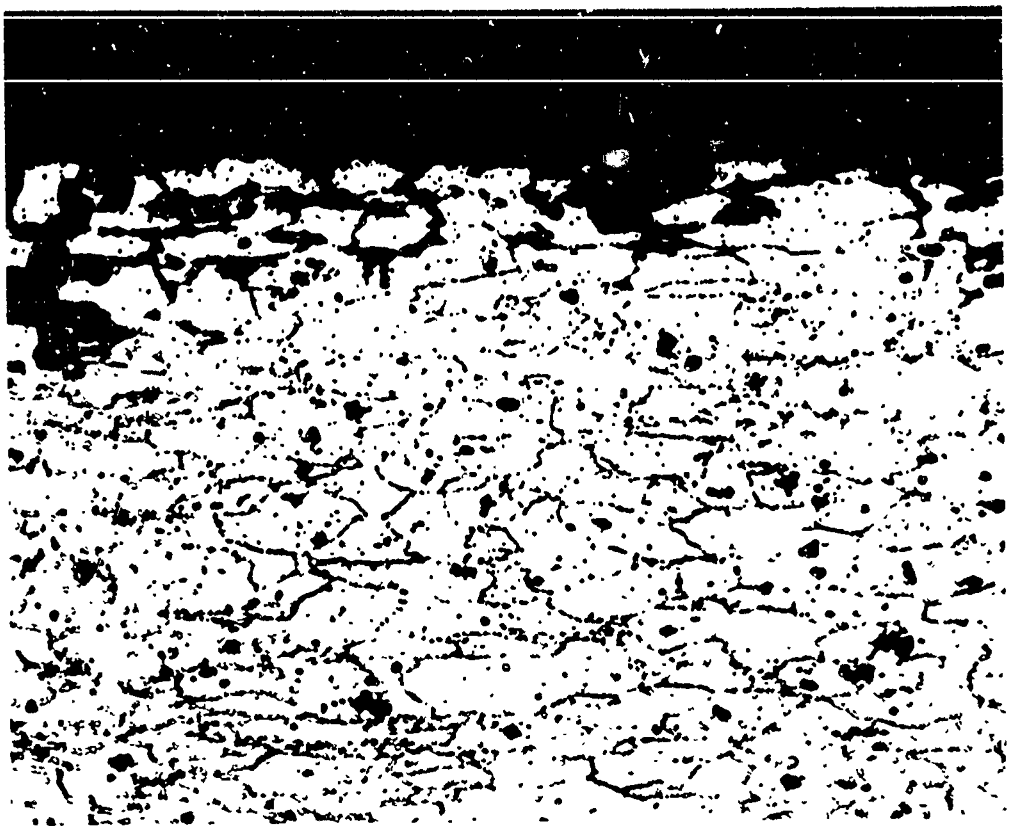


Figure 33. Intergranular corrosion in 5086-H34 alloy. Keller's etch; X500.

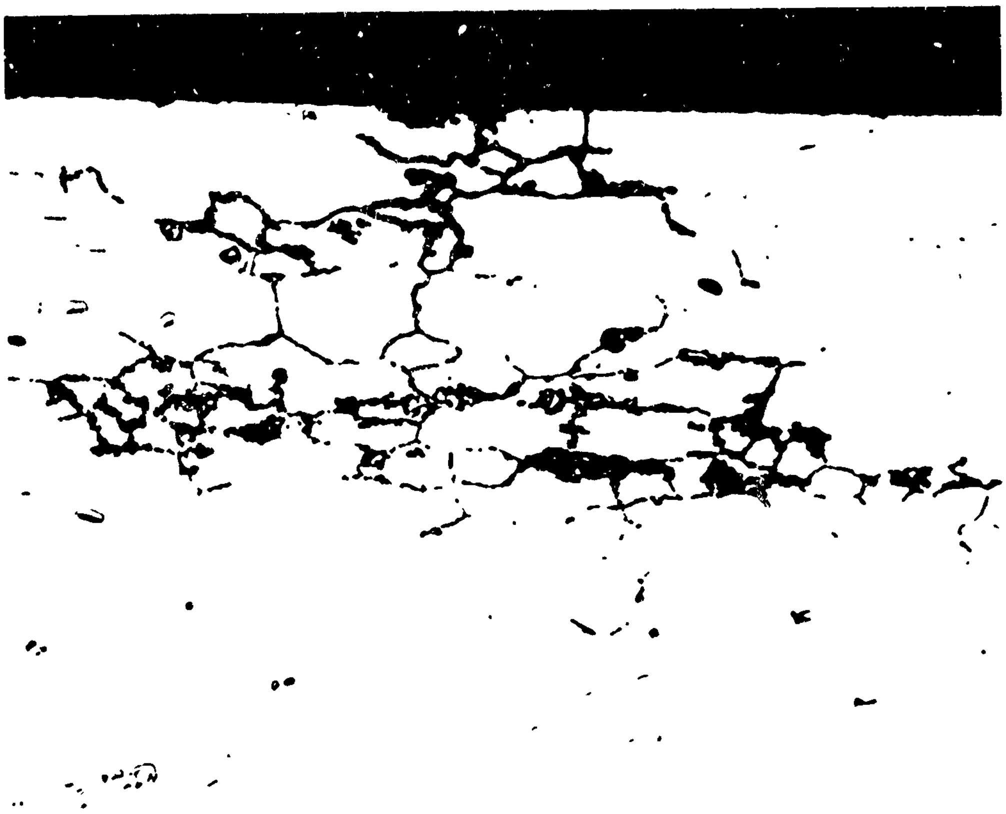


Figure 34. Intergranular corrosion in 6061-T6 alloy. Unetched; X500.

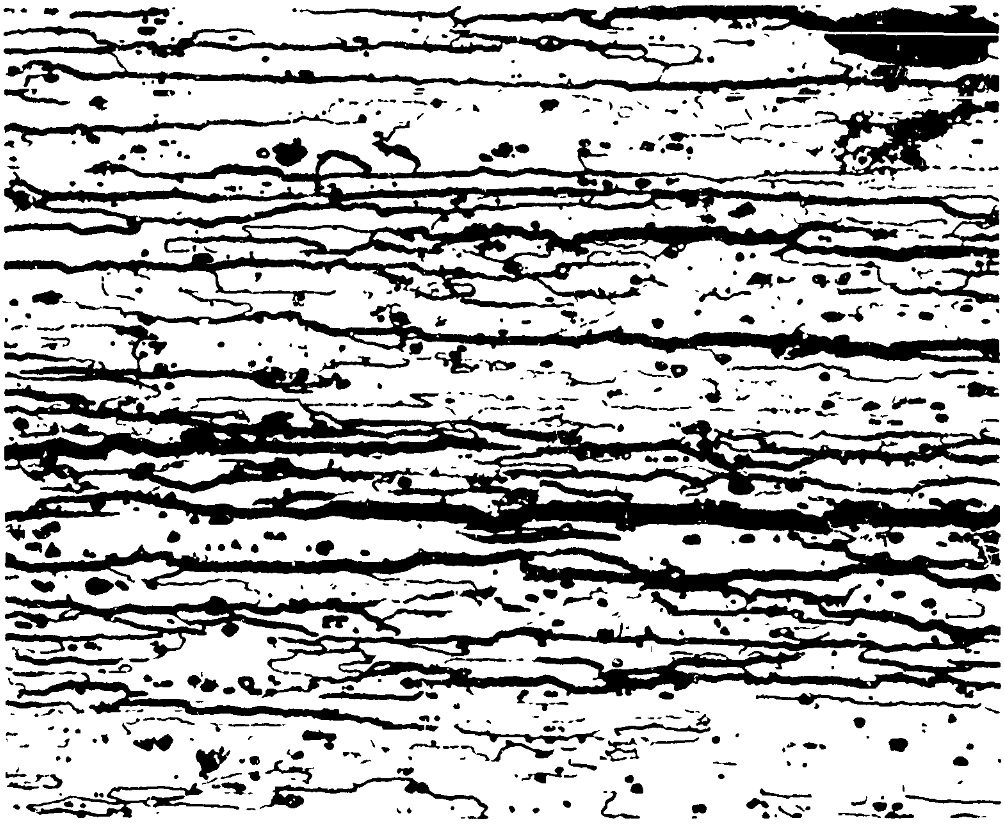


Figure 35. Exfoliation type of intergranular corrosion in 7178-T6 aluminum alloy. Keller's etch; X200.

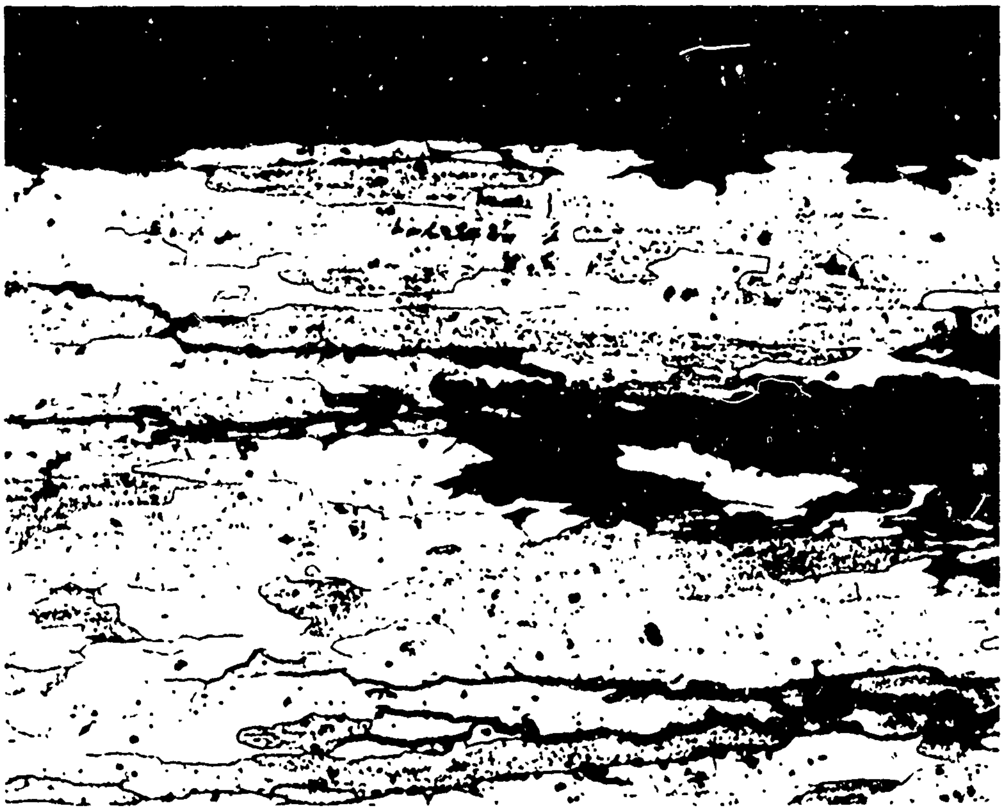
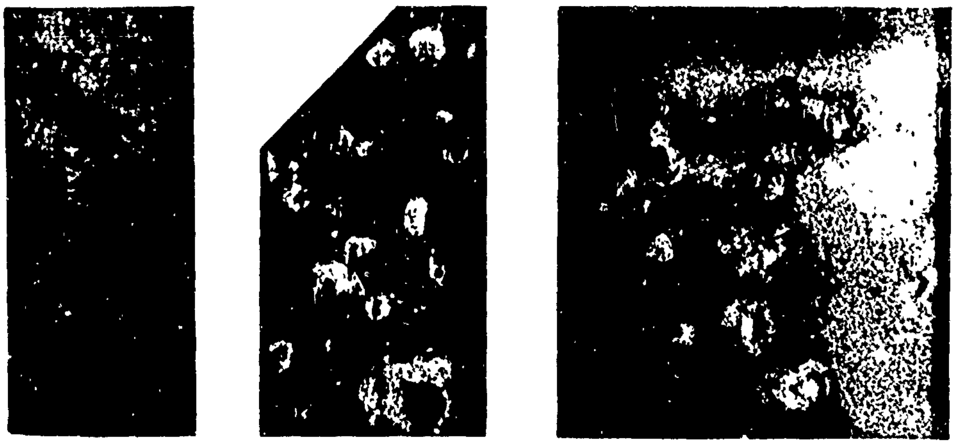


Figure 36. Exfoliation type of intergranular corrosion in 7039-T6. Keller's etch; X200.



-H112
3 x 3 x 1/2-in.
extruded L

-H32
1/2-in. rolled plate

-H34
1/8-in rolled sheet

Figure 37. Effect of strain-hardening on the corrosion of 5086 aluminum alloy after 751 days of exposure at a depth of 5,640 feet in the Pacific Ocean.

A practical case of line corrosion on an aluminum alloy was encountered with the alclad 7178-T6 aluminum alloy buoys used in the installation of the STU structures. During the retrieval of STU I-3 after 123 days of exposure, the buoy, which was 500 feet below the surface, was found to be corroded (Figure 38). The white corrosion products on the bottom hemisphere cover areas where the alclad layer had corroded through to the core material. The top hemisphere was blistered, the blisters being as large as 2 inches in diameter and 0.75 inch high. One of these blisters is shown in Figure 39. The hole in the top of the blister indicates the origin of the failure: originally a pinhole in the cladding where seawater gained access to the interface between the cladding alloy and the core alloy. When this blister was sectioned to inspect the corrosion underneath, it was found to be filled with white crystalline aluminum oxide corrosion products (Figure 40). It appeared that seawater penetrated the alclad layer at a defect or at a particle of a cathodic metal (iron), and the corrosion was then concentrated at the interface between the two alloys. The thickness of the remaining alclad layer indicated that it had not been sacrificed to protect the core alloy as was its intended function. On the other hand, the selective corrosion of the alclad layer on the bottom hemisphere and the uncorroded core material showed that, in this case, the cladding alloy was being sacrificed to protect the core material as intended.

Figure 38. Alclad 7178-T6 buoy after recovery on board ship.

Figure 39. A blister from the top hemisphere of the buoy shown in Figure 38.

