

Technical Note N-1008

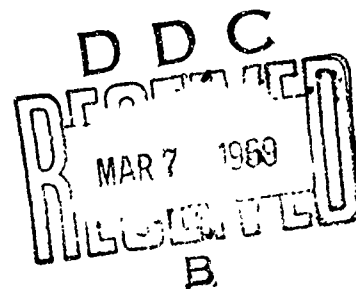
CORROSION OF MATERIALS IN HYDROSPACE-PART V - ALUMINUM ALLOYS

By

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PREFACE

Since 1959, the Naval Civil Engineering Laboratory has been developing the technology necessary for designing, constructing, inspecting and maintaining structures and fixed equipment on the ocean floor. A part of this program is to determine the effects of deep ocean environments on the corrosion of metals and alloys.

A Submersible Test Unit (STU) was designed, on which many test specimens can be mounted. The STU can be lowered to the ocean floor for long periods of exposure, then retrieved.

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 west-southwest of Port Hueneme, California, latitude $33^{\circ}44'N$ and longitude $120^{\circ}45'W$. Test Site II (nominal depth of 2,500 feet) is 75 nautical miles west of Port Hueneme, California, latitude $34^{\circ}06'N$ and longitude $120^{\circ}42'W$. In addition, a surface sea water exposure site (V) was established at Point Mugu, California, latitude $34^{\circ}06'N$ and longitude $119^{\circ}07'W$, to obtain surface immersion data for comparison purposes.

This report presents the results of the evaluations of aluminum alloys at the above three sites.

CORROSION OF MATERIALS IN HYDROSPACE-PART V - ALUMINUM ALLOYS

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ABSTRACT

A total of 900 specimens of 40 different aluminum alloys were exposed at depths of 2,500 and 6,000 feet in the Pacific Ocean for periods of time varying from 123 to 1064 days in order to determine the effects of deep ocean environments on their corrosion resistance.

Corrosion rates, types of corrosion, pit depths, stress corrosion cracking resistance, changes in mechanical properties and compositions of corrosion products are presented.

Alloys 2219-T87, 7079-T6, 7178-T6 and Alclad 7079-T6 were susceptible to stress corrosion cracking.

Alloys 2024-T3, 7039-T6, 7075-T6, 7079-T6 and 7178-T6 were attacked by the exfoliation type of corrosion.

All the alloys were attacked by pitting and crevice types of corrosion.

With reference to aluminum alloys, sea water at depth was more aggressive than at the surface and the bottom sediments were more corrosive than the sea water at depth in the Pacific Ocean.

Aluminum alloys not susceptible to stress corrosion cracking and exfoliation corrosion can be used for deep sea applications if adequately protected and if brought to the surface periodically for maintenance of the protective system.

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INTRODUCTION

The development of deep diving vehicles which can stay submerged for long periods of time has focused attention on the deep ocean as an operating environment. This has created a need for information concerning the behavior of common materials of construction as well as newly developed materials with promising potentials, at depths in the oceans.

Since 1959, the Naval Civil Engineering Laboratory has been developing the technology necessary for designing, constructing, inspecting and maintaining structures and fixed equipment on the ocean floor. A part of this program is to determine the effects of deep ocean environments on the corrosion of metals and alloys.

In order to determine the effects of deep ocean environments on the corrosion of metals and alloys, a Submersible Test Unit (STU) was designed, on which many test specimens can be mounted. A unit is shown in the inset of Figure 1.

The test sites for the deep ocean exposures are shown in Figure 1, and their specific geographical locations are given in Table 1. The complete oceanographic data at these sites, obtained from NCEL cruises between 1961 and 1967, are summarized in Figure 2. Initially, it was decided to utilize the site at the 6,000 foot depth (STU I-1, 2, 3, & 4). Because of the minimum oxygen concentration zone found between the 2,000 and 3,000 foot depths, during the early oceanographic cruises, it was decided to establish a second site (STU II-1 and II-2) at a nominal depth of 2,500 feet. For comparative purposes, the surface water site V was established. Even though the actual depths are shown in the tables, the nominal depths of 6,000 and 2,500 feet are used throughout the text.

A summary of the characteristics of the waters 10 feet above the bottom sediments at the two deep ocean exposure sites and 5 feet below the surface at the surface exposure site is given in Table 1.

Sources of information pertaining to the biological characteristics of the bottom sediments, biological deterioration of materials, detailed oceanographic data, and construction, emplacement and retrieval of STU structures are given in Reference 1. Bottom sediments as used herein means the water-mud interface to a mud depth of about six inches.

The procedures for the preparation of the specimens for exposure and for evaluating them after exposure are described in Reference 2.

Previous reports pertaining to the performance of materials in the deep ocean environments are given in References 1 through 9.

This report presents a discussion of the results of the corrosion of aluminum alloys obtained for the seven exposure periods shown in Table 1.

RESULTS AND DISCUSSIONS

The results presented and discussed herein also include the corrosion data for aluminum alloys exposed on the STU structures for the International Nickel Co., Inc. Permission for their incorporation in this report has been granted by Dr. T. P. May, Reference 10.

Results from other participants in the NCEL exposures are also included; they were the Annapolis Division, Naval Ship Research and Development Center (Reference 11) and the Chemistry Division, NCEL (Reference 12).

Deep ocean corrosion results from the Atlantic Ocean (References 13 and 14), surface water corrosion data from the Atlantic Ocean (Reference 15) and surface water corrosion data from the Pacific Ocean (References 16 and 17) are included for comparison purposes.

The chemical compositions of the aluminum alloys are given in Table 2.

The resistance of aluminum and aluminum alloys to corrosion is due to a relatively chemically inert film of aluminum oxide which forms on its surface. The usual corrosion product film that forms on aluminum in water at temperatures below 70°C is Bayerite (β - $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$).

When aluminum is immersed in water the oxide film thickens much more rapidly than it does in air. The rate of growth decreases with time and reaches a limiting thickness which depends on the temperature, the oxygen content of the water, the ions present and the pH.

In sea water this naturally formed protective film breaks down more readily and its repair and growth is retarded by the chloride ion. Since this failure of the protective film is usually local, corrosion is in the form of pitting.

CORROSION

The corrosion rates, maximum and average pit depth, pitting frequency, pitting factor and depth of crevice corrosion are given in Tables 3 through 9 and are shown graphically in Figures 2 through 27.

1000 Series Alloys

The corrosion rates, pit depths and types of corrosion of the 1000 Series alloys are given in Table 3. The corrosion rates and pit depths are shown graphically in Figures 3 and 4.

Surface sea water corrosion rates for 1100 alloy decreased with increasing duration of exposure and were lower than those for equivalent periods of exposure at depths of 2,500 and 6,000 feet. However, in the bottom sediments (hereafter the term "bottom sediments" will be

shortened to "sediments") the corrosion rates at the 2,500 foot depth were lower than those in surface sea water (hereafter "water" will be used in place of "sea water") while at 6,000 feet they were higher than at the surface.

With increasing duration of exposure at the 2,500 foot depth, the corrosion rates in the water decreased and in the sediments they increased.

The corrosion rates in water at the 6,000 foot depth increased with increasing duration of exposure through 750 days and thereafter decreased. In the sediments the overall trend was for the corrosion rates to decrease with increasing duration of exposure.

Compared to the 1100 alloy, in general the 1180 alloy corroded at about the same rates at the 2,500 foot depth, at slightly higher rates at the surface, and at lower rates at the 6,000 foot depth.

The pitting corrosion of the 1100 alloy was erratic while the crevice type of corrosion occurred in nearly all exposures, Table 3. In most cases the specimens were perforated by crevice corrosion.

Comparisons of the corrosion rates of 1100 alloy at depth and at the surface in both the Pacific and Atlantic oceans are shown in Figure 4. The corrosion rates at the surface in the Pacific Ocean in the NCEL tests at Point Mugu were higher than those in the Atlantic Ocean at Harbor Island, N. C., (hereafter shortened to "Harbor Island") Reference 15 and those in the Pacific Ocean, Panama Canal Zone, (hereafter shortened to "Panama Canal") Reference 17. The corrosion rates at a depth of 5,600 feet in the Atlantic Ocean, Reference 13, were higher than those at the surface at all locations but were lower than those in water at the 6,000 foot depth in the Pacific Ocean. In the Pacific Ocean at a depth of 2,500 feet in water the corrosion rates were about the same as at the 5,600 foot depth in the Atlantic Ocean after 400 days of exposure. (Hereafter "in the Pacific Ocean" will be deleted after 2,500 and 6,000 foot depths).

Aluminum alloy 1100 corroded at slower rates when partially immersed in the sediments than in water at depths of 2,500 and 6,000 feet. The 1100 alloy corroded at higher rates in water at a depth of 6,000 feet than in surface exposures and for any other depth of exposure in both oceans, particularly after 400 days of exposure.

Aluminum alloy 1180 which is purer than alloy 1100, corroded at about the same rate as the 1100 alloy at the 2,500 foot depth after 400 days of exposure. Like the 1100 alloy it was perforated by crevice corrosion and there were only incipient pits on its surface.

2000 Series Alloys (Aluminum-Copper Alloys)

The corrosion rates, pit depths and types of corrosion of the 2000 series alloys are given in Table 4. The corrosion rates and pit depths are shown graphically in Figures 5 and 6.

The corrosion rates of 2014-T6 at the 2,500 foot depth were high in both water and when partially embedded in the sediments, being higher in the water after 402 days of exposure. The average and maximum pit depths were also high with pitting frequencies of 2 per square inch in the sediments and 4.5 per square inch in water. The pitting factor is the maximum measured pit depth in mils divided by the corrosion rate as mils penetration per year obtained from weight loss determinations. The pitting factors were 5 in the water and 7 in the sediments. A pitting factor of 1.0 signifies uniform corrosion. Alloy 2014-T6 was also corroded intergranularly.

The corrosion rates of 2024-0 alloy were higher in surface waters than in water at the 2,500 foot depth; however, they were lower than those in water at the 6,000 foot depth for equivalent periods of exposure as shown in Figure 5.

Corrosion rates also increased with time of exposure in surface waters. The corrosion rates in water at the 2,500 foot depth were constant with time of exposure while those in the sediments increased with time. At the 6,000 foot depth the general trend was for the corrosion rates to decrease with increasing duration of exposure both in water and sediments.

At both depths the 2024-0 specimens were perforated (0.062") by pitting corrosion within 400 days of exposure. By contrast the maximum pit depth after 366 days of exposure at the surface was 34 mils. Thus 2024-0 pitted twice as rapidly at depth as at the surface.

The corrosion rates, maximum and average pit depths for alloy 2219-T81 are given in Table 4 and shown graphically in Figure 6.

The corrosion rates at the surface after 181 days of exposure were higher than at the 2,500 and 6,000 foot depths for comparable periods of exposure. The corrosion rates in water increased with duration of exposure at the 2,500 foot depth while those in the sediment were constant. At the 6,000 foot depth the corrosion rates in water increased during the first 400 days of exposure and decreased thereafter with increasing time of exposure. The corrosion rates in the sediments followed the same trend but were lower than those in the water except after 1064 days of exposure.

The maximum and average pit depths at the surface after 181 days of exposure were the same as those at the 2,500 foot depth but were deeper than those at the 6,000 foot depth for comparable periods of exposure.

At the 2,500 foot depth the maximum and average pit depths in water and in the sediments increased with duration of exposure. However, the average pit depths were deeper in the water than in the sediments. The characteristics of the pits on the 6" x 12" specimens were quite different for the two exposure periods. There were numerous small diameter pits after 197 days of exposure but after 402 days of exposure there were large deep crater-like pits, some as large as 1.5 inches in diameter. The specimens were also attacked by crevice and edge corrosion.

At the 6,000 foot depth the maximum pit depths tended, in general, to increase with time whereas the average pit depths increased during the first 400 days of exposure and thereafter became constant with time. The specimens partially embedded in the sediments were perforated by pitting after 400 days of exposure and the average pit depths increased with duration of exposure. All the specimens were also attacked by crevice and edge corrosion.

The 2219-T81 specimens at the surface and at both depths, in addition to pitting, crevice and edge corrosion, were attacked by intergranular corrosion along the grain boundaries.

Aluminum alloy 2219 in the T87 heat treated condition was less susceptible to corrosion than when in the T81 condition after 400 days of exposure at the 2,500 foot depth except for crevice corrosion attack which was more severe.

De Luccia, Reference 18, reported extensive intergranular corrosion and maximum pit depths of 40 mils outside the weld and heat affected zone of welded 2219-T81 aluminum alloy after 123 days of exposure at a depth of 5,640 feet in the Pacific Ocean.

3000 Series Alloys (Aluminum - Magnesium)

The corrosion rates and pit depths of aluminum alloy 3003 are given in Table 5 and shown graphically in Figures 7 and 8.

The corrosion rates of 3003 alloy decreased with increasing duration of exposure in surface waters and in water at the 2,500 foot depth but they were lower at the surface than at the 2,500 foot depth for comparable periods of exposure. The corrosion rate at the 6,000 foot depth after 123 days of exposure was lower than at the surface and at the 2,500 foot depth after 181 and 197 days of exposure but was higher than at both the surface and at the 2,500 foot depth after 400 days of exposure. At the 6,000 foot depth the corrosion rate of 3003 alloy in water increased sharply for the first 400 days of exposure and thereafter decreased gradually.

The corrosion rates of 3003 alloy partially immersed in the sediments at the 2,500 foot site increased slightly with time and were lower than those in the water. In the sediments at the 6,000 foot depth the corrosion rates decreased gradually with increasing duration of exposure and were lower than those in the water except after 123 days of exposure. The corrosion rates in the sediments at the 6,000 foot depth were higher than those in the sediments at the 2,500 foot depth.

The maximum pit depth was deeper in water after 197 days of exposure at the 2,500 foot depth than either at the surface after 181 days of exposure or at the 6,000 foot depth after 123 days of exposure. However, the average pit depths were similar, varying from 16 to 19.5 mils. At the 2,500 foot depth the maximum and average pit depths, both in the water and in the sediments increased with duration of exposure but the pits were deeper in the sediments than in the water. After 400 days of

exposure at the 6,000 foot depth specimens of 3003 alloy both in the water and in the sediments were perforated by pitting corrosion. The average pit depths at the 6,000 foot depth, in both the water and the sediments reached a plateau after 400 days of exposure. The alloy was also attacked severely by crevice corrosion at both depths.

A comparison of the corrosion rates of 3003 alloy at both depths with the corrosion rates at the surface at various locations is shown in Figure 8. After exposure for 400 days at the 6,000 foot depth the corrosion rates in water and in sediments were higher than those at any of the surface locations; Port Hueneme Harbor, Point Mugu, and Harbor Island. After the same period of exposure at the 2,500 foot depth the corrosion rates in both the water and the sediments were the same as the corrosion rate in Port Hueneme Harbor. One noteworthy comparison is the difference between the corrosion rates in Port Hueneme Harbor versus those at Point Mugu. The two sites are about five miles apart yet the corrosion rates in Port Hueneme Harbor were approximately twice those at Point Mugu for 3003.

The corrosion rates and the maximum and average pit depths for Alclad 3003 are given in Table 5 and shown graphically in Figure 9.

The corrosion rates in surface water decreased with increasing duration of exposure and were less than those at depths of 2,500 and 6,000 feet for equivalent periods of exposure. The corrosion rates in water at both depths also decreased with increasing duration of exposure as did the corrosion rates in the sediment at the 6,000 foot depth. However, the corrosion rates in the sediments at the 2,500 foot depth increased with duration of exposure.

The maximum depth of pitting in the surface water exposure was constant with duration of exposure and was much less than those at both depths. At both depths also, the maximum and average pit depths were comparable. They were comparable because, in most cases, the corrosion did not attack the core material. The cladding material was sacrificed in favor of the core material. However, the cladding material was sacrificed at a much faster rate at both depths than at the surface as well as at faster rates on the portions of the specimens embedded in the sediments than on the specimens exposed in the water. In some cases as much as 20 to 60 percent of the cladding had been sacrificed within 400 days. Usually the portions of the specimens embedded in the sediments were almost completely denuded of their Alclad layers.

5000 Series Alloys (Aluminum - Magnesium)

The corrosion rates and maximum and average pit depths are given in Table 6 and shown graphically in Figures 10 through 20.

The corrosion rates for 5052 alloy are shown graphically in Figure 10. Also shown in this figure are data from other deep ocean exposures and surface exposures at other locations. The corrosion rates at the 6,000 foot depth, both in water and the sediments, were

greater than those at the 2,500 foot depth, 4,500 foot depth in the Atlantic Ocean and all surface exposures. After 400 days of exposure the corrosion rates were similar at the 2,500 foot depth, both in water and in sediments, and the surface exposures at Port Hueneme Harbor, at Point Mugu, and at Harbor Island. The corrosion rates at a depth of 4,500 feet in the Atlantic Ocean, Tongue-of-the-Ocean after 200 days of exposure were about the same as those at the surface locations after 400 days of exposure. The corrosion rates at the 6,000 foot depth decreased with increasing duration of exposure but after 1050 days of exposure they were still from 5 to 11 times greater than those at the surface at Harbor Island.

The corrosion rates of the 5454 alloy are shown graphically in Figure 11. The corrosion rates for the unwelded alloy at the surface decreased with increasing duration of exposure, were higher than those at the 2,500 foot depth for equivalent periods of exposure, and were lower than those at the 6,000 foot depth. At the 2,500 foot depth the corrosion rates of the unwelded alloy, both in the water and in the sediments, decreased with increasing duration of exposure. At the 6,000 foot depth the corrosion rate of the unwelded alloy was lower in the sediment than in the water. The corrosion rates of the welded alloy at the 2,500 foot depth increased with duration of exposure in both the water and the sediments and those in the sediments were slightly higher than those in the water. In the water at the 6,000 foot depth the corrosion rates of the welded alloy increased with duration of exposure through 400 days and decreased thereafter through 750 days of exposure. In the sediment the corrosion rates decreased with increasing duration of exposure.

The average pit depths of the unwelded 5454 alloy were about the same in the water as in the sediments at both depths although those at the 6,000 foot depth were deeper after 403 days of exposure than those after 197 days of exposure at the 2,500 foot depth. The average pit depths of the welded alloy increased with time of exposure in the water at both depths. However, the reverse was true in the sediments at both depths, the average pit depths decreased with increasing duration of exposure.

The corrosion rates and maximum and average pit depths of the 5456 alloy are shown graphically in Figure 12. For equivalent periods of exposure the corrosion rate of the 5456-H321 alloy at the surface was lower than that at the 2,500 foot depth but higher than that at the 6,000 foot depth; also the maximum and average pit depths at the surface were less than those at the 2,500 foot depth. At the 2,500 foot depth the corrosion rates were about the same in water as in the sediments and decreased with increasing time of exposure. The corrosion rates in water at the 6,000 foot depth increased with duration of exposure through 751 days of exposure and thereafter decreased through 1064 days of exposure. After 1064 days of exposure at a depth of 6,000 feet and 400 days at both depths the corrosion rates were equivalent to the corrosion rate at the surface after 181 days of exposure (1.0 to 1.3 MPY).

The corrosion rates in the sediments at the 6,000 foot depth varied with no general trend to either decrease or increase with increasing time of exposure.

The average pit depths in water increased with time of exposure at both depths while the maximum pit depths increased at the 2,500 foot depth and decreased at the 6,000 foot depth. In the sediments, both the maximum and average pit depths decreased with increasing duration of exposure at the 2,500 foot depth while, at the 6,000 foot depth, the maximum pit depths varied with increasing duration of exposure and the average pit depths decreased during the first 400 days of exposure and thereafter increased as the time of exposure increased. There was no correlation between corrosion rates and maximum or average pit depths partially because of the crevice and edge corrosion and in some cases the absence of measurable pits on the surfaces of the specimens.

The corrosion rates of the 5456 in the H343 condition were, in most cases, less than those of the alloy in the H321 condition as shown in Figure 12. These differences can be attributed not only to the difference in the strain hardening of the alloy (H321 and H343) but also to the difference in specimen size. The specimens of the alloy in the H321 condition were 6" x 12" while those in the H343 condition were 1" x 6". There were a few specimens in the H32 and H321 condition which were 1" x 6" and in all cases their corrosion rates were considerably less than their companion 6" x 12" specimens (they were not pitted) as shown in Table 6.

The corrosion rates and maximum and average pit depths of aluminum alloy 5083 are shown graphically in Figure 13. The corrosion rates at the surface decreased with increasing duration of exposure and the rate after 181 days of exposure was higher than that after 197 days of exposure in the water for the unwelded alloy at a depth of 2,500 feet. However, the corrosion rate after 366 days of exposure at the surface was lower than those at both depths after 400 days of exposure. At the 2,500 foot depth the corrosion rates of the unwelded alloy in water increased with duration of exposure while those in the sediments were practically constant. For the same period of exposure the corrosion rate in water at the 6,000 foot depth was considerably higher than that at the 2,500 foot depth but was only slightly higher in the sediments. The corrosion rate of the welded alloy in surface water was considerably higher than those in water at both depths for equivalent periods of exposure. The corrosion rates of the welded alloy increased with time of exposure in water but were practically constant in the sediment at the 2,500 foot depth. At the 6,000 foot depth the corrosion rates in water increased through the first 400 days of exposure and thereafter decreased; in the sediment they increased with time.

The maximum and average pit depths of the unwelded 5083 alloy were deeper in the water than in the sediment after 200 days of exposure at the 2,500 foot depth and the maximum pit depths decreased with increasing time of exposure. At the 6,000 foot depth the pit depths of the unwelded alloy were considerably deeper than those at the 2,500 foot

depth. The maximum and average pit depths of the welded alloy were, in most cases, deeper than those of the unwelded alloy for corresponding periods of exposure. The maximum and average pit depths of the welded alloy in water at the 2,500 foot depth increased with time while those in the sediments decreased with increasing time of exposure and they were lower than those in the water. At the 6,000 foot depth the maximum and average pit depths increased through the first 400 days of exposure and thereafter decreased while those in the sediments decreased with increasing time of exposure. In most cases, the maximum and average pit depths were deeper at the 6,000 foot depth than at the 2,500 foot depth for equivalent periods of exposure.

A comparison of the corrosion rates of aluminum alloy 5083 at the surface at Harbor Island,¹⁵ and those at depth in the Pacific Ocean, is shown in Figure 14. The 5083 alloy corroded at higher rates both in the water and sediments at both depths than at the surface at Harbor Island.

The corrosion rates of aluminum alloy 5086 in the H34, H112 and H32 tempers are shown graphically in Figure 15. For equivalent periods of exposure the corrosion rate of 5086-H34 at the surface was greater than in the water at both depths. At the 2,500 foot depth the corrosion rates in water decreased with increasing time of exposure while those in the sediments increased with time. At the 6,000 foot depth the corrosion rates of the 5086-H34 alloy in the water increased through 751 days of exposure and thereafter decreased through 1064 days of exposure. In the sediments at 6,000 feet the corrosion rates decreased during the first 403 days of exposure and then increased after 1064 days of exposure.

At the surface the average pit depths of 5086-H34 alloy were slightly deeper than those at the 2,500 foot depth for equivalent periods of exposure. In the sediments at the 2,500 foot depth, the maximum and average pit depths of 5086-H34 were shallower after the longer period of exposure. In the water at the 6,000 foot depth the average pit depths of 5086-H34 increased with time while the depths of the average pits in the sediments decreased during the first 400 days of exposure and thereafter increased rapidly through 1064 days of exposure.

At the surface the corrosion rates of 5086 alloy in the H34, H112 and H32 tempers were comparable after 181 days of exposure. The corrosion rate of the 5086-H32 alloy decreased with increasing time of exposure at the surface. The corrosion rates of 5086-H32 at the surface and at the 2,500 foot depth were comparable after about one year of exposure.

Comparison of the corrosion rates of 5086-H34 alloy at both depths, 2,500 and 6,000 feet, with those at a depth of 5,600 feet in the Atlantic Ocean is shown in Figure 16. The corrosion rates in the Atlantic Ocean were considerably lower than those at either depth and at the surface in the Pacific Ocean.

The average corrosion rates and average pit depths for all the

aluminum-magnesium alloys (5000 series) are given in Table 7 and the corrosion rates are shown graphically in Figure 17. As shown in Figure 17 the corrosion rates of the aluminum-magnesium alloys at the surface and at the 2,500 foot depth decrease with increasing duration of exposure for periods of time as long as 400 days and they are comparable. In general, the corrosion rates both in water and in the sediments at the 6,000 foot depth are greater than those at the surface as well as for those at the 2,500 foot depth; they tend to decrease with increase in duration of exposure; and after 35 months of exposure, are comparable.

The average pit depth values in Table 7 show that there is no definite or consistent behavior with regard to pitting corrosion. The average depths of the pits neither increase nor decrease consistently with increasing time of exposure. There is, however, one definite relationship which is clearly evident; for equivalent periods of exposure the average pit depth in water at the 6,000 foot depth was twice as deep as that at the surface and the average pit depth at the 2,500 foot depth was three times as deep as that at the surface. It is also possible to make another correlation; it can be stated that for equivalent periods of exposure the average pit depths of the aluminum-magnesium alloys increase as the oxygen concentration of the water decreases. This is shown in Figure 18.

To determine whether or not the magnesium content of the aluminum-magnesium alloys (5000 Series) affected the corrosion of aluminum, the corrosion rates were plotted against the magnesium contents of the alloys. These graphs are shown in Figures 19 and 20 for the corrosion rates after 400 days of exposure at the 2,500 and 6,000 foot depths respectively. The curve in Figure 19 shows very good correlation between the magnesium contents of the alloys and their corrosion rates after 400 days of exposure at the 2,500 foot depth; the corrosion rates increased with the magnesium content of the alloy. However, no such relationship was obtained between the magnesium contents of the alloys and their corrosion rates after 400 days of exposure at the 6,000 foot depth as shown in Figure 20.

6000 Series Alloys (Aluminum-Magnesium-Silicon)

The corrosion rates and pit depths of aluminum-magnesium-silicon alloy 6061 are given in Table 8 and shown graphically in Figures 21 to 23.

For equivalent periods of exposure the corrosion rates at the surface were lower than those in the sea water at the 2,500 foot depth and after 403 days of exposure at the 6,000 foot depth but were higher than those after 123 days of exposure at the 6,000 foot depth as shown in Figure 21. The corrosion rates at the surface decreased with increasing duration of exposure. At the 2,500 foot depth the corrosion rates in both the water and the sediments increased with time of exposure.

At the 6,000 foot depth the corrosion rates in the water increased through 750 days of exposure and thereafter decreased through 1064 days of exposure. In the sediments at the 6,000 foot depth the corrosion rates varied erratically for various times of exposure.

The maximum pit depths increased with time of exposure at the surface and were either the same depth or less than those in water at both depths for equivalent periods of exposure. At the 2,500 foot depth, the maximum and average pit depths in water and in the sediments increased with time of exposure with those in the water being either deeper than, or the same as those in the sediments. The maximum and average pit depths both in the water and in the sediments at the 6,000 foot depth increased with duration of exposure with those in the sediment generally being deeper than those in the water. For equivalent periods of exposure the pits were deeper at the 2,500 foot depth than at the 6,000 foot depth.

The corrosion rates and the maximum pit depths appear to increase as the concentration of oxygen in the waters decreases. This influence of oxygen on 6061-T6 after 12 to 13 months of exposure is shown in Figure 22.

Comparisons of the corrosion rates of aluminum alloy 6061-T6 at depth and at the surface in both the Atlantic and Pacific Oceans are shown in Figure 23. The corrosion rates at the surface at Harbor Island,¹⁵ and at the Panama Canal¹⁷ were lower than at depth in both oceans and are comparable. The corrosion rates at the surface at Point Mugu were higher than the other surface corrosion rates. The corrosion rates at 5,600 feet in the Atlantic Ocean¹³ were lower than those at depths of either 2,500 feet or 6,000 feet in the Pacific Ocean. Specimens of 6061-T6 were exposed on the STU structures for the Naval Ship Research and Development Center, Annapolis Division and their corrosion rates were much higher than the NCEL results. No explanation is offered to resolve this difference in corrosion behavior at this time.

In addition to pitting the 6061-T6 alloy was also attacked by the edge and the crevice types of corrosion.

7000 Series Alloys (Aluminum - Zinc)

The corrosion rates and pit depths of the aluminum-zinc (7000 Series) alloys are given in Table 9 and are shown graphically in Figures 24 to 27.

Alloys 7002-T6 and Alclad 7002-T6

The corrosion rates and pit depths for these alloys are shown in Figure 24. The corrosion rates for 7002-T6 alloy in water decreased from the 2,500 to the 6,000 foot depth and in the sediments they increased. At the 2,500 foot depth the corrosion rates of the Alclad 7002-T6 were lower than those of the bare alloy both in water and in the

sediments. At the 6,000 foot depth the corrosion rate of the Alclad alloy in water was slightly higher than that of the bare alloy while the corrosion rate of the Alclad alloy in the sediment was considerably less than that of the bare alloy.

The average and maximum pit depths of the Alclad alloy at both depths were much shallower than those in the bare alloy. Even though considerable areas of the cladding alloy had been sacrificed by corrosion (80% had been sacrificed after 403 days of exposure in the sea water at a depth of 6,000 feet) in some cases, the protective action is reflected by the decrease in the pit depths.

Alloy 7039-T6

Because of the extensive exfoliation corrosion (Table 9) of this alloy after the initial periods of exposures (123 days at 6,000 feet and 197 days at 2,500 feet), it was not possible to obtain weight losses, measure pit depths or determine changes in mechanical properties. The extent of exfoliation of 7039-T6 in water after 403 days of exposure at a depth of 6,000 feet is shown in Figure 25. The exfoliated specimens were nearly four times thicker than the original 0.25 inch thickness.

