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# Seawater Corrosion Handbook

Edited by M. Schumacher

NOYES DATA CORPORATION

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# FOREWORD

Here is a practical book that will help anyone encountering the insidious corrosion problems that can be caused by seawater. The book constitutes a review containing carefully excerpted and collated data from diverse and difficult-to-locate sources.

The technological information to be found here is based on studies by research teams from U.S. Naval Research Laboratories and other research teams under the auspices of various government agencies.

The first chapter is really an overview and deals with the general aspects concerning the corrosion of metals in marine environments: MCIC Report 78-37 entitled *Corrosion of Metals in Marine Environments* by W.K. Boyd and F.W. Fink, Metals and Ceramics Information Center, Columbus, Ohio, March 1978.

The second chapter deals with the corrosion at various depths and is from Technical Report R834: *Corrosion of Metals and Alloys in the Deep Ocean* by F.M. Reinhart, Naval Civil Engineering Laboratory, Port Hueneme CA, Feb. 1976.

The third chapter treats the effects of microorganisms. Material for this chapter was elaborated from three reports. The first original report is a preprint of a scientific paper entitled *Biofouling and Effects of Organic Compounds and Microorganisms on Corrosion Processes* by S.M. Gerchakov and B. Sallman, Dept. of Microbiology, University of Miami School of Medicine, Sept. 1977. The second report (SR 004-03-01, Task 0589, Lab. Project 9400-72, Tech. Memo 3) is entitled *Corrosion at 4500 Foot Depth in Tongue-of-the-Ocean* by E. Fischer and S. Finger, U.S. Naval Applied Science Laboratory, Brooklyn, NY, March 1966. The third original report

is entitled *Influence of Marine Organisms on the Life of Structural Steels in Seawater* by C.R. Southwell et al., Naval Research Laboratory, Washington, D.C., March 1974.

The fourth chapter is an annotated bibliography containing meaningful abstracts referring to the corrosion of metals. It stems from a paper by L.A. Beaubien found in NRL Report No. 7447 entitled *Behavior of Materials in a Subsurface Ocean Environment* by L.A. Beaubien et al., Naval Research Laboratory, Washington, D.C., July 1972. This chapter has its own author and materials index.

The fifth chapter treats the possible deterioration of nonmetallic materials when immersed or in contact with seawater and is also based on NRL Report No. 7447 cited for the fourth chapter.

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The table of contents is organized in such a way as to serve as a subject index and to provide easy access to the information contained in this book. To guide the researcher to further literature on the difficult topic of seawater corrosion each chapter is followed by a lengthy list of references. There are 194 tables and 126 figures included throughout the text.

In order to keep the price of this large and extensive book to a reasonable level, most of it has been reproduced by photo offset directly from the original typeset reports and these cost savings have been passed on to the reader. Some of the illustrations and parts of the text may be less acceptable than desired; however, they are reproduced from the best material available to us.

# INTRODUCTION

So long as man continues to explore the ocean and its environs for minerals, alternate foods, and other products of the sea, he must undertake a corresponding search for materials which can withstand the deteriorating effects of that environment. The serviceability of the metals and nonmetals employed in seawater structures cannot be disregarded. As man devotes more and more effort to offshore drilling, ocean mining, extractive metallurgy, and offshore meteorology, he must develop the best possible materials for use in the new technologies.

Fundamental to the development of such substances is a knowledge of how they will behave in various marine environments. In attempting to obtain such information, various industrial organizations, governmental agencies, and educational institutions have conducted thorough testing of construction materials to observe their action under exposure to ocean surroundings for extended periods of time. Reports covering the information gathered by these organizations are presented in this book dealing with corrosion of materials in marine environments.

Many substances corrode, especially under stress. "To corrode" means to dissolve or wear away gradually, particularly by chemical action; in a broad sense it simply means to impair, to consume, to deteriorate. It is in this wide sense of deterioration that this book will consider the behavior not only of metals, but also of nonmetals, in marine environments. The last chapter of this book, for example, discusses the action of seawater on such substances as polymers, ceramics, fabrics, electronic components and explosives. The susceptibility of these materials to biological attack and chemical deterioration in seawater must be evaluated to determine their usefulness in marine applications.

By "marine environments" is meant any of the

physical conditions ranging from mist-laden sea air to mud at the ocean's floor which surround any substance employed in ocean technology. Such variables as temperature, wind velocity, solar radiation, and oxygen content of the water must be considered. A high oxygen content, for instance, induces corrosion. In the Atlantic Ocean, where oxygen content is fairly high at all levels, corrosion would be expected to exceed that in the Pacific Ocean, where the oxygen content reaches a minimum around a depth of 2,000 feet (provided, of course, that other variable factors are the same).

Bacteria, too, play a part in corrosion. Sulfate-reducing bacteria such as those found in bottom sediments and ocean mud produce sulfides which are corrosive to such metals as steel and copper. On the other hand, biological fouling may provide protection against corrosive attack. Complete covers of marine fouling can reduce corrosion of steel by preventing the oxygen essential to the corrosion mechanism from reaching the metal surface. A marine environment containing metabolic products such as mannitol formed by the reaction of bacteria on seaweeds will, however, accelerate the corrosion of certain metals.

In the first chapter of this book a comprehensive report covering the various factors governing corrosion specifically as it relates to metallic compositions used in ocean environments is presented. Considerable performance data on corrosion of metals and their alloys are offered for review.

The effect of ocean depth and exposure at different sites on the corrosion rate of 20,000 specimens of 475 different alloys exposed by the Naval Civil Engineering Laboratory for periods of time ranging from about 3 months to 3 years is the subject of the report in the second chapter. Extensive data are presented in tabular form.

The next chapter covers in depth the role of microorganisms in seawater deterioration. Experiments with various environments involving bacterial fouling are discussed. Long- and short-term exposures of structural carbon steel in seawater suitable for the growth of microorganisms show the important influence of those organisms in corrosion processes. Results also indicate that research should be conducted to investigate further the possibility of curbing corrosion by selective inhibition of bacteria which foster corrosion.

The annotated bibliography for corrosion of metals, which comprises the fourth chapter, supplements the list of references included in each of the

other chapters and directs the researcher to the literature on this subject.

As previously mentioned, the final chapter examines whether nonmetallic substances such as plastics, textiles and magnetic tape will deteriorate when immersed in seawater.

In the final analysis, factors other than corrodibility, such as cost, efficiency, and lifetime durability of a particular material, will also influence a design engineer's decision to choose that material for marine equipment. The data provided in this book can assist the designer in making a wise selection.

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# **CORROSION OF METALS IN MARINE ENVIRONMENTS**

## **AN OVERVIEW**

Material for the following chapter is from a report prepared under the sponsorship of the Department of Defense by W.K. Boyd and F.W. Fink, of the Metals and Ceramics Information Center (MCIC), Corrosion and Technology Research Section, Battelle's Columbus Laboratories, Columbus, Ohio. The MCIC is a Department of Defense Information Analysis Center operated by Battelle-Columbus under Contract Number DSA-900-75C-1803 for the U.S. Defense Supply Agency.

The report is a companion volume to MCIC-74-23, "Corrosion of Metals in the Atmosphere," also written by Boyd and Fink. It was originally printed in 1970 as DMIC Report 245 and was reprinted in 1975 as MCIC-75-245R. In 1977, this report was updated by extending its coverage to information on the performance of metals in marine environments which had become available since July of 1970. This search was greatly facilitated by the availability to MCIC of a continuous series of reviews on the corrosion of metals which were published by MCIC in its respective newsletters entitled "Reviews of Recent Developments—Corrosion and Compatibility," "Review of Metals Technology—Corrosion and Compatibility," and the "Current Awareness Bulletin" over the periods ending in December 1972, December 1976, and September 1977, respectively. Many of these reviewed articles, which were all prepared by W.E. Berry of the Batelle Columbus Corrosion and Electrochemical Technology Section, were incorporated directly into this report. D.J. Maykuth of the Materials Development Section, who edited DMIC Report 245, also performed this same service in the 1977 review.

In preparing the revision, all of the new information was appended to the original body of the report in a section entitled "Update 1977" which follows the same organization and format as the original report. In addition, several new sections were included to deal topically with the seawater corrosion of fasteners, coated structural metals, and composites and miscellaneous materials in addition to a review of recent desalination experiences with metals and alloys.

It should be noted that, in the recent data review, numerous references were noted to studies conducted using 3 to 3½% sodium chloride solutions, particularly those involving stress corrosion cracking and fatigue crack growth. While such sodium chloride solutions are not equivalent, for most purposes, to seawater, these references have been included in the updated section in the belief that these results will be useful to the reader.

## INTRODUCTION

The scientific exploration and exploitation of the ocean depths is now proceeding at a greatly accelerated pace. Hydro-space activities in general are receiving national attention. Typical areas of current interest can be roughly classified as off-shore mineral development (oil, gas, sulfur, salt, diamonds, and coal); food production (fish, shellfish, plants, etc.); seawater extraction (magnesium, bromine, salt, and fresh water); and off-shore meteorology (control of storms).

There has been particularly rapid progress in the development of equipment for deep-ocean investigation and underwater activities. A new deep-diving technology has been developed complete with special-purpose submersibles, some with external work arms for salvage, recovery, and exploration. New types of surface vessels also are rapidly being developed — examples being hovercraft, hydrofoil ships, nuclear-powered and jet-engine-powered vessels, and a great variety of work boats and research vessels. In addition, the oil and gas industry has built large numbers of off-shore platforms, pipelines, underwater storage, and shore facilities. There are now over 14,000 off-shore steel structures in the Gulf area alone and more are being added.

All this increased activity has taxed the ingenuity of the designers of equipment and facilities which must be specially tailored to meet the hostile ocean environments. Before choosing the materials of construction for an off-shore structure, ship, submersible, ocean-floor installation, or instrument package, many factors must be considered. Among these are the initial cost of the materials, their efficiency in the intended design, the predicted lifetime of the materials as influenced by corrosion processes, function, and interactions of stress. In most systems for ocean service, a major expense is the maintenance required to keep the facility or equipment in operation.

Many materials when fabricated into a system deteriorate in seawater service in unexpected manners, unlike their predicted behavior established in laboratory saline solutions. The chemical reactions of seawater with materials are complex. The organic and living matter also present tends to complicate further the manner in which materials fail.

This report is presented in response to the large number of requests received by DMIC for assistance in the selection of materials for equipment or facilities to be used in the ocean environment. Before reviewing the corrosion behavior of the individual materials, the factors which affect their behavior in seawater and in the marine atmosphere are reviewed.

The report is based on a review of selected literature items, discussions with marine technologists, and information derived from Battelle's own research programs in the marine corrosion field. Reports dealing primarily with corrosion results and deterioration behavior in actual ocean environments rather than in laboratory simulations have provided the most reliable information.

## THE OCEAN ENVIRONMENT

Seawater covers more than 70 percent of the earth's surface and is the most abundant naturally occurring

electrolyte. Most of our common metals and alloys of construction are attacked by seawater or mist-laden sea air. Since the behavior of materials may vary widely, depending on the exposure conditions, their performance is commonly discussed according to the specific environmental zone involved, namely, atmosphere, splash, tidal, shallow ocean, deep ocean, and mud. A classification of typical marine environments is presented in Table 1.

### Atmosphere

In the atmosphere, the intensity of the attack is influenced greatly by the amount of salt particles or mist which collects on the metal surface. Salt deposition varies with wind and wave conditions, height above the sea, exposure, etc. Since sea salts, especially the calcium and magnesium chlorides, are hygroscopic, there is a tendency to form a liquid film on the metal surface. This is particularly true where the dewpoint is reached during daily or seasonal weather changes. Typically, the value drops off rapidly, decreasing to a negligible amount about 1 mile inland, except during violent wind storms. In some areas, however, measurable salt may be found well inland.

Another factor that affects corrosion behavior is solar radiation. This may stimulate photosensitive corrosion reactions on metals like copper or iron and biological activity such as fungi, which help trap corrosive moisture and dust. Coral dust, combined with sea salt, is particularly corrosive at tropical sites.

The amount of rain, and the distribution during a given time period, affects the corrosion rate in marine atmospheres. Frequent rain may tend to reduce the attack by rinsing off any salt residue. In some cases, corrosion on the sheltered side may be worse than that on the exposed side, since dust and air-borne sea-salt contamination is not washed off.

Fungi and molds may deposit on the metal and increase corrosivity mainly by holding moisture to the surface.

In general, the tropical marine environments are considered more corrosive than arctic marine environments, with temperate environments somewhere in between. Temperature alone, of course, is not the entire explanation for the observed differences, since the other factors involved in corrosion also vary with geographical location.

### Splash Zone

Materials in the splash zone are almost continuously wet with well-aerated seawater. Biofouling does not take place in the splash zone. Where the wind and ocean combine to provide violent seawater conditions, the impinging water may add to the destruction at the splash zone.

For a number of materials, particularly steel, the splash zone is the most aggressive of all the marine zones. The entrained air bubbles in the seawater also tend to make it more destructive in removing protective films or dislodging coatings. Paint films normally deteriorate more rapidly in the splash zone than in other zones.

Metals like stainless steels and titanium tend to be resistant in the splash zone, since the well-aerated condition promotes passivity.

TABLE 1. CLASSIFICATION OF TYPICAL MARINE ENVIRONMENTS

Marine Zone	Description of Environment	Characteristic Corrosion Behavior of Steel
Atmosphere (above splash)	Minute particles of sea salt are carried by wind. Corrosivity varies with height above water, wind velocity and direction, dew cycle, rainfall, temperature, solar radiation, dust, season, and pollution. Even bird droppings are a factor.	Sheltered surfaces may deteriorate more rapidly than those boldly exposed. Top surfaces may be washed free of salt by rain. Coral dust combined with salt seems to be particularly corrosive to steel equipment. Corrosion usually decreases rapidly as one goes inland.
Splash	Wet, well-aerated surface, no fouling.	Most aggressive zone for many metals, e.g., steel. Protective coatings are more difficult to maintain than in other zones.
Tidal	Marine fouling is apt to be present to high-water mark. Oil coating from polluted harbor water may be present. Usually, ample oxygen is available.	Steel at tidal zone may act cathodically (well aerated) and receive some protection from the corrosion just below tidal zone, in case of a continuous steel pile. Isolated steel panels show relatively high attack in tidal zone. Oil coating on surface may reduce attack.
Shallow water (near surface and near shore)	Seawater usually is saturated with oxygen. Pollution, sediment, fouling, velocity, etc., all may play an active role.	Corrosion may be more rapid than in marine atmosphere. A calcareous scale forms at cathodic areas. Protective coatings and/or cathodic protection may be used for corrosion control. In most waters a layer of hard shell and other biofouling restricts the available oxygen at the surface and thus reduces corrosion. (Increased stress on structure from weight of fouling must be provided for).
Continental-shelf depths	No plant fouling, very much less animal (shell) fouling with distance from shore. Some decrease in oxygen, especially in the Pacific, and lower temperature.	
Deep ocean	Oxygen varies, tending to be much lower than at surface in Pacific but not too different in Atlantic. Temperature near 0 C. Velocity low; pH lower than at surface.	Steel corrosion often less. Anode consumption is greater to polarize same area of steel as at surface. Less tendency for protective mineral scale.
Mud	Bacteria are often present, e.g., sulfate reducing type. Bottom sediments vary in origin, characteristics, and behavior.	Mud is usually corrosive, occasionally inert. Mud-to-bottom water corrosion cells seem possible. Partly embedded panels tend to be rapidly attacked in mud. Sulfides are a factor. Less current than in seawater is consumed to obtain cathodic polarization for buried part of structure.

## Tide Zone

As with the splash zone, surfaces at the tide zone are in contact with well-aerated seawater, for at least a part of the day. The temperature of the metal surface is influenced by both the temperature of the air and that of the seawater, but is most apt to be close or equal to the temperature of the ocean. Tidal flow varies with location, and for such materials as steel, greater tidal movement is associated with an increase in rate of attack. Marine organisms will settle on the metal surface in the tide zone. In some cases, this may result in partial protection of a metal surface as for steel or the local attack may be accelerated as with stainless steels.

One also has to differentiate between the behavior of isolated experimental panels in the tide zone, and the typical case, occurring in practice, where a structure such as a pile extends from the atmosphere through the splash and tide zones into the submerged and mud zones. For a continuous steel pile, rapid attack takes place on that part of the surface just below the water line, with the portion at the water line being the cathode and receiving protection at the expense of the metal below. Since this zone is shifting continuously and ample oxygen is available, cathodic polarization is not likely to develop as it may on a portion of the surface continuously immersed.

For the isolated-panel situation, the corrosion rate in the tide zone tends to be higher than that under the conditions described above, since the isolated panel does not receive cathodic protection during a portion of each day.

## Immersed Condition

The corrosion behavior of metals in seawater may be classified into two major types, according to whether the corrosion rate is controlled (1) largely by the reaction at the cathode or (2) by the presence of a tightly adherent, thin oxide, passive film. Steel is the best example of a metal whose rate of attack is under cathodic control in seawater. Zinc and magnesium also are examples. Passive metals are best illustrated by the behavior of titanium or the high nickel-chromium-molybdenum alloys such as Hastelloy C. In some seawater environments austenitic stainless steels are passive.

The noble metals platinum, gold, and silver, for example, do not owe their corrosion behavior to a passive film. They are inherently resistant by virtue of their thermodynamic characteristics, or nobility.

Much of the discussion here concerns the behavior of plain-carbon steel, since (1) it is the most widely used material of construction in marine service and (2) the factors affecting its behavior have been studied in great detail. The rate of attack of this steel is largely controlled by the availability of oxygen at the cathode. The oxygen supply and other factors pertaining to steel corrosion are discussed below.

At shallow depths, the oxygen supply is normally at or close to saturation. Biological activity likewise is at a maximum and includes both plant and animal life. The temperature at the surface is considerably warmer than at moderate or great depths and varies with geographical location.

Biofouling, particularly of the hard-shell variety, reduces attack on steel by (1) reducing the velocity of oxygen-carrying seawater and (2) acting as a diffusion barrier to oxygen at

cathodic sites. Cathodic sites may also develop a calcium carbonate-type mineral scale which provides protection similar to that provided by biofouling.

When seawater is diluted, as in harbors, an unsaturated condition with respect to calcium carbonate may develop which prevents the formation of protective mineral scale. Pollution may make the water more corrosive and may also kill marine life, thus preventing biofouling. The sulfide content or ammonia content of polluted waters tends to increase the corrosion action of seawater on copper-base metals and steel.

The factors that affect the rate of corrosion in shallow waters also are of importance for waters above the continental shelf. The depth of these waters varies, ranging up to approximately 1000 feet.

The oxygen supply may be somewhat less as the depth increases, and this, as explained elsewhere, affects the corrosion behavior. Temperature tends to drop with depth, especially the first 100 feet or so. This tends to reduce the rate of attack, as compared with that in warmer, well-aerated, surface water.

The velocity may drop to low values in many localities, often at a depth of 60 to 100 feet. Corrosion rates of metals like steel usually are lower under the less aggressive conditions.

Beyond depths of 60 to 100 feet, any biofouling is entirely animal, since plants cannot exist below the depths to which solar radiation penetrates. Usually there is less fouling as one proceeds away from shore, since the major source of animal embryos is from breeding activities near the shore. Also there usually is apt to be considerably less fouling with increase in depth at any given distance from shore.

## Deep Ocean

The oxygen supply at great depths is usually sufficient for some corrosion to take place. At several sites off the Pacific coast, oceanographers have established that a minimum level (of about 0.2 ml of oxygen per liter of seawater) of oxygen exists at about 2,000 feet down, which may be characteristic of the entire ocean near the West Coast<sup>(1)</sup> (see Figure 1). This is ascribed to the consumption of oxygen by decaying microorganisms descending slowly from the surface. At greater depths in these Pacific areas, bottom currents originating in the Arctic supply oxygenated water.

Waters used in the Navy's Tongue of the Ocean (TOTO) deep-sea test program in the Atlantic have a high oxygen level all the way to the bottom. Oceanographers explain the fact that the biological oxygen demand is much less in the Atlantic waters because the total population of microorganisms is much smaller. In other words, decaying organisms in these Atlantic waters do not exhaust the available oxygen supply. The variation in oxygen with depth at the TOTO site is given in Table 2.(2)

Another factor that affects corrosion is the change in pH, as shown in Figure 1. The lower pH found in waters at great depth may be partly explained on thermodynamic grounds, since the pH is reduced by extreme pressure alone. However, it is also known that the carbon dioxide-calcium bicarbonate-calcium carbonate equilibrium tends to be shifted; that is, the dissolved calcium carbonate in the deep ocean tends to be slightly below saturation, while, conversely, at the surface it is frequently supersaturated.<sup>(3)</sup> One would, therefore, expect that



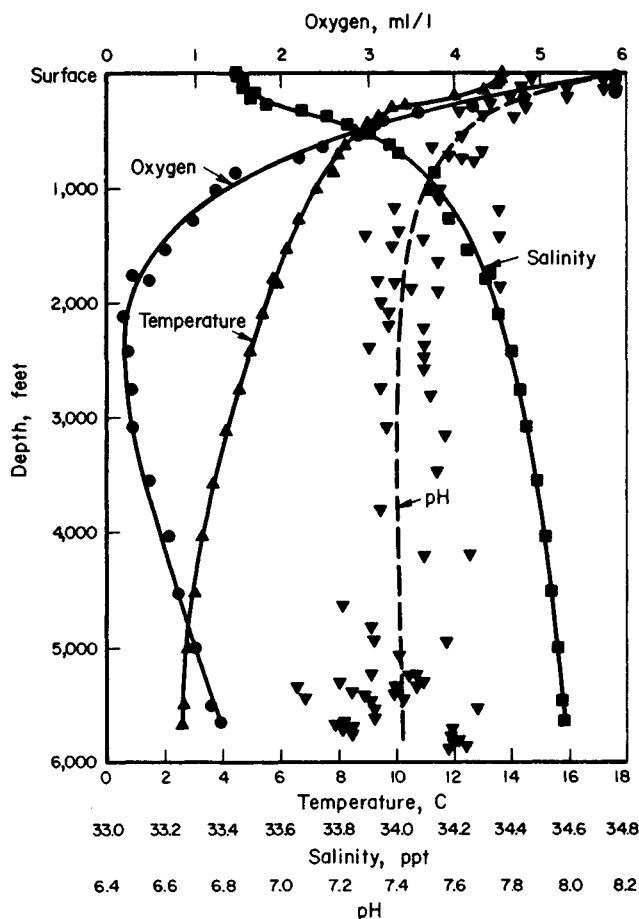


FIGURE 1. OCEANOGRAPHIC DATA TAKEN IN THE PACIFIC OCEAN AT A SITE WEST OF PORT HUENEME, CALIFORNIA<sup>(1)</sup>

Used with permission of U. S. Naval Civil Engineering Laboratory

TABLE 2. HYDROGRAPHIC ASPECTS OF TONGUE-OF-THE-OCEAN WATER (ATLANTIC OCEAN)<sup>(2)</sup>

Depth, feet	Temperature, C	Salinity, o/oo	Oxygen, ml/l
Surface	24.08	36.79	4.59
33	—	36.73	4.58
66	24.09	36.72	4.61
164	24.14	36.73	4.26
249	24.13	36.78	4.42
331	24.14	36.79	4.42
495	23.92	36.74	4.15
663	22.35	36.70	4.15
820	19.27	36.56	4.13
1158	17.31	36.36	3.92
1654	13.78	35.82	3.46
1985	11.73	35.55	3.19
2316	10.03	35.33	3.11
2648	8.09	—	3.59
3310	—	35.04	4.96
4967	4.18	35.00	5.73
5100	4.12	35.00	5.26
19567	4.0	—	5.73

in deep waters, there would be less tendency to form a protective mineral scale, as compared with surface waters. It has been observed, for example, that the consumption of sacrificial anodes, for providing cathodic protection, is significantly greater at extreme depths, e.g., 5,000 feet, than in surface waters.

#### Mud Zone

The environmental behavior of the mud zone is complex, and studies have only been made in a few instances. The physical, chemical, and biological properties of sediments can be expected to influence corrosivity.

Bottom sediments, both shallow and deep, usually contain bacteria. The sediments are anaerobic, and gases developed by bacterial action include  $\text{NH}_3$ ,  $\text{H}_2\text{S}$ , and  $\text{CH}_4$ . The pressure may increase the bacterial activity. The sulfate-reducing bacteria, which also are found in soils, produce sulfides which are corrosive to metals such as steel and copper.

Practical experience with the mud zone comes from observations of off-shore structures, and with experimental piles driven in shallow waters. Steel often is attacked more slowly in the mud zone than in the seawater above. Polarization by cathodic current is more readily achieved, largely because of the restricted oxygen supply.

#### Factors Affecting the Corrosivity of Seawater

Since seawater is a complex, delicately balanced solution of many salts containing living matter, suspended silt, dissolved gases, and decaying organic material, the individual effect of each of the factors affecting the corrosion behavior is not readily separated, as is the case for a simple salt solution. Because of the interrelation between many of the variables in the seawater environment, an alteration in one may affect the relative magnitude of others.

The factors which affect the amount and rate of corrosion may be divided into chemical, physical, and biological. An overall summary of these environmental factors and their relation to iron corrosion is presented in Table 3.

The roles of oxygen, biological activity, temperature, velocity, salinity, and pH are discussed in more detail in the following paragraphs.

#### Oxygen

The dissolved oxygen content is a major factor affecting the corrosivity of seawater. For many common metals, a higher oxygen content is accompanied by an increase in the rate of attack. This results from the fact that corrosion rate of local anodes is dependent on the cathode reaction. Depolarization is more rapid with the increase in arrival of oxygen at the cathode, and this in turn is a function of the amount dissolved in the seawater and the velocity of flow at the surface. Water low in oxygen flowing at a high velocity could provide as much oxygen to the cathodic surface as water high in oxygen moving slowly past the surface.

The oxygen level in seawater may range up to 12 ppm<sup>(4)</sup>. Photosynthesis of green plants, wave action, etc., tend to

increase the oxygen level, whereas the biological oxygen demand of decomposing dead organisms will reduce it. For a given location, seasonal variation in oxygen level resulting from the above actions will, in turn, influence corrosion behavior.

For metals like copper and iron, complete elimination of oxygen will reduce the corrosion to negligible amounts. This method is under active study for control of corrosion in desalination equipment.

Metals depending on a passive film for corrosion protection, e.g., aluminum or stainless steel, often corrode rapidly where the oxygen supply to the metal surface is restricted.

TABLE 3. FACTORS IN SEAWATER ENVIRONMENT<sup>(a)</sup>

Chemical	Physical	Biological
Dissolved Gases <sup>(1)</sup>	Velocity <sup>(3)</sup>	Biofouling <sup>(6)</sup>
Oxygen	Air bubbles	Hard-shell types
Carbon dioxide	Suspended silt	Types without hard shells
		Mobile and semimobile types
Chemical Equilibrium <sup>(2)</sup>	Temperature <sup>(4)</sup>	Plant Life
Salinity		Oxygen generation
pH		Carbon dioxide consumption
Carbonate solubility		
	Pressure <sup>(5)</sup>	Animal Life
		Oxygen consumption
		Carbon dioxide generation

(a) Using Iron as reference, the following trends are typical:

- (1) Oxygen is a major factor in promoting corrosion.
- (2) The tendency to form protective scale (carbonate-type) increases with higher pH.
- (3) Increasing velocity tends to promote corrosion, especially if entrained matter also is present.
- (4) Temperature increase tends to accelerate attack.
- (5) Pressure may affect corrosion, see text.
- (6) Biofouling can reduce attack, or promote local corrosion cells.

### Biological Activity

When a metal or other surface is first immersed in seawater, a biological slime tends to develop in a matter of hours. Some authorities consider this film of living bacteria and other microorganisms to be attractive to embryonic fouling organisms looking for a place to settle. During an active season, a great variety of organisms are found on an immersed surface. Usually of most concern, from a corrosion point of view, are the sessile organisms. They arrive at the slime-covered surfaces in minute embryonic form and become firmly attached. Once attached, they rapidly transform to the mature form and become immobile. Clapp, on page 433 of Reference 4, lists the following most common forms of sessile fouling organisms:

- (1) Organisms which build hard shells:
  - (a) Annelids
  - (b) Barnacles
  - (c) Encrusting bryzoa
  - (d) Mollusks
  - (e) Corals.
- (2) Organisms without hard shells
  - (a) Marine algae
  - (b) Filamentous bryzoa
  - (c) Coelenterates or hydroids
  - (d) Tunicates
  - (e) Calcareous and siliceous sponges.

A variety of other biofouling organisms also are found associated with the above types, some of which have a degree or more of mobility.

Fouling is a major factor in the performance of marine facilities. Structures in the water can be overloaded by the extra weight of fouling; buoys can lose buoyancy, and fuel consumption becomes excessive on the badly fouled hulls of ocean-going vessels.

### Temperature

An increase in temperature normally is expected to speed up a chemical reaction according to thermodynamic considerations. This also would be the case for the corrosion reaction in seawater were it possible to hold all other variables fixed. Since it is not normally possible to do this, the effect of temperature has to be established indirectly. Oxygen solubility decreases with increase in temperature; biological activity increases as one goes from, e.g., cold arctic to warm tropic water; and the chemical equilibrium involved in the precipitation of calcium carbonate and magnesium hydroxide is altered so that calcareous scale is more likely to deposit on the metal as the temperature is raised.

For temperature variations of a seasonal nature, iron, copper, and many of their alloys show a higher rate of attack during the warm months. On the other hand, when seawater is heated at atmospheric pressure, it loses dissolved gases, especially oxygen, and it has a tendency to precipitate a protective scale. Both these actions tend to reduce the attack.

### Velocity

Many metals are sensitive to velocity effects in seawater. For metals like iron or copper, there is a critical velocity, beyond which corrosion becomes excessive. Passive metals, e.g., titanium, certain nickel-chrome-molybdenum alloys, and stainless steels tend to be more resistant in high-velocity seawater.

Special forms of corrosion are associated with seawater velocity, e.g., (1) erosion-corrosion caused by high-velocity silt-bearing seawater; (2) impingement attack, where air bubbles are present, and (3) cavitation, where collapsing vapor bubbles cause mechanical damage and often corrosion damage as well.

### Salinity

The major oceans of the world are completely connected in the Southern hemisphere and mixing is continuous. The composition of seawater for a salinity of 35 o/oo<sup>(\*)</sup> is given in Table 4. It is important to note that, in most cases, the relative proportion of salts does not vary appreciably in interconnected seas. Variations in salinity in open-ocean surface water typically range from 32 to 37.5 o/oo. In this range, the corrosion of common metals is not appreciably affected.

\*Salinity is defined as the total weight in grams of solid matter dissolved in 1000 grams of water. Thus, a salinity of 35 o/oo indicates a solid matter content of 35 grams per 1000 grams of seawater or a solid content of 35,000 ppm. Salinity is usually determined by measurement of chlorinity (i.e., chloride-ion content in grams per 1000 grams of water) of the seawater, and then derivation from the relationship  $S \text{ o/oo} = 1.805 \text{ Cl o/oo} + 0.030$ .<sup>(5)</sup>



TABLE 4. COMPOSITION OF SEAWATER AND IONIC CONSTITUENTS(6)

Constituent	G/Kg of Water of		Cations, percent		Anions, percent	
	Salinity, 35 o/oo					
Chloride	19.353	Na+	1.056	Cl-	1.898	
Sodium	10.76	Mg++	0.127	SO <sub>4</sub> -	0.265	
Sulphate	2.712	Ca++	0.040	HCO <sub>3</sub> -	0.014	
Magnesium	1.294	K+	0.038	Br-	0.0065	
Calcium	0.413	Sr++	0.001	F-	0.0001	
Potassium	0.387					
Bicarbonate	0.142	Total	1.262	Total	2.184	
Bromide	0.067					
Strontium	0.008					
Boron	0.004					
Fluoride	0.001					

In some of the more isolated seas, a great variation in salinity is observed (see Table 5). Since the salinity variations are accompanied by other changes, the total effect on the corrosion behavior has to be established in each case. Oxygen solubility will be appreciably lower in the Caspian Sea than in seawater of 35 o/oo salinity. Diluted seawater, as found in mouths of rivers, may be more corrosive even though the electrolyte itself may be less aggressive. Ordinary seawater is usually more saturated with respect to carbonate solubility; in diluted seawater, however, an unsaturated condition exists and there is less tendency to form protective carbonate-type scale which, in effect, increases corrosivity. Marine-organism activity is reduced or eliminated in diluted seawater, and there may be less tendency to form a protective layer of biofouling.

TABLE 5. TOTAL SOLIDS IN OCEAN WATERS(7)

Body of Water	Total Dissolved Solids, ppm
Baltic Sea	8,000
Black Sea	22,000
Atlantic Ocean	37,000
Mediterranean Sea	41,000
Caspian Sea	13,000
Irish Sea	32,500

## pH

The pH of seawater may vary slightly depending on the photosynthetic activity. Plant matter consumes carbon dioxide and affects the pH during daylight hours. The carbon dioxide content in seawater is influenced, close to the surface, by the exchange with carbon dioxide in the atmosphere. The slight daily shift in pH from, say, 8.0 to 8.2 has little direct effect on the corrosion behavior; however, it can be a factor in calcareous-scale deposition, which affects the corrosivity.

As pressure is increased, pH is reduced according to thermodynamic considerations. Thus, at great depths, there is some evidence of less tendency for protective carbonate-type scale formation.

## Forms of Corrosion

The factors which affect the corrosion of exposed metal surfaces in the different environmental zones have been discussed in the preceding sections. When actual metal structures are exposed to these ocean environments certain types of attack are most commonly experienced.(8) Often these are related to features in the design or metallurgy.

The most common forms of corrosion for environments are galvanic corrosion, pitting, and crevice attack. Sand or dust erosion by wind action can augment corrosion in a marine atmosphere, whereas seawater velocity effects such as impingement or cavitation may be important in an application involving underwater service.

### Galvanic Attack

Because seawater is an excellent electrolyte, severe corrosion often occurs when two different metals are coupled together and exposed to a marine environment. One metal in the couple will be anodic to the other. The degree of attack depends partly on the relative position of the two metals in the galvanic series for seawater. A galvanic series for flowing seawater is presented in Table 6. Usually the farther apart in the series, i.e., the greater the difference in potential, the greater will be the acceleration of the attack on the anodic member of the couple. However, polarization effects tend to alter the behavior. In seawater, coupling of titanium or stainless steel to carbon steel tends to cause less acceleration of attack than coupling of copper to steel, because the former two metals are more readily polarized than the latter. It can be shown for a metal like carbon steel, whose corrosion rate is usually controlled by the total cathodic area available, that the ratio between the area of the cathode and the anode is important. A small anode (e.g., steel) coupled to a large cathode (e.g., copper) and immersed in seawater will result in a greatly increased rate of attack. The reverse situation of a small cathode coupled to a large anode will have only a minor influence on the rate of attack.

To control or prevent the accelerated attack involved in a galvanic couple, certain principles should be observed. First, the possibility of breaking the electrical circuit by providing an insulating barrier at the junction of the two metals should be considered. Second, if dependable isolation is not feasible, the cathodic member of the couple should be covered with a nonconducting protective coating. By reducing this area, or eliminating the cathode entirely, corrosion is correspondingly controlled in a safe manner. Under no circumstances should only the anode be painted. Any defect or holiday in the coating then will result in the entire cathodic area being coupled to a small area of anode material, and extremely high rates of penetration can be expected.

In the atmosphere, galvanic-couple corrosion is confined to a short distance, usually a fraction of an inch, from the joint between the two metals. Under immersed conditions, galvanic-couple corrosion may be significant for metals in electrical contact as much as, say, 100 feet or more apart, such as between the bronze propeller and an exposed area on the steel hull of an oceangoing vessel. Some examples of galvanic couples and their corrosion behavior are given in Table 7.

TABLE 6. GALVANIC SERIES IN SEAWATER FLOWING AT 13 FPS (TEMPERATURE ABOUT 25 C)(9)

Material	Steady-State Electrode Potential, volts (Saturated Calomel Half-Cell)
Zinc	-1.03
Aluminum 3003-(H)	-0.79
Aluminum 6061-(T)	-0.76
Cast iron	-0.61
Carbon steel	-0.61
Stainless steel, Type 430, active	-0.57
Stainless steel, Type 304, active	-0.53
Stainless steel, Type 410, active	-0.52
Naval rolled brass	-0.40
Copper	-0.36
Red brass	-0.33
Bronze, Composition G	-0.31
Admiralty brass	-0.29
90Cu-10Ni, 0.82Fe	-0.28
70Cu-30Ni, 0.47Fe	-0.25
Stainless steel, Type 430, passive	-0.22
Bronze, Composition M	-0.23
Nickel	-0.20
Stainless steel, Type 410, passive	-0.15
Titanium(a)	-0.15
Silver	-0.13
Titanium(b)	-0.10
Hastelloy C	-0.08
Monel-400	-0.08
Stainless steel, Type 304, passive	-0.08
Stainless steel, Type 316, passive	-0.05
Zirconium(c)	-0.04
Platinum(c)	+0.15

(a) Prepared by powder-metallurgy techniques. Sheath-compacted powder, hot rolled, sheath removed, cold rolled in air.

(b) Prepared by iodide process.

(c) From other sources.

### Crevice Attack

This form of corrosion usually is most serious under immersed conditions or in the splash zone. Metals that require plenty of oxygen to continuously repair the breaks in the oxide film and thus maintain passivity tend to be susceptible to crevice attack in seawater. The relative susceptibility to crevice attack as depicted in Figure 2, shows stainless steels and some of the aluminum alloys to be the most sensitive.

If the oxygen in the stagnant seawater in the crevice is consumed in repairing new breaks in the passive film at a higher rate than fresh oxygen can diffuse in from the outside, rapid corrosion tends to take place under the crevice, as illustrated in Figure 3. The driving force comes from a differential aeration cell, with the surface outside the crevice in contact with oxygen-bearing seawater acting as the cathode. In accordance with electrochemical principles, the cathodic and anodic currents must be equal. In the typical case, because of the small area of the anode under the crevice, the current density or rate of local attack can be extremely high. Once such a cell has been initiated it is difficult to arrest.

TABLE 7. EXAMPLES OF GALVANIC COUPLES IN SEAWATER

Metal A	Metal B	Comments
<u>Couples That Usually Give Rise to Undesirable Results on One or Both Metals</u>		
Magnesium	Low-alloy steel	Accelerated attack on <u>A</u> , danger of hydrogen damage on <u>B</u> .
Aluminum	Copper	Accelerated pitting on <u>A</u> ; ions from <u>B</u> attack <u>A</u> . Reduced corrosion on <u>B</u> may result in biofouling on <u>B</u> .
Bronze	Stainless steel	Increased pitting on <u>A</u> .
<u>Borderline, May Work, But Uncertain</u>		
Copper	Solder	Soldered joint may be attacked but may have useful life.
Graphite	Titanium or Hastelloy C	
Monel-400	Type 316 SS	Both metals may pit.
<u>Generally Compatible</u>		
Titanium	Inconel 625	
Lead	Cupronickel	

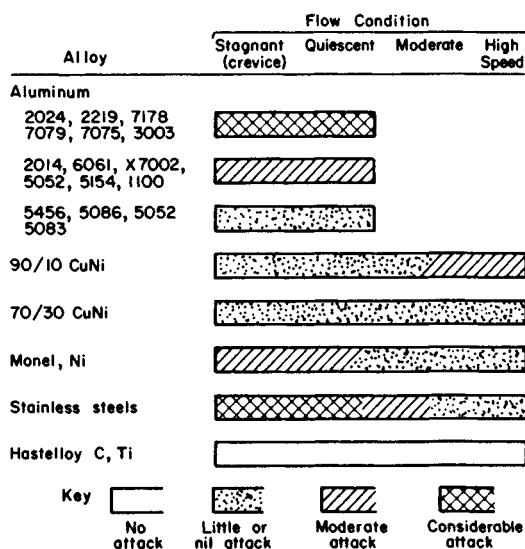


FIGURE 2. COMPARATIVE LOCALIZED ATTACK (CREVICE CORROSION AND PITTING) OF SOME IMPORTANT MARINE ALLOYS AS A FUNCTION OF SEAWATER FLOW CONDITIONS(10)

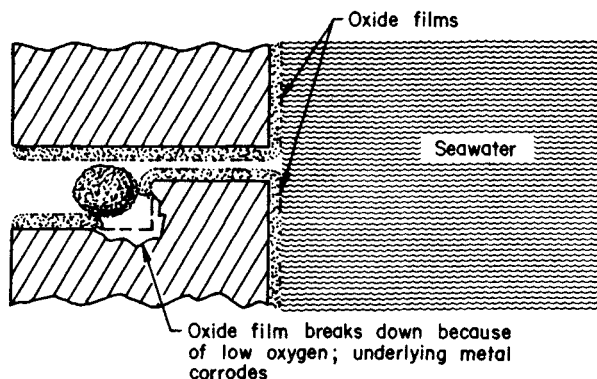


FIGURE 3. CREVICE CORROSION OF STAINLESS STEEL AT AN O-RING SEAL IN SEAWATER(10)

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Ellis and LaQue(11) have demonstrated, using Type 430 stainless steel, the effect of enlarging the area external to the crevice on attack. Figure 4 shows a straight-line relation between weight loss and external area as might be expected from Faraday's law. A plot of pit depth against area in Figure 5 shows more scatter. This experiment was conducted in seawater flowing at 1 to 2 feet per second for 87 days. Crevice attack can be controlled, as demonstrated here, by reducing the area of metal external to the crevice. Cathodic protection will largely eliminate the attack by polarizing the cathodic area to that of the anode under the crevice.

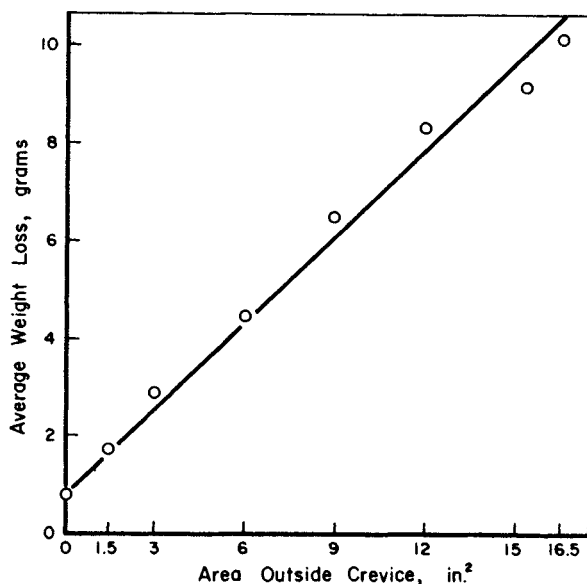


FIGURE 4. AVERAGE WEIGHT LOSS OF SPECIMENS AS RELATED TO AREA OF SPECIMEN OUTSIDE THE CREVICE(11)

Crevice attack also is observed in the atmosphere. A conductive film will form when both salt deposit and high humidity or moisture are present. This continuous film of salt water at the crevice is needed to permit the operation of the corrosion cell.

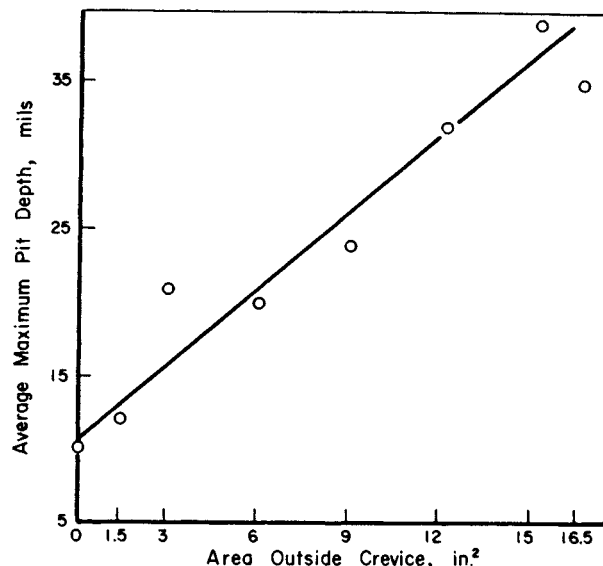


FIGURE 5. RELATION BETWEEN AVERAGE MAXIMUM PIT DEPTH WITHIN THE CREVICE VERSUS AREA OF SPECIMEN OUTSIDE THE CREVICE(11)

For copper and its alloys, crevice attack usually is not too significant in the atmosphere. However, under immersed conditions, a different form of attack from that with ferrous- or aluminum-base materials is observed. Both in the crevice and external surface, copper ions enter solution. The flowing seawater tends to remove copper ions from the external surface, resulting in a differential metal-ion cell. The higher concentration of copper ions in the crevice becomes cathodic, and the external area just outside the crevice becomes the anode.

Crevice attack is observed because of design features such as gaskets, washers, rivets, etc., and also may be formed by marine fouling organisms, such as barnacles or mollusks, settling on the surface.

#### Pitting

Corrosion that develops in highly localized areas on a metal surface, where the remaining metal surface often is not attacked to any great extent, is referred to as pitting. Pitting on metals exposed to the atmosphere may be initiated by discrete salt particles or atmospheric contaminants. Surface features or metallurgical factors, such as inclusions, breaks in the protective film, segregation, and surface defects, also may be involved in the initiation of pitting.