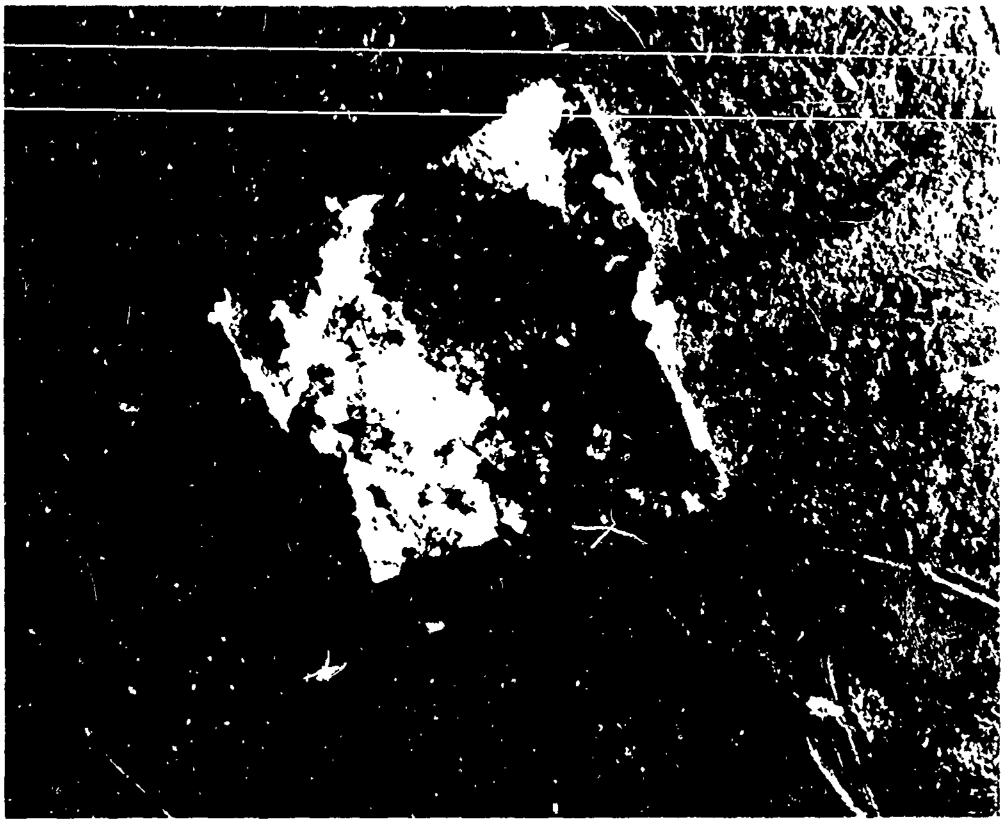


Figure 40. The crystalline aluminum oxide corrosion products, in situ, which filled the blister shown in Figure 39.

An attempt was made to repair these buoys for reuse by grinding off all traces of corrosion before painting. It was found that the corrosion had penetrated along the interface between the cladding alloy and the core alloy for considerable distances from the edges of the blisters and the edges of the holes where the alclad layer had been sacrificed. Polished transverse sections taken from the buoy through these corroded areas corroborated the indications found from the grinding operations. An illustration of this interfacial penetration is shown in Figure 41. Metallurgical examination of these polished and etched sections showed that the corroded paths were, in fact, entirely in the alclad material, with a thin diffusion layer of material between the corrosion path and the core material, as shown in Figure 42. The white layer of material above the corroded path is cladding alloy and the thin gray line between it and the core alloy (bottom) is the zone of diffusion alloy.

Blistering of alclad aluminum alloys such as encountered with these alclad 7178-T6 spheres was very unusual — in fact, unique. Blistering due to corrosion and the rapid rate of sacrifice of alclad layers had not been encountered by the author and other investigators in surface seawater applications. Because of this unique blistering the Research Laboratories of the Aluminum Company of America undertook an exhaustive investigation to determine the mechanism of this behavior.

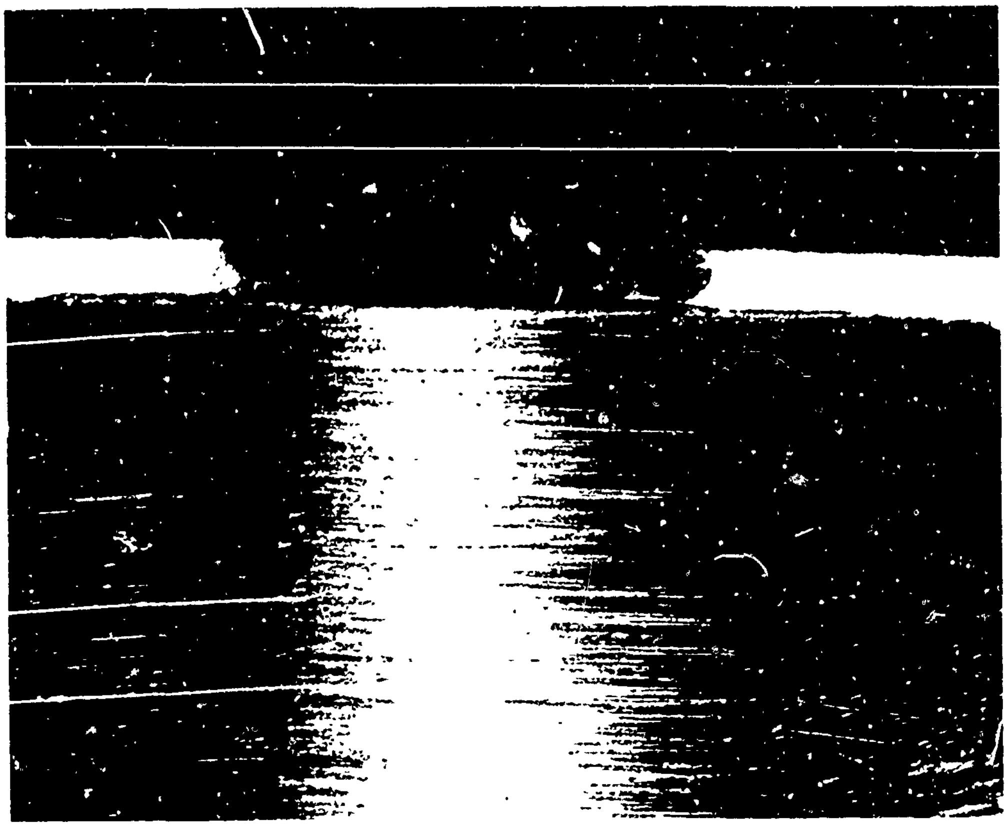


Figure 41. Corrosion at interface between the alclad layer and the core alloy of an alclad 7178-T6 buoy; X4.

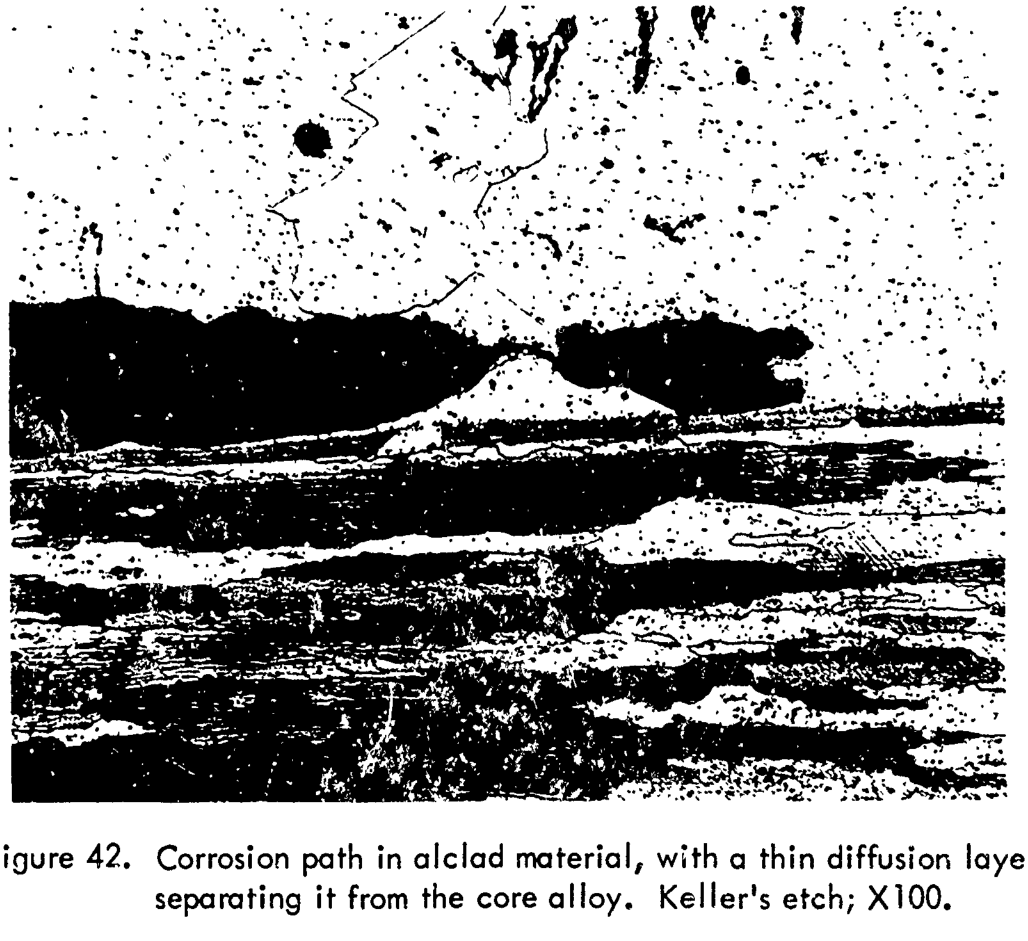


Figure 42. Corrosion path in alclad material, with a thin diffusion layer separating it from the core alloy. Keller's etch; X100.

The results of this investigation were as follows: "It has been shown that blistering of a deep-sea sphere constructed of 3/4" thick Alclad (7072)7178-T6 plate was caused by preferential corrosion of a highly anodic layer in the cladding near the core-cladding interface. Metallographic examination showed that, after pitting penetrated the cladding, corrosion progressed laterally and the corrosion products caused blistering. Microprobe analysis showed that this zone developed because of the higher rate of diffusion of zinc over copper from the core to the cladding. This zone is characterized by a high zinc (1.5-2.5%) and a low copper (0.5-0.15%) content. The theoretical solution potential of this anodic region should range from 1010 mv to 1030 mv."[22]

That this type of blistering has been encountered on buoys at depths from 300 to 6,800 feet emphasizes the fact that there is some factor present which either is more influential at depth or is not present at the surface. The fact that this thin anodic zone is probably present in all alclad 7178-T6 products and, as such, is not blistered during surface seawater exposures indicates that the seawater environments at depths of 300 feet and greater differ from the seawater environments at the surface, at least with respect to the corrosion behavior of this alloy.

No explanation of the "why" of this blistering is proposed at this time. Work on the effect of all the possible variables will have to be conducted to obtain an answer to "why?" The "how" has been determined.[22]

Mechanical Properties. The percent change in the mechanical properties of the exposed aluminum alloys is given in Table 17.

The data in Table 17 show that the mechanical properties of the following alloys were adversely affected by corrosion when exposed for different periods of time at different depths in the Pacific Ocean: 2219-T81, 3003-H14, alclad 3003-H12, 6061-T6, 039-T6, 7079-T6, and 7178-T6.

A decrease in all three mechanical properties (tensile strength, yield strength, and elongation) signifies an adverse effect caused by corrosion. Usually, the effect of corrosion is first reflected by a decrease in the elongation because of the susceptibility of aluminum alloys to pitting in seawater. This is illustrated by the large decreases in the elongation of the alclad 3003-H12 alloy after 123 and 1,064 days of exposure.

The mechanical properties of the 5,000-series alloys (5454-H32, 5456-H321, 5456-H343, 5083-H113, and 5086-H34) were not affected by exposures for periods of time for as long as 1,064 days at a depth of 5,300 feet. Although there were decreases of 24 and 28% in the elongation of 5456-H321, there was also an increase of 28% in another test; hence, no significant change from a practical standpoint. This same reasoning applies to the decrease of 47% and the increase of 44% in the elongation for 5086-H34.

However, there were a few deep pits in these alloys and at these pits the bursting strength of a pressurized container or the imploding resistance of a nonpressurized structure could be lowered.

Table 17. Percent Changes in Mechanical Properties of Aluminum Alloys

Alloy	Environment[1]	Original Properties			Percent Ch					
					123 Days at 5,640 Feet			197 Days at 2,340 Feet		
		Tensile Strength (ksi)	Yield Strength (ksi)	Elongation (%)	Tensile Strength	Yield Strength	Elongation	Tensile Strength	Yield Strength	Elongation
2219-T81	W	67.3	50.7	9.8	-	-	-	-	-	-
	M	-	-	-	-	-	-	-	-	-
2219-T81	W	64.7	50.0	11.8	-	-	-	-8.0	-8.0	-45.0
	M	-	-	-	-2.9	-1.2	-42.4	-1.9	-4.0	-15.3
3003-H14	W	22.5	21.4	17.5	-	-	-	-5.3	-8.9	+10.3
	M	-	-	-	-4.4	-7.5	-42.9	-7.1	-11.7	+20.0
Alclad 3003-H12	W	18.7	17.5	13.7	-	-	-	+1.0	+2.3	+7.3
	M	-	-	-	-2.1	-0.6	-41.6	+0.5	+0.6	+10.9
5454-H32	W	40.5	30.6	13.0	-	-	-	-0.7	-1.6	-3.9
	M	-	-	-	-	-	-	+0.7	0.0	-2.3
5454-H32W [2]	W	35.3	15.7	13.5	-	-	-	-3.1	-8.9	-3.7
	M	-	-	-	-1.1	+9.6	-11.1	-2.0	-4.5	-1.5
5456-H321	W	55.5	38.8	13.5	-	-	-	-4.1	-9.8	-5.9
	M	-	-	-	-10.0	-5.4	-24.4	-3.2	-10.6	+5.9
5456-H343	W	57.8	45.6	9.2	0.0	+1.5	+27.2	-5.2	-1.1	+8.7
(1 x 6 in.)	M	-	-	-	-	-	-	-1.0	-1.5	+35.9
5083-H113	W	50.1	37.8	14.0	-	-	-	-0.6	-0.8	+5.7
	M	-	-	-	-	-	-	-2.0	-0.3	0.0
5083-H113W[2]	W	42.1	19.6	13.3	-	-	-	+6.0	+1.0	+20.3
	M	-	-	-	-3.8	-0.5	+25.6	+5.0	-1.5	+21.8
5086-H34	W	48.3	37.2	11.8	-	-	-	-4.6	-6.0	+4.2
	M	-	-	-	-0.8	+1.6	-0.8	-4.6	-5.4	+4.2
6061-T6	W	47.4	41.3	16.2	-	-	-	-5.5	-1.0	-40.0
	M	-	-	-	-7.0	-1.2	-52.5	-4.9	+1.2	-43.2
6061-T6	W	47.5	41.1	17.7	-	-	-	-	-	-
	M	-	-	-	-7.6	-2.4	-63.3	-	-	-
7039-T6	W	69.0	60.1	14.0	-	-	-	-2.0	-1.8	-3.9
	M	-	-	-	-3.5	-2.5	-15.7	-1.9	-1.5	0.0
7079-T6	W	76.5	67.0	10.6	-66.3	-62.7	-73.6	-30.5	-4.5	-24.5
	M	-	-	-	-	-	-	-3.5	-3.3	-21.7
7178-T6	W	85.2	79.4	8.3	-19.0	-16.0	-15.7	-22.3	-	-75.9
(1 x 6 in.)	M	-	-	-	-	-	-	-15.7	-51.6	-27.7