Alloy 7079-T6

The corrosion rates and pit depths of aluminum alloy 7079-T6 are shown graphically in Figure 24.

The corrosion rates in water and in the sediments at the 2,500 foot depth decreased with an increase in the duration of exposure and those in the water were greater than those in the sediments. For equivalent periods of exposure the corrosion rates in water and in the sediments at the 6,000 foot depth were higher than those at the 2,500 foot depth except that they were the same in the sediment after the initial periods of exposure (197 and 123 days). The corrosion rates in water at the 6,000 foot depth decreased with an increase in the duration of exposure. Even though there was an initial increase in the corrosion rates in the sediments at the 6,000 foot depth through the first 403 days of exposure the overall trend was to decrease.

In general, the maximum and average pit depths at the 2,500 foot depth decreased with an increase in the duration of exposure and those in the water were deeper than those in the sediments. The specimens in the water were completely penetrated (77 mils) by pitting corrosion within 197 days of exposure.

At the 6,000 foot depth, the specimens both in the water and in the sediments were completely penetrated by pitting corrosion within 123 days of exposure. After 751 days of exposure there were as many as 35 perforations in one 6" x 12" specimen. For the shorter periods of exposure (123 and 403 days) the average pit depths decreased with an increase in duration and they were deeper in the water than in the sediment.

As shown in Table 9, other types of corrosion manifested on this alloy were, crevice, edge and exfoliation. The crevice corrosion varied from 32 mils after 123 days of exposure to complete penetration (79 mils) during 751 days of exposure. The exfoliation type of corrosion was not severe enough to cause serious delamination as found on the 7039-T6 alloy.

A comparison of the corrosion rates of 7079-T6 at depth in the Pacific Ocean with those in the Atlantic Ocean is shown in Figure 26. This alloy corroded at considerably lower rates at a depth of 5,600 feet in the Atlantic Ocean than at depths of either 2,500 feet or 6,000 feet in the Pacific Ocean. The average and maximum pit depths reported after 111 days of exposure in the Atlantic Ocean¹³ were 16 mils and 11 mils respectively while those found after 123 days in the Pacific Ocean were 77 mils (penetration) and 62 mils respectively.

A comparison of the corrosion rates and pit depths of Alclad 7079-T6 with those of the bare 7079-T6 after equivalent periods of exposure (Table 9) shows the beneficial protection of the cladding alloy in decreasing the depth of pitting.

Alloy 7178-T6

The corrosion rates and pit depths for the 7178-T6 alloy are given in Figure 27.

At the 2,500 foot depth the corrosion rates in water were essentially constant with time but they decreased with an increase in duration of exposure in the sediments. The corrosion rates in the water and in the sediments at the 2,500 foot depth were lower than those at the 6,000 foot depth for equivalent periods of exposure. After an increase in the corrosion rate in water at the 6,000 foot depth during the first 403 days of exposure, the corrosion rate of the 7178-T6 alloy decreased thereafter.

The depth of the pits, maximum and average, at the 2,500 foot depth increased with duration of exposure; there were no pits 1 mil deep after 197 days of exposure. After 123 days of exposure at the 6,000 foot depth, pit depths were deeper than after 197 days at the 2,500 foot depth; however, the reverse was true after 400 days of exposure at these depths. At the 6,000 foot depth the depths of the pits decreased during the first 403 days of exposure and thereafter increased with time of exposure.

OTHER MANIFESTATIONS OF CORROSION

Crevice Corrosion

The data in Tables 3, 4, 5, 6, 8 and 9 show that practically all the aluminum alloys were susceptible to crevice corrosion at depth in the Pacific Ocean. In most cases crevice corrosion was more severe at

depth than at the surface, there being more alloys susceptible at the 2,500 foot depth than at the 6,000 foot depth. The crevice corrosion at the 2,500 foot depth of alloys 1100-H14, 2219-T81, 3003-H14, Alclad 3003-H12, 5052-O, 5454-H32, 5456-H321, 5083-H113, 5086 and 6061-T6 was deeper than at the surface after equivalent periods of exposure. At the 6,000 foot depth crevice corrosion of aluminum alloys 2219-T81, 3003-H14, Alclad 3003-H12, 5052-O and 6061-T6 was more severe than at the surface for equivalent periods of exposure. At the 2,500 foot depth crevice corrosion was more severe than at the 6,000 foot depth after equivalent periods of exposure of alloys 1100-H14, 2024-O, 3003-H14, 5456-H321, 5083-H113, 6061-T6, 7002-T6, Alclad 7002-T6 and 7079-T6.

These data show that in general the severity of crevice corrosion increased as the concentration of oxygen in the water decreases.

Intergranular Corrosion

Metallurgical examinations of the alloys showed the presence of intergranular corrosion and intergranular precipitation as given in Table 10. The intergranular type of corrosion varied in depth from 5 to 6 grains deep 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 28 to 31. 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 appeared 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 with an electron microscope would be required to determine the presence or absence of intermetallic compounds at the grain boundaries.

An illustration of the effect of strain-hardening and a low temperature stabilization treatment on the corrosion behavior of 5086 aluminum alloy is shown in Figure 32. The 1/2-inch thick rolled plate in the -H32 condition and the 1/8-inch thick 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 intergranular precipitation and intergranular corrosion of the 5086-H34 alloy is shown in Figure 28. 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 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.

A practical case of unusual 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 300 feet below the surface, was found to be corroded (Figure 33). The white corrosion products on the bottom hemisphere cover areas where the cladding alloy had corroded through to the core material. The top hemisphere was blistered, the blisters being as large as 2 inches in diameter and 0.1 inches high. One of these blisters is shown in Figure 34. The hole in the top of the blister indicates the origin of the failure: originally a pinhole in the cladding alloy where sea water 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 35). It appeared that sea water penetrated the cladding alloy at a defect or a pit was initiated at a particle of a cathodic metal (probably iron), and the corrosion was then concentrated at the interface between the two alloys (cladding alloy and core alloy). 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.

When an attempt was made to repair these buoys for reuse by grinding off all traces of corrosion prior to 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 cladding alloy layer had been sacrificed. Polished transverse sections taken from the buoy through these corroded areas corroborated the indications found from grinding operations. An illustration of this interfacial penetration is shown in Figure 36. Metallurgical examinations showed that the corroded paths were, in fact, entirely in the cladding alloy, with a thin diffusion layer of material between the corrosion path and the core material, as shown in Figure 37. 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. Blistering due to corrosion and the rapid rate of sacrifice of Alclad layers had not been encountered previously by the author and other investigators in surface water applications. Because of this unique blistering one of the spheres was sent to the Research Laboratories of the Aluminum Company of America where an investigation was made to determine the mechanism of this behavior.

Wei¹⁹ showed that there was preferential diffusion of zinc over

copper from the core alloy into this interfacial zone. The high zinc and low copper contents of this interfacial zone rendered it anodic to both the cladding and core alloys. Selective attack was inevitable once corrosion reached this anodic diffusion zone.

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 sea water exposures indicates that the sea water environments at depths of 300 feet and greater differ from the sea water environments at the surface, at least with respect to the corrosion behavior of this alloy.

Stress Corrosion

Specimens of the aluminum alloys given in Table 11 were exposed in the stressed condition at stresses equivalent to 50 or 75 percent of their respective yield strengths. Alloys 2219-T87, 7079-T6, Alclad 7079-T6 and 7178-T6 failed by stress corrosion cracking during 402 days of exposure at the 2,500 foot depth.

These same four alloys were also attacked by intergranular corrosion when in the unstressed condition as shown in Table 10.

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 of corrosion products at different depths and for different times of exposure were as follows:

<u>Source of Products</u>	<u>Findings</u>
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.
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.
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.

MECHANICAL PROPERTIES

The original mechanical properties of the aluminum alloys are given in Table 12 and the percentage change in these mechanical properties due to exposure at depths in the water are shown graphically in Figures 38 to 41.

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 manifested by a decrease in the elongation because of the susceptibility of aluminum alloys to pitting in sea water. This is illustrated by the large decreases in the percent elongation of the Alclad 3003-H12 alloy after 123, 402, 751 and 1064 days of exposure.

The mechanical properties of 1100-H14, 1180, all the 5000 series alloys except 5456-H321 after 751 days of exposure, Alclad X7002-T6 and Alclad 7079-T6 were not affected by exposure in water at depths of 2,500 and 6,000 feet.

The alloys whose mechanical properties were adversely affected were 2014-T6, 2219-T81, 2219-T87, 3003-H14, Alclad 3003-H12, 5456-H321 after 751 days of exposure, 6061-T6, X7002-T6, 7039-T6, 7079-T6 and 7178-T6. In some cases the pitting corrosion (7079-T6) and exfoliation (7039-T6) were so severe that it was not possible to conduct tensile tests.

The tensile strength of 6061-T6 aluminum alloy continuously immersed in flowing sea water (1.25 ft./sec.) at Kure Beach, N.C., increased by 1 percent after 3 years of exposure²⁰ as contrasted to a decrease of 11 percent after 35 months of exposure at a depth of 6,000 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 two years of continuous immersion in sea water at Hayling Island off the coast of England.²¹ This indicates that sea water at a depth of 6,000 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.

The protective value of Alclad coatings in preventing adverse effects on the mechanical properties of the alloys is illustrated in Figure 41. Comparing the changes in the mechanical properties of X7002-T6 with those of Alclad X7002-T6 and those of 7079-T6 with those of Alclad 7079-T6 after equivalent periods of exposure shows that those of the bare alloys were adversely affected while those of the Alclad alloys were unaffected.

SUMMARY

The purpose of this investigation was to determine the effects of deep ocean environments on the corrosion of aluminum alloys. To accomplish this a total of 900 specimens of 40 different alloys were exposed

at nominal depths of 2,500 and 6,000 feet in the Pacific Ocean for six time periods varying from 123 to 1064 days.

All the aluminum alloys exposed at depth in the Pacific Ocean were attacked by pitting, edge or crevice corrosion. The depths of the pits of the bare alloys varied from incipient pitting (less than 1 mil) to complete penetration (125 mils). The pittings of the Alclad alloys was to complete penetration of the cladding alloys with pitting of the core alloys. Most of the alloys were susceptible to crevice corrosion and many of them were completely penetrated.

There were no definite correlations or trends exhibited by the aluminum alloys with regard to the depths of pits between exposures at the surface and at depths in the Pacific Ocean. For example, the maximum pit depths were deeper at depths than at the surface for equivalent periods of exposure for the following alloys: 2024-0 after 400 days of exposure; 3003-H14 at the 2,500 foot depth; Alclad 3003-H12; 5454-H32; 5456-H321 at the 2,500 foot depth; 5083-H113; 5083-H113 welded; 5086-H34 at the 2,500 foot depth; and 6061-T6. The maximum depths of the pits of the following alloys were deeper at the surface than at depths: 2024-0 after 6 months; 2219-T6 at a depth of 6,000 feet; 3003-H14 at the 6,000 foot depth; 5456-H321 at the 6,000 foot depth; and 5086-H34 at the 6,000 foot depth. Although there were twice as many cases where the maximum pit depths were deeper at depth than at the surface, there was no consistency in the behavior of the alloys themselves; sometimes there were reversals with regard to duration of exposure and in others, with regard to depth of exposure.

The maximum pit depths at the 2,500 foot depth were deeper than at the 6,000 foot depth after equivalent periods of exposure on alloys 2219-T6; 3003-H14 after 6 months; welded 5454-H32 after 6 months; 5456-H321 in sea water; 5086-H34; 6061-T6; and 7079-T6 after 400 days. For the reverse situation where the maximum pit depths were deeper at the 6,000 foot depth than at the 2,500 foot depth the following alloys were in this category; 1100-H14; 2024-0 after 6 months; 3003-H14 after 400 days; 5454-H32; welded 5454-H32 after 400 days; 5456-H321 in the sediments; 5456-H321; 5083-H113; welded 5083-H113; 7079-T6; and 7178-T6 after 6 months.

In some cases, the maximum pit depths were deeper in the sediments than in the water: alloys in this category were 1100-H14; 2219-T6; 3003-H14; 5086-H34; 6061-T6 and; 7039-T6. Alloys whose maximum pit depths were deeper in water than in the sediments were 2014-T6; 2024-0; 5454-H32; welded 5083-H113; 7079-T6 and 7178-T6. In the case of alloys; welded 5454-H32, and 5456-H321 the maximum pit depths were the same at both the 2,500 and 6,000 foot depths.

There were more cases where the depths of the maximum pits increased with time of exposure than where they did not increase with time of exposure; the ratio was about 3:2. The greater majority of the increases in maximum pit depths with time were exposures in water. Those alloys whose maximum pit depths increased with time were:

1100-H14 in the sediment at the 6,000 foot depth; 2024-0 at the surface, in water at 2,500 feet and in both water and the sediment at 6,000 feet; 2219-T81 at the surface, in both water and the sediments at 2,500 and 6,000 feet; 3003-H14 in both water and the sediments at 2,500 and 6,000 feet; welded 5454-H32 in water at 2,500 and 6,000 feet; 5456-H321 in water at 2,500 feet; 5083 in the sediment at 2,500 feet; welded 5083-H113 in water at 2,500 and 6,000 feet; 5086-H34 in water and the sediments at 6,000 feet; 6061-T6 at the surface, and in both water and the sediments at 2,500 and 6,000 feet; and 7178-T6 in water at 6,000 feet. Those alloys whose maximum pit depths did not increase with increasing duration of exposure were: welded 5454-H32 in the sediments at 2,500 and 6,000 feet; 5456-H321 in the sediments at 2,500 and 6,000 feet; welded 5083-H113 in the sediments at 2,500 feet; 5086-H34 in water and the sediment at 2,500 feet, and; 7079-T6 in water and the sediment at 2,500 feet.

The average pit depth data were very similar to the maximum pit depth data with regard to increasing or decreasing in depth with increasing duration of exposure and the majority of the increases being in sea water exposures.

Averaging the corrosion rates and the average pit depths of all the 5000 series alloys showed that in water: after 6 months of exposure the corrosion rates at the surface were higher than at depth; after 400 days of exposure the corrosion rates at the surface and at the 2,500 foot depth were the same but lower than that at the 6,000 foot depth; at the surface and at 2,500 feet the corrosion rates decreased with increasing duration of exposure; at 6,000 feet the corrosion rates increased during the first 400 days of exposure and thereafter decreased through 1064 days of exposure. In the sediments the corrosion rates at the 2,500 foot depth decreased with increasing duration of exposure but at the 6,000 foot depth there were variations with duration of exposure with the overall being nearly constant with increasing duration of exposure. In water the average pit depths were deeper at depths than at the surface; at 2,500 feet they increased in depth with time; at 6,000 feet they increased in depth through the first 400 days of exposure and thereafter were essentially constant. The average depth of the pits decreased with increasing duration of exposure in the sediments at 2,500 feet and there was an overall increase in the average pit depths with time at the 6,000 foot depth.

Groove corrosion, however, was consistently more severe at depth than at the surface.

Many of the alloys corroded intergranularly; 2014-T3, 2024-T3, 2219-T81, 2219-T87, 3003-H14, 5454-H32 welded, 5456-H321, 5456, 5456-H343, 5083-H113, 5083-H113 welded, 5086-H32, 5086-H34, 6061-T6, 7002-T6, 7039-T6, 7075-T6, Alclad 7075-T6, 7079-T6, Alclad 7079-T6 and 7178-T6. Alloys 2024-T3, 7039-T6, 7075-T6, 7079-T6 and 7178-T6 were also exfoliated.

Alloys 2219-T87, 7079-T6, Alclad 7079-T6 and 7178-T6 were susceptible

to stress corrosion cracking at depth in the Pacific Ocean.

Because of the proneness of aluminum alloys to localized corrosion, corrosion rates calculated from weight loss data are not satisfactory criteria by themselves for assessing the corrosion behavior of aluminum alloys as they are for other classes of alloys such as the low-alloy steels. However, when considered with other corrosion criteria such as pitting, crevice attack, intergranular corrosion, etc. they do contribute to the complete picture.

For equivalent periods of exposure the following alloys corroded at greater rates at depths in the Pacific Ocean than at the surface: 1100-H14, 2024-0 at 6,000 feet; 3003-H14 at 2,500 feet; Alclad 3003-H12; 5052-0 after 6 months at 2,500 and 6,000 feet; 5454 after 1 year at 6,000 feet; 5456-H321 at 2,500 feet; 5083-H113 after 1 year at 2,500 and 6,000 feet, and; 6061-T6 at 2,500 feet. Those alloys which corroded at greater rates at the surface than at depth were: 2024-0 at 2,500 feet; 2219-T81; 3003-H14 after 6 months at 6,000 feet; 5052-0 after 1 year at 2,500 feet; 5454 at 2,500 feet; 5456-H321 at 6,000 feet; 5083-H113 after 6 months at 2,500 feet; welded 5083-H113; 5086-H34 and; 6061-T6 at 6 000 feet.

At the 2 500 foot depth the following alloys corroded at greater rates than at the 6 000 foot depth: 1100-H14 after 6 months in water; 2219-T6 after 6 months in water and sediment and 1 year in water; 3003-H14 after 6 months in water; Alclad 3003-H12 after 6 months in water and 1 year in water and sediment; welded 5454-H32 after 6 months in water and 1 year in the sediment; 5456-H321 after 6 months in water and the sediment and 1 year in the sediment; welded 5083-H113 after 6 months in water; 5086-H34 after 6 months in water and 1 year in water and sediment and; 6061-T6.

The following alloys corroded at greater rates at the 6,000 foot depth than at the 2,500 foot depth; 1100-H14 after 6 months in the sediment and 1 year in water and the sediment; 2024-0; 2219-T81 after 1 year in the sediment; 3003-H14 after 6 months in the sediment and 1 year in water and the sediment; Alclad 3003-H12 after 6 months in the sediment; 5052-0; 5454-H32; welded 5454-H32 after 6 months in the sediment and 1 year in water; 5456-H321 after 1 year in water; 5456-H343 in water; 5083-H113; welded 5083-H113 after 6 months in the sediment and 1 year in water and the sediment; 5086-H34 after 6 months in the sediment; 7079-T6 and; 7178-T6.

The corrosion rates of the following alloys increased with duration of exposure: 1100-H14 in the sediment at 2,500 feet; 2024-0 at the surface and in the sediment at 2,500 feet; 2219-T81 in water at 2,500 feet; 3003-H14 in the sediment at 2,500 feet; Alclad 3003-H12 in the sediment at 2,500 feet; welded 5454-H32 at 2,500 feet; 5083-H113 in water at 2,500 feet; welded 5083-H113 at 2,500 feet and in the sediment at 6,000 feet; 5086-H34 in the sediment at 2,500 feet; 6061-T6 at 2,500 feet and; 7178-T6 in water at 2,500 feet.

The corrosion rates of the following alloys decreased with increas-

ing duration of exposure: 1100-H14 at the surface and in the water at 2,500 feet; 2024-0 in water at 2,500 feet; 3003-H14 at the surface, in water at 2,500 feet and in the sediment at 6,000 feet; Alclad 3003-H12 at the surface and in the water at 2,500 and 6,000 feet; 5454-H32 at the surface and at 2,500 feet; welded 5454-H32 in the sediment at 6,000 feet; 5456-H321 at 2,500 feet; 5083-H113 at the surface and in the sediment at 2,500 feet; 5086-H34 in water at 2,500 feet; 6061-T6 at the surface; 7079-T6 at 2,500 feet and in water at 6,000 feet and; 7178-T6 in the sediment at 2,500 feet.

There was neither a constant increase nor a constant decrease in the corrosion rates with increase in duration of exposure of some of the alloys at the 6,000 foot depth. They were: 1100-H14 in water, the corrosion rates increased through 751 days and then decreased with an overall increase; 1100-H14 in the sediments where there was an overall decrease; 2024-0 in water where the corrosion rates increased through 400 days of exposure and thereafter decreased with an overall decrease; 2024-0 in the sediments where there was an overall decrease; 2219-T81 in water where there was an increase through 400 days and thereafter a decrease with a net decrease; 2024-0 in the sediment where there was an increase through 400 days and thereafter a decrease with an overall increase; 3003-H14 in water where there was an increase through 400 days and thereafter a decrease with an overall increase; Alclad 3003-H12 in the sediment where there was an overall decrease. Also, 5454-H32 in water where there was an increase through 400 days and thereafter a decrease with an overall increase; 5456-H321 in water where there was an increase through 750 days and thereafter a decrease with an overall increase; 5456-H321 in the sediments where the corrosion rates decreased, increased, and again decreased with an overall decrease; 5456-H343 in water where there was an overall decrease; welded 5083-H113 in water where there was an overall increase; 5086-H34 in water where there was an increase through 750 days and thereafter a decrease with an overall increase; 5086-H34 in the sediment where there was a decrease followed by an increase with a slight overall decrease; 6061-T6 in water where there was an increase through 750 days and thereafter a decrease with the corrosion rates becoming practically constant after 400 days of exposure, 6061-T6 in the sediment where the overall corrosion rate was nearly constant through 1064 days of exposure; 7079-T6 in the sediment where there was a slight increase followed by a decrease with an overall decrease and; 7178-T6 in water where there was an increase through 400 days and thereafter a decrease with an overall decrease.

Comparisons of the deep ocean data and surface data from both the Atlantic and Pacific Oceans showed differences in behavior. The corrosion rates of alloys 1100-H14, 5086-H34, 6061-T6 and 7079-T6 were greater at a depth of 6,000 feet in the Pacific Ocean than at a depth of 5,600 feet in the Tongue-of-the-Ocean, Atlantic Ocean and that of 5052 was greater than at a depth of 4,500 feet in the Tongue-of-the-Ocean, Atlantic Ocean. The corrosion rate of 1100-H14 in the sediment

at a depth of 6,000 feet was the same as that in water at a depth of 5,600 feet in the Tongue-of-the-Ocean, Atlantic Ocean after 1050 days of exposure. The corrosion rates at a depth of 6,000 feet in the Pacific Ocean were greater than at the surface at the given locations for the following alloys: 1100-H14 at Harbor Island, Panama Canal, Port Hueneme Harbor and Point Mugu; 3003-H14 and 5052 at Harbor Island, Port Hueneme Harbor and Point Mugu; and 6061-T6 at Harbor Island, and the Panama Canal. After 1 year of exposure the corrosion rates of 1100-H14 alloy in the sediment at a depth of 2,500 feet was the same as those at the surface at Harbor Island, Panama Canal and Point Mugu. The corrosion rates of alloy 3003-H14 at the 2,500 foot depth were the same as those at the surface at Port Hueneme Harbor after one year of exposure; and those at the surface at Port Hueneme Harbor were twice those at the surface at Point Mugu. The corrosion rates of alloy 5052 at a depth of 2,500 feet were the same as those at the surface at Harbor Island, Port Hueneme Harbor and Point Mugu. The corrosion rates of welded 5083-H113 at depths of 2,500 and 6,000 feet and the unwelded alloy at a depth of 2,500 feet were greater than those at the surface at Harbor Island. The corrosion rates of the unwelded and welded 5083-H113 at the 2,500 foot depth were the same as those at the surface at Point Mugu after one year of exposure and were higher than those at Harbor Island.

Before aluminum alloys can corrode in any environment, the naturally formed protective oxide film must fail, thus permitting access of the environment to the bare metal surface. The time to failure is directly influenced by the environment and by the influence of alloying ingredients in the alloy on the morphology and the properties of the oxide film. In a surface sea water environment this protective oxide film breaks down more readily than in most other environments and its repair and growth is retarded by the chloride ion.

In surface sea water the corrosion rates of aluminum alloys usually decrease with time. Surface sea water is saturated with oxygen at all times, the pressure is atmospheric, the pH is usually about 8.0, the temperature varies with the seasons, and there is usually movement of the sea water (tidal action).

At the depths at which these exposures were conducted the concentrations of oxygen in the sea water were much lower than at the surface, the temperatures were constant and much lower than at the surface, there were no appreciable currents, the pH values were lower than at the surface, and the pressures were higher than at the surface. In addition, there was significant amounts of phosphate in the sea water as indicated by the presence of significant amounts of phosphate in the aluminum alloy corrosion products. Another condition was the presence of a transparent, hard, shiny film which had formed on some of the alloys particularly during the first 123 days of exposure at the 6,000 foot depth.

The protective oxide films on the aluminum alloys were undoubtedly

affected by one or more of the above variables such that they failed in a different manner or in a different period of time. This difference in behavior, in turn, influenced the corrosion behavior of the alloys such that, for many of them, their corrosion rates were erratic as shown in the previous paragraphs.

Maximum pit depths at depths of 2,500 and 6,000 feet of alloys 1100, 3003 and 6061-T6 were deeper than those at the surface at Harbor Island after equivalent periods of exposure.

The cladding alloys on the Alclad alloys effectively protected the core alloys against pitting corrosion and impairment of mechanical properties for the duration of time they were exposed at depth.

Corrosion products consisted of amorphous $\text{Al}_2\text{O}_3 \cdot x\text{H}_2\text{O}$, NaCl , SiO_2 , Na , Mg , Si , Cu , Fe , Ti , Ca , Mn , Zn , chloride, sulphate and phosphate ions.

The mechanical properties of 1100-H14, 1180, the 5000 Series alloys except 5456-H321, Alclad 7002-T6 and Alclad 7079-T6 were unaffected by exposure at depth in the Pacific Ocean. The alloys whose mechanical properties were adversely affected by exposure at depth in the Pacific Ocean were: the 2000 Series alloys; the 3000 Series alloys; 5456-H321; 6061-T6; and the 7000 Series alloys except Alclad 7002-T6 and Alclad 7079-T6.

CONCLUSIONS

Based on corrosion rates, exfoliation attack, depth of crevice corrosion, and maximum and average pit depths, water at depth in the Pacific Ocean was judged to be more aggressive than at the surface.

The sediment was considered more corrosive than the water at depth because of the large areas of attack on the portions of the specimens embedded in the sediment.

The alloys which were susceptible to the exfoliation type of corrosion would not be suitable for sea water applications. These alloys were 2024-T3, 7039-T6, 7075-T6, 7079-T6 and 7178-T6.

The balance of the aluminum alloys, because of either pitting or crevice attack or both and the lowering of their mechanical properties, should not be used for sea water applications without suitable protection. Protection such as painting, anodizing or galvanic anodes preferably in combination should be provided.

The cladding alloys on the Alclad alloys protected the core alloys from corrosion and adverse effects on their mechanical properties. However, because of the rapid rate of removal of the sacrificial cladding alloys protection should be provided to them for sea water applications.

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Table 1. STU Locations and Bottom Water Characteristics

Site No.	Lat. N	Longit. W	Depth, ft	Exposure, Days	Temp. °C	Oxygen, ml/l	Salinity, ppt	pH	Current Knots, Av.
Surface	-	-	65	-	11-17	5.4-6.5	33.76	7.9-8.3	Variable
I-1	33°46'	120°37'	5300	1064	2.6	1.2	34.51	7.5	0.03
I-2	33°44'	120°45'	5640	751	2.3	1.3	34.51	7.6	0.03
I-3	33°44'	120°45'	5640	123	2.3	1.3	34.51	7.6	0.03
I-4	33°46'	120°46'	6780	403	2.2	1.6	34.40	7.7	0.03
II-1	34°06'	120°42'	2340	197	5.0	0.4	34.36	7.5	0.06
II-2	34°06'	120°42'	2370	402	5.0	0.4	34.36	7.5	0.06
V	34°06'	119°07'	5	181	12-19	3.9-6.6	33.51	8.1	Variable

Table 2. Chemical Composition of Aluminum Alloys, Percent by Weight.