Under immersed conditions the environmental factors that favor pitting usually are (1) relatively stagnant conditions, (2) the presence of heavy metal ions such as copper (in the case of aluminum), and (3) local deposits of foreign matter. In respect to the third factor, pitting resembles crevice attack. Usually a metal susceptible to pitting also will be found susceptible to crevice attack.

#### Impingement

Many metals are sensitive to seawater velocity. Copper and steel are good examples. As the velocity is increased beyond

some critical point, rapid attack may ensue. Often, under turbulent conditions, air bubbles are entrapped in the water. When the rapidly flowing seawater with bubbles impinges against a metal surface, protective films may be destroyed and the metal may be locally attacked. Deposits on the metal surface may promote local turbulence. A horseshoe-shaped groove often develops when the stream is diverted around an object. The pattern of horseshoe "prints" is that of a horse moving upstream.

When there is suspended matter in the seawater, the combined erosion-corrosion can be much more severe than the sum of the individual erosion and corrosion effects when each is determined separately.

Impingement corrosion and cavitation damage are sometimes mistaken for each other. In some cases both types of damage may be involved.

#### Cavitation

If the ambient pressure is reduced to the vapor pressure of seawater at the seawater temperature, boiling occurs. Under high-velocity conditions, local boiling is often observed in practice. For example, seawater passing at high speeds over the surface of an impeller or propeller will develop extremely low pressures at sudden changes in section, such as at the blade tips. Vapor bubbles are formed which may collapse again at some other point downstream. The repeated pounding caused by the collapse of these vapor bubbles tends to promote, in time, local compressive failures on the metal surface. Flakes of metal are removed, leaving fresh active metal exposed to the corrosive seawater. Thus, cavitation in seawater usually involves both loss of metal by mechanical damage and by corrosion.

Cavitation often can be controlled by (1) reducing the speed or velocity as in a ship's propeller or a pump impeller or (2) increasing the seawater pressure.

### CORROSION OF METALS IN THE MARINE ENVIRONMENT

#### Carbon Steel

Plain-carbon steel is the most important metal in marine service, and has been widely used for many years in marine construction. More recently, low-alloy steels of higher strength have been finding increasing application. Related ferrous materials such as cast irons, wrought iron, and ingot iron are sometimes used in special applications. Steels are selected for marine service because of such factors as availability, cost, ease of fabrication, design experience, and physical and mechanical properties.

The behavior of steel and other ferrous materials tends to show striking differences in the various exposure zones. Thus, one cannot apply the results from an atmospheric exposure to an application involving fully immersed conditions. The sections which follow give selected details of the corrosion of steel in each type of marine environment.

#### Atmosphere

Steel. Mild steel corrodes in a marine atmosphere at rates ranging from 1 to 30 mpy.(12) Some of this wide variation can be ascribed to factors in the environment, some to variations in certain residual elements in the steel, and some to the surface condition of the steel as originally exposed.

The first and most important factor influencing steel's performance in a marine atmosphere is the type of exposure. Whenever the prevailing wind and surf combine to cause large amounts of spray to be entrained and transported to the metal surface, high corrosion rates are normally observed. The rate of attack also may be affected by rainfall, humidity, temperature, solar radiation, dust, fungi, bird droppings, etc. Tropical marine environments usually are more severe than those in the temperate zone.(13)

The amount of sea salt deposited on a surface decreases rapidly with increasing distance inland. Detectable amounts have been observed from 1 to 10 miles inland. For example, Ambler and Bain(14) made a study of the amount of salt particles collected on wet cloth in relation to distance from the coast of Nigeria. The salt collected was compared with the corrosion rate of mild steel at each site. These data, presented in Figure 6, suggest that considerable salt is carried up to 10 miles inland. The surf at the Nigerian coast is very violent and a mist cloud some 30 feet high is plainly visible at all times except during violent wind storms.

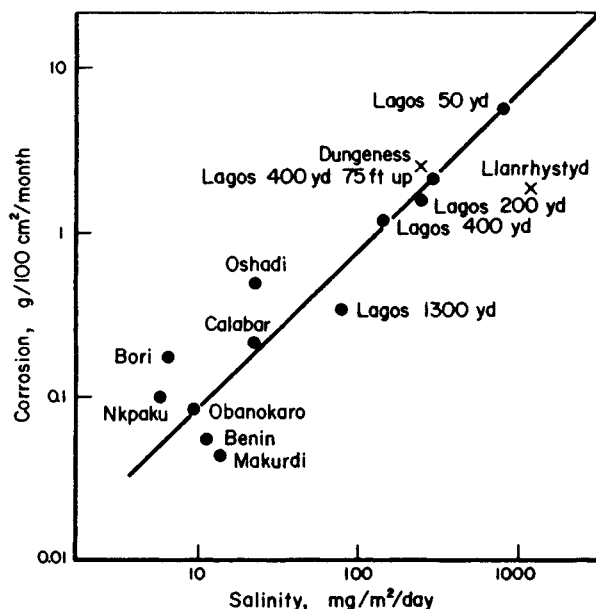


FIGURE 6. RELATION BETWEEN CORROSION OF MILD STEEL AND SALINITY AT EXPOSURE SITES IN NIGERIA(14)

Airborne salt was measured as salinity of water on a wet cylindrical cloth (wet-candle method).

The same effect on the corrosion behavior is also illustrated by results from two corrosion test lots at Kure Beach, North Carolina. At the 80-foot lot (distance from mean tide line), one set of open-hearth iron panels showed an average rate of attack of 31.5 mpy compared with 2.6 mpy for the 800-foot lot.

At Cristobal, Panama Canal Zone, the NRL rack is 300 feet from shore and 55 feet above sea level. Panels at this location show an attack rate of 2.3 mpy compared with 1.5 mpy for a similar steel at the 800-foot rack at Kure Beach. From other experience at Kure Beach, N. C., it is known that if the panels were raised from the normal rack height of a few feet above sea level to the 55-foot elevation, the rate of attack would increase and would be more nearly that observed at Cristobal. Thus, location of the test site and the local climate both influence the corrosion rate.

Hadfield and Main<sup>(15)</sup> reported the results of the British Sea Action Committee. Four different heats of carbon steels and three irons were exposed for 5 years to the marine atmosphere at Auckland, New Zealand, Plymouth, England, Colombo, Ceylon, and Halifax, Nova Scotia. The average penetration for these seven materials is shown graphically in Figure 7 (along with half tide and total immersion results), and pitting behavior is presented in Figure 8. From a marine-corrosion standpoint, Halifax appears to have the mildest climate, and Colombo the most severe. For steels, the maximum depth of pitting was at Colombo. The comparison also demonstrates the wide differences in corrosivity among the three environmental zones, namely, atmospheric, half tide, and total immersion.

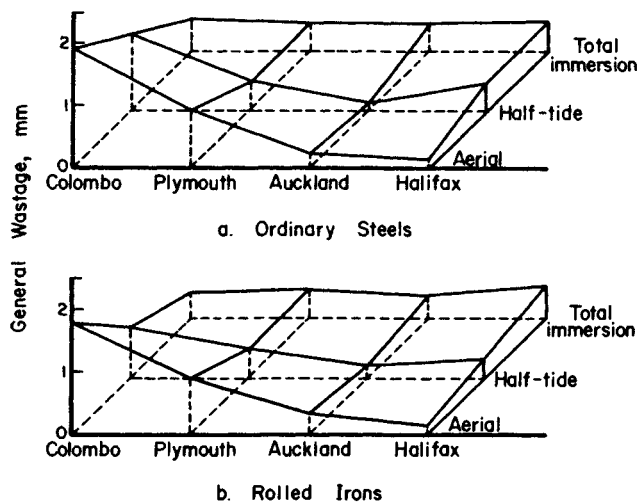


FIGURE 7. INFLUENCE OF CLIMATE AND CONDITIONS OF 5 YEARS' EXPOSURE ON THE GENERAL WASTAGE OF THE ORDINARY STEELS AND ROLLED IRONS<sup>(15)</sup>

Marine-exposure data from atmospheric test stations with widely different climates are presented in Table 8. From a study of the data, one is tempted to draw conclusions as to the relative corrosivity of the marine environments in each local region. In view of the above discussion on the location of test racks, it is apparent that these results should not be interpreted too literally.

The second factor that affects the performance of steel in the marine atmosphere is the presence of residual elements, such as copper, in the composition. Steels of the highest purity tend to corrode at the maximum rate. Residual amounts of copper, nickel, chromium, silicon, and phosphorus are found to reduce the rate of attack.<sup>(9,12,16)</sup> These elements are intentionally added to develop strength, as will be discussed later in the section on Low-Alloy Steels. Their presence affects the

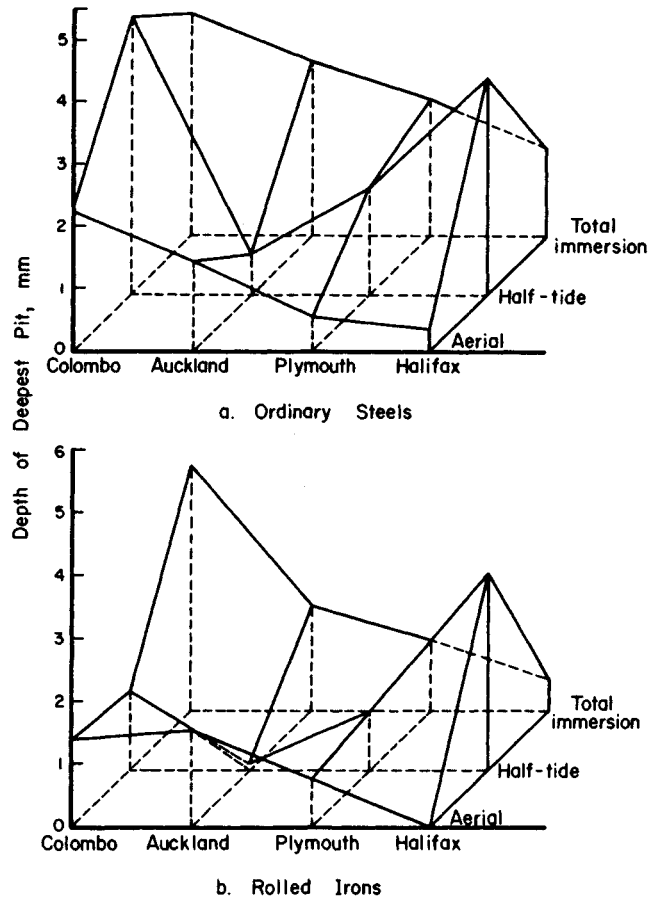


FIGURE 8. INFLUENCE OF CLIMATE AND CONDITIONS OF 5 YEARS' EXPOSURE ON THE PITTING OF THE ORDINARY STEELS AND ROLLED IRONS<sup>(15)</sup>

TABLE 8. MARINE ATMOSPHERIC CORROSION BEHAVIOUR OF FERROUS MATERIALS AT DIFFERENT MARINE SITES<sup>(12,15)</sup>

Site	Exposure Time, years	Corrosion Rate, mpy (Calculated From Weight Loss)		
		Open Hearth Iron	Carbon Steel	Wrought Iron <sup>(a)</sup>
Kure Beach, N. C. (80-foot lot)	1 1.5 to 3.5	31.5	47	—
Daytona Beach, Fla. (300-foot lot)	1	9.1		
Sandy Hook, N. J.	1	3.3		
Kure Beach, N. C. (800-foot lot)	1 1.5 3.5 7.5	2.6 2.7 <sup>(b)</sup>	1.6 1.5 1.3	— — —
Block Island, R. I.	1.1 3.3	8.6 <sup>(b)</sup>	2.7 2.6	— —
Halifax, Nova Scotia	5	1.2	0.62	1.2
Auckland, New Zealand	5	3.3	1.37	2.2
Plymouth, England	5	8.2	2.03	4.7
Colombo, Ceylon	5	17.9	17.3	11.0
Cristobal, Panama Canal Zone (300-foot lot)	0 to 4 4 to 8		2.8 2.3	3.5 2.1

(a) Exposed for same period as carbon steel panels.

(b) High-purity iron with 0.02 percent copper.



tightness of the rust coat and therefore its relative protective-ness. Marine climates, where there is frequent wetting and drying of the rust film, show this effect more markedly.

A third factor affecting the steel's performance in the marine atmosphere is the condition of the surface as exposed. For example, when hot-rolled steel is used for construction, the mill scale is sometimes left on. The rate of penetration, based on weight loss, and the depth of pitting are greater for a mill-scaled surface than for, say, a pickled surface. This point is illustrated by the results of 8 years' exposure of steel panels at Cristobal, Panama Canal Zone (see Figure 9).(17) When the surface is wet with salt spray, the mill scale will serve as a relatively large cathode to the small anodes formed at breaks in the scale, and this will result in intense local attack.

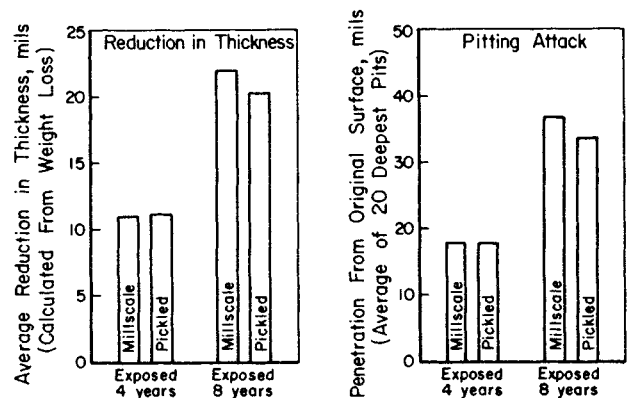


FIGURE 9. COMPARISON OF EFFECTS OF MILLSCALE AND PICKLED SUBSURFACES ON THE CORROSION RESISTANCE OF UNALLOYED LOW-CARBON STEEL EXPOSED TO THE TROPICAL MARINE ATMOSPHERE AT CRISTOBAL, CANAL ZONE(17)

Wrought Iron. As made in this country in recent years, wrought iron is essentially a dead mild steel to which an oxide-silicate slag has been added, while still molten. As is the case with carbon steel, unprotected wrought iron is rapidly attacked by exposure to marine atmospheres. A comparison of the behavior of wrought iron and steel is shown in Figure 10 for the first 8 years of the 16-year Navy exposure program at Cristobal, Panama Canal Zone.(13,17) Carbon-steel behavior at the 800-foot lot, Kure Beach, N. C., is also shown for comparison. It is to be noted that the rate of penetration for steel and wrought iron after 8 years' exposure is quite similar. Both materials showed considerable pitting.

The excellent marine resistance of the older type of puddled wrought iron is frequently mentioned. Some wrought-iron Coast Guard lighthouses at the Gulf and Florida coasts have lasted for over 100 years. It is reported that a frequent maintenance application of a protective zinc and wool fat mixture played a role in the good performance. (Both above and below the water line, good corrosion behavior was exhibited by these puddled-wrought-iron structures, although damage in the splash zone has had to be repaired several times during the 100 years.)

Eight-Year Corrosion Behavior, mils

Metal	W.I.	Low-C Steel	Cu Steel	Low-Alloy Steel
Avg red in thickness	22.1	20.4	17.6	9.0 to 10.1
Avg of deepest 20 pits	29	34	32	12 to 18
Deepest pit	61 (P)	67*	66(P)	17 to 63 (P)

P = perforated \* probably perforated

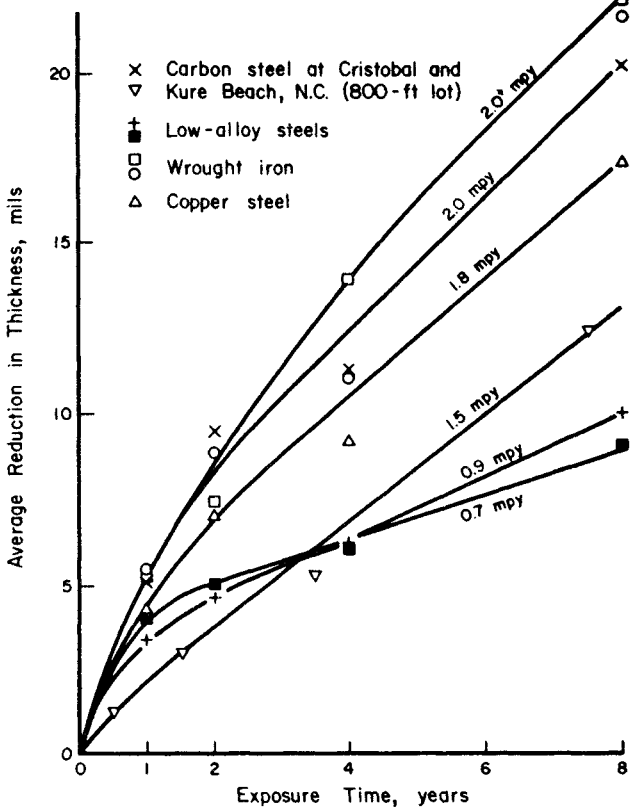


FIGURE 10. CORROSION RESULTS FOR WROUGHT IRON AND STEELS AFTER EIGHT YEARS' ATMOSPHERIC EXPOSURE AT CRISTOBAL, CANAL ZONE(12,13,17)

Splash and Tide

Carbon steel corrodes particularly rapidly in the splash zone. The corrosion rates in the splash zone may be of the order of ten times higher than those for the same metal in the submerged condition. The ready access of oxygen and the fact that the surface is continuously wet with seawater tends to make the splash zone the most aggressive of marine environments. Figure 11 gives the results of a short-term experiment in which continuous 12-foot steel strips as well as individual steel panels were exposed to the splash and tide zones. Note that one individual panel in the splash zone had a weight-loss penetration of 24.1 mils or about 50 mpy.(16) This was about five to six times that for the completely submerged panels. Note also that the continuous-strip panel evinced a rate of attack in the splash zone about half that for an individual panel at the same location. Humble(18), see Figure 12, shows the typical corrosion profile of a steel pile after a 5-year exposure at Kure Beach, N. C. The splash zone shows more than four times the rate of the immersed zone.

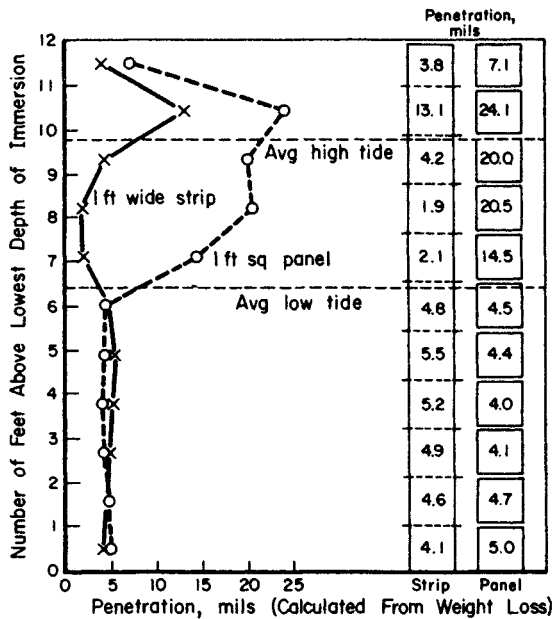


FIGURE 11. CORROSION OF STEEL EXPOSED ABOVE, IN, AND BELOW TIDAL RANGE FOR 151 DAYS AT KURE BEACH, N.C.(18)

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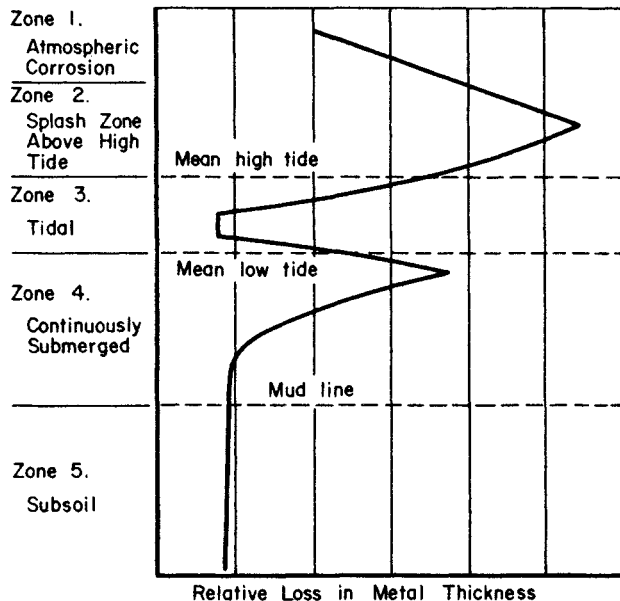


FIGURE 12. CORROSION PROFILE OF STEEL PILING AFTER 5 YEARS' EXPOSURE IN SEAWATER AT KURE BEACH, N.C. (INTERNATIONAL NICKEL CO.)(18)

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Biofouling may develop in the tide zone and confer some protection. (Barnacles for example can live alternately in and out of the water, doing their feeding during the period when they are submerged.) This helps explain the lower corrosion rates in the tide zone, which often are less than those in the splash zone, as can be seen in Figure 11 and in Figure 12. The tide zone receives some cathodic protection from the attack in

the submerged zone as will be discussed. Isolated panels, as shown in Figure 11, corrode almost as rapidly in the tide zone as in the splash zone. Longer exposure periods would have demonstrated the protective effect of biofouling in the tide zone.

A graphical comparison of corrosion behavior in the tide zone with that in the atmosphere and immersed condition is shown in Figures 7 and 8. Note the maximum depth of pitting for both carbon steels and rolled irons at the tide zone at each site. Pitting shows a different order of severity from the general attack. For ordinary steels, panels exposed at Colombo show the greatest weight loss but those at Halifax show the deepest pitting.

The results of exposing carbon steel at the mean tide level in the Pacific Ocean off the Panama Canal Zone are shown in Figure 13(19). The average rate of penetration, calculated from weight loss, was 2.7 mpy. The maximum pit depth, however, was 98 mils for the 16-year period. Wrought iron tested for 8 years showed a lower rate of attack, i.e., 1.4 mpy.

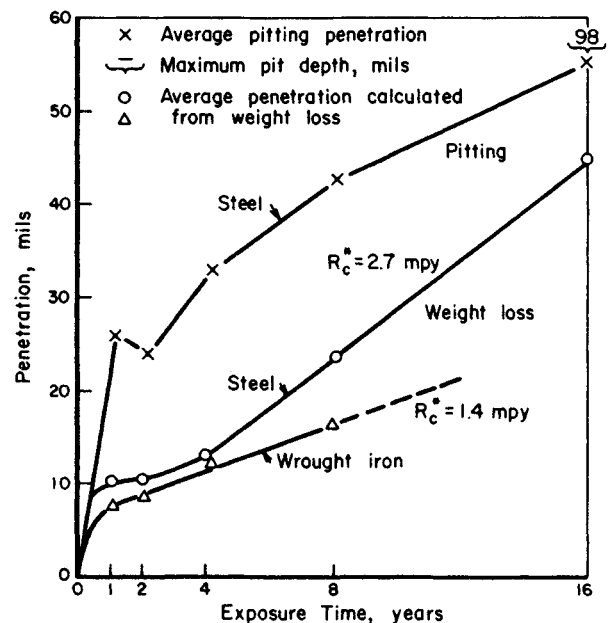


FIGURE 13. CORROSION OF CARBON STEEL AND WROUGHT IRON AT MEAN TIDE IN PACIFIC OCEAN OFF PANAMA CANAL(19)

\* $R_c$  is the final rate based on the tangent to the curve.

It should be emphasized that the splash zone and also, in some cases, the tide zone are the sites where corrosion protection is most needed. Figures 14 and 15 illustrate the severely localized deterioration in the splash zone when no provision is made for corrosion control. Either extra wall thickness or a suitable protective coating should have been provided.



FIGURE 14. LOCALIZED CORROSION IN SPLASH ZONE OF BULKHEAD AND SHEET STEEL PILING ON PACIFIC ISLAND(20)

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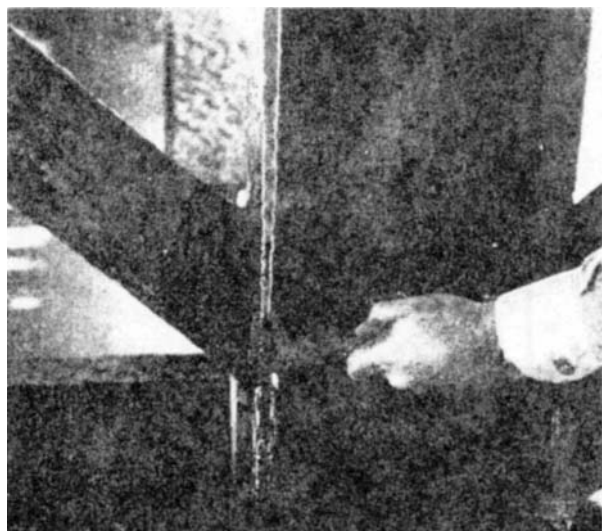


FIGURE 15. RESULTS OF NINE YEARS' EXPOSURE OF 10-INCH BARE-STEEL H PILING AT BRIDGE PIER EXPOSED TO SEAWATER(20)

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#### Submerged

**General Behavior.** A summary of the factors which affect the rate of attack of carbon steel immersed in seawater is given in Table 9. Since the corrosion behavior of steel is under cathodic control, any action which affects the rate of delivery of the oxygen needed to depolarize cathodic regions can have a marked effect on the rate of attack. Normally a rust coating, a calcareous scale, or a layer of biofouling will develop within a few months on the surface and provide an interfering barrier. The decrease in corrosion rate with time for steel and wrought iron is illustrated in Figure 16.(21) Biofouling and calcareous scale, no doubt, played a major role in the rapid decrease observed during the first year of exposure for these experiments.

TABLE 9. CORROSION FACTORS FOR CARBON STEEL IMMERSSED IN SEAWATER

Factor in Seawater	Effect on Iron and Steel
Chloride ion	Highly corrosive to ferrous metals. Carbon steel and common ferrous metals cannot be passivated. (Sea salt is about 55 percent chloride.)
Electrical conductivity	High conductivity makes it possible for anodes and cathodes to operate over long distances, thus corrosion possibilities are increased and the total attack may be much greater than that for the same structure in fresh water.
Oxygen	Steel corrosion is cathodically controlled for the most part. Oxygen, by depolarizing the cathode, facilitates the attack; thus a high oxygen content increases corrosivity.
Velocity	Corrosion rate is increased, especially in turbulent flow. Moving seawater may (1) destroy rust barrier and (2) provide more oxygen. Impingement attack tends to promote rapid penetration. Cavitation damage exposes fresh steel surface to further corrosion.
Temperature	Increasing ambient temperature tends to accelerate attack. Heated seawater may deposit protective scale, or lose its oxygen; either or both actions tend to reduce attack.
Biofouling	Hard-shell animal fouling tends to reduce attack by restricting access of oxygen. Bacteria can take part in corrosion reaction in some cases.
Stress	Cyclic stress sometimes accelerates failure of a corroding steel member. Tensile stresses near yield also promote failure in special situations.
Pollution	Sulfides, which normally are present in polluted seawater greatly accelerate attack on steel. However, the low oxygen content of polluted waters could favor reduced corrosion.
Silt and suspended sediment	Erosion of the steel surface by suspended matter in the flowing seawater greatly increases the tendency to corrode.
Film formation	A coating of rust, or rust and mineral scale (calcium and magnesium salts) will interfere with the diffusion of oxygen to the cathode surface, thus slowing the attack.



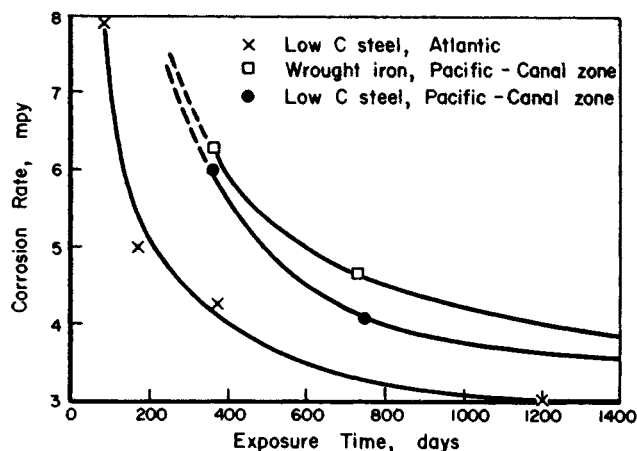


FIGURE 16. CORROSION RATES OF STEEL AND WROUGHT IRON IN SEAWATER AT SHALLOW DEPTHS(21)

For exposures where the velocity is high or turbulent, protective deposits may be removed (or may not form) and the more rapid oxygen delivery to cathodic areas allows the attack to proceed at the anode sites at a greatly increased rate.

Other factors which can be expected to increase the rate of attack are pollution, increase in temperature, and erosion by suspended solids. Sulfides in polluted water promote local attack, although their presence often is accompanied by less oxygen. The temperature effect has been observed at Wrightsville Beach, N. C., where the corrosion rate of steel in seawater during the summer when the water temperature is 80 to 85 F is 50 percent higher than that during the winter when the water temperature is only 45 F, even though the total oxygen content is lower. Oxygen-solubility data are plotted in Figure 17. Tidal currents carrying silt or a slurry of sand have been observed to increase the attack on steel piling.

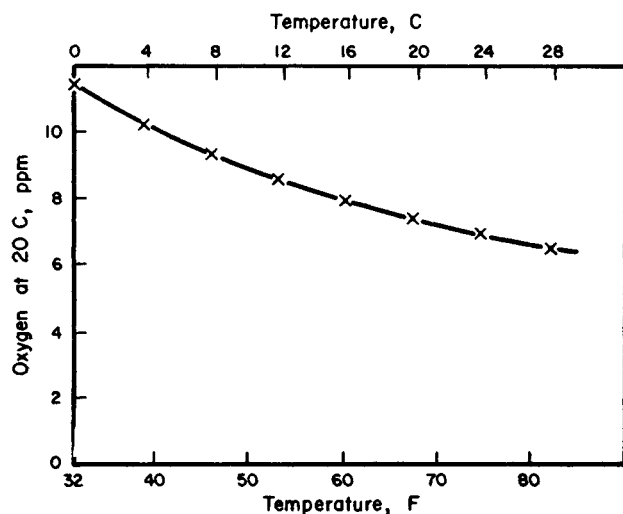


FIGURE 17. SOLUBILITY OF OXYGEN IN SEAWATER OF 35 o/oo SALINITY(22)

**Specific Results.** In panel tests in seawater at widely different marine locations, average rates of penetration for steel and other related ferrous materials were found to range from 2 to 5 mpy. For example, carbon-steel panels immersed for periods up to 16 years in the Pacific Ocean near the Panama Canal Zone showed an average corrosion rate between the 2nd and 16th year of 2.7 mpy (Figure 18), while wrought iron showed 2.4 mpy between the 2nd and 8th year. Reinhart's data showing the relation between corrosion rate and exposure time for ferrous metals is presented in Figure 16. A rapid decline in rate after the first few years is evident.

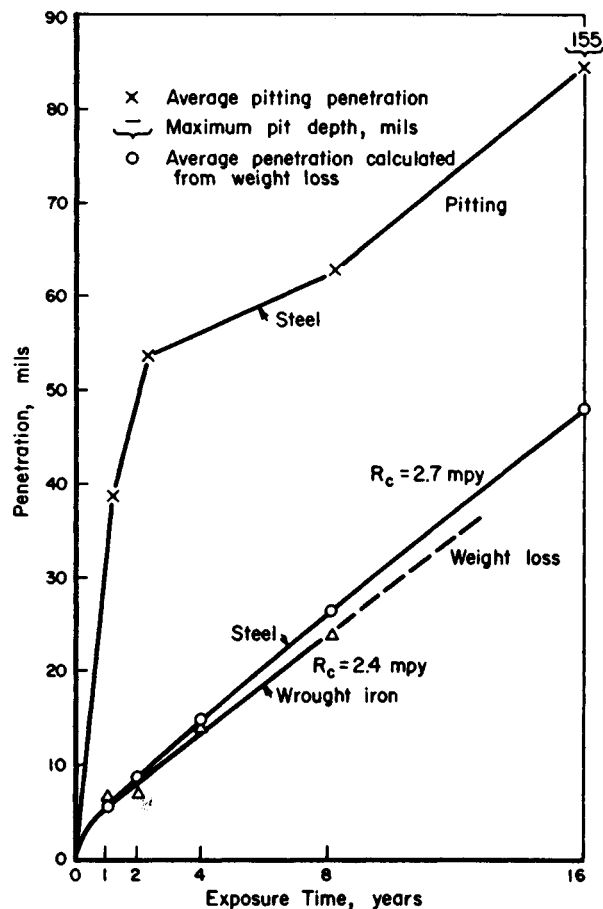


FIGURE 18. CORROSION OF CARBON STEEL AND WROUGHT IRON CONTINUOUSLY IMMERSSED IN SEAWATER(19)

Larrabee(23) has examined heavy sections of 10-inch H piling taken from the sea after 23.6 years at the Santa Barbara, California, waterfront. For those sections between low tide and 5 feet above the ocean bottom, the attack rate was  $1.5 \pm 0.25$  mpy. On the basis of this experience, the rate for steel exposed under similar conditions would be expected to be no more than 2 mpy. A summary of the average rate of penetration for mild steel at various sites is given in Table 10.

Hadfield and Main's results from their 5-year program, show little difference from site to site for the average corrosion penetration, namely 3.4 to 4 mpy (see Figure 7).(15)

TABLE 10. CORROSION BEHAVIOR OF MILD CARBON STEEL IMMERSSED IN SEAWATER AT VARIOUS SITES<sup>(19,23-25)</sup>

Site	Exposure Time, years	Penetration Rate, mpy
Harbor Island, N. C.	3.3	2.1
Kure Beach, N. C.	7.5	4.0
	8	2.2
Santa Barbara, California	23.6	1.25 to 1.75
Panama Canal (Pacific Ocean)	16	2.7
San Diego (polluted seawater)	1.5	2.2

It may seem a bit surprising to find wide variations in the rate of attack for steel in the atmosphere, and only minor differences in the behavior of steel under immersed conditions at widely different geographical locations. In tropical waters, the fouling is massive and tends to restrict the attack. In cold waters, there is much less fouling and more oxygen. Such factors as these apparently are self-compensating, and help explain the observed similarity.

**Pitting Behavior.** From the discussion so far one would expect that all the designer has to do is to adopt about a 3-mpy corrosion allowance and not worry about the protection of a fully submerged steel structure. The pitting behavior, however, must be considered, especially for a pipe, tank, or vessel where perforation results in failure.

Pitting was noted in the 16-year experiments at the Canal Zone area of the Pacific, see Figure 18. For the first 2 years, the mean of 60 deepest pits (10 per panel) was about 53 mils or 10 times the average rate per year. After 2 years, the curve for pit depth plotted against time is roughly parallel to the weight-loss curve, with an indicated increase of about 2.2 mpy. A pit with a depth of 155 mils, however, was observed on one of the replicate panels after 16 years.

Hadfield and Main show pitting behavior at four sites in Figure 8. A summary of this information is given in Table 11. The maximum pitting for the immersed condition is up to eight times the penetration rate calculated from the weight loss.

TABLE 11. AVERAGE DEPTH OF MAXIMUM PITTING FOR CARBON STEELS AND IRONS AFTER 5 YEARS' EXPOSURE TO SEAWATER AT DIFFERENT SITES<sup>(15)</sup>

Site	Average Pitting Depth, mils	
	Half Tide	Total Immersion
Auckland	13.4	87.5
Halifax	51.6	40.9
Plymouth	111.8	67.6
Colombo	132.2	147.5

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Pitting attack tends to vary with the type of seawater involved. In polluted San Diego Harbor<sup>(25)</sup>, corrosion pitting for mild steel was found to be as high as 60 mpy in 1 year, see Table 12. For steel piping in ships systems handling aerated seawater pitting rate may range up to 50 mpy.<sup>(26)</sup>

TABLE 12. PITTING CORROSION OF MILD STEEL SUBMERGED IN SAN DIEGO HARBOR (POLLUTED SEAWATER)(a)(25)

Exposure Time, days	No. of Panels	Penetration, mils	
		Avg. of 5 Deepest Pits per Panel	Deepest Pit per Panel
155	6	13 to 24	18 to 30
361	12	20 to 53	29 to 60
552	6	32 to 41	26 to 50

(a) Weight-loss penetration averaged 2.2 mpy for this exposure.

Pitting may be more intense if the mill scale is left on. Mill scale, as in the atmosphere, is protective except at breaks in the scale which become anodic. Because of the relatively large cathodic area, the rate of attack at the local anodes is intense.

The rate of attack is difficult to establish for cast iron since it tends to graphitize (form of parting) in seawater. On first inspection, specimens may appear in excellent condition. However, specimens which have been exposed for a period of years usually show an outer soft layer of graphite and corrosion products. Graphitized cast iron acts as a cathode when coupled to, say, a fresh piece of steel or iron. Cast iron has long life largely because of the heavy wall required to produce a cast structure. Its actual rate of attack in seawater often is double that for steel.

**Deep Ocean.** Corrosion rates for carbon steels tend to be lower in the deep ocean than in surface waters. This is shown in a recent summary of the behavior of iron and steel given by Reinhart<sup>(1)</sup> (see Figures 19 and 20). In general, the rate of attack tends to decrease with time. The average penetration, calculated from the weight loss for this series of experiments, ranges from about 0.6 to 8 mpy. The low temperature and the very low rate of movement of bottom waters at both the Atlantic and Pacific sites may help explain the lower rates observed.

In the Pacific, the oxygen content of the seawater at around 2,000 feet reaches a minimum; this is ascribed to the biological oxygen demand of decaying organisms and waste products. In the Atlantic, oxygen levels are fairly high at all depths. These differences are illustrated in the tabulation below.

Depth, feet	Oxygen Content, ml/l	
	Atlantic	Pacific
0	4.59	5.8
2000	3.11	0.25
5000	5.73	1.0

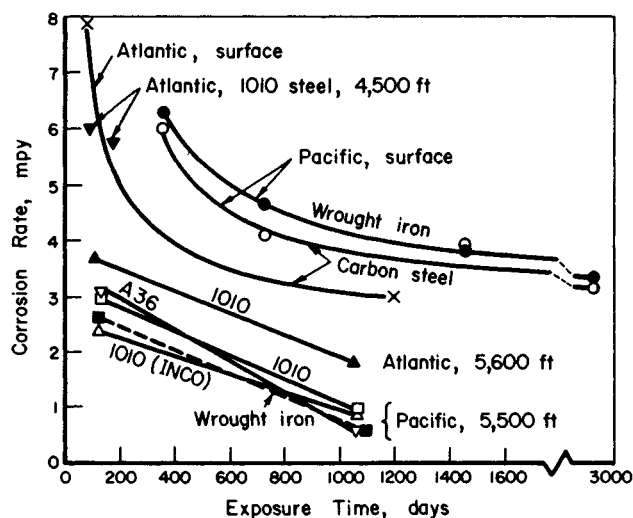


FIGURE 19. CORROSION RATES OF CARBON STEELS IN THE ATLANTIC AND PACIFIC OCEANS AT VARIOUS DEPTHS<sup>(1)</sup>

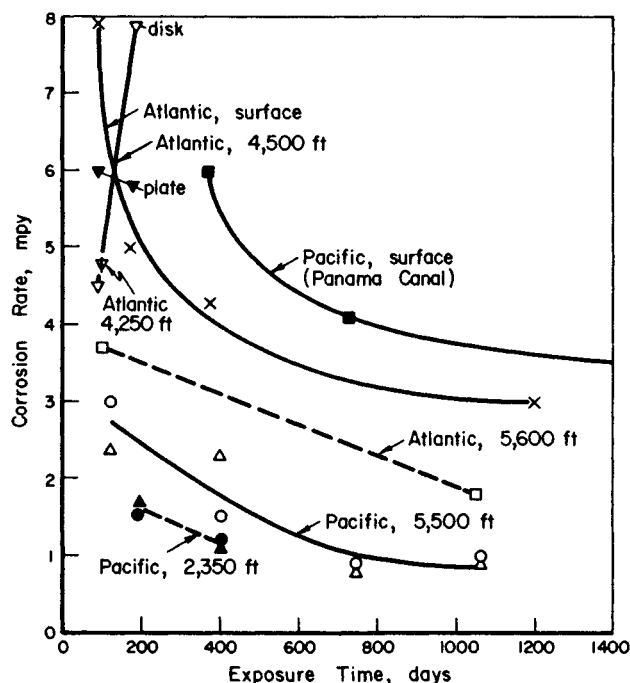


FIGURE 20. CORROSION RATES OF LOW-CARBON STEELS AT VARIOUS LOCATIONS<sup>(1)</sup>

#### Mud

Bottom conditions vary, but local attack is sometimes observed just above the mud zone or in the bottom mud itself. As in the soil, bottom mud is often aggressive to steel because of the presence of sulfate-reducing bacteria.

For steel structures standing in the mud, not only may the anodic and cathodic sites be a considerable distance apart, but their location may shift somewhat with time.

#### Low-Alloy Steels

Low-alloy high-strength steels contain small amounts of such elements as copper, chromium, nickel, molybdenum, silicon, and manganese to provide added strength to the carbon-steel base. Low-alloy steels are not sold on the basis of analysis but on the basis of their strength. The total of the added elements is usually around 2 to 3 percent. Most of the low-alloy steels are outstandingly resistant, as compared with plain, low-carbon steel, when exposed to the atmosphere. This is especially true for industrial sites but there also is considerable advantage in their use at marine locations.

The low-alloy steels show greatly improved resistance to marine atmospheres, as a result of the development of a fine-grained tightly adherent rust coat. The life of a low-alloy steel structural part may be approximately five times as long as that of a similar carbon steel part. Many low-alloy high-strength steels also show superior performance in the splash zone. A good marine coating will last longer when applied to a properly prepared low-alloy-steel surface than when applied to a carbon steel substrate.

Under mean tide or fully immersed conditions, low-alloy steels are no more resistant than carbon steel. For submerged conditions, high strength is becoming an important consideration. Under this design criterion, as will be seen, the corrosion allowance for low-alloy high-strength steel must be equal to or greater than that provided for carbon steel in submerged service. This extra corrosion allowance tends to offset the normal weight-saving advantage of high-strength steels when they are employed in seawater.

The characteristic behavior of low-alloy steels in the different marine environmental zones is discussed separately in the sections which follow.

#### Atmosphere

The first indication that composition affected corrosion behavior was the observation some 55 years ago that copper-bearing steels showed improved endurance in industrial atmospheres. Later it was found that the copper-bearing steels also performed better than plain-carbon steel at ocean sites.

Among others, the Navy and the ASTM have provided information on the excellent behavior of copper-bearing and low-alloy steels at marine sites. In the Navy program, after an 8-year exposure at Cristobal, Panama Canal Zone<sup>(13,17)</sup>, the penetration rate calculated from weight loss, for low-alloy steels ranged from 0.7 to 0.9 mpy, as illustrated in Figure 10. At the 800-foot lot at Kure Beach, N. C., the 15.5 year results indicated a rate of 0.3 mpy or less for low-alloy steels. Table 13 identifies the compositions of the steels used in the ASTM tests and gives the weight losses determined. Selected results from Table 13 are plotted in Figure 21, which shows total alloy content versus weight loss due to corrosion for the 15.5-year exposure. A wide range of compositions gave improved resistance. In general, a total alloy content of 2.0 percent for these types of steels seems to provide the maximum return in performance.