[1] W = specimens exposed on sides of STU in water, M = specimens exposed in base of structure, partially embedded in bottom sedim

[2] Welded.

loys

n Mechanical Properties of Aluminum Alloys Due to Corrosion

t Ch	Percent Change After —										
	ys at 5,640 Feet		197 Days at 2,340 Feet			1,064 Days at 5,300 Feet (1 x 6-in. specimens)			1,064 Days at 5,300 Feet (6 x 12-in. specimens)		
ition	Yield trength	Elongation	Tensile Strength	Yield Strength	Elongation	Tensile Strength	Yield Strength	Elongation	Tensile Strength	Yield Strength	Elongation
	-	-	-	-	-	-25.3	-17.4	-56.1	-	-	-
	-	-	-	-	-	-	-	-	-	-	-
.0	-	-	-8.0	-8.0	-45.0	-	-	-	-	-	-
.3	-1.2	-42.4	-1.9	-4.0	-15.3	-	-	-	-18.1	-13.6	-57.6
.3	-	-	-5.3	-8.9	+10.3	+0.9	-10.3	+20.0	-6.2	-36.0	-41.1
.0	-7.5	-42.9	-7.1	-11.7	+20.0	-	-	-	-4.0	-8.4	-38.9
.3	-	-	+1.0	+2.3	+7.3	+2.7	+1.1	+36.5	+3.7	+1.7	-13.9
.9	-0.6	-41.6	+0.5	+0.6	+10.9	-	-	-	+1.1	+1.1	-59.9
.9	-	-	-0.7	-1.6	-3.9	-	-	-	-	-	-
.3	-	-	+0.7	0.0	-2.3	-	-	-	-	-	-
.7	-	-	-3.1	-8.9	-3.7	-	-	-	-	-	-
.5	+9.6	-11.1	-2.0	-4.5	-1.5	-	-	-	-	-	-
.9	-	-	-4.1	-9.8	-5.9	+0.7	-3.6	+28.2	-4.0	-10.1	-28.1
.9	-5.4	-24.4	-3.2	-10.6	+5.9	-	-	-	-7.7	-9.5	-17.0
.7	+1.5	+27.2	-5.2	-1.1	+8.7	-1.2	-3.3	+30.4	-	-	-
.9	-	-	-1.0	-1.5	+35.9	-	-	-	-	-	-
.7	-	-	-0.6	-0.8	+5.7	-	-	-	-	-	-
.0	-	-	-2.0	-0.3	0.0	-	-	-	-	-	-
.3	-	-	+6.0	+1.0	+20.3	-	-	-	-	-	-
.8	-0.5	+25.6	+5.0	-1.5	+21.8	-	-	-	-	-	-
.2	-	-	-4.6	-6.0	+4.2	+1.7	-11.6	+44.1	-1.7	+0.3	-6.8
.2	+1.6	-0.8	-4.6	-5.4	+4.2	-	-	-	-2.9	-0.8	-46.6
.0	-	-	-5.5	-1.0	-40.0	-11.6	-9.4	-79.6	-	-	-
3.2	-1.2	-52.5	-4.9	+1.2	-43.2	-	-	-	-10.5	-8.0	-42.6
-	-	-	-	-	-	-	-	-	-	-	-
-	-2.4	-63.3	-	-	-	-	-	-	-	-	-
3.9	-	-	-2.0	-1.8	-3.9	-	-	-	-	-	-
.0	-2.5	-15.7	-1.9	-1.5	0.0	-	-	-	-	-	-
4.5	-62.7	-73.6	-30.5	-4.5	-24.5	-	-	-	-	-	-
1.7	-	-	-3.5	-3.3	-21.7	-	-	-	-	-	-
5.9	-16.0	-15.7	-22.3	-	-75.9	-4.2	-32.9	+12.0	-	-	-
7.7	-	-	-15.7	-51.6	-27.7	-	-	-	-	-	-

sedim base of structure, partially embedded in bottom sediment.

The tensile strength of 6061-T6 aluminum alloy continuously immersed in flowing sea (1.25 ft/sec) at Kure Beach, N. C., was increased by 1% after 3 years of exposure[21] as contrasted to a decrease of 10% after 35 months of exposure at a depth of 5,300 feet in the Pacific Ocean. Also, there was no loss in the tensile strength of a British alloy (H10), whose chemical composition is similar to 6061, after 2 years of continuous immersion in seawater at Hayling Island off the coast of England.[23] This would indicate that seawater at a depth of 5,300 feet in the Pacific Ocean is more corrosive than at the surface in the Atlantic Ocean at Kure Beach, N. C., and at Hayling Island, England.

Stress Corrosion. Aluminum alloys 5454-H32 and 5083-H113, butt welded with a 5052 filler rod, were exposed after stressing them at stresses equivalent to 75% of their respective yield strengths (see Table 17 for the original yield strengths) at a depth of 2,340 feet for 197 days. There were no stress corrosion failures in either of these welded alloys while exposed in this environment.

Corrosion Products. The corrosion products from some of the aluminum alloys were analyzed by X-ray diffraction, spectrographic analysis, quantitative chemical analysis, and infrared spectrophotometry. The results of these analyses were as follows:

Source of Products	Findings
5086	Amorphous $Al_2O_3 \cdot XH_2O$, NaCl, SiO_2, Al, Na, Mg, Cu, Fe, Si, Ti, 5.8% chloride ion, 26.2% sulfate ion, considerable phosphate ion present
3003-H14	Amorphous $Al_2O_3 \cdot XH_2O$, NaCl, SiO_2, Al, Na, Si, Mg, Fe, Cu, Ca, Mn, 3.58% chloride ion, 18.77% sulfate ion, considerable phosphate ion present
7079-T6	Amorphous $Al_2O_3 \cdot XH_2O$, NaCl, Al metal, Al, Cu, Mg, Mn, Zn, Na, Ca, traces of Ti and Ni, 2.82% chloride ion, 16.74% sulfate ion, considerable phosphate ion present

Copper Alloys

The chemical compositions of the copper alloys are given in Table 18 and the metallurgical and surface conditions in Table 19. The corrosion rates and types of corrosion are given in Table 20, and the corrosion rates are shown graphically in Figures 43 and 44.

The copper alloys were all corroded uniformly over their surfaces, as shown in Table 20, except for Muntz metal after 197 days of exposure at a depth of 2,340 feet. In this case there was irregular surface corrosion with a few pits, the maximum depth of which was 10 mils, the average depth 2.3 to 3.0 mils, and the pitting frequency 1 pit in every 10 to 24 sq in. These low pitting frequencies indicate a few pits randomly oriented over the surfaces of the specimens. There was slight crevice corrosion on a few alloys: Muntz metal, arsenical admiralty, phosphor bronze D, and aluminum bronze.

All these copper alloys consistently corroded at slower rates at a depth of 2,340 feet than at a depth of 5,640 feet, as shown in Figure 43. Also, the specimens partially embedded in the bottom sediments generally corroded at slower rates than those totally exposed in the seawater above the sediments.

This decrease in corrosion at 2,340 feet can only be attributed to the lower oxygen concentration at this depth. The corrosion rate of a copper-nickel alloy (70-30, low Fe) suspended at a depth of 2,500 feet was the same as when exposed in the water when the bottom was at a depth of 2,340 feet (Figure 43).

It is also interesting that the corrosion rates of the copper-nickel alloys gradually decreased as the nickel concentration increased.

An increase in the iron content of the copper-nickel alloy (70-30) from 0.5 to 5.3 decreased the corrosion rate of this alloy markedly.

Corrosion rates in quiet seawater for some of the alloys completely immersed at the surface at Kure Beach, N. C., by other investigators are also shown for comparison purposes in Figure 43. The corrosion rates for arsenical admiralty and copper-nickel (70-30) low iron alloy at the surface were lower than those at depths of 2,340 feet and 5,640 feet in the Pacific Ocean, and the corrosion rates for copper, Muntz metal, phosphor bronze A, and silicon bronze at the surface were either the same as or higher than those at 2,340 feet and 5,640 feet in the Pacific Ocean.

Data of other investigators from a depth of 5,600 feet in the Atlantic Ocean and surface data from Kure Beach, N. C.; Port Hueneme, California; and the Pacific Ocean, Panama Canal Zone, for copper and phosphor bronze A are shown for comparison purposes with NCEL data at depth in the Pacific Ocean (Figure 44). The corrosion rate for copper decreases with time at a depth of 5,600 feet in the Atlantic Ocean and initially is higher than that for copper at a depth of 5,640 feet in the Pacific Ocean.

Table 18. Chemical Composition of Copper Alloys, Percent by Weight

Alloy	Cu	Pb	Fe	Sn	Zn	Ni	Al	P	As	Mn	Si
Copper ETP[1]	99.958	-	-	-	-	-	-	-	-	-	-
Muntz metal	60.69	0.02	<0.02	-	39.29	-	-	-	-	-	-
As admiralty	71.19	-	0.01	1.00	27.77	-	-	-	0.027	-	-
Phosphor bronze A	94.64	<0.05	<0.05	4.94	<0.10	-	-	0.26	-	-	-
Phosphor bronze D	90.00	<0.05	<0.05	9.23	<0.10	-	-	0.17	-	-	-
Al bronze	90.11	<0.02	3.15	-	0.15	-	6.59	-	-	-	-
Si bronze	95.49	-	<0.02	-	-	-	-	-	-	1.18	3.28
Cu -Ni, 95-5	91.98	-	1.24	-	-	6.25	-	-	-	0.53	-
Cu -Ni, 90-10	89.04	-	1.16	-	-	9.42	-	-	-	0.38	-
Cu -Ni, 80-20	78.62	-	0.62	-	-	20.41	-	-	-	0.35	-
Cu -Ni, 70-30, 0.5 Fe	68.61	-	0.53	-	-	30.53	-	-	-	0.33	-
Cu -Ni, 70-30, 5.3 Fe	64.02	-	5.27	<0.05	<0.05	29.95	-	-	-	0.75	-
Ni -Mn bronze	54.58	0.02	1.66	0.70	remainder	3.77	1.73	-	-	3.06	-

[1] Electrolytic tough pitch.

Table 19. Condition of Copper Alloys

Alloy	Surface and Metallurgical Conditions
Copper ETP[1/]	Annealed
Muntz metal	Annealed
As admiralty	Annealed
Phosphor bronze A	Annealed
Phosphor bronze D	Annealed, soft
Al bronze	Annealed
Si bronze	Annealed
Cu - Ni, 95-5	Annealed
Cu - Ni, 90-10	Annealed
Cu - Ni, 80-20	Annealed
Cu - Ni, 70-30, 0.5 Fe	Annealed
Cu - Ni, 70-30, [illegible] Fe	Annealed
Ni - Mn bronze	Cast

[1/] Electrolytic tough pitch.

Table 20. Corrosion Rates of Copper Alloys

Alloys	Environment[1]	Exposure (days)	Depth (feet)	Corrosion Rate[2]		Remarks
				MDD	MPY	
Copper, ETP[3]	W	123	5,640	9.71	1.56	Uniform corrosion
Copper, ETP	M	123	5,640	8.10	1.30	Uniform corrosion
Copper, ETP	W	197	2,340	5.11	0.82	Uniform corrosion
Copper, ETP	M	197	2,340	1.51	0.24	Uniform corrosion
Muntz metal[4]	W	123	5,640	9.23	1.58	Uniform corrosion, crevice corrosion
Muntz metal	M	123	5,640	7.64	1.31	Uniform corrosion, crevice corrosion
Muntz metal	W	197	2,340	4.28	0.73	Irregular surface corrosion, pits, 10 mils maximum, 2.3 mils average, 1 pit/10 sq in.
Muntz metal	M	197	2,340	3.15	0.54	Irregular surface corrosion, pits, 5 mils maximum, 3.0 mils average, 1 pit/24 sq in.
As admiralty	W	123	5,640	5.65	0.95	Uniform corrosion, crevice corrosion
As admiralty	M	123	5,640	6.13	1.03	Uniform corrosion, crevice corrosion
As admiralty	W	197	2,340	3.88	0.65	Uniform corrosion
As admiralty	M	197	2,340	1.32	0.22	Uniform corrosion, crevice corrosion to 3 mils
Phosphor bronze A	W	123	5,640	3.63	0.59	Uniform corrosion
Phosphor bronze A	M	123	5,640	2.73	0.44	Uniform corrosion
Phosphor bronze A	W	197	2,340	1.80	0.29	Uniform corrosion
Phosphor bronze A	M	197	2,340	2.05	0.33	Uniform corrosion, 3 pits in portion in mud, maximum 12 mils
Phosphor bronze D	W	123	5,640	2.96	0.48	Uniform corrosion, crevice corrosion

Continued

Phosphor bronze D	M	123	5,640	2.15	0.35	Uniform corrosion, crevice corrosion
Phosphor bronze D	W	197	2,340	2.50	0.41	Uniform corrosion
Phosphor bronze D	M	197	2,340	1.06	0.17	Uniform corrosion
Al bronze[4]	W	123	5,640	2.96	0.54	Uniform corrosion, crevice corrosion
Al bronze	M	123	5,640	1.43	0.26	Uniform corrosion, crevice corrosion
Al bronze	W	197	2,340	1.66	0.2[illegible]	Uniform corrosion
Al bronze	M	197	2,340	0.74	0.13	Uniform corrosion
Si bronze	W	123	5,640	9.75	1.64	Uniform corrosion
Si bronze	M	123	5,640	10.41	1.75	Uniform corrosion
Si bronze	W	197	2,340	5.10	0.86	Uniform corrosion
Si bronze	M	197	2,340	3.69	0.62	Uniform corrosion
Ni -Mn bronze[5]	W	123	5,640	2.59	0.47	Uniform corrosion
Ni -Mn bronze	W	197	2,340	2.22	0.40	Uniform corrosion
Ni -Mn bronze	M	197	2,340	1.96	0.36	Uniform corrosion
Cu - Ni, 95-5	W	123	5,640	9.47	1.52	Uniform corrosion
Cu - Ni, 95-5	M	123	5,640	9.43	1.52	Uniform corrosion
Cu - Ni, 95-5	W	197	2,340	5.55	0.89	Uniform corrosion
Cu - Ni, 95-5	M	197	2,340	3.62	0.58	Uniform corrosion
Cu - Ni, 90-10	W	123	5,640	9.74	1.56	Uniform corrosion
Cu - Ni, 90-10	M	123	5,640	7.49	1.20	Uniform corrosion
Cu - Ni, 90-10	W	197	2,340	5.15	0.83	Uniform corrosion
Cu - Ni, 90-10	M	197	2,340	3.22	0.52	Uniform corrosion
Cu - Ni, 80-20	W	123	5,640	7.78	1.25	Uniform corrosion
Cu - Ni, 80-20	M	123	5,640	7.96	1.28	Uniform corrosion

Continued

Table 20. Continued.