Alloy	Gauge (in.)	Si	Fe	Cu	Mn	Ng	Cr	Ni	Zn	Ti	Al (3)
1100	--	--	--	--	--	--	--	--	--	--	99.0
1100-0	--	0.57	(Si + Fe)	0.14	0.03	--	--	--	--	--	R
1100-H14	0.050	0.14	0.55	0.14	--	--	--	--	0.06	--	R
1180-H14	0.050	0.06	0.08	0.002	0.002	--	--	--	--	--	R
2014-T6	0.050	0.91	0.53	4.23	0.80	0.32	0.03	0.01	0.08	0.02	R
2024	0.064	--	--	4.3	0.6	1.5	--	--	--	--	R
2219-T81(1)	0.064	0.20	0.30	6.3	0.30	0.02	--	--	0.10	0.06	R
2219-T87(2)	0.040	0.08	0.12	6.54	0.26	0.02	0.02	0.02	0.03	0.02	R
3003-H14	0.125	0.60	0.70	0.20	1.25	--	--	--	0.10	--	R
3003-H14	0.063	0.20	0.58	0.13	1.05	0.01	0.01	0.01	0.01	--	R
3003-	--	0.15	0.45	0.15	1.25	--	--	--	0.05	--	R
3003-H24	--	0.10	0.48	0.16	1.10	--	--	--	0.08	--	R
3003	--	--	--	--	1.2	--	--	--	--	--	R
Alclad 3003-H12	0.125	0.06	0.70	0.20	1.25	--	--	--	0.10	--	R
Core		0.70	(Si + Fe)	0.10	0.10	0.10	--	--	1.0	--	R
Cladding											
5050-H34	0.050	0.18	0.64	0.04	--	1.19	--	--	--	--	R
5052	--	--	--	--	--	2.5	0.25	--	--	--	R
5052-H22	--	0.23	(Si + Fe)	0.05	0.01	2.50	0.23	--	0.07	--	R
5052-H34	0.050	0.13	0.30	0.02	--	2.31	0.22	--	--	--	R
5454-H32	0.162	0.40	(Si + Fe)	0.10	0.75	2.7	0.13	--	0.25	0.20	R
5454	--	--	--	--	0.03	1.0	0.02	--	--	--	R
5456-H321	0.125	0.40	(Si + Fe)	0.10	0.75	5.0	0.13	--	0.25	0.20	R
5456-H34	0.050	0.18	0.32	0.36	0.26	5.08	0.02	0.02	0.05	--	R
5456-H343	0.125	0.40	(Si + Fe)	0.10	0.75	5.0	0.13	0.02	0.25	0.20	R
5083-H113	0.500	0.40	0.40	0.10	0.65	4.5	0.15	--	0.25	0.15	R
5083	--	--	--	0.15	0.6	4.5	--	--	--	--	R
5086-H34	0.125	0.40	0.50	0.10	0.45	4.0	0.15	--	0.25	0.15	R
5086-H32	0.064	0.15	0.25	0.05	0.32	3.75	0.12	--	0.12	0.01	R
5086	--	--	--	--	0.3	4.0	0.15	--	--	--	R
6061-T6	0.125	0.60	0.70	0.27	0.15	1.0	0.25	--	0.25	0.15	R
6061	--	--	--	0.25	--	1.0	0.28	--	--	--	R

Table 2. (cont'd)

Alloy	Gauge (in.)	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Al(3)
7002-T6	0.063	0.11	0.17	0.78	0.17	2.73	0.19	<0.02	3.76	0.04	R
Alclad 7002-T6	0.063	--	--	--	--	--	--	--	--	--	--
Core (7002)	--	--	--	0.75	0.18	2.5	0.20	--	3.5	--	R
Cladding (7072)	--	--	--	--	--	--	--	--	1.0	--	R
7039-T6	0.250	0.11	0.17	--	0.22	2.8	0.21	--	4.0	0.02	R
7039-T64	0.500	0.30	0.40	0.10	0.25	2.8	0.20	--	4.0	0.10	R
Alclad 7075-0	--	--	--	--	--	--	--	--	--	--	--
Core (7075)	--	0.17	0.25	1.53	0.06	2.45	0.22	--	5.65	0.03	R
Cladding (7072)	--	0.39	(Si + Fe)	0.05	<0.01	0.10	0.03	--	1.34	--	R
7079-T6	0.063	0.14	0.12	0.64	0.20	3.50	0.16	--	4.30	0.03	R
Alclad 7079-T6	0.063	--	--	--	--	--	--	--	--	--	--
Core (7079)	--	--	--	0.6	0.2	3.3	0.17	--	4.3	--	R
Cladding (7072)	--	--	--	--	--	--	--	--	1.0	--	R
7178-0	--	0.19	0.15	1.73	0.05	2.50	0.19	--	6.31	0.04	R
7178-T6	0.064	0.50	0.70	2.0	0.03	2.75	0.3	--	6.8	0.10	R
7178-T6	0.050	0.12	0.25	1.75	0.02	2.44	0.25	--	6.67	0.06	R

Footnotes

- (1) Other elements present are: 0.10% V, 0.17% Zr.
 (2) Other elements present are: 0.10% V, 0.15% Zr.
 (3) R = Remainder

Table 3. Corrosion Rates and Pit Depths of Aluminum (1000 Series)

Alloy	Envl-(1) ronment	Exposure		Corro- sion Rate, MPY(2)		Pit Depth, Mils		PFTR(3)	Crevice Corrosion Depth, Mils(4)	Type of Corro- sion(4)	Source(5)
		Days	Depth Feet	MPY(2)		Max.	Ave.				
1100-H14	W	123	5640	2.0		39	-	19.5	-	P	INCO (10)
1100-H14	S	123	5640	3.1		41	-	13.2	-	P	INCO (10)
1100-H14	W	403	6780	4.1		-	-	-	62(PR)	SC	INCO (10)
1100-H14	S	403	6780	1.3		62(PR)	-	47.7	62(PR)	SC,SP	INCO (10)
1100-H14	W	751	5640	4.5		-	-	-	62(PR)	SC	INCO (10)
1100-H14	S	751	5640	2.0		-	-	-	62(PR)	SC	INCO (10)
1100-O	W	1064	5300	3.0		-	-	-	62(PR)	SC	INCO (10)
1100-H14	W	1064	5300	1.8		-	-	-	-	SP,SC	INCO (12)
1100-H14	S	1064	5300	1.0		-	-	-	62(PR)	SC	INCO (10)
1100-H14	W	197	2340	5.6		-	-	-	62(PR)	SC	INCO (10)
1100-H14	S	197	2340	<0.1		-	-	-	-	IP,IC	INCO (10)
1100-H14	W	402	2370	1.6		-	-	-	-	SC	INCO (10)
1100-H14	S	402	2370	0.5		26	-	52.0	62(PR)	C,P	INCO (10)
1100-H14	W	402	2370	0.9		-	-	-	26	SC,IP	NCEL
1100-H14	S	402	2370	0.5		-	-	-	50(PR)	SC,IP	NCEL
1100-H14	W	182	5	1.4		-	-	-	50(PR)	SC	INCO (10)
1100-H14	W	366	5	0.6		13	-	21.7	13	SC,P	INCO (10)
1180-H14	W	402	2370	1.0		-	-	-	50(PR)	SC,IP	NCEL
1180-H14	S	402	2370	0.8		-	-	-	50(PR)	SC,IP	NCEL

- (1) W - Totally exposed in sea water on sides of structure. S - Exposed in base of structure so that the lower portions of the specimens were embedded in the bottom sediments.
(2) MPY - mils penetration per year calculated from weight loss.
(3) Fitting factor - maximum measured pit depth divided by MPY.
(4) Symbols for types of corrosion: C - Crevice; I - Incipient; P - Pitting; S - Severe; PR - Perforation.
(5) Numbers refer to references at end of paper.

Table 4. Corrosion Rates and Pit Depths of Aluminum-Copper Alloys. (2000 Series)

Alloy	Environ- ment (1)	Exposure		Corrosion Rate, MPY (2)	Pit Depth, Mils		Pitting		Crevice Corrosion Depth, Mils	Type of Corrosion (5)	Source (6)
		Days	Depth, Feet		Max	Ave	FFQ (3)	PFTR (4)			
2014-T6	W	402	2370	5.4	27.0	19.3	4.5	5.0	50 (PR)	SC, P, IG	NCEL
2014-T6	S	402	2370	3.5	25.0	16.4	1.9	7.1	50 (PR)	SC, P, IG	NCEL
2024-0	W	123	5640	5.2	28.0	--	--	5.4	--	P	INCO (10)
2024-0	S	123	5640	3.4	27.0	--	--	7.9	--	P	INCO (10)
2024-0	W	403	6780	6.2	62 (PR)	--	--	10.0	--	SP	INCO (10)
2024-0	S	403	6780	1.2	--	--	--	--	55	SC	INCO (10)
2024-0	W	751	5640	2.8	65 (PR)	--	--	23.2	65 (PR)	SC, SP	INCO (10)
2024-0	S	751	5640	2.6	65 (PR)	--	--	25.0	--	SP	INCO (10)
2024-0	W	1064	5300	1.9	62 (PR)	--	--	32.6	62 (PR)	SC, SP	INCO (10)
2024-T3	W	1064	5300	1.9	--	--	--	--	--	C, P, XF	INCO (12)
2024-0	S	1064	5300	1.6	55.0	--	--	34.4	--	SP	INCO (10)
2024-0	W	197	2340	3.1	19.0	--	--	6.1	--	SE, P	INCO (10)
2024-0	S	197	2340	0.1	--	--	--	--	--	IC, IP	INCO (10)
2024-0	W	402	2370	3.0	62 (PR)	--	--	--	62 (PR)	SC, SP	INCO (10)
2024-0	S	402	2370	0.8	--	--	--	--	--	E	INCO (10)
2024-0	W	181	5	3.8	32	--	--	8.4	32	C, P	INCO (10)
2024-0	W	366	5	4.1	34	--	--	8.3	34	C, P	INCO (10)
2219-T81	W	123	5640	2.0	16.0	12.1	9.0	8.0	15	C, GP, IG	NCEL
2219-T81	S	123	5640	1.9	20.0	15.8	7.0	10.8	10	C, GP, IG	NCEL
2219-T81 (1x6)	W	403	6780	2.9	14.0	11.0	10.7	4.8	27	C, E, GP, IG	NCEL
2219-T81	S	403	6780	4.2	35.0	24.7	3.5	8.3	38	C, E, GP, IG	NCEL
2219-T81 (1x6)	S	403	6780	3.4	24.0	15.5	4.1	7.1	26	C, E, GP, IG	NCEL
2219-T81	S	403	6780	2.7	62 (PR)	19.7	3.4	23.7	34	C, E, GP, IG	NCEL
2219-T81	W	751	5640	2.4	30.0	18.7	3.0	12.5	24	C, E, GP, IG	NCEL
2219-T81	W	1064	5300	1.5	47.0	20.4	11.4	3.3	--	SLE, GP, IG	NCEL
2219-T81 (1x6)	W	1064	5300	1.6	26.0	19.2	5.0	16.2	47	C, GP, IG	NCEL
2219-T81	S	1064	5300	1.5	48.0	25.0	9.3	32.0	--	GP, IG	NCEL
2219-T81	W	197	2340	2.6	25.0	18.8	33.4	9.6	--	SLE, GP, IG	NCEL
2219-T81	S	197	2340	2.0	32.0	16.3	18.5	16.0	--	E, GP, IG	NCEL
2219-T81	W	402	2370	4.5	78.0	58.3	0.2	17.3	69	C, SE, SP, IG	NCEL
2219-T81	S	402	2370	2.0	50.0	29.4	0.3	25.0	66	C, SE, SP, IG	NCEL
2219-T81	W	181	5	3.5	24.0	19.4	6.7	6.9	--	GP, IG	NCEL
2219-T87 (1x6)	W	402	2370	1.7	20.0	13.9	8.3	11.8	40 (PR)	SC, UP, IG	NCEL
2219-T87 (1x6)	S	402	2370	1.1	16.0	10.8	5.9	14.5	40 (PR)	SC, UP, IG	NCEL

Table 4. (cont'd)

- (1) W - totally exposed in sea water on sides of structure.
 S - exposed in base of structure such that the lower portions of the specimens were embedded in the bottom sediment.
- (2) MPY - Mils penetration per year calculated from weight loss.
- (3) Pitting Frequency - number of pits per square inch of surface.
- (4) Pitting Factor - maximum measured pit depth in mils divided by MPY.
- (5) Symbols for types of corrosion:
- C - Crevice
 - E - Edge
 - G - General
 - I - Incipient
 - P - Pitting
 - PR - Perforation
 - S - Severe
 - SL - Slight
 - U - Uniform
 - XF - Exfoliation
 - IC - Intergranular corrosion
- (6) Numbers refer to reference at end of paper.

Table 5. Corrosion Rates and Pit Depths of Aluminum-Manganese Alloys (3000 Series)

Alloy	Environ- ment	Exposure		Corrosion		Pit Depth		Pitting		Crevice Corrosion, Depth, Mils	Type of Corrosion ⁵	Source ⁶
		Days	Depth, Feet	Rate MPY ²		Max	Ave	PFQ ³	PFTR ⁴			
3003-H14	W	123	5640	0.5		27	19.4	4.8	54.0	32	C, P	NCEL
3003-	W	123	5640	0.6		--	--	--	--	28	C	INCO(10)
3003-H14	W	123	5640	1.9		55.0	50.4	4.7	29.0	68	C, E, P	NCEL
3003-	S	123	5640	3.6		--	--	--	--	50 (PR)	S	INCO(10)
3003-H14	W	403	6780	3.9		125 (PR)	82.2	0.4	32.1	66	SC, SP	NCEL
3003-	W	403	6780	3.8		--	--	--	--	50 (PR)	SC	INCO(10)
3003-H14	S	403	6780	3.7		125 (PR)	77.0	0.3	33.8	52	SC, SP	NCEL
3003-	S	403	6780	1.3		--	--	--	--	50 (PR)	SC	INCO(10)
3003-H14	W	751	5640	2.3		125 (PR)	64.1	1.0	54.3	125 (PR)	SC, SP	NCEL
3003-	W	751	5640	3.0		--	--	--	--	40 (PR)	SC	INCO(10)
3003-H14	S	751	5640	2.5		125 (PR)	86.9	0.3	50.0	125 (PR)	SC, SP	NCEL
3003-	S	751	5640	1.8		--	--	--	--	40 (PR)	SC	INCO(10)
3003-H14	W	1064	5300	2.1		29.0	12.1	0.5	13.8	94	SC, SP, E	NCEL
3003-H14	W	1064	5300	2.2		125 (PR)	85.0	1.4	56.8	--	SC, SP, SE	INCO(10)
3003-	W	1064	5300	2.8		--	--	--	--	--	(7)	NCEL
3003-	W	1064	5300	1.8		--	--	--	--	--	SC, SE	INCO(12)
3003-H24	W	1064	5300	1.8		--	--	--	--	--	SC, E	NCEL(12)
3003-H14	S	1064	5300	1.9		125 (PR)	76.0	1.5	65.8	--	EXE, SP	NCEL
3003-	S	1064	5300	1.0		--	--	--	--	50 (PR)	SC	INCO(10)
3003-H14	W	197	2340	2.4		48.0	16.0	1.6	20.0	28	SE, P, C	NCEL
3003-	W	197	2340	1.4		--	--	--	--	40 (PR)	SC	INCO(10)
3003-H14	S	197	2340	1.6		55	20.6	0.3	26.5	25	C, E, SP	NCEL
3003-	S	197	2340	0.1		--	--	--	--	--	IC, IP	INCO(10)
3003-H14	W	402	2370	1.4		91.0	--	--	65.0	93	C, SE, (8)	NCEL
3003-	W	402	2370	1.1		--	--	--	--	40 (PR)	SC	INCO(10)
3003-H14	S	402	2370	1.7		115.0	48.3	0.1	67.6	70	SC, SP	NCEL
3003-	S	402	2370	0.5		--	--	--	--	50 (PR)	SC	INCO(10)
3003-H14	W	181	5	1.1		33	18.1	1.5	30.0	--	E, P	NCEL
3003-	W	181	5	1.0		--	--	--	--	--	IP	INCO(10)
3003-	W	366	5	0.6		--	--	--	--	--	IP	INCO(10)

Table 5. (Cont'd)

Alloy	Environ- ment	Exposure		Corrosion Rate MPY ²	Pit Depth Mils.		Pitting		Crevice Corrosion, Depth, Mils	Type of Corrosion ⁵	Source ⁶
		Days	Depth, Feet		Max	Ave	PFQ ³	PFTR ⁴			
Alclad 3003-H12	W	123	5640	0.2	18.0	14.6	0.1	90.0	15	SLE, B, C, (9)	NCEL
Alclad 3003	W	123	5640	2.7	--	--	--	--	--	G	INCO (10)
Alclad 3003-H12	W	123	5640	2.8	19.5	14.5	13.5	7.0	--	SLE, B, C, (9)	NCEL
Alclad 3003	S	123	5640	2.6	--	--	--	--	--	G	INCO (10)
Alclad 3003-H12	W	403	6780	0.4	14.0	13.0	0.2	35.0	14	C, P, SLE	NCEL
Alclad 3003	W	403	6780	2.5	--	--	--	--	--	G	INCO (10)
Alclad 3003-H12	S	403	6780	0.2	14.0	13.0	0.2	70.0	13	C, P, SLE	NCEL
Alclad 3003	S	403	6780	0.4	--	--	--	--	--	(10)	INCO (10)
Alclad 3003-H12	W	751	5640	0.3	13.0	12.8	0.1	43.3	13	C, P, E	NCEL
Alclad 3003	W	751	5640	1.4	--	--	--	--	--	G	INCO (10)
Alclad 3003-H12	S	751	5640	2.4	14.0	13.2	0.4	5.8	14	C, P, E (9)	NCEL
Alclad 3003	S	751	5640	1.5	--	--	--	--	--	U	INCO (10)
Alclad 3003-H12	W	1064	5300	0.7	20.0	16.5	0.4	29.0	13	C, P (11)	NCEL
Alclad 3003-H12	W	1064	5300	0.3	15.0	14.8	0.2	50.0	--	P (9)	NCEL
Alclad 3003	(1x6)	1064	5300	1.5	--	--	--	--	--	U	INCO (10)
Alclad 3003-H12	S	1064	5300	0.8	16.0	15.6	0.6	20.0	13	C, P (12)	NCEL
Alclad 3003	S	1064	5300	0.6	--	--	--	--	--	U	INCO (10)
Alclad 3003-H12	W	197	2340	2.2	15.0	13.1	2.8	6.8	13	C, P (9)	NCEL
Alclad 3003	W	197	2340	2.3	--	--	--	--	--	G	INCO (10)
Alclad 3003-H12	S	197	2340	1.1	14.0	12.5	4.7	12.7	13	C, P (13)	NCEL
Alclad 3003	S	197	2340	0.1	2.0	--	--	--	2	C, P	INCO (10)
Alclad 3003-H12	W	402	2370	2.2	14.0	12.9	2.1	6.4	15	C, P (14)	NCEL
Alclad 3003	W	402	2370	1.6	--	--	--	--	--	(15)	INCO (10)
Alclad 3003-H12	S	402	2370	1.8	13.0	7.2	4.5	7.2	14	C, P (16)	NCEL
Alclad 3003	S	402	2370	0.4	--	--	--	--	--	(17)	INCO (10)
Alclad 3003-H12	W	181	5	1.0	--	--	--	--	--	IP	NCEL
Alclad 3003	W	181	5	1.0	2.0	--	--	--	--	MP	INCO (10)
Alclad 3003	W	366	5	0.5	2.0	--	--	--	--	MP	INCO (10)

Table 5. (Cont'd)

- (1) W - Totally exposed in sea water on sides of structure.
S - Exposed in base of structure so that the lower portions of the specimens were embedded in the bottom sediment.
- (2) MPY - Mils penetration per year calculated from weight loss.
- (3) Pitting Frequency - number of pits per square inch of surface.
- (4) Pitting Factor - maximum measured pit depth divided by MPY.
- (5) Symbols for types of corrosion:
 B - Blistering
 C - Crevice
 E - Edge
 EX - Extensive
 G - General
 I - Incipient
 N - Numerous
 P - Pitting
 PR - Perforation
 S - Severe
 SL - Slight
 U - Uniform
- (6) Numbers refer to references at end of paper.
- (7) About 40% of specimen gone.
- (8) One pit only.
- (9) Large area of cladding gone.
- (10) Non-uniform cladding loss.
- (11) Non-uniform cladding loss, 18%, one area 7 sq. in.
- (12) Non-uniform cladding loss, 13%, one area 5 sq. in.

Table 5. (Cont'd)

- (13) Cladding gone in one area, 7 sq. in., cladding gone on 2" wide strip across bottom of specimen in sediment.
- (14) Twenty (20) % of cladding gone and incipient pitting in denuded areas.
- (15) Sixty (60) % of cladding gone.
- (16) Incipient pitting in areas where 18% of the cladding was gone, cladding gone on 2" high strip across bottom of specimen embedded in bottom sediment.
- (17) Twenty (20) % of cladding gone.

Table 6. Corrosion Rates and Pit Depths of Aluminum - Magnesium Alloys (5000 Series)

Alloy	Environ- ment (1)	Exposure		Corro- sion Rate (2)	Pit Depth Mils		Pitting		Crevice Corrosion Depth, Mils	Type of Corrosion (5)	Source (6)
		Days	Depth, Feet		Max.	Ave.	PFQ (3)	PFTR (4)			
5050-H34	W	402	2370	0.1	-	-	-	-	31	C,IP	NCEL
5050-H34	S	402	2370	0.2	-	-	-	-	31	C,IP	NCEL
5052-0	W	123	5640	3.7	-	-	-	-	65 (PR)	SC	INCO(10)
5052-0	S	123	5640	4.0	-	-	-	-	65 (PR)	SC	INCO(10)
5052-0	W	403	6780	4.5	-	-	-	-	62 (PR)	SC	INCO(10)
5052-0	S	403	6780	1.2	-	-	-	-	62 (PR)	SC	INCO(10)
5052-0	W	751	5640	2.2	65 (PR)	-	-	29.5	65 (PR)	SC,SP	INCO(10)
5052-0	S	751	5640	3.2	-	-	-	-	62 (PR)	SC	INCO(10)
5052-0	W	1064	5300	3.1	-	-	-	-	65 (PR)	SC	INCO(10)
5052-H22	W	1064	5300	0.4	-	-	-	-	-	-	NCEL(12)
5052-0	S	1064	5300	1.5	-	-	-	-	62 (PR)	SC	INCO(10)
5052-0	W	197	2340	1.8	-	-	-	-	65 (PR)	SC	INCO(10)
5052-0	S	197	2340	<0.1	-	-	-	-	-	IC,IP	INCO(10)
5052-H34	W	402	2370	0.2	-	-	-	-	34	C,IP	NCEL
5052-0	W	402	2370	0.4	-	-	-	-	20	C	INCO(10)
5052-H34	S	402	2370	0.2	-	-	-	-	50 (PR)	SC,IP	INCO(10)
5052-0	S	402	2370	0.3	-	-	-	-	-	SB at C	INCO(10)
5052-0	W	181	5	1.2	-	-	-	-	-	IP	INCO(10)
5052-0	W	366	5	0.6	5.0	-	-	-	5	C,P	INCO(10)
5454-H32	W	403	6780	0.9	38.0	28.0	20.0	42.2	-	MOE,MOP	NCEL
5454-H32	S	403	6780	0.5	37.0	27.0	19.0	74.0	-	MOE,MOP	NCEL
5454-H32	W	197	2340	0.7	24.0	9.0	1.0	34.3	-	SLE,P	NCEL
5454-H32	S	197	2340	0.6	16.0	8.1	0.5	26.7	-	SLE,P	NCEL
5454-H32	W	402	2370	0.3	-	-	-	-	39	IP,C	NCEL
5454	W	402	2370	0.4	-	-	-	-	28	C	INCO(10)
5454-H32	S	402	2370	0.3	-	-	-	-	33	IP,C	NCEL
5454	W	402	2370	0.6	-	-	-	-	80 (PR)	SC	INCO(10)
5454	W	181	5	1.0	-	-	-	-	-	IP	INCO(10)
5454	W	366	5	0.5	-	-	-	-	-	ET	INCO(10)
5454-H32(16)	W	123	5640	0.1	7.0	2.9	<0.1	70.0	-	FP(7)	NCEL
5454-H32(16)	S	123	5640	1.1	49.0	45.6	23.0	44.5	-	SP,E,S,HA	NCEL

Table 6. (Cont'd)

Alloy	Environ- ment (1)	Exposure		Corro- sion Rate, MPY (2)	Pit Depth Mils		Pitting		Crevice Corrosion Depth, Mils	Type of Corrosion (5)	Source (6)
		Days	Depth, Feet		Max.	Ave.	PFQ (3)	PFTR (4)			
5454-H32, (16)	W	403	6780	1.7	64.0	46.4	14.2	37.6	-	PE, (8)	NCEL
5454-H32, (16)	S	403	6780	0.6	42.0	32.0	13.8	70.0	-	PE, (8)	NCEL
5454-H32, (16)	W	751	5640	0.9	65.0	50.1	6.0	72.2	-	E, P, SLWA	NCEL
5454-H32, (16)	W	197	2340	0.3	41.0	28.0	15.8	136.7	-	MOP, (9)	NCEL
5454-H32, (16)	S	197	2340	0.6	49.0	31.6	13.2	81.7	Severe	SC, MOP (9)	NCEL
5454-H32, (16)	W	402	2370	0.6	42.0	34.5	1.1	70.7	-	P, PWA (10)	NCEL
5454-H32, (16)	S	402	2370	0.7	22.0	15.9	0.3	31.4	-	P, (11)	NCEL
5456-H321	W	123	5640	<0.1	-	-	-	-	-	SIC, SLET	NCEL
5456-H321	S	123	5640	2.1	49.0	40.0	6.2	23.3	33	C, E, P	NCEL
5456-H321	W	403	6780	1.0	-	-	-	-	50	SC, E, IP	NCEL
5456-H321	S	403	6780	0.8	44.0	27.7	0.7	55.0	32	C, E, FP	NCEL
5456-H321	W	751	5640	2.0	53.0	34.1	0.1	26.5	25	C, E, FP	NCEL
5456-H321	S	751	5640	2.2	50.0	31.3	0.6	22.7	45	SC, E, FP	NCEL
5456-H321	W	1064	5300	0.6	-	-	-	-	-	C, EXE	NCEL
5456-H321	W	1064	5300	1.3	43.0	36.5	0.7	35.8	37	C, EXE, FP	NCEL
5456-H321	S	1064	5300	1.5	36.0	33.0	1.5	24.0	46	C, EXE, FP	NCEL
5456-H321	W	197	2340	2.7	17.0	14.7	0.2	6.3	36	C, E, FP	NCEL
5456-H321	S	197	2340	2.6	43	18.9	0.2	16.5	18	C, E, FP	NCEL
5456-H321	W	402	2370	1.1	41.0	20.7	0.1	37.3	44	C, E, P	NCEL
5456-H321	W	402	2370	0.6	-	-	-	-	5	C, E	NCEL
5456-H321	S	402	2370	1.2	14.0	8.2	0.2	11.7	32	C, E, P	NCEL
5456-H321	S	402	2370	0.7	-	-	-	-	21	C, E	NCEL
5456-H321	W	181	5	1.2	12.0	5.9	1.1	10.0	-	P	NCEL
5456-H34	W	1064	5300	1.0	63.0	51.0	4.2	57	-	C, E, P	NCEL
5456-H343	W	123	5640	1.0	25.0	15.3	-	25.0	-	ICFP	NCEL
5456-H343	W	403	6780	0.2	-	-	-	-	28	C, IP	NCEL
5456-H343	S	403	6780	0.2	-	-	-	-	28	C, IP	NCEL
5456-H343	W	751	5640	1.1	-	-	-	-	64 (PR)	SC, SLE	NCEL
5456-H343	W	1064	5300	0.1	35.0	32.5	40.1	350	35	C, EFP	NCEL
5456-H343	W	197	2340	0.4	-	-	-	-	-	C, E	NCEL
5456-H343	S	197	2340	0.3	-	-	-	-	-	C, E	NCEL
5083-H113	W	403	6780	4.0	59.0	52.6	1.2	14.8	-	SE, P	NCEL
5083-H113	S	403	6780	0.7	68.0	50.0	1.1	97.1	-	E, P	NCEL
5083-H113	W	197	2340	0.5	23.0	23.0	-	46.0	-	E, (12)	NCEL

Table 6. (Cont'd)

Alloy	Environ- ment (1)	Exposure		Corro- sion Rate, MPY (2)	Pit Depth Mils		Pitting		Crevice Corrosion Depth, Mils	Type of Corrosion (5)	Source (6)
		Days	Depth, Feet		Max.	Ave.	PFQ (3)	PFTR (4)			
5083-H113	S	197	2340	0.6	14.0	12.5	-	23.3	-	E, (13)	NCEL
5083-H113	W	402	2370	0.6	-	-	-	-	52	SC, IP	NCEL
5083	W	402	2370	1.0	-	-	-	-	31	C	INCO (10)
5083-H113	S	402	2370	0.6	-	-	-	-	57	SC, IP	NCEL
5083	S	402	2370	0.4	17.0	-	-	-	-	P	INCO (10)
5083-H113	W	181	5	1.2	-	-	-	-	3	C, IP	NCEL
5083	W	181	5	1.0	-	-	-	-	-	ET	INCO (10)
5083	W	366	5	0.6	-	-	-	-	-	ET	INCO (10)
5083-H113(16)	W	123	5640	0.0	27.5	17.1	-	-	-	IP (13)	NCEL
5083-H113(16)	S	123	5640	0.9	65.0	53.7	5.5	72.2	-	FP	NCEL
5083-H113(16)	W	403	6780	2.1	92.0	72.8	6.0	43.8	-	SLE, P,	NCEL
5083-H113(16)	S	403	6780	1.1	66.0	49.0	1.0	60.0	-	SLE, P,	NCEL
5083-H113(16)	W	751	5640	1.6	83.0	64.2	2.0	51.9	-	F, P,	NCEL
5083-H113(16)	W	197	2340	0.3	57.0	26.3	0.7	190.0	-	P,	NCEL
5083-H113(16)	W	197	2340	0.7	55.0	25.6	0.2	78.6	-	P,	NCEL
5083-H113(16)	W	402	2370	0.8	58.0	42.1	3.3	72.5	-	E, P,	NCEL
5083-H113(16)	S	402	2370	0.8	48.0	19.0	<0.1	60.0	-	E, P, SLWA (14)	NCEL
5083-H113(17)	W	181	5	0.9	-	-	-	-	-	ET	NCEL
5086-H34	W	123	5640	0.1	-	-	-	-	-	ET	NCEL
5086-H34	S	123	5640	1.4	13.0	7.8	<0.1	9.3	50	SC, E, P	NCEL
5086-H34	W	123	2500	<0.1	-	-	-	-	-	ET	NCEL
5086-H34	W	403	6780	0.6	-	-	-	-	53	SC, IP	NCEL
5086-H34	S	403	6780	0.8	11.0	4.0	0.4	13.9	48	SC, P	NCEL
5086-H34	W	751	5640	2.0	72.0	46.0	1.0	36.0	60	SC, E, P	NCEL
5086-H34	W	1064	5300	0.9	73	64.8	0.2	81.0	69	SC, SE, P	NCEL
5086-H34	W	1064	5300	0.8	12.0	6.0	<0.1	15.0	69	C, FP, SE	NCEL
5086-H34	S	1064	5300	1.2	75	62.6	0.5	62.5	50	C, SE, P, (15)	NCEL
5086-H34	W	197	2340	0.7	29.0	3.6	<0.1	41.4	-	IC, SLE, FP	NCEL
5086-H34	W	197	2340	1.1	53.0	39.9	0.8	48.2	38	SE, C, P	NCEL
5086-H34	W	402	2370	0.6	-	-	-	-	5	IC, IP,	NCEL
5086-H34	S	402	2370	1.3	17.0	11.0	<0.1	13.1	48	C, P,	NCEL
5086-H34	W	181	5	1.3	6.0	4.0	0.1	4.6	-	FP	NCEL
5086-H32	W	402	2370	0.4	-	-	-	-	18	C, IP	NCEL
5086	W	402	2370	0.8	-	-	-	-	35 (PR)	SC	INCO (10)

Table 6. (Cont'd)

Alloy	Environment (1)	Exposure		Corrosion Rate, MPY (2)	Pit Depth, Mils		Pitting		Crevice Corrosion Depth, Mils	Type of Corrosion (5)	Source (6)
		Days	Depth, Feet		Max.	Ave.	PFQ (3)	PFTR (4)			
5086-H32	S	402	2370	0.5	-	-	-	-	18	C, IP	NCEL (10)
5086	S	402	2370	0.7	-	-	-	-	35 (PR)	SC	INCO (10)
5086-H32	W	181	5	1.0	-	-	-	-	-	IP	NCEL (10)
5086	W	181	5	1.2	-	-	-	-	-	IP	INCO (10)
5086	W	366	5	0.5	5.0	-	-	-	5	C, P	INCO (10)
5086-H112(18)	W	181	5	1.1	-	-	-	-	-	IP	NCEL

- (1) W - Totally exposed in sea water on sides of structure; S - Exposed in base of structure such that the lower portions of the specimens were embedded in the bottom sediment.
- (2) MPY - Mils penetration per year calculated from weight loss.
- (3) Pitting Frequency - number of pits per square inch of surface.
- (4) Pitting Factor - maximum measured pit depth divided by MPY.
- (5) Symbols for types of corrosion: B - Blistering; C - Crevice; E - Edge; ET - Etched; EX - Extensive; F - Few; I - Incipient; MO - Moderate; S - Severe; SL - Slight; P - Pitting; PR - Perforated; WA - Weld attack.
- (6) Numbers refer to references at end of paper.
- (7) Total of 6 measurable pits.
- (8) Bands of pits at edge of and outside heat affected zone.
- (9) Some pitting at edge of heat affected zone.
- (10) Crack in weld bead.
- (11) Area 4 sq. in. in sediment corroded to 94 mils deep.
- (12) One measurable pit.
- (13) Two measurable pits.
- (14) Pits at edge of weld bead, 8 sq. in. area in sediment 71 mils deep.
- (15) Area 6 sq. in. in sediment 60 mils deep.
- (16) Welded with 5052 rod.
- (17) Welded with 5183 filler wire by the MIG process.
- (18) Angle, 3" x 3" x $\frac{1}{2}$ ".