TABLE 13. CORROSION OF LOW-ALLOY STEELS IN A MARINE ATMOSPHERE – 15.5 YEARS AT 800-FOOT LOT, KURE BEACH, N.C.(12)

Group	Description	Composition, percent									Approx. Total Alloy Content, percent	Weight Loss <sup>(a)</sup> , mg/dm <sup>2</sup>
		Carbon	Manganese	Silicon	Sulfur	Phosphorus	Nickel	Copper	Chromium	Molybdenum		
I	High-purity iron plus copper	0.020	0.020	0.003	0.03	0.006	0.05	0.020	–	–		
		0.020	0.023	0.002	0.03	0.005	0.05	0.053	–	–	0.1	43
		0.02	0.07	0.01	0.03	0.003	0.18	0.10	–	–	0.4	29.8
II	Low-phosphorus steel, plus copper	0.040	0.39	0.005	0.02	0.007	0.004	1.03	0.06	–	1.5	17.3
III	High-phosphorus steel, plus copper	0.09	0.43	0.005	0.03	0.058	0.24	0.36	0.06	–	1.2	16.9
		0.095	0.41	0.007	0.05	0.104	0.002	0.51	0.02	–	1.0	16.5
IV	High-manganese and -silicon steels, plus copper	0.17	0.67	0.23	0.03	0.012	0.05	0.29	0.14	–	1.4	16.6
V	Copper steel, plus chromium and silicon	0.072	0.27	0.83	0.02	0.140	0.03	0.46	1.19	–	2.9	6.3
VI	Copper steel, plus molybdenum	0.17	0.89	0.05	0.03	0.075	0.16	0.47	–	0.28	1.9	11.8
VII	Nickel steel	0.16	0.57	0.020	0.02	0.015	2.20	0.24	–	–	3.0	9.4
		0.19	0.53	0.009	0.02	0.016	3.23	0.07	–	–	3.9	9.2
		0.17	0.58	0.26	0.01	0.007	4.98	0.09	–	–	5.9	6.1
		0.13	0.23	0.07	0.01	0.007	4.99	0.03	0.05	–	5.4	7.5
VIII	Nickel steel, plus chromium	0.13	0.45	0.23	0.03	0.017	1.18	0.04	0.65	0.01	2.6	10.5
IX	Nickel steel, plus molybdenum	0.16	0.53	0.25	0.01	0.013	1.84	0.03	0.09	0.24	3.0	9.8
X	Nickel steel, plus chromium and molybdenum	0.10	0.59	0.49	0.01	0.013	1.02	0.09	1.01	0.21	3.4	6.5
		0.08	0.57	0.33	0.01	0.015	1.34	0.19	0.74	0.25	3.4	7.6
XI	Nickel-copper steel	0.12	0.57	0.17	0.02	0.01	1.00	1.05	–	–	2.8	10.6
		0.09	0.48	1.00	0.03	0.055	1.14	1.06	–	–	3.8	5.6
		0.11	0.43	0.18	0.02	0.012	1.52	1.09	–	–	3.2	10.0
XII	Nickel-copper steel, plus chromium	0.11	0.65	0.13	0.02	0.086	0.29	0.57	0.66	–	2.4	10.5
		0.11	0.75	0.23	0.04	0.020	0.65	0.53	0.74	–	2.9	9.3
		0.08	0.37	0.29	0.03	0.089	0.47	0.39	0.75	–	2.4	9.1
XIII	Nickel-copper steel, plus molybdenum	0.03	0.16	0.01	0.03	0.009	0.29	0.53	–	0.08	1.1	18.2
		0.13	0.45	0.066	0.02	0.073	0.73	0.573	–	0.087	2.0	11.2

(a) A weight loss of 10 mg/dm<sup>2</sup>/15.5 years = 0.32 mpy.

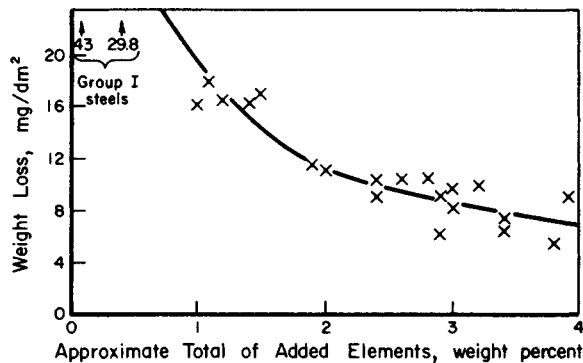


FIGURE 21. CORROSION OF SELECTED LOW-ALLOY STEEL PANELS EXPOSED IN MARINE ATMOSPHERE AT THE 800-FOOT LOT, KURE BEACH, N.C., FOR 15.5 YEARS(12)

A general picture of the relative resistance of low-alloy steels, copper-bearing steels, and pure iron in a marine atmosphere is shown in Figure 22. Endurance is shown as the time required for a 4 x 6-inch panel to lose 12 grams. For a pure iron panel, the time required was only 5 months, but for a typical low-alloy steel panel, 32 months was required, or over 6 times as long.

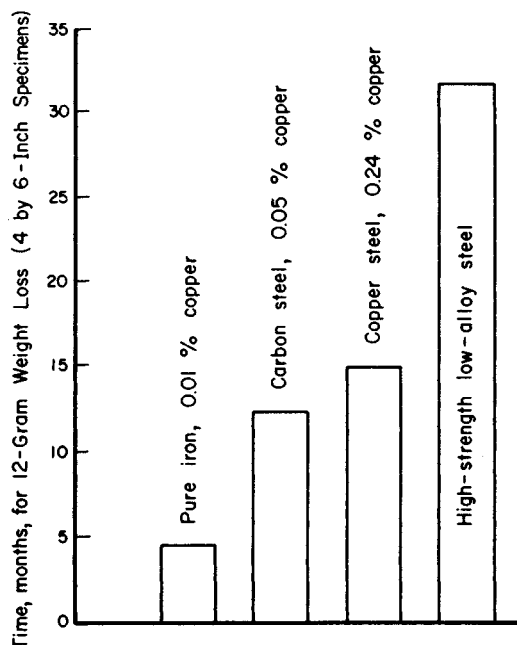


FIGURE 22. RELATIVE DURABILITIES OF STEELS IN A MARINE ATMOSPHERE(27)

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LaQue(9) published a series of curves showing the individual benefit of copper, nickel, and chromium additions to steel in his Edgar Marburg lecture. These data are for 7.5 years of exposure at the 800-foot lot, Kure Beach, N. C., and are summarized in the paragraphs which follow.

Effect of Copper. The addition of 0.3 percent copper to mild steel would provide the maximum performance, as illustrated by Figure 23. Assuming that the attack is equal on each side of the panel (which usually is not the case), the average rate of penetration for a 0.2 percent copper-bearing steel would be about 1.4 mpy, or about half the rate for open-hearth iron at this same site. As shown in Figure 24, an even lower rate of 1.1 mpy is obtained for 0.2 percent copper steel when the higher phosphorus content of Bessemer steel is used as the base.

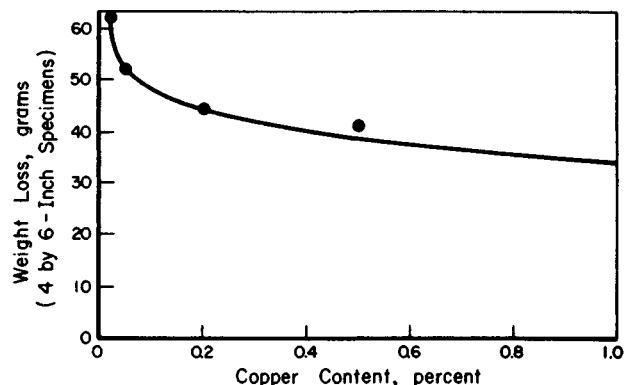


FIGURE 23. EFFECT OF COPPER CONTENT ON CORROSION OF OPEN-HEARTH STEEL IN MARINE ATMOSPHERE AT KURE BEACH, N.C. (90 MONTHS' EXPOSURE)(9)

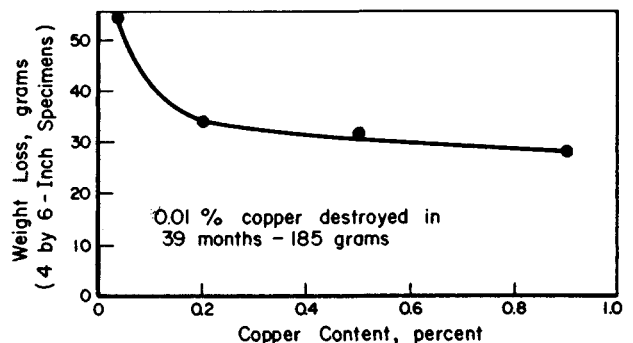


FIGURE 24. EFFECT OF COPPER CONTENT ON CORROSION OF BESSEMER STEEL IN MARINE ATMOSPHERE AT KURE BEACH, N.C. (90 MONTHS' EXPOSURE)(9)

Other information indicates that the major improvement, over pure iron, is imparted by the first 0.03 percent of copper.(9) While there is no question of the increased benefit from the addition of, say, 0.15 to 0.3 percent copper, some authorities recommend 0.4 to 0.5 percent for maximum performance.

Effect of Nickel. Nickel additions to iron in the range of 0.1 to 0.5 percent are less effective than copper additions in promoting increased resistance to the marine atmosphere.

However, higher additions of nickel, e.g., 1 to 5 percent, are effective in promoting corrosion resistance, as can be seen in Figure 25. In the experiment depicted in the figure, corrosion was reduced 50 percent, as compared with that for iron, by the addition of 2 percent nickel.

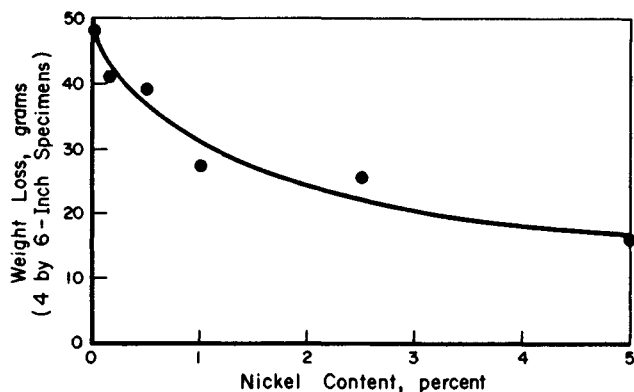


FIGURE 25. EFFECT OF NICKEL CONTENT ON CORROSION OF STEEL IN MARINE ATMOSPHERE AT KURE BEACH, N.C. (90 MONTHS' EXPOSURE)(9)

**Effect of Chromium.** The results for a series of alloys containing chromium exposed to the marine atmosphere are shown in Figure 26. Of importance to this discussion is the effect of chromium additions of 2 percent or less as compared with the effect of similar additions of copper or nickel. Some estimate can be obtained by reading off the values corresponding to 0.2, 1.0, and 2.0 percent additions in Figures 24 through 26. With 1 to 2 percent addition of either copper, nickel, or chromium, the corrosion rate is half that for an unalloyed carbon-steel panel (see Table 14).

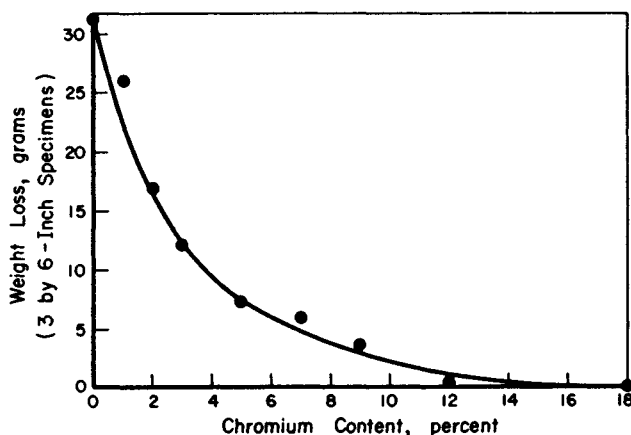


FIGURE 26. EFFECT OF CHROMIUM CONTENT ON CORROSION OF STEEL IN MARINE ATMOSPHERE AT KURE BEACH, N.C. (90 MONTHS' EXPOSURE)(9)

TABLE 14. FIVE-YEAR WEIGHT LOSS AS DETERMINED GRAPHICALLY FOR STEEL WITH COPPER, NICKEL, OR CHROMIUM ADDITIONS

Amount Added, wt %	Copper			Nickel				Chromium			
	0	0.2	1	0	0.2	1	2	0	0.2	1	2
Weight Loss per Panel, grams	> 50	34	28	48	42	31	25	32	30	22	17

**Alloy Combinations.** In light of the above comparisons, it is interesting to compare the effects on the marine resistance when different alloy combinations of these and other elements are tried. Data for a series of low-alloy steels with total alloy additions of up to 3.5 percent are presented in Figure 27. Note, for example, that the corrosion resistance of Alloy M with phosphorus, silicon, copper, nickel, and chromium additions is equivalent to that of Alloy F with negligible chromium or silicon and higher levels of copper and nickel.

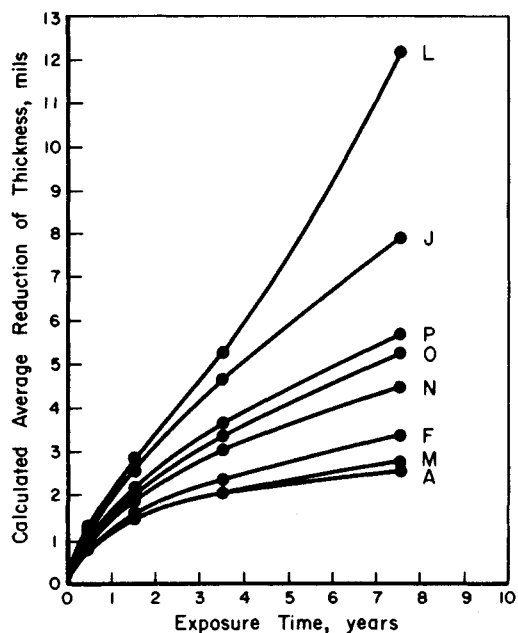


FIGURE 27. EFFECT OF EXPOSURE TIME ON CORROSION OF STEELS IN MARINE ATMOSPHERE AT KURE BEACH, N.C.(28)

Steel	Composition, percent							
	C	Mn	P	S	Si	Cu	Ni	Cr
A(a)	0.09	0.24	0.15	0.024	0.80	0.43	0.05	1.1
M(a)	0.06	0.48	0.11	0.030	0.54	0.41	0.51	1.0
F(a)	0.05	0.36	0.05	0.016	0.008	1.1	2.0	0.01
N(a)	0.11	0.55	0.08	0.026	0.06	0.55	0.28	0.31
O(a)	0.16	1.4	0.013	0.021	0.18	0.30	0.50	0.03
P(a)	0.23	1.5	0.018	0.021	0.19	0.29	0.04	0.08
J(b)	0.19	0.52	0.008	0.039	0.01	0.29	0.05	0.05
L(b)	0.16	0.42	0.013	0.021	0.01	0.02	0.02	0.01

(a) High-strength low-alloy steels.

(b) Structural carbon and structural copper steels.



The following groups of alloys, selected from Table 13, show excellent resistance to the marine environment.

Group	Alloy Content, weight percent							Weight Loss, mg, dm <sup>2</sup>
	Mn	Si	Ni	Cu	Cr	Mo	Total	
V	0.27	0.83	0.03	0.46	1.19	—	2.9	6.3
VII	0.58	0.26	4.98	0.09	—	—	5.9	6.1
X	0.59	0.49	1.0	0.09	1.01	0.21	3.4	6.5
XI	0.48	1.00	1.14	1.06	—	—	3.8	5.6

The example alloys from Groups V, X, and XI all are about equal in total alloy content and performance. The Group VII example alloy, which features a high nickel content, requires a higher total alloy content for the same resistance.

**Tight Rust Formation.** The benefit derived from the addition of copper to steel exposed to an industrial atmosphere has been ascribed to the relatively insoluble basic sulfates, from the SO<sub>2</sub> in the polluted air, which slowly develop in the rust film. Additions of nickel, chromium, and — to a lesser degree — silicon and phosphorus also were found to promote relatively insoluble corrosion products.(12)

The film of electrolyte on a panel at a marine atmospheric site is high in chlorides, as one would expect, and lower in sulfate. Since basic chlorides are not so insoluble as the basic sulfates predominating in the hydrated iron oxide film developed at industrial sites, one would not expect the film developed at a marine site to be as protective. This is found to be the case. The manner in which protective rust coats do form under marine conditions is less understood than that in the case of the industrial atmosphere.

The formation of the rust coat is influenced by the amount of salt mist carried in by the prevailing wind, rainfall, sunshine, fungi, humidity cycle, dust, and, at some marine sites, pollution. (Occasionally, a trace of SO<sub>2</sub> is present in the atmosphere at the Kure Beach, N. C., lots, some 15 miles from Wilmington, the nearest city). As with carbon steel, the amount of sea salt reaching the exposed surface and retained on the surface greatly affects the rate of attack.

A well-known widely used alloy, Cor-Ten, has the composition range shown in Table 15. The ASTM specification covering this type of alloy does not provide for a specific composition range. For marine service, a heat containing, say, about 0.3 percent or more copper plus other additions such as nickel, chromium, and silicon, totaling at least 1.5 percent, is recommended.

The 80-foot lot at Kure Beach, N. C., is one of the most corrosive test sites in use for marine-atmosphere testing. Even under these severe conditions, the low-alloy steel corrodes at a lower rate than mild steel, see Figure 28. However, the indicated rate for the low-alloy steel at this location is sufficiently high to require protection in comparable environments for many applications.

TABLE 15. COMPOSITION RANGES AND TYPICAL COMPOSITION FOR HIGH-STRENGTH LOW-ALLOY STEEL<sup>(a)</sup>

Element	Composition, percent	
	Range	Typical
C	0.12 max	0.09
Mn	0.20-0.50	0.38
P	0.07-0.15	0.09
S	0.05 max	0.033
Si	0.25-0.75	0.48
Cu	0.25-0.55	0.41
Cr	0.30-1.25	0.84
Ni	0.65 max	0.28

(a) COR-TEN, U.S. Steel Corp.

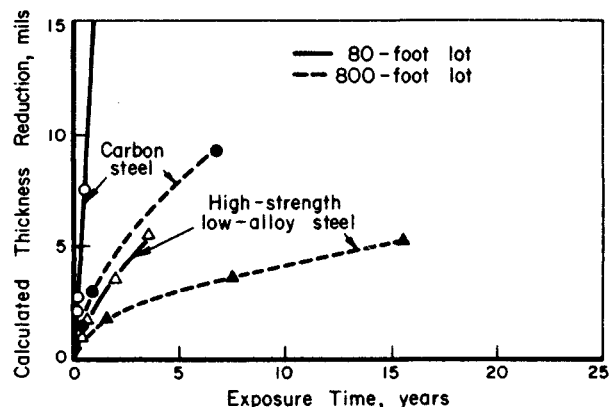


FIGURE 28. COMPARISON OF CORROSION RESULTS FOR VARIOUS STEELS IN MARINE ATMOSPHERE, KURE BEACH, N. C.(29)

**Pitting Attack.** Some idea of the pitting performance of low-alloy steels in a severe marine climate is provided by the results from the Canal Zone site. A few of the exposure panels were perforated after 8 years, i.e., they showed greater than 63 mils penetration. More typically, the deepest pits ranged from 17 to 28 mils. Thus, a pitting allowance of 4 mils per year would be conservative for a low-alloy-steel structure where perforation would cause failure.(13,17) Pitting data are tabulated above Figure 10.

#### Splash and Tide

Ordinary steels, it will be recalled, corrode at extremely high rates in the splash zone. When the exposure is such that the steel is almost continually wetted by surf and spray, the corrosion rate, based on weight loss, may average as high as 50 mpy at least initially.

In recent years it has been demonstrated that some low-alloy steels undergo decidedly less corrosion at the splash zone than does carbon steel.

Some experimental results developed by Larrabee(30) are presented in Table 16. At the 1.5- and 2.5-foot level, the loss in thickness for the carbon steel (BO1468) was several times higher than that for the low-alloy steels. The alloy with 0.5 percent copper and 0.5 percent nickel (BO1458) performed particularly well. Although the plot of corrosion rate versus alloy content plot reveals some scatter in the data, as a general rule the alloys with higher alloy content are proportionally more resistant.

TABLE 16. AVERAGE DECREASE IN THICKNESS OF 20-FOOT SPECIMENS AFTER 5 YEARS' EXPOSURE TO SPLASH, SEAWATER, AND MUD ZONES AT HARBOR ISLAND, N. C.(a)(30)

Average Feet From Top	Decrease in Thickness, mils						
	BO1468	BO1458	BO1389	BO1457	BO1459	BO1467	BO1456
	Sheet Steel	Ni-0.54% Cu-0.52% P-0.12%	Ni-0.55% Cu-0.22% P-0.17%	Ni-0.54% Cu-0.20% P-0.11%	Ni-0.55% Cu-0.20% P-0.14%	Ni-0.28% Cu-0.20% P-0.14%	Ni-0.28% Cu-0.22% P-0.17%
0.5(b)	9	11	12	9	24	9	10
1.5	87	13	16	30	18	21	21
2.5	98	17	26	54	30	45	73
Approximate High-Tide Line							
3.5	48	4	9	9	7	6	22
4.5	1	1	2	1	2	1	2
5.5	0	1	2	2	7	3	2
6.5	14	37	34	41	29	28	24
Approximate Low-Tide Line							
7.5	56	52	52	64	53	42	46
8.5	45	41	44	49	42	38	34
9.5	52	38	41	49	49	43	32
10.5	53	48	40	49	42	41	32
11.5	45	39	35	49	42	37	32
12.5	46	37	38	46	32	35	33
Approximate Ground Line							
13.5	45	13	24	37	11	12	18
14.5	29	6	24	24	6	7	17
15.5	21	5	5	14	5	6	18
16.5	22	10	13	11	7	15	28
17.5	30	18	22	10	12	28	31
18.5	30	12	15	10	22	25	34
19.5	27	15	24	17	39	38	31

Note: Approximate mean high tide 2 to 3 feet from tops of specimens; approximate mean low tide about 6 feet from tops of specimens.

- (a) Specimens were exposed in 1951; figures quoted were calculated from losses in weight.  
 (b) Unrealistic values because of partial protection from top supporting member.

If carbon steel were used as sheet steel piling at this site, a corrosion allowance of 20 mpy would be required, and the highest loss would be just above the high tide line. With Alloy Steel BO1458, a 10 mpy corrosion allowance would be ample, and this would provide for the attack in the submerged condition. A graphical comparison of the 5-year results for these two steels is shown in Figure 29. It is of particular interest to compare the shape of the minimum thickness curve for each steel, which shows that the maximum attack for each zone is less, on the whole, for the low-alloy steel. Other experiences with low-alloy steels, especially in exposures where the wave action is vigorous, also indicate that they have considerable merit for splash-zone service.

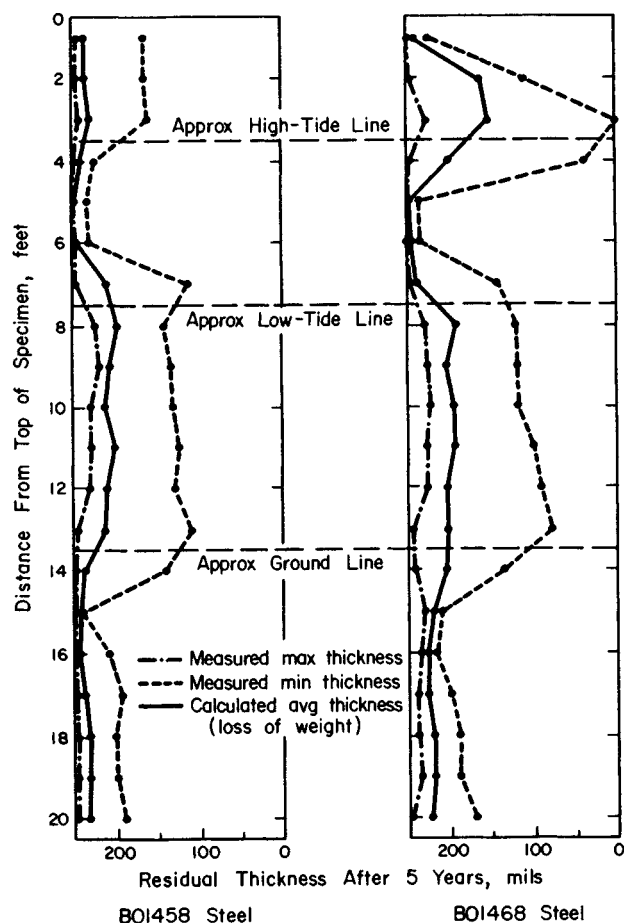


FIGURE 29. COMPARISON OF CORROSION RESULTS FOR TWO STEELS IN MARINE ENVIRONMENTS(30)  
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#### Submerged

Low-alloy steels show weight-loss penetrations in the range of about 2.5 to 5 mpy when fully immersed in seawater. Thus, a low-alloy steel offers no particular corrosion advantage over carbon steel in applications involving submergence in the ocean.

Examples of corrosion rates for plain-carbon steel and low-alloy steels after 8 and 16 years in the Pacific Ocean near the Panama Canal are given in Table 17 and Figures 30, 31, and 32. The corrosion rate based on the weight loss of 2 and 5 percent nickel steels is similar to that of carbon steel, see Figure 30. However, in some instances, the low-alloy steels evince rates of attack higher than that of carbon steel. Thus, the pitting penetration after 8 years on the nickel-bearing steels (Figure 30) was much deeper than that for plain-carbon steel. Also, over 16 years' exposure, the rate of attack for Alloys J and L was almost double that for mild steel (see Figure 31).

Corrosion rates in the same range are found at Kure Beach, N. C., on the basis of 4.5 years of exposure (see Table 18).



TABLE 17. COMPOSITION OF STRUCTURAL STEELS AND THEIR CORROSION RATES IMMERSSED 14 FEET DEEP IN THE PACIFIC OCEAN NEAR THE PANAMA CANAL ZONE<sup>(19)</sup>

Type	Composition, percent										Corrosion Rate, mpy	
	C	Mn	P	S	Si	Cr	Ni	Cu	Mo		8 Yr	16 Yr
Unalloyed low carbon (A)	0.24	0.48	0.040	0.027	0.008	0.03	0.051	0.080	-	2.9	2.7	
Copper bearing (D)	0.22	0.44	0.019	0.033	0.009	Trace	0.14	0.35	-	3.0	-	
Nickel (2%) (E)	0.20	0.54	0.012	0.023	0.18	0.15	1.94	0.63	-	3.8	2.7	
Nickel (5%) (F)	0.13	0.49	0.010	0.014	0.16	0.10	5.51	0.062	-	3.6	2.7	
Chromium (3%) (G)	0.08	0.44	0.010	0.017	0.13	3.16	0.16	0.11	0.02	5.8	3.8	
Chromium (5%) (H)	0.08	0.41	0.020	0.019	0.20	5.06	0.11	0.062	0.52	4.3	3.5	
Low alloy (Cu-Ni) (I)	0.08	0.47	0.007	0.026	0.060	None	1.54	0.87	-	3.0	2.7	
Low alloy (Cu-Cr-Si) (J)	0.15	0.45	0.113	0.026	0.47	0.68	0.49	0.42	-	5.3	4.8	
Low alloy (K)	0.078	0.75	0.058	0.022	0.04	Trace	0.72	0.61	0.13	2.7	2.5	
(Cu-Ni-Mn-Mo)												
Low alloy (Cr-Ni-Mn) (L)	0.13	0.60	0.089	0.021	0.15	0.55	0.30	0.61	0.059	5.5	5.0	

TABLE 18. CORROSION RATES OF STEELS IN SEAWATER AT KURE BEACH, N.C.(28)

Steel	Average Penetration for Each Surface, mpy		
	1.5 Yr	2.5 Yr	4.5 Yr
Cor-Ten	4.2	4.3	3.8
Tri-Ten	4.4	3.8	3.0
Ni-Cu	5.3	4.5	3.5
Cr-Mo	1.4	1.6	1.6
Structural carbon	4.8	4.1	3.3

Steel	Compositions, percent								
	C	Mn	P	S	Si	Cu	Ni	Cr	Mo
Cor-Ten	0.08	0.36	0.08	0.026	0.31	0.41	0.49	0.73	-
Tri-Ten	0.17	1.2	0.026	0.025	0.18	0.31	0.53	0.07	-
Ni-Cu	0.19	0.44	0.030	0.032	0.025	0.81	1.8	0.22	-
Cr-Mo	0.07	0.39	0.014	0.020	0.09	0.020	0.04	2.6	0.52
Structural carbon	0.25	0.42	0.020	0.032	0.025	0.012	0.02	0.06	-

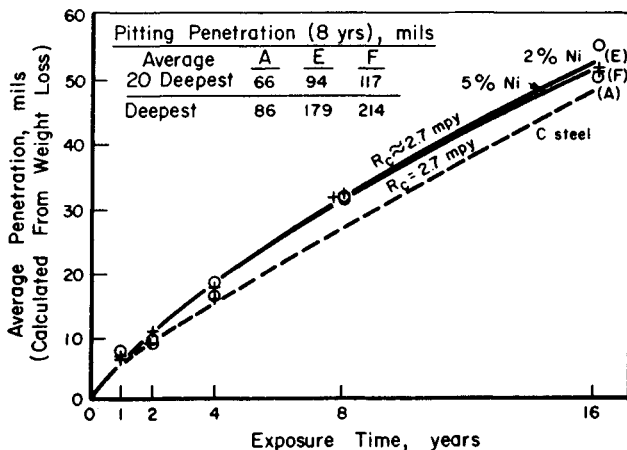


FIGURE 30. SEA-IMMERSION CORROSION OF 2 PERCENT AND 5 PERCENT NICKEL STEELS<sup>(19)</sup>

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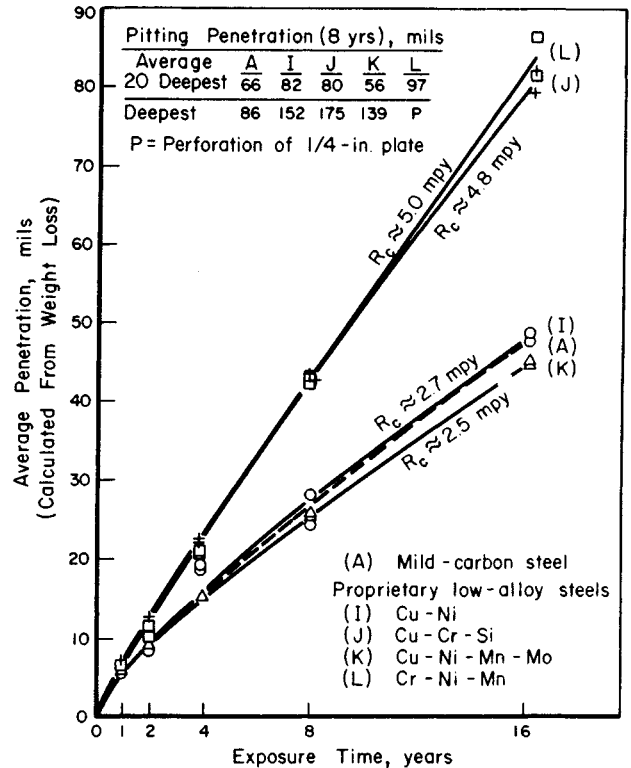


FIGURE 31. SEA-IMMERSION CORROSION OF PROPRIETARY LOW-ALLOY STEELS<sup>(19)</sup>

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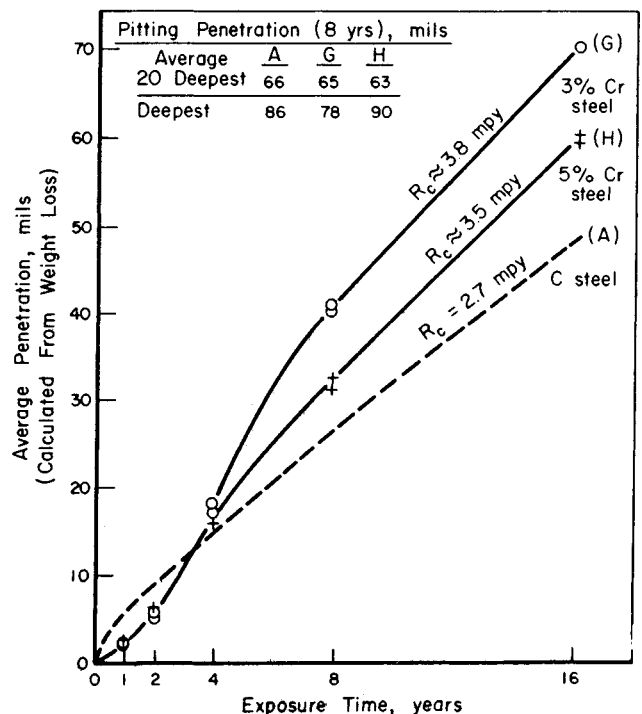


FIGURE 32. SEA-IMMERSION CORROSION OF 3 PERCENT AND 5 PERCENT CHROMIUM STEEL<sup>(19)</sup>

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The early work reported by Hudson in England, and some results at Kure Beach, N. C., reported by LaQue, suggested chromium additions were beneficial in seawater. In the many experiments with the alloying elements usually considered for low-alloy steels, significant improvement was obtained only for chromium. There appeared to be a benefit with an addition of about 3 percent chromium, particularly in retarding the rate of attack over the first few years. More recent results, however, have demonstrated that for longer term exposures, the chromium-bearing steels tend to corrode at rates considerably higher than that of carbon steel. See, for example, the 16-year exposure data from the immersed condition in the Pacific Ocean off the Panama Canal plotted in Figure 32. After the third year, the corrosion rates for the 3 and 5 percent chromium steels are higher than that for the unalloyed carbon steel.(19)

Since the resistance of low-alloy steels to the marine atmosphere is often, say, two to ten times more than that of ordinary carbon steel, it is of interest to inquire why this is not also true in seawater. The special conditions in the atmosphere which lead to the formation of basic salts and subsequent tight rust coats on low-alloy steels are found not to operate in the submerged condition. For low-alloy steels and carbon steel, the rust coat formed in contact with seawater is closely similar in its effect of gradually slowing down the rate of attack with time, i.e., retarding the arrival of oxygen at cathodic surfaces.

In deep-ocean experiments conducted west of Port Hueneme, California, carbon steel and low-alloy steels (for composition, see Table 19) show corrosion rates ranging from 0.5 to 2.0 mpy (see Table 20). These rates are lower than those that would be obtained in surface waters for the same period of time. A comparison of the Pacific Ocean results with data from other sites is shown in Figure 33. The curve for carbon steel in surface water at Harbor Island, N. C. is believed to be typical of steels in such environments.

**Pitting Attack.** The low-alloy steels, as a group, develop deeper pits than does carbon steel. This is demonstrated by the 8-year results from the Panama-Pacific exposures given in Table 21. The total penetration calculated from the weight loss (Column 1) is compared with the average of the 20 deepest pits (Column 2) and with the deepest pit (Column 3). Assuming that the average of the 20 deepest pits is a more significant criterion than the deepest pit, one can compare this average pitting value with the weight-loss penetration. The ratio of these two values for low-carbon steel at the 14-foot depth is 2.6. The range for the alloy steels, some of which have higher weight-loss penetrations to start with, is 1.6 to 3.7. At the mean tide level, the factor is lower, as is the pit depth for many of the steels involved in the comparison.

For a given strength, the designer would be tempted to specify a thinner wall for a low-alloy steel in a seawater application. Since the corrosion rate is higher if anything, corrosion failure would be more rapid. Thus, from a design standpoint, the corrosion allowance for a low-alloy steel should be greater than that for a low-carbon steel. However, low-alloy steels have good strength characteristics and if protective coatings were applied, these steels could be employed to advantage. Cathodic protection must be applied with care for high-strength low-alloy steels since some tend to be more susceptible to hydrogen damage than does carbon steel.

#### Stainless Steels

Stainless steels, as a class, find only limited application in marine environments. Their successful use is predicated on control of the environment to maintain passivity or the use of protective measures to control local attack. Stainless steels usually do well in marine atmospheres where the passivity can be maintained by bold exposure of the surface. High-velocity conditions in seawater also are favorable. In quiet seawater, local attack such as pitting is apt to cause failure.

TABLE 19. CHEMICAL COMPOSITION OF IRON AND STEELS, WEIGHT PERCENT(1)

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

(a) High-strength, low-alloy steel.

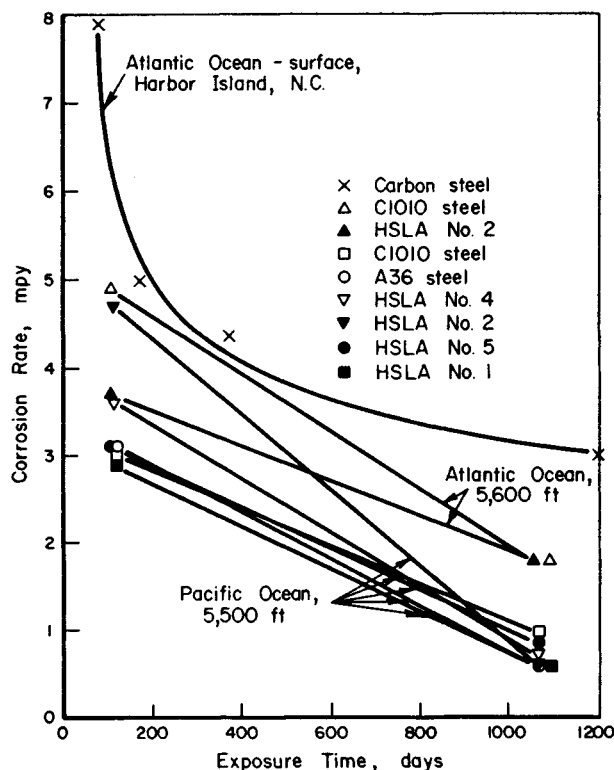


FIGURE 33. CORROSION RATES OF LOW ALLOY STEELS(1)

See Table 19 for compositions.

Stress-corrosion-cracking failures also have occurred. However, high-strength stainless steels, when correctly chosen, strengthened, and aged will perform well in marine atmospheres.

#### Atmosphere

In general, the three grades of stainless steels, namely, martensitic, ferritic, and austenitic, have good to excellent resistance in marine atmospheres. The austenitic grades are preferred because of their greater resistance to staining. At first, a superficial yellow stain develops, but after a few years it may become reddish in color. It can be readily removed with metal polish.

Corrosion rates for the austenitic grades are low, and pitting or crevice attack is not normally experienced in the atmosphere if simple precautions are taken.

A Type 304 panel exposed at the 800-foot lot at Kure Beach, N. C., corroded at a rate of less than 0.1 mpy. At the 80-foot lot, Type 304 panels showed somewhat more staining but negligible attack after 11 years. Type 316 panels have a higher order of resistance than Type 304 under the same exposure conditions. The results of 8-year atmospheric exposures at Cristobal, Canal Zone, for these stainless steels are compared in Figure 34. Note that the austenitic grades were free from pitting or weight loss.

TABLE 20. CORROSION OF WROUGHT IRON AND STEELS IN DEEP-OCEAN WATER WEST OF PORT HUENEME, CALIFORNIA(1)

Exposure	Wrought Iron	Carbon Steel	ASTM A36	Penetration, mpy				
				High-Strength Low-Alloy Steel				
				No. 1	No. 2	No. 3	No. 4	No. 5
2.9 yr at 5,300 ft	0.6(a)	0.8	0.6	0.6(a) (0.6)	0.5	0.7(a)	1.1(a) (0.7)	0.7(a) (0.8)
0.54 yr at 2,340 ft	2.0	1.5(a) (1.5)	1.7(a) (1.7)	1.4(a) (1.3)	1.4(a) (1.5)	—	—	1.4(a) (1.4)

(a) Sample showed crevice attack and, where measured, the amount of this attack is given in parentheses.

TABLE 21. CORROSION PENETRATION OF ALLOY STEELS IMMERSED IN THE PACIFIC OCEAN NEAR THE PANAMA CANAL ZONE AFTER 8 YEARS(19)

[See Table 17 for the Composition(19)]

Steel	Type	Mean Tide				Penetration, mils			
		1	2	3(b)	Ratio(a)	14 Ft. Below Surface			
						1	2	3(b)	Ratio(a)
A	Low carbon	23.2	40	65	1.7	25.5	66	86	2.6
D	Copper bearing	24.2	45	63	1.9	27.7	63	108	2.3
E	Ni (2%)	22.9	39	50	1.7	31.7	94	179	3.0
F	Ni (5%)	20.0	39	75	2.0	32.0	117	214	3.7
G	Cr (3%)	25.7	82	93	3.2	40.5	65	78	1.6
H	Cr (5%)	24.5	88	99	3.6	32.0	63	90	2.0
I	Low alloy (Cu-Ni)	39.7	70	134	1.8	26.4	82	152	3.2
J	Low alloy (Cu-Cr-Si)	21.1	47	54	2.2	43.2	80	175	1.8
K	Low alloy (Cu-Ni-Mn-Mo)	24.8	40	94	1.6	25.5	56	139	2.2
L	Low alloy (Cr-Ni-Mn)	20.5	39	50	1.9	43.9	97	259 (p)(c)	2.2

(a) Ratio of average of 20 deepest pits to weight-loss penetration. The higher the number, the greater is the pitting tendency in relation to the corrosion rate.

(b) 1 = calculated from weight loss

2 = average of 20 deepest pits

3 = deepest pit.

(c) p = completely perforated.

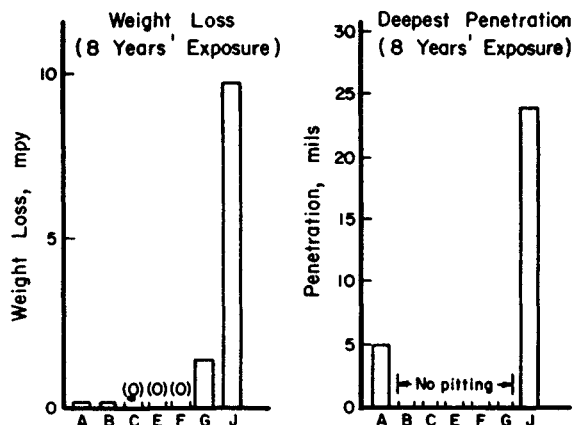


FIGURE 34. COMPARISON OF CORROSION DAMAGE OF STAINLESS STEEL, PHOSPHOR BRONZE, AND LOW-ALLOY STRUCTURAL STEEL IN TROPICAL MARINE ATMOSPHERE AT CRISTOBAL, CANAL ZONE(31)

A — Type 410 SS (13 Cr)

B — Type 430 SS (17 Cr)

C — Type 301 SS (17-7)

E — Type 316 SS (18-13 and Mo)

F — Type 321 SS (17-10 and Ti)

G — Phosphor Bronze

I — Low-alloy steel with Cu, Ni, Mn, Mo

The martensitic stainless steels, as typified by Type 410, may experience rust after only a few months of exposure to the marine atmosphere. Type 410 has the minimum chromium content (12 percent) required for passivity, and local breakdown may be experienced. The deepest pit on a panel exposed at Cristobal for 8 years was 5 mils (see Figure 34); however, the weight-loss penetration was only 0.007 mpy.

Type 430, a ferritic grade stainless steel, becomes rusted over part of its surface after a year or so. The higher chromium content (17 percent) as compared with Type 410, promotes greater resistance to pitting. The general corrosion attack at marine sites, such as at Cristobal, is barely measurable on a weight-loss basis.(31)

#### Splash

The stainless steels, as a group, usually do well in the splash zone. The availability of well-aerated seawater tends to maintain the passivity of stainless steels without difficulty, provided crevices and shielded areas are avoided in the design. Since the splash zone is above the point at which marine life develops on the metal surface, biofouling is not a factor.

As with atmospheric exposure, the austenitic grades are superior to the martensitic and ferritic grades.

The 300 series, particularly Types 304 and 316, have been used with success for small deck-mounted fittings for seagoing pleasure boats and other craft. Removal of sea-salt deposits by hosing with fresh water plus occasional polishing will keep such fittings in good condition.

When such deposits are allowed to accumulate, particularly at crevices, there is a tendency for local attack. This has been observed between the strands of stainless steel rope, in the threads of tensioning screws, and at the point where wire ropes enter swaged ferrules.

#### Tide

Even though the tide zone is well aerated a large part of the time, there are factors present in this environmental zone that interfere with the maintenance of passivity. Marine animals, such as barnacles and mollusks, as well as other types of fouling settle in the tide zone (and below) and shield the surface from the oxygen needed for passivity. Crevice attack at structural joints, etc., also is more apt to take place in the tide zone, where during the immersed portion of the day, relatively large areas outside the crevice are available to serve as cathodes. Furthermore, the time is too short in the tide zone for polarization to take place.

Of the stainless steels, only the austenitic grades are normally considered for seawater service. However, in the tide zone, the poor behavior is illustrated by results given in Table 22. After 8 years in the Pacific off the Canal Zone, weight-loss penetration for three austenitic stainless steels ranged from 0.02 (Type 316) to 0.11 (Type 304) mpy. The deepest penetration for the three alloys ranged from 30 to 110 mils in the same period.

#### Submerged

Special measures are required if stainless steels are to be employed, without failure, under immersed conditions in seawater. Either the surface must be maintained passive or cathodic protection must be applied.

A high flow rate of seawater by the surface brings passivating oxygen and promotes repair of breaks in the film. High velocities also keep the surface free of biofouling. On the other hand, cathodic protection is essential for corrosion control in quiet seawater, to prevent or eliminate the danger of crevice attack, pitting, tunnelling, edge corrosion, and all forms of selective attack.