Alloys	Environment[1]	Exposure (days)	Depth (feet)	Corrosion Rate[2]		Remarks
				MDD	MPY	
Cu - Ni, 80-20	W	197	2,340	4.58	0.74	Uniform corrosion
Cu - Ni, 80-20	M	197	2,340	3.04	0.49	Uniform corrosion
Cu - Ni, 70-30, 0.5 Fe	W	123	5,640	7.36	1.18	Uniform corrosion
Cu - Ni, 70-30, 0.5 Fe	M	123	5,640	4.95	0.80	Uniform corrosion
Cu - Ni, 70-30, 0.5 Fe	W	123	2,500	3.89	0.63	Uniform corrosion
Cu - Ni, 70-30, 0.5 Fe	W	197	2,340	4.39	0.71	Uniform corrosion
Cu - Ni, 70-30, 0.5 Fe	M	197	2,340	1.29	0.21	Uniform corrosion
Cu - Ni, 70-30, 5.3 Fe	W	123	5,640	1.48	0.24	Uniform corrosion
Cu - Ni, 70-30, 5.3 Fe	M	123	5,640	0.93	0.15	Uniform corrosion
Cu - Ni, 70-30, 5.3 Fe	W	197	2,340	0.71	0.11	Uniform corrosion
Cu - Ni, 70-30, 5.3 Fe	M	197	2,340	0.39	0.06	Uniform corrosion

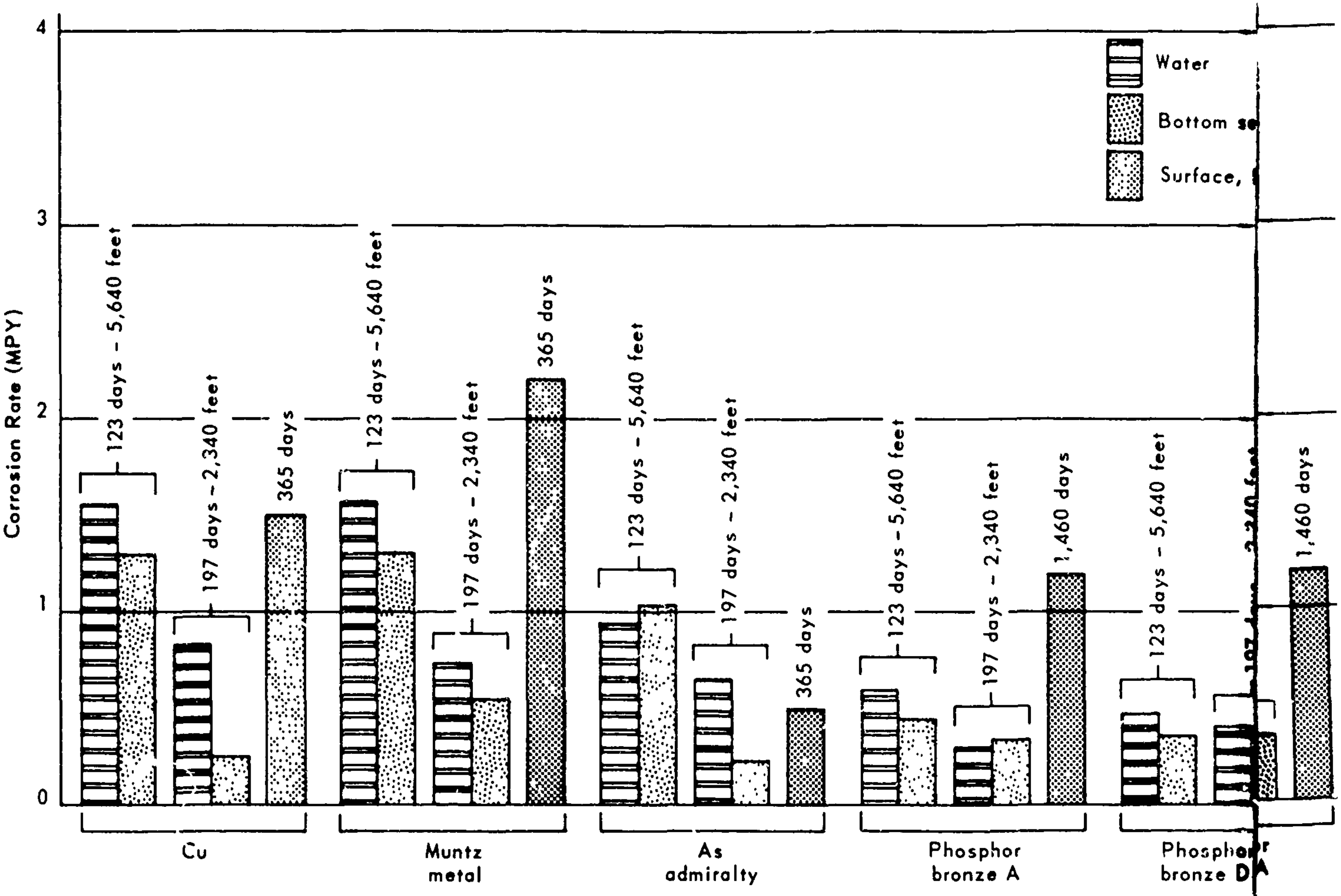
[1] W = specimens exposed on sides of STU in water; M = specimens exposed in base of STU, partially embedded in bottom sediment.

[2] MDD = milligrams per square decimeter per day; MPY = mils penetration per year.

[3] Electrolytic tough pitch.

[4] Dezincified.

[5] Traces of dealuminification.


Corrosion Rate (MPY)
0
1
2
3
4
Water
Bottom se
Surface,
123 days – 5,640 feet
197 days – 2,340 feet
365 days
1,460 days
Cu
Muntz metal
As admiralty
Phosphor bronze A
Phosphor bronze D

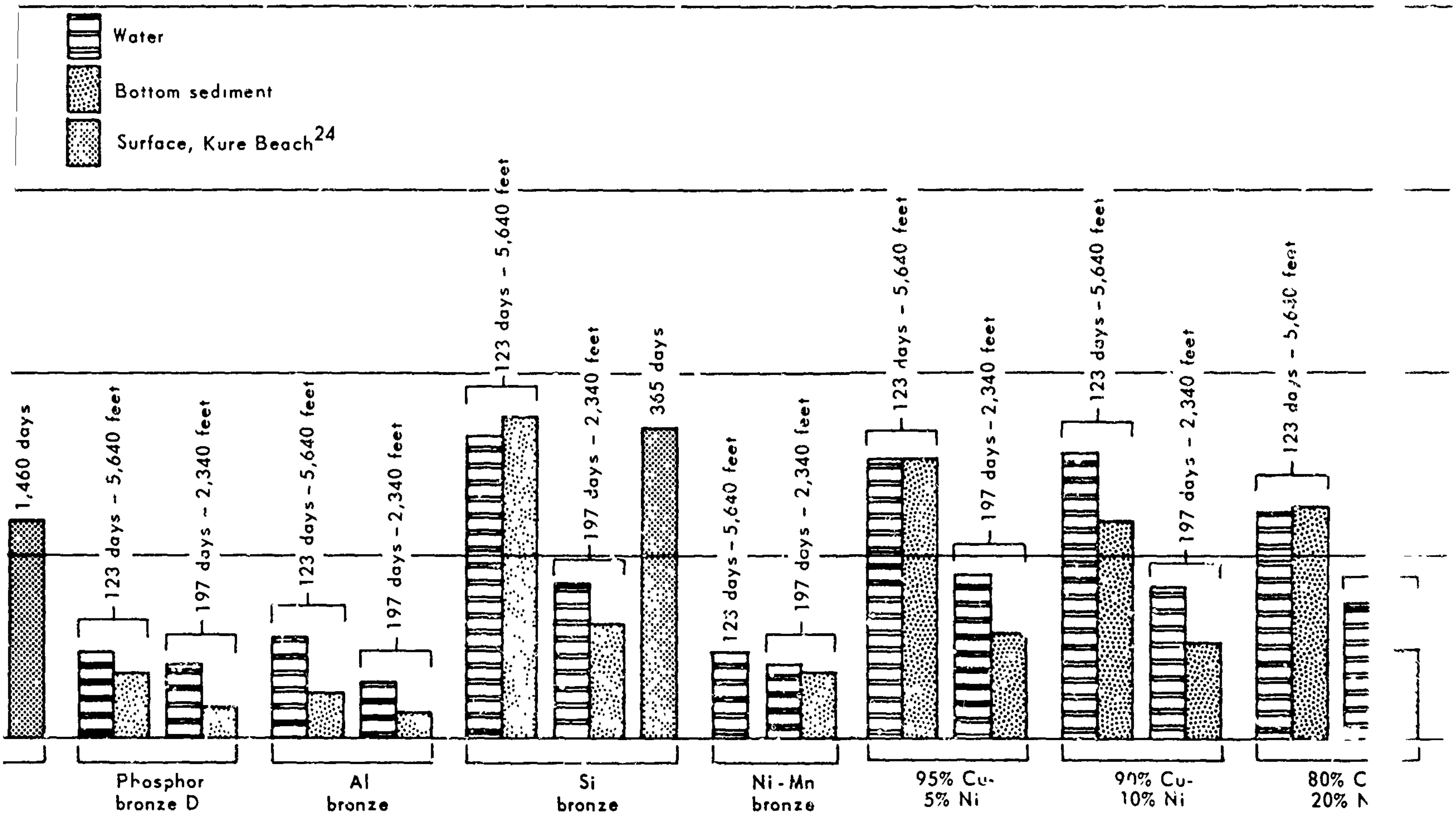
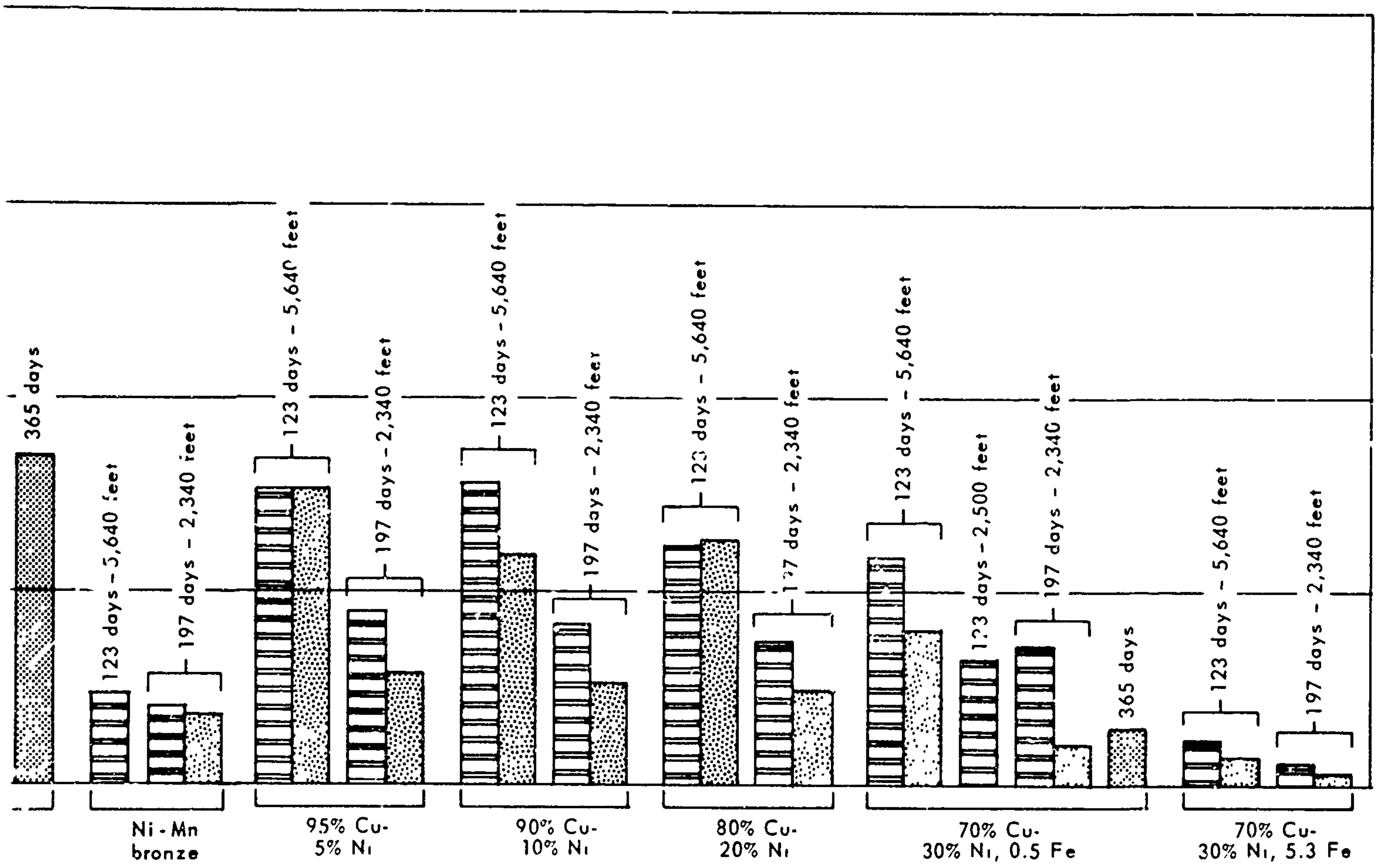


Figure 43. Corrosion of copper alloys.