Table 7. Average Corrosion Rates and Average Pit Depths of Al-Mg Alloys (5050, 5052, 5454, 5456, 5083 and 5086)

Exposure, Days	Depth, Feet	Average Corrosion Rate, MPY		Average Pit Depths, Mils,	
		Water	Sediment	Water	Sediment
181	5	1.1		5.0	
366	5	0.6		--	
197	2340	0.9	0.8	17.4	22.8
402	2370	0.6	0.6	32.4	13.5
123	5640	0.8	1.9	11.8	36.5
403	6780	1.9	0.7	50.0	31.6
751	5640	1.6	2.7	48.6	29.7
1064	5300	1.0	1.4	46.2	47.8

Table 8. Corrosion Rates and Pit Depth of Aluminum-Magnesium-Silicon Alloys (6000 Series)

Alloy	Environ- ment	Exposure		Corrosion Rate MPY ²	Pit Depth, Mils		Pitting		Crevice Corrosion, Depth, Mils	Type of Corrosion ⁵	Source ⁶
		Days	Depth, Feet		Max	Ave	PFQ ³	PFIR ⁴			
6061-T6, Lot 1	W	123	5640	0.1	--	--	--	--	--	IP	NCEL
6061-T6, Lot 2	W	123	5640	0.0	5.0	1.8	--	--	10	C, P (7)	NCEL
6061-T6, Lot 1	S	123	5640	0.9	32	22.0	2.8	35.6	--	SLC, P	NCEL
6061-T6, Lot 2	S	123	5640	1.6	31	25.6	3.6	19.4	32	C, P	NCEL
6061-T6, Lot 1	W	403	6780	1.0	58	48.4	0.7	58.0	55	C, P	NCEL
6061-T6, Lot 1	S	403	6780	0.7	60	45.3	1.3	85.7	51	C, P	NCEL
6061-T6, Lot 1	W	751	5640	0.4	65	42.6	0.1	162.5	65	C, E, P	NCEL
6061-T6, Lot 2	W	751	5640	1.8	56	43.9	1.4	11.1	48	C, P	NCEL
6061-T6, Lot 1	S	751	5640	1.3	72	52.3	0.4	55.4	75	C, E, P	NCEL
6061-T6, Lot 2	S	751	5640	1.9	40	36.0	1.5	21.1	--	E, P	NCEL
6061-T6, Lot 1	W	1064	5300	0.6	77	63.2	0.4	128.3	60	C, P	NCEL
6061-T6, Lot 1	W	1064	5300	1.0	59	21.3	0.3	59.0	66	C, P, E	NCEL
6061-T6, Lot 1	S	1064	5300	1.0	77	63.3	0.6	77.0	--	C, E, P	NCEL
6061-T6, Lot 1	W	197	2340	1.2	47	39.8	2.2	39.2	42	C, P	NCEL
6061-T6, Lot 1	S	197	2340	1.3	46	31.4	4.4	37.6	--	C, P	NCEL
6061-T6, Lot 1	W	402	2370	2.0	75	51.4	2.8	37.5	66	C, P	NCEL
6061	W	402	2370	1.2	--	--	--	--	32 (PR)	SC	INCO(10)
6061-T6, Lot 1	S	402	2370	1.2	76	51.4	1.0	73.3	60	C, P	NCEL
6061	W	402	2370	0.7	--	--	--	--	32 (PR)	SC	INCO(10)
6061-T6, Lot 1	W	181	5	1.0	--	--	--	--	8	C, IP	NCEL
6061	W	181	5	1.2	5	--	--	--	--	P	INCO(10)
6061	W	366	5	0.9	11	--	--	4.2	--	C, P	INCO(10)
6061	W	366	5	0.9	11	--	--	12.2	11	C, P	INCO(10)

- (1) W - Totally exposed in sea water on sides of structure.
 S - Exposed in base of structure such that the lower portions of the specimens were embedded in the bottom sediment.
 (2) MPY - Mils penetration per year calculated from weight loss.
 (3) Pitting Frequency - number of pits per square inch of surface.
 (4) Pitting Factor - maximum measured pit depth divided by MPY.

Table 8. (Cont'd)

(5) Symbols for type of corro' on:

C - Crevice
E - Edge
I - Incipient
P - Pitting
PR - Perforated
S - Severe
SL - Slight

(6) Numbers refer to references at end of paper.

(7) Total of 6 measurable pits.

Table 9. Corrosion Rates and Pit Depths of Aluminum-Zinc Alloys (7000 Series)

Alloy	Environment	Exposure		Corrosion Rate MPY ²	Pit Depth		Pitting		Crevice Corrosion Depth, Mils	Corrosion Type ⁵	Source ⁶
		Days	Depth, Feet		Max	Ave	FFQ ³	FFTR ⁴			
7002-T6	W	403	6780	1.2	62 (PR)	42.9	0.3	51.7	--	E, P	NCEL
7002-T6	S	403	6780	3.2	62 (PR)	--	--	19.4	--	E, P	NCEL
7002-T6	W	402	2370	1.6	30	20.7	0.2	18.8	62 (PR)	C, P	NCEL
7002-T6	S	402	2370	1.9	5	--	--	2.6	62 (PR)	C, P (7)	NCEL
Alclad 7002-T6	W	403	6780	1.4	5	4.0	--	3.6	--	P (8)	NCEL
Alclad 7002-T6	S	403	6780	0.2	4	4.0	--	20.0	--	P (9)	NCEL
Alclad 7002-T6	W	402	2370	0.8	5	--	--	--	5	C, (10)	NCEL
Alclad 7002-T6	S	402	2370	1.0	5	--	--	--	5	C, P, (11)	NCEL
7039-T6	W	123	5640	0.7	3.0	1.4	0.1	4.3	--	C, XF	NCEL
7039-T6	S	123	5640	2.1	38	24.0	0.1	18.1	2	C, P, XF	NCEL
7039-T6	W	403	6780	--	--	--	--	--	--	EXXF	NCEL
7039-T6	S	403	6780	--	--	--	--	--	--	EXXF	NCEL
7039-T6	W	751	5640	--	--	--	--	--	--	EXXF	NCEL
7039-T6	S	751	5640	--	--	--	--	--	--	EXXF	NCEL
7039-T6	W	197	2340	1.9	27	18.5	0.1	14.2	--	P, XF	NCEL
7039-T6	S	197	2340	1.2	61	33.5	0.2	50.8	--	P, XF	NCEL
7039-T6	W	402	2370	--	--	--	--	--	--	EXXF	NCEL
7039-T6	S	402	2370	--	--	--	--	--	--	EXXF	NCEL
7039-T6	W	181	5	1.1	--	--	--	--	--	EX	NCEL
7039-T6 (12)	W	181	5	1.2	--	--	--	--	--	IP	NCEL
Alclad 7075-O	W	1064	5300	1.1	--	--	--	--	--	U	NCEL (12)
7075-T6	W	123	5640	5.2	79 (PR)	62.2	6.8	15.2	36	C, E, P, XF	NCEL
7075-T6	S	123	5640	3.0	77 (PR)	55.1	10.7	25.7	32	C, S, P, XF	NCEL
7075-T6	W	403	6780	5.1	77 (PR)	37.5	26.3	15.1	36	C, SE, P	NCEL
7075-T6	S	403	6780	3.4	57	34.6	18.1	16.8	36	C, SE, P	NCEL
7075-T6	W	751	5640	2.8	79 (PR)	--	37.5	28.2	79 (PR)	C, P, XF	NCEL
7075-T6	S	751	5640	2.7	77 (PR)	--	21.5	28.5	77 (PR)	C, P, XF	NCEL

Table 9. (Cont'd)

Alloy	Environ- ment ¹	Exposure		Corrosion Rate, MPY ²	Pit Depth,		Pitting		Crevice Corrosion Depth, Mils	Corrosion Type ³	Source ⁶
		Days	Depth, Feet		Max	Ave	PFQ ⁴	PFTR ⁴			
7079-T6	W	197	2340	4.7	77(PR)	58.3	3.6	16.4	46	C, E, P, XT	NGEL
7079-T6	S	197	2340	3.0	49	33.3	1.6	16.3	55	C, E, P, XF	NGEL
7079-T6	W	402	2370	1.6	16	10.4	<0.1	10.0	35	C, SE, P	NGEL
7079-T6	S	402	2370	1.4	21	9.6	0.1	15.0	27	C, SE, P	NGEL
Alclad 7079-T6	W	402	2370	0.6	4	4	--	6.7	4	C, P, B	NGEL
Alclad 7079-T6	S	402	2370	0.5	4	4	--	8.0	4	C, P, B (13)	NGEL
7178-0	W	1064	5300	2.7	60(PR)	--	--	--	60 (PR)	C, P	NGEL (12)
7178-T6	W	173	5640	4.1	43	36.1	--	10.5	--	C, P XF	NGEL
7178-T6	W	403	6780	4.9	15	14.5	1.2	3.0	35	C, SE, P, XF	NGEL
7178-T6	S	403	6780	4.4	25	15.5	0.7	5.7	30	C, SE, P, XF	NGEL
7178-T6	W	751	5640	1.5	36	22.1	1.3	24.0	30	C, SE, P, XF	NGEL
7178-T6	W	1064	5300	1.4	45	25.4	0.5	32.1	39	C, SE, P, XF	NGEL
7178-T6	W	197	2340	3.2	--	--	--	--	--	C, XF	NGEL
7178-T6	S	197	2340	2.4	--	--	--	--	--	C, XF	NGEL
7178-T6	W	402	2370	3.3	34	12.5	5.1	10.3	34	C, E, P, XF	NGEL
7178-T6	S	402	2370	1.8	31	9.1	4.3	17.2	34	C, E, P, XF	NGEL

(1) W - totally exposed in sea water on sides of structure

S - exposed in base of structure such that the lower portions of the specimens were embedded in the bottom sediment.

(2) MPY - Mils penetration per year calculated from weight loss.

(3) Pitting Frequency - number of pits per square inch of surface.

(4) Pitting Factor - maximum measured pit depth divided by MPY.

Table 9. (Cont'd)

(5) Symbols for type of corrosion:

B - Blistering
C - Crevice
E - Edge
ET - Etched
EX - Extensive
I - Incipient
P - Pitting
PR - Perforated
S - Severe
U - Uniform
XF - Exfoliation

(6) Numbers refer to references at end of paper.

(7) Part of specimen gone and only one pit.

(8) 8% of cladding gone.

(9) 10% of cladding gone.

(10) Small areas of cladding penetrated.

(11) 15% of cladding gone.

(12) Welded with 7039 wire by the MIG process.

(13) 15% of cladding gone.

Table 10. Intergranular Corrosion and Intergranular Precipitation in Aluminum Alloys.

Alloy	Intergranular Corrosion	Intergranular Precipitation
2014-T6	Yes	Yes
2024-T3	Yes*	Yes
2219-T81	Yes	No
2219-T87	Yes	Yes
3003-H14	Yes	No
5454-H32 welded	Yes	No
5456-H321	Yes	Yes
5456-(BA28- $\frac{1}{2}$ H)	Yes	Yes
5456-H343	Yes	Yes
5083-H113	Yes	Yes
5083-H113, welded	Yes	Yes
5086-H32	Yes	Yes
5086-H34	Yes	Yes
6061-T6	Yes	Yes
X7002-T6	Yes	Yes
7039-T6	Yes*	Yes
7075-T6	Yes*	Yes
Alclad 7075-T6	Zone attack on line between clad and core alloys	
7079-T6	Yes*	Yes
Alclad 7079-T6	Yes, along a line in core alloy next to clad layer	Yes
7178-T6	Yes*	Yes

* - Exfoliated

Table 11. Stress Corrosion of Aluminum Alloys.

Alloy	Stress, KSI	Strength, Percent	Exposure, Days	Depth, Feet	Specimens	
					Exposed	Failed
1100-H14	7.5	50	402	2370	3	0
1100-H14	11.8	75	402	2370	3	0
1180	6.3	50	402	2370	3	0
1180	9.5	75	402	2370	3	0
2014-T6	30.8	50	402	2370	3	0
2014-T6	46.1	75	402	2370	3	0
2219-T81	25.0	50	402	2370	3	0
2219-T81	37.5	75	402	2370	3	0
2219-T87	25.3	50	402	2370	3	0
2219-T87	37.9	75	402	2370	3	3
3003-H14	6.1	50	402	2370	3	0
3003-H14	9.1	75	402	2370	3	0
5050-H34	11.0	50	402	2370	3	0
5050-H34	16.6	75	402	2370	3	0
5052-H34	14.9	50	402	2370	3	0
5052-H34	22.4	75	402	2370	3	0
5454-H32 (1)	12.0	75	403	6780	2	0
5454-H32 (1)	11.8	75	197	2340	3	0
5454-H32 (1)	11.8	75	402	2370	3	0
5456-H32	20.2	50	402	2370	3	0
5456-H32	30.4	75	402	2370	3	0
5083-H113 (1)	15.0	75	403	6780	2	0
5083-H113 (1)	14.6	75	197	2340	3	0
5083-H113 (1)	14.6	75	402	2370	3	0
5086-H32	15.1	50	402	2370	3	0
5086-H32	22.7	75	402	2370	3	0
X7002-T6	30.2	50	402	2370	3	0
X7002-T6	45.4	75	402	2370	3	0
Alclad X7002-T6	28.3	50	402	2370	3	0
Alclad X7002-T6	42.5	75	402	2370	3	0
7079-T6	33.6	50	402	2370	3	2
7079-T6	50.4	75	402	2370	3	3
Alclad 7079-T6	35.0	50	402	2370	3	1
Alclad 7079-T6	52.5	75	402	2370	3	2
7178-T6	40.7	50	402	2370	3	0
7178-T6	61.2	75	402	2370	3	3

(1) Welded

Table 12. Original Mechanical Properties of Aluminum Alloys.

Alloy	Thickness, in.	Tensile Strength, KSI	Yield Strength, (0.2% offset) KSI	Elongation in 2", Percent
1100-H14	0.050	19.3	17.9	7.0
1180	0.050	14.9	13.9	10.7
2014-T6	0.050	68.4	61.5	11.0
2219-T81	0.125	64.7	50.0	11.8
2219-T81	0.062	67.3	50.7	9.8
2219-T87	0.040	61.4	50.6	10.0
3003-H14	0.120	22.5	21.4	17.5
3003-H14	0.063	20.9	19.1	8.3
Alclad 3003-H12	0.125	18.7	17.5	13.7
5050-H34	0.050	27.8	22.1	8.2
5052-H34	0.050	37.2	29.8	9.2
5083-H113	0.260	50.1	37.8	14.0
5083-H113, welded	0.260	42.1	19.6	13.3
5086-H32	0.063	44.2	30.2	13.5
5086-H34	0.125	48.3	37.2	11.8
5454-H32	0.160	40.5	30.6	13.0
5454-H32, welded	0.160	35.3	15.7	13.5
5456-H321	0.130	55.5	38.8	13.5
5456-H32	0.048	49.5	36.2	15.0
5456-H343	0.066	57.8	45.6	9.2
6061-T6	0.123	47.5	41.2	17.0
X7002-T6	0.063	70.1	58.2	14.3
Alclad X7002-T6	0.062	64.7	53.5	15.0
7039-T6	0.268	69.0	60.1	14.0
7079-T6	0.077	76.4	67.0	10.7
Alclad 7079-T6	0.062	78.2	68.9	12.3
7178-T6	0.064	85.2	79.4	8.3
7178-T6	0.050	89.9	80.9	12.2

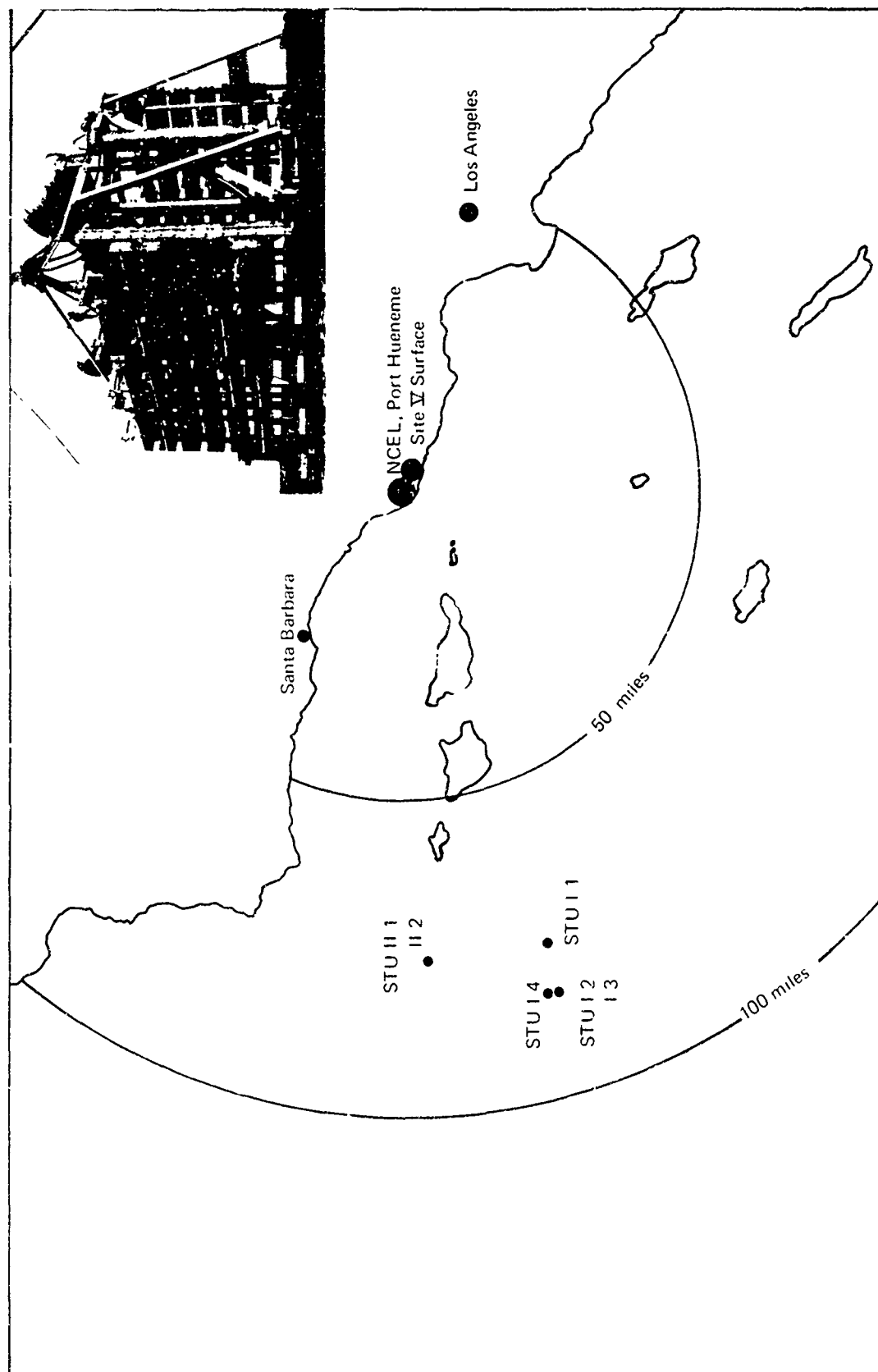


Figure 1. Area map showing STU sites off the Pacific Coast;
STU structure in inset.

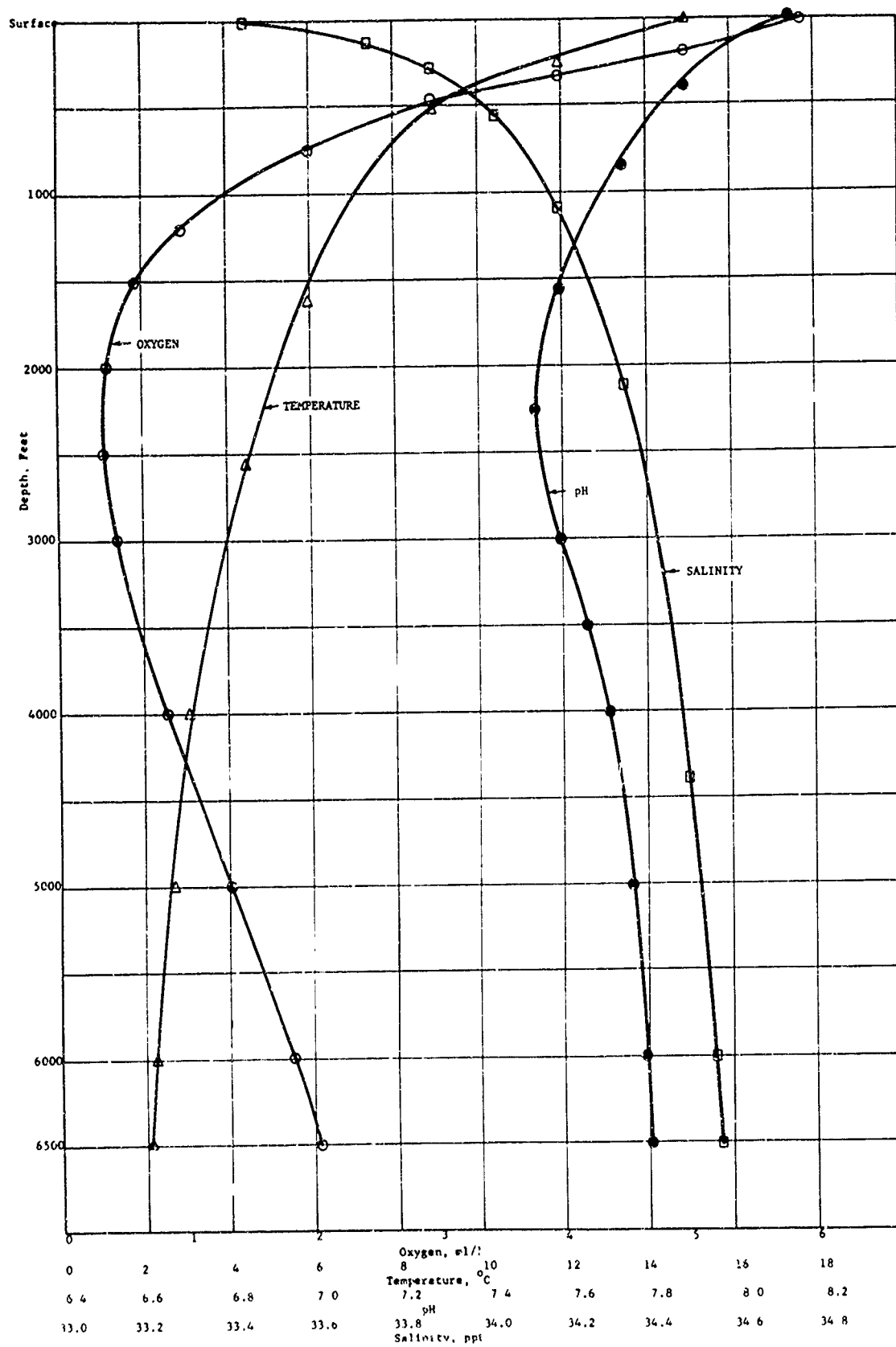


Figure 2 Oceanographic data at STU sites

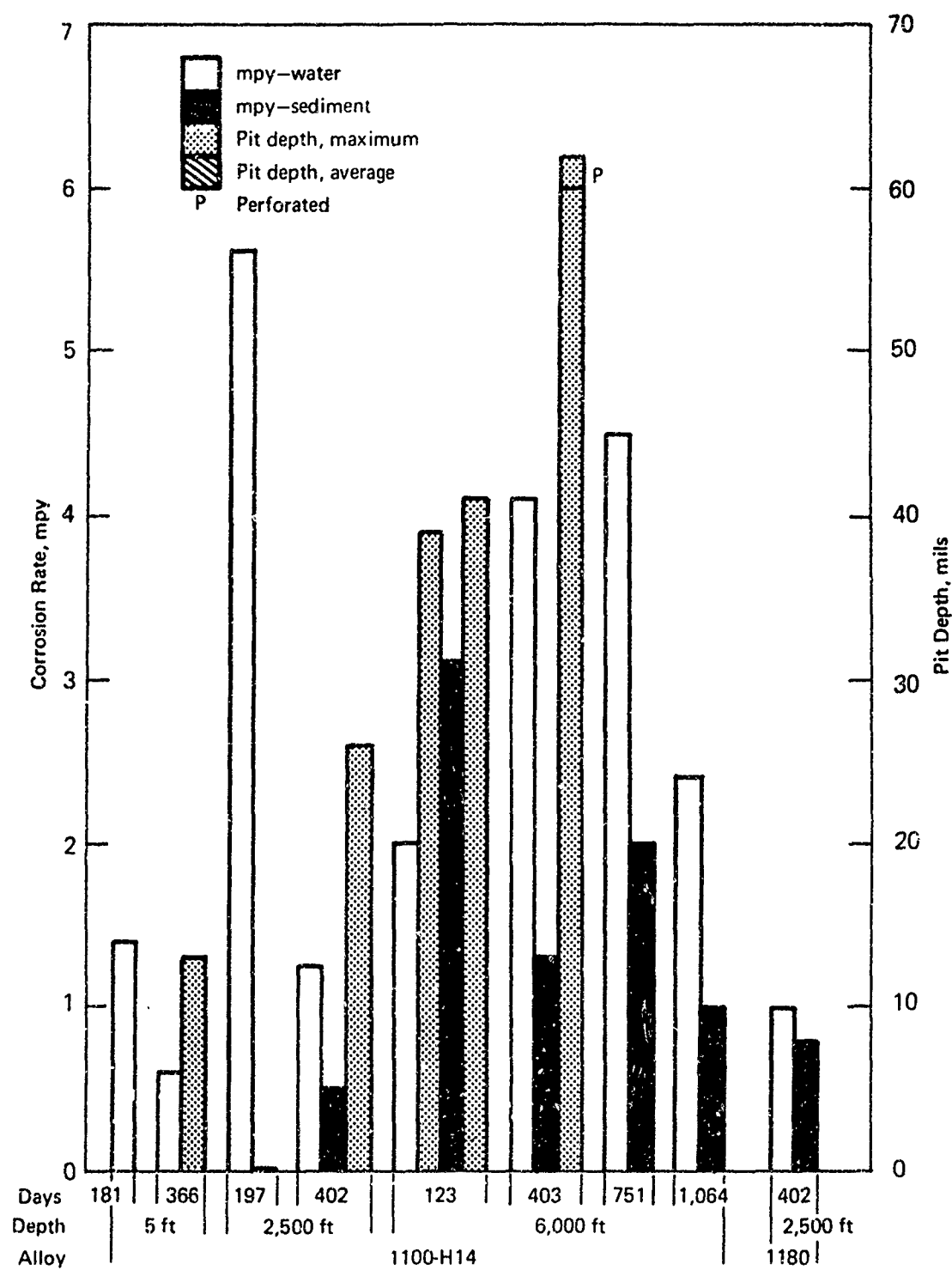


Figure 3. Corrosion rates, maximum and average pit depths of 1000 Series alloys.