TABLE 22. COMPREHENSIVE EVALUATION OF CORROSION DAMAGE OF STAINLESS STEELS, EXPOSED TO MARINE ENVIRONMENTS IN THE PANAMA CANAL ZONE(31)

Metal	Stainless Steel	Type of Exposure	Corrosion Rate, mpy			Average of 20 Deepest Pits(a), mil			Deepest Pit(a), mil			Loss in Tensile Strength(b), percent	Type of Corrosion Attack(c)
			1 Yr	4 Yr	8 Yr	1 Yr	4 Yr	8 Yr	1 Yr	4 Yr	8 Yr	4 Yr	4 Yr
A	Type 410 (13 Cr)	Seawater immersion	2.98	1.97	1.75	61(11)	148	161	260(p)	260(p)	259(p)	(d)	KQH
		Seawater mean tide	0.50	0.41	0.42	46	67	67	66	173	152	0	JKQ
		Seashore	0.040	0.013	0.005	0(0)	3	0(0)	0(0)	5	0(0)	0	KR
B	Type 430 (17 Cr)	Seashore	0.025	0.008	0.004	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	0	KR
C	Type 301 (17 Cr, 7 Ni)	Seashore	0.00	0.001	0.001	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	0	K
D	Type 302 (18 Cr, 8 Ni)	Seawater immersion	1.46	0.88	0.69	70(12)	107	140	261(p)	286(p)	236	(d)	KQ
		Seawater mean tide	0.18	0.12	0.11	7(13)	26	57	16	82	110	0	JK
E	Type 316 (18-13 and Mo)	Seawater immersion	0.59	0.07	0.25	44(7)	48	154	245(p)	93	245(p)	0	KQ
		Seawater mean tide	0.06	0.03	0.02	5(9)	7(12)	16	23	22	30	1	JK
		Seashore	0.00	0.00	0.00	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	1	K
F	Type 321 (17-10 and Ti)	Seawater immersion	1.16	0.81	0.62	64(8)	175	193	270(p)	273(p)	272(p)	(d)	KQ
		Seawater mean tide	0.13	0.08	0.08	8(11)	37	56	26	60	93	(d)	JKQ
		Seashore	0.005	0.001	0.001	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	1	K

(a) Pit depths referred to the original surface of the metal either by measurement from an uncorroded surface or by calculation using the original and final average measured thickness of the sample. Average of 20 deepest pits represents average of the 5 deepest pits measured on each side of duplicate specimens. (Area, 2.25 sq ft on immersed specimens, and 0.89 sq ft on atmospheric specimens); values in parentheses indicate total number averaged when less than 20 measurable pits. Perforation of plate by deepest pit is indicated by (p).

(b) Changes in tensile strength calculated on basis of 1/4-inch-thick metal coverage of 4 tests on immersed specimens, average of 3 tests on atmospheric specimens).

(c) H – concentration cell, J – marine fouling contact, K – no visible attack, Q – pitting attack (random), R – localized attack (random).

(d) Intensity and distribution of pitting prevented satisfactory tensile testing.

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Martensitic stainless steels cannot be effectively maintained in the passive conditions in seawater by either high velocity or cathodic protection. The ferritic stainless steels also are not amenable to these methods. Both the martensitic and ferritic alloys are susceptible to hydrogen damage resulting from the use of cathodic protection. For these reasons only the austenitic grades are usually specified for seawater service.

Other modes of failure include intergranular attack at the sensitized zone for some welded assemblies and stress-corrosion cracking. These types of failure can be readily avoided by selecting the proper alloy heat treatment or method of assembly.

An overall summary of the behavior of selected stainless steels in surface seawaters is presented in Table 23. While all grades of stainless steel are susceptible to pitting and crevice attack, those with higher alloy content usually are more resistant.

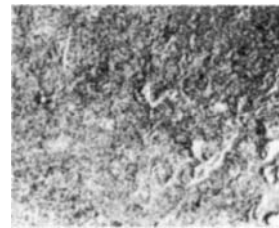
TABLE 23. SUMMARY OF THE BEHAVIOR OF REPRESENTATIVE STAINLESS STEELS IN SURFACE SEAWATER

Stainless Steel	Pitting and Crevice Attack	Cathodic Protection	High Velocity	Comments
Type 410 (martensitic)	Very susceptible	Not applicable (hydrogen damage)	Not used	Not suitable for immersed service
Type 430 (ferritic)	Susceptible, but longer induction period than Type 410	Not applicable (hydrogen damage)	Not used	Not suitable for immersed service
17-4 PH (martensitic precipitation hardening)	Susceptible	Effective for control of crevice and pitting	Good performance	Velocity must be continuous at approximately 5 fps or more to maintain passivation
Type 304 (austenitic)	Susceptible	Effective for control of crevice and pitting	Good performance	
Type 316 (austenitic)	Susceptible; pit initiation may be retarded, but attack, once started, often equals that for Type 304	Effective for control of crevice and pitting	Excellent performance	
Alloy 20 Cb (austenitic)	Less susceptible	Effective for control of crevice and pitting	Excellent performance	

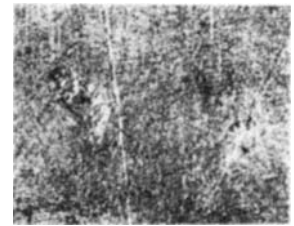
The austenitic grades, such as Type 304 and 316, are susceptible to pitting, as illustrated in Figure 35, and crevice attack. They will give satisfactory service if the passivity is maintained by a velocity of 5 fps or more. In quiet seawater, cathodic protection is essential to control pitting and crevice attack.

The addition of molybdenum may be of advantage in high-velocity service, such as a pump impeller. There is some indication that the molybdenum provides a longer induction period before pitting or crevice attack commences; that is, molybdenum additions decrease the probability of local attack. Thus, if Type 316 rather than Type 304 were used for the pump, in the example just cited, the passivity would normally take longer to break down during an emergency shutdown.

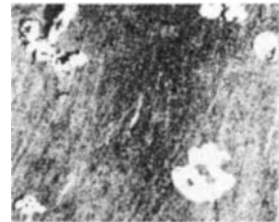
In shallow quiet water, Types 302, 321, and 316 showed high rates of local attack, as shown in Table 22. Deep-ocean experience for Types 304 and 316 was varied, but local attack often took place (see Table 24).



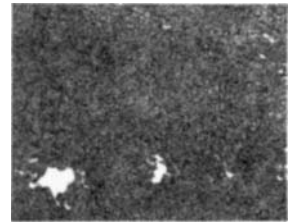
70/30 Copper - Nickel  
Deepest pit - 18 mils  
Avg pit depth - 10 mils



90/10 Copper - Nickel  
Deepest pit - 8 mils  
Avg pit depth - 4 mils



Type 316 Stainless Steel  
Deepest pit - 113 mils  
Avg pit depth - 72 mils



Type 304 Stainless Steel  
Deepest pit - 250 mils (perforated)

FIGURE 35. PITTING ATTACK ON PANELS IMMERSSED FOR 3 YEARS IN FLOWING SEAWATER AT LESS THAN 2 FPS AT WRIGHTSVILLE BEACH, NORTH CAROLINA  
Used with permission of International Nickel Company

Under these conditions some biofouling tends to develop on the stainless steels and, to a much lesser extent, on the cupronickels.(32)

TABLE 24. DEEP-OCEAN BEHAVIOR OF STAINLESS STEELS

Type	Depth(a)	Exposure Time, days	Crevice Attack, mils		Local Corrosion
			Water	Mud	
410	2,340	197	10	15	Edge and tunnel attack
	5,640	123	Slight	Slight	Severe tunnel
430	2,340	197	17	19	Tunnel
	5,300	1,064	25,97	40	Severe tunnel
304	2,340	197	11	Slight	Edge, tunnel
	5,300	1,064	21	29	None in water; tunnel in mud
304L	2,340	197	8	18	Tunnel
	5,300	1,064	27, perforated	0	Severe tunnel
316	2,340	197	0	0	None visible
	5,300	1,064	21,12	0	None
	5,640	123	0	0	Slight edge
316L	2,340	197	18	12	None visible
	5,300	1,064	25,8	20	Ditto
	5,640	123	Slight	Slight	"
Alloy 20 Cb	2,340	197	Slight	Slight	None visible; attack at wall of bolt hole
	5,300	1,064	0	-	None visible
	5,640	123	0	0	Ditto

(a) Oxygen level at 2,340 feet is 0.60 ppm; that at 5,300 feet is about 1.70 ppm.



Alloy 20Cb has been found superior to Types 304 and 316 in seawater service, particularly at high velocity. It also appears to have greater resistance to crevice attack in quiet seawater. However, as is the case with the entire 300 series, this alloy requires cathodic protection to control pitting and crevice attack under low-velocity conditions. In deep-ocean waters, the lack of corrosion at the crevice area and the absence of pitting was noteworthy (see Table 24). After 3 years at 5300 feet, no crevice attack was observed. It is likely, however, that if crevice specimens of different geometry were exposed a sufficiently long period, crevice attack would develop.

Type 410 stainless steel, as with the martensitic alloys in general, is not suitable for service immersed in seawater. Some form of severe local corrosion is apt to occur both in surface and deep-ocean waters. For example, panels 0.260 inch thick, were completely perforated after 1 year in the Pacific off the Panama Canal (see Table 22) although the corrosion, calculated from weight loss, was only 1.75 mpy. Type 410 panels also showed severe tunnel, edge, and crevice attack in the deep ocean (see Table 24).

At the present time, there does not appear to be a good method of controlling the corrosion attack for straight-chromium stainless steels under immersed conditions. High-velocity seawater is not effective for maintaining passivity. Cathodic protection at current densities necessary to achieve polarization tends to promote blistering or hydrogen cracking from the hydrogen generated.(33)

Type 430, a ferritic alloy, like the martensitic grades, is subject to local attack in seawater both in shallow and deep exposures. At Kure Beach, N.C., the maximum pit depth was 60 mils in 1.5 years.(4) In test exposures, occasional panels do well, i.e., are free of attack for the initial period. While the higher chromium content of Type 430 compared with Type 410 may account for longer induction period sometimes observed, it cannot be depended upon. In one side-by-side deep-ocean exposure, Type 430 was attacked similarly to Type 410 (see Table 24). Once attack has started, the rate of penetration may be extremely rapid. As with Type 410, neither high-velocity nor cathodic protection can be relied upon as a means of corrosion control. In view of this, Type 430 and other similar ferritic stainless steels cannot be recommended for the immersed conditions in seawater.

The 17-4 PH alloy is an example of the martensitic precipitation-hardening steels. If used with a heat treatment to provide moderate strength, e.g., with aging at 1025 F or above, 17-4 PH can be used effectively in seawater. As with the austenitic grades, this alloy will remain passive in high-velocity seawater. In quiet seawater, it can and should be provided with cathodic protection to control pitting and crevice attack. In general, corrosion experience has been favorable when the alloy is correctly applied.

## Mud

Bottom sediments vary some in composition and in marine activity. Sulfate-reducing bacteria have been identified in the mud zone. Since oxidizing agents are absent, one would expect stainless steels to lose passivity at local sites and, as a result, to undergo pitting and crevice attack. Such is actually the case. In most cases, as summarized in Table 24, the corrosion behavior in the mud zone (Pacific off California) is similar to that observed for the same alloy in the water just above the ocean bottom.

Bottom sediments at other areas may behave quite differently. Some of the sediments on the Atlantic floor are described as inert, and, when tightly compacted around a sample, might stop all attack.

## Crevice Attack and Pitting Corrosion

In the discussion, up to this point, the typical failure of stainless steels by pitting and crevice attack has been emphasized. Crevice attack or pitting usually starts out as a differential aeration cell. In the case of the crevice, for example, the slow diffusion of oxygen down into the crevice may not be sufficient to maintain passivity. The surface external to the crevice, with an ample supply of oxygen, becomes the cathode, whereas the active sites in the crevice become the local anodes.

The rate of crevice attack is related to the cathodic area available external to the crevice, and is also a function of the oxygen solubility. Wheatfall has demonstrated these relationships in experiments conducted in deep ocean and at the surface.(34) His results are presented in Figure 36. For each of three seawater oxygen levels, 0.60 ppm, 1.70 ppm, and 6.77 ppm, there was an increase in weight loss under the crevice as the area outside of the crevice, serving as the cathode, was enlarged.

For the highest oxygen level, the attack was an order of magnitude greater than that for the lowest oxygen level. When the depth of penetration was plotted versus the cathode area, the data were scattered, as might be expected. It is the weight loss, not penetration, which is a direct function of the current flowing.

From this experiment, it can be seen that reducing the area of the cathode is a method of corrosion control. One might, for example, paint the area external to the crevice.

Lennox, et al.(35) have reported the results shown in Figure 37. The local attack on stainless steel in surface seawater can be controlled effectively by coupling to an iron or an aluminum anode. Crevice corrosion was markedly reduced, but the slight random pitting, not associated with crevices, was only slightly improved.

## Stress-Corrosion Cracking of High-Strength Alloys

High-strength stainless steels are of particular interest to aircraft designers. Since many types of aircraft operate in marine atmospheres, the performance of these high-strength stainless materials with high tensile loading is of great importance. Alloys that can be strengthened to 150-ksi yield and higher are of most interest.

Depending on the grade, strengthening is accomplished by cold rolling, precipitation hardening, and/or phase changes. The four main grades are the austenitic, the semiaustenitic age hardenable, the martensitic age hardenable, and the martensitic.

The characteristic performance of each class in marine environments is discussed below.



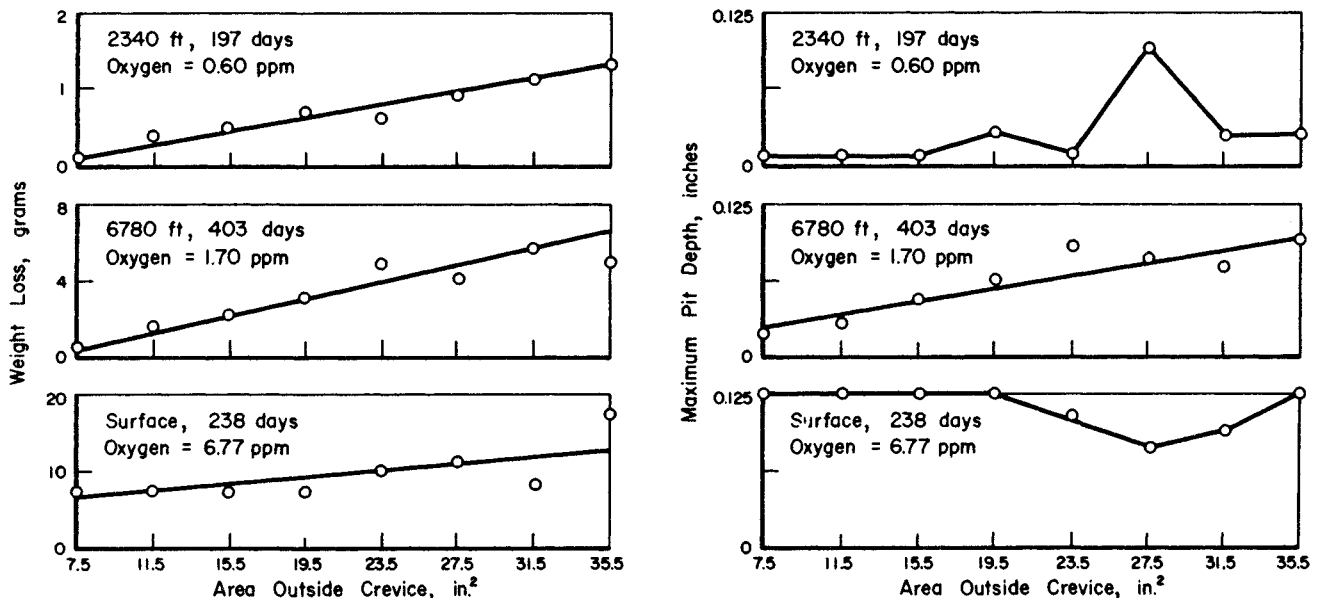


FIGURE 36. RELATION OF WEIGHT LOSS AND MAXIMUM PIT DEPTH IN THE CREVICE TO AREA OF SPECIMEN OUTSIDE THE CREVICE FOR TYPE 304 STAINLESS STEEL AT VARIOUS DEPTHS<sup>(34)</sup>

Used with permission of American Society of Naval Engineers  
(Specimen perforated at maximum pit depth = 0.125 inch.)

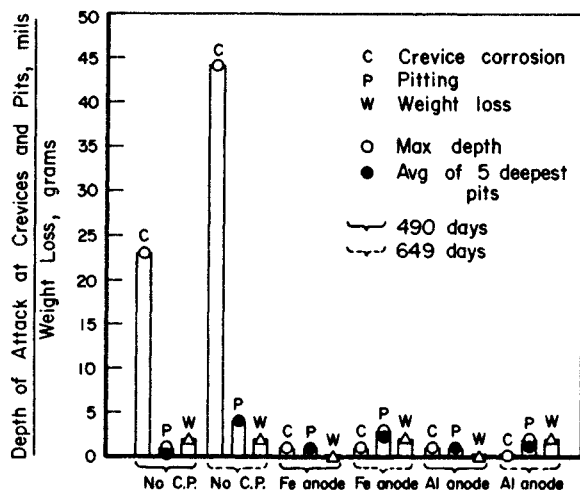


FIGURE 37. DEPTH OF ATTACK AND WEIGHT LOSS FOR TYPE 316 STAINLESS STEEL AFTER 490 AND 649 DAYS IN SEAWATER AT KEY WEST, FLORIDA, WITH AND WITHOUT CATHODIC PROTECTION<sup>(35)</sup>

**Austenitic.** High-strength austenitic stainless steels, as a class, are very resistant to marine atmospheres. They derive their high strength by cold work, which is usually followed by heat treatment to restore some ductility. In the cold-worked and annealed condition, they have remarkably good resistance to stress-corrosion cracking in aggressive marine atmospheres. This resistance, however, is lost at a joint made by welding. These steels will also fail at elevated temperatures, such as in the boiling 42 percent  $MgCl_2$  test and in hot seawater.<sup>(12)</sup> In

only a few cases have failures been reported for ambient temperatures. In the solution-annealed condition, the austenitic stainless steels are not susceptible to stress-corrosion cracking during marine environmental exposure at ambient temperature.<sup>(36)</sup> On the other hand, sensitized austenitic grades are susceptible to intergranular stress-corrosion cracking in marine atmospheres.

Of the austenitic stainless steels, that most frequently chosen for high-strength service is Type 301 (18Cr-7Ni). As shown in Table 25, test samples with an applied stress of 188 ksi showed no failure at the 80-foot lot in Kure Beach, N.C., for 6.7 years. High strengths also can be obtained with the 200 series alloys containing manganese, such as Types 201 and 202. Table 25 gives performance data for these two steels as well as for a proprietary type containing 15 weight percent manganese.

TABLE 25. BEHAVIOR OF STRESSED COLD-ROLLED AUSTENITIC STAINLESS STEELS IN THE MARINE ATMOSPHERES<sup>(a)(37,38)</sup>

Alloy	Cold Work	Heat Treatment <sup>(b)</sup> , F	Yield Stress, ksi	Applied Stress		Exposure Time <sup>(c)</sup> , days
				KSI	Percent of Yield Strength	
Type 201	60	1100	188	141	75	702 F, 2226 F
	60	800	229	171	75	2460 NF
Type 202	60	1100	187	164	87.5	678 F
	60	800	215	161	75	2460 NF
Type 301	40	1100	151	126	83	2460 NF
	40	800	231	188	81	2460 NF
	60	800	238	178	75	240 NF
	Extra hard	750	271	190	70	347 F(d)
18 Cr-15 Mn <sup>(e)</sup>	60	1100	221	197	88	2460 NF
	60	800	239	179	75	2460 NF

(a) Bent-beam specimens exposed at the 50-foot lot, Kure Beach, N. C.

(b) Heat treated for 2 hours at temperature indicated.

(c) F = failure; NF = no failure.

(d) One specimen out of eight failed; rest still OK at this time.

(e) Proprietary steel (USS Tenelon) containing small amounts of nickel and nitrogen.

(USS Tenelon). For certain combinations of cold rolling and heat treatment, samples of each of these alloys withstood applied tensile stresses ranging between 161 and 197 ksi for up to 6.7 years without stress-corrosion cracking. Some combinations of cold work and heat treatment resulted in failures. For example, Type 201 was cold worked to 60 percent and heat treated for 2 hours at 1100 F. An applied stress of 141 ksi (75 percent of yield) resulted in one failure at 702 days and another at 2,226 days.

In seawater, the cold-worked austenitic grade stainless steels, e.g., Type 301, seem to have a great tendency to local attack such as pitting. Cathodic protection is required if such local attack is to be avoided. Fortunately, the austenitic grades are not sensitive to hydrogen damage at the potentials required to control pitting. One would expect that by cathodically protecting suitably strengthened Type 301 parts they could be made to perform under stress with satisfaction in seawater equal to that obtained in the marine atmosphere.

**Precipitation Hardening.** The precipitation-hardening stainless steels may be subdivided into two groups: (1) martensitic and (2) semiaustenitic. They owe their great strength to the finely divided precipitate which develops on cooling from a supersaturated solution.

In Figure 38, Phelps(37) has summarized stress-corrosion behavior of these and other high-yield-strength steels in a marine atmosphere. Most of the failures for the precipitation-hardening types occurred during the first year in alloys which had been heat treated to yield strengths of 180 ksi or above (all samples were stressed to 75 percent of their yield strength). Even at these high stress levels, some coupons have not failed after more than 4 years' exposure.

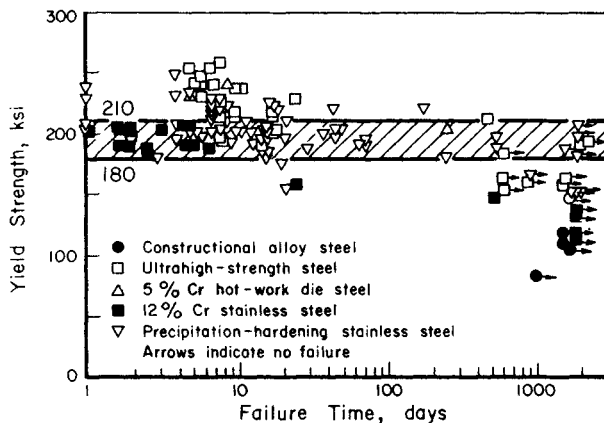


FIGURE 38. STRESS-CORROSION BEHAVIOR OF STEELS EXPOSED TO MARINE ATMOSPHERE AT 75 PERCENT OF YIELD STRENGTH(37)

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The precipitation-hardening stainless steels vary in their resistance to stress-corrosion cracking, depending on the treatment employed to obtain the desired strength. The martensitic type is hardened by heat treatment. Alloy 17-4 PH is one of the best known of this group. In the solution-treated and aged condition, a copper-rich phase precipitates which not only increases hardness but also marine resistance.

The martensitic-type 17-4 PH is found to be quite immune to stress-corrosion cracking if aged at 1000 F or above. Aging at 900 F makes the alloy susceptible to cracking in a marine atmosphere. Denhard reported no failure in more than 6.6 years for coupons (1) aged at 1025 F and given an applied stress of 140 ksi and (2) aged at 1150 F and given an applied stress of 105 ksi.(36)

Slunder,(38) in his DMIC review, presented the data for 17-4 PH shown in Table 26. The only failures at that time were for the 900 F heat treatment.

TABLE 26. STRESS-CORROSION-CRACKING RESULTS AT 80-FOOT LOT, KURE BEACH, FOR 17-4 PH ALLOY IN VARIOUS CONDITIONS OF TREATMENT(38)

Alloy and Condition	Applied Stress		Number of Specimens		Average Time to Failure, days	Exposure Time of Unfailed Specimens, days
	Percent of Yield Strength	KSI	Exposed	Failed		
Not Welded						
17-4 PH, H 900	90	162.9	5	0	—	322
	75	135.8	5	0	—	322
17-4 PH, H 1025	90	139.9	5	0	—	322
	75	116.6	5	0	—	322
17-4 PH, H 1075	90	135.7	5	0	—	322
	75	113.1	5	0	—	322
17-4 PH, H 1150	90	101.9	5	0	—	322
	75	84.9	5	0	—	322
17-4 PH, H 900	90		5	3	322	560
17-4 PH, H 1150	90		5	0	—	560
Welded, Then Solution Treated and Aged						
17-4 PH, H 900	90	164.3	5	5	68	—
	75	137.0	5	4	114	322
17-4 PH, H 1025	90	143.6	5	0	—	322
	75	119.7	5	0	—	322
17-4 PH, H 1075	90	138.4	5	0	—	322
	75	115.4	5	0	—	322
17-4 PH, H 1150	90	117.4	5	0	—	322
	75	97.8	5	0	—	322
Solution Treated, Welded, and Aged						
17-4 PH, H 900	90	164.7	5	5	20	—
	75	137.3	5	5	31	—
17-4 PH, H 1025	90	144.7	5	0	—	322
	75	120.6	5	0	—	322
17-4 PH, H 1075	90	135.0	5	0	—	322
	75	112.5	5	0	—	322
17-4 PH, H 1150	90	103.9	5	0	—	322
	75	86.6	5	0	—	322

This alloy has found application in aircraft exposed to the marine environment, and also in underwater service. Unlike ordinary martensitic steels, the 17-4 PH stainless can be provided with cathodic protection to control pitting and crevice attack in seawater. In addition to stress-corrosion-cracking resistance, it also has good corrosion fatigue properties. Thus, it finds application as shafts, hydrofoils, propellers for ice breakers, and various deck-located fittings, etc., where high-strength is desired along with corrosion resistance.

As judged by laboratory investigations, a newly developed alloy of the martensitic precipitation-hardening type (PH 13-8Mo) appears to have a higher order of resistance to stress-corrosion cracking in marine environments than has 17-4 PH.

The semiaustenitic-type stainless steels can be hardened by cold work followed by aging, or they can be given a thermal treatment to produce precipitation hardening. The stress-corrosion behavior is affected by the type of strengthening treatment employed.

In general, semiaustenitic precipitation-hardening alloys, with mechanical properties produced by thermal treatments show a behavior in marine atmospheres which is similar but somewhat superior to that of the martensitic stainless steels. When the strengthening is produced by cold working, the aged semiaustenitic alloys more closely resemble the austenitic stainless steels in their resistance to stress-corrosion cracking.

Some examples of the behavior of these steels are presented in Tables 27, 28, and 29. Heat treatments are described in Table 30. It should be mentioned that the 80-foot-rack at Kure Beach, N.C., represents a much more severe exposure than the 800-foot rack. Thus, the time to failure in Tables 27 and 28 cannot be compared directly with those in Table 29.

TABLE 27. STRESS-CORROSION-CRACKING BEHAVIOR AT THE 80-FOOT RACK, KURE BEACH, N. C., FOR SEMIAUSTENITIC PRECIPITATION – HARDENING STAINLESS STEELS(38)

Alloy and Condition	Applied Stress		Number of Specimens		Average Time to Failure, days	Exposure Time of Unfailed Specimens, days	Direction
	Percent of Yield Strength	KSI	Exposed	Failed			
PH 15-7Mo, TH 1050	75	140	12	9	16	240	Longitudinal
	60	127	5	5	182	—	Transverse
	60	125	5	4	73	466	Transverse
	60	124	5	2	71	466	Transverse
	40	85	5	0	—	466	Transverse
	40	84	5	0	—	466	Transverse
	40	82	5	0	—	466	Transverse
	40	82	5	0	—	466	Transverse
PH 15-7Mo, RH 950	90	182	—	—	12(a)	—	Longitudinal
	75	152	12	12	16	—	Longitudinal
	50	101	—	0(a)	—	175	Longitudinal
	60	131	5	5	28.2	—	Transverse
	60	132	5	5	22.2	—	Transverse
	60	131	5	5	19	—	Transverse
	40	87	5	4	173	466	Transverse
	40	88	5	4	74	466	Transverse
	40	87	5	1	82	466	Transverse
PH 15-7Mo, RH 1050	60	131	5	4	140	466	Transverse
	60	129	5	4	339	466	Transverse
	40	88	5	0	—	466	Transverse
	40	86	5	0	—	466	Transverse
PH 15-7Mo, BCHT	60	140	5	5	24.2	—	Transverse
	60	140	5	5	44.2	—	Transverse
	40	93	5	5	49.6	—	Transverse
	40	94	5	5	61.6	—	Transverse
17-7 PH, TH 1050	75	110	27	7	21	320	Longitudinal
17-7 PH, TH 950	90	181	—	—	1(a)	—	Longitudinal
	75	151	4	4	1	—	Longitudinal
	50	101	—	—	5(a)	—	Longitudinal
17-7 PH, RH 950	90	183	—	—	2(a)	—	Longitudinal
	75	152	30	21	5	380	Longitudinal
	50	102	—	—	16(a)	—	Longitudinal
AM 355, CRT 850	10	23.8	2	0	—	68	Longitudinal
	35	83.4	2	0	—	321	Longitudinal
	50	119.1	2	2	66	—	Longitudinal
	70	166.8	2	2	112	—	Longitudinal
	35	73.4	2	0	—	321	Longitudinal
	50	104.8	2	0	—	321	Longitudinal
	70	146.8	2	0	—	321	Longitudinal
	70	146.8	2	0	—	321	Longitudinal
AM 355, SCCRT 850	10	30.4	2	0	—	68	Longitudinal
	35	106.4	2	0	—	461	Longitudinal
	50	152.0	2	1	319	461	Longitudinal
	70	212.8	2	2	21	—	Longitudinal

(a) Average of three or more specimens.

TABLE 28. RESULTS OF EXPOSURE AT 80-FOOT LOT, KURE BEACH, N. C., FOR SEMIAUSTENITIC PRECIPITATION-HARDENING STAINLESS STEELS(36)

Alloy	Condition	Yield Stress, ksi	Applied Stress, ksi	Time to Failure, days	Test Direction(a)
17-7 PH	RH 950	203	181	1	L
PH 15-7Mo	RH 950	202	182	12	L
PH 14-8Mo	SRH 950	202	182	100	T

(a) L = longitudinal coupons

T = transverse coupons

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TABLE 29. STRESS-CORROSION-CRACKING PERFORMANCE AT THE 800-FOOT RACK, KURE BEACH, N. C., FOR SEMIAUSTENITIC PRECIPITATION-HARDENING STAINLESS STEELS(38)

Alloy and Condition	Applied Stress		Number of Specimens		Average Time to Failure, days	Exposure Time of Unfailed Specimens, days	Direction
	Percent of Yield Strength	KSI	Exposed	Failed			
PH 15-7Mo, TH 1050	75	161	5	3	103	746	Transverse
	75	164	5	5	39.8	—	Transverse
	60	127	5	0	—	466	Transverse
	60	125	5	0	—	466	Transverse
	60	124	5	0	—	466	Transverse
	50	107	5	0	—	746	Transverse
	50	109	5	0	—	746	Transverse
	40	85	5	0	—	466	Transverse
	40	84	5	0	—	466	Transverse
	40	82	5	0	—	466	Transverse
PH 15-7Mo, RH 1050	60	131	5	0	—	466	Transverse
	60	129	5	0	—	466	Transverse
	40	88	5	0	—	466	Transverse
PH 15-7Mo, RH 950	75	174	5	5	68.8	—	Transverse
	75	175	5	5	14.2	—	Transverse
	60	131	5	4	179	466	Transverse
	60	132	5	4	126	466	Transverse
	60	131	5	4	164	466	Transverse
	50	116	5	5	169.4	—	Transverse
	50	117	5	5	98.8	—	Transverse
	40	87	5	1	346	466	Transverse
	40	88	5	0	—	466	Transverse
	40	87	5	0	—	466	Transverse
PH 15-7Mo, BCHT	60	140	5	5	236.2	—	Transverse
	60	140	5	5	101.4	—	Transverse
	40	93	5	0	—	466	Transverse
	40	94	5	3	333	466	Transverse
PH 15-7Mo, CH 900	75	196	5	0	—	746	Transverse
	50	131	5	0	—	746	Transverse
17-7 PH, TH 1050	75	151	5	2	100	746	Transverse
	75	134	5	0	—	746	Transverse
	50	101	5	0	—	746	Transverse
	50	89	5	0	—	746	Transverse
17-7 PH, RH 950	75	168	5	5	7.4	—	Transverse
	75	165	5	5	51.6	—	Transverse
	50	112	5	5	30.2	—	Transverse
	50	110	5	1	116.	746	Transverse
17-7 PH, CH 900	75	214	5	0	—	746	Transverse
	50	143	5	0	—	746	Transverse
AM 355, CRT 850	10	23.8	2	0	—	68	Longitudinal
	35	83.4	2	0	—	321	Longitudinal
	50	119.1	2	0	—	321	Longitudinal
	70	166.8	2	2	152	—	Longitudinal
AM 355, CRT 850	35	73.4	2	0	—	321	Longitudinal
	50	104.8	2	0	—	321	Longitudinal
	70	146.8	2	1	177	321	Longitudinal
AM 355, SCCRT 850	10	30.4	2	0	—	68	Longitudinal
	35	106.4	2	0	—	461	Longitudinal
	50	152.0	2	0	—	461	Longitudinal
	70	212.8	2	0	—	461	Longitudinal

TABLE 30. HEAT TREATMENT OF THE SEMIAUSTENITIC PRECIPITATION-HARDENABLE STAINLESS STEELS(38)

Alloy	Condition	Austenite Conditioning		Transformation	Age or Temper	
		Temperature, F	Time, minutes		Temperature, F	Time, hours
17-7 PH	TH 1050	1400	90	Cool to 60 F within 1 hr, hold 30 min	1050	1-1/2
	TH 950	1400	90	Cool to 60 F within 1 hr, hold 30 min	950	1-1/2
	RH 950	1750	10	Hold 8 hr at -100 F	950	1
	TH 1075	1400	90	Cool to 32-60 F within 1 hr, hold 30 min	1075	1-1/2
	TH 1050	1400	90	Cool to 60 F within 1 hr, hold 30 min	1050	1-1/2
	RH 950	1750	10	Hold 8 hr at -100 F	950	1
	CH 900	—	—	Cold rolled at mill	900	1
PH 15-7Mo	TH 1050	1400	90	Cool to 60 F within 1 hr, hold 30 min	1050	1-1/2
	RH 950	1750	10	Hold 8 hr at -100 F	950	1
	RH 950	1750	20	Hold 5 hr at -110 F	950	1
	BCHT	1625	20	Cool to 1000 F in 45 min, air cool to room temp, 5 hr at -100 F	900	8
	TH 1050	1400	90	Cool to 60 F within 1 hr, hold 30 min	1050	1-1/2
	RH 950	1750	10	Hold 8 hr at -100 F	950	1
	CH 900	—	—	Cold rolled at mill	900	1
	BCHT	1675	20	Cool to 1000 F in 45 min, cool to room temp, 8 hr at -100 F	900	24
AM 350	SCT 850	1710	20	3 hr at -110 F	850	3
	BCHT	1675	20	Cool to 1000 F in 45 min, cool to room temp, 8 hr at -100 F	900	24
AM 355	SCT 850	1710	20	3 hr at -110 F	850	3
	BCHT	1675	20	Cool to 1000 F in 45 min, cool to room temp, 8 hr at -100 F	900	24
	CRT 850	—	—	Cold rolled	850	—
	SCCRT 850	—	—	Subzero cooled, cold rolled	850	—

As shown in Table 27, specimens of 17-7 PH in three types of heat treatments and at applied stresses ranging from 101 to 183 ksi showed failure at the 80-foot rack in 1 to 21 days. Not all samples had failed in the period reported. Seven out of 27 specimens stressed to 116 ksi failed, whereas the other 20 were still alright after 320 days. At the 800-foot rack, samples in the CH 900 treatment did not fail in 746 days and gave superior performance to samples of the same alloy in two other conditions (see Table 29). These results suggest that this alloy, as strengthened by cold rolling, is much more resistant to stress-corrosion cracking. Note also that none of the thermal treatments produce such high yield strengths as is the case when this alloy is cold rolled, e.g., 270 ksi for CH 900 and 217 ksi for RH 950.

Although not evident from the data presented in Tables 27 and 29, more recent experience indicates that PH 15-7Mo is more resistant, on a comparable basis, to stress-corrosion cracking in the marine atmosphere than is 17-7 PH. Although the TH condition is more resistant than the RH, the CH treatment is preferred in the PH 15-7Mo alloy for highest strength, e.g., 200 ksi or more.(36)

A relatively new alloy of the semiaustenitic type, PH 14-8Mo, exhibits superior resistance to both the 17-7 PH and PH 15-7Mo alloys to stress-corrosion cracking in the marine atmosphere. As shown in Table 28, no failures occurred in PH 14-8Mo specimens exposed for 1100 days (more than 3 years), whereas the 17-7 PH and PH 15-7Mo failed in only a few days.(36) All the alloys were heat treated to develop comparable strength levels.

AM 355, which resembles 17-7 PH and PH 15-7Mo in the CRT 850 treatment, withstood more than 321 days at the 80-foot rack at Kure Beach with 146.8-ksi applied stress.

**Martensitic Straight Chromium Stainless Steels.** Martensitic stainless steels are susceptible to stress-corrosion cracking in marine atmospheres. The degree of susceptibility varies with alloy content and/or variations in the thermal treatment used to develop their high strength.

Martensitic stainless steels, tempered between 650 F and 1000 F, are quite sensitive to stress-corrosion cracking. A stress relief below 650 F often is beneficial, but for marine service, tempering above 1000 F gives better results.(36)

Phelps, in a summary of his results presented in Figure 38, shows the stress-corrosion cracking behavior of the 12 percent chromium, high-yield-strength stainless steel.(37) This alloy is representative of the martensitic stainless group under discussion. Each point on the chart represents the average time to failure for five or more specimens. While a few failures are noted in the yield-strength range of 150 to 180 ksi, the great majority of the failures occurred above 180 ksi.

#### Nickel and Nickel-Base Alloys

Nickel is resistant to marine atmospheres.(39) Its performance in seawater on the other hand, is variable. Passivity can be maintained in flowing seawater, but in quiet seawater nickel tends to lose its passive film at local sites and pitting ensues.(40)



The main contribution of nickel in the marine field is as an alloying constituent. A series of alloys with copper, including Monel-400 and the cupronickels, are all resistant to marine environments and find extensive use.

Nickel-rich iron alloys behave much like nickel, and are not outstanding in their resistance to marine environments.

The nickel-chrome alloys, such as Inconel 600 with 15 percent chromium, are very resistant to the marine atmosphere. As with austenitic stainless steels, the nickel-chrome alloys are susceptible to local attack such as pitting under immersed conditions.

Among the most resistant metals available for seawater service are nickel-base alloys containing large percentages of molybdenum and chromium. These alloys, of which Hastelloy C is the best known, are completely resistant to all common marine environments.

### Atmosphere

Nickel. Nickel corrodes at rates of the order of 0.01 mpy or less in the marine atmosphere.<sup>(39,41)</sup> Its main useful field of application is not as a structural metal but as a coating, such as an electroplate. Specially tailored combinations of electrodeposits of copper, nickel, and chromium provide years of economical protection to steel or zinc-base die castings exposed to marine atmospheres.

Nickel panels have been exposed to the marine atmosphere to establish rates of penetration. At the 80-foot lot in Kure Beach, N.C., the weight-loss penetration for a 7-year exposure was 0.0095 mpy and the deepest pit was 1.4 mils.<sup>(41)</sup> At Cristobal, Canal Zone, the rate for 16 years' exposure was 0.0075 mpy with negligible pitting.<sup>(40)</sup> These examples with nickel sheet confirm the good experience with nickel coatings. The resistance of nickel to marine atmospheres is of the same order as that found for rural atmospheres.<sup>(42)</sup> Compare, for example, the results of ASTM exposures, as reported by Copson<sup>(39)</sup> in Table 31. Note also the effect on nickel when the marine atmosphere becomes polluted, as at Sandy Hook. The corrosion rate at this marine site near New York is an order of magnitude higher than that at unpolluted marine sites and reflects the presence of sulfur products in the atmosphere.

TABLE 31. ATMOSPHERIC CORROSION BEHAVIOR OF NICKEL AND MONEL-400 AFTER 10 AND 20 YEARS IN THE MARINE ATMOSPHERE<sup>(39)</sup>

Metal	Site	Corrosion Rate, mpy		Exposure
		10 years	20 years	
Nickel	Key West, Florida	.0050	.0041	Marine
	La Jolla, California	.0047	.0056	Marine
	State College, Pennsylvania	.0066	.0085	Rural
	Sandy Hook, N. J.	.0313	—	Polluted marine
Monel-400	Key West, Florida	.0065	.0045	Marine
	La Jolla, California	.0077	.0064	Marine
	State College, Pennsylvania	.0050	.0067	Rural
	Sandy Hook, N. J.	.0266	—	Polluted marine

Nickel-Copper. Typical alloys in the nickel-copper series contain 60 to 70 percent nickel, up to 2 percent iron, and around 1 percent or less manganese, with the remainder copper. The best known and most widely used in the marine field is Monel-400. Another alloy, Monel-K500, is a harder composition by virtue of the 2.8 percent aluminum addition.

The nickel-copper alloys, as typified by Monel-400, have good resistance to marine atmospheres, although they will tarnish and show weathering.<sup>(4)</sup> For example, after 7 years at Kure Beach, N.C., a light green patina, darker at the edges of the panel, had developed on Monel-400.<sup>(41)</sup> These specimens show low rates of corrosion, e.g., 0.014 mpy after 7 years at Kure Beach<sup>(41)</sup> and after 16 years at Cristobal.<sup>(40)</sup> The rates at the ASTM sites shown in Table 31 are even lower than those mentioned above.

This good behavior is borne out by experience. Monel-400 has given years of excellent service as a material of construction in marine applications, such as deck-mounted fittings, corrosion racks, etc.

Monel-400, like stainless steels, is susceptible to oxygen-concentration-cell corrosion. Thus, crevices and other areas where sea-salt solutions may be trapped and set up local cells should be avoided in designing.

Nickel-Chromium. The nickel-base group of alloys known as the Inconels owe their excellent resistance to corrosion primarily to the presence of 15 to 22 percent chromium. The compositions for a variety of these and other nickel alloys are grouped according to their relative corrosion behavior in Table 32.

The performance of Inconel 600 is typical of what can be expected from this compositional range. At the 80-foot lot at Kure Beach, a corrosion rate, calculated from weight loss, of 0.0016 mpy was obtained after 7 years, with a maximum pit depth of 1.3 mils.<sup>(41)</sup>

TABLE 32. CLASSIFICATION OF NICKEL ALLOYS WHICH MAY FIND SPECIAL APPLICATION IN MARINE ENVIRONMENTS

Alloy	Composition, weight percent	Remarks
<u>Class I. Most Resistant</u>		
Hastelloy C	57Ni-16Cr-17Mo-plus Fe, W, Co	Completely resistant except at welds
Hastelloy C-276	57Ni-16Cr-17Mo-plus Fe, W, Co	Low carbon (<0.02 C) can be welded
Inconel 625	61Ni-22Cr-9Mo plus Fe, Cb	Approaches Hastelloy C in total resistance
MP35N	35Ni-35Co-20Cr-10Mo	Excellent, so far, in preliminary experiments
Chlorimet-3	60Ni-18Cr-18Mo plus Fe, Si	Cast alloy; excellent for pumps, etc.
Rene 41	56Ni-11Co-19Cr-10Mo-3.1Ti	Good-to-excellent resistance to pitting
Hastelloy X	52Ni-22Cr-9Mo-19Fe plus W, Co	Ditto
<u>Class II. Very Resistant</u>		
Hastelloy F	46Ni-22Cr-7Mo-21Fe	Usually satisfactory; molybdenum content provides resistance to pitting
Hastelloy G	45Ni-21Cr-7Mo-20Fe-2Cu-2.5Co	
Illium R	68Ni-21Cr-5Mo-3Cu	
Inconel 700	46Ni-28Co-15Cr-4Mo plus Ti, Al	
Elgiloy	15Ni-40Co-20Cr-7Mo-15Fe-2Mo	
Inconel 718	53Ni-19Cr-3Mo-18Fe plus Co, Ti, Al	
<u>Class III. Resistant, Some Pitting</u>		
Inconel 600	76Ni-16Cr-7Fe	May be some pitting at sites where seawater is stagnant
Inconel X750	73Ni-15Cr-7Fe plus Cb, Ti, Al	
Incoloy 800	32Ni-21Cr-46Fe	
Incoloy 815	42Ni-22Cr-30Fe-3Mo-2Cu	
Monel-400	66Ni-32Cu-2Fe	
Monel-K500	65Ni-30Cu-1Fe-3Al	



Nickel-Chromium-Iron. Nickel-rich iron alloys containing about 30 to 45 percent nickel, 20 to 30 percent chromium, and iron are much more passive than nickel and are very resistant to marine atmospheres. The combination of these amounts of nickel and chromium increases the range of conditions in which these alloys will remain passive. In marine atmospheres contaminated by industrial pollution, i.e., sulfur compounds, some tarnishing may occur but the corrosion attack should be insignificant.

After 7 years at Kure Beach, N.C., panels of Incoloy 800 and Incoloy 825 at the 80-foot lot showed weight-loss penetrations of only 0.006 mpy. The deepest pits were 0.9 and 0.7 mil, respectively.(42) Because of other experience, one might expect the 3.0 percent molybdenum content of Incoloy 825 to confer some benefit. This alloy tends to remain bright longer than the molybdenum-free Incoloy 800 in marine exposures. However, on prolonged exposure, both alloys tend to develop a thin rust stain, usually in association with edges or minor pits.(41)

Nickel-Chromium-Molybdenum. The nickel-base alloys listed in Table 32 with 16 to 22 percent chromium and 9 to 18 percent molybdenum are the most resistant of the structural metals to all known marine environments in general. The titanium-base metals alone have comparable resistance.

Alloys of this type now in common use include Hastelloy C, Hastelloy C-276, Inconel 625, and Chlorimet-3 (casting alloy). All have outstandingly good resistance to the marine atmosphere. For example, a Hastelloy C mirror is still bright and shiny after about 20 years' exposure at Kure Beach. Where the cost can be justified, any of these alloys will provide corrosion-free performance in marine atmospheres.