365 days
123 days - 5,640 feet
197 days - 2,340 feet
Ni-Mn bronze
123 days - 5,640 feet
197 days - 2,340 feet
95% Cu-5% Ni
123 days - 5,640 feet
197 days - 2,340 feet
90% Cu-10% Ni
123 days - 5,640 feet
197 days - 2,340 feet
80% Cu-20% Ni
123 days - 5,640 feet
123 days - 2,500 feet
197 days - 2,340 feet
365 days
70% Cu-30% Ni, 0.5 Fe
123 days - 5,640 feet
197 days - 2,340 feet
70% Cu-30% Ni, 5.3 Fe

er alloys.

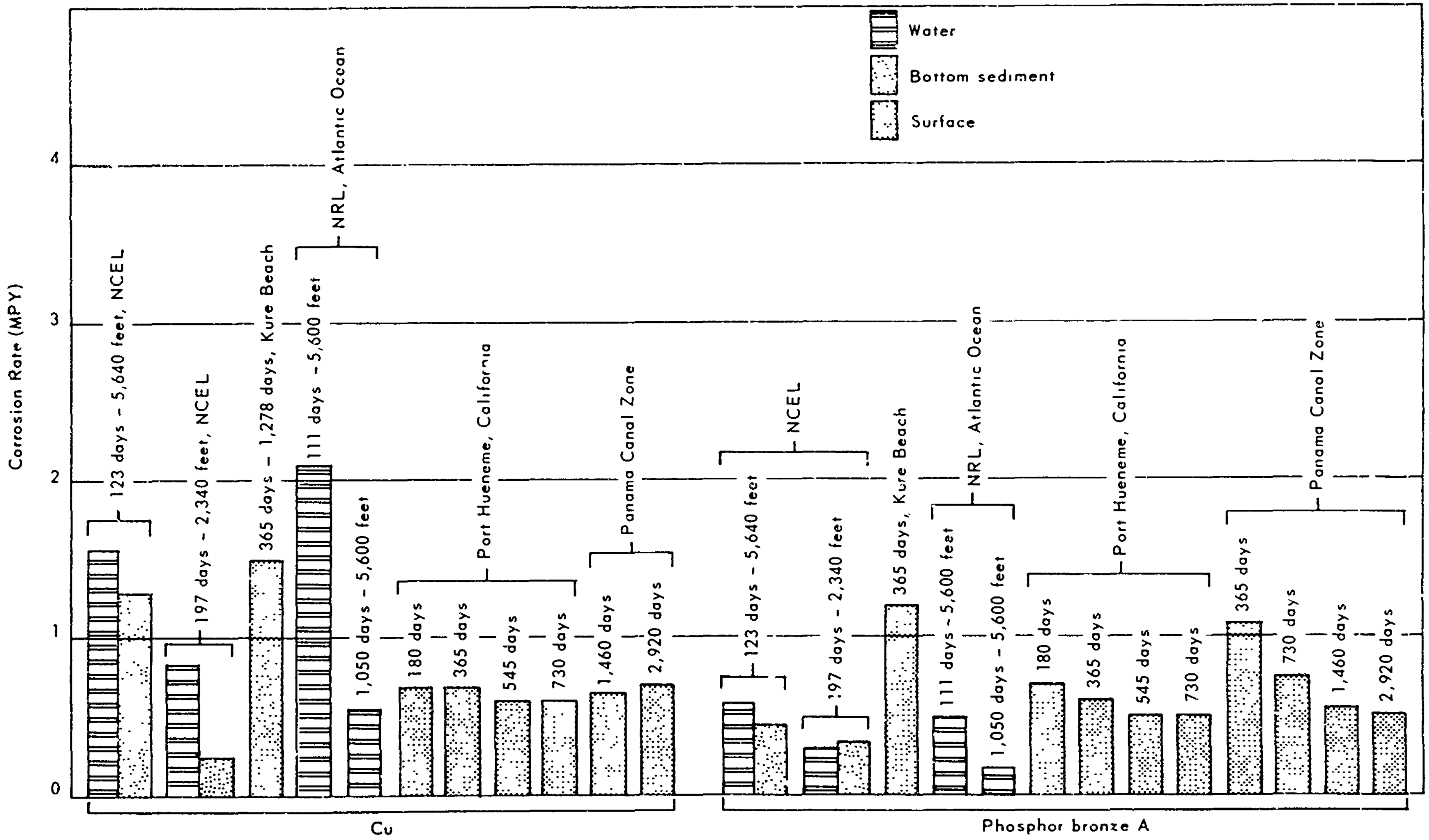


Figure 44. Corrosion of copper and phosphor bronze A at different depths in different localities for various periods of time.

The corrosion rate for copper after 365 days of exposure at the surface at Kure Beach, N. C., in the Atlantic Ocean is the same as that after 123 days at a depth of 5,640 feet in the Pacific Ocean. The corrosion rates for copper at the surface in the Pacific Ocean at Port Hueneme, California, and at the Panama Canal Zone were the same and remained constant for periods of exposure from 180 to 2,900 days (6 months to 8 years) and are somewhat lower than the rate reported at Kure Beach, N. C. They are also lower than the rates at depth in both the Pacific and Atlantic, except for 1,050 days in the Atlantic, where, again, they are the same.

The corrosion of phosphor bronze A was different in that its corrosion rate at depth in the Pacific Ocean was the same as at depth in the Atlantic Ocean for equivalent periods of exposure (123 and 111 days). Its corrosion rate was essentially constant in the Pacific Ocean at Port Hueneme, California, and decreased with time in the Pacific Ocean at the Panama Canal Zone. The corrosion rates for 365 days of exposure at the surface in the Atlantic Ocean at Kure Beach, N. C., and in the Pacific Ocean at the Panama Canal Zone were the same.

Three of the alloys, wrought Muntz metal and aluminum bronze, and cast nickel-manganese bronze, were also susceptible to selective corrosion. Muntz metal and nickel-manganese bronze were dezincified, as shown in Figures 45 and 46. In both, the zinc-rich beta phases were attacked initially. Traces of a similar type of attack, which is known as dealuminification, were found in the aluminum bronze, as shown in Figure 47.

Mechanical Properties. The percent change in the mechanical properties of the exposed copper alloys is given in Table 21.

The mechanical properties were unaffected by exposure to seawater, except that there were small decreases in the yield strengths of copper, Muntz metal, arsenical admiralty, phosphor bronze A, and silicon bronze, exposed at a depth of 2,340 feet.

Stress Corrosion. The copper alloys which were stressed at 35, 50, and 75% of their respective yield strengths, and their susceptibility to stress corrosion cracking at depths of 2,340 feet and 5,640 feet, are given in Table 22.

None of the alloys were susceptible to stress corrosion cracking at stresses as great as 75% of their respective yield strengths when exposed for 197 days at a depth of 2,340 feet.

Corrosion Products. The corrosion products from some of the copper alloys were analyzed by X-ray diffraction, spectrographic analysis, quantitative chemical analysis, and infrared spectrophotometry. The results of these analyses were as follows:

Source of Products	Findings
Nickel - manganese bronze	Copper chloride, $CuCl_2 \cdot 2H_2O$; copper hydroxy - chloride, $Cu_2(OH)_3Cl$; Cu; Al; Fe; Si; Na; no Mn detectable; 0.91% chloride ion; 11.53% sulfate ion; considerable phosphate ion present; 35.98% copper as metal
Aluminum bronze	Copper - oxy - chloride, $CuCl_2 \cdot 3CuO \cdot 4H_2O$; cupric chloride $CuCl_2$; Cu; Al; Fe; Mg; Ca; Si; 0.91% chloride ion; 8.99% sulfate ion; considerable phosphate ion present
Copper - nickel, 70-30%, high Fe	Nickel hydroxide, $Ni(OH)_2$; cupric chloride, $CuCl_2$; Cu; Ni; Fe; Mg; Na; traces of Si and Mn; 4.77% chloride ion; 0.80% sulfate ion; considerable phosphate ion present; 43.63% metallic copper

Nickel Alloys

The chemical compositions of the nickel base alloys are given in Table 23 and the surface conditions in Table 24. The corrosion rates and types of corrosion are given in Table 25 and are shown graphically for the Ni - Cu 400 alloy in Figure 48.

The corrosion of Ni 200 was entirely of the crevice corrosion type, which was manifested in two ways: (1) in the crevice formed by bolting two pieces of the alloy together with nylon bolts and nuts; and (2) at the sheared ends, where microcracks were formed because of the deformation caused by the shearing operation. In the latter, seawater entered the microcracks, where the oxygen was soon consumed, thus creating a difference in oxygen concentration between the seawater inside the cracks and the seawater outside the cracks. The areas deficient in oxygen became anodic to the other areas, and since these anodic areas were small in relation to the total area of a specimen, the current density on the anodic area and potential difference between the two would be expected to be great. This difference in potential caused an increase in the corrosion rate on these anodic areas.

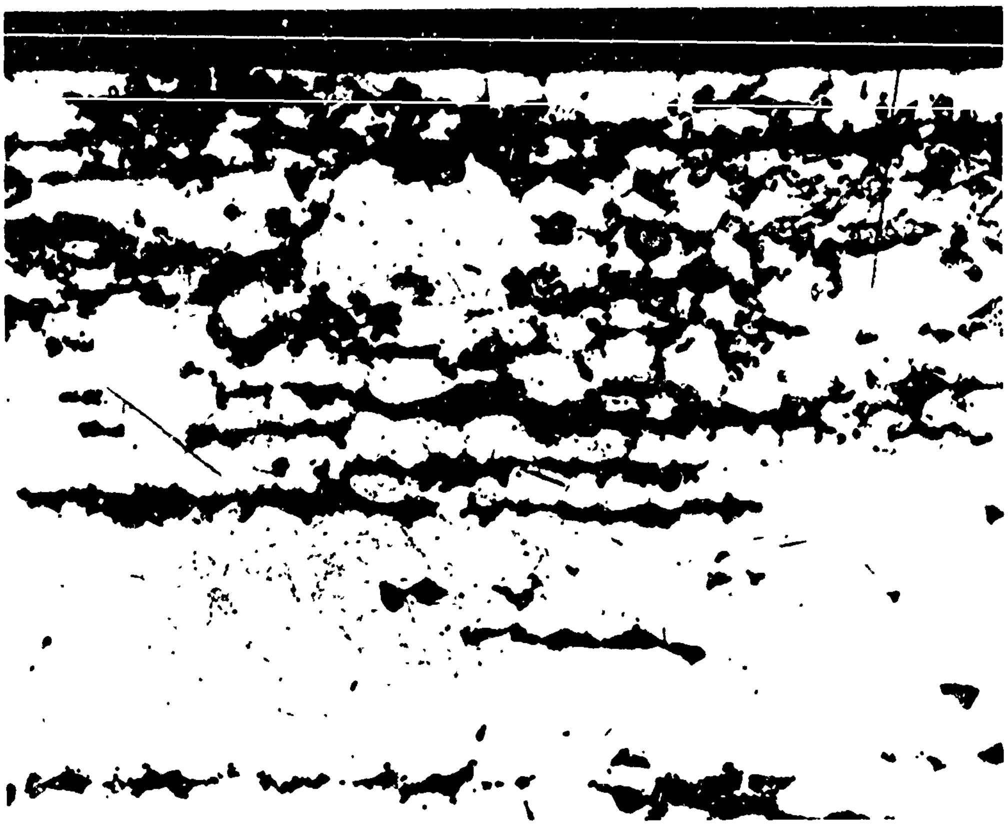


Figure 45. Dezincification of Muntz metal. Unetched; X200.

Figure 46. Dezincification of nickel-manganese bronze. Unetched; X500.

Figure 47. Dealuminification of aluminum bronze. Unetched; X500.

Table 21. Percent Changes in Mechanical Properties of Copper Alloys Due to Corrosion

Alloy	Environment[1]	Original Properties			Percent Change After —					
					123 Days at 5,640 Feet			197 Days at 2,340 Feet		
		Tensile Strength (ksi)	Yield Strength (ksi)	Elongation (%)	Tensile Strength	Yield Strength	Elongation	Tensile Strength	Yield Strength	Elongation
Copper ETP[2]	W	33.4	14.2	52.0	-	-	-	-8.1	-18.3	-1.9
	M	-	-	-	+1.5	-5.6	-1.9	-7.5	-18.3	-5.4
Muntz	W	5[illegible].5	24.4	52.8	-	-	-	-6.5	-14.2	-9.1
	M	-	-	-	-3.8	-3.3	-5.9	-6.0	-19.2	-2.5
As admiralty	W	50.9	19.0	66.0	-	-	-	-6.5	-22.1	-3.0
	M	-	-	-	-0.4	-3.2	-2.0	-5.7	-18.9	-3.0
Phosphor bronze A	W	51.3	25.0	64.2	0.0	-2.8	+3.3	-3.7	-12.8	-2.6
	M	-	-	-	-	-	-	-2.7	-12.8	+0.8
Phosphor bronze D	W	63.9	27.9	69.8	-	-	-	+0.6	-1.9	+3.2
	M	-	-	-	+0.6	0.0	0.0	-0.6	-4.7	+2.0
Al bronze	W	84.6	51.2	45.0	+0.2	+0.2	-8.5	+0.5	-1.8	-8.2
	M	-	-	-	-	-	-	+0.1	-1.8	-6.7
Si bronze	W	64.4	27.5	61.3	-	-	-	-0.2	-14.5	-5.4
	M	-	-	-	+1.7	+4.0	-2.4	-3.1	-13.4	-0.8
Cu-Ni, 95-5	W	47.6	32.0	33.0	+1.1	+16.3	+2.1	-3.8	-9.4	+6.7
	M	-	-	-	-	-	-	-3.2	-8.4	+7.0
Cu-Ni, 90-10	W	42.7	15.9	42.0	+3.3	+11.3	0.0	-0.5	+1.3	-1.9
	M	-	-	-	-	-	-	-0.9	-0.6	-2.9
Cu-Ni, 80-20	W	49.1	20.5	43.6	-	-	-	+0.2	-4.9	+2.9
	M	-	-	-	-0.4	-2.9	+1.6	+1.2	-7.3	-0.7
Cu-Ni, 70-30, 0.5 Fe	W	58.3	26.4	41.2	-	-	-	-2.9	-12.9	+3.2
	M	-	-	-	+1.0	-2.3	+2.7	-2.2	-5.7	-1.7
Cu-Ni, 70-30, 5.3 Fe	W	78.3	41.2	35.2	-	-	-	+1.4	0.0	0.0
	M	-	-	-	+2.2	+4.9	+0.9	+0.8	-8.0	0.0
Ni-Mn bronze	W	70.6	31.0	20.0	-1.8	-10.0	+25.0	-3.3	-15.7	+15.0
	M	-	-	-	-	-	-	-3.5	-17.4	+16.5

[1] W = specimens exposed on sides of STU in water;
M = specimens exposed in base of STU, partially embedded in bottom sediment.