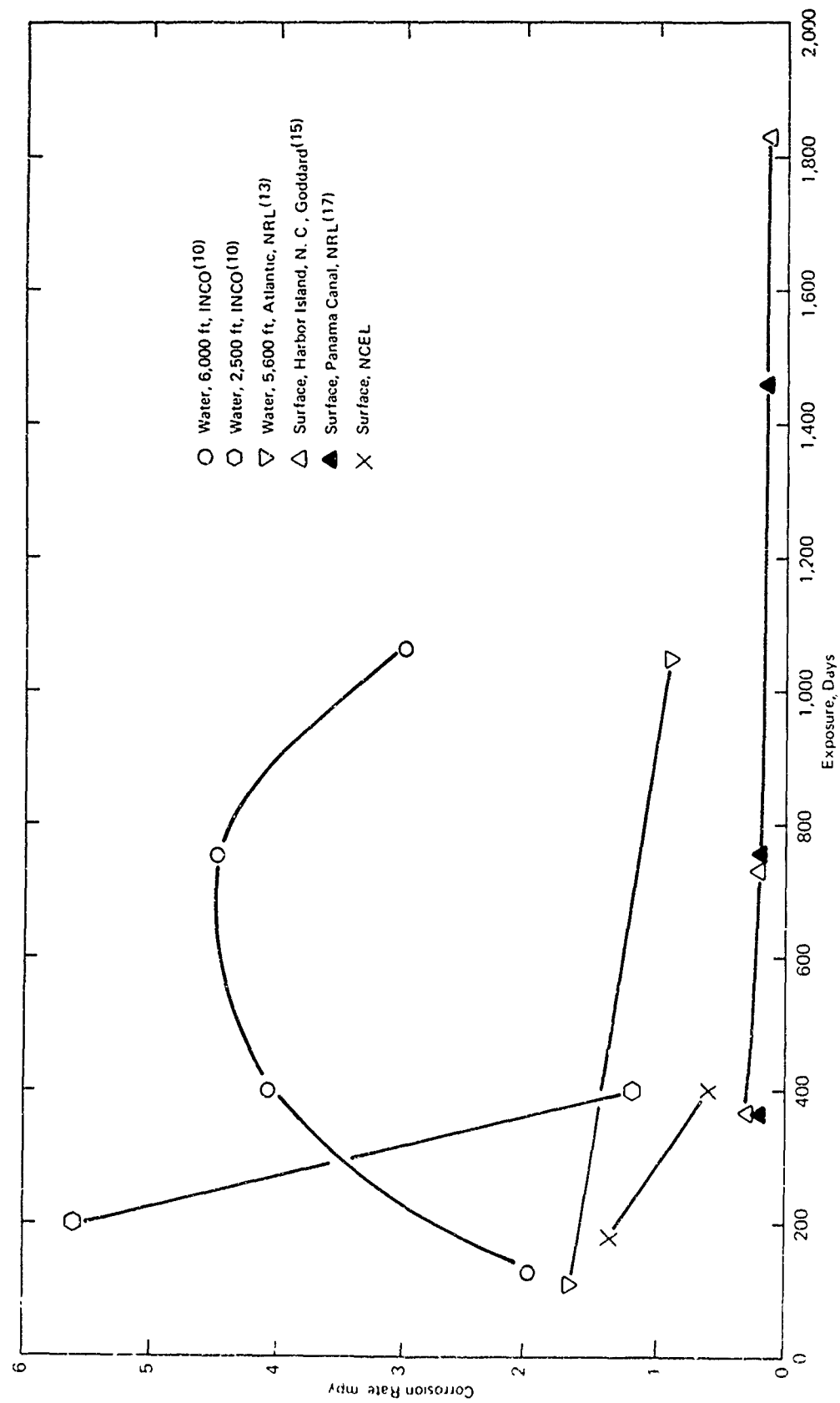


Figure 4. Corrosion rates of 1100 alloy in sea water at different locations.

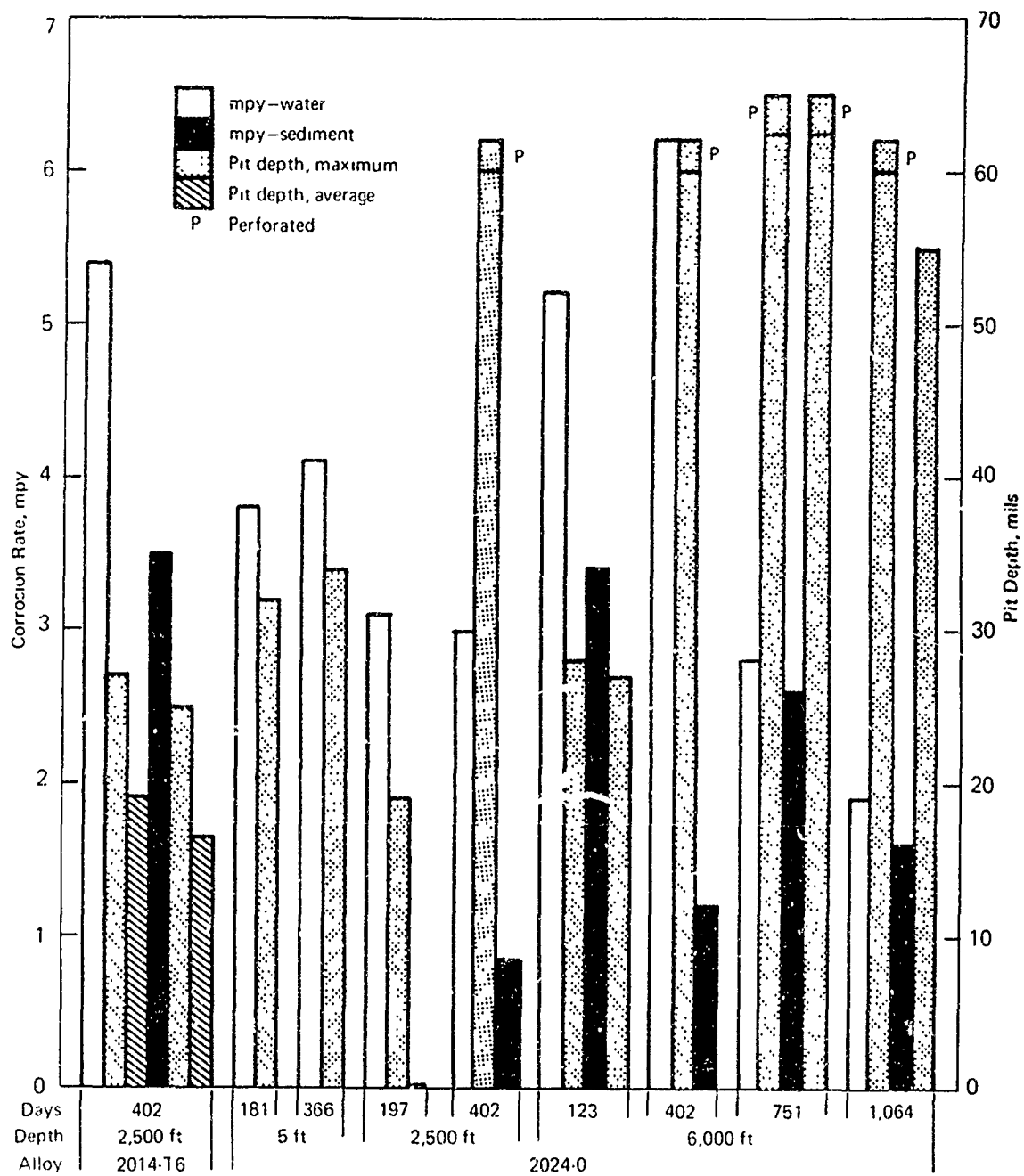


Figure 5. Corrosion rates, maximum and average pit depths of 2000 Series alloys.

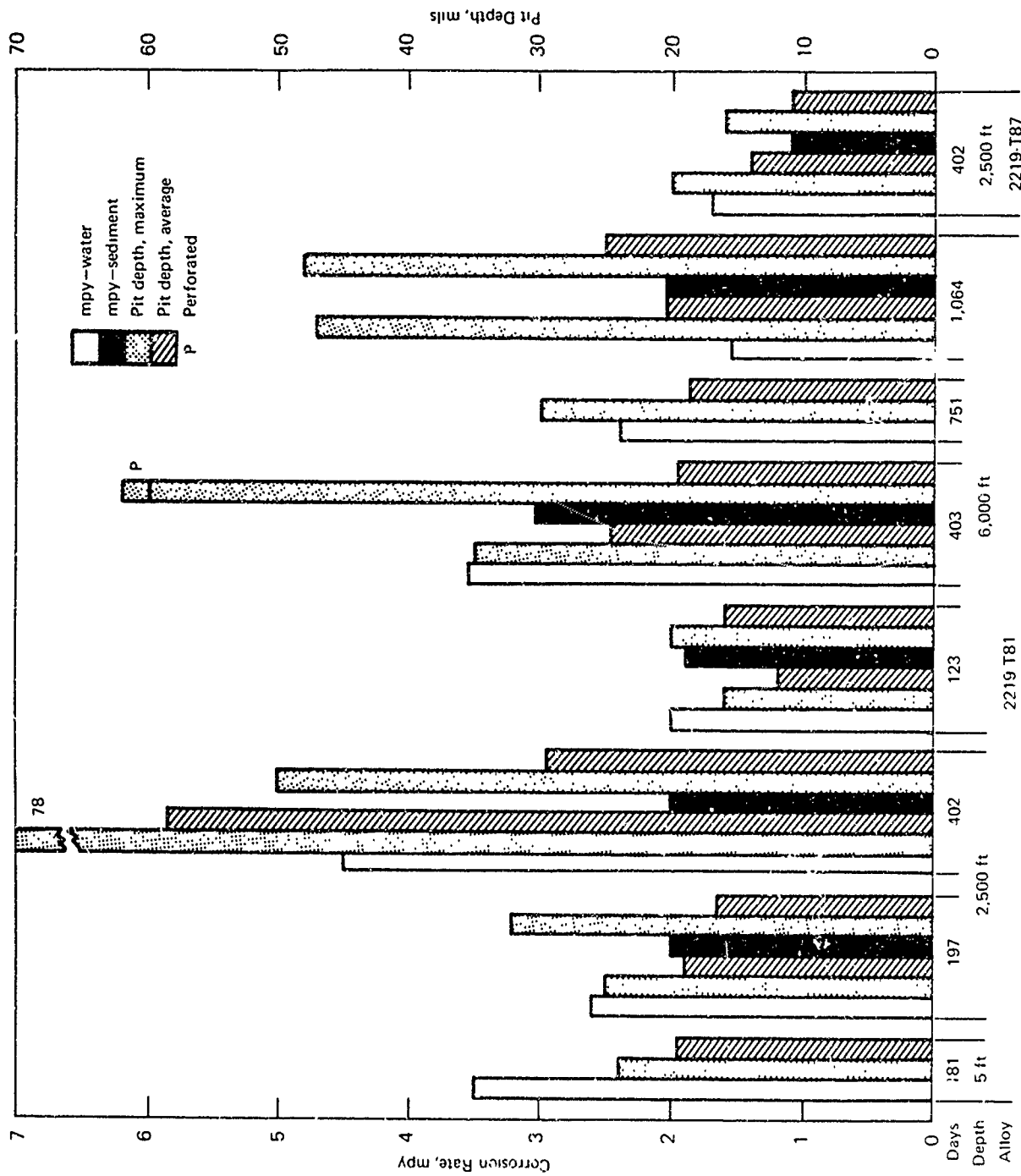


Figure 6. Corrosion rates, maximum and average pit depths of 2219 alloy.

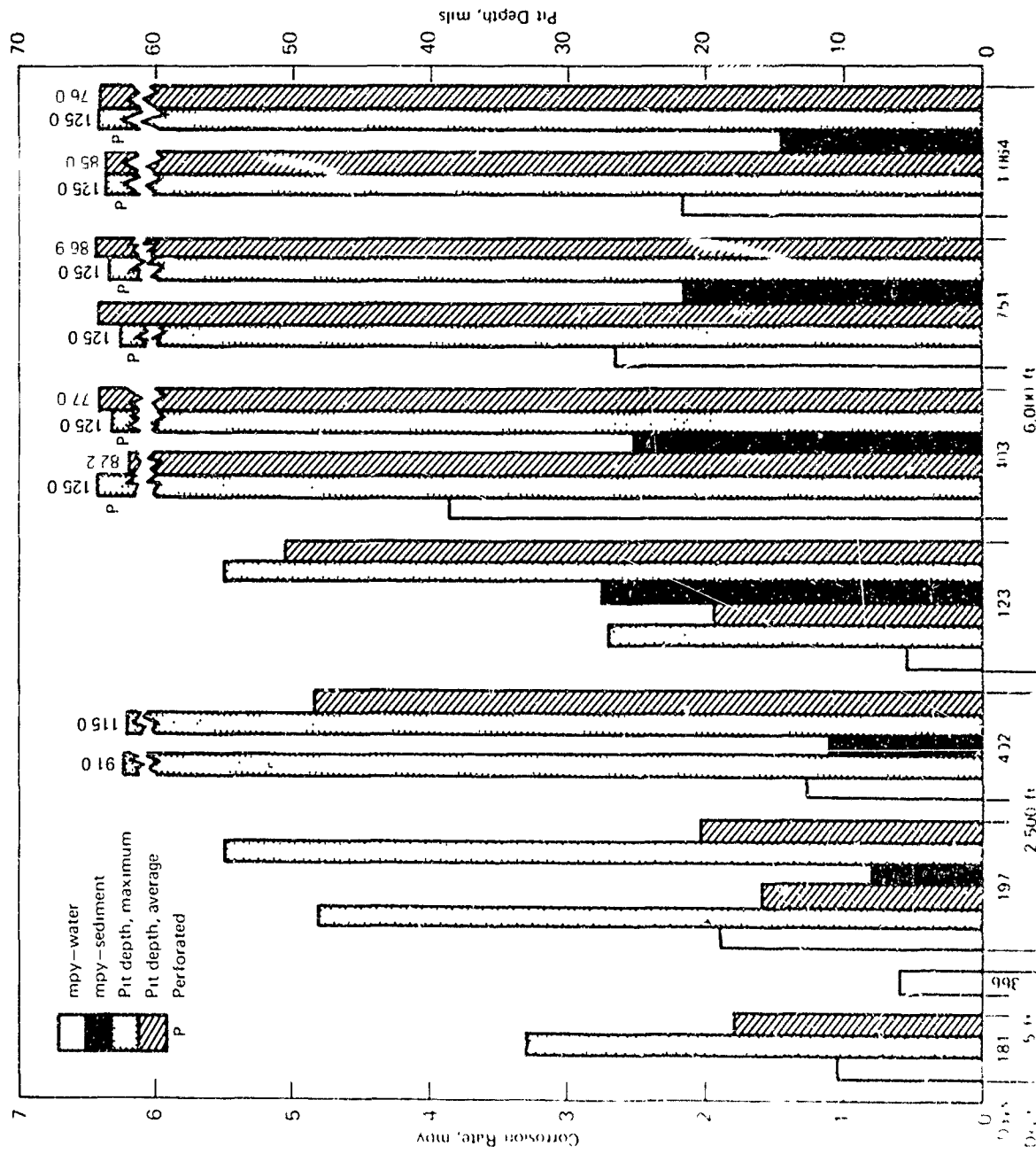


Figure 7. Corrosion rates, maximum and average pit depths of 3003 alloy.

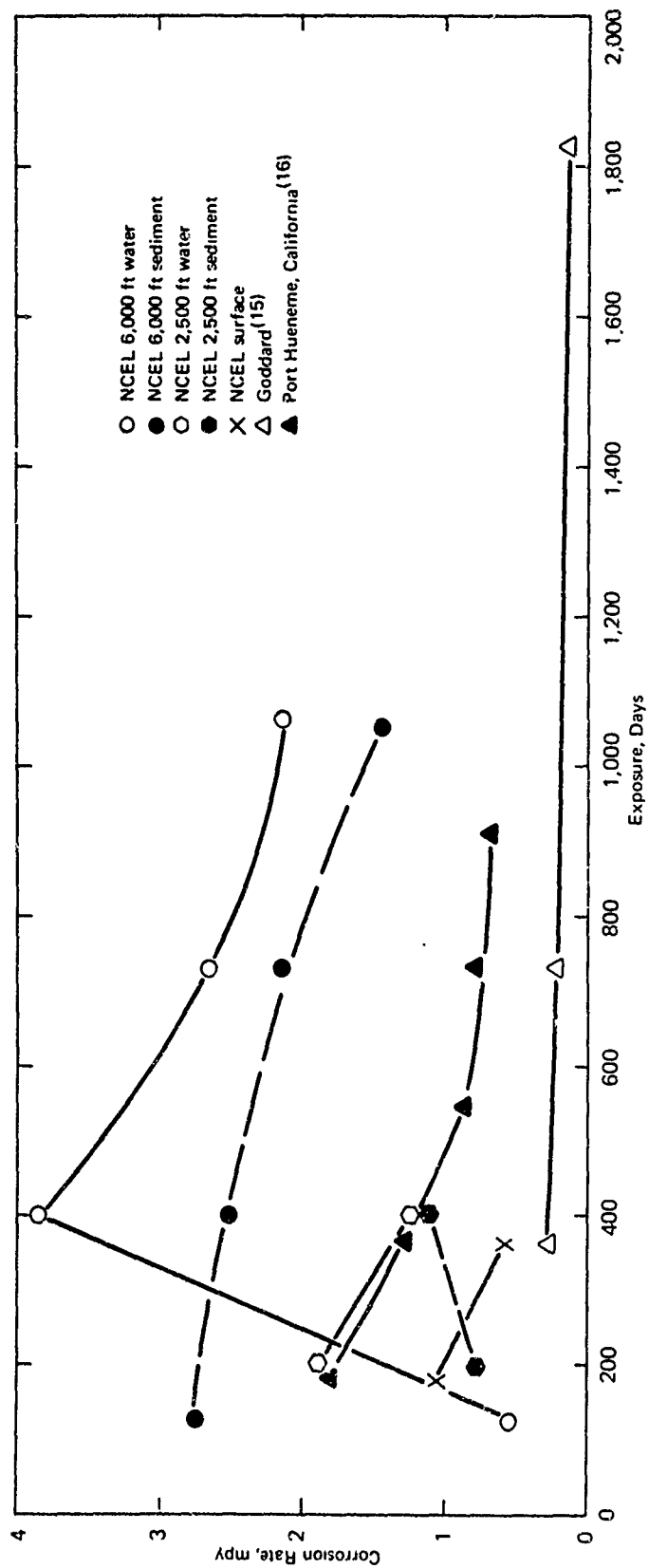


Figure 8. Corrosion rates of 3003 alloy at different depths and surface locations in the oceans.

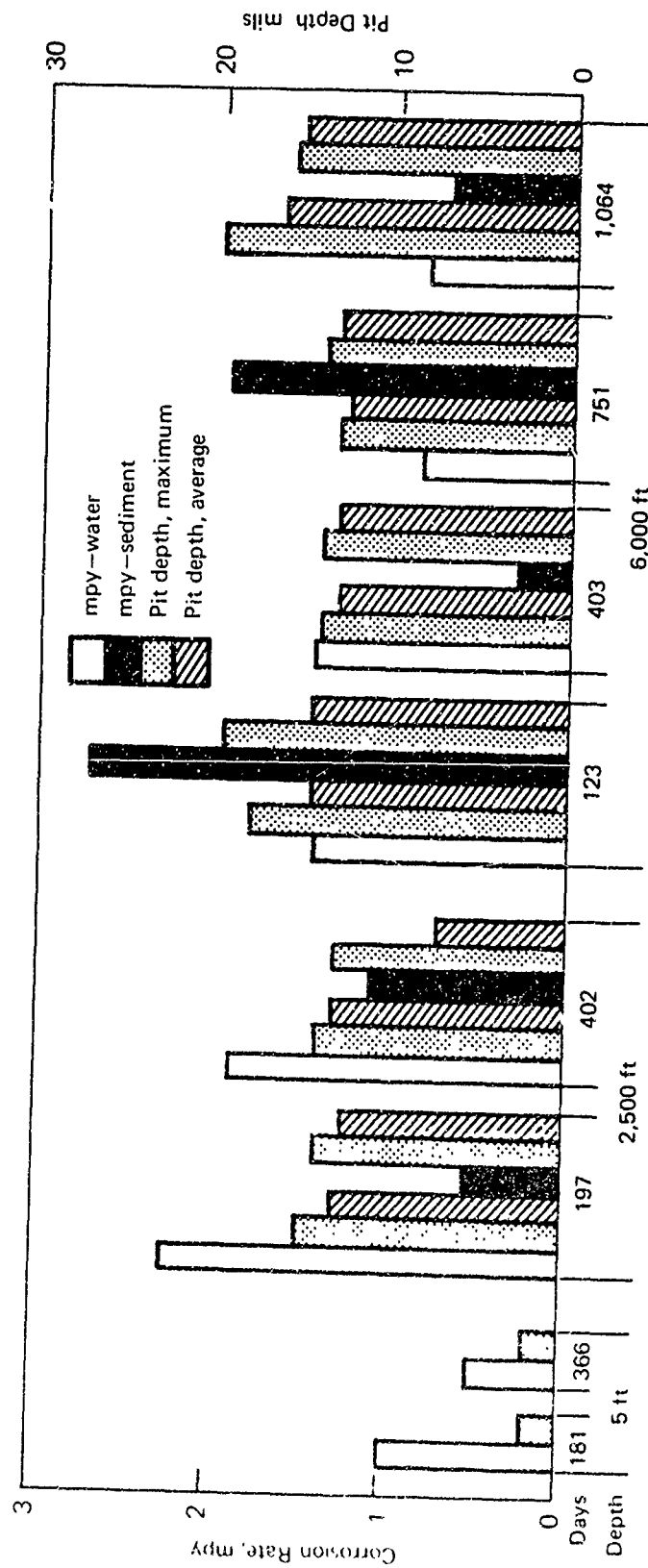


Figure 9. Corrosion rates, maximum and average pit depths of Alclad 3003 alloy.

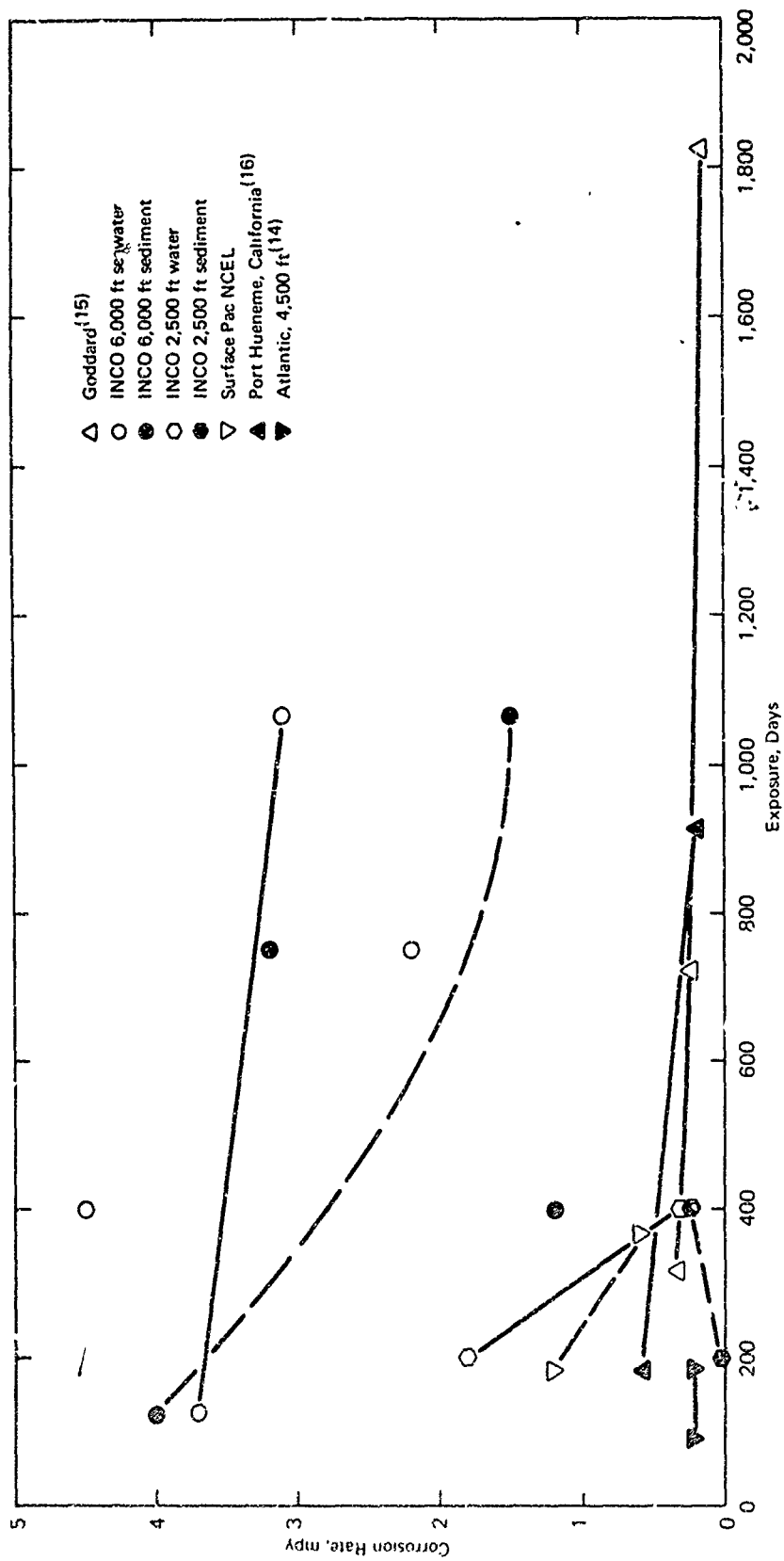


Figure 10. Corrosion rates of 5052 alloy at different depths and surface locations in the oceans.

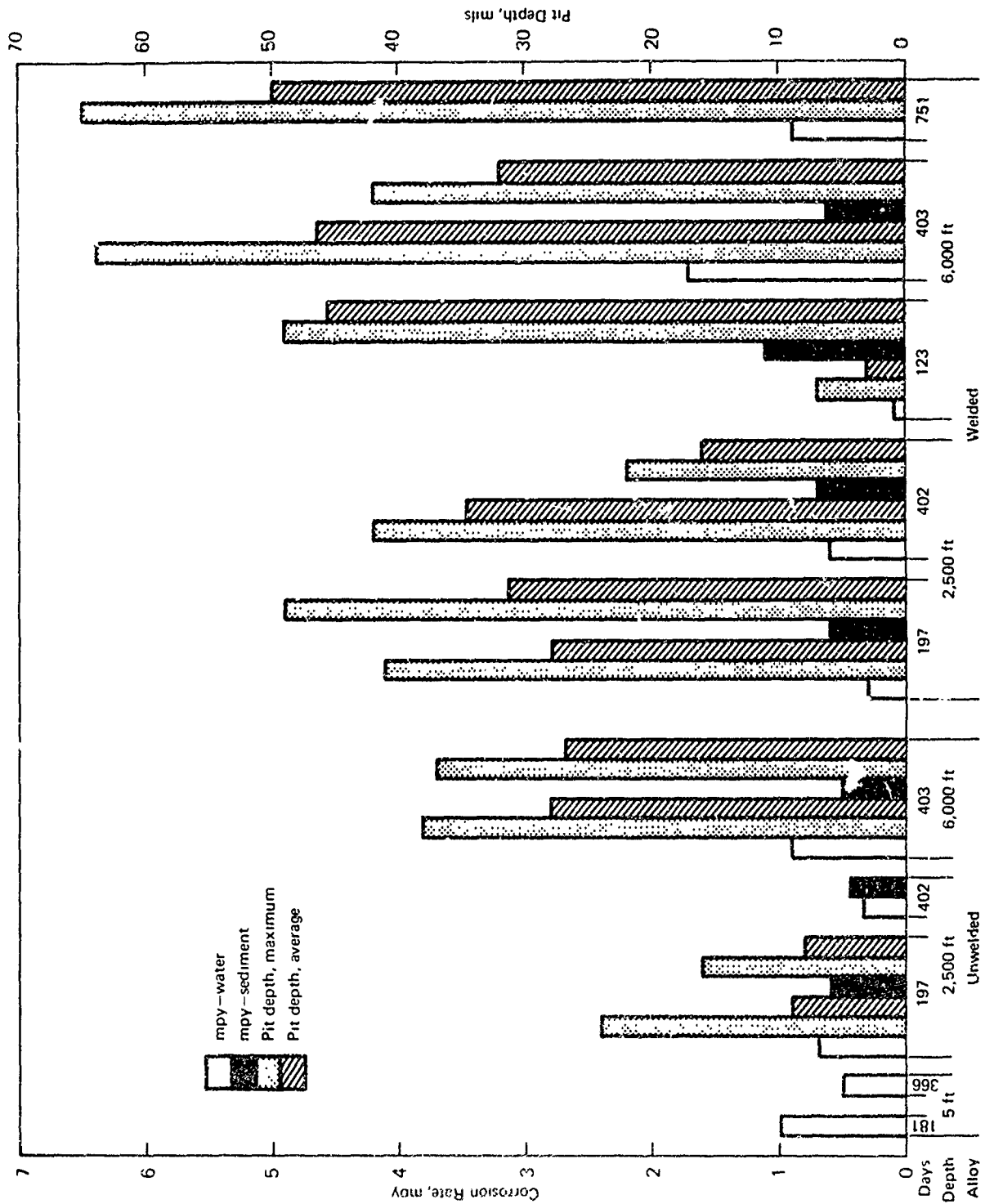
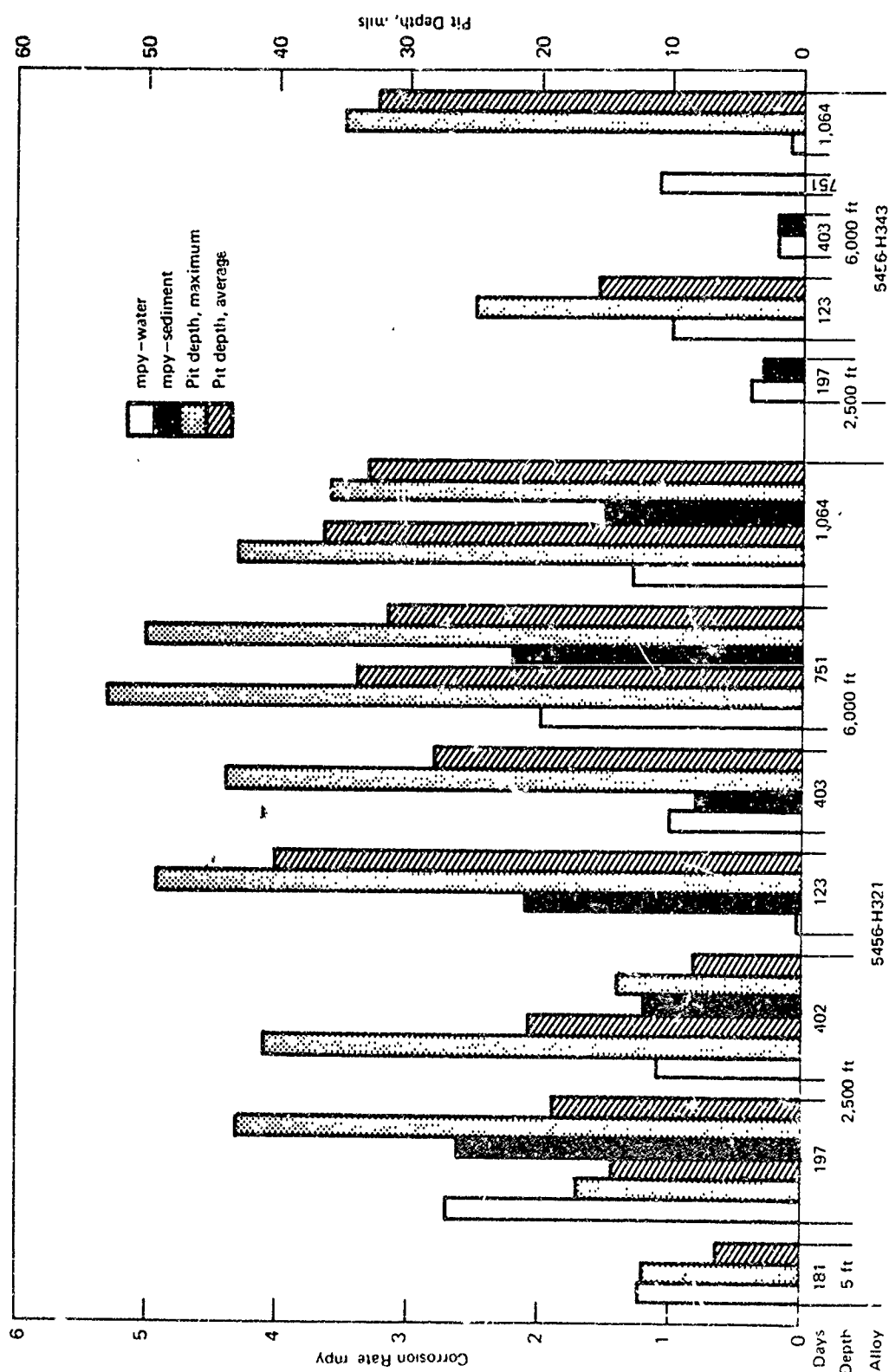


Figure 11. Corrosion rates, maximum and average pit depth of 5454-H32 alloy.