The composition and general performance of another series of nickel-bearing alloys with high chromium and molybdenum contents are also presented in Table 32. Early reports

for the new alloy, MP35N, indicate it to be equal to Hastelloy C in marine performance. It should be mentioned that it is not susceptible to stress-corrosion cracking. Illium R and Elgiloy also are corrosion-free in marine atmospheres.

### Splash

As mentioned earlier, nickel and its alloys require well-aerated conditions to maintain the surface passive. In the splash zone these requirements are readily met. Frequent splashing will keep even the Class III alloys of Table 32 passive, as long as the surface is clean and free of deposits and pockets where seawater can collect. This usually can be accomplished by proper design, and is facilitated by the fact that no biofouling takes place in the splash zone.

### Tide

Nickel alloys will become covered with marine fouling, such as barnacles and shell fish, in the tide zone and below. Thus, passivity is difficult to maintain on nickel, the nickel-copper, nickel-chromium-iron, and the nickel-chromium alloys. The nickel-chromium-molybdenum alloys, however, will remain passive in spite of the biofouling at the tide zone.

Half-tide behavior, reported for nickel and Monel-400 in the Pacific Ocean off the Panama Canal Zone, is summarized in Table 33. After 16 years, nickel showed a weight-loss penetration of only 0.27 mpy. However, the maximum pit penetration was 121 mils, and the pits were wide and deep. Thus, nickel has no particular advantage as a cladding or plating material in this exposure environment.

TABLE 33. CORROSION OF NICKEL AND MONEL-400 IN MARINE ENVIRONMENTS AT PANAMA CANAL ZONE(40)

Metal	Exposure	Weight-Loss			Depth of Pitting, mils						Type of Corrosion Attack <sup>(b)</sup>
		Penetration, mpy			Avg of 20 Deepest <sup>(a)</sup>			Deepest Penetration			
		1 Yr	4 Yr	16 Yr	1 Yr	4 Yr	16 Yr	1 Yr	4 Yr	16 Yr	
Nickel (99%)	Seawater										
	Immersion	2.40	1.30	1.21	125	121	142	245	248	249	JQHK
	Mean tide	0.35	0.33	0.27	(0)	47	61	0	105	121	JQ
	Atmospheric Marine	0.01	0.01	<0.01	(0)	(0)	(0)	0	0	0	K
Monel-400 (cold rolled)	Seawater										
	Immersion	1.64	1.04	0.54	17	27	33	42	41	55	RJ
	Mean tide	0.10	0.12	0.17	(0)	(0)	14	0	00	21	JR
	Atmospheric Marine	0.04	0.02	0.01	(0)	(0)	(0)	0	0	0	AK
Monel-400 (hot rolled)	Seawater										
	Immersion	2.09	1.01	0.52	43	53	56	90	82	80	RJ
	Mean tide	0.11	0.18	0.16	(0)	16(15)	24	0	20	36	JR

(a) Numbers in parentheses indicate number of measurable pits when less than 20. A measurable pit is >5 mils.

(b) A – uniform attack, H – concentration cell, J – fouling contact, K – no visible attack, Q – pitting (randomly distributed), R – local attack (randomly located).

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Monel-400 showed a weight-loss penetration of 0.17 mpy and a maximum pit depth of 24 mils during the 16-year period. It is evident that the copper addition has provided some improvement in pitting resistance over that of nickel. General experience indicates that the pit depth on Monel-400 rarely exceeds 50 mils in the tide zone. Pits develop slowly and do not increase appreciably in depth after the eighth year. Cupronickels, which are discussed elsewhere, are more resistant in this environment and tend to show only slight pitting in the same exposure condition.

Monel-400 has been used with success as a cladding over steel to protect piling at the tide-splash zone area of off-shore structures. An allowance for corrosion of, say, 50 mils would be desirable in view of the pitting that will take place.

At the half-tide exposure, nickel-chromium and nickel-chromium-iron alloys will tend to show pitting and other forms of local attack.<sup>(40)</sup> As with stainless steels, the areas under fouling such as barnacles and at crevices are subject to attack. However, as a class, these alloys are somewhat more resistant than the austenitic grades of stainless steel.

Alloys in the nickel-chromium-molybdenum group, as represented by Hastelloy C, have outstanding resistance to the tide-zone environmental conditions. Since the alloys listed as Class I in Table 32 are particularly resistant to the attack of the chloride ion, they could be used in the half-tide zone under conditions where no corrosion at all could be tolerated.

#### Submerged

Nickel can be maintained passive under immersed conditions in rapidly flowing seawater. Corrosion rates range up to 5 mpy.<sup>(4)</sup> In quiet seawater, nickel becomes covered with bio-fouling and passivity is lost under these deposits as well as at crevices. As shown in Table 33, nickel exhibited a weight-loss penetration of 1.21 mpy after 16 years in the Pacific.<sup>(40)</sup> Panels 0.250 inch thick were completely perforated by local pitting as early as the first year. In deep-ocean exposures, weight-loss penetrations varied from <0.1 to 1.8 mpy.<sup>(43)</sup> Crevice attack tended to cause perforation for exposures as short as 197 days. There was very little general surface corrosion, practically all of it being pitting. The edge penetration also observed was attributed to microcracks formed during the shearing of the panels.

From this discussion it is evident that nickel, itself, does not have good resistance to seawater, especially under low-velocity conditions. Should it become desirable to use nickel in a seawater application, cathodic protection could be applied with a sacrificial metal such as zinc. Pitting corrosion can be controlled by the application of sufficient cathodic current to polarize the nickel surface.

Nickel-Copper. In high-velocity applications, the nickel copper alloys as represented by Monel-400 and Monel-K500 have excellent resistance to seawater. Passivity can be maintained, and the water motion tends to prevent fouling. Results of hydrofoil tests are presented in Table 34 which shows that both of these Monel alloys are greatly superior to copper-base alloys and steels.

TABLE 34. HIGH-VELOCITY SEAWATER IMPINGEMENT(a)

Velocity	135 fps (91 mph)	
Duration	30 days	
Exposed Area	3.5 sq in.	
Material	Weight Loss, grams	Corrosion Rate, mpy
Inconel 718	0.007	0.2
Inconel X-750	0.008	0.2
Inconel 600	0.010	0.3
Incoloy 825	0.011	0.3
Monel-400	0.016	0.4
Monel-K500	0.017	0.4
Ni-Al bronze	1.223	31
Naval brass	1.676	42
HY-80 steel	2.113	57
Medium C steel	6.518	176
High-tensile steel	8.167	220
Cast iron(b)	6.788	600

- (a) Data provided by The International Nickel Co., New York, N. Y.  
 (b) In test only 10 days.

On the other hand, in quiet seawater, Monel-400, Monel-K500, and similar alloys have a tendency to pit or to experience local attack at screened areas. For example, in Pacific surface-seawater tests, Monel-400 showed a weight-loss penetration of only 0.54 mpy after 16 years and only 0.29 mpy during the last 8 years. However, during the 16-year exposure, pits up to 56 and 80 mils deep were encountered on samples of cold-rolled and hot-rolled panels, respectively.<sup>(40)</sup> As shown in Figure 39, most of the pitting takes place during the first year after which the pits tend to spread out rather than deepen.

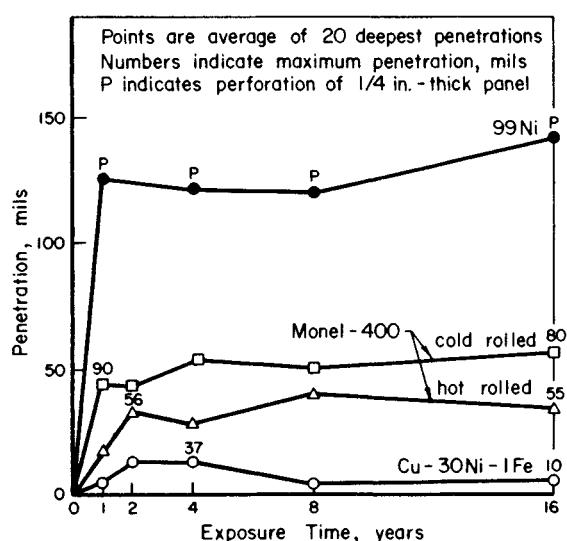


FIGURE 39. PITTING BEHAVIOR OF NICKEL, MONEL, AND 70Cu-30Ni-1Fe ALLOY IMMERSSED IN PACIFIC SEAWATER FOR 16 YEARS<sup>(40)</sup>

A comparison of a few other well-known metals with Monel-400 is shown in Figure 40. From the standpoint of weight-loss penetration, Monel-400 corrodes at about the same order of magnitude as zinc. The 6061 aluminum alloy shows much less attack, but experiences deeper pits in the same exposure.(40) Cupronickel and aluminum bronze are found superior to Monel-400 in respect to both pitting and weight-loss penetration. Corrosion rates in quiet seawater for Monel and stainless steel are compared in Table 35. Note that the pits on the Monel alloys are broader and less deep. Monel was less susceptible to crevice attack than were the stainless steels.

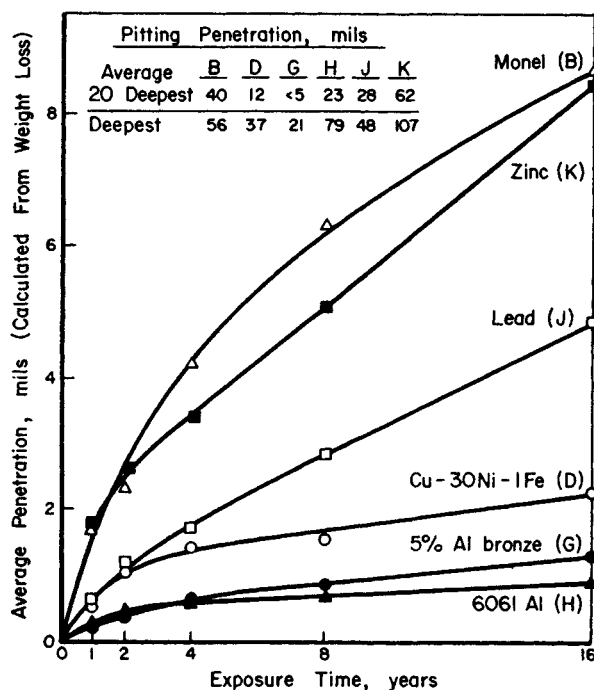


FIGURE 40. COMPARISON OF VARIOUS METALS AFTER 16 YEARS' IMMERSION IN LOW-VELOCITY PACIFIC SEAWATER OFF THE PANAMA CANAL(40)

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As shown in Figure 41, the weight-loss penetration of Monel-400 in deep-ocean environments, is typically about 1 mpy or less. However, Monel-400 is subject to severe pitting attack in the deep ocean, as illustrated in Figure 42. Under these conditions, the weight-loss penetration typically ranged from 0.3 to 1.1 mpy and crevice attack ranged from negligible to complete perforation or 125 mils.(43)

To control the tendency for pitting in quiet seawater, it would be desirable to provide cathodic protection, as by galvanically coupling a Monel item to a large steel surface. As with nickel, if impressed current is used, it may be necessary to polarize just to the pitting potential, since the general corrosion is not excessive.

Monel-400 and Monel-K500 are used mainly in high-velocity applications in the immersed condition. These applications include such items as pump impellers and small propellers.

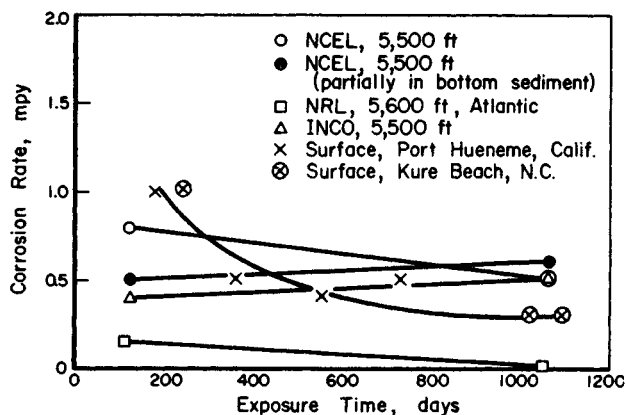


FIGURE 41. CORROSION OF MONEL-400 ALLOY IMMERSSED IN SEAWATER AT SHALLOW AND DEEP OCEAN SITES(1)

**Nickel-Chromium-Molybdenum.** Before discussing the individual alloys for which information is available, one can cite some general effects of alloy composition on the corrosion behavior of nickel-chromium-molybdenum alloys. Nickel, itself, is prone to pitting. When chromium is added to nickel, as represented by the 80Ni-20Cr composition (Nichrome) or by Inconel 600, the passive film is strengthened greatly but not sufficiently to prevent crevice and pitting attack in seawater. Thus, the nickel-chrome and nickel-chrome-iron compositions can be used in seawater only where the velocity will be such as to maintain the passive film or if cathodic protection is used. In general, these alloys are much more resistant to local attack than nickel; local breakdown may take years to develop under some conditions.

When molybdenum is added to nickel, the tendency to local attack is virtually eliminated, as is the case with Hastelloy B (which contains 28 percent molybdenum and 5 percent iron). When the nickel is modified with suitable amounts of both chromium and molybdenum, the extremely good resistance of such alloys as Hastelloy C, Inconel 625, etc., is obtained. Thus, each of these additions contributes to the improvement of the corrosion behavior of the nickel-base composition.

Inconel 600 and X750 alloys will remain passive in flowing, well-aerated seawater, but will be attacked at crevices. Pitting also occurs. Both these alloys do well with cathodic protection in quiet seawater and both are resistant to chloride-ion stress-corrosion cracking. Deep-ocean crevice-attack results for Inconel 600 are presented in Figure 43. It is to be noted that the crevice attack has led to perforation in one case.

Inconel 718 is much more resistant to crevice attack, no doubt because of the 3 percent molybdenum addition. It is a good alloy for erosion corrosion and strength. Recent applications in the marine field include hydrofoils, bolts, and propellers.

TABLE 35. CORROSION RATES AND DEPTH OF ATTACK ON SPECIMENS EXPOSED FOR 3 YEARS IN QUIET SEAWATER(a)

(Specimen dimensions, 4 x 12 inches)

Material	Thickness, inch	Fouling Rate(b)	Weight Loss, grams	Corrosion Rate, mpy	Localized Attack, mils		Remarks
					Max	Avg(c)	
Monel-400	0.062	2	36.6	(d)	41	36	Numerous broad pits
	0.062	2	34.2	(d)	52	48	Numerous broad pits, single perforation from opposing pits
Monel-K500	0.125	2	33.0	(d)	39	30	Numerous broad pits, 5-8 mils; deeper attack in large areas on back side
	0.125	2	32.6	(d)	55	33	Numerous broad pits, 5-8 mils; deeper attack in large areas on back side
304 stainless steel	0.125	2	16.8	(d)	Perforated		Crevice corrosion beneath barnacles and at sheared edges
	0.125	2	17.4	(d)	119	42	Crevice corrosion beneath barnacles and at sheared edges
316 stainless steel	0.125	2	4.0	(d)	72	50	Crevice corrosion beneath barnacles and at sheared edges
	0.125	2	4.8	(d)	60	45	Crevice corrosion beneath barnacles and at sheared edges
Incoloy 825	0.125	1	0.2	0.1	7	1	Crevice corrosion beneath barnacles
	0.125	1	0.2	0.1	1	1	Crevice corrosion beneath barnacles

- (a) Data from joint test program – Los Angeles Department of Water and Power and The International Nickel Company, Inc.  
(b) 10 = free of fouling, 0 = completely fouled.  
(c) Average of five deepest pits.  
(d) Weight loss due to localized corrosion.

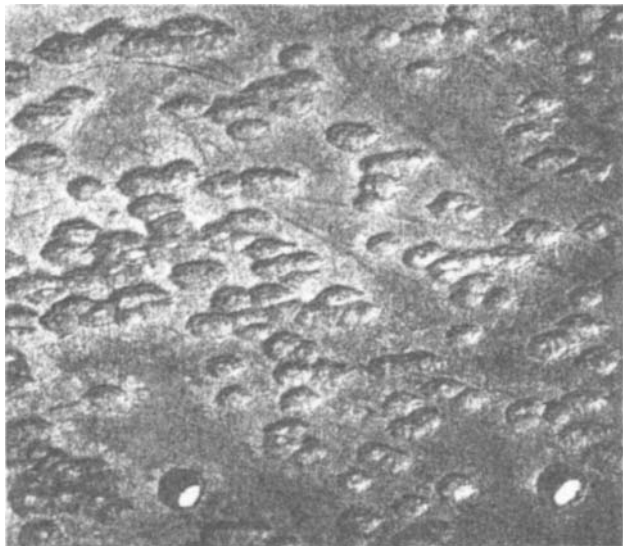


FIGURE 42. PITTING CORROSION OF MONEL 400 AFTER 1,064 DAYS OF EXPOSURE AT A DEPTH OF 5300 FEET(43)

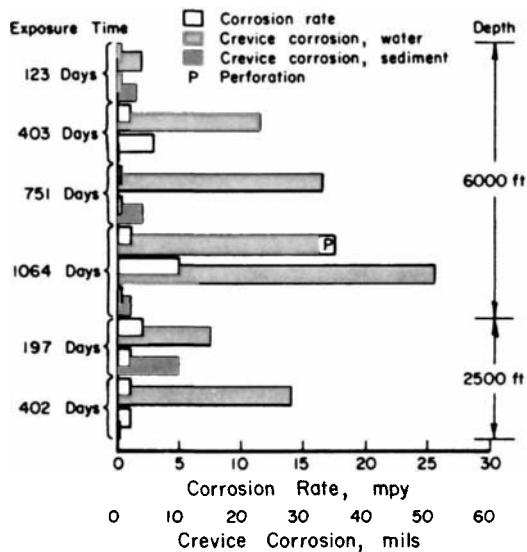


FIGURE 43. CORROSION RATES AND DEPTHS OF CREVICE CORROSION OF INCONEL 600(44)

Incoloy 800, as shown in Table 36, does well in deep-ocean environments. This excellent behavior is unexpected and is not consistent with its composition, since it is closely related to the pit-susceptible austenitic-grade stainless steels.

TABLE 36. DEEP-OCEAN BEHAVIOR OF Ni-Cr-Fe, Ni-Cr, AND Ni-Cr-Mo ALLOYS(43)

Alloy	Exposure Time, days	Depth, feet	Corrosion Rate, mpy		Crevice Corrosion, mils		Notes on Attack
			Water	Mud	Water	Mud	
Inconel 600	123-1,064	2,340-6,780	<0.1-0.5	<0.1-0.3	4-51	3-10	Mostly local crevice, some pitting
Inconel X750	123-1,064	2,340-6,780	<0.1-0.4	<0.1	0-47	0-9	Crevice attack in water and mud
Inconel 718	402	2,370	<0.1	<0.1	0	4	Slight crevice in mud zone
Incoloy 800	123-1,064	2,340-6,780	<0.1	<0.1	0	1-6	Trace of crevice in mud zone; most samples OK
Incoloy 825	123-1,064	2,340-6,780	<0.1	<0.1	0-22	0-8	Most samples OK
Inconel 625	402	2,370	<0.1	<0.1	None	None	
Hastelloy C	123-1,064	2,340-6,780	<0.1	<0.1	None	None	

Under immersed conditions, Incoloy 825 may be locally attacked in quiet seawater under fouling and at crevices. However, its resistance to pitting and crevice attack is much greater than that of the austenitic-grade stainless steels. The rate of attack after 3 years was 0.018 mpy for the totally immersed condition, as well as in the half-tide and the splash zones. In these particular exposures, local attack did not develop in the well-aerated splash zone, nor under the totally immersed condition. In the latter condition, pitting may eventually take place, unless the surface is continuously provided with well-aerated seawater. (See Table 35 for shallow-water results for Incoloy 825.) In hot seawater, this alloy is resistant to stress-corrosion cracking and thus finds application in seawater heat-exchanger service.

Hastelloy C and Inconel 625 are the best known of the nickel-chromium-molybdenum alloys. Under immersed conditions, their corrosion resistance is equaled only by that of titanium materials.

An example of the resistance of Inconel 625 in shallow seawater environments is given in Table 37. No corrosion of any significance was observed in any of these aggressive environments after exposures of up to 3 years. Circular welds on material annealed at 1800 F prior to welding also showed no significant attack after 1 year of exposure.

TABLE 37. DESCRIPTION OF SEAWATER CORROSION TESTS ON INCONEL 625 IN WHICH NEGLIGIBLE ATTACK WAS OBSERVED(a)

- (1) Tests with 0.25 inch diameter 7 x 19 wire rope at Wrightsville Beach, North Carolina, in ambient seawater.  
Exposures: (a) trough at 2 fps, (b) water line, (c) tidal zone, and (d) partial mud burial.
- (2) Tests with 4 x 12 panels with plain crevice (1.25-inch fiber washer), and welded configurations (2-inch-diameter circular weld ground flush).  
Exposures: (a) quiet seawater and (b) trough at 2 fps.

(a) Data provided by The International Nickel Company, New York, N. Y. (1968).

Hastelloy C has been tested in a great variety of seawater environments and found extremely resistant. A few selected examples are presented in Table 38. Note that Hastelloy C will withstand high velocity, elevated temperatures, stagnant

TABLE 38. CORROSION OF HASTELLOY C IN SEAWATER ENVIRONMENTS(a)

Type of Test	Site	Seawater Conditions			Oxygen, ppm	Duration	Corrosion(b), mpy	Notes
		Temp, F	pH	Velocity, fps				
Spool	Curacao	82	6.6	(Pump suction)	3.5	3 yr	0.4	No pitting
Spool	—	325	—	0.5	—	3.3 yr	<0.1	
Coupon	Wrightsville Beach, N.C.	51	8.0±	128	Sat'd	30 days	0.2	
Sandblasted plate	Ditto	Ambient	8.0±	Low	Sat'd	10 yr	0.016	No pitting or crevice attack
Sheet tensile rotating in autoclave	Navy Laboratory at Annapolis, Md.	350	—	10	—	1080 hr	(Weight gain)	
Navy erosion test	Wrightsville Beach, N.C.	86	8.0±	20	Sat'd	60 days	0.63	

(a) Taken from literature supplied by The International Nickel Company and Union Carbide Corporation.

(b) Weight losses were so small that cleaning and weighing errors may be the major factor, especially for plate samples.



conditions, etc. In other tests it has withstood seawater temperatures as high as 550 F. Hastelloy C, in other words, is completely resistant to conditions involving impingement attack, crevice attack, heat transfer, etc. It also does not fail by stress-corrosion cracking in seawater at tensile strengths close to the yield.

It should be mentioned that welds in Hastelloy C tend to fail by intergranular attack in hot seawater. Carbide formation at the sensitized zones is evidently responsible. By using a modification of Hastelloy C (Hastelloy C-276) with less than 0.02 percent carbon, this welding problem can be avoided.

Chlorimet-3, a cast alloy, is related in composition to the above two alloys. All evidence would suggest that it also is entirely resistant to seawater environments.

In line with the discussion of the need for adding both chromium and molybdenum to nickel, in order to provide passivity and resistance to local attack, deep-ocean results have shown that Hastelloy X, F, and G have negligible crevice attack and good resistance to general attack in seawater. René 41, judging from its composition, should be excellent in seawater.

Elgiloy has been known for some years as a resistant alloy for special applications involving seawater. As a spring material it can be used in seawater without risk of failure.

Illium R has excellent resistance to seawater, although it is not quite the equal of Hastelloy C.

Similarly, the new multiphase, MP35N alloy has shown no attack after 4 years' exposure in seawater, and the behavior of this alloy in seawater is expected to be similar to that for Hastelloy C.

**Galvanic Coupling.** Part of the galvanic series is shown in Table 39 for reference purposes. Note that some of the nickel-bearing alloys are among the most cathodic, e.g., Hastelloy C,

TABLE 39. PART OF GALVANIC SERIES OF METALS IN FLOWING SEAWATER SHOWING METALS AT THE MOST NOBLE END(45)

Copper	(Least Noble)
Silicon bronze	
Red brass	
Aluminum brass	
G Bronze	
Admiralty brass	
Cupronickel 90Cu-10Ni	
Cupronickel 70Cu-30Ni	
Nickel	
Inconel 600	
Nickel-aluminum bronze	
Silver	
Titanium	
Type 304 stainless steel (passive)	
Inconel 625	
Hastelloy C	
Monel-400	
Type 316 stainless steel (passive)	
Incoloy 825	
Graphite	
Platinum	(Most Noble)

Monel-400, and Incoloy 825. When any of these alloys are coupled to alloys higher on the list, such as the copper-base alloys, there is a tendency for galvanic corrosion. For example, Inconel 625 wire cable performs well in seawater. Cupronickel (70Cu-30Ni) also does well. However, the corrosion attack on cupronickel fittings tightly clamped to Inconel 625 cable has been excessive and has led to their failure.

Another example is provided by the Navy results illustrated in Figure 44. Coupling of Monel-400 to phosphor bronze resulted in a greatly accelerated attack on the bronze, even with partial galvanic protection of the Monel-400. Coupling of stainless steel (which in the passive state has a potential close to that of Monel-400) to bronze did not cause nearly so great an increase in the attack on bronze as did coupling bronze to Monel-400. The explanation is that Monel-400 polarizes less readily than stainless steel.

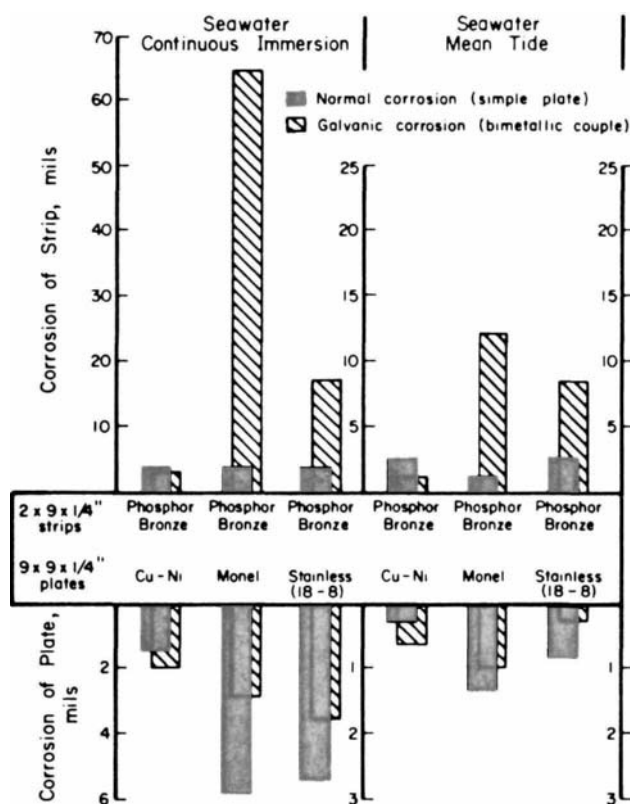


FIGURE 44. GALVANIC EFFECTS WITH SEMIONOBLE METAL COUPLES IN TROPICAL SEAWATER(40)

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Average penetration (calculated from weight loss for 8 years' exposure).

Mud

Both nickel and nickel-copper alloys show localized attack when exposed to bottom sediments. For example, in deep-ocean experiments, some panels of nickel were perforated in the water and also in the mud exposure.(43) Some experience with nickel-copper alloys, such as Monel-400, suggests that if either of these materials is to be used in the mud zone, local attack must be controlled by cathodic protection, combined, where feasible, with a protective coating.



For the nickel-base alloys with chromium, iron, molybdenum, and other additions, the behavior in the mud zone tends to follow that in the quiet ocean (see Table 36). An alloy of 80Ni-20Cr (Nichrome), for example, showed crevice attack in both the mud zone and in the water just above the bottom. Alloys like Inconel 625 and Hastelloy C were completely free from attack in the mud zone. Incoloy 825 occasionally showed crevice attack both at the sea bottom and in the mud.(43)

It is concluded that the loss of passivity at local sites can occur almost as readily in the mud zone as in quiet seawater. The degree of penetration may be eventually as deep, but probably will require much more time. As shown in Table 36, Inconel 718 and Incoloy 800 showed more tendency to crevice attack in the mud zone than in deep-ocean water. In all other cases for susceptible alloys, the reverse was true.

### Cobalt

Cobalt has a very low rate of attack in the marine atmosphere. At Kure Beach, North Carolina, a corrosion rate of 0.1 to 0.2 mpy was established at both the 80- and 800-ft lots.(46) Cobalt as an electroplate may corrode more readily than nickel. The corrosion products tend to give a reddish cast to the surface. A comparison of composite electroplates of chromium with (1) cobalt, (2) cobalt-nickel, and (3) nickel undercoats shows that each gives roughly the same protection to steel in marine atmospheres.(47) Cobalt can be classed as a resistant metal in the marine atmosphere. As with nickel, some local attack may be expected where salt and deposits set up corrosion cells.

In seawater, electrolytic cobalt is reported to have an average corrosion rate of 0.7 mpy after an exposure of 2 years.(46) In 4 percent sodium chloride, cobalt is readily passivated, but is inferior to nickel in this respect. It would appear that cobalt in quiet seawater would tend to pit.

Cobalt alloys such as Haynes Stellite No. 30 and Haynes Stellite No. 21 (cobalt-base Cr-Mo alloys) are very resistant to seawater.

### Copper and Copper-Base Alloys

Copper alloys find application in a wide variety of marine environments.(49) For some types of service, such as ship propellers or surface condensers, special alloys have been developed to provide the optimum combination of corrosion resistance and desired physical properties.

An essential feature of the behavior of copper and its alloys in marine environments is the development of a protective film. The films developing in the atmosphere and in seawater differ in composition. In general, a greater number of alloys develop protective films in the atmosphere than in seawater.

### Atmosphere

In marine atmospheres, part of the basic copper sulfate which comprises the major portion of the patina that normally forms in a urban atmosphere is replaced by the basic copper

chloride.(49) In addition to the sulfate and chloride, a small quantity of basic copper carbonate may be present, as well as layers of cuprous oxide next to the metal.(50)

The patina developed on the bronze Statue of Liberty has been analyzed and represents the situation for a polluted marine atmosphere. It consists of 95 percent basic copper sulfate  $[\text{CuSO}_4 \cdot 3\text{Cu}(\text{OH})_2]$  and 5 percent basic copper chloride  $[\text{CuCl}_2 \cdot 3\text{Cu}(\text{OH})_2]$ .(51)

Copper and copper alloys exhibit low rates of attack in marine atmospheres. Typical exposure data for both temperate and tropical marine exposures are presented in Tables 40 through 42. Some differences in the rate of attack between exposure sites and between various alloys will be noted; however, these differences are small and in general have little or no practical significance. On the basis of weight-loss measurements, corrosion rates over periods of up to 20 years are 0.01 to 0.17 mpy. As would be expected, rates of attack experienced in tropical zones are higher than those in temperate exposures. From the standpoint of alloy additions, slight beneficial trends are indicated for aluminum, nickel, and zinc, whereas those alloys containing silicon and tin tend to be somewhat less resistant than copper alone. As previously pointed out, these trends are not so significant as to dictate the use of one alloy over another except for an extremely critical application.

TABLE 40. SUMMARY OF ATMOSPHERIC CORROSION RESULTS FOR COPPER ALLOYS AFTER 16 YEARS' EXPOSURE AT CRISTOBAL, PANAMA CANAL ZONE(52)

Metal	Corrosion Rate(a), mpy			Loss in Tensile Strength(b), percent	
	4 Yr	8 Yr	16 Yr	8 Yr	16 Yr
Copper	0.095	0.071	0.048	3.7	4.5
Silicon bronze	0.162	0.136	0.116	0.0	3.9
Phosphor bronze	0.100	0.076	0.060	6.6	2.4
Aluminum bronze	0.038	0.029	0.024	1.5	2.4
Commercial bronze	0.055	0.037	0.031	2.3	3.3
Low brass	0.040	0.029	0.023	4.8	3.2
Cartridge brass	0.028	0.023	0.021	5.3	3.6
Naval brass	0.033	0.026	0.024	2.7	6.8
Muntz metal	0.035	0.029	0.028	4.3	8.4
Manganese bronze	0.075	0.041	0.038	6.0	8.0

(a) The corrosion rate, as measured by the tangent to the curve at each time interval, is given here. This rate is lower than that obtained by taking the mils penetration from weight loss, and dividing it by the total number of years.

(b) 1/16-inch-thick sheet samples.

The high-zinc brasses (naval brass, Muntz metal, and manganese brass), although exhibiting low rates of penetration on the basis of weight loss, were found to have lost considerably more strength than other alloys in the series (see Table 40). These materials exhibited dezincification as a result of exposure to the marine environment. In general, copper alloys with 15 percent or more zinc are susceptible to dezincification in marine atmospheres. For single-phase brasses, the attack can be controlled by small additions of arsenic, antimony, or phosphorus. About 0.02 percent arsenic is very effective. Note that Muntz metal, which contained 0.19 percent arsenic, showed loss of strength because of dezincification. In this two-phase alloy, the inhibitor is not effective in preventing dezincification.

TABLE 41. MARINE ATMOSPHERIC RESULTS FOR COPPER ALLOYS AFTER 2 AND 7 YEARS<sup>(41)</sup>

CDA No.(a)	Commercial Designation or Composition	Penetration, mpy (Calculated From Weight Loss)				Appearance After 7 Years at Kure Beach, N.C.
		2 Years		7 Years		
		A(b)	C(c)	A	C	
110	Tough Pitch Cu	0.072	0.065	0.065	0.025	Brown film, smooth, slight patina near edges
<u>Tin</u>						
505	Phos. Bronze, 1.25% Sn	0.083	0.042	0.069	0.017	"Mink brown", slight patina
510	Phos. Bronze, 5% Sn	0.150	0.088	0.099	—	Maroon film, heavy etch
<u>Aluminum</u>						
637	Alum. Bronze	0.017	0.009	0.013	—	Light tan film, smooth
<u>Nickel</u>						
	1.85 Ni, 0.03 Fe	0.134	0.145	0.044	0.036	Dark brown, mottled with green at edges
704	6.34 Ni, 0.01 Fe	0.069	0.052	0.033	—	Dark brown, plus patina streaks on panel face
707	9.16 Ni, 0.18 Fe	0.052	0.039	0.038	—	Uniform maroon with patina at edges
711	22.76 Ni, 0.04 Fe	0.036	0.024	0.031	—	Greenish brown, green near edges, slight etch
	42.75 Ni, 0.30 Fe	0.018	0.012	0.019	0.005	Greenish brown, slight green near edges
<u>Zinc</u>						
420	Tin brass	0.058	0.042	0.024	—	Dark maroon, smooth
230	Red brass	0.051	0.038	0.033	0.026	Brown-maroon film, smooth
260	Cartridge brass	0.034	0.023	0.030	0.017	Brown-maroon film, smooth, very slight patina
<u>Nickel-Zinc</u>						
745	10% nickel- silver	0.030	0.020	0.024	0.010	Brown with slight patina film in center, green near edges, smooth
752	18% nickel- silver	0.030	0.020	0.021	—	Brown film in center, green near edges, smooth

(a) Copper Development Association number; see Appendix, Table A-1, for nominal alloy compositions.

(b) A = 80-foot lot, Kure Beach, N.C.

(c) C = Point Reyes, California.

TABLE 42. CORROSION RATES OF COPPER AND COPPER ALLOYS IN MARINE ATMOSPHERES BASED ON LOSS IN WEIGHT AFTER 10 AND 20 YEARS' EXPOSURE(53)<sup>a</sup>

CDA No.(a)	Alloy	Corrosion Rate, mpy					
		Sandy Hook, New Jersey		La Jolla, California		Key West, Florida	
		10 Yr	20 Yr	10 Yr	20 Yr	10 Yr	20 Yr
110	Electrolytic tough pitch copper	0.028	—	0.056	0.050	0.022	0.025
122	Phosphorized copper	0.028	—	0.046	0.055	0.021	0.020
655	Silicon bronze, 3.1% Si, 1.1% Mn	0.045	—	0.078	0.053	0.040	—
521	Phosphor bronze, 8% Sn, 0.1% P	0.050	—	0.089	0.092	0.031	0.028
614	Aluminum bronze, 8% Al	0.056	0.047	0.008	0.006	0.012	0.002
	High-tensile brass, 20-24% Zn, 2.5-5% Mn, 3-7% Al, 2-4% Fe	0.113	0.178	0.078	0.089	0.068	0.078
230	Red brass, 15% Zn	0.047	—	0.023	0.011	0.020	0.017
260	70-30 brass, 30% Zn	0.039	—	0.011	0.006	0.015	0.009
442	Admiralty metal, 29% Zn, 1% Sn	0.039	—	0.011	0.006	0.015	0.009
732	Copper-nickel-zinc, 75% Cu, 20% Ni, 5% Zn	0.042	—	0.013	0.016	0.012	0.010
	Copper-nickel-tin, 70% Cu, 29% Ni, 1% Sn	0.045	—	0.011	0.014	0.014	0.011

(a) See Appendix, Table A-1, for nominal alloy compositions.

(b) Dash denotes 20-year specimens lost.

### Splash and Tide

The corrosion behavior of copper alloys in the splash zone more nearly follows their performance in the atmosphere than in immersed conditions. As a general rule, any copper alloy that has good resistance to a severe marine atmosphere, such as Cristobal, Canal Zone, will also do well in the splash zone.

Alloys exposed at mean tide show corrosion rates ranging from about 20 to 60 percent of those observed for alloys under fully immersed conditions. Thus the behavior under fully immersed conditions can be used as a guide for the selection of a resistant alloy in a half-tide application. The resistance of an isolated panel of copper in the tide zone is superior to that in the fully immersed condition, and is in marked contrast to the relatively poor behavior of an isolated steel panel at the half-tide level. Weight-loss curves for the half-tide performance of copper alloys after 16 years is given in Figure 45.(52) Note the lower rates obtained as compared with the same alloys under fully immersed conditions in Figure 46.

### Submerged, Corrosion Factors

There is extensive application of copper-base alloys under submerged conditions. In seawater, copper alloys behave somewhat differently from some other metals such as steel and aluminum. Before presenting corrosion data, the factors involved in the attack by seawater and typical failure mechanisms for copper and its alloys are reviewed.

The factors which affect the performance in seawater include film formation, oxygen content, velocity, temperature, metal-ion concentration, and biofouling. Galvanic couples with copper more often have an adverse effect on the behavior of the other metal in the couple by causing it to corrode more rapidly. Dezincification is a common form of failure for high-zinc brasses, whether coupled or not. The factors listed above are interrelated and their relative order of importance may change with the specific conditions in each situation.

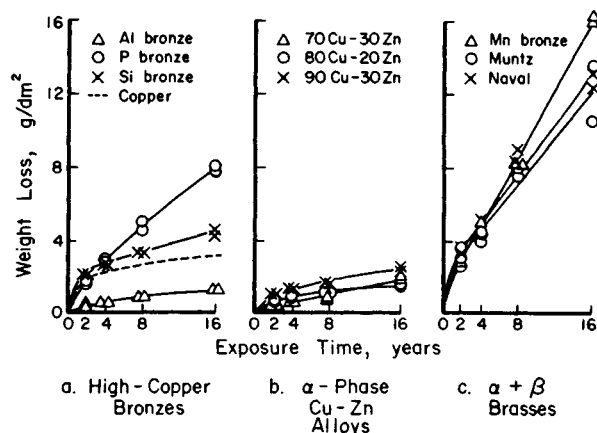


FIGURE 45. CORROSION WEIGHT LOSS AS A FUNCTION OF TIME FOR COPPER ALLOYS EXPOSED AT MEAN-TIDE ELEVATION IN TROPICAL SEAWATER(52)

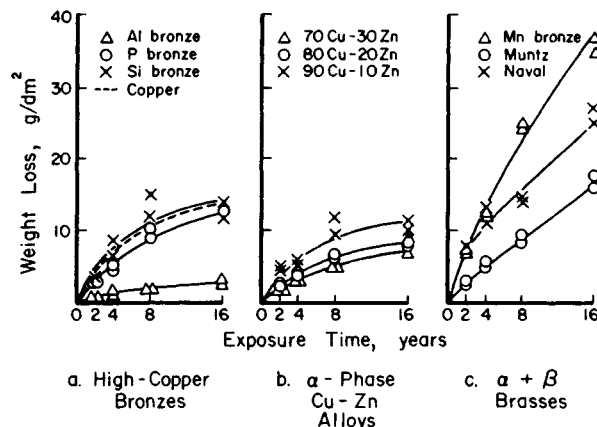


FIGURE 46. CORROSION WEIGHT LOSS AS A FUNCTION OF TIME FOR COPPER ALLOYS CONTINUOUSLY IMMERSSED IN TROPICAL SEAWATER(52)

**Film Formation.** Although copper is a noble metal, the main reason for its satisfactory performance in a seawater application is that a protective film of cuprous oxide forms directly on the metal surface. Often products deposit on top of this film and may contribute to the protection. These may be cupric oxychloride, cupric hydroxide, or basic copper carbonate and calcareous materials.(54)

In condenser-tube practice, especially resistant films are often produced in the presence of iron. Cupronickels containing iron develop a dark, resistant film.(55) In a recent patent, iron has been added to aluminum brass to promote film formation.(56) Ferrous sulfate has also been added to seawater flowing through aluminum-brass condenser tubes to form the iron film with considerable benefit. More recently,(57) laboratory studies suggest that ferrous ions are oxidized to lepidocrocite by dissolved oxygen, which forms a colloid and is

deposited electrophoretically at the cathode. This film acts as a cathodic or safe inhibitor by polarizing the reduction of oxygen.

Polluted seawater often has hydrogen sulfide or other sulfides present. The copper sulfide film formed on the metal surface in polluted seawater is more cathodic than the corrosion film developed in clean seawater. If there are breaks in the sulfide film, local attack is stimulated greatly by the large area of active cathode. Some alloys show much less tendency to develop such films. Cupronickels and aluminum-copper alloys, for example, are more resistant to polluted seawater than say copper and ordinary brass, as shown in Table 43.

TABLE 43. BEHAVIOR OF COPPER ALLOYS IN SEAWATER UNDER VARIOUS CONDITIONS(58-60)

Alloy	Resistance to Indicated Factors(a)				Velocity Behavior
	Dezincification	Turbulence	Biofouling	Pollution	
Copper	NA	P	E	F	Velocity sensitive
Red brass	G	F	G	F	Better than copper, but velocity sensitive
Arsenical admiralty brass	G	F	G	F	Poor impingement, as compared with other alloys
Arsenical aluminum brass	G	G	F	G	Good to excellent resistance to high velocity
90-10 cupronickel plus iron	NA	G+	F	G	Good to excellent in high velocity
70-30 cupronickel plus iron	NA	E	F	G	Excellent in high velocity more tendency to pit in stagnant seawater than 90-10 alloy

(a) E - excellent  
G - good  
F - fair  
P - poor  
NA - not applicable.

**Oxygen Content.** On clean metal surfaces, the most important factor influencing the corrosiveness of seawater to copper alloys is the seawater oxygen level. The corrosion reaction can be affected in at least three ways: (1) depolarization of cathode areas, (2) oxidation of cuprous ions to the more corrosive cupric state, and (3) the promotion of a protective film on the metal surface, as discussed above. In recirculating systems, when all oxygen is removed from the seawater, the rate of attack on copper alloys may be of the order of 1 percent of that observed with fully aerated seawater. The same effect can be obtained by completely deaerating the seawater as shown in Figure 47. For copper or an alloy with a protective film, the oxygen must diffuse through the film for corrosion to continue. Corrosion rates tend to decrease with time during the formation of such protective films. The oxygen level then becomes of much less significance in the rate of further attack.

**Velocity.** Copper and some of its alloys are sensitive to velocity effects. On the other hand, copper can withstand stagnant seawater better than many other metals. The usual recommended maximum velocity for copper in seawater is about 3 fps. Alloying with such elements as nickel or aluminum greatly improves the resistance to impingement attack. Recommended maximum velocities for other alloys based on condenser-tube experience in clean seawater are given in Table 44.

In completely oxygen-free seawater, such as is used in some sections of distillation-type desalination plants, there is evidence that velocities somewhat higher than those listed in Table 44 probably can be tolerated.

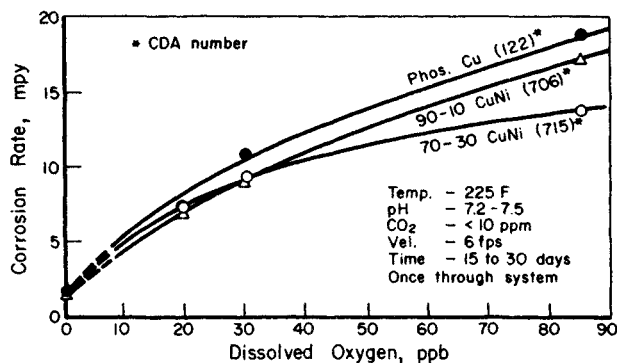


FIGURE 47. EFFECT OF DISSOLVED OXYGEN IN SEAWATER ON THE CORROSION RATE OF COPPER ALLOYS(54A)

TABLE 44. RECOMMENDED MAXIMUM VELOCITY TO REDUCE TENDENCY TO IMPINGEMENT AND TO OTHER VELOCITY EFFECTS IN CLEAN SEAWATER(32,61)

Alloy	CDA No.	Maximum Velocity, fps
Copper	110	3
Arsenical admiralty brass	443	6
Arsenical aluminum brass	687	10(a)
90Cu-10Ni (1.5 Fe)	706	12(a)
70Cu-30Ni (0.7 Fe)	715	15(a)

(a) Typical condensers are run at 8 fps or less.