[2] Electrolytic tough pitch.

Table 22. Stress Corrosion of Copper Alloys

Alloy	Stress (ksi)	Percent of Yield Strength	Exposure (days)	Depth (feet)	Number of Specimens	Number Failed
Cu	10.7	75	197	2,340	3	0
Muntz metal	27.8	50	197	2,340	3	0
Muntz metal	41.6	75	197	2,340	3	0
As admiralty	25.5	50	197	2,340	3	0
As admiralty	38.2	75	197	2,340	3	0
Phosphor bronze A	25.7	50	197	2,340	3	0
Phosphor bronze A	38.5	75	197	2,340	3	0
Phosphor bronze D	22.4	35	197	2,340	3	0
Phosphor bronze D	32.0	50	197	2,340	3	0
Phosphor bronze D	47.9	75	197	2,340	3	0
Al bronze	29.6	35	197	2,340	3	0
Al bronze	42.3	50	197	2,340	3	0
Al bronze	63.5	75	197	2,340	3	0
Si bronze	22.5	35	197	2,340	3	0
Si bronze	32.2	50	197	2,340	3	0
Si bronze	48.3	75	197	2,340	3	0
Cu - Ni, 95-5	23.8	50	197	2,340	3	0
Cu - Ni, 95-5	35.7	75	197	2,340	3	0
Cu - Ni, 80-20	36.8	75	197	2,340	3	0
Cu - Ni, 70-30, 0.5 Fe	29.2	50	197	2,340	3	0
Cu - Ni, 70-30, 0.5 Fe	43.7	75	197	2,340	3	0
Cu - Ni, 70-30, 5.3 Fe	27.4	35	197	2,340	3	0
Cu - Ni, 70-30, 5.3 Fe	39.2	50	197	2,340	3	0
Cu - Ni, 70-30, 5.3 Fe	58.7	75	197	2,340	3	0

Table 23. Chemical Composition of Nickel Alloys, Percent by Weight

Alloy	Ni	Cu	Si	S	Fe	Mn	C	Cr	Mo	Other
Ni 200	99.50	0.02	0.07	0.006	0.04	0.29	0.05	-	-	-
Ni - Cu 400	65.17	32.62	0.10	0.007	0.90	1.06	0.11	-	-	-
Ni - Fe - Cr - 825	41.12	1.61	0.31	0.01	30.86	0.82	0.05	21.12	2.94	Ti 1.00, Al 0.14
Ni - Mo - Cr - "C"	remainder	-	0.62	0.009	6.32	0.52	0.05	15.33	16.71	W 3.53, Co 0.96, V 0.26, P 0.010

Table 24. Condition of Nickel Alloys

Alloy	Surface and Metallurgical Conditions
Ni 200	Cold rolled, annealed
Ni - Cu 400	Cold rolled, annealed
Ni - Fe - Cr - 825	Cold rolled, annealed
Ni - Mo - Cr - Fe - W - "C"	Annealed, pickled

Table 25. Corrosion Rates of Nickel Alloys

Alloy	Thickness (in.)	Environment[1]	Exposure (days)	Depth (ft)	Corrosion Rate[2]		Crevice Corrosion, Depth (mils)	Type of Corrosion
					MDD	MPY		
Ni 200	0.123	W	1,064	5,300	7.2	1.2	8	Extensive, edge (ends only), due to shearing, no surface corrosion
Ni 200	0.123	M	1,064	5,300	6.2	1.0	perforated	Extensive, edge (ends only), due to shearing, no surface corrosion
Ni 200	0.123	W	123	5,640	4.3	0.7	slight	Extensive, edge (ends only), due to shearing; no surface corrosion
Ni 200	0.123	M	123	5,640	9.9	1.6	slight	Extensive, edge (ends only), due to shearing, no surface corrosion
Ni 200	0.123	W	197	2,340	3.0	0.5	43	Extensive, edge (ends only), due to shearing, no surface corrosion
Ni 200	0.123	M	197	2,340	2.9	0.5	none	Extensive, edge (ends only), due to shearing, no surface corrosion
Ni - Cu 400	0.127	W	1,064	5,300	2.9	0.5	6	Nonuniform, surface
Ni - Cu 400	0.127	M	1,064	5,300	3.6	0.6	perforated	Edge; random broad pits, 47 mils maximum, 35 mils average, 1.5 sq in.
Ni - Cu 400	0.127	W	123	5,640	5.0	0.8	none	Uniform
Ni - Cu 400	0.127	M	123	5,640	3.2	0.5	none	Uniform
Ni - Cu 400	0.127	W	123	2,500	2.5	0.4	none	Uniform
Ni - Cu 400	0.127	W	197	2,340	2.5	0.4	11	General pitting, 10 mils maximum, 9.5 mils average, 14/sq in.
Ni - Cu 400	0.127	M	197	2,340	1.7	0.3	none	Uniform
Ni - Fe - Cr - 825	0.125	W	123	5,640	0.00	0.000	none	No visible corrosion
Ni - Fe - Cr - 825	0.125	M	123	5,640	0.00	0.000	none	No visible corrosion
Ni - Fe - Cr - 825	0.125	W	197	2,340	0.05	0.009	none	No visible corrosion
Ni - Fe - Cr - 825	0.125	M	197	2,340	0.05	0.009	8	No visible corrosion
Ni - Mo - Cr - "C"	0.050	W	1,064	5,300	0.008	0.001	trace	No visible corrosion
Ni - Mo - Cr - "C"	0.050	W	1,064	5,300	0.000	0.000	none	No visible corrosion
Ni - Mo - Cr - "C"	0.050	M	1,064	5,300	0.000	0.000	none	No visible corrosion
Ni - Mo - Cr - "C"	0.050	W	123	5,640	0.04	0.007	none	No visible corrosion
Ni - Mo - Cr - "C"	0.050	M	123	5,640	0.04	0.007	none	No visible corrosion
Ni - Mo - Cr - "C"	0.050	W	197	2,340	0.000	0.000	none	No visible corrosion
Ni - Mo - Cr - "C"	0.050	M	197	2,340	0.000	0.000	none	No visible corrosion

[1] W = specimens exposed on sides of STU in water, M - specimens exposed in base of STU, partially embedded in bottom sediment.

[2] MDD = milligrams per square decimeter per day; MPY - mils penetration per year.

[3] Specimens 1" x 6"; all others 6" x 12".

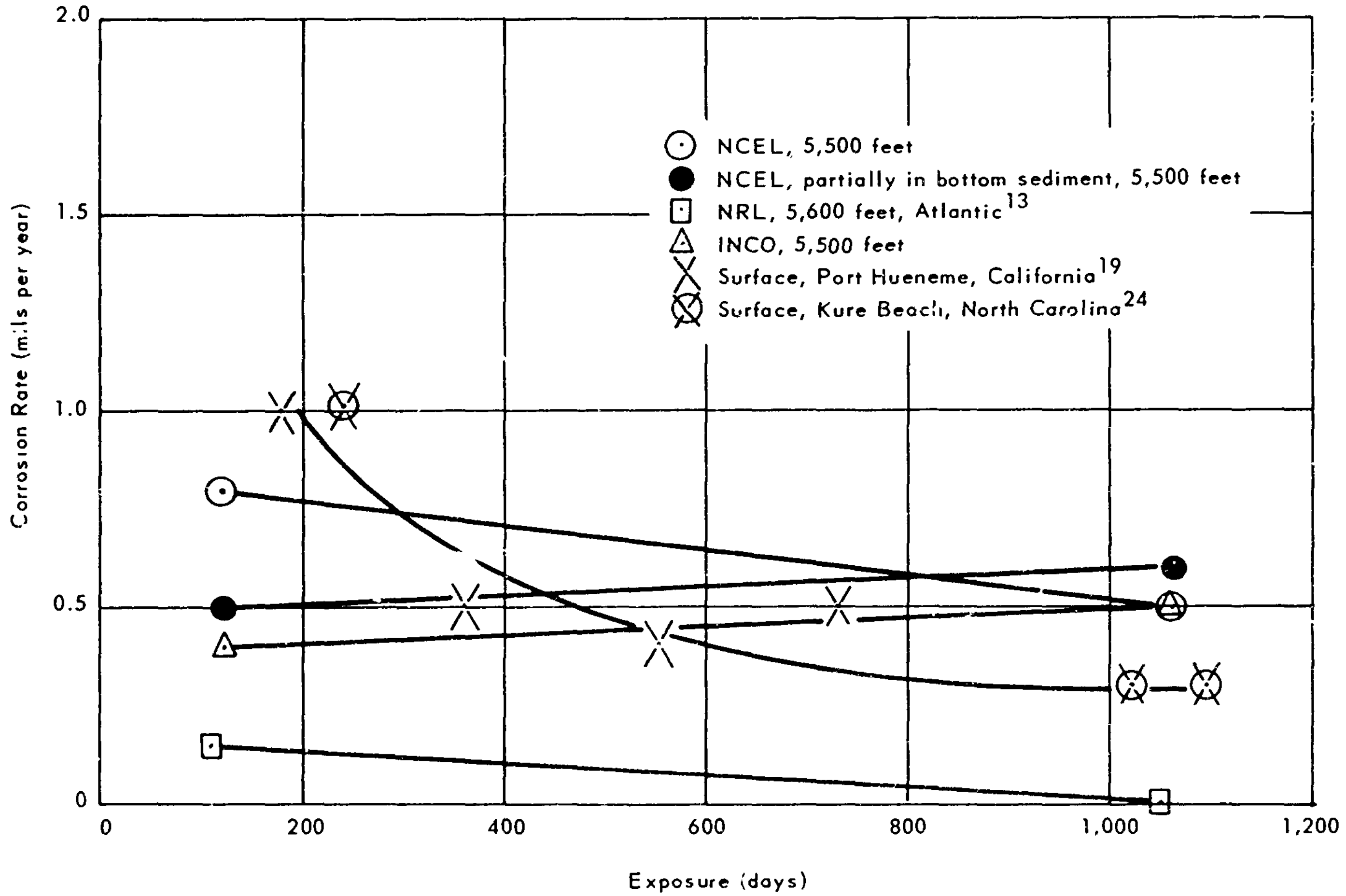


Figure 48. Corrosion of Ni - Cu 400 alloy immersed in seawater.

There was no visible corrosion of the Ni - Fe - Cr - 825 and the Ni - Mo - Cr - "C" alloys. The corrosion rates recorded for these two alloys either as milligrams per square decimeter per day or as mils penetration per year are of no significance. These differences are logically within the experimental error due to weighing, since the original and final weights could not be made on the same balance. The two instances of slight crevice corrosion, one for each alloy, indicate that these two alloys have very good resistance to crevice corrosion.

The Ni - Cu 400 alloy was corroded uniformly during the shorter periods of exposure (123 days at 5,640 feet and 2,500 feet, and 197 days in the bottom sediment at 2,340 feet) except for the specimens exposed in the water at a depth of 2,340 feet. These specimens were uniformly pitted over their surfaces with a maximum pit depth of 10 mils, an average pit depth of 9.5 mils, and a pitting frequency of 14 pits/sq in. of surface. The pits were filled with greenish-blue corrosion products, and the sides of the pits were covered with a black, granular type of film. X-ray diffraction, spectrographic analysis, quantitative chemical analysis, and infrared spectrophotometry showed that these corrosion products were composed of nickel hydroxide ($Ni[OH]_2$), cupric chloride ($CuCl_2$), copper oxy-chloride ($CuCl_2 \cdot 3CuO.4H_2O$), metallic copper, the pattern of a compound which so far is unidentifiable, 0.33% chloride ion, 0.85% sulfate ion, and a considerable amount of phosphate ion.

After 1,064 days of exposure at a depth of 5,300 feet the Ni - Cu 400 alloy exposed in the water was nonuniformly corroded over the surface. In many cases there were grooves with a maximum depth of 2 mils. These grooves were very similar to the hydroids found on other materials. The specimens partially embedded in the bottom sediment were attacked at the edges, and there were randomly distributed broad deep pits on the surfaces. The maximum depth of these pits was 47 mils, with an average depth of 35 mils, and the pits were distributed on an average of 1.5/sq in. of surface. The corrosion products again were greenish blue, and the sides and bottoms of the pits as well as the edges were covered with a black, granular type of film. Chemical analyses showed that in addition to the compounds, metals, elements, and ions found on the water specimens at a depth of 2,340 feet, a small amount of nickel sulfide (NiS) was present. The corrosion products on uncleaned specimens exposed in the water and in the bottom sediment are shown in Figure 49. The specimen at the top was about 8 feet above the bottom sediment and entirely in the water; the bottom specimen was embedded in the bottom sediment to a depth of about 2.5 inches. The detail of a pit partially filled with corrosion products is shown in Figure 50.

During acid cleaning, deposits of copper were noted in the bottoms of some pits and on the edges of the specimens. The presence of metallic copper was verified by metallographic examinations (from 100 to 1,000 magnifications) of polished sections through pits.

It has been shown that Ni - Cu 400 alloy will also pit when completely immersed in surface seawater when the seawater is either stagnant or slowly moving.[25] The very low currents at the NCEL test sites at depth in the Pacific Ocean would be equivalent to quiet seawater.