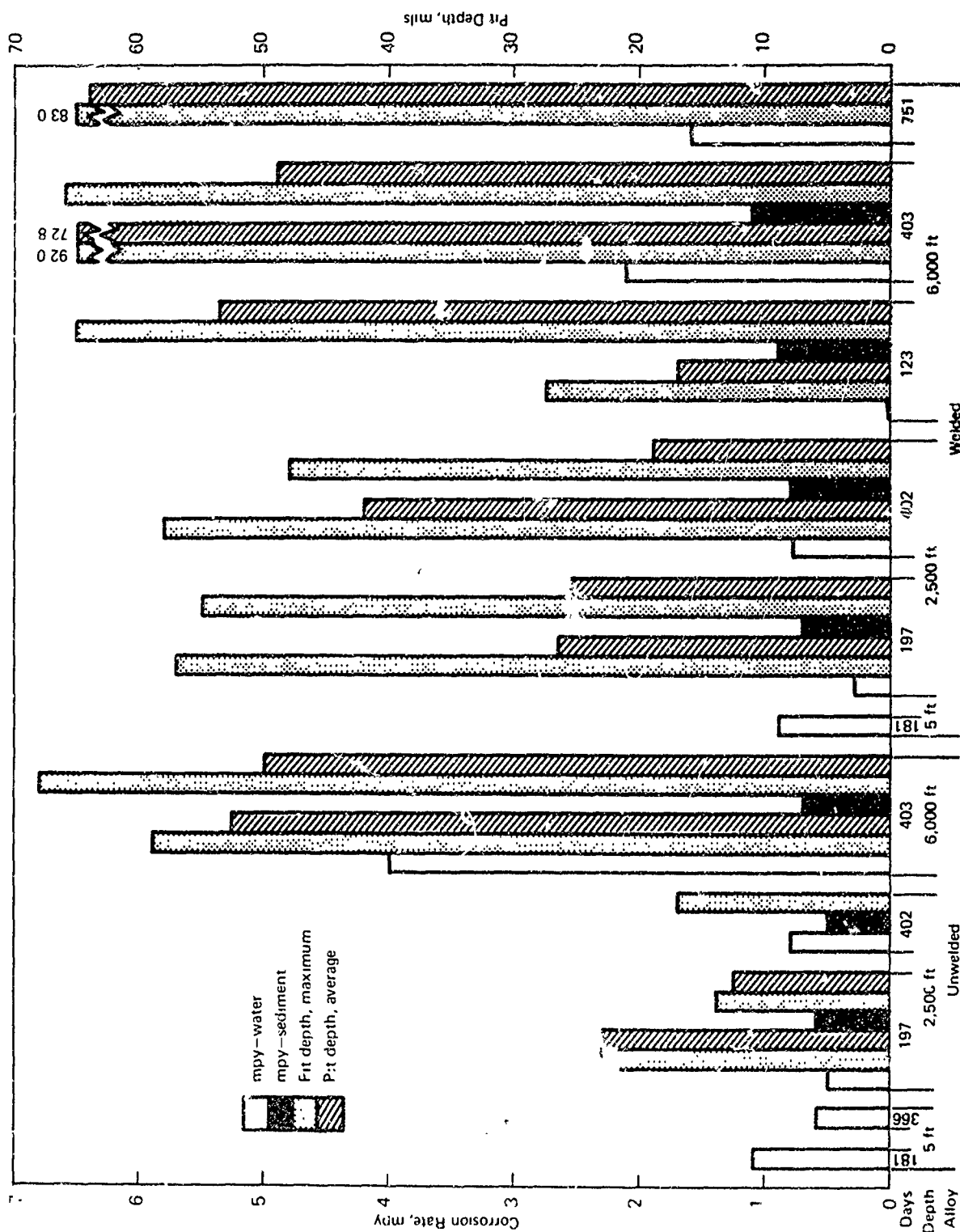


Figure 13. Corrosion rates, maximum and average pit depths of 5083-H113 alloy.

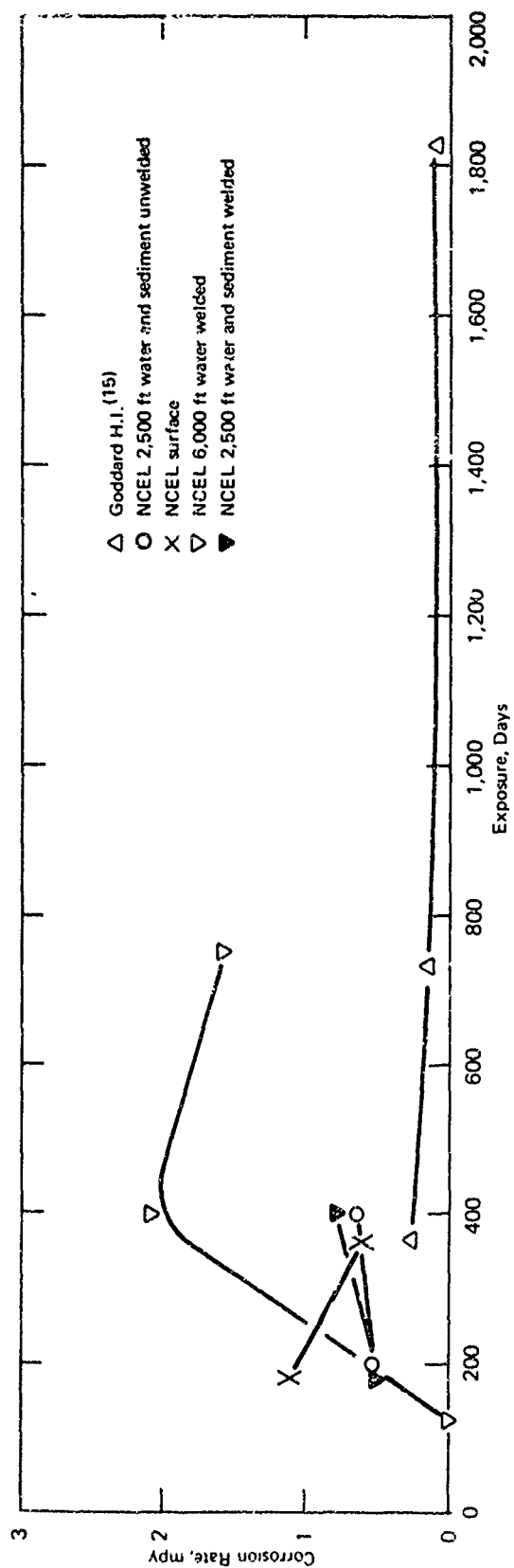


Figure 14. Corrosion rates of 5083 alloy at the surface and at depth in the oceans.

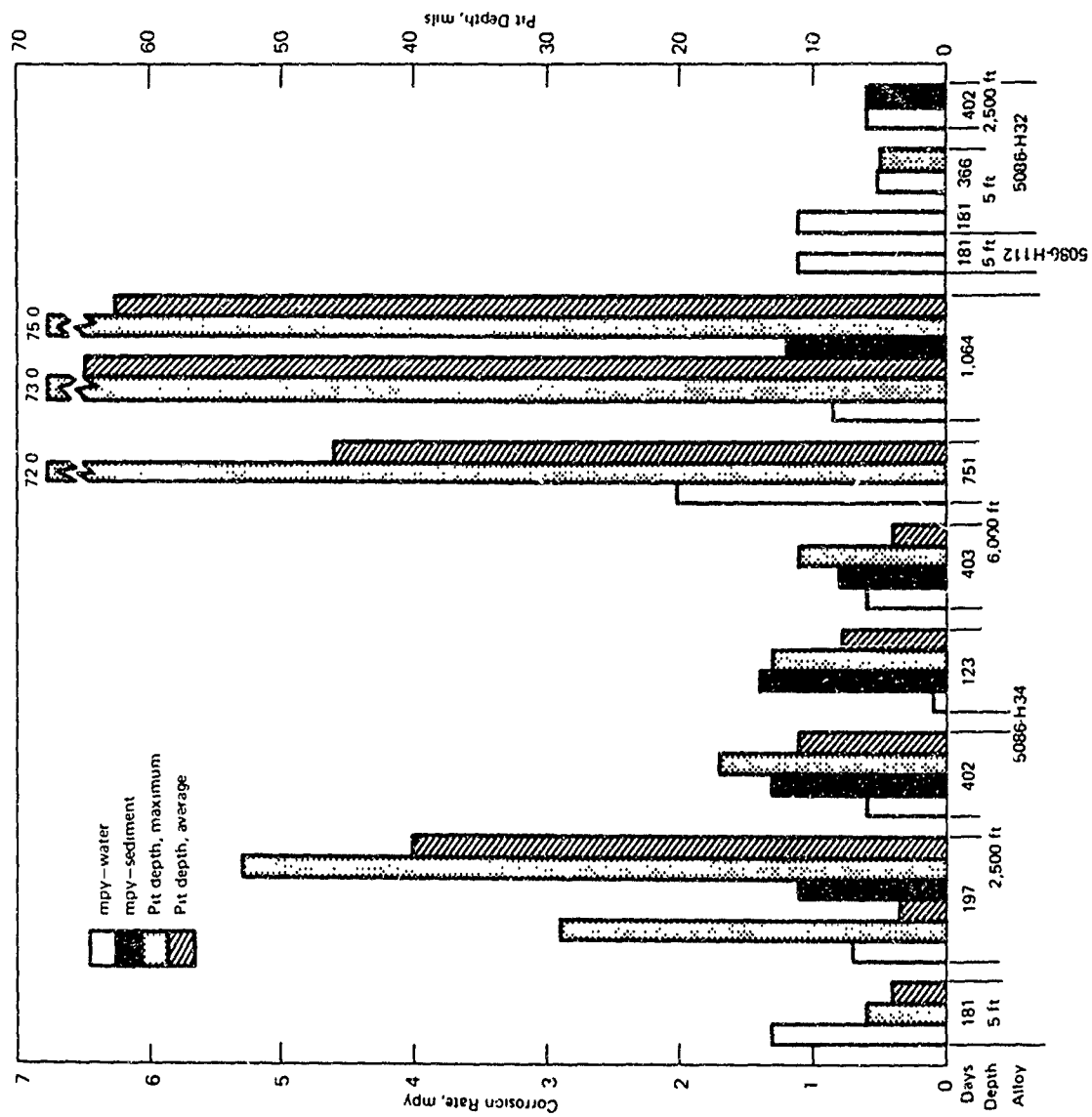


Figure 15. Corrosion rates, maximum and average pit depths of 5086 alloy.

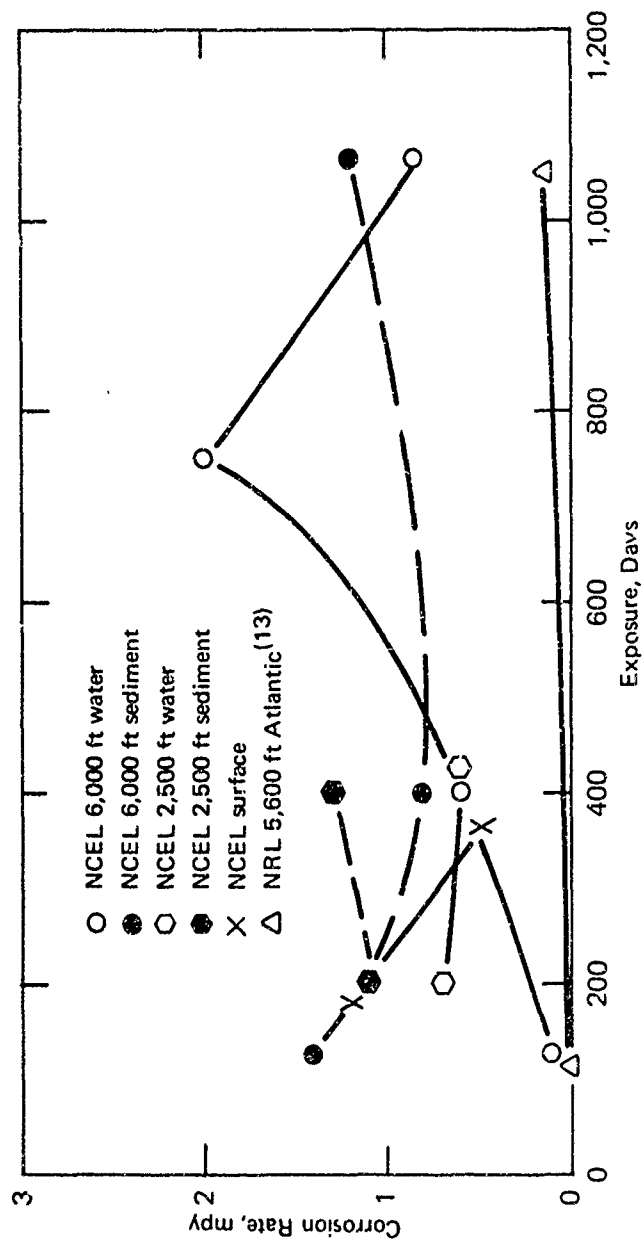


Figure 16. Corrosion rates of 5086-H34 alloy at the surface and at depth in the oceans.

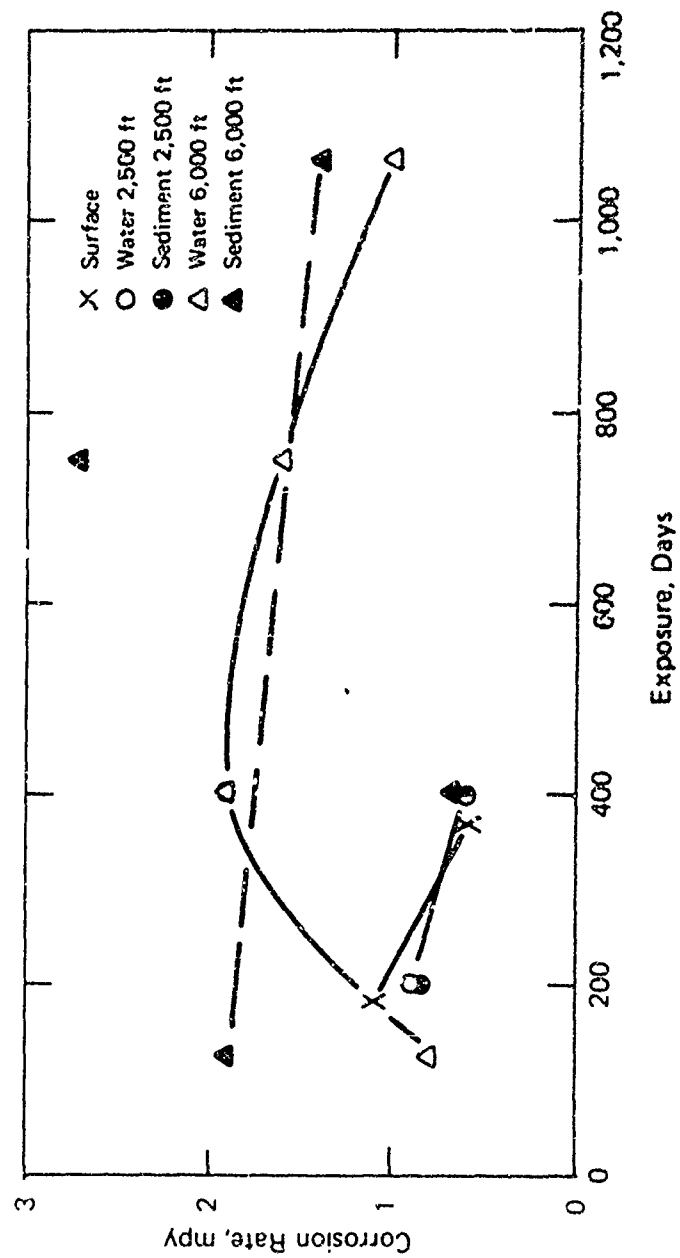


Figure 17. Average corrosion rates of all the 5000 Series alloys at the surface and at depths in the Pacific Ocean.

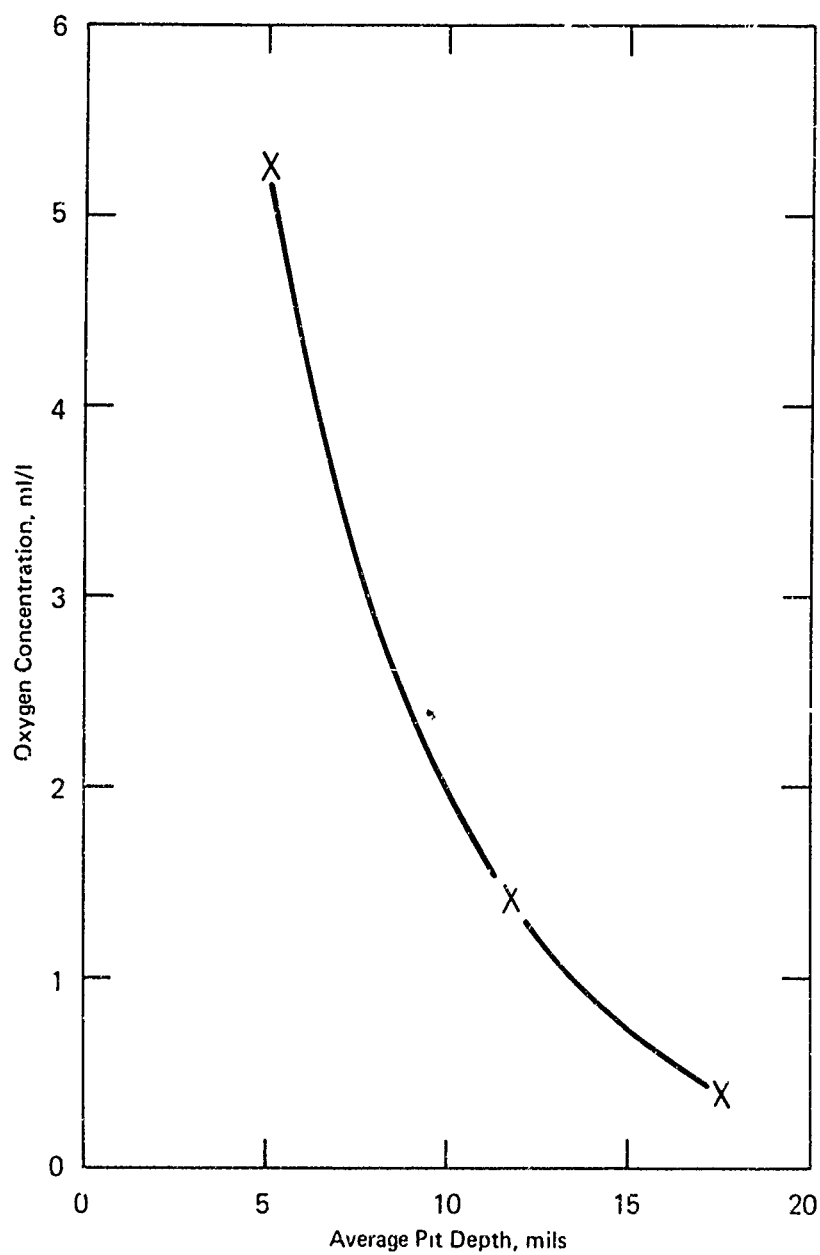


Figure 18. Average pit depths of aluminum-magnesium alloys (5000 Series) vs oxygen concentration of sea water.

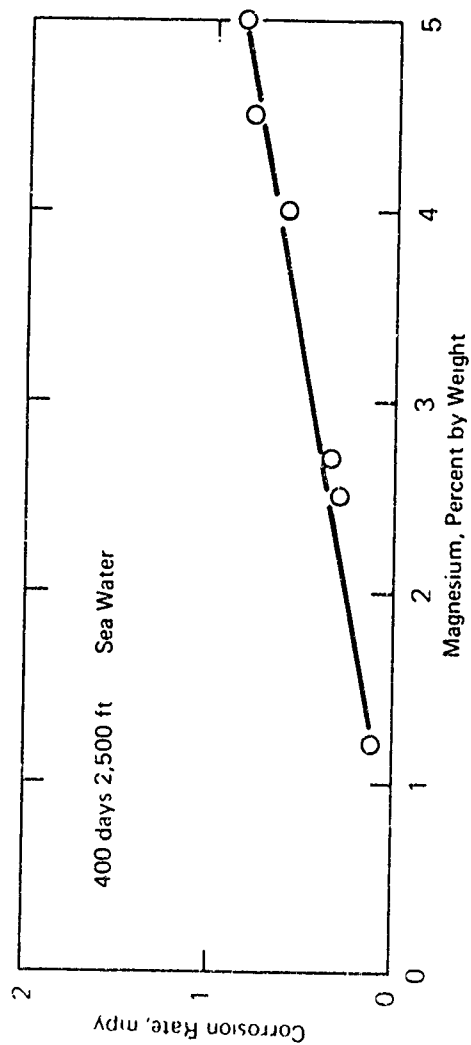


Figure 19. Corrosion rates vs magnesium content of aluminum-magnesium alloys (5000 Series), 400 days at 2,500 foot depth.

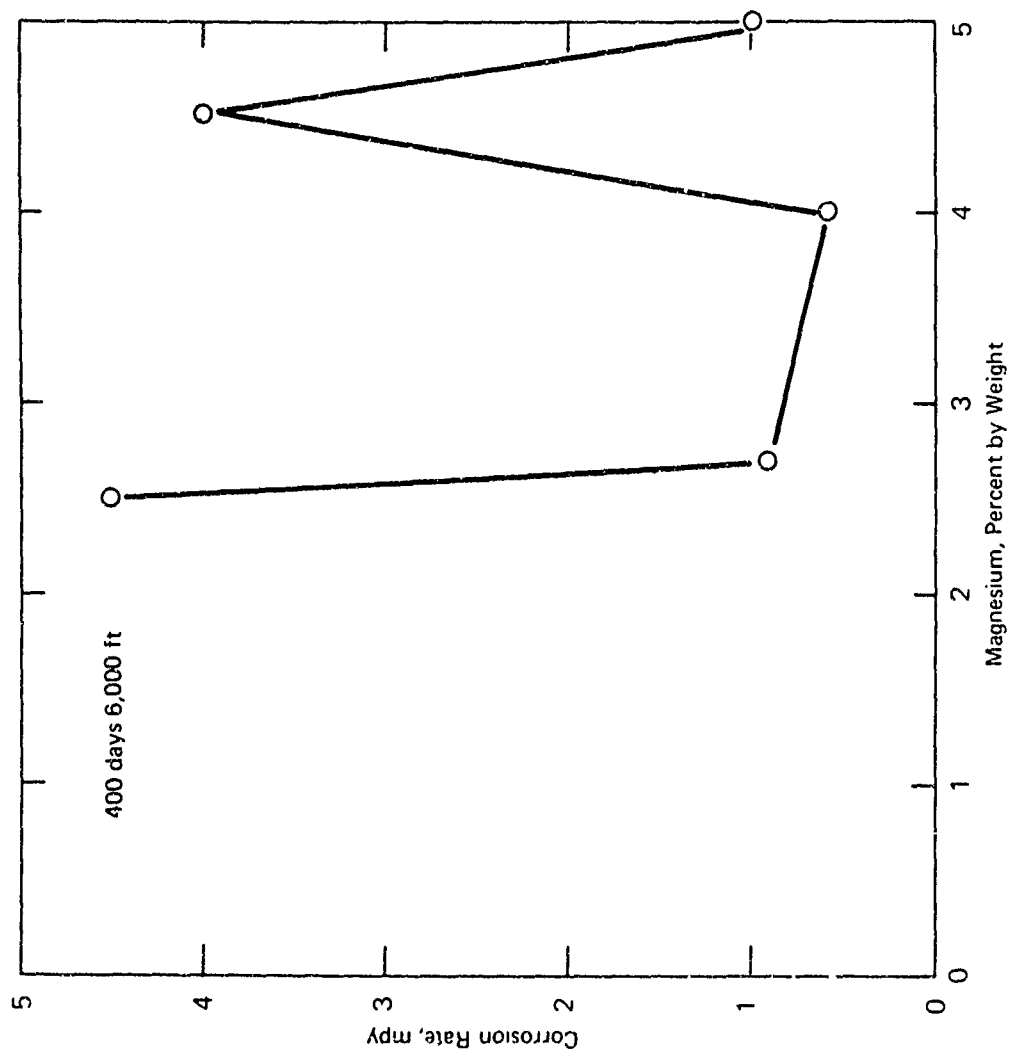


Figure 20. Corrosion rates vs magnesium content of aluminum-magnesium alloys (5000 Series), 400 days at 6,000 foot depth.