**Temperature.** The corrosion rate for copper alloys usually is higher, other factors being the same, as the temperature is raised. Pump impellers, condenser tubes, valves, etc., tend to corrode at higher rates in seawater at summer temperatures at Wrightsville Beach, N. C., than at winter temperatures. Copper alloys also show higher rates of attack in the warm waters of the Pacific Ocean near the Panama Canal Zone as compared with those obtained in water off the coast of California.

When seawater is heated to higher temperatures, both the reduced oxygen content and the greater tendency to form mineral scale tend to make the environment less aggressive, and corrosion rate decreases, as illustrated in Figure 48.

**Metal-Ion Concentration.** Copper enters seawater as cuprous ions. Oxygen in the seawater tends to convert the cuprous ions to cupric ions. Since cupric ions can attack copper to form more cuprous ions, copper ions and oxygen in solution increase the attack. This is observed in piping systems and recirculating system.

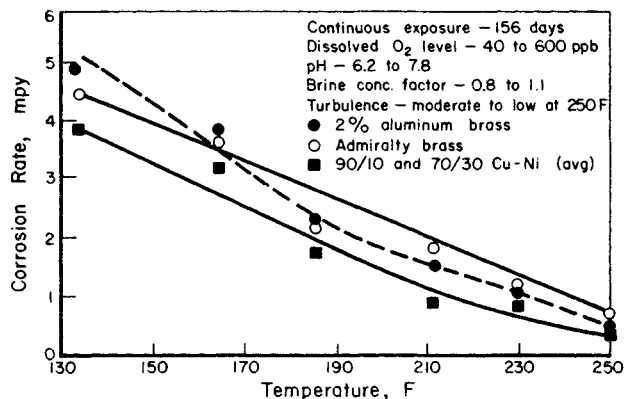


FIGURE 48. EFFECT OF TEMPERATURE ON CORROSION RATE OF COPPER-BASE HEAT-EXCHANGER TUBE MATERIALS IN DEAERATED NORMAL SEAWATER AT FREEPORT PLANT(62)

A higher concentration of metal ions tends to form under a crevice, whereas any copper ions formed outside the crevice are swept away by the current. Under these circumstances, local attack takes place on the copper just outside the crevice.

Copper ions also promote pitting and local attack of less noble metals such as aluminum or steel.

**Biofouling.** The corrosion behavior of copper alloys influences their tendency to biofoul. Normally the presence of copper ions in the water film adjacent to the corroding metal surface is toxic to marine life. At a corrosion rate of 6 mg/dm/day, no fouling occurs in a typical situation. This amounts to about 1 mpy for copper. If the copper or copper-rich alloy surface is provided with cathodic protection as, for example, when coupled to steel, aluminum, or another anodic metal, the copper-alloy corrosion may be reduced or cease altogether. Under the latter condition, biofouling will appear on the surface.

**Galvanic Attack.** Since copper is cathodic to most other metals in seawater, galvanic attack is usually a factor affecting the other metal in the couple rather than the copper. In general, copper alloys may be safely coupled to each other in seawater. There are cases where the proper galvanic relationship results in longer life. Tube sheets of copper alloy are usually selected so as to be slightly anodic to the tubing alloy, e.g., naval-brass tube sheet with aluminum-brass tubes.

**Dezincification.** Corrosion by dezincification usually occurs on high-brass alloys in seawater and in other environments. The first step in dezincification is now considered to be the dissolution of both the copper and the zinc. The copper ions are then reduced to copper close to the point where dissolution took place.

Dezincification may take several forms, e.g., the plug type where a mass of copper displaces the original brass, or the layer type where a cross section shows an even layer of porous copper underneath which the metal is not attacked. The copper

mass may show growth rings of dense copper layers interspersed with bands of cuprous oxide.

Related processes occur less frequently on (1) copper-aluminum alloys (dealuminification) and (b) copper-nickel alloys (denickelification). In recent years, the terms dealloying and parting have been introduced to refer to the general phenomenon.

#### Submerged, Stress-Corrosion Cracking

Copper alloys sometimes fail by stress corrosion in seawater service. Manganese bronze propellers, with high residual stresses, have failed by stress-corrosion cracking. Roller-expanded copper-alloy tubes in tube sheets, especially when expanded beyond the back face of the tube sheet, have failed during shutdown. Seawater algae slimes, high in nitrogen compounds, are considered responsible.(53) Most of the stress-corrosion failures of copper alloys reported in the literature have identified the presence of ammonia in the environment or some nitrogen compound such as amines or nitric acid which could convert to ammonia. Since contaminated seawater may contain ammonia, alloys susceptible to stress-corrosion cracking should not be used at high tensile-stress levels (residual or applied).

In general, high-zinc brasses and certain aluminum brasses are particularly susceptible to stress-corrosion cracking, whereas cupronickels, copper, and high-copper alloys, in general, are less susceptible.

#### Submerged, Corrosion Data

Copper. Copper corrodes typically at rates varying from 0.5 to 2 mpy in shallow and deep-ocean environments. A summary of recent information is presented in Figure 49.(54)

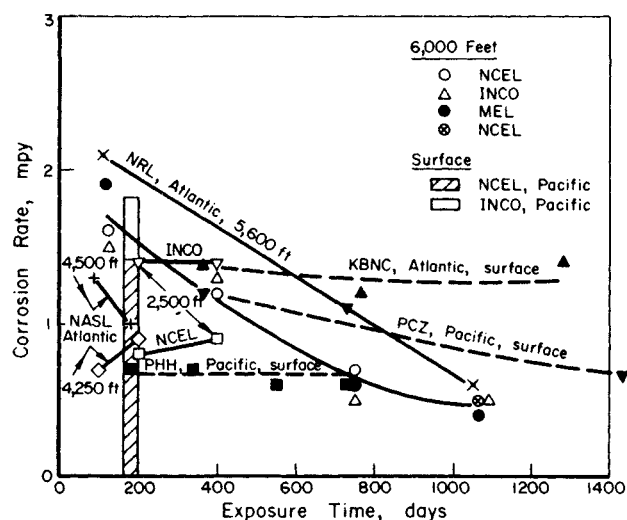


FIGURE 49. CORROSION RATES OF COPPER IN SEAWATER(54)

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After 16 years at shallow depths in the Pacific off of the Panama Canal Zone, copper showed a rate of attack of 0.20 mpy. The deepest pit, as recorded in Table 45, was 57 mils (since pitting often is most rapid during the first few years, an average pitting rate is without significance). Single-phase brasses as well as silicon and phosphor bronze corrode at about the same rate as copper. In the slowly moving seawater involved in these exposures, copper is relatively insensitive to the amount of oxygen present.

TABLE 45. SUMMARY OF FULL IMMERSION RESULTS FOR COPPER ALLOYS AFTER 16 YEARS IN THE PACIFIC OFF THE PANAMA CANAL ZONE(52)

Metal	Corrosion Rate, mpy	Deepest Pit, mils	Loss in Tensile Strength, percent	Notes
Copper	0.376(a) 0.20(b)	57	5.2	Local attack; resistant to fouling
Silicon bronze	0.365 0.20	36	3.5	Ditto
Phosphor bronze	0.342 0.18	29	7.0	Ditto
Aluminum bronze	0.079 0.053	21(c)	3.2	Fouling attack; pitting not significant
Commercial bronze	0.308 0.18	51	5.1	Local and fouling attack
Low brass	0.233 0.10	46	3.3	Dezincification random
Cartridge brass	0.244 0.10	(d)	20.0	Ditto
Naval brass (Sn)	0.779 0.41	(d)	57.6	Dezincification, uniform
Muntz metal (As)	0.511 0.31	(d)	45.5	Dezincification, nonuniform
Manganese bronze	1.072 0.80	36	45.8	Ditto

(a) Values in this column are total penetration divided by 16 (years).

(b) Values in this column were estimated graphically at 16 years.

(c) Eight-year panel, no deep pit on 16-year panel.

(d) Not applicable, dezincification damage.

**High-Copper Alloys.** Alloys of commercial importance, as far as seawater is concerned, include beryllium-copper, iron-modified copper, and phosphorized copper. The addition of 2 percent beryllium (Table 46) is slightly beneficial as compared with the corrosion rate of unalloyed copper. Welded specimens showed rates similar to those of specimens in the unwelded condition.

TABLE 46. CORROSION OF COPPER AND BERYLLIUM-COPPER IN SEAWATER

CDA No.(a)	Metal	Depth, feet	Time, days	Corrosion Rate, mpy (Calculated From Weight Loss)
102	Copper	5	181	1.4
102	Copper	2370	402	0.9, 1.4
172	Be-copper	5	181	0.1 (0.1)(b)
172	Be-copper	2370	402	0.6 (0.5)(b)

(a) See Appendix, Table A-1, for nominal alloy composition.

(b) These values for chain specimens.

Phosphorized copper and copper behave very similarly in seawater. The corrosion rate of the iron-modified copper alloy, e.g., CDA No. 194 with 2.3 percent iron, is considerably lower than that of copper, judging from preliminary reports on the ability of this alloy to form protective films in seawater. It is performing well as welded tubing in saline waters.

**Brasses.** The copper-zinc alloys vary widely in their resistance to seawater. High-zinc alloys tend to fail by dezincification, especially those with two or more phases present. Alloys with 15 percent zinc or less are not so likely to fail by this mechanism. An excessive loss in strength after exposure to seawater is a good indication that dezincification has taken place. After 16 years at shallow depths in the Pacific Ocean, alloys of 30 percent or more zinc show strength losses ranging from 20 to 60 percent (Figure 50).

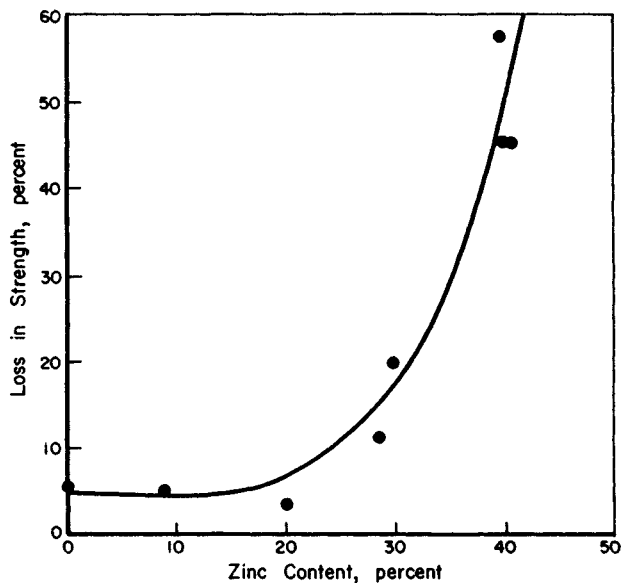


FIGURE 50. EFFECT OF ZINC CONTENT ON LOSS IN STRENGTH FOR BRASSES AFTER 16 YEARS' SUBMERSION IN THE PACIFIC OCEAN NEAR THE PANAMA CANAL ZONE(52)

Deep- and shallow-ocean experience with red brass (CDA No. 230) is summarized in Figure 51. Note that corrosion rates range from 0.5 to 2 mpy, which is similar to the rates for copper. Red brass can be used for undersea service where a material with more strength than copper is required.

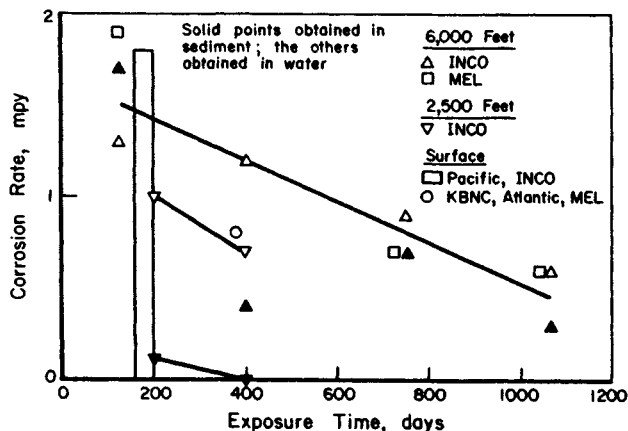


FIGURE 51. CORROSION RATES OF RED BRASS(54)

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Dezincification of both admiralty brass and aluminum brass in seawater can normally be inhibited by small additions of arsenic, antimony, or phosphorus. The behavior of arsenical admiralty brass is summarized in Figure 52 for both deep- and shallow-ocean environments. No dezincification was observed in any of these exposures. Since this alloy is readily available, it, like copper, can be specified for ordinary construction.

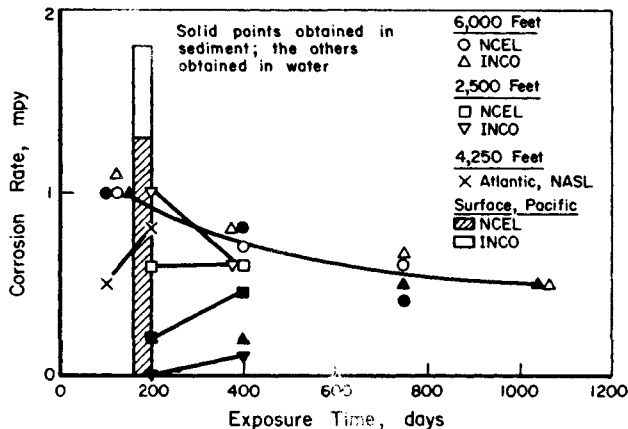


FIGURE 52. CORROSION RATES OF ARSENICAL ADMIRALTY BRASS(54)

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In the brass family, the alloy most resistant to seawater is aluminum brass. It is normally fortified with arsenic (CDA No. 687). The corrosion behavior for this alloy is summarized in Figure 53. Note that it corrodes at a rate of about 0.8 mpy or less.

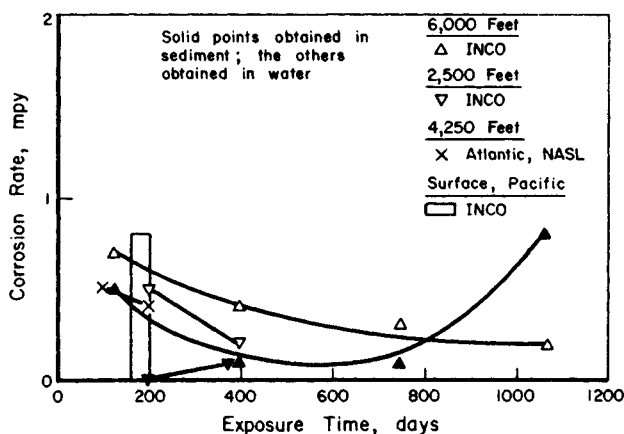


FIGURE 53. CORROSION RATES OF ALUMINUM BRASS(54)

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Bronzes. The corrosion rate after 16 years in the Pacific near the Canal Zone is given for several bronzes in Table 45. Note the low rate of 0.05 mpy for an aluminum bronze. Both silicon bronze and phosphor bronze show a rate of about 0.2 mpy, which is similar to that for copper. The depth of the deepest pit in these bronze alloys ranged from 21' to 36 mils as compared with 57 mils for copper.

Deep- and shallow-ocean experience for silicon bronze is summarized in Figure 54. Note that corrosion rates range from 0.5 to 2 mpy for seawater exposure. The corrosion rates of 5 and 7 percent aluminum bronzes are presented in Figure 55. The rates for the 5 percent alloy are all 1 mpy or less. For the 7 percent alloy, shallow-water rates as high as 2.9 mpy are reported, compared with a rate of 1.4 mpy at 6000 feet. An examination of the 7 percent aluminum alloy showed dealuminification on about half of the specimens.(54) On the 5 percent aluminum alloy, corrosion was uniform. Thus, for service in seawater, the 5 percent aluminum alloy would be recommended.

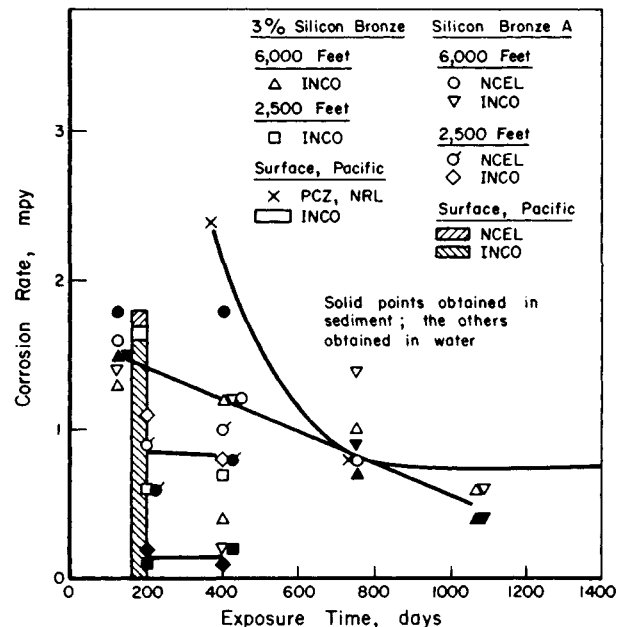


FIGURE 54. CORROSION RATES OF SILICON BRONZES(54)

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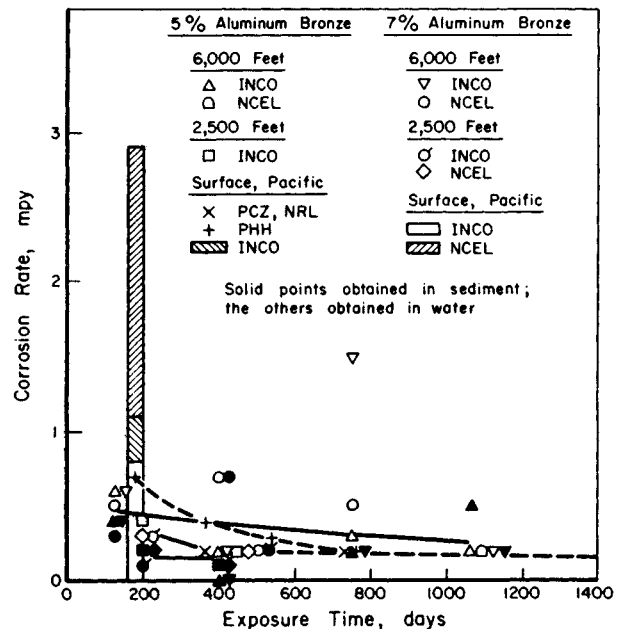


FIGURE 55. CORROSION RATES OF WROUGHT ALUMINUM BRONZES(54)

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Cupronickels. The cupronickels are perhaps the most useful of all commercially available copper alloys in seawater.(63) Corrosion rates for three of these alloys in both shallow- and deep-ocean waters are summarized in Figure 56. These rates range from a maximum of 1.3 mpy for a short-time exposure to 0.8 mpy after several years.

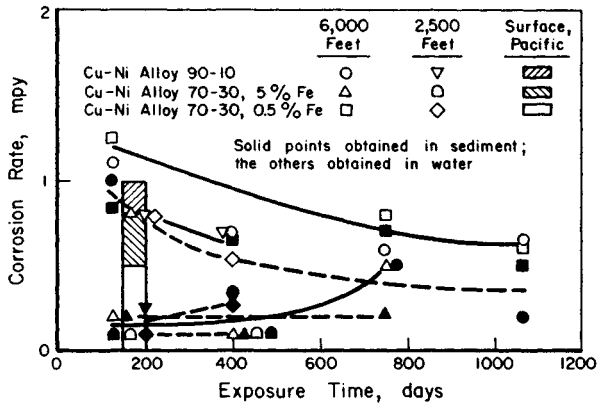


FIGURE 56. CORROSION RATES OF COPPER-NICKEL ALLOYS(54)

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#### Submerged, Heat-Exchanger-Corrosion

The three most commonly used copper-base alloys for heat-exchanger service are 70 Cu-30Ni-0.5Fe, 90Cu-10Ni-1.4Fe, and arsenical aluminum brass, 76Cu-22Zn-2Al-0.02As. Arsenical admiralty (70Cu-29Zn-1Sn-0.02As) brass formerly was recommended for seawater service but is not now favored. A new copper-iron alloy (97.7Cu-2.3Fe-0.03P) is showing promising results in seawater and is expected to compete with the above three alloys for heat-exchanger applications. Because it can be used in the hard-drawn condition, thinner tube walls can be employed. This, plus the fact that this alloy has higher conductivity than presently used alloys, should result in a reduction in the cost of a heat exchanger of a given capacity.

An overall comparison of the relative behavior of the cupronickels, aluminum brass, and several other copper materials is given in Table 43. These heat-exchanger alloys and their general characteristics are briefly discussed below.

**Arsenical Admiralty Brass.** Admiralty brass without arsenic tends to dezincify and become a porous mass of copper with little strength. The use of arsenic-modified admiralty brass in marine condensers dates back to the 1920s. The arsenic-modified alloy, however, is not so resistant to impingement attack as the cupronickels and aluminum brass. Admiralty brass is susceptible to impingement attack particularly at the tube entrance zone, near the tube sheet. More resistant condenser-tube alloys have been available for some time. Generally, admiralty brass is not used for condenser tubes in cases where seawater velocities are above 5 or 6 fps.

Todhunter(64) has compared the performance of four condenser-tube alloys at the Harbor Steam Plant, Los Angeles Department of Water and Power. The percent failures of tube bundles of each alloy since 1950 is shown in Figure 57. Admiralty brass is definitely the poorest performer of the four alloys under these service conditions. Experimental results

reported by May(65) in Table 47 also indicate that the cupro-nickel alloys are superior to admiralty brass in both cold and hot seawater.

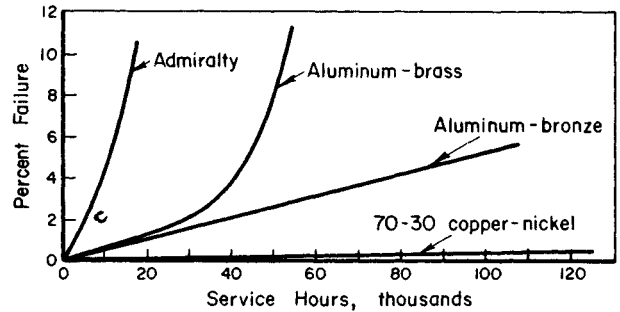


FIGURE 57. COMPARATIVE PERFORMANCE OF CONDENSER TUBES AT THE HARBOR STEAM PLANT, LOS ANGELES, CALIFORNIA(64)

TABLE 47. COMPARISON OF CORROSION DATA ON NORMAL SEAWATER AND SEAWATER BRINE AT COLD AND ELEVATED TEMPERATURES(65)

	Cold Seawater	Hot Seawater
Temperature	80 F	187 F
pH	8.2	8.2
Oxygen, ppm	8.5	7.8
Salinity: g/l	35	59.3
<b>Materials</b>	<b>Corrosion Rate, ipy</b>	
Monel-400	0.0003	0.0004
Type 304 stainless steel	0.0030(a)	0.0001
Carbon steel	0.0290	0.0220
70-30 copper-nickel	0.0015	0.0014
90-10 copper-nickel	0.0028	0.0011
Aluminum brass	0.0019	0.0025
Admiralty brass	0.012	0.0019

(a) Severe pitting under insulator.

Admiralty brass could be used in a distillation plant during the lower temperature stages. Admiralty brass corrodes more rapidly in aerated heated seawater. Mattson and Fuller(62) reported that at temperatures up to 126 F, unmodified admiralty brass dezincified after 4 years in deaerated seawater.

**Arsenical Aluminum Brass.** Arsenical aluminum brass has been very successful in many applications involving seawater service. As with admiralty brass, arsenic is required to prevent dezincification. The iron-modified aluminum brass, mentioned on page 42, would seem to have promise in view of the benefit of iron additions to copper and copper-nickel alloys in seawater service.(56) The aluminum content promotes a type of protective film which is more resistant to impingement than is the case with ordinary brasses.

Aluminum brass is shown to be superior to admiralty brass, but inferior to cupronickel (see Figure 57). The Los Angeles harbor waters are polluted, and under these circumstances, aluminum brass does not perform so well as the 70-30 cupronickel alloy. In clean seawater, aluminum brass often gives service equal to that given by the 90 copper-10 nickel-iron alloy, and is selected because of its lower cost. The results for a variety of seawater conditions, under which the aluminum brass alloy showed corrosion resistance similar to that of the 90Cu-10Ni+Fe alloy, are given in Tables 48 through 51.

90-10 and 70-30 Cupronickels. Both the 90-10 and 70-30 cupronickels, with iron additions (see Table 51) have outstandingly good resistance to seawater. Seawater velocities can be higher with the cupronickels than with most other copper alloys. However, because of the excessive pumping costs involved in actual practice, advantage of this velocity characteristic is not normally employed to the fullest extent.

Navy experience with 70-30 cupronickel alloys on 20 destroyers showed that, on the average, 0.37 percent of the condenser tubes plugged after 20 years of service. Some of the tubes failed on the steam side. Coastal plants using clean seawater show even better performance. In polluted seawater, the rate of plugging for cupronickel is about nine times higher, but it is still much superior to that of other copper alloys.

TABLE 48. RESULTS OF CORROSION TESTS AFTER 156 DAYS IN MISCELLANEOUS ENVIRONMENTS AT FREEPORT(62)

Spool	24	25	26			
Location	Plant-effluent discharge Pit(a)	Distilled fresh water from Effect 12(b)	Down stream condensate from Effect 1(c)			
Dissolved Oxygen	Almost normal for Seawater	Deaerated	Deaerated			
Temperature (Avg), F	105	130	261			
pH	7.5-7.8	7.5	8.5			
Turbulence	Moderate	Moderate	Moderate			
Exposed Metals	Corr. Rate(e), mpy	Max. Pitting(f), mils	Corr. Rate(e), mpy	Max. Pitting(f), mils	Corr. Rate(e), mpy	Max. Pitting(f), mils
Carbon steel	26	Perf(g)	14	None	0.6	None
Type 304 stainless steel(h)	2.1	Perf(i)-PC	<0.1	4P	0.3	None
Type 316 stainless steel(h)	0.1	17C	<0.1	None	0.3	None
Cast alloy 20(h)	0.3	6C	—	—	0.4	None
Monel-400(h)	0.5	15C	0.3	5P	0.9	None
70-30 copper-nickel	1.0	24C	0.2	None	0.3	None
90-10 copper-nickel	0.7	None	0.2	Trace-P	0.4	None
2% aluminum brass	0.8	None	0.3	None	0.4	None
Cast iron	31	None	27	None	2.9	None
Ni-Resist iron Type 1	5.5	None	13	None	0.9	None
Ni-Resist iron Type D-2	6.3	None	11	None	1.0	None

- (a) Specimens continuously submerged in mixture of cooling seawater from Condenser 312 and seawater brine from Effect 12.  
 (b) In discharge line from Pump P-42.  
 (c) In discharge line from Pump P-31.  
 (d) Near Seawater intake pit.  
 (e) Average corrosion calculated from weight loss.  
 (f) Attack in 156 days. P = surface pitting. C = crevice attack.  
 (g) Specimens 0.040 inch thick failed by general corrosion and thinning.  
 (h) Corrosion is limited largely to localized attack producing pits.  
 (i) Specimens 0.038 inch thick.

TABLE 49. RESULTS OF CORROSION TESTS AFTER 90 DAYS IN DEAERATED SEAWATER BRINE(a) AT SAN DIEGO(62)

(In-heat exchanger circuit prior to evaporators)												
Spool	4		5		6		7		8		9	
Location(b)	Inlet WB Stage 34		Inlet WB Stage 24		Inlet WB Stage 16		Inlet WB Stage 8		Inlet WB Stage 1		Outlet WB Brine Heater	
Temperature (Range and Avg), F	85-95, 90		105-115, 107		129-148, 133		163-178, 166		191-215, 196		200-225, 205	
Exposed Metals	Corr.(c) Rate, mpy	Max(d) Pitting, mils	Corr.(c) Rate, mpy	Max(d) Pitting, mils	Corr.(c) Rate, mpy	Max(d) Pitting, mils	Corr.(c) Rate, mpy	Max(d) Pitting, mils	Corr.(c) Rate, mpy	Max(d) Pitting, mils	Corr.(c) Rate, mpy	Max(d) Pitting, mils
Carbon steel	6.2	None	10	None	13	None	21	None	14	None	22	Perf(e)
3% nickel steel	8.4	None	14	None	15	None	20	None	11	None	15	None
Type 316 stainless steel	<0.1	3C	<0.1	4C	<0.1	4C	<0.1	2C	<0.1	6C	<0.1	8C
Wrought Alloy 20	<0.1	2C	<0.1	1C	<0.1	Trace-C	<0.1	4C	<0.1	1C	<0.1	3C
Incoloy 825	<0.1	2C	<0.1	1C	<0.1	Trace-C	<0.1	2C	<0.1	5C	<0.1	2C
Monel-400	0.5	None	0.5	None	0.4	None	0.3	None	0.3	Trace-P	0.3	None
70-30 copper-nickel	0.8	None	0.7	None	0.6	Trace-P	0.5	None	0.4	None	0.4	None
90-10 copper-nickel	0.7	None	0.8	None	0.7	None	0.6	None	0.5	None	0.6	None
2% aluminum brass	0.9	None	0.7	None	0.6	None	0.6	None	0.5	None	0.7	None
Admiralty brass	1.0	None	1.0	None	0.9	None	0.8	None	0.5	None	1.1	None
10% Al-5% Ni bronze	0.8	None	0.6	None	0.5	None	0.4	None	0.4	None	0.6	None
Muntz metal	0.8(f)	None	0.9(f)	None	0.8(f)	None	0.9(f)	None	0.9(f)	None	1.7(f)	None
Cast iron	11	None	14	None	15	None	23	None	15	None	22	None
Ductile iron	11	None	16	None	18	None	22	48(g)	17	None	27	None
3% Ni-1% cast iron	11	None	12	None	16	None	20	None	12	None	16	None
Ni-Resist iron Type 1	3.3	None	4.4	None	2.9	None	3.2	None	2.7	None	3.1	None
Ni-Resist iron Type D-2	2.7	None	3.2	None	2.7	None	3.7	None	2.7	None	3.2	None

- (a) Dissolved oxygen 5 ppb, brine concentration factor 1.5 to 2.0, pH 7.0 to 7.5, moderate turbulence.  
 (b) End plate of water box of condenser of stage indicated, except Spool 9 in direct path of brine heater discharge. WB = water box.  
 (c) Average corrosion calculated from weight loss.  
 (d) Attack in 90 days. P = surface pitting. C = crevice attack.  
 (e) Very rough surface, failed by general corrosion.  
 (f) Dezincification was observed.  
 (g) Maximum erosion at spacer.

TABLE 50. RESULTS OF CORROSION TESTS AFTER 90 DAYS IN FLASHING DEAERATED HOT SEAWATER BRINE<sup>(a)</sup> AT SAN DIEGO<sup>(62)</sup>  
(In flash chambers of evaporator stages)

Spool	10		11		12		13		14		15		16	
Location <sup>(b)</sup>	Stage 1 Near Inlet		Stage 1 Near Outlet		Stage 8 Near Outlet		Stage 16 Near Outlet		Stage 24 Near Outlet		Stage 31 Near Outlet		Stage 36 Near Outlet	
Temperature (Range and Avg), F	196-218, 200		196-218, 200		169-192, 174		141-158, 144		116-128, 118		102-106, 103		90-92, 90	
Brine-concentration factor	1.5-2.0		1.5-2.0		1.6-2.1		1.7-2.1		1.7-2.2		1.7-2.2		1.7-2.2	
	Corr.(c) Rate, mpy	Max(d) Pitting, mils	Corr.(c) Rate, mpy	Max(d) Pitting, mils	Corr.(c) Rate, mpy	Max(d) Pitting, mils	Corr.(c) Rate, mpy	Max(d) Pitting, mils	Corr.(c) Rate, mpy	Max(d) Pitting, mils	Corr.(c) Rate, mpy	Max(d) Pitting, mils	Corr.(c) Rate, mpy	Max(d) Pitting, mils
Exposed Metals														
Carbon steel	15	None	16	None	14	None	10	None	7.0	None	7.0	None	5.8	None
3% nickel steel	8.2	None	11	None	12	None	9.4	None	7.5	None	6.7	None	5.1	None
Type 316 stainless steel	<0.1	3C	<0.1	8C	<0.1	2C	<0.1	4C	<0.1	1C	<0.1	4C	<0.1	Trace-C
Wrought Alloy 20	<0.1	2C	<0.1	6C	<0.1	2C	<0.1	2C	<0.1	Trace-C	<0.1	Trace-C	<0.1	2C
Incoloy 825	<0.1	2C	<0.1	4C	<0.1	Trace-C	<0.1	Trace-C	<0.1	Trace-C	<0.1	1C	<0.1	Trace-C
Monel-400	0.2	Trace-PC	0.4	1P	0.2	Trace-P	0.1	Trace-P	0.1	Trace-CP	0.1	None	<0.1	None
70-30 copper-nickel	0.3	None	0.5	None	0.2	None	0.2	None	0.1	None	0.2	None	0.3	None
90-10 copper-nickel	0.5	None	0.6	None	0.3	None	0.3	None	0.3	None	0.3	None	0.4	None
2% aluminum brass	0.5	None	1.0	2P	0.4	None	0.3	None	0.3	None	0.4	Trace-P	0.3	None
Admiralty brass	0.8	None	1.0	None	0.5	None	0.5	None	0.6	None	0.6	Trace-P	0.5	None
10% Al-5% Ni bronze	0.4	None	0.4	4P	0.3	None	0.3	None	0.3	None	0.4	None	0.3	None
Muntz metal	0.9(e)	None	1.3(e)	None	0.5	None	0.5	None	0.5(e)	None	0.6(e)	None	0.6	None
Cast iron	11	None	13	None	11	None	8.8	None	8.6	None	6.4	None	5.7	None
Ductile iron	15	None	17	23(f)	14	None	10	None	9.6	None	8.0	None	6.4	None
3% Ni-1% Cr cast iron	9	None	14	None	8.6	None	8.9	None	5.9	None	6.4	None	4.8	None
Ni-Resist iron Type 1	2.2	None	3.0	None	2.1	None	2.1	None	1.5	None	2.3	None	1.9	None
Ni-Resist iron Type D-2	3.2	None	2.5	None	2.3	None	2.0	None	2.2	None	2.4	None	1.8	None

(a) Dissolved oxygen 5 ppb, pH 7.0 to 7.5, moderate turbulence except at Spools 10 and 11.

(b) Submerged near inlet or outlet of flash chamber of evaporator stage indicated.

(c) Average corrosion calculated from weight loss.

(d) Attack in 90 days. P = surface pitting. C = crevice attack.

(e) Dezincification was observed.

(f) Maximum erosion at spacer.

TABLE 51. CORROSION OF CONDENSER TUBES IN POLLUTED AND CLEAN SEAWATER<sup>(66)</sup>

Alloy	Velocity, 7.5 fps Duration, 64 days		
	Corrosion Rate, mpy		
	CDA No.(a)	Clean Seawater	Polluted Seawater (3 PPM H <sub>2</sub> S)
90/10 Cu-Ni	706	3	34
70/30 Cu-Ni	715	5	26
2% Al brass	687	3	22
6% Al brass	608	5	21
As admiralty brass	443	13	35
Phosphor copper	122	14	105

(a) See Appendix, Table A-1, for nominal alloy compositions.

Of the two alloys, 70Cu-30Ni alloy is usually preferred for more extreme conditions because of its superior corrosion resistance. However, in stagnant seawater, it has a greater tendency to pit than does the 90Cu-10Ni alloy.

In recent years, the 90Cu-10Ni-1.4Fe alloy has received much wider application in both condensers and heat exchangers for desalination plants. Recent cost studies indicate that a 20-gauge 90-10 cupronickel tube is competitive with an 18-gauge aluminum-brass tube. Because of the better performance of the 90-10 cupronickel, it should last longer in spite of the thinner gauge.

Some corrosion results from Office of Saline Water plants as reported by Fuller<sup>(62)</sup> are given in Tables 48, 49, and 50. It can be seen that, for oxygen-free seawater, the advantage of the cupronickels over other copper alloys is not too significant. However, during excursions from normal operating practice, there would be an advantage to having cupronickel-alloy construction. A plot of data from the Freeport, Texas, plant, shown in Figure 48, shows the cupronickel alloys to be slightly superior to admiralty brass and aluminum brass.

A survey of heat-exchanger tubes used in 55 multistage flash distillation plants was conducted by E. H. Newton and J. D. Birkett.<sup>(67)</sup> Most of the tube failures resulted from pitting perforation on the seawater side. Some failures also resulted from distillate corrosion and were ascribed to poor venting of oxygen and carbon dioxide. In the heat-reject stages, seaweed and shells frequently lodged on the tube wells, causing impingement or cavitation attack.

A summary of Newton and Birkett's results for the Office of Saline Water is given in Table 52. It is to be noted that the tube performance of 70Cu-30Ni is superior to that of arsenical aluminum brass or 90Cu-10Ni. A further breakdown of the performance of arsenical aluminum brass tubes compared with that of 90Cu-10Ni tubes is shown in Table 53. From this study, it is evident that the cupronickel tube is superior at the place of highest temperature, namely the brine heater. The arsenical aluminum alloy would be chosen on a performance and cost basis for the reject and recovery stages and for all tubes. Designers of these plants have frequently installed 90Cu-10Ni in those areas where the temperature and other factors were more severe. In an experimentally controlled side-by-side comparison, the behavior of the two alloys probably would be more similar than indicated here.

TABLE 52. COPPER-ALLOY-TUBING PERFORMANCE IN 55 MULTISTAGE FLASH DISTILLATION PLANTS<sup>(67)</sup>

	Arsenical Aluminum Brass	90/10 Cu/Ni	70/30 Cu/Ni	Titanium
Number of Units Using Alloy Tubes(a)	37	18	16	1
Number of Units With Failed Tubes	14	8	0	0
Percent of Units With Failed Tubes	38%	44%	0	0
Service Times (All Tubes), months	9-96	9-79	24-124	26
Average Range	45	39	71	26
Service Time (Failed Tubes), months	10-88	12-79	0	0
Average Range	50	48	0	0
Total Inside Area of Tubes, sq ft	2,415,052	290,416	306,473	72,810
Inside Area of Failed Tubes, sq ft	9,089	2,779	0	0
Percent Failed	0.38	0.96	0	0

(a) Some of the 55 plants used more than one alloy.

TABLE 53. TUBE-AREA FAILURE ACCORDING TO SECTION OF MULTISTAGE FLASH PLANT

Section of Plant	Failure, percent	
	Arsenical Aluminum Brass	90Cu-10Ni
Reject Stage	0.52	1.00
Recovery Stage	0.34	0.25
Brine Heater	1.67	0.93
All Tubes	0.38	0.96

### Titanium and Titanium-Base Alloys

Of presently known materials, titanium and its alloys are among the most resistant to marine environments at ambient temperatures. In most marine applications, a thin oxide film forms on titanium materials and provides complete protection. Under rather special conditions, this passive film will sometimes break down. In spite of titanium's excellent corrosion behavior, three problem areas pertaining to marine environments have been encountered:<sup>(68)</sup> (1) the corrosion pitting observed at oxygen-starved crevices when the seawater is heated to 250 F and above, (2) stress-corrosion cracking in the presence of tensile stresses and a surface flaw, and (3) stress-corrosion cracking when stressed, salt-contaminated titanium is heated to 500 F or higher. Alloy modification and heat treatment can, however, effectively reduce the sensitivity of titanium materials to these types of premature failure.

Normally the oxidizing conditions present in typical marine environments promote the passivity of titanium. Mechanically or chemically damaged surfaces are repaired almost instantly, as shown by studies of potential.

During the last decade, a number of high-strength titanium alloys have been made available commercially. While these alloys have extremely attractive strength-to-density ratios, a knowledge of their corrosion behavior is needed to insure their correct application for service in marine environments.

### Atmosphere

Titanium and its alloys have outstanding resistance to marine atmospheres. At ambient temperatures, they are immune to crevice attack, pitting, and general corrosion.

Titanium alloys have been used in a variety of forms including wire rope, bolted joints with crevices, weldments, etc., with no significant attack by seawater mist or marine air. In marine atmospheric rack exposures, titanium alloys, regardless of type, show no signs of local attack. A slight discoloration is sometimes observed.

Corrosion rates of other selected materials are compared with titanium in Table 54 for a severe marine environment.<sup>(69)</sup> (If Hastelloy C or one of the related nickel-chromium-molybdenum alloys had been included in the comparison it would have shown negligible weight loss similar to titanium.)

TABLE 54. CORROSION RATE OF MATERIALS EXPOSED TO THE ATMOSPHERE FOR 5 YEARS AT KURE BEACH, N. C.<sup>(69)</sup>

Materials	Corrosion Rate(a), mpy	
	80-ft Lot	800-ft Lot
Titanium	Nil	Nil
Alclad 24S-T3	0.0197	0.0034
Alclad 75S-T6	0.0278	0.0034
Type 302 stainless	0.0009	Nil
Type 316 stainless	0.0013	Nil
Inconel	0.0014	0.0003

(a) Average corrosion rates from three specimens.

**Galvanic Attack.** When titanium metals are coupled to common metals like steel or aluminum and exposed to the atmosphere, local acceleration of attack on the anodic member of the couple will take place at or close to the joint, during the period when a wet salt film is present. Coupling of titanium to copper results in some increased attack of the copper, but with stainless steels the galvanic effect of titanium is minimal. Atmospheric galvanic-couple results are summarized in Table 55.

### Splash and Tide

Titanium and its alloys show excellent resistance in the splash and tide zones. The well-aerated seawater in the splash zone is conducive to passivation. Although fouling organisms settle on titanium in the tide zone, there is ample oxygen present to maintain titanium passive. At ambient temperatures,



TABLE 55. EFFECTS OF GALVANIC COUPLING OF TITANIUM TO SELECTED METALS EXPOSED TO THE MARINE ATMOSPHERE IN THE 80-FOOT RACKS AT KURE BEACH, N.C.(69)

Metal Coupled to Titanium	360-Day Exposure			4 Years and 8 Months' Exposure		
	Uncoupled Corr. Rates(a), mpy	Coupled Corr. Rate, mpy		Uncoupled Corr. Rates(a), mpy	Coupled Corr. Rate, mpy	
		Metal Area 7 X Ti Area(b)	Metal Area 1/7 X Ti Area(c)		Metal Area 7 X Ti Area(b)	Metal Area 1/7 X Ti Area(c)
FS-1 magnesium	1.26	2.50	5.5	0.88(d)	1.17(d)	3.52(d)
Alclad 24S-T3	0.06	0.277	0.86	0.0549	0.2130	0.291
52S-1/2H	0.05	0.056	0.199	0.0845	0.0362	0.0813
Alclad 75S-T6	0.10	0.460	0.99	0.0525	0.0786	0.393
Copper	0.12	0.022	0.42	0.0852	0.1350	0.241
Steel (low carbon)	6.13	9.82	Lost	—	—	—
Monel	Nil	0.020	0.032	0.0152	0.0197	0.0320
Inconel	0.011	0.006	0.003	0.0025	0.0029	0.0032
Type 302 stainless	Nil	0.009	0.023	0.0083	0.0091	0.0015
Type 316 stainless	0.004	0.004	0.003	0.0035	0.0029	0.0058

(a) Average of one 6 x 1.5-inch specimen and two 0.75 x 1.5-inch specimens.

(b) One 6 x 1.5-inch specimen.

(c) Average of two 0.75 x 1.5-inch specimens.

(d) Three years and 160 days of exposure.

the rate of attack is so extremely low that only a trace of oxygen is needed to maintain passivity. Thus at crevices or under barnacles, titanium is found completely resistant. Titanium does not pit in the splash and tide zones.

#### Shallow and Deep Ocean

Titanium also has excellent resistance to shallow- and deep-ocean environments. It is one of the few metals that is completely resistant at all depths. The susceptibility of certain alloys to stress-corrosion cracking is discussed separately as are galvanic couple effects with metals either anodic or cathodic to titanium.

A comparison of titanium with other metals after 4.5 years in flowing seawater is given in Table 56. Corrosion rates are calculated from the weight loss. In the case of titanium the loss was so small that it was at the extreme limit of accuracy for the analytical balance used in the experiment.(69) Exposures have now been expanded to include numerous alloys at shallow- and deep-ocean environments. As shown in Table 57, titanium alloys are found to be completely resistant in a wide variety of ocean environments.

TABLE 56. MATERIALS IMMERSSED IN SEAWATER FLOWING AT 3 FPS IN TROUGH AT KURE BEACH, N. C.(69)

Materials(a)	483 Days			4-1/2 Years		
	Corr. Rate, mpy	Max Face Pitting, in.	Max Edge Pitting, in.	Corr. Rate, mpy	Max Face Pitting, in.	Max Edge Pitting, in.
Titanium	Nil	None	None	0.00003	None	None
Alclad 24S-T3	1.10	None	None	1.17	0.035(b)	0.050
Alclad 75S-T6	1.21	None	None	0.781	0.035(b)	0.20
Type 302 stainless	0.08	0.031	0.060	0.088	0.060	0.20
Type 316 stainless	0.16	0.020	0.10	0.061	0.050	0.10
Inconel	Nil	0.008	None	0.094	0.035(b)	0.10

(a) Three specimens of each.