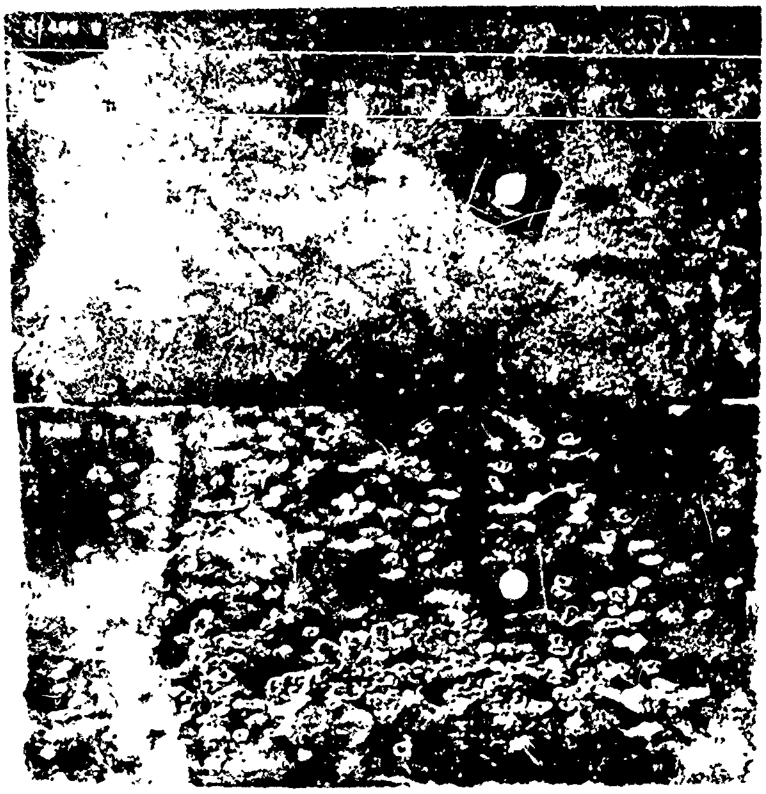


Figure 49. Ni - Cu 400 alloy after 1,064 days at 5,300 feet. Top specimen was in the water and bottom specimen partially in bottom sediment.

Figure 50. Corrosion pit on mud specimen in Figure 49 showing detail of attack.

A comparison of the corrosion rates of Ni-Cu 400 alloy immersed in seawater at various depths is shown in Figure 48. The initial corrosion rates at a nominal depth of 5,500 feet for 123 days were lower than those at the surface, but were slightly higher after 1,064 days of exposure. However, the corrosion rates of this alloy exposed at a depth of 5,600 feet in the Atlantic Ocean were much lower than those at a nominal depth of 5,500 feet in the Pacific Ocean and lower than those at the surface.

There was some crevice corrosion in the artificially created crevices of the Ni-Cu 400 alloy after 197 days of exposure at a depth of 2,340 feet and in both the water and the bottom sediment after 1,064 days of exposure at a depth of 5,300 feet.

Mechanical Properties. The percent change in the mechanical properties of the exposed nickel alloys is given in Table 26. There were no significant changes in the mechanical properties of any of the alloys.

Stress Corrosion. Only one alloy (Ni-Mo-Cr-"C") was exposed in the stressed condition. It was stressed at stresses equivalent to 35, 50, and 75% of its yield strength and exposed at depths of 2,340 feet and 5,640 feet (Table 27). This alloy was not susceptible to stress corrosion cracking during the periods of time and at the depths it was exposed.

Titanium Alloys

The chemical compositions of the titanium alloys are given in Table 28 and the surface conditions in Table 29. The corrosion rates of the alloys are given in Table 30.

All these alloys, both unwelded and welded, were unaffected by exposure to seawater and in the bottom sediments at depths of 2,340 feet and 5,640 feet for periods of time of 197 days and 123 days, respectively. This performance is in agreement with that obtained by other investigators for titanium alloys exposed at the surface in the Atlantic Ocean.[26, 27]

Mechanical Properties. The percent change in the mechanical properties of the exposed titanium alloys is given in Table 31. The mechanical properties were not affected by exposures of 123 days and 197 days at depths of 5,640 feet and 2,340 feet, respectively.

Stress Corrosion. The titanium alloys which were stressed at 35, 50, and 75% of their respective yield strengths, and their susceptibility to stress corrosion cracking at depths of 2,340 feet and 5,640 feet, are given in Table 32. The titanium alloys were not susceptible to stress corrosion cracking during the periods of time they were exposed at the various depths in the Pacific Ocean. However, other investigators have found that certain titanium alloys are susceptible to stress corrosion cracking under certain conditions.

Table 26. Percent Changes in Mechanical Propertie

Alloy	Environment[1]	Original Properties						
					123 Days at 5,640 Feet			197
		Tensile Strength (ksi)	Yield Strength (ksi)	Elongation (%)	Tensile Strength	Yield Strength	Elongation	Tensile Strength
Ni 200	W	65.1	17.5	46.0	-	-	-	-0.2
	M	-	-	-	-0.9	-16.0	-0.4	+0.2
Ni - Cu 400	W	75.1	28.8	44.3	-	-	-	+2.5
	M	-	-	-	+2.1	+1.4	+0.5	+2.0
Ni - Fe - Cr - 825	W	108.1	52.3	37.8	+0.4	+3.8	0	+0.6
	M	-	-	-	-	-	-	+0.1
Ni - Mo - Cr - "C"	W	120.8	60.0	43.0	+3.0	+4.5	-0.5	+3.0
	M	-	-	-	-	-	-	+3.1

[1] W = specimens exposed on the sides of the STU in water; M = specimens exposed in base of STU, partially

Table 27. Stress Corrosion of

Alloy	Stress (ksi)	Percent of Yield Strength	Expo (da
Ni - Mo - Cr - Fe - W-"C"	21.0	35	1
Ni - Mo - Cr - Fe - W-"C"	21.0	35	1
Ni - Mo - Cr - Fe - W-"C"	30.0	50	1
Ni - Mo - Cr - Fe - W-"C"	30.0	50	1
Ni - Mo - Cr - Fe - W-"C"	45.0	75	1
Ni - Mo - Cr - Fe - W-"C"	45.0	75	1

rties anical Properties of Nickel Alloys Due to Corrosion

197 D		Percent Change After —								
		197 Days at 2,340 Feet			1,064 Days at 5,300 Feet (1 x 6-in. specimens)			1,064 Days at 5,300 Feet (6 x 12-in. specimens)		
ile gth	ition	Tensile Strength	Yield Strength	Elongation	Tensile Strength	Yield Strength	Elongation	Tensile Strength	Yield Strength	Elongation
.2		-0.2	-11.4	-3.7	-	-	-	-0.5	-10.9	-14.6
.2	4	+0.2	-8.6	-4.4	-	-	-	+0.6	-9.7	-12.0
.5		+2.5	+1.0	-1.8	-	-	-	+2.5	+4.9	-3.4
.0	5	+2.0	+1.4	+0.5	-	-	-	-	-	-
.6		+0.6	+5.4	-4.8	-	-	-	-	-	-
.1		+0.1	+2.3	-0.8	-	-	-	-	-	-
.0	5	+3.0	-1.2	+17.0	+3.8	+12.5	+17.9	+3.2	-0.8	+12.3
.1		+3.1	+0.2	+19.1	-	-	-	+3.1	-34.0	+14.4

lly en STU, partially embedded in the bottom sediment.

n of N ess Corrosion of Nickel Alloys

Exposu (days	cent of Yield ength	Exposure (days)	Depth (ft)	Number of Specimens	Number Failed
123	35	123	5,640	3	0
197	35	197	2,340	3	0
123	50	123	5,640	3	0
197	50	197	2,340	3	0
123	75	123	5,640	3	0
197	75	197	2,340	3	0

Table 28. Chemical Composition of Titanium Alloys, Percent by Weight

Alloy	C	Fe	N_2	H_2	Al	V	Cr	Sn	Mn	Ti
75 A	0.027	0.20	0.026	0.004	-	-	-	-	-	remainder
6 Al - 4 V	0.023	0.15	0.015	0.006- 0.007	6.0	3.9	-	-	-	remainder
6 Al - 4 V[1]	0.025	0.13	0.015	0.007	5.9	4.0	-	-	-	remainder
5 Al - 2.5 Sn[1]	0.025	0.34	0.014	0.011	5.1	-	-	2.2	0.007	remainder
13 V - 11 Cr - 3 Al[1]	0.027	0.17	0.027	0.008	3.[illegible]	13.4	11.4	-	-	remainder

[1] Transverse butt welds across the width of the 1 x 6-in. and 6 x 12-in. specimens and 3-in.-diameter ring welds in the center of 6 x 12-in. specimens.

Table 29. Condition of the Titanium Alloys

Alloy	Surface and Metallurgical Conditions
75 A	Annealed and pickled
6 Al - 4 V	Annealed and pickled
6 Al - 4 V, welded	Annealed and pickled
5 Al - 2.5 Sn, welded	Annealed and pickled
13 V - 11 Cr - 3 Al, welded	Annealed and pickled

Table 30. Corrosion Rates of Titanium Alloys

Alloy	Environment[1]	Exposure (days)	Depth (feet)	Corrosion Rate[2]		Remarks
				MDD	MPY	
75 A	W	123	5,640	0.000	0.000	No visible corrosion
75 A	M	123	5,640	0.000	0.000	No visible corrosion
75 A	W	197	2,340	0.000	0.000	No visible corrosion
75 A	M	197	2,340	0.000	0.000	No visible corrosion
6 Al - 4 V	W	123	5,640	0.000	0.000	No visible corrosion
6 Al - 4 V	M	123	5,640	0.000	0.000	No visible corrosion
6 Al - 4 V	W	197	2,340	0.000	0.000	No visible corrosion
6 Al - 4 V	M	197	2,340	0.000	0.000	No visible corrosion
5 Al - 2.5 Sn, C weld[3]	W	123	5,640	0.052	0.017	No visible corrosion
5 Al - 2.5 Sn, B weld[4]	W	123	5,640	0.000	0.000	No visible corrosion
5 Al - 2.5 Sn, C weld	M	123	5,640	0.043	0.014	No visible corrosion
5 Al - 2.5 Sn, B weld	M	123	5,640	0.000	0.000	No visible corrosion
5 Al - 2.5 Sn, C weld	W	197	2,340	0.000	0.000	No visible corrosion
5 Al - 2.5 Sn, B weld	W	197	2,340	0.000	0.000	No visible corrosion
5 Al - 2.5 Sn, C weld	M	197	2,340	0.000	0.000	No visible corrosion
5 Al - 2.5 Sn, B weld	M	197	2,340	0.000	0.000	No visible corrosion
6 Al - 4 V, C weld	W	123	5,640	0.000	0.000	No visible corrosion
6 Al - 4 V, B weld	W	123	5,640	0.054	0.011	No visible corrosion
6 Al - 4 V, C weld	M	123	5,640	0.000	0.000	No visible corrosion
6 Al - 4 V, B weld	M	123	5,640	0.000	0.000	No visible corrosion
6 Al - 4 V, C weld	W	197	2,340	0.000	0.000	No visible corrosion
6 Al - 4 V, B weld	W	197	2,340	0.000	0.000	No visible corrosion
6 Al - 4 V, C weld	M	197	2,340	0.000	0.000	No visible corrosion
6 Al - 4 V, B weld	M	197	2,340	0.000	0.000	No visible corrosion

Continued

Table 3C. Continued.

Alloy	Environment[1]	Exposure (days)	Depth (feet)	Corrosion Rate[2]		Remarks
				MDD	MPY	
13 V-11 Cr-3 Al, C weld	W	123	5,640	0.000	0.000	No visible corrosion
13 V-11 Cr-3 Al, B weld	W	123	5,640	0.017	0.005	No visible corrosion
13 V-11 Cr-3 Al, C weld	M	123	5,640	0.042	0.012	No visible corrosion
13 V-11 Cr-3 Al, B weld	M	123	5,640	0.000	0.000	No visible corrosion
13 V-11 Cr-3 Al, C weld	W	197	2,340	0.000	0.000	No visible corrosion
13 V-11 Cr-3 Al, B weld	W	197	2,340	0.000	0.000	No visible corrosion
13 V-11 Cr-3 Al, C weld	M	197	2,340	0.000	0.000	No visible corrosion
13 V-11 Cr-3 Al, B weld	M	197	2,340	0.000	0.000	No visible corrosion

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[1] W = specimens exposed on sides of STU in water; M = specimens exposed in base of STU, partially embedded in bottom sediment.

[2] MDD = milligrams per square decimeter per day; MPY = mils penetration per year.

[3] C weld = 3-in.-diameter ring weld in center of specimen.

[4] B weld = transverse butt weld across width of specimen.

Table 31. Percent Changes in Mechanical Properties of Titanium Alloys Due to Corrosion

Alloy	Environment[1]	Original Properties			Percent Change After —					
					123 Days at 5,640 Feet			197 Days at 2,340 Feet		
		Tensile Strength (ksi)	Yield Strength (ksi)	Elongation (%)	Tensile Strength	Yield Strength	Elongation	Tensile Strength	Yield Strength	Elongation
Ti -75 A	W	87.2	70.1	29.7	-	-	-	+5.2	+8.6	-10.8
	M	-	-	-	+3.6	+5.0	-4.7	+3.8	+7.2	-11.5
Ti -6 Al -4 V	W	139.7	136.0	14.0	-	-	-	+3.4	+4.0	+5.7
	M	-	-	-	-	-	-	+1.1	+2.4	-2.1
Ti -6 Al -4 V	W	148.4	139.3	12.5	-	-	-	-	-	-
	M	-	-	-	-	-	-	-	-	-
Ti -5 Al -2.5 Sn	W	130.1	122.6	14.0	-	-	-	-	-	-
	M	-	-	-	-	-	-	-	-	-
Ti -13 V -11 Cr -3 Al	W	143.9	139.5	8.5	-	-	-	-	-	-
	M	-	-	-	-	-	-	-	-	-

[1] W = specimens exposed on sides of STU in water; M = specimens exposed in base of STU, partially embedded in bottom sediment.