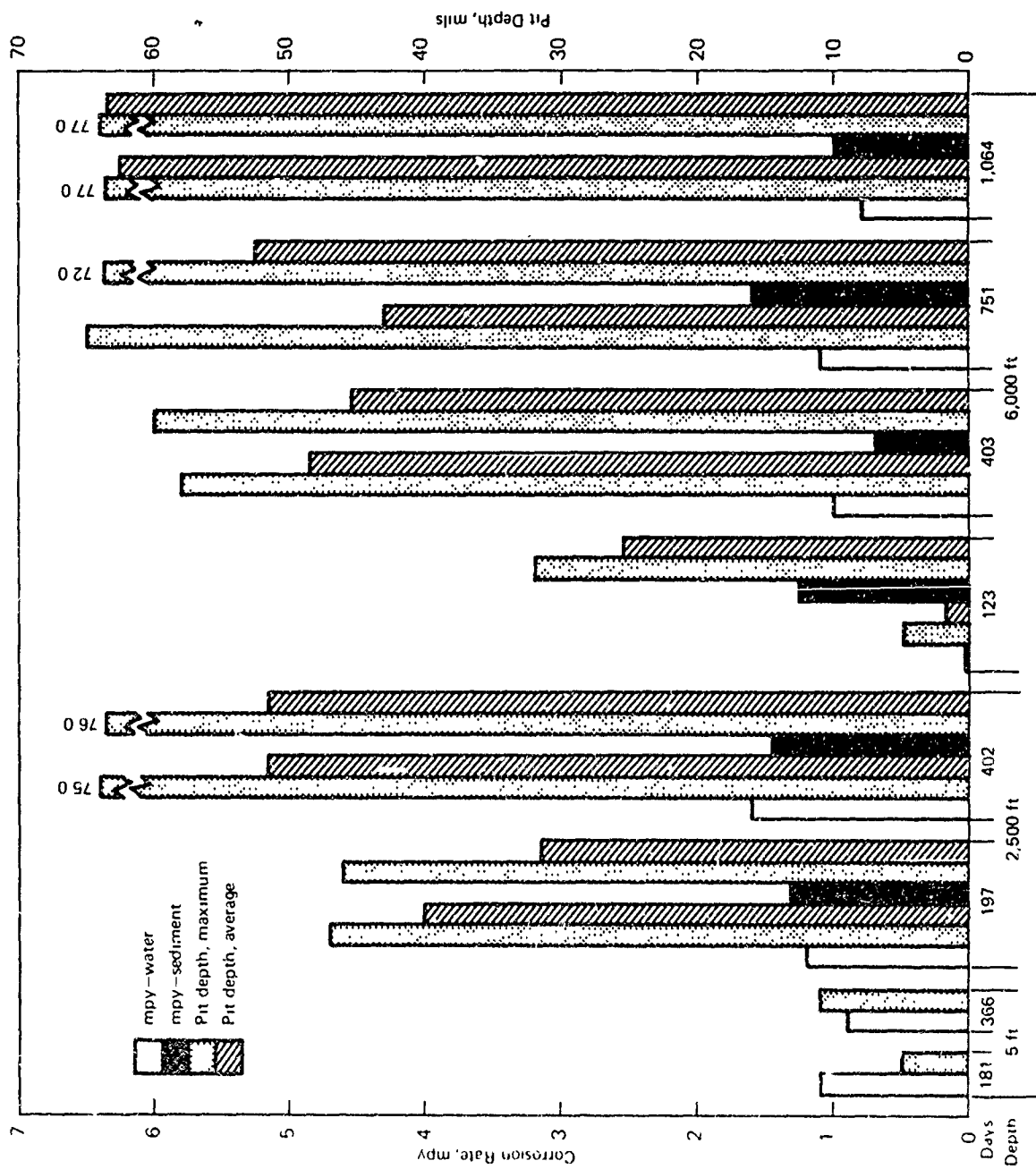


Figure 21. Corrosion rates, maximum and average pit depths of 6061-T6 alloy.

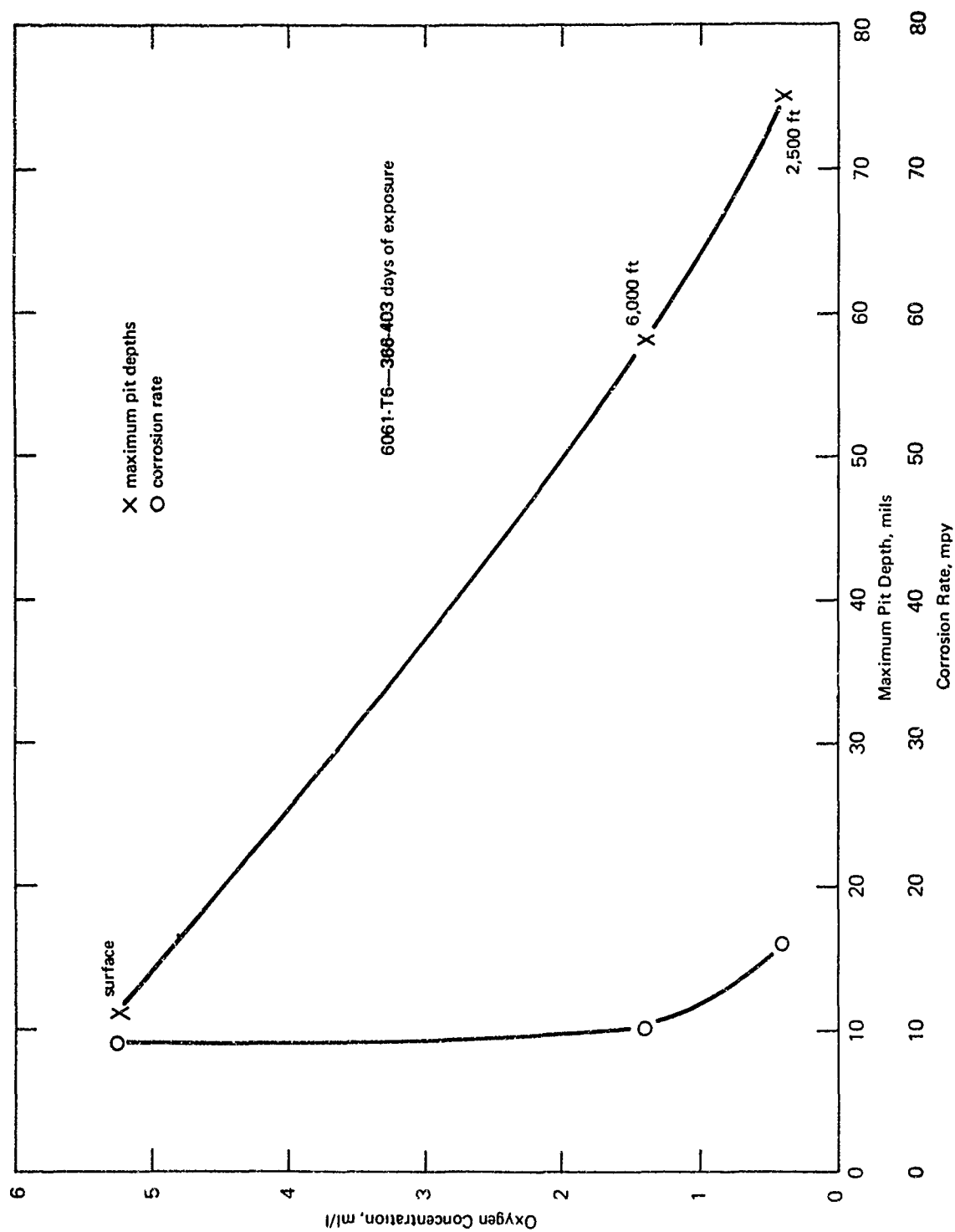


Figure 22. Corrosion rates and maximum pit depths of 6061-T6 alloy vs oxygen concentration after 1 year of exposure.

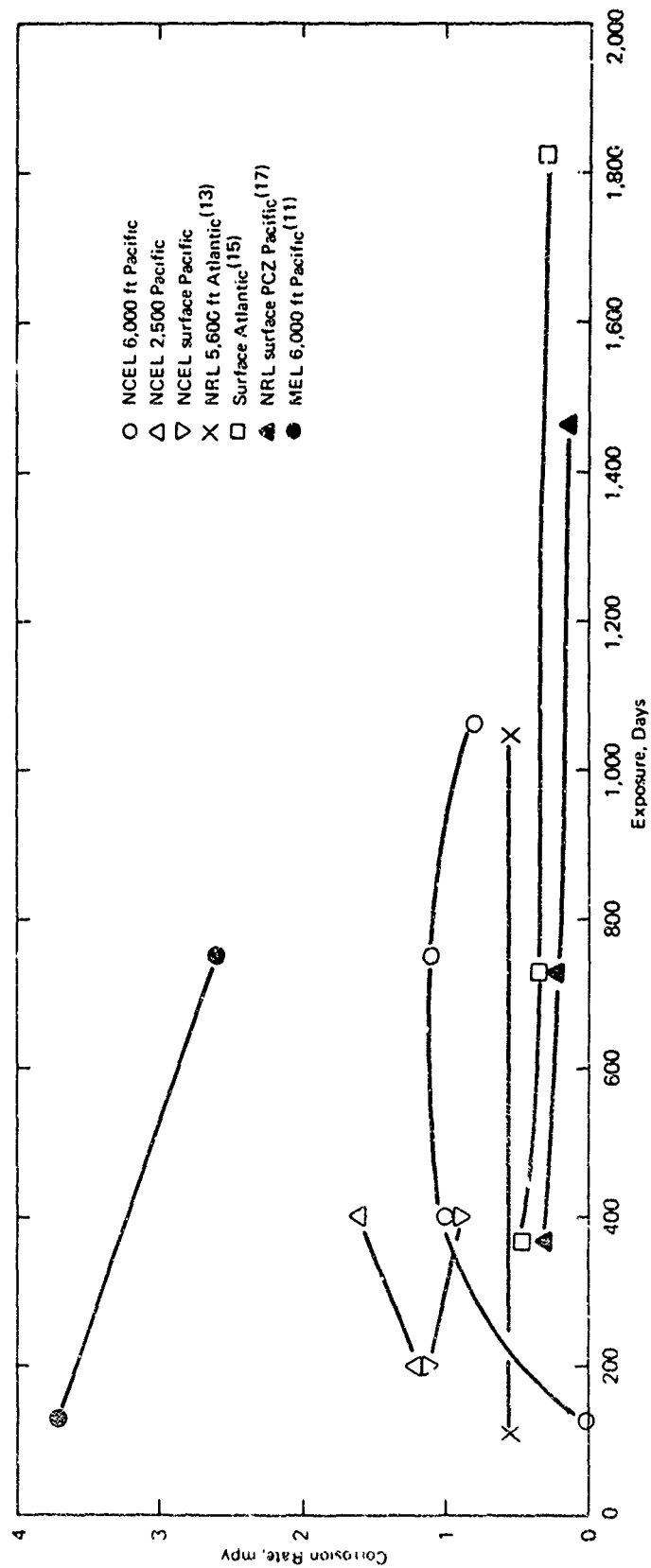


Figure 23. Corrosion rates of 6061-T6 alloy in sea water in the oceans.

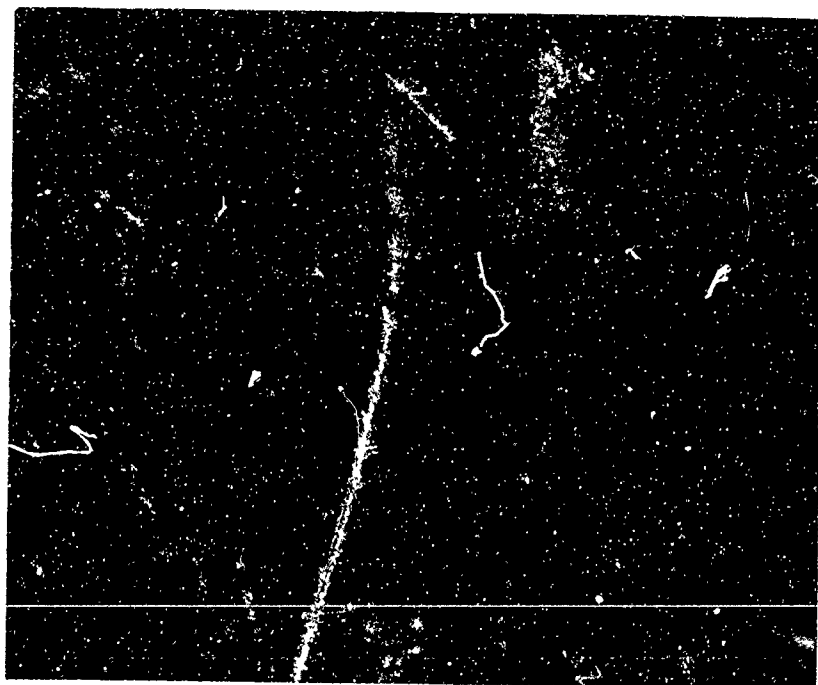


Figure 25. Severe exfoliation of 7039-T6 after 403 days of exposure at a depth of 6 000 feet. Plate thickness has increased four times.

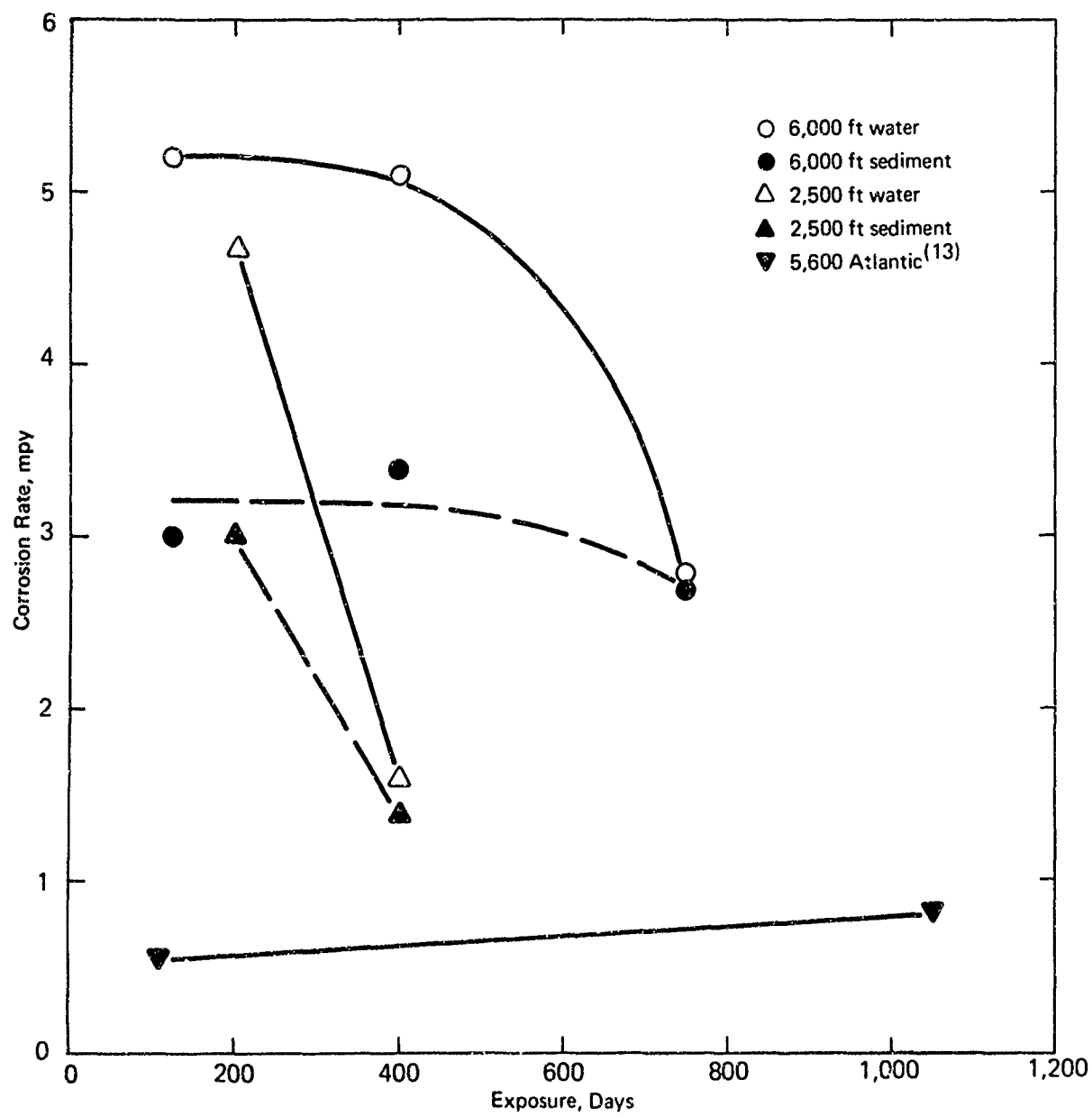


Figure 26. Corrosion rates of 7079-T6 alloy at depths in the Atlantic and Pacific Oceans.

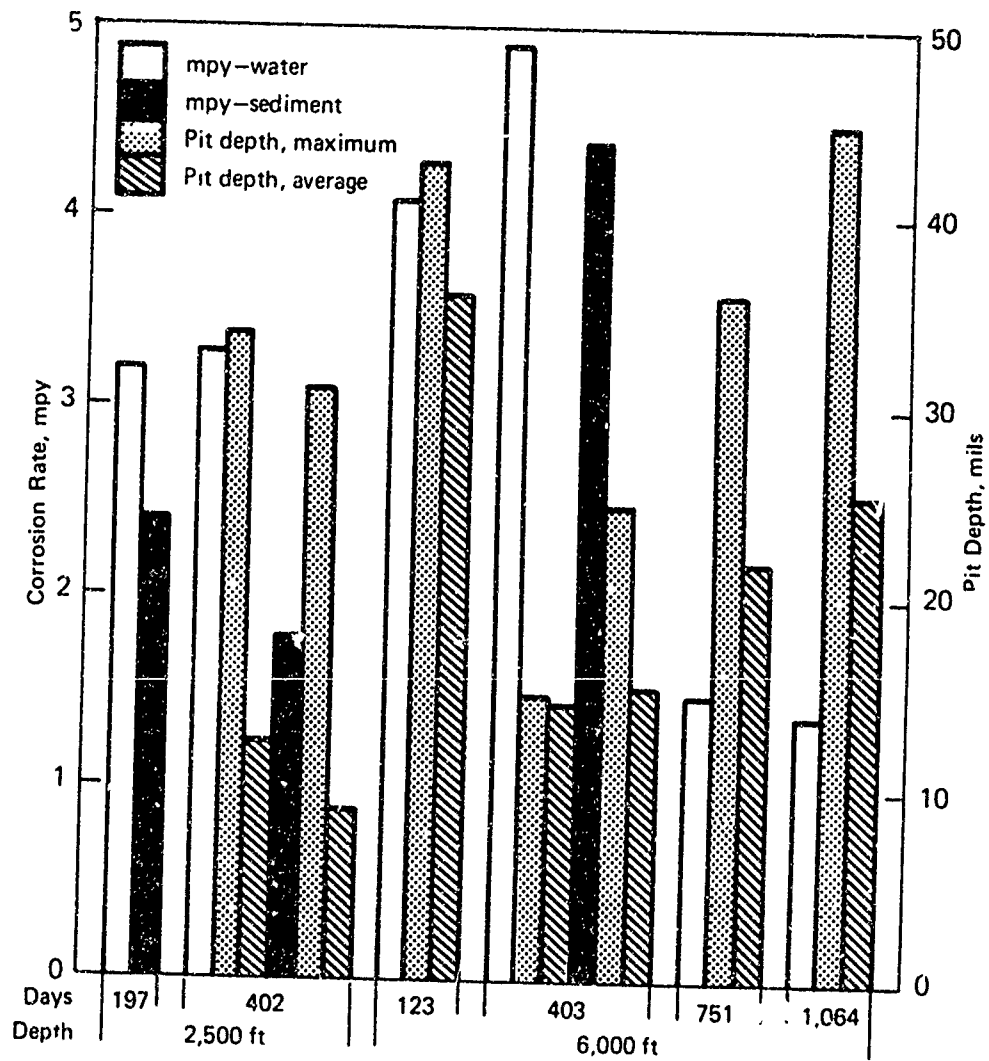


Figure 27. Corrosion rates, maximum and average pit depths of 7178-T6 alloy.

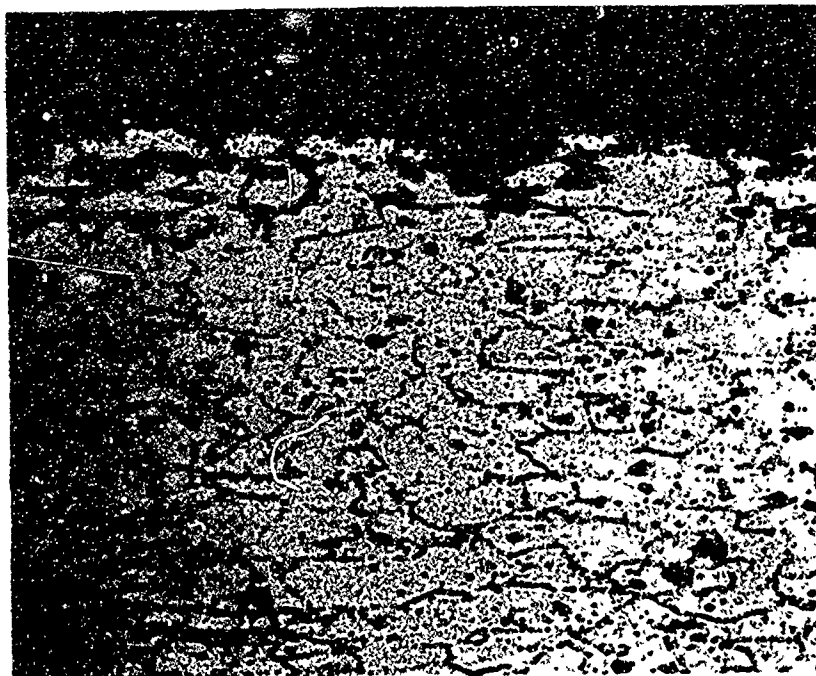


Figure 28. Intergranular corrosion and intergranular precipitation in 5086-H34 alloy. Keller's etch. X500.

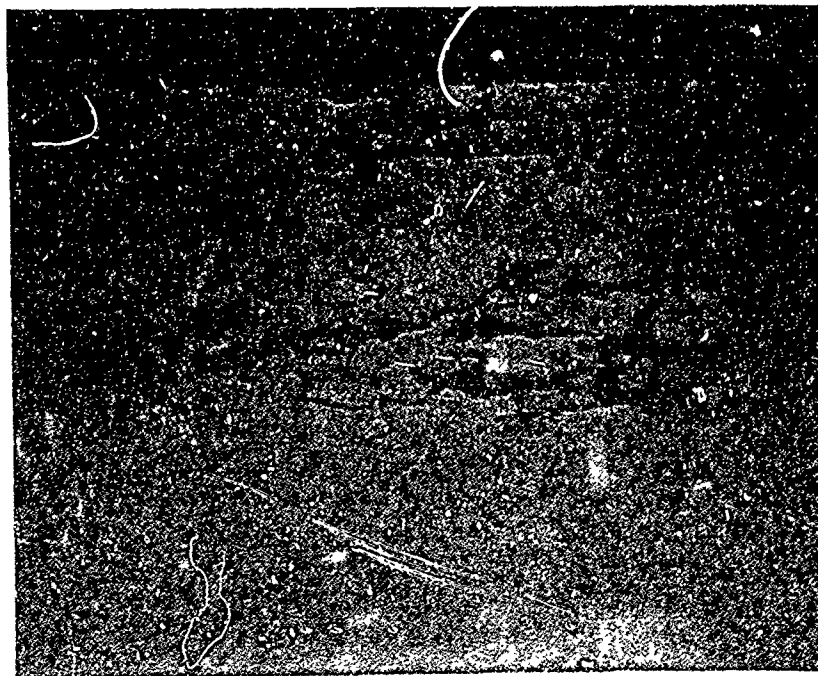


Figure 29. Intergranular corrosion in 6061-T6 alloy. Unetched. X500.

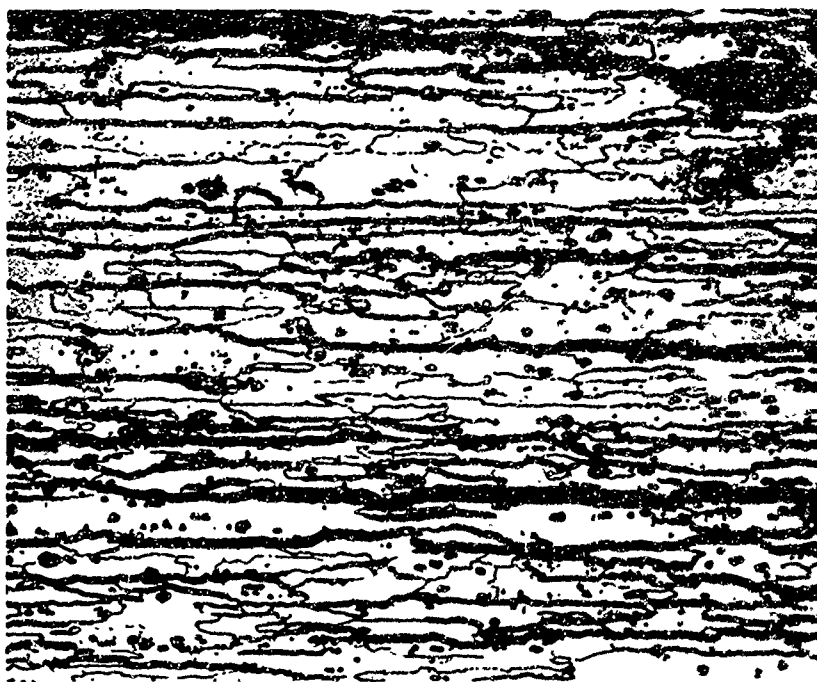


Figure 30. Exfoliation type of intergranular corrosion in 7178-T6 alloy. Keller's etch. X200.



Figure 31. Exfoliation type of intergranular corrosion in 7039-T6 alloy. Keller's etch. X200.

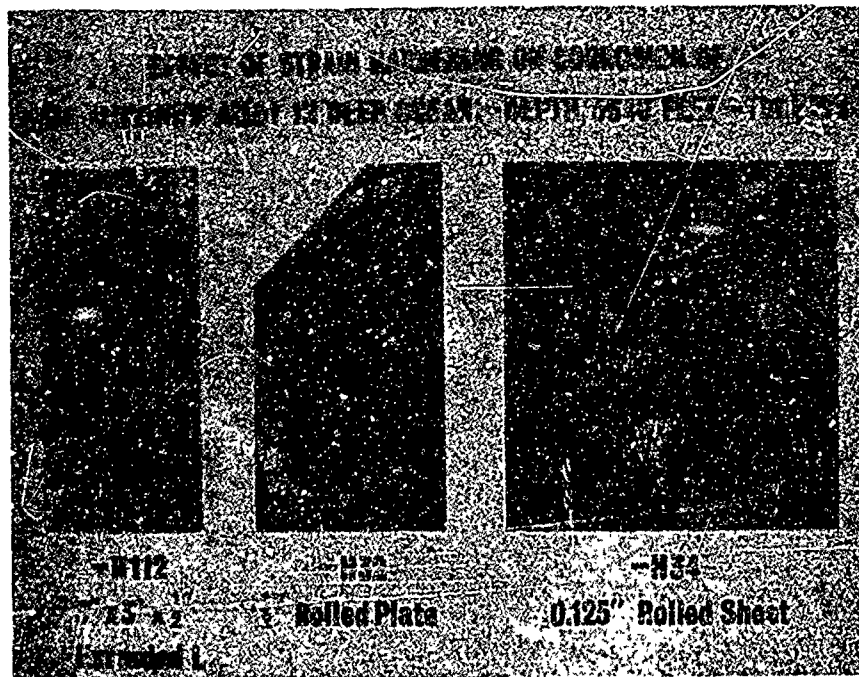


Figure 32. Effect of strain hardening on the corrosion of 5086 alloy after 751 days of exposure at a depth of 6,000 feet in the Pacific Ocean.

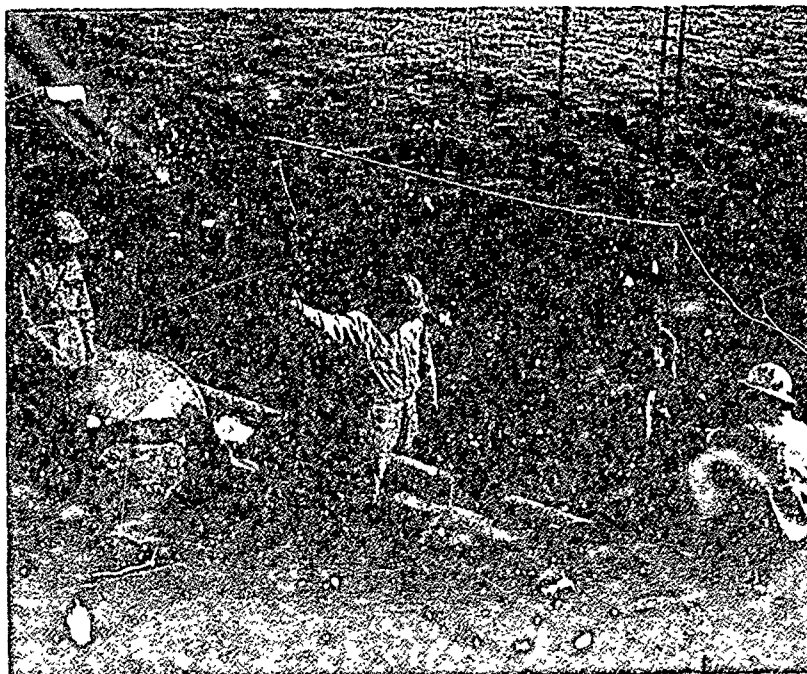


Figure 33. Alclad 7178-T6 buoy on board ship after recovery.

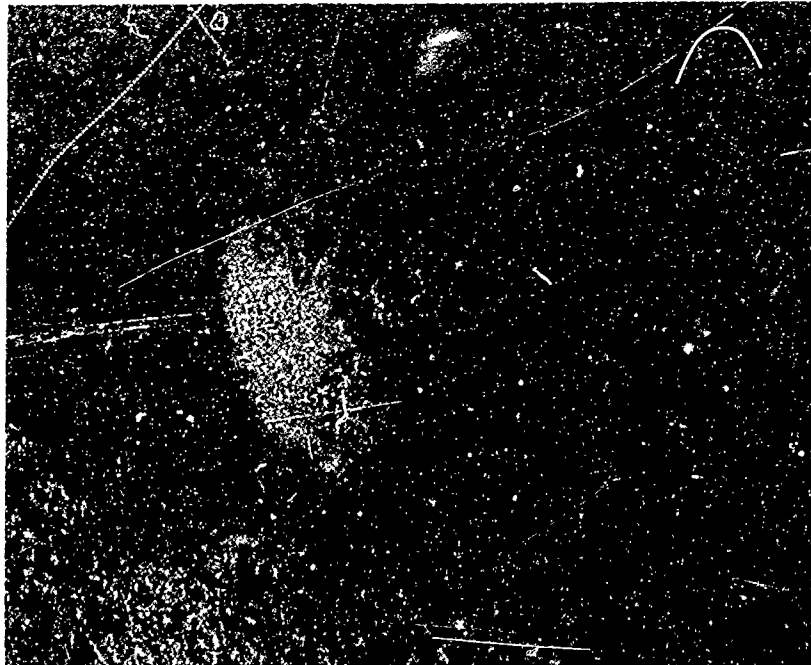


Figure 34. A blister on the top hemisphere of the buoy shown in Figure 33.