(b) Specimens perforate with pits.

Not only is titanium completely resistant to seawater environments, but it also is resistant to (1) polluted seawater, (2) diluted seawater found in some harbors, and (3) to seawater containing such gases as chlorine, ammonia, hydrogen sulfide, or excess carbon dioxide, and (4) to hot seawater.

Velocity. Titanium has the ability to withstand extremely high seawater velocities with negligible attack. Numerous investigators have established that titanium and many of its alloys will withstand seawater at all velocities of current technical interest. For example, Danek(71) exposed five alloys for 30 days in seawater at 120 fps (see Table 58). All alloys showed very low rates of attack, as did Hastelloy C and Alloy 20.

Titanium also has excellent resistance to impingement attack and to cavitation attack in seawater. Hohman(72) has reported the jet erosion-corrosion rates shown in Figure 58. In this comparison, titanium alloys Ti-6Al-4V and Ti-8Al-2Cu-1Ta were superior to other candidate materials. Thus, for applications like hydrofoils, the combination of excellent resistance to seawater at all velocities and high strength, makes titanium alloys an ideal choice.

Galvanic Attack. Current marine practice is to select titanium only when its higher cost, compared with that of steel or aluminum, can be justified. A complete design of a marine facility in titanium does not yet exist. Normally titanium is associated with other metals in the structure. When titanium is electrically coupled to a common metal, it acts to increase the total cathodic area available to the local anodes on the other metal. Since the corrosion of steel and aluminum, for example, is cathodically controlled, increasing the cathodic area by coupling with titanium allows increased corrosion of the more anodic member. Passive titanium is more noble than practically all other common metals as shown by the galvanic series in Table 6.

The extent of the accelerated attack on the other metal in the couple is governed by the difference in potential between the two metals in seawater, the resistance of the electrical circuit, and the polarization effects resulting from the passage of electric current.

These factors are strongly influenced by the relative areas of the titanium and the other metal of the couple. A small area of titanium coupled to a large area of an anodic metal such as steel, for example, will not greatly accelerate the corrosion of



TABLE 57. SUMMARY OF CORROSION OF TITANIUM AND TITANIUM ALLOYS IN SEAWATER<sup>(70)</sup>

Alloy	Number of Exposures	Exposure Time, days	Exposure Depth, feet	Type of Corrosion Observed
Unalloyed Ti (grade unknown)	10	123-1,064	2,350-6,780	None visible (<0.1 mpy) <sup>(a)</sup>
Unalloyed Ti (Grade RC 55)	4	90-199	4,250-4,500	None visible (<0.1 mpy) <sup>(a)</sup>
Unalloyed Ti (Grade 75A)	8	123-751	5-6,780	None visible (0.0 mpy)
Ti-5Al-2.5Sn	12	123-751	5-6,780	None visible (<0.1 mpy)
Ti-7Al-12Zr	1	123	5,640	None visible (0.0 mpy)
Ti-7Al-2Cb-1Ta	2	181	5	None visible (Fouling stains)
Ti-8Mn	1	402	2,370	
Ti-4Al-3Mo-1V	3	402-1,064	2,370-330	None visible (0.0 mpy)
Ti-6Al-4V	20	123-1,064	5-6,780	None visible (<0.1 mpy, mostly 0.0) <sup>(a)</sup>
Ti-13V-11Cr-3Al	12	123-751	5-6,780	None visible (<0.1 mpy, mostly 0.0)

(a) One panel was reported as 0.19 mpy.

TABLE 58. EFFECT OF VELOCITY ON TITANIUM ALLOYS IN SEAWATER<sup>(71)</sup>

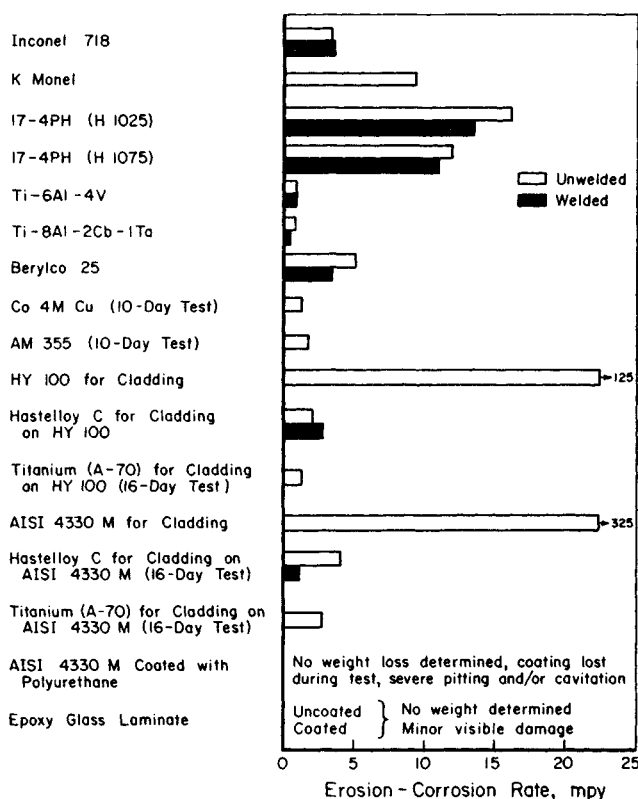
Alloy	Corrosion Rate, at 120 FPS <sup>(a)</sup> , mpy
Commercial Ti	0.29
Ti-6Al-4V	0.44
Ti-13V-11Cr-3Al	0.38
Ti-5Al-2.5Sn	0.22
Ti-7Al-2Cb-1Ta	0.16
Hastelloy C	0.19
Alloy 20	0.38

(a) Calculated from weight loss per unit area.

the latter. Increased attack on a small area of steel will result from coupling it to a large area of titanium.

Some idea of the galvanic corrosion resulting from an anodic to cathodic area ratio of (a) 1 to 10 and (b) 10 to 1 in seawater can be gained from Figure 59. For carbon steel, the actual increment of extra attack is off-scale for the unfavorable ratio of 1 (steel) to 10 (titanium).

Because of the polarization characteristics of titanium, coupling it to steel results in less galvanic corrosion than if the titanium in the couple were replaced by copper, even though the open-circuit potential of a steel-to-copper couple is actually 200 mv less than that for a steel-to-titanium couple. The polarization characteristics for these two couples are shown in Figure 60.<sup>(74)</sup> The weight loss on the steel, in this experiment, was 7 times greater for coupling to copper than for coupling to titanium.

FIGURE 58. RATES FOR JET EROSION-CORROSION IN SEAWATER FOR 30 DAYS AT 90 KNOTS<sup>(72)</sup>

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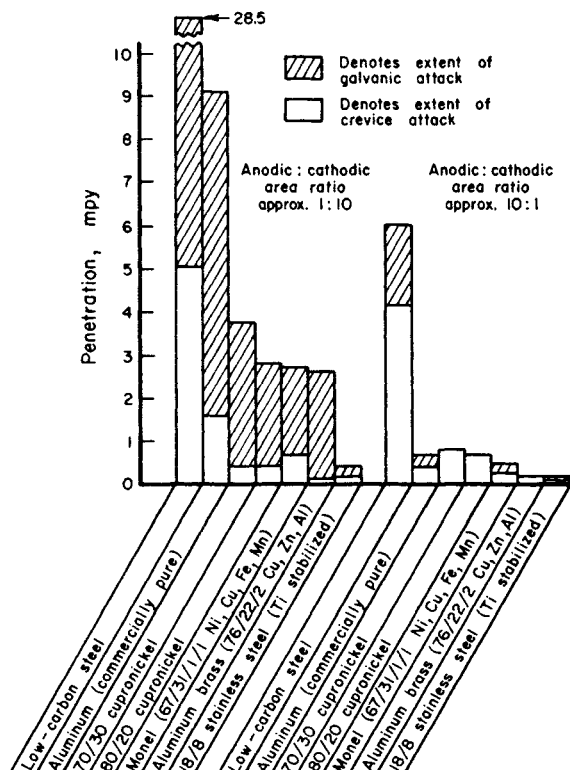


FIGURE 59. BEHAVIOR OF METAL-TO-TITANIUM GALVANIC COUPLES EXPOSED FOR 2,500 HOURS IN AERATED SEAWATER<sup>(73)</sup>

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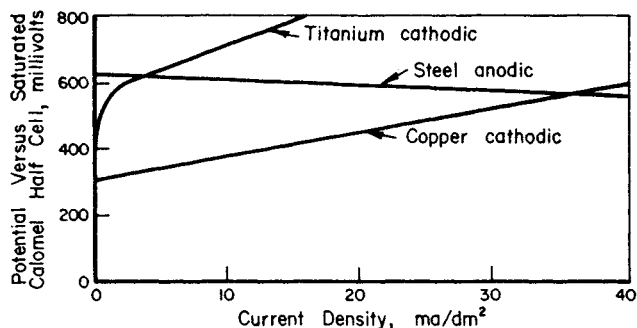


FIGURE 60. CATHODIC POLARIZATION OF COPPER AND TITANIUM AND THE ANODIC POLARIZATION OF STEEL IN SEAWATER<sup>(74)</sup>

Titanium is readily passivated not only as the cathode in a couple but also as the anode. Platinized titanium is widely used as an impressed-current anode with complete success. In this example, the anodically polarized titanium is not corroded to any great extent.

## Mud Zone

Ocean-bottom sediments vary according to their origin. Some are formed by mechanical deterioration of rocks and minerals, such as by rivers and glaciers. Another type consists of the shells and skeletons of animals. Typically, these sediments contain organic matter. Although the mud zone can present special corrosion problems to common metals, chiefly because of the presence of sulfides produced by the action of sulfate-reducing bacteria, this is not a factor in the case of titanium and its alloys. Titanium and its alloys are found to be completely resistant in both shallow- and deep-ocean sediments. However, titanium alloys found to be susceptible to stress-corrosion cracking in seawater are also susceptible to this type of failure in the sediment.

## Stress-Corrosion Cracking

Early exposure tests on titanium materials included stressed specimens in both seawater and atmospheric environments. On the basis of the results of simple U-bend or four-point loaded specimens, the passive film on smooth surfaces of titanium and its alloys gives complete protection to marine environments even under high tensile stresses. The lack of stress-corrosion cracking was considered to be related to the fact that no local corrosion, such as pits, which could act as stress raisers and stimulate the formation of cracks, developed on the titanium surface.

In recent years there has been serious concern that the results of such exposure tests on stressed panels of titanium materials in marine and other chloride-ion environments did not permit full evaluation of the susceptibility to stress-corrosion cracking. Surface defects are often present in actual structures, which may arise from weldments, fabrication damage such as force-fitting, etc. Brown<sup>(76)</sup> considered this situation and first presented, in November 1964, a stress-corrosion test to evaluate the susceptibility of titanium materials in chloride solutions while under stress in a cantilever-beam test machine. The key to the method is obtaining a notch of sufficient acuity to allow stress-corrosion cracking to proceed in a susceptible alloy. With this test, and other developments, the mechanism of stress-corrosion-cracking failure is now better understood. Essentially, the fracture toughness of the alloy, with the surface defect, is reduced by the presence of the chloride ion.

The nature and size of the defect or critical flaw can be expected to play a significant role in whether or not stress-corrosion cracking failure will take place.

Judy and Goode<sup>(77)</sup> have studied the critical flaw depth for a whole series of titanium alloys in 3.5 percent sodium chloride using the cantilever-beam method. While sodium chloride solution is not equivalent, for most purposes, to seawater, in the present test it should give an order of merit which is indicative of seawater behavior. Even though a number of alloys are relatively insensitive, most of them, as shown in Figure 61, can be made to stress-corrosion crack at some combination of flaw geometry and applied stress.

Preliminary screening tests indicate the following alloys to be insensitive to seawater crack propagation for the conditions used:

Ti-2Al-4Mo-4Zr\*  
 Ti-4Al-3Mo-1V  
 Ti-5Al-2Sn-2Mo-2V\*  
 Ti-6Al-2Mo\*  
 Ti-6Al-2Sn-1Mo-1V\*  
 Ti-6Al-2Sn-1Mo-3V\*  
 Ti-6Al-2Cb-1Ta-0.8Mo  
 Ti-6.5Al-5Zr-1V\*  
 Ti-7Al-2.5Mo\* (as received and beta annealed + WQ + 1100 F, aged 2 hr).

In general, all alpha alloys and near-alpha alloys are susceptible, whereas alpha-beta alloys are resistant. The effect of seawater on titanium alloys is summarized in Table 59. At the present time, the Ti-6Al-4V alloy with low interstitials (low oxygen) is considered one of the best of the more insensitive commercial alloys for seawater service.

One of the alloys listed in Table 59 is the super-alpha alloy Ti-8Al-2Cb-1Ta. When first developed, it was found metallurgically unstable and highly susceptible to stress-corrosion cracking in seawater. Lowering the aluminum content 1 percent did not alter the susceptibility to cracking. Research has since established that the presence of an embrittling constituent in the structure of the metal probably is an essential feature of the seawater stress-corrosion susceptibility. Titanium-aluminum alloys with Ti<sub>3</sub>Al present are apt to be prone to stress-corrosion cracking. This constituent tends to be present in alloys with 4 percent or more of aluminum. In addition to the aluminum content, other elements are found to play a role. Oxygen contents higher than 0.8 percent decrease the tolerance for aluminum. Isomorphous beta stabilizers such as molybdenum, vanadium, or columbium increase the tolerance for aluminum, although higher oxygen contents decrease their effectiveness.

On the basis of this concept, the excellent stress-corrosion-cracking characteristics of the Ti-6Al-2Cb-1Ta-0.8Mo, Ti-6.5Al-1Cb-1Ta-1.2Mo, and the Ti-7Al-2.5Mo alloys are explained. In each case, the beta stabilizers, particularly the molybdenum content, allow the employment of higher aluminum contents in the alloy.

The thermal history of an alloy will alter its degree of susceptibility. The Ti<sub>3</sub>Al formation is dependent on the aging time of the alloy in the alpha plus Ti<sub>3</sub>Al field which extends up to 1100 F-1300 F for aluminum contents of 4 to 8 percent. By rapid quenching through this temperature range, TiAl<sub>3</sub> formation can be prevented and the sensitivity to stress-corrosion cracking in seawater can be reduced.(80)

Methods other than adjustment of composition and heat treatment have been studied for the control of stress-corrosion cracking. Cathodic current will, under some conditions, arrest the metal dissolution at the root of a crack. Once the polarizing current is removed, the dissolution will resume. A rapidly moving crack will not be arrested by cathodic current.

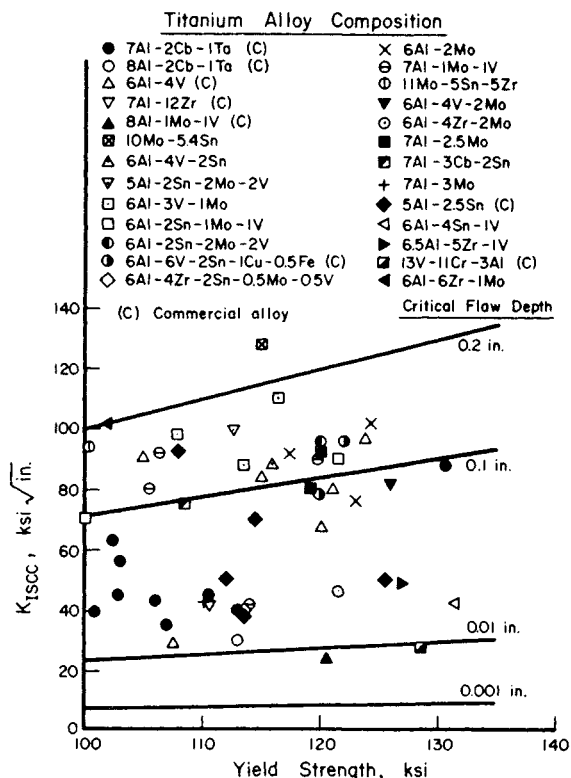


FIGURE 61. STRESS-CORROSION-CRACKING RESISTANCE INDEX FOR TITANIUM ALLOYS IN 3.5 PERCENT SALT WATER(77)

Alloys which have shown some degree of susceptibility are listed below, but not necessarily in order of susceptibility(78):

Unalloyed titanium (with high oxygen content, i.e., 0.317 percent)

Ti-8Mn

Ti-2.5Al-1Mo-11Sn-5Zr-0.2Si (IMI-679)

Ti-3Al-11Cr-13V

Ti-4Al-4Mn

Ti-5Al-2.5Sn

Ti-6Al-2.5Sn\*

Ti-6Al-4V (standard grade)

Ti-6Al-3Cb-2Sn\*

Ti-6Al-4V-1Sn\*

Ti-6Al-4V-2Co\*

Ti-6Al-6V-2.5Sn\*

Ti-7Al-2Cb-1Ta

Ti-7Al-3Cb (as received and beta annealed)\*

Ti-7Al-3Mo\*

Ti-7Al-2Cr-1Ta\*

Ti-7Al-3Cb-2Sn\*

Ti-8Al-1Mo-1V

Ti-8Al-3Cb-2Sn\*.

\* = Experimental compositions.

TABLE 59. EFFECT OF SEAWATER ON TITANIUM ALLOYS<sup>(78)</sup>

Alloy	Condition	Test Conditions to Cause Failure <sup>(a)</sup>					
		In Air			In Seawater		
		Slow-Notch	Static Load		Static-Load Cantilever Test		
		Bend Test	Cantilever Test		Nominal	Fracture	
		Nominal	Bending		Bending	Appearance	
		Stress,	Stress,	Time,	Stress,	Time,	Seawater
		ksi	ksi	min	ksi	min	Embrittled?
<b>Alpha Alloys</b>							
Unalloyed Ti (RS-70)	Alpha rolled	182	157	45	64	3	Yes
	Alpha rolled + 1400 F, 16-hr AC	—	—	—	104	1	Yes
Ti-5Al-2.5Sn	Alpha-beta rolled	170	—	—	65	3	Yes
Ti-6Al-2.5Sn	Beta rolled	233	181	40	110	3	Yes
	Alpha-beta rolled	221	166	760	109	6	Yes
<b>Near-Alpha Alloys</b>							
Ti-8Al-2Cb-1Ta	Beta rolled	186	—	—	129	Immed	Yes
Ti-7Al-3Cb <sup>(b)</sup>	Beta rolled	232	—	—	110	10	Yes
Ti (0.06 O <sub>2</sub> ) <sup>(b)</sup>	Alpha-beta rolled	193	166	70	125	3	Yes
Ti-7Al-3Cb <sup>(b)</sup>	Beta rolled	235	—	—	144	Immed	Yes
Ti (0.1 O <sub>2</sub> ) <sup>(b)</sup>	Alpha-beta rolled	256	—	—	131	4	Yes
Ti-7Al-3Cb-2.5Sn <sup>(b)</sup>	Beta rolled	200	—	—	111	1	Yes
	Alpha-beta rolled	213	—	—	114	9	Yes
Ti-6Al-3Cb-2Sn <sup>(b)</sup>	Beta rolled	220	—	—	120	Immed	Yes
Ti-7Al-3Cb-2Sn <sup>(b)</sup>	Beta rolled	233	—	—	158	Immed	Yes
Ti-8Al-3Cb-2Sn <sup>(b)</sup>	Beta rolled	110	—	—	126	Immed	Yes
Ti-6.5Al-5Zr-1V <sup>(b)</sup>	Alpha-beta rolled	222	186	180	186	200	No
<b>Alpha-Beta Alloys</b>							
Ti-6Al-2Sn-1Mo-1V <sup>(b)</sup>	Alpha-beta rolled	209	196	9	180	1430	No
Ti-6Al-4V (low O <sub>2</sub> )	Alpha-beta rolled	—	—	—	180	Immed	No
Ti-6Al-4V (high O <sub>2</sub> )	Alpha-beta rolled	101	135	15	103	150	No
Ti-6Al-2Mo <sup>(b)</sup>	Alpha-beta rolled	—	—	—	165	180	No
	Alpha-beta rolled + 1750 F, 1-hr AC + 1100 F, 2-hr AC	—	—	—	191	1	No
Ti-7Al-2.5Mo <sup>(b)</sup>	Alpha-beta rolled	209	198	500	169	Immed	No
	Alpha-beta rolled + 1735 F, 1-hr WQ	216	—	—	192	150	No
	Alpha-beta rolled + 1735 F, 1-hr WQ + 1100 F, 2-hr AC	205	166	25	135	13	No
Ti-5Al-2Sn-2Mo-1V <sup>(b)</sup>	Beta rolled	242	190	6	177	105	No
	Alpha-beta rolled	185	171	1	143	110	No
Ti-6Al-2Sn-3V-1Mo <sup>(b)</sup>	Beta rolled	211	115	1845	120	342	No
	Alpha-beta rolled	192	106	1780	140	2	No

(a) All specimens were fatigue cracked to a total notch depth of 25 to 35 percent.

Immed = Immediate.

(b) Experimental compositions.

Cathodic current also can be provided by applying a coating of a sacrificial metal such as zinc. However, metallic (and organic) coatings are more difficult to apply on titanium than on, say, aluminum. Most of the coatings that have been tried are not successful.

### Pitting Attack

At ambient temperatures, titanium and its alloys are completely free from pitting attack in marine environments. In general, the potentials of titanium alloys in saline solutions at room temperatures are considerably more noble than the spontaneous corrosion potential. However, pitting can be induced by the passage of anodic current.

Since titanium and its alloys are excellent candidate materials for applications involving handling of hot seawater in desalination and hot brines in the chemical industry, it is of interest to establish whether there is a greater susceptibility to pitting at elevated temperatures.

Posey and Bohlman<sup>(81)</sup> conducted an electrochemical investigation of pitting in saline solutions. The effect of temperature on the pitting potential of titanium and several alloys with aluminum present was measured in 1M NaCl. As shown in Figure 62, titanium has a very high pitting potential (more than 9.0 volts) at ordinary temperatures, but as the temperature is elevated to 200 C (392 F), the pitting potential drops to a low value. A small addition of 1 or 2 percent of aluminum had little effect, while additions of 4 percent and higher

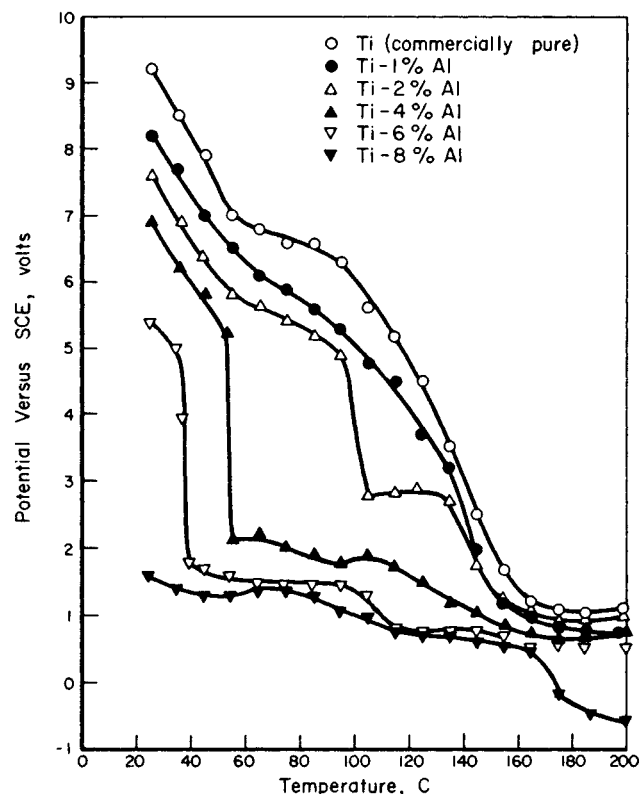


FIGURE 62. EFFECT OF TEMPERATURE ON PITTING POTENTIALS OF TITANIUM-ALUMINUM ALLOYS IN 1 M NaCl<sup>(81)</sup>

resulted in a marked drop in the pitting potential, especially at lower temperatures. Thus, titanium alloys with 4 percent or more aluminum can be expected to have less resistance to pitting as the temperature is raised beyond 60 C (130 F). Other experiments demonstrated that as little as 1 percent molybdenum markedly increased the pitting potential at elevated temperatures [above 125 C (275 F)].<sup>(81)</sup>

This experimental investigation of pit susceptibility of titanium and the effect of temperature agrees well with the limited information available on the behavior of titanium in hot seawater. The largest desalination plant using titanium heat exchangers has been operating at St. Croix Island for almost 4 years. Inspections made so far indicate no pitting on any of the titanium components for seawater temperatures ranging from 200 F to as high as 250 F, see Table 52.

### Crevice Corrosion

Crevice corrosion on titanium materials has been experienced in hot saline solutions, including seawater. The attack is more likely to develop with increase in (1) temperature, (2) salt concentration, and (3) time. Lower pH solutions also tend to be more active. Crevices that are restricted show a greater tendency to be attacked. In seawater and its brines, the attack has been observed at as low as 250 F.

Crevice attack may be considered a form of pitting at the restricted interfaces between mating surfaces. One of the surfaces may be other than titanium, for example, Teflon or other gasket material. Although the mechanism involved in crevice corrosion appears to be similar to that involved in pitting, for titanium there may be differences. The electrochemistry of crevice corrosion on titanium has been investigated by Griess.<sup>(82)</sup> Polarization studies were made of the effects of temperature, pH, and chloride ion concentration. As shown in Figure 63, a higher critical current density is required for passivity as the temperature is increased. Similarly, as the pH of the chloride solution, using hydrochloric acid, was decreased, the critical current density also increased. At low pH values, increasing the chloride concentration also raised the critical current density required for passivation.

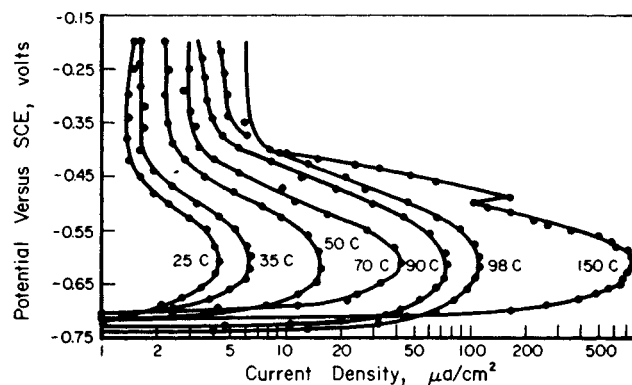


FIGURE 63. THE EFFECT OF TEMPERATURE ON THE ANODIC POLARIZATION OF TITANIUM IN 0.9 M NaCl-0.1 M HCl<sup>(82)</sup>

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From this and other experimental evidence, certain aspects of crevice attack on titanium can be explained. As with other metals, a differential aeration cell will initiate the action. At ordinary temperatures this cell does not operate, since the amount of oxygen required to maintain passivity in the crevice is so low that it is not consumed. At elevated temperatures the oxygen required to repair breaks in the passive film may be insufficient and local active sites may develop, lowering the potential in the crevice. To maintain electrochemical neutrality, chloride ions migrate into the crevice and sodium ions migrate to the outside. This results in increased acidity and accelerated local attack.<sup>(82)</sup> Once initiated, the corrosion can continue as a differential concentration cell, whether oxygen is present or not.

This mechanism seems to fit the salient facts of crevice attack. For titanium materials, attack will not take place unless the crevice is sufficiently restricted and temperature and concentration are favorable. An approximation of crevice attack in actual practice as related to salt concentration and temperature is shown in Figure 64. Attack on unalloyed titanium (Grade Ti-50A) is not to be expected in seawater until the temperature is about 250 F, or, say, 300 F with the Ti-0.2Pd alloy. The superior corrosion resistance of the Ti-0.2Pd alloy is attributed to enrichment of palladium on the crevice surface by the initial attack and its promotion of cathodic passivation.<sup>(84)</sup> Alloys containing molybdenum or nickel also should be more resistant to crevice attack.<sup>(82)</sup>

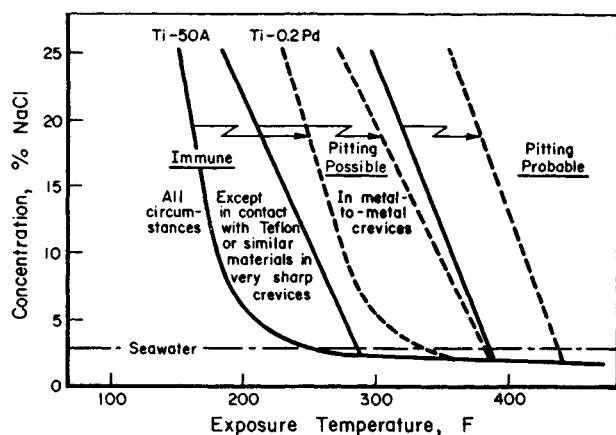


FIGURE 64. IMMUNITY OF TITANIUM (AND ITS 0.2 Pd ALLOY) FROM CREVICE CORROSION IN SALT SOLUTIONS<sup>(83)</sup>

#### Hot-Salt Cracking

During the early period of development of titanium, hot forming of sheet materials and creep testing in the laboratory sometimes resulted in an unexpected loss of properties. These failures were traced to salt contamination on the metal surface, and the phenomenon has since been known as hot-salt cracking. This type of failure has been repeatedly demonstrated in laboratory experiments by applying a thin layer of salt to a heated sample and maintaining a high temperature with a high stress for time periods ranging from a few to several thousand hours.<sup>(79)</sup>

In the marine field, there are several applications of titanium materials where the service conditions involve a combination of sea-salt contamination and elevated temperature, which at first appearance seem to be similar to the requirements for hot-salt cracking. For example, jet engines as used in

marine-based aircraft or on decks of aircraft carriers are known to ingest salt air or salt spray into their air-compressor intakes. Fuel for these engines may also be contaminated by seawater getting into the ship's tanks from seawater ballasting. Salt-contaminated external titanium surfaces on present and future supersonic transocean aircraft might be expected to fail because of development of high temperature on leading edges during flight.

Actually, there have been no reported failures of titanium components in any of these applications from hot-salt cracking in service. However, an intensive study has been conducted in recent years in order to find alloys resistant to this failure mode and to establish methods of prevention.

All of the commercial alloys, with the possible exception of unalloyed titanium, are susceptible to some degree to hot-salt cracking. The temperature range of greatest susceptibility is 550 to 800 F, although failures are occasionally reported outside these limits.

Susceptibility to attack varies with composition. High aluminum content is particularly undesirable, e.g., the Ti-8Al-1Mo-1V alloy is very susceptible to hot-salt cracking.<sup>(85)</sup> Alloys with 6 percent or less aluminum generally have more resistance to hot-salt cracking. For example, the widely used Ti-6Al-4V alloy has intermediate resistance to hot-salt cracking. Among the most resistant alloys are Ti-4Al-3Mo-1V and Ti-2.25Al-1Mo-1.1Sn-5Zr-0.25Si.

Under present conditions of marine service, titanium alloys apparently do not experience the temperature, stress, and time combination which leads to hot-salt cracking. The cyclic temperature of the service may inhibit the conditions which cause cracking at constant temperature in the laboratory. However, it is conceivable that the new use of jet engines on the decks of seagoing vessels, where they may run continuously for several hundred hours at a time, could duplicate the time and temperature conditions that cause hot-salt cracking in the laboratory.

#### Aluminum and Aluminum-Base Alloys

Aluminum alloys are finding ever-increasing application in marine environments. For marine structures, the 5086\*-H32 or -H34 alloy has been widely used. It has excellent resistance to corrosion, is weldable, and can be strain hardened to provide moderately high strength. Other 5000 series alloys which also find use are 5083 and 5456. For applications requiring higher strength, the corrosion-resistant 6061-T6 has often been selected. The welding of 6061 causes loss in ductility, but the alloy can be heat treated to provide higher strength than is available with 5086-H32.

Alloys with relatively poor corrosion performance in marine environments include the 7000 series (zinc and magnesium), the 2000 series (copper), and the 4000 series (silicon).

Since the corrosion resistance depends on the maintenance of the passive oxide film, aluminum and its alloys generally are most resistant in those marine environments where the metal surface is freely exposed to well-aerated seawater or to the atmosphere. Failures by local attack such as by pitting, crevice corrosion or exfoliation, or stress cracking are characteristic of many alloys, particularly the high-strength alloys.

\*For the readers' convenience, the compositions of the aluminum alloys cited are listed according to alloy designation in the Appendix, Table A-2.



A discussion of the behavior of aluminum alloys in each type of marine environment and some examples of successful application are given in the following sections.

### Atmosphere

Alloys which exhibit good behavior when exposed to marine atmospheres include 1100, 3003, 3004, 5052, 5056, 5083, 5085, 5154, 5456, and 6061. When aluminum alloys are exposed to an aggressive marine location, the initial corrosion rate, based on weight loss, may be as high as 4 mpy. After a year or so, the rate usually tapers off to a low value approaching 0.1 mpy.

The good performance of Alloy 1100 is illustrated in Table 60, which summarizes 10- and 16-year exposure data from widely different marine sites. Even at La Jolla, California, where the mist-laden air and high wind combine to bring a heavy deposit of salt to the metal surface, the total loss in thickness in 10 years was only 0.56 mil.

TABLE 60. TEN-YEAR WEATHERING RESULTS FOR 1100 ALUMINUM IN MARINE ATMOSPHERES(86)  
(Panels 9 x 12 x 0.035 Inch)

Site	Corrosion Rate(a), mpy	Tensile Loss, percent
Sandy Hook, N. J.	0.002	3.1
Key West, Fla.	0.004	1.7
La Jolla, Calif.	0.028	14.1
Cristobal, C. Z.(b)	0.007	-

(a) Calculated from weight loss.

(b) Sixteen-year exposure.(88)

Corrosion rates at three marine sites for Alloys 1100, 1180, 3003, 5050, 5052, 5154, 5086, and 6061, as summarized by Ailor(87), are presented in Table 61. After 5 years, the highest rate observed for any of the alloys was 0.025 mpy. For the heat treatments indicated in the table, all the alloys are resistant and show very low rates of attack.

TABLE 61. MARINE-EXPOSURE RESULTS FOR ALUMINUM ALLOYS(87)

Alloy(a)	Corrosion Rates, mpy (Calculated From Weight Loss)									
	Bohus-Malmon, Sweden			Arenzano, Italy,	Kure Beach, North Carolina					
	1 Yr	3.06 Yr(b)	5.12 Yr	1.75 Yr	80-Foot Lot			800-Foot Lot		
	1 Yr	2 Yr	5 Yr	1 Yr	2 Yr	5 Yr	1 Yr	2 Yr	5 Yr	
1100-H14	0.009	0.002	0.010	0.035	0.027	0.028	0.018	0.021	0.022	0.009
1180-H14	0.008	0.003	0.006	0.024	0.024	0.023	0.025	0.020	0.018	0.009
3003-H14	0.009	0.003	0.009	0.036	0.037	0.027	0.018	0.022	0.021	0.009
5050-H34	0.009	0.003	0.007	0.023	0.026	0.022	0.015	0.020	0.014	0.007
5052-H34	0.008	0.006	0.007	0.020	0.028	0.021	0.010	0.018	0.014	0.009
5154-H34	0.009	0.004	0.007	0.023	0.023	0.020	0.013	0.018	0.014	0.007
5086-H34	0.007	0.001	0.007	0.023	0.023	0.019	0.010	0.018	0.013	0.010
6061-T6	0.011	-	0.012	0.041	0.033	0.027	0.019	0.034	0.021	0.011

(a) H14 = strain hardened; H34 = strain hardened, then stabilized; T6 = solution heat treated, then artificially aged.

(b) Values reflect insufficient cleaning after exposure.

Corrosion rates for Alloys 1100 and 6061, exposed at Cristobal, Canal Zone, are given in Table 62. The attack was uniform (pits less than 5 mils deep) for the entire 16 years, with an average penetration of 0.007 mpy for each alloy.(88)

For atmospheric service, the aluminum-magnesium alloys, e.g., 5050, 5052, 5086, and 5154, are considered among the most suitable. Alloy 6061 is also highly satisfactory.

Because of its resistance to attack, aluminum is usually exposed without added surface protection. However, anodizing may be used to enhance the resistance of the natural oxide film. Even better results are achieved with a protective coating. Paint adheres well to aluminum and a suitable marine formulation will provide long-lasting additional protection. Marine experience with aluminum structures has shown that repainting is required only about half as often as would be the case for the same marine paint system applied to steel construction.

**Pitting Attack.** Since many aluminum alloys tend to pit in marine atmospheres, this behavior must be considered in a specific application. Five-year results at three marine sites for alloys 1180, 3003, 6061, and 5086, are presented in Figure 65.

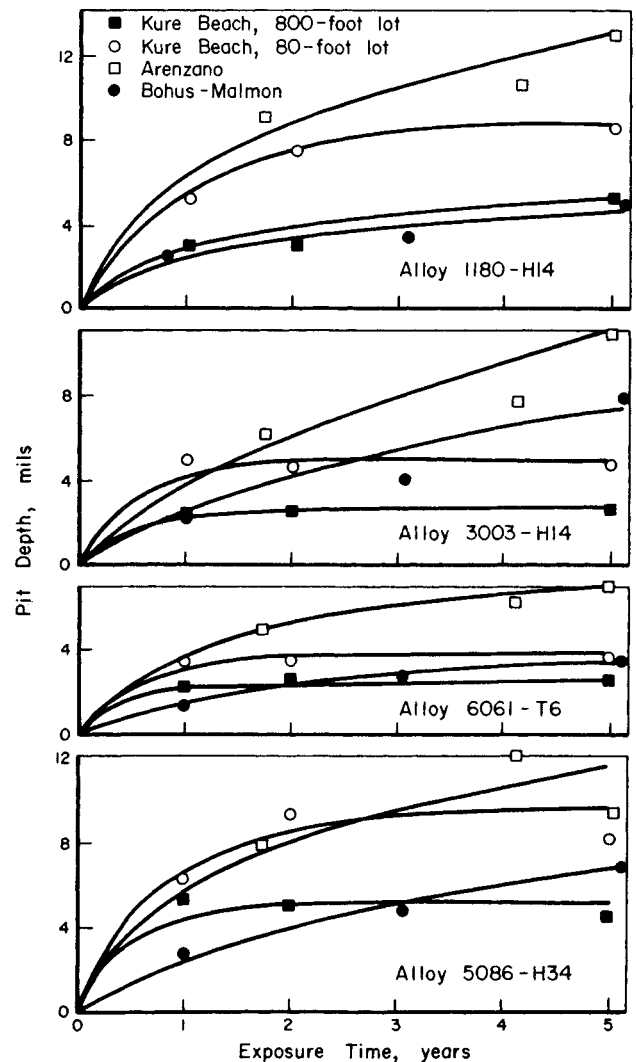


FIGURE 65. MAXIMUM MEASURED PIT DEPTHS FOR ALUMINUM ALLOYS IN SELECTED MARINE ATMOSPHERES(87)

TABLE 62. CORROSION OF ALUMINUM ALLOYS EXPOSED 16 YEARS IN THREE TROPICAL ENVIRONMENTS IN THE PANAMA CANAL ZONE(88)

	Average Penetra- tion(a), mils			Depth of Pitting(b), mils						Tensile Strength Loss % (c), 8 Yr	Type of Corrosion Attack(d), 16 Yr
				Average of 20 Deepest Pits			Deepest Pits				
	1 Yr	8 Yr	16 Yr	1 Yr	8 Yr	16 Yr	1 Yr	8 Yr	16 Yr		
<u>Alloy 1100</u>											
<u>Immersion</u>											
Seawater	0.28	0.61	0.97	9(13)	11	17	15	19	33	2	J
Mean Tide	0.06	0.31	0.53	11(9)	14	39	29	37	67	1	JQ
<u>Atmospheric</u>											
Marine	0.01	0.02	0.11	N	N	N	N	N	N	0	A
<u>Alloy 6061</u>											
<u>Immersion</u>											
Seawater	0.28	0.73	0.91	N	23	14	N	49	79	0	J
Mean Tide	0.04	0.13	0.29	N	N	17	N	N	41	0	J
<u>Atmospheric</u>											
Marine	0.03	0.03	0.11	N	N	N	N	N	N	1	A

(a) Calculated from weight loss and specific gravity.

(b) Represents depth of penetration from original surface; N – measurable pits; number in parentheses gives number of measurable pits when less than 20.

(c) Percent change in tensile strength calculated on basis of 1/4–inch–thick metal and average of four tests for underwater specimens, and 1/16–inch–thick metal and average of three tests for atmospheric specimens.

(d) A – uniform attack; J – marine fouling contact; Q – pitting attack (random).

In this comparison, Alloy 6061 showed the best performance, with maximum pitting ranging from 3 to 7 mils. Note that the pitting tends to taper off with time. In an ASTM exposure test, the maximum depth of pitting after 20 years' exposure was found to be 14 mils for Alloy 1100-H14 and 10.2 mils for Alloy 3003-H14. The maximum penetration was higher than usually experienced. Other experience suggests that 3003 is superior to 1100 as regards pitting resistance in the atmosphere. Since the rate of pitting decreases with time, designers can allow for it in structural applications such as storage tanks, where penetration would mean failure. In marine service, pits are observed both on the skyward and groundward faces of boldly exposed surfaces.

In general, alloys such as 5083, 5086, 5154, 5052, and 6061 are being used for applications involving resistance to marine atmosphere. Typical applications include deck houses and superstructure on ships and off-shore structures, and towers and buildings on shore-based marine establishments.

#### Splash and Tide

Alloys suitable for atmospheric service also do well in the splash zone. Well-aerated seawater splashing on the aluminum surface tends to maintain passivity. As with other environmental zones, crevices and pockets where seawater can collect should be avoided. Although there may be less tendency for pits to initiate in the splash zone, once started the rate of attack may be quite high.

The corrosion rate can be expected to be higher in mean-tide exposure than in the splash zone but less than in the fully

immersed condition. Pitting attack on the other hand may be quite similar, regardless of the exposure condition. A comparison of the mean-tide and submerged conditions in the Pacific off the Canal Zone is shown in Figure 66 for Alloys 6061-T and 1100. The mean-tide loss is only half that resulting from continuous immersion. The weight-loss attack was similar for both alloys in the mean-tide condition but the pitting was more severe for the 1100 alloy. After 8 years' exposure, the loss in strength at mean-tide exposure was 0 percent and 1 percent, respectively, for these two alloys. While either alloy

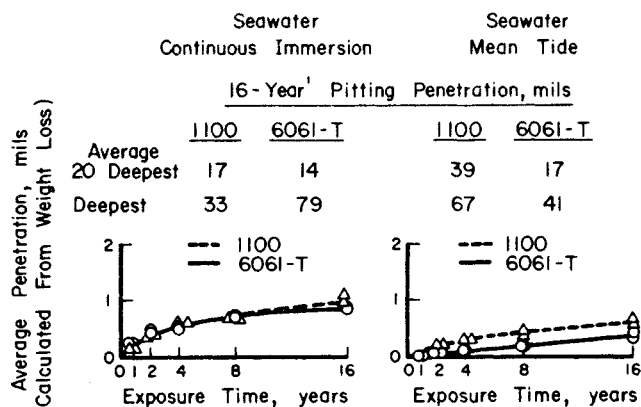


FIGURE 66. COMPARISON OF ALUMINUM ALLOY 6061-T WITH COMMERCIALLY PURE 1100 ALUMINUM FOR 16 YEARS OF EXPOSURE IN SEAWATER ENVIRONMENTS(88)

could be used, Alloy 6061 normally would be selected. As shown in Table 62, after 16 years the weight-loss penetration was 0.29 and 0.53 mil and the deepest pits were 41 and 67 mils, for the 6061 and 1100 alloys, respectively.

### Submerged

For service in seawater, certain alloys are found to have superior corrosion resistance. In some cases, special heat treatments as well as carefully controlled composition are required to achieve the best results. Alloys which find application in seawater include 1100, 1180, 3003, 5050, 5052, 5456, 5083, 5086, and 6061.

**Pitting Attack.** Aluminum alloys tend to pit in seawater. This type of localized breakdown is accelerated greatly by the chloride ions present. Pitting is often associated with metallurgical factors such as grain boundaries.<sup>(89)</sup> One should expect a lower rate of penetration as the oxygen content of seawater is increased, although other factors may mask this effect in practice. Oxygen content, rather than depth, affected the pitting behavior in Pacific Ocean experiments as Reinhart<sup>(90)</sup> has shown. He finds the pitting attack of several aluminum-magnesium (5000 series) alloys at three oxygen levels to be the highest at the lowest oxygen level (see Figure 67).