Table 32. Stress Corrosion of Titanium Alloys

Alloy	Stress (ksi)	Percent of Yield Strength	Exposure (days)	Depth (feet)	Number of Specimens	Number Failed
75 A	24.5	35	197	2,340	3	0
75A	35.0	50	197	2,340	3	0
75A	52.6	75	197	2,340	3	0
6 Al - 4 V	47.6	35	123	5,640	3	0
6 Al - 4 V	47.6	35	197	2,340	3	0
6 Al - 4 V	68.0	50	123	5,640	3	0
6 Al - 4 V	68.0	50	197	2,340	3	0
6 Al - 4 V	102.0	75	123	5,640	3	0
6 Al - 4 V	102.0	75	197	2,340	3	0
6 Al - 4 V, butt welded	48.8	35	123	5,640	3	0
6 Al - 4 V, butt welded	48.8	35	197	2,340	3	0
6 Al - 4 V, butt welded	69.7	50	123	5,640	3	0
6 Al - 4 V, butt welded	69.7	50	197	2,340	3	0
6 Al - 4 V, butt welded	104.5	75	123	5,640	3	0
6 Al - 4 V, butt welded	104.5	75	197	2,340	3	0
5 Al - 2.5 Sn, butt welded	42.9	35	123	5,640	3	0
5 Al - 2.5 Sn, butt welded	42.9	35	197	2,340	3	0
5 Al - 2.5 Sn, butt welded	61.3	50	123	5,640	3	0
5 Al - 2.5 Sn, butt welded	61.3	50	197	2,340	3	0
5 Al - 2.5 Sn, butt welded	92.0	75	123	5,640	3	0
5 Al - 2.5 Sn, butt welded	92.0	75	197	2,340	3	0
13 V - 11 Cr - 3 Al, butt welded	48.8	35	123	5,640	3	0
13 V - 11 Cr - 3 Al, butt welded	48.8	35	197	2,340	3	0
13 V - 11 Cr - 3 Al, butt welded	69.8	50	123	5,640	3	0
13 V - 11 Cr - 3 Al, butt welded	69.8	50	197	2,340	3	0
13 V - 11 Cr - 3 Al, butt welded	104.6	75	123	5,640	3	0
13 V - 11 Cr - 3 Al, butt welded	104.6	75	197	2,340	3	0

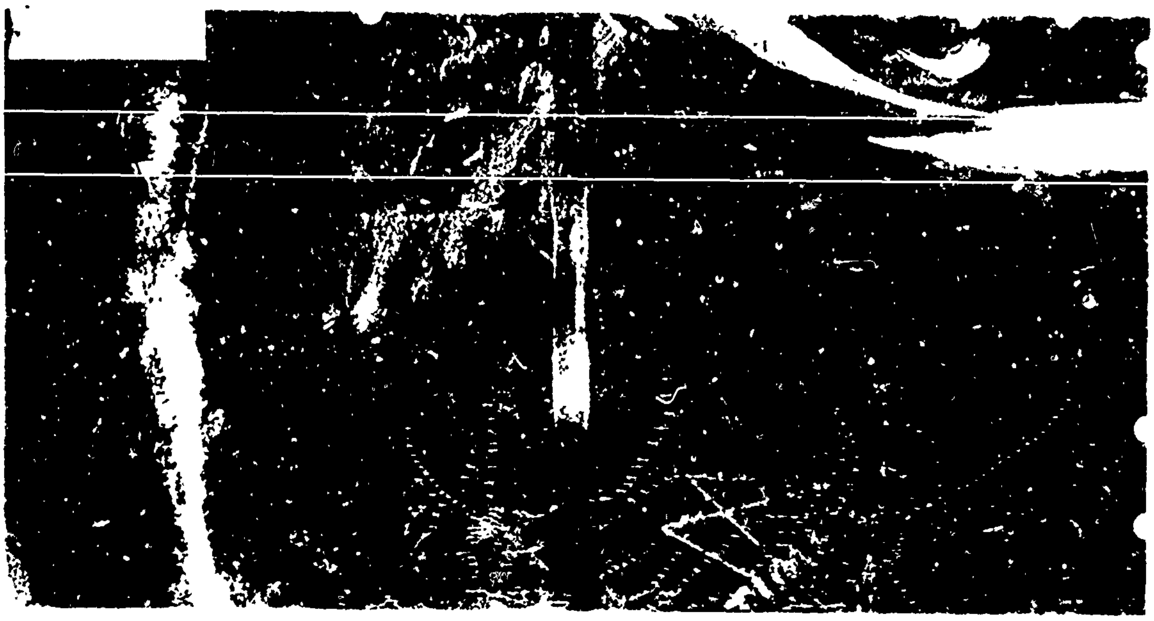

Figure 51. Hydroids on 13 V - 11 Cr - 3 Al titanium alloy.

Marine Organisms

Marine organisms commonly known as hydroids were found at all depths, especially on the surfaces of the more corrosion-resistant materials. They were found on the aluminum alloys, stainless steels, nickel alloys, and titanium alloys. A typical example of hydroids on a specimen of a titanium alloy is shown in Figure 51. Hydroids are also shown in Figure 26. Evidence of their attachment remained on the materials after removal of the corrosion products by chemical solutions. However, their tracks appeared to be only a staining of the alloys, since no indentations of the surface could be measured or could be detected by metallographic examinations of polished transverse sections at 1,000 magnifications.

SUMMARY

The purpose of this investigation was to determine the effects of deep ocean environments on the corrosion of materials. To accomplish this, specimens of materials representing nearly all classes of alloys were exposed on the bottom of the Pacific Ocean at different depths for different periods of time.

The corrosion of the alloys in these environments was evaluated by means of weight losses, pit depths, pitting frequencies, types of attack, changes in mechanical properties, metallographic examinations, and corrosion product analyses.

The results are reported of the evaluations of 1,590 specimens of 107 different alloys exposed at depths of 2,340, 5,300, and 5,640 feet for 197, 1,064, and 123 days, respectively.

Steels

The steels were corroded uniformly over their surfaces. Their average corrosion rate at a nominal depth of 5,500 feet was about one-third of that of comparable steels at the surface and was twice that at a depth of 2,340 feet. When the steels were partially embedded in the bottom sediments, their corrosion rates were essentially the same as when they were totally exposed in the seawater. Their corrosion rates decreased with an increase in the time of exposure. The mechanical properties of the steels, anchor chains, and wire ropes were unimpaired, except for those of galvanized plow steel and type 316 stainless steel wire ropes. The steels were not susceptible to either crevice corrosion or stress corrosion cracking. The stressed wire ropes were not susceptible to stress corrosion cracking. A sprayed and sealed aluminum coating protected the sheet steel. About 50% of the aluminum coating on the wire rope had disappeared after 1,064 days of exposure. The wire ropes protected with zinc coatings varied from being 100% rusted for those with the lighter coatings to about 5% rusted for the heaviest coating. The corrosion products were composed chiefly of hydrated ferric oxide, ferrous hydroxide, and iron oxide - hydroxide.

Stainless Steels

All the stainless steels except type 316, type 316L, 20-Cb, and 17 Cr - 7 Ni - 0.7 Ti - 0.2 Al were attacked by pitting, edge, and crevice corrosion. The corrosion of the stainless steels in the bottom sediments was about the same as those in seawater. The mechanical properties of only three stainless steels (type 430, type 304L, and 18 Cr - 14 Mo - 0.5 N) were adversely affected by corrosion. The precipitation hardening stainless steels 15-7 AMV heat-treated to the RH950 and RH1150 conditions and the welded steels 17-7 PH - TH1050 were susceptible to stress corrosion cracking. Type 405 stainless steel was attacked by the intergranular type of corrosion.

Aluminum Alloys

All the aluminum alloys were attacked by pitting, edge, and crevice corrosion. In addition, alloys 7039-T6 and 7079-T6 were susceptible to the exfoliation type of corrosion. Aluminum alloys 7178-T6, 6061-T6, 5086-H34, 2219-T81, 3003-H14, welded 5454-H32, 5456-H321, and 5456-H343, 5083-H113, 7039-T6, and 7079-T6 were susceptible to intergranular corrosion. The corrosion rates of most of the aluminum alloys increased with an increase in the time of exposure at a nominal depth of 5,500 feet and were lower at this depth than at 2,340 feet. The depths of the pits increased with time at a nominal depth of 5,500 feet, and for comparable periods of exposure the depths of the pits in some alloys were greater at a depth of 2,340 feet than at a depth of 5,640 feet. There was no consistency between the behavior of specimens of the alloys exposed in seawater and partially embedded in the bottom sediments. The mechanical properties of aluminum alloys 2219-T81, 3003-H14, alclad 3003-H12, 6061-T6, 7079-T6, and 7178-T6 were adversely affected by exposure to seawater at depth.

Copper Alloys

All the copper alloys were corroded uniformly over their surfaces except Muntz metal. They corroded at slower rates when partially embedded in the bottom sediments than when totally exposed in seawater and at slower rates at a depth of 2,340 feet than at a depth of 5,640 feet. Wrought Muntz metal and cast nickel-manganese bronze were attacked by dezincification and aluminum bronze by dealuminification. The corrosion rate of a copper-nickel alloy (70-30, 5.0 Fe) was considerably lower than an alloy containing only 0.5% iron. High nickel content copper-nickel alloys corroded at slower rates than the low nickel content alloys. The mechanical properties of the copper alloys were unaffected. The copper alloy corrosion products were composed chiefly of cupric chloride, copper hydroxy-chloride, and copper oxy-chloride, as well as nickel hydroxide on the copper-nickel alloys.

Nickel Alloys

The Ni-Fe-Cr-825 and Ni-Mo-Cr-"C" alloys were uncorroded, but nickel 200 alloy was attacked by edge and crevice corrosion. Nickel-copper 400 alloy was corroded uniformly for the shorter periods of exposure, and by edge and pitting corrosion after 1,064 days of exposure. The mechanical properties of the nickel alloys were unaffected by exposure at depth in seawater. The corrosion products were composed chiefly of nickel hydroxide, cupric chloride, copper oxy-chloride, and a small amount of nickel sulfide.

Titanium Alloys

The titanium alloys were immune to corrosion and stress corrosion cracking by seawater.

CONCLUSIONS

1. Ordinary construction steels, alloy steels, and high-strength low-alloy steels are suitable for deep sea applications where the strength-to-weight ratio and the buoyancy-to-weight ratio are not important factors. Because the corrosion is uniform, the life of a structure fabricated from these steels is predictable, hence the corrosion factor can be incorporated in its design.

2. Stainless steels, in general, are not recommended for deep sea applications for long periods of constant immersion. Types 316 and 316L and alloy 20-Cb are suitable for some applications under certain conditions.

3. Because of their high strength-to-weight ratios and high buoyancy-to-weight ratios, aluminum alloys are suitable for short-time constant immersion or intermittent immersion applications. Preventive measures must be incorporated into the design and construction of aluminum alloy structures to eliminate the possibility of crevice corrosion. Protective systems would prolong the useful life of aluminum alloy structures.

4. For applications where strength and weight are not major considerations, those copper alloys which are not susceptible to dezincification and dealuminification are suitable for deep sea applications because their corrosion is uniform.

5. For applications where low strength-to-weight ratio, moderate strength, and excellent corrosion resistance are required, nickel base alloys Ni - Fe - Cr - 825 and Ni - Mo - Cr - "C" are suitable.

6. The titanium alloys in this investigation can be used in many applications where maximum corrosion resistance and a high strength-to-weight ratio are the dictating factors.

RECOMMENDATIONS

1. In order to obtain a definite trend of the corrosion of materials at a depth of 2,500 feet, it will be necessary to conduct tests of longer duration (2 and 4 years). This is considered necessary because of the differences in the behavior of some alloys at 2,500 feet and at 5,500 feet.

2. The bottom sediment and water-sediment interface are two environments requiring further investigation because of the indications of their greater aggressiveness toward some alloys. The hydrogen sulfide produced by sulfate-reducing bacteria could cause premature failure of some of the high-strength materials with promising potential.

3. Because the most logical method of fabrication for watertight, pressure-resistant applications is by welding, considerable information should be obtained on welded alloys prepared by the different welding processes and with different composition rods. The joining of dissimilar metals by welding should be included in the investigation.

4. The paucity of information on the susceptibility of welded alloys to stress corrosion cracking indicates the need for further investigation. Catastrophic failures of welded assemblies are, many times, due to insufficient information on the susceptibility of the alloy to stress corrosion cracking when welded. An example is the reported susceptibility to stress corrosion cracking of certain titanium alloys when welded in thick sections and having intentionally induced small cracks.

5. Since many of the alloys corroded at slower rates at a depth of 2,500 feet than at a depth of 5,500 feet, the question arises as to whether their corrosion rates increase with an increase in depth below 5,500 feet. Therefore, if structures at greater depths are contemplated, these depths should be investigated. Since the oxygen concentration curve versus depth is not linear, results of studies to date do not permit the reliable prediction of the behavior of alloys at other depths.

6. Simulation tests in the laboratory might provide indications or trends that would help clarify the above unanswered questions. Before such tests can be conducted in the present NCEL deep ocean simulation facility it will be necessary to provide controls capable of maintaining variables within certain limits so that the desired deep ocean environment can be simulated.

7. It is thought that more complete oceanographic information might provide answers to the anomalous behavior of some alloys at depth. Such information as the hydrogen sulfide, carbon dioxide, and oxygen contents; the phosphate ion concentration; and more complete data on bottom currents at the water-sediment interface would probably provide the reasons for some if not all of the anomalies.

8. Because no surface data on the corrosion of the alloys in this investigation are available for the general latitude and longitude in the Pacific Ocean in the vicinity of NCEL, it is recommended that the NCEL exposures being initiated be continued for a period of 3 years. These surface data will be comparable with the NCEL deep ocean data.

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13 ABSTRACT

A total of 1,590 specimens of 107 different alloys were exposed by the Naval Civil Engineering Laboratory at depths of 2,340, 5,300, and 5,640 feet at two sites in the Pacific Ocean for 197, 1,064, and 123 days to determine the effects of deep ocean environments on the corrosion of materials.

The corrosion rates, pit depths, types of corrosion, changes in mechanical properties, and analyses of corrosion products of the alloys are presented.

Titanium alloys and two nickel base alloys (Ni-Fe-Cr-825 and Ni-Mo-Cr-"C") were immune to corrosion. The corrosion rates of copper alloys and steels decreased with a decrease in the oxygen concentration of the seawater and with increasing time of exposure at a nominal depth of 5,500 feet. The corrosion rates of most of the aluminum alloys increased with increasing time of exposure and with decreasing oxygen concentration of seawater. Muntz metal, and nickel-manganese bronze were attacked by dezincification and aluminum bronze by dealuminification. All the stainless steels except types 316 and 316L, 20-Cb and 17 Cr - 7 Ni - 0.7 Ti - 0.2 Al were attacked by pitting corrosion. Only two precipitation hardened stainless steels were susceptible to stress corrosion cracking. The oceanographic parameters varied with depth. Changes in temperature and oxygen concentration exerted the most influence on the corrosion of the alloys.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Corrosion						
Stress corrosion						
Deep ocean						
Mechanical properties						
Steels						
Stainless steels						
Precipitation hardening						
Aluminum alloys						
Copper alloys						
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