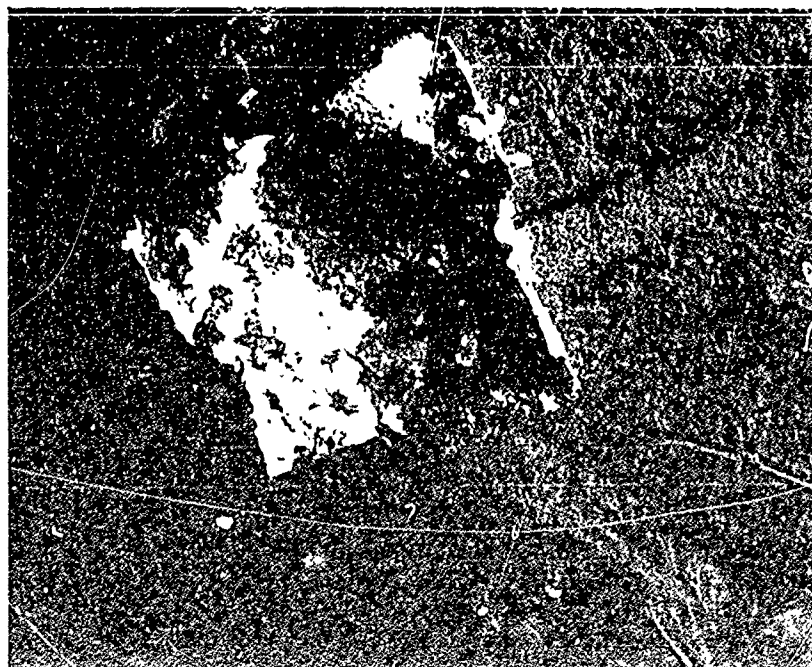


Figure 35. Crystalline aluminum oxide corrosion products, in situ, which filled the blister shown in Figure 34.

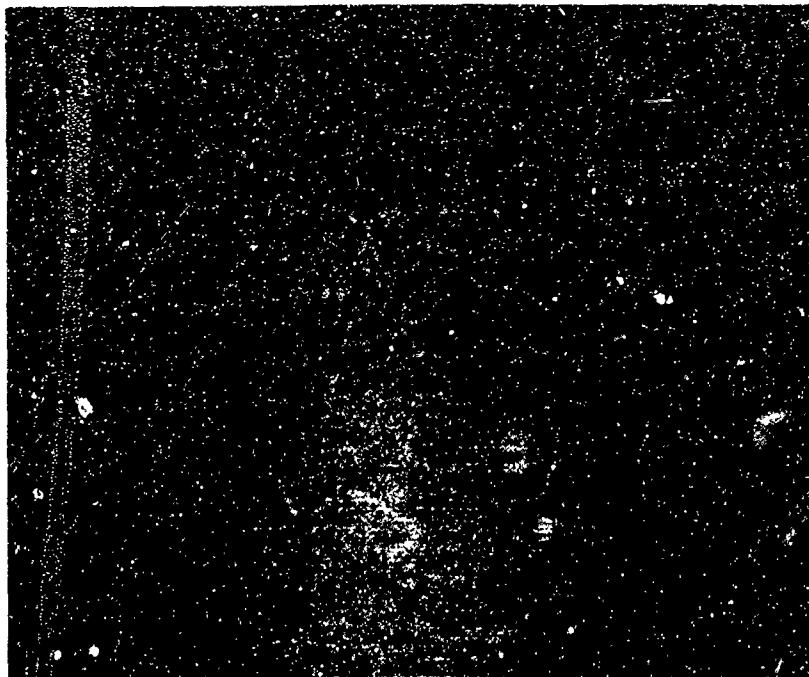


Figure 36. Corrosion at interface between cladding alloy and core alloy of an Alclad 7178-T6 buoy. X4.

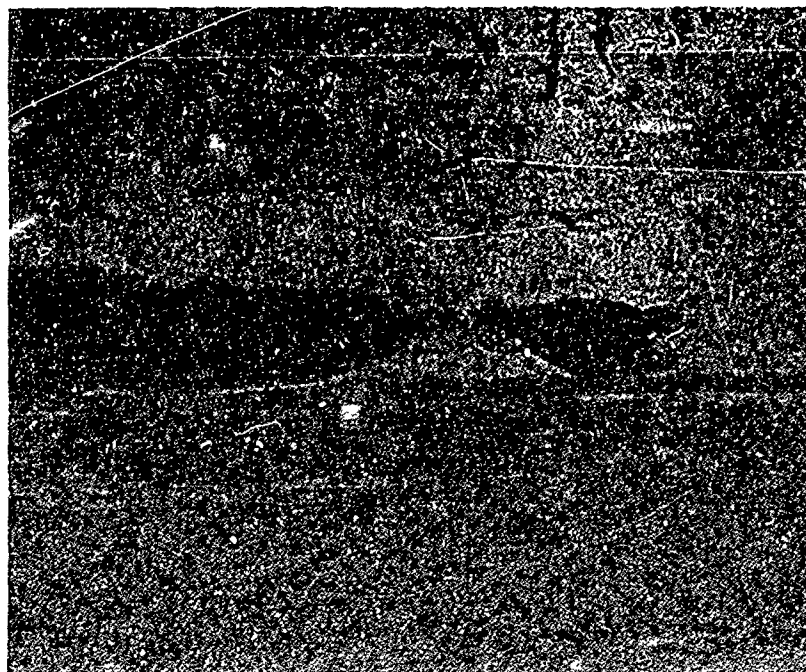


Figure 37. Corrosion path in cladding alloy with a thin diffusion layer separating it from the core alloy. Keller's etch. X100.

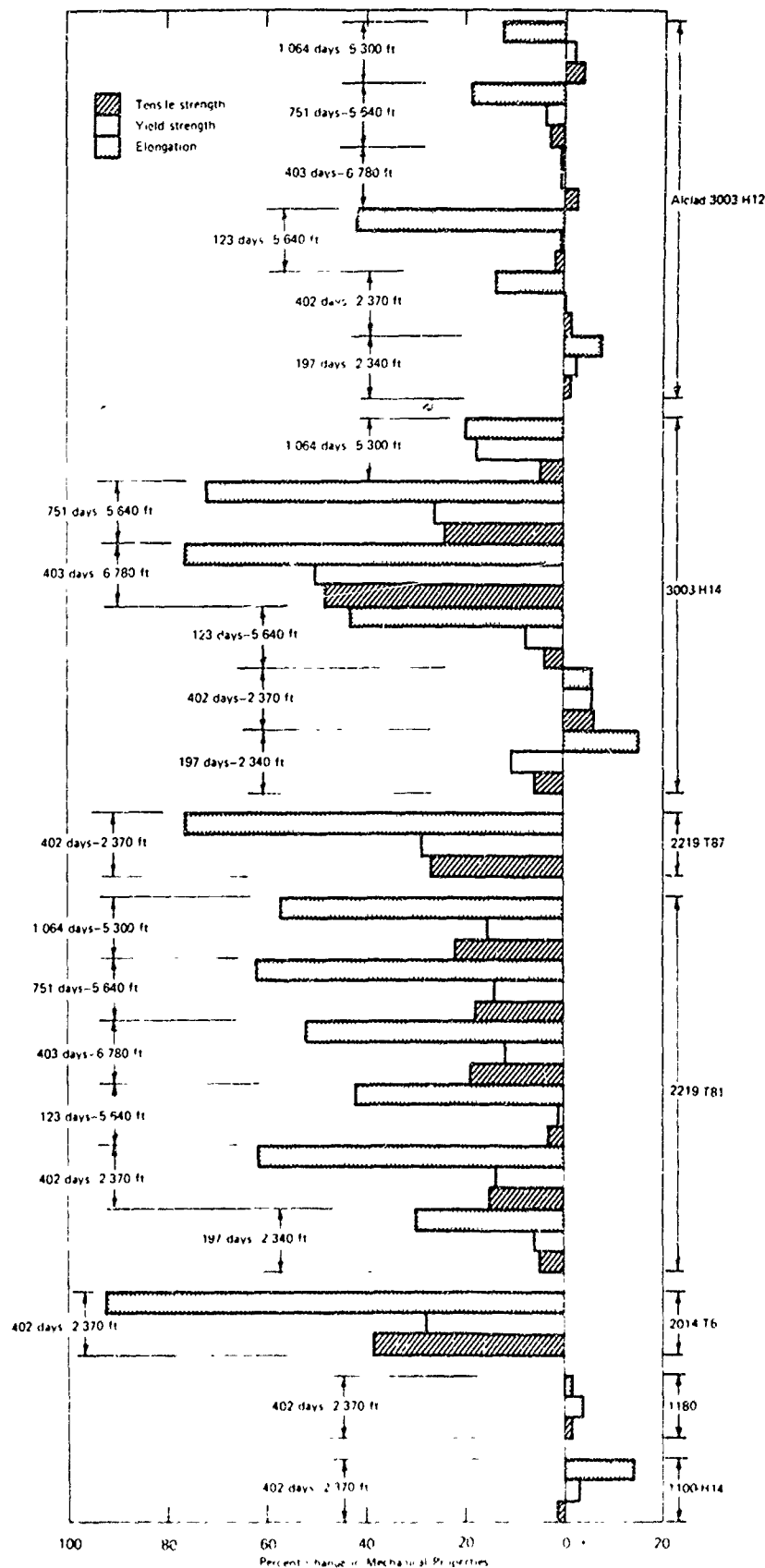


Figure 38. Changes of mechanical properties with exposure.

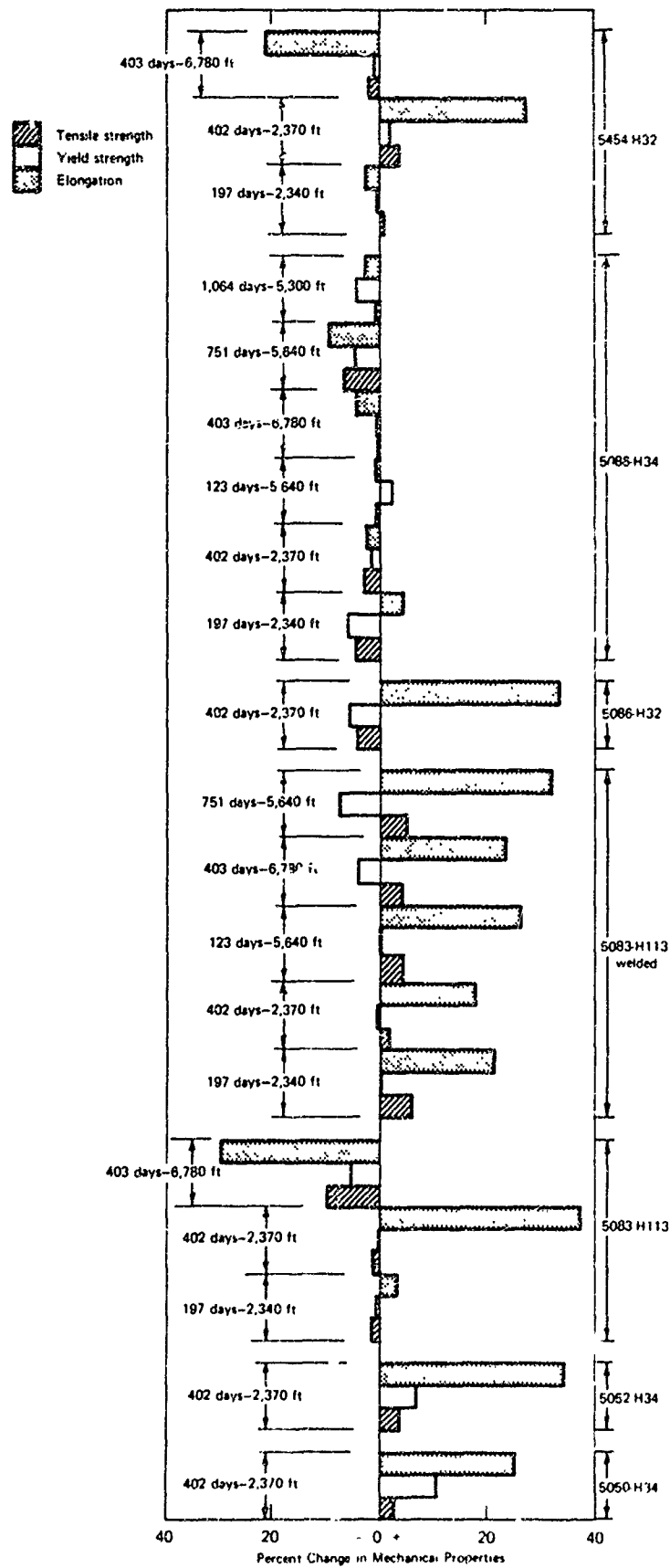


Figure 39. Changes of mechanical properties with exposure.

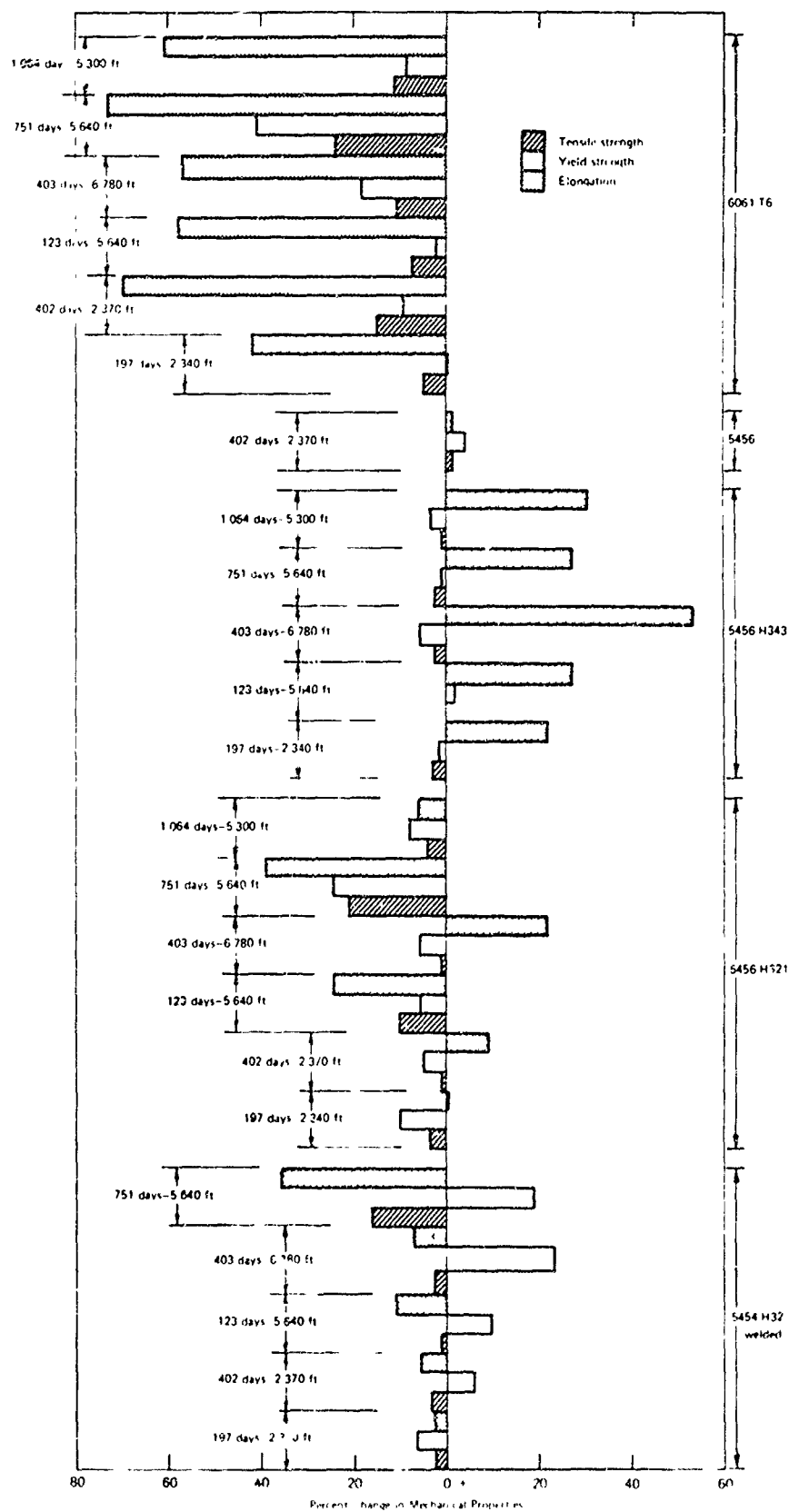


Figure 40. Changes of mechanical properties with exposure.

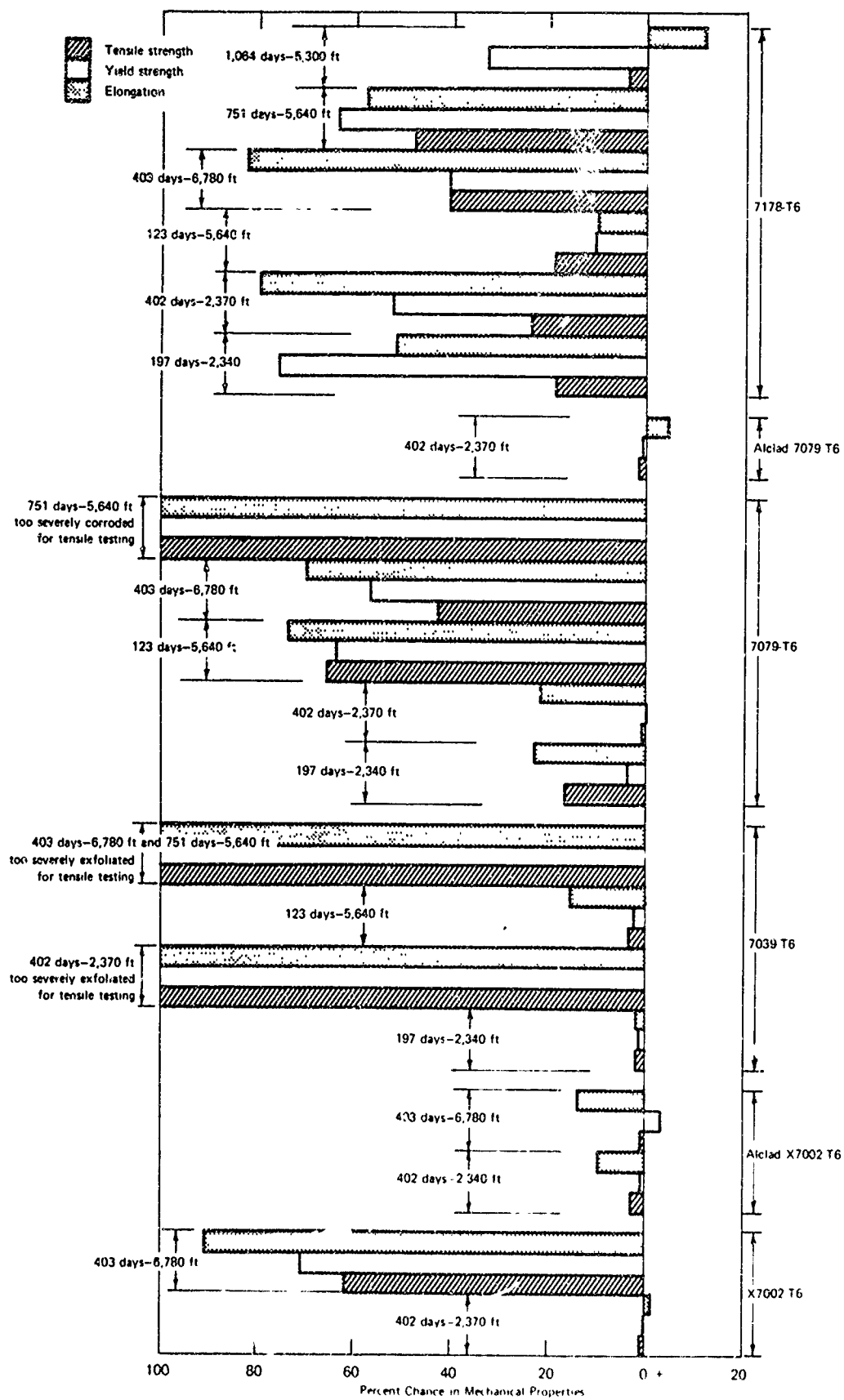


Figure 41. Changes of mechanical properties with exposure.

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13. ABSTRACT		
A total of 900 specimens of 40 different aluminum alloys were exposed at depths of 2,500 and 6,000 feet in the Pacific Ocean for periods of time varying from 123 to 1064 days in order to determine the effects of deep ocean environments on their corrosion resistance. Corrosion rates, types of corrosion, pit depths, stress corrosion cracking resistance, changes in mechanical properties and compositions of corrosion products are presented. Alloys 2219-T87, 7079-T6, 7178-T6 and Alclad 7079-T6 were susceptible to stress corrosion cracking. Alloys 2024-T3, 7039-T6, 7075-T6, 7079-T6 and 7178-T6 were attacked by the exfoliation type of corrosion. All the alloys were attacked by pitting and crevice types of corrosion. With reference to aluminum alloys, sea water at depth was more aggressive than at the surface and the bottom sediments were more corrosive than the sea water at depth in the Pacific Ocean. Aluminum alloys not susceptible to stress corrosion cracking and exfoliation corrosion can be used for deep sea applications if adequately protected and if brought to the surface periodically for maintenance of the protective system.		

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14	KEY WORDS	LINK A		LINK B		LINK C	
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	Stress corrosion cracking						
	Mechanical properties						
	Exfoliation						
	Intergranular						
	Bottom sediments						



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Encl: (1) Figures 21 and 22

1. Please remove Figures 21 and 22 from subject technical note and
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W. F. Burkart

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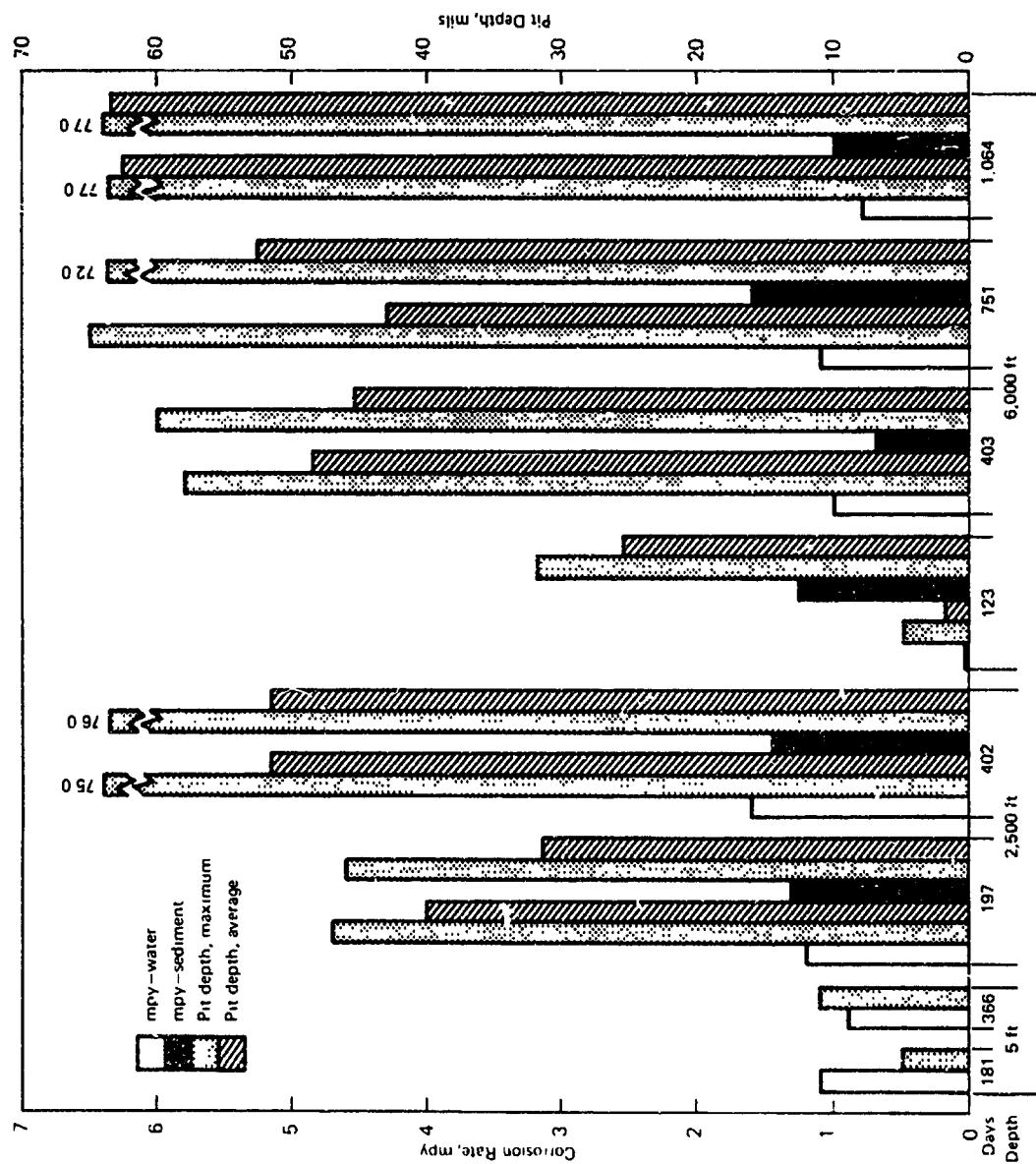


Figure 21. Corrosion rates, maximum and average pit depths of 6061-T6 alloy.

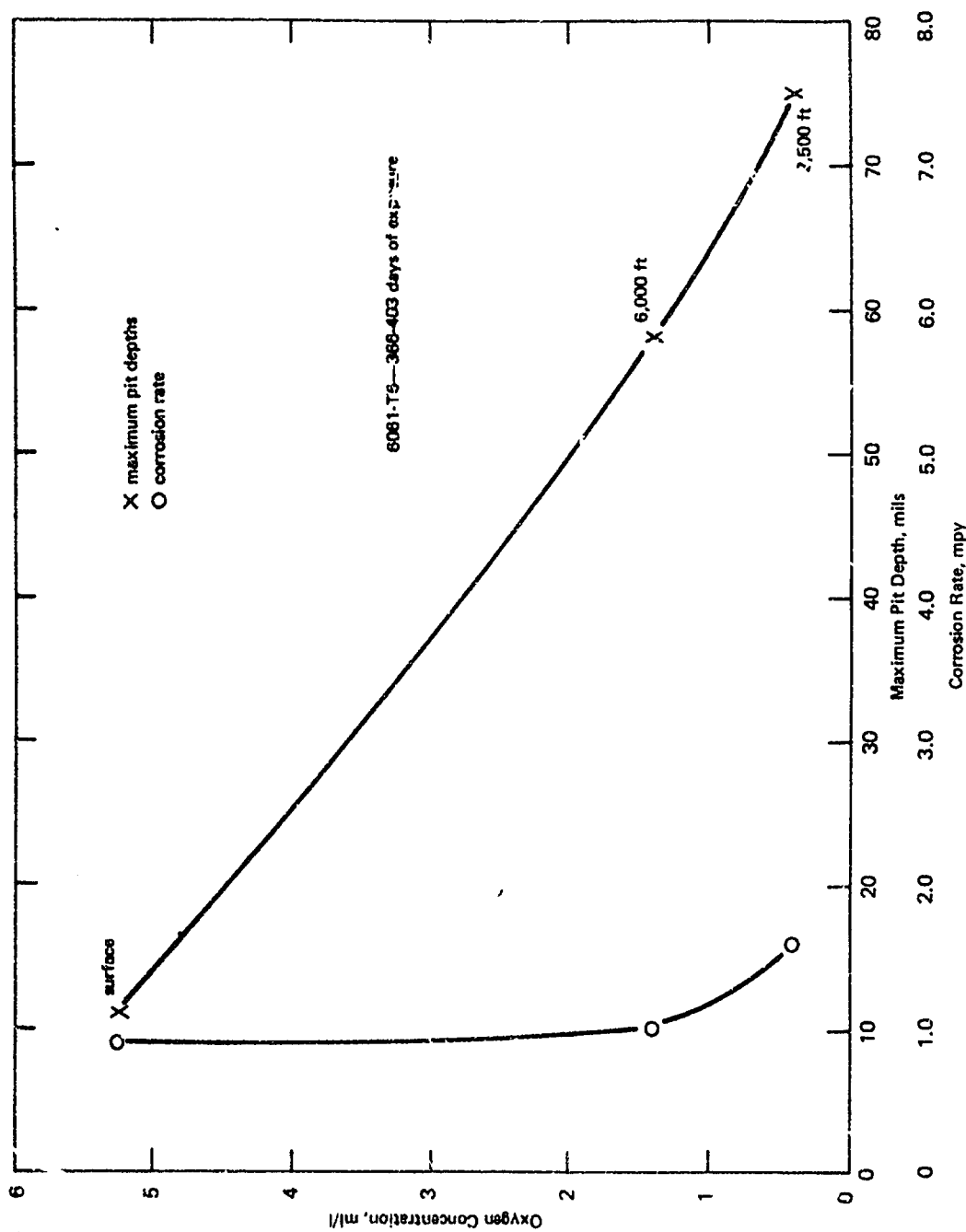


Figure 22. Corrosion rates and maximum pit depths of 6061-T6 alloy vs oxygen concentration after 1 year of exposure.