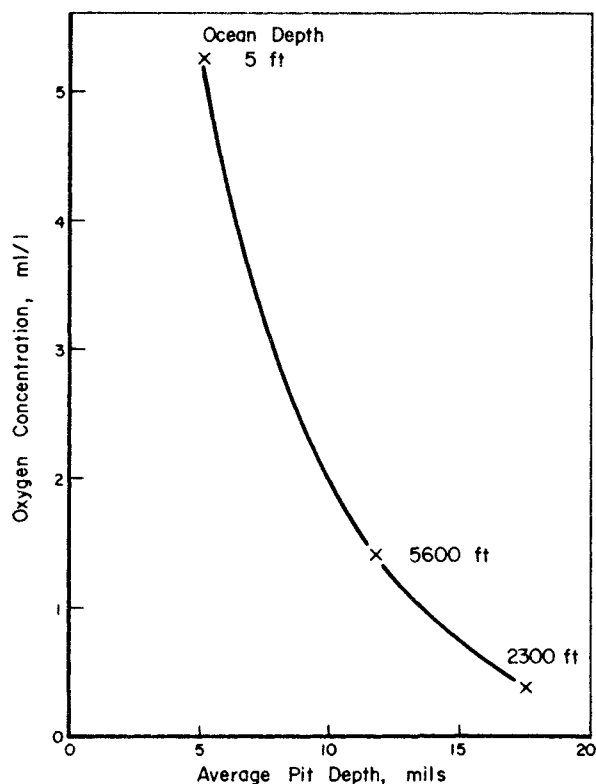


FIGURE 67. RELATION BETWEEN AVERAGE PIT DEPTHS OF ALUMINUM-MAGNESIUM ALLOYS (5000 SERIES) AND OXYGEN CONCENTRATION OF SEAWATER<sup>(90)</sup>

The pitting rate is highest during the first year or so of exposure, after which it attenuates to much lower rates. For some alloys, pitting is not a serious problem, at least in well-aerated surface water. Groover, et al.<sup>(91)</sup> found that the

comparative sensitivity of aluminum alloys to pitting could be established by measuring their electropotential in seawater. Alloys with relatively electronegative potentials (i.e., -0.69 to -0.89 volt versus the Ag/AgCl reference electrodes) tended to be more susceptible to pitting and crevice attack than alloys with more electropositive potentials. These results, plotted in Figure 68, show the high-strength alloys of the 2000 and 7000 series to be particularly susceptible to pitting, whereas alloys in the 5000 series are relatively immune. It is interesting to note that a heat treatment for a given alloy which results in a less-negative potential also increases the susceptibility to pitting, compare 5052-H32 with 5052-H34 or 6061-T6 with 6061-T651.

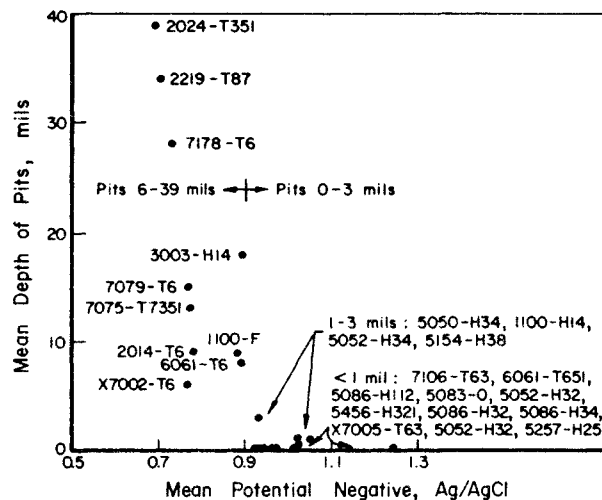


FIGURE 68. RELATION BETWEEN PITTING CHARACTERISTICS AND ELECTRODE POTENTIALS OF ALUMINUM ALLOYS EXPOSED IN SEAWATER AT KEY WEST, FLORIDA<sup>(91)</sup>

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Pitting data for aluminum alloys are more difficult to compare because of the large variation in the behavior of replicate panels. A pit, once started, may deepen at a very high rate, after which it may attenuate or stop altogether. Some trends can be observed, however, among alloys for long periods of exposure and for heat treatments for a given alloy. The pitting resistance of Alloy 6061 in the T4 heat treatment, for example, is superior to that in the T6 condition (Table 63).

TABLE 63. MAXIMUM PITTING DURING 10-YEAR EXPOSURE OF PLATE SPECIMENS<sup>(89)</sup>

Alloy	Pitting Depth, mils		
	Harbor Island, N. C.	Halifax, N. S.	Equimalt, B. C.
1100-H14	40	32	30
3003-H14	21	22	20
6061-T4	14	33	50
6061-T6	95	54	116
7072-P(a)	56	150	26
7075-T6	66	P(a)	P(a)

(a) P = perforated.

Godard and Booth(89) summarize the results for five alloys after 10 years' exposure at three marine sites. Alloy 7075-T6 showed poor resistance to pitting attack, whereas Alloys 1100-H14 and 3003-H14 were somewhat less severely attacked.

In pipe experiments with an aluminum alloy containing 0.02Cu, 0.21Fe, 0.11Si, and 0.016Ti, pitting was shown to

decrease as the velocity of the seawater increased from 1 to 5 fps. Beyond 5 fps, the pitting rate again increased.(89)

The depth of pitting tends to be higher in the deep ocean than in surface waters. Even resistant alloys such as the 5000 series show severe pitting. An overall picture of the relative pitting tendency in deep Pacific waters is shown in the bar graph in Figure 69.

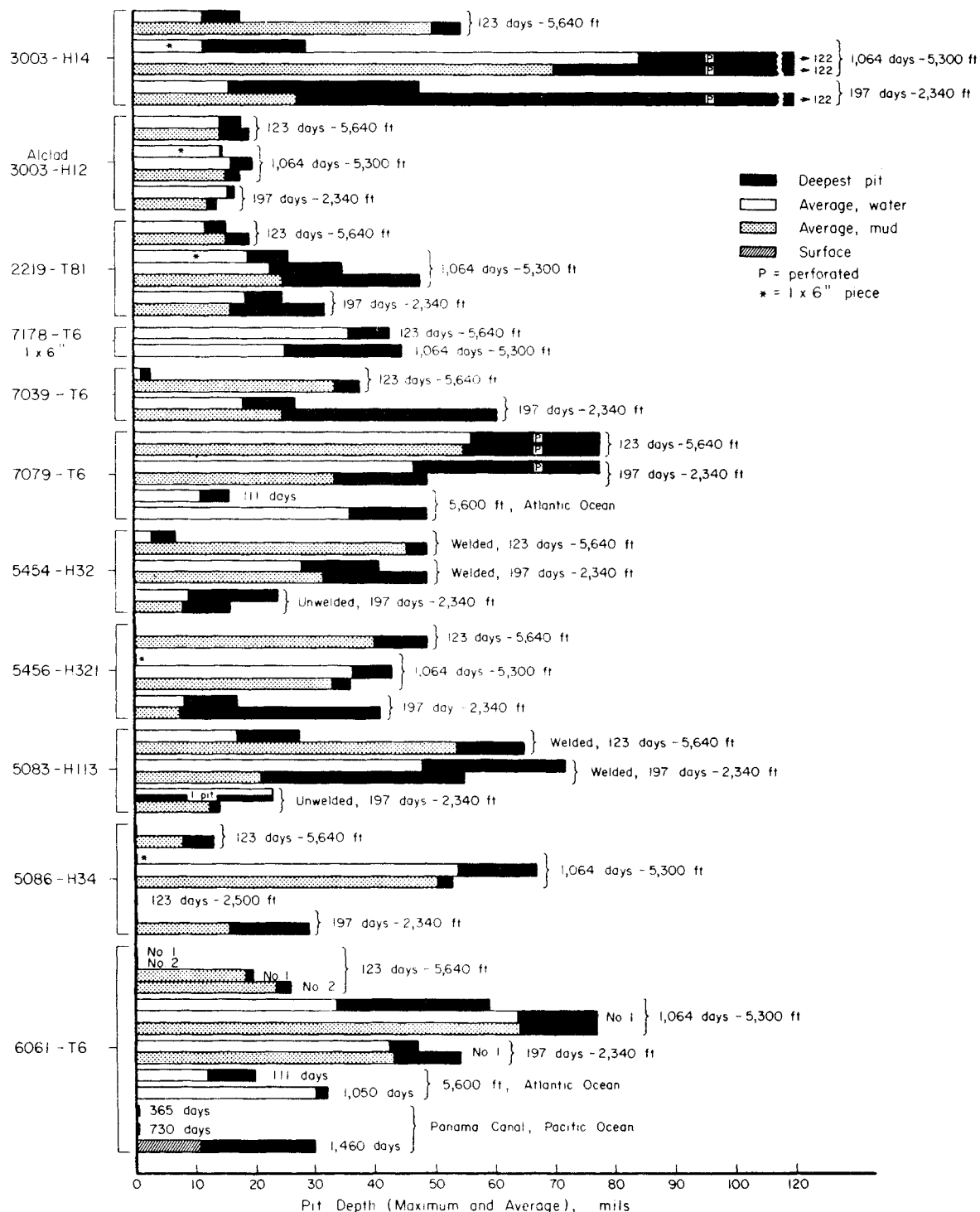


FIGURE 69. PITTING OF ALUMINUM ALLOYS IN THE PACIFIC OCEAN OFF PORT HUENEME, CALIFORNIA(1)

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**Crevice Attack.** A rather common form of attack on aluminum alloys is crevice attack. While practically all alloys are susceptible, there are differences. Usually, an alloy's relatively high susceptibility to pitting attack is indicative that it will also tend to be susceptible to crevice attack, and vice versa.

Since there are no standard crevices, the amount of attack depends largely on the geometry of the crevice and the ratio of anode (under the crevice) to cathode (external area). As might be expected, information on crevice-attack behavior in seawater is scattered and usually not comparable.

The 5000 series of alloys as a group have a relatively high resistance to crevice attack in seawater. Table 64 summarizes the 1-year results obtained by the Navy at Key West.<sup>(91)</sup> There is a close correlation between these results and the pitting characteristics versus electropotential plotted in Figure 68. For example, Alloys 3003-H14, 6061-T6, 1100 F, 7075-T7351, and 7079-T6 all have electropotentials corresponding to pit susceptibility, whereas the 5000 series have potentials indicating relative immunity to pitting. Since the crevice-attack results in Table 64 are similar to the pitting characteristics, Figure 68 can be used to predict sensitivity to either type of attack.

TABLE 64. COMPARISON OF ATTACK OF SELECTED ALUMINUM ALLOYS TO CREVICE CORROSION AFTER 1-YEAR EXPOSURE TO SEAWATER AT KEY WEST, FLORIDA<sup>(91)</sup>

Alloy	Deepest Attack, mils			
	2	3-5	6-10	11-20
1100 F				X
1100-H14		X		
3003-H14				X
5050-H34		X		
5052-H32		X		
5052-H34		X		
5083-O	X			
5086-H32	X			
5086-H34	X			
5086-H112	X			
5154-H38		X		
5257-H25	X			
5456-H321	X			
6061-T6				X
6061-T651	X			
X7002-T6		X	X	
X7005-T63	X			
7075-T7351				X
7079-T6				X

In deep-ocean waters, crevice attack as well as pitting attack can be expected to be more severe. There is evidence that pitting is more severe with depth because of the lower oxygen content, as discussed earlier, but for crevice attack the information is scanty. Alloy 1100-H14 showed negligible crevice attack in a surface experiment, but was perforated at the crevice (62 mils) in less than 200 days in the deep ocean. Similarly, Alloy 6061-T6 showed 8 mils at the surface and 42 mils in deep water. Alloy 5052-O showed no crevice attack at the surface, but complete perforation at the crevice (more than 65 mils) in deep-ocean tests running less than 200 days. These and other results are presented in Table 65.

TABLE 65. CORROSION OF ALUMINUM ALLOYS IN SEAWATER AT SURFACE AND IN DEEP OCEAN WEST OF PORT HUENEME, CALIFORNIA<sup>(92)</sup>

Alloy	Exposure		Corrosion Rate <sup>(a)</sup> , mpy	Pit Depth		Crevice-Corrosion Depth, mils	Corrosion Type <sup>(b)</sup>
	Days	Depth, feet		Max	Avg		
1100-H14	181	5	1.4	—	—	—	SC
	197	2340	5.6	—	—	62(PR) <sup>(b)</sup>	SC
	123	5640	1.9	39	—	—	P
3003-H14	181	5	1.1	33	17.6	—	P
	197	2340	1.4	—	—	40(PR)	C
	197	2340	2.7	48	21.5	28	SE,P,C
3003	123	5640	0.6	—	—	28	C
	123	5640	0.5	27	19.5	32	E,P,C
Alclad 3003	181	5	1.0	2	—	—	P
Alclad 3003-H12	181	5	1.0	—	—	—	IP
Alclad 3003	197	2340	2.3	—	—	—	G
Alclad 3003-H12	197	2340	2.2	15	14.3	13	P,C
Alclad 3003	123	5640	2.7	—	—	—	G
Alclad 3003-H12	123	5640	0.2	18	14.6	15	SLE,B,P,C
5052-O	181	5	1.2	—	—	—	IP
	197	2340	1.8	—	—	65(PR)	SC
	123	5640	3.7	2	—	65(PR)	SC
5083	181	5	1.0	—	—	—	Et
5083-H113	181	5	1.2	—	—	3	C,IP,IG <sup>(c)</sup>
5083-H113, welded	181	5	0.9	—	—	—	Et
5086	181	5	1.2	—	—	—	IP
5086-H32	181	5	1.0	—	—	—	IP,IG <sup>(c)</sup>
5086-H34	181	5	1.2	6	4	—	P,IG
5086-H112, angle	197	2340	0.7	29	—	—	SLE-P
	123	5640	0.1	—	—	—	SLE,SLC
	181	5	1.1	—	—	—	IP
5454	181	5	1.0	—	—	—	IP
5456-H321	181	5	1.2	12	7	—	P
	197	2340	2.7	17	11.7	—	P
	123	5640	0.1	—	—	—	SLE,SLC
6061	181	5	1.2	5	—	—	P
6061-T6	181	5	1.0	—	—	8	IP,C,IG
	197	2340	1.1	47	44.1	42	C,P
	123	5640	0.1	—	—	—	IP

(a) Calculated from weight loss.

(b) B - blistering, C - crevice, E - edge, Et - etched, G - general, I - incipient, IG - intergranular, P - pitting, PR - perforated, S - severe, SL - slight.

(c) Intergranular corrosion on edges of specimens.

**Galvanic Coupling.** Aluminum corrosion is affected by galvanic coupling to other metals. The corrosion rate is accelerated greatly by contact with copper-base alloys. Even copper alloys corroding in the vicinity of aluminum, but electrically isolated, can stimulate pitting attack as a result of the copper ions migrating to the aluminum surface, depositing as metallic copper, and setting up local galvanic cells. Thus, copper-alloy construction should never be combined with aluminum in seawater applications, whether coupled or not.

Galvanic coupling can be beneficial. Anodes of aluminum or zinc galvanically coupled to aluminum alloys will reduce the pitting and corrosion attack. Recent Navy results are summarized in Table 66. Pitting for susceptible alloys was reduced from as much as 40 mils to 3 mils in 1 year by use of a

suitable sacrificial aluminum (or zinc) anode. Magnesium



TABLE 66. DEPTH OF ATTACK FOR ALUMINUM ALLOYS AFTER 368 DAYS' EXPOSURE IN SEAWATER, KEY WEST, FLORIDA(91)

Alloy	Depth of Attack(a), mils	
	No Cathodic Protection	With Cathodic Protection(b)
5052-H32; 5083-O 5086-H32; H34, H112 5257-H25, 5456-H321 6061-T651; X7005-T63 7106-T63	< 1	< 1
1100-H14; 5050-H34; 5052-H34; 5154-H38; Alc. X7002-T6; Alc. 7178-T6(c)	1-4	1 mil except 1100-H14 (2 mils), and Alc. 7178-T6 (4 mils)(c)
1100-F; 2014-T6; 6061-T6; X7002-T6(d)	5-10	1 mil or less except 2014-T6 (2 mils)
3003-H14; 7079-T6; 7075-T7351	11-20	1 mil or less
2024-T351; 2219-T87; 7178-T6(d)	25-40	3 mils or less; 7178-T6(d)

(a) Based on average of five deepest penetrations.

(b) Aluminum anode used.

(c) Edges cracked severely.

(d) Edges cracked.

anodes should not be used, since their higher voltage will overprotect and increase the pH developed at the cathode. Aluminum is amphoteric and will be attacked under these alkaline conditions.

Another method of control is to clad the susceptible alloy with a sacrificial metal. As long as the cladding is not consumed, the underlying metal will be protected. Note the reduced degree of pitting of Alclad 3003-H12 as compared with that of the unclad alloy in Figure 69.

High-strength alloys in the 2000 and 7000 series are generally not suitable in seawater. However, with corrosion control, such as paint and cathodic protection, high-strength alloys are used occasionally. Alloys such as X7002-T6 and 7178-T6 tend to delaminate or exfoliate in seawater.(91) This is really a form of intergranular attack on these wrought materials where the grains have been enlarged in the plane of rolling. Local corrosion also is associated with weldments, especially in alloys that obtain their strength by heat treatment, such as the aluminum-copper and the aluminum-zinc-magnesium-copper series.

Stress-corrosion cracking is a problem with high-strength alloys in marine and other environments and is discussed separately.

Highlights of the corrosion behavior of individual alloys, frequently used in marine service, are discussed below.

**1000 Series.** From a corrosion viewpoint, Alloy 1100 has good resistance to seawater. However, because of its low strength, other, more suitable alloys usually are chosen for a marine application. The corrosion behavior of Alloy 1100 is summarized in Figures 70 and 71. In surface waters, both the corrosion rate (as determined by weight loss) and the depth of pitting attack are relatively low. In the Pacific Ocean after 16 years, the corrosion rate was 0.97 mpy.(88) Groover, et al.(91) found a maximum depth of attack of 12 mils in 1 year on Alloy 1100-F in the crevice area. However, the attack on the exposed surface was less than 1 mil. Alloy 1100-H14 showed a mean depth of pitting of less than 3 mils in 1 year. مراجع استادیان و مهندسين مواد

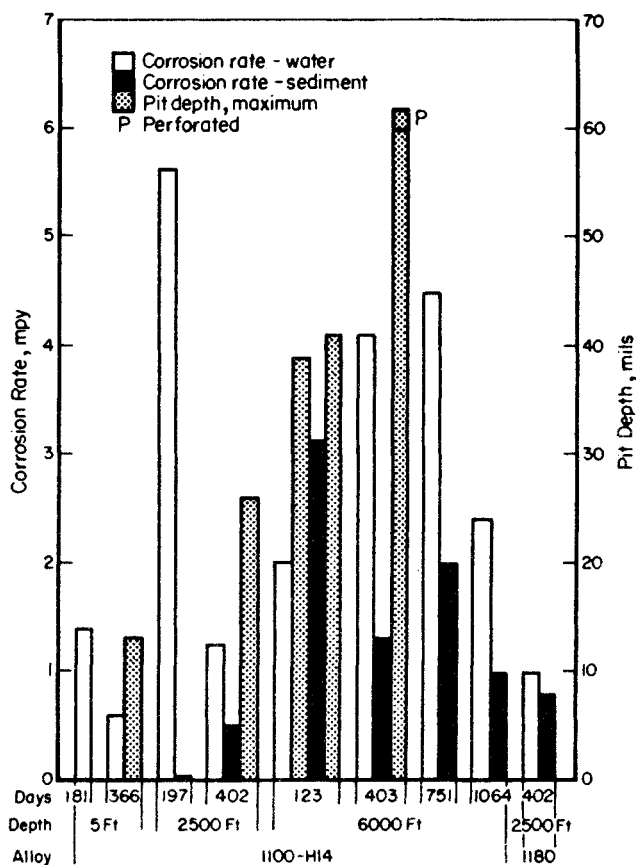


FIGURE 70. CORROSION RATES AND MAXIMUM AND AVERAGE PIT DEPTHS OF 1000 SERIES ALLOYS IN PACIFIC OCEAN WEST OF PORT HUENEME(90)

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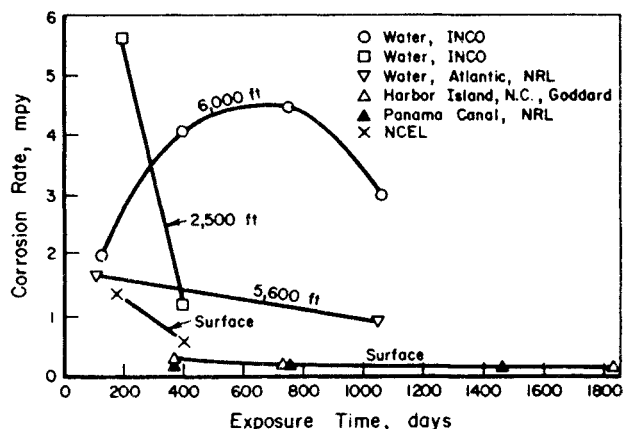


FIGURE 71. CORROSION RATES OF 1100 ALLOY IN SEAWATER AT DIFFERENT LOCATIONS(90)

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Groover, et al.(91) compared the pitting and crevice-attack behavior in surface water at Key West, Florida, for Alloy 1100 in the F and H14 tempers. These data are shown in Figure 72. Pitting was minor for either heat treatment but the H14 seemed to provide better resistance to crevice attack. Deeper water than in the surface water. Ailor(93) compares Alloy 1180-H14 with other aluminum alloys in surface water and in



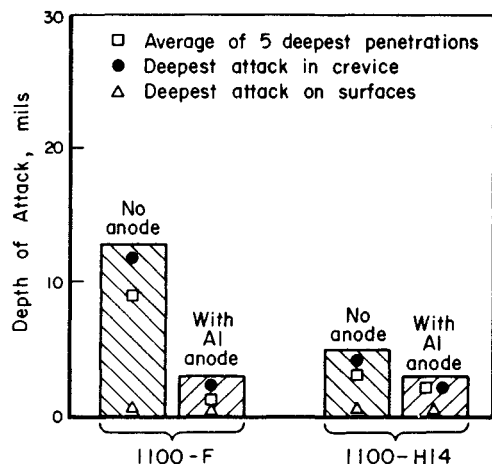


FIGURE 72. CORROSION AND EFFECT OF CATHODIC PROTECTION ON 1100-F AND 1100-H14 ALLOYS AFTER 368 DAYS' SEAWATER EXPOSURE AT KEY WEST, FLORIDA(91)

ocean water at 2,370 feet in Figure 73. Alloy 1100-H14 showed a maximum depth of pitting at 5,640 feet of 39 mils in 123 days compared to 13 mils at a depth of 5 feet for an exposure of 366 days.(90)

As shown in Figure 74, Alloy 1180-H14 — compared with the 5000 Alloy series and with 6061 — showed higher pitting attack after 1 year at 2,370 feet. Normally it is expected that high alloy purity will promote pitting resistance, but this is not the case for this exposure condition.

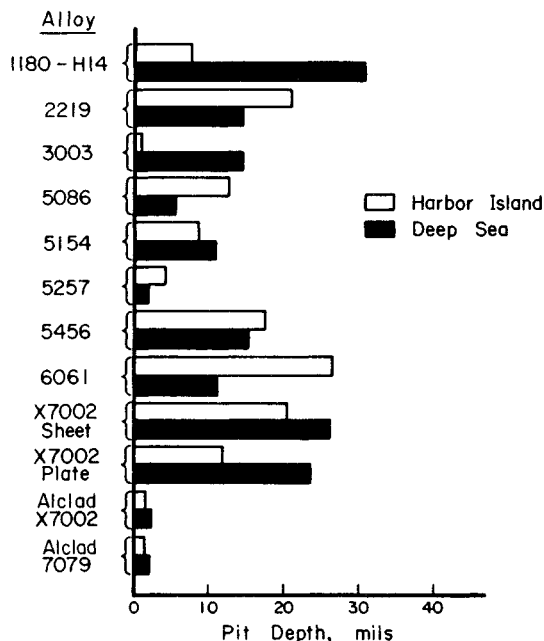


FIGURE 73. RELATION BETWEEN AVERAGE PIT DEPTH (20 DEEPEST PITS) AFTER 1-YEAR EXPOSURE AT THE SURFACE AND AT 2,370 FEET AT HARBOR ISLAND, N. C., AND IN PACIFIC OFF PORT HUENEME, CALIFORNIA(93)

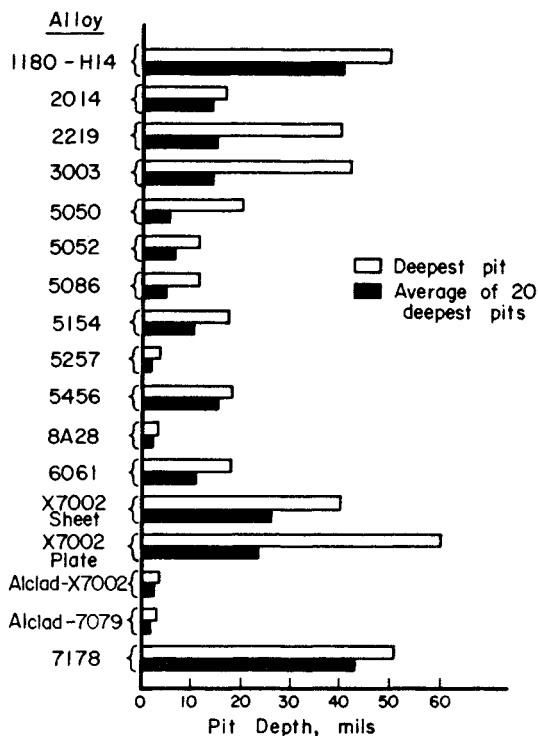


FIGURE 74. MEASURED PIT DEPTHS AFTER 1-YEAR EXPOSURE AT 2,370 FEET IN PACIFIC OCEAN WEST OF PORT HUENEME, CALIFORNIA(93)

Since the 5000 series alloys are more corrosion resistant to shallow- and deep-ocean environments and have other attractive properties, it is concluded that there is no particular advantage in the selection of a 1000 series alloy for most marine applications.

**Alloy 3003.** A study of Figures 68, 69, and 74 shows that Alloy 3003-H14 has a tendency to pit in seawater. In addition, it exhibited a higher rate of general attack than did the 1100 alloy at Key West, Florida.(91) However, the high-purity Alloy 1180-H14 shows a greater tendency to pit in surface and deep-ocean environments than does Alloy 3003.(93)

Corrosion-rate data for Alloy 3003, based on weight loss, are shown in Figures 75 and 76. There is some indication that well-aerated surface waters are less corrosive to this alloy than deep-ocean waters. Corrosion rates of less than 2 mpy seem typical for this alloy in surface waters, whereas rates as high as 4 mpy are observed in the deep ocean.

By cladding the 3003 alloy with a suitable layer of unalloyed aluminum, the tendency to rapid pitting can be alleviated (see Figures 69 and 77). Furthermore, the corrosion rate is reduced to about half. However, once the cladding has been removed by corrosion, the core metal (3003) will revert to the higher rate. In typical cases, the life is extended several years by cladding, but the strength is reduced for a given total thickness.

**5000 Series.** Among the 5000 series alloys, those which find application in seawater installations include 5052, 5083, 5086, 5154, and 5454. As with aluminum alloys in general, the

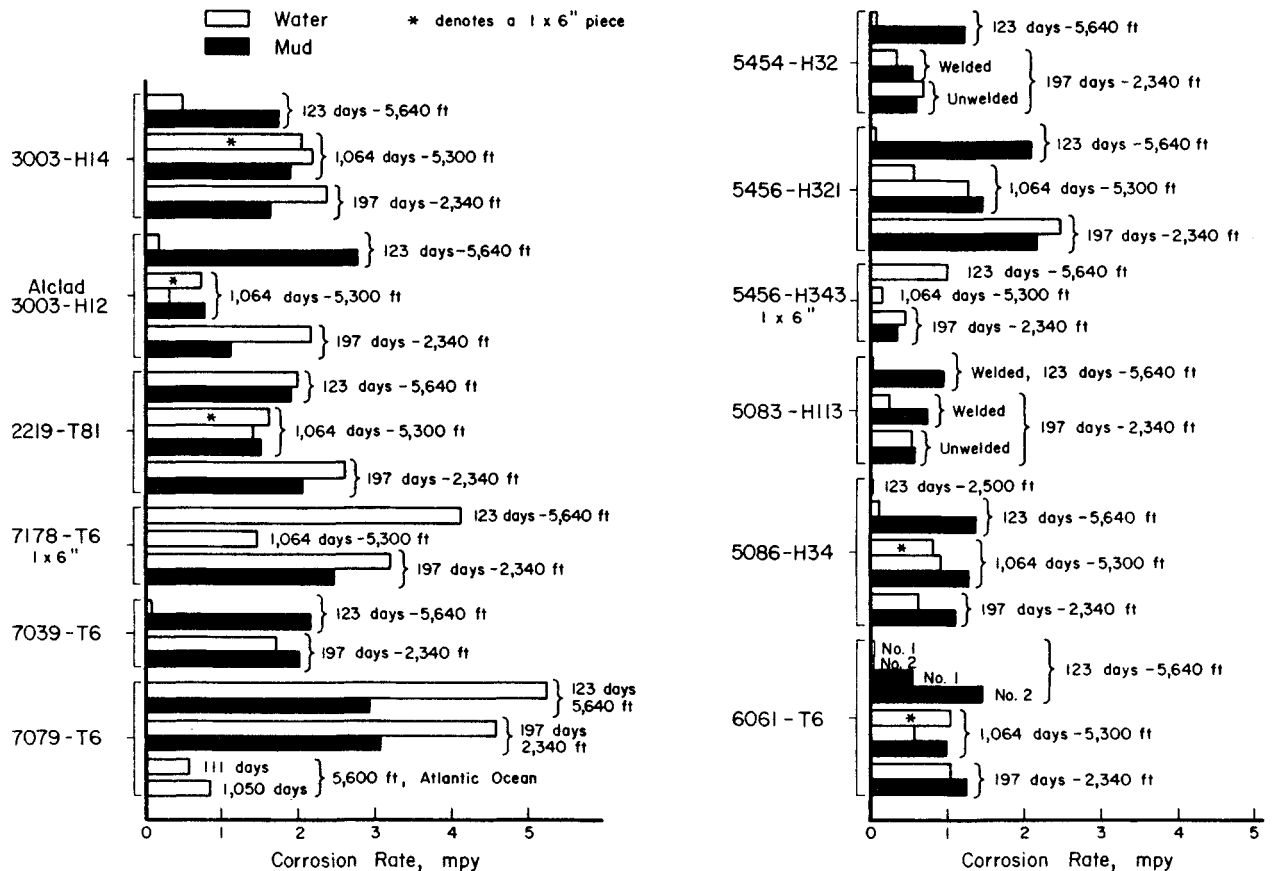


FIGURE 75. CORROSION RATES OF ALUMINUM ALLOYS IN THE DEEP OCEAN (PACIFIC OCEAN UNLESS OTHERWISE SPECIFIED)(1)

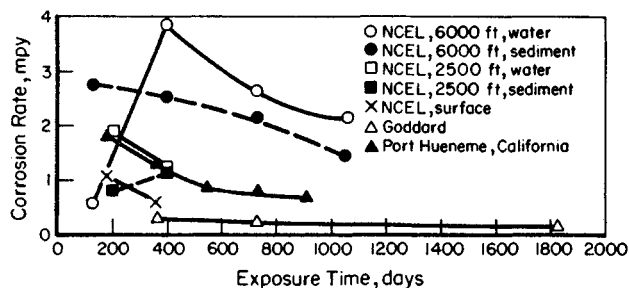


FIGURE 76. CORROSION RATES OF 3003 ALLOY AT DIFFERENT DEPTHS AND SURFACE LOCATIONS IN THE OCEANS(90)

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5000 series alloys tend to pit. Reinhart's data for both shallow- and deep-ocean waters are summarized in Table 67.(90) Corrosion rates of 2 mpy or less are reported at all depths, while the average of the deepest pits may be as much as 50 mils. After 1-year exposure in the surface water at Key West, Florida, all 5000 series alloys showed a mean pit depth of less than 3 mils (see Figure 68).

Pitting and crevice-attack data are summarized for three alloys, 5050-H34, 5052-H32, 5052-H34, and 5083-O, in Figure 78. Usually the crevice attack was the more evident, but all three alloys have excellent resistance. (Also note the higher

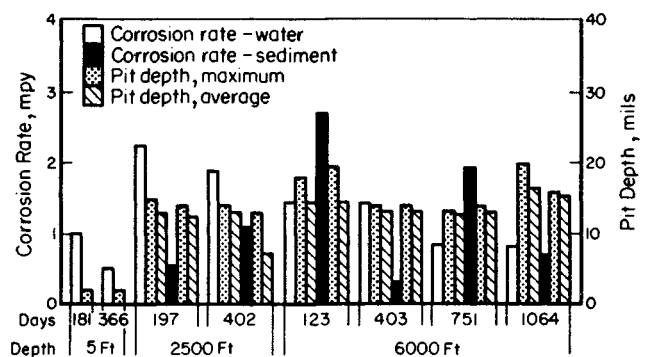


FIGURE 77. CORROSION RATES AND MAXIMUM AND AVERAGE PIT DEPTHS OF ALCLAD 3003 ALLOY(90)

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attack for Alloy 3003-H14 as compared with the 5000 alloys shown in Figure 78.)

To illustrate the fact that the corrosion rate is not far different for these alloys at the surface and at ocean depths, consider Alloy 5086-H34. In well-aerated surface water the corrosion rate ranges from about nil to about 1 mpy. In deep-ocean water a rate as high as 2 mpy has been obtained (Figure 79).

TABLE 67. AVERAGE CORROSION RATES AND AVERAGE PIT DEPTHS OF Al-Mg ALLOYS (5050, 5052, 5454, 5456, 5083 AND 5086)(90)

Exposure Time, 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

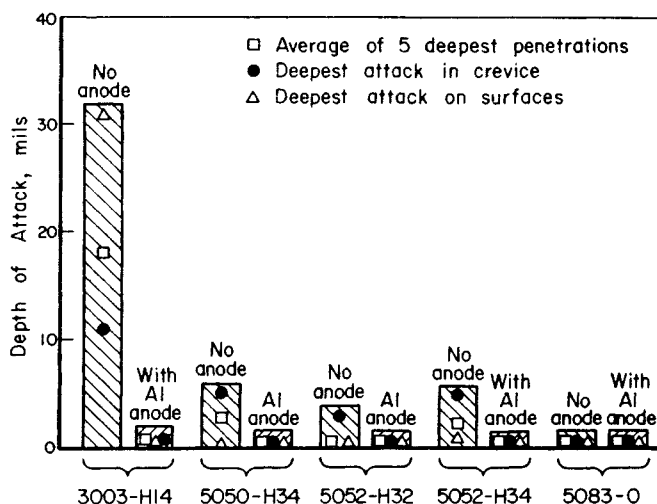


FIGURE 78. CORROSION AND EFFECT OF CATHODIC PROTECTION OF 3000 AND 5000 SERIES ALUMINUM ALLOYS EXPOSED FOR 368 DAYS IN SEAWATER AT KEY WEST, FLORIDA(91)

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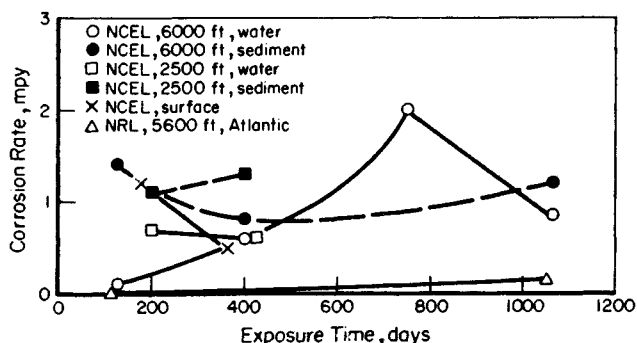


FIGURE 79. CORROSION RATES OF 5086-H34 ALLOY AT THE SURFACE AND AT VARIOUS DEPTHS IN THE OCEANS(90)

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The pit formance of Alloy 5086-H34 is quite a different matter. Pit depths of less than 5 mils are typical in surface waters, but may range anywhere from 50 to 75 mils in deep-ocean water. These facts are illustrated by the bar graph in Figure 80.

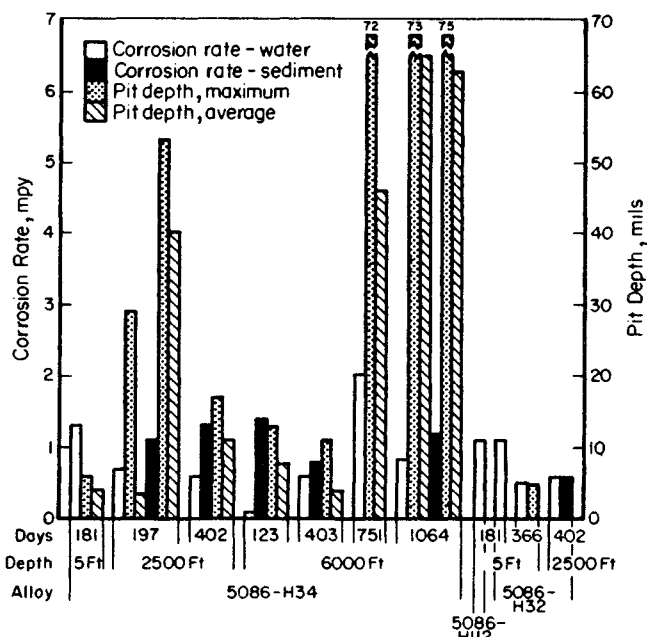


FIGURE 80. CORROSION RATES AND MAXIMUM AND AVERAGE PIT DEPTHS OF 5086 ALLOY(90)

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The 5000 series of alloys, if they are to see deep-ocean service, may be provided with galvanic anodes to reduce the tendency toward pitting and crevice attack. With such precautions, they should give satisfactory service, except as noted below.

There is some evidence that alloys with high magnesium content, e.g., Alloy 5456 with 5.25 percent magnesium, are not resistant to seawater corrosion in some of the heat-treatment conditions that develop maximum strength. For example, Alloy 5456 in the H34 heat-treatment condition is found susceptible to exfoliation, craterlike pitting, and severe corrosion. Stress corrosion, as discussed elsewhere, can take place when the heat treatment results in an intergranular precipitate of a magnesium-aluminum compound. Alloys with less than about 4.5 percent magnesium seem to be relatively immune to the effects of heat treatment on corrosion behavior.

Alloy 6061. Of all the aluminum alloys used in seawater applications, Alloy 6061 appears to be the most frequently selected. This alloy combines good strength with good resistance to seawater. Corrosion rates for both deep- and shallow-ocean environments are summarized in Figure 81.(90) In both Atlantic and Pacific surface waters, corrosion rates are of the order of 0.3 mpy. At the lower oxygen levels in Pacific deep-ocean exposures, the rate is higher, typically around 1 to 2 mpy, although rates up to 3 mpy at 6,000 feet have been observed (see Figure 81). The 16-year results for the surface-water condition in the Pacific Ocean are shown in Figure 66. Alloy 6061-T was found to corrode at 0.91 mpy.

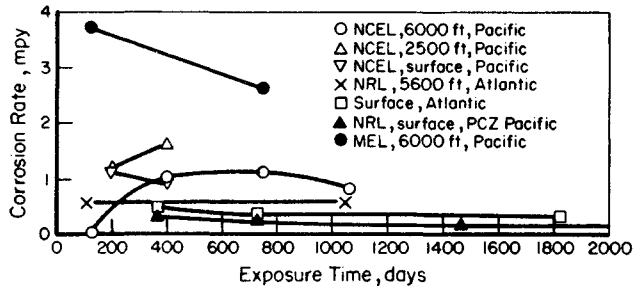


FIGURE 81. CORROSION RATES OF 6061-T6 ALLOY IN SEAWATER IN THE OCEANS<sup>(90)</sup>  
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As with other aluminum alloys, Alloy 6061 tends to pit in seawater exposures. Figure 82 shows the higher pitting rates obtained in deep water, as compared with those in surface water. The main effect seems to be oxygen availability rather than depth, per se. Although weight loss is not greatly affected, there is a striking increase in depth of pitting with decrease in oxygen concentration, as shown in Figure 83. It should be stated that the pitting behavior of 6061-T6 tends to vary some from lot to lot. At 5,640 feet, for example, some panels were entirely free from pitting, whereas others showed severe attack. Ailor<sup>(93)</sup> has compared the pitting tendency of Alloy 6061-T4 with other aluminum-base alloys (Figure 74). Here, Alloy 6061 compares favorably with many of the 5000 series alloys in the same program, such as 5050-H34 and 5052-H34.

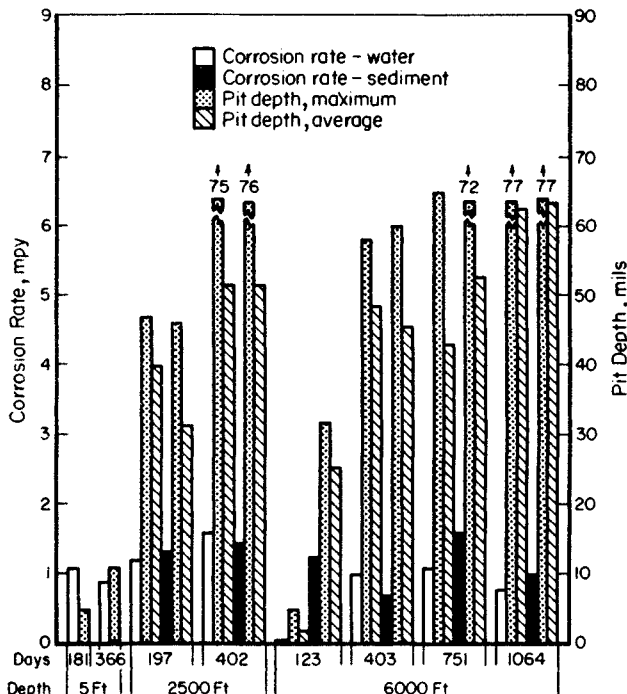


FIGURE 82. CORROSION RATES AND MAXIMUM AND AVERAGE PIT DEPTHS OF 6061-T6 ALLOY<sup>(90)</sup>

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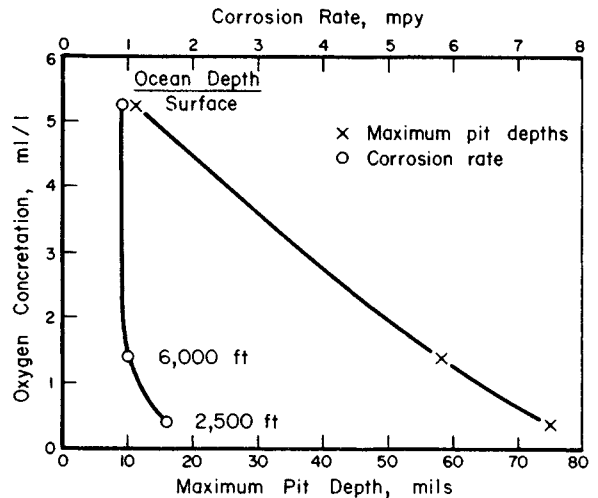


FIGURE 83. CORROSION RATES AND MAXIMUM PIT DEPTHS OF 6061-T6 ALLOY AS RELATED TO OXYGEN CONCENTRATION AFTER 1 YEAR OF EXPOSURE<sup>(90)</sup>

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#### Mud Zone

Ocean-bottom sediments vary considerably in composition, depending on their origin. Experiments conducted in the Pacific off Port Huemene<sup>(1)</sup> have provided most of the information on the performance of aluminum alloys imbedded in the mud. The sediment in this area contains various organisms, including sulfate-reducing bacteria. Since aluminum alloys are resistant to sulfides, one might expect them to do well in the mud zone. Such is not the case, however. Probably because of the low oxygen content in the sediment, the depth of pitting in the mud zone is high and of the same order as that in the deep ocean. For example, panels of 6061-T6 both in the mud and just above it showed maximum pits of 78 mils after 3 years at 5,300 feet. As shown in Figure 69, the 5000 series alloys (as well as others) all tend to pit severely in the mud zone.

Until more experience has been developed, the corrosion allowance for exposure of aluminum alloys to the mud zone should be similar to that employed for exposure in the deep ocean.

#### Stress Corrosion of High-Strength Alloys

**2000 and 7000 Series Alloys.** High-strength aluminum alloys of the 2000 and 7000 series are susceptible to stress-corrosion cracking in marine environments. The degree of sensitivity varies with composition and heat treatment. Heat treatments which produce highest strength are most apt to increase susceptibility to stress-corrosion cracking. The alloys may also suffer rapid intergranular corrosion. This is particularly true for alloys with heat treatments that reduce susceptibility to stress-corrosion cracking.

The information on stress-corrosion cracking of aluminum alloys is based on (1) service experience, (2) marine exposure

of experimental panels, and (3) the 3.5 percent NaCl alternate-immersion test in the laboratory.\* Not all alloys respond to this laboratory environment to the same degree as they do actual marine atmosphere. For example, the performance of aluminum alloys 7178-T651, 7079-T651, and X7006-T631 is compared in Figure 84. Although the two seacoast atmospheres give different results, performance of the same order of merit is developed by the three alloys.(96) A quite different order of merit is developed in the 3.5 percent NaCl test. The acidified 5 percent NaCl, applied by an intermittent spray, is found to provide better correlation with marine experience for these three alloys, but not necessarily for all aluminum alloys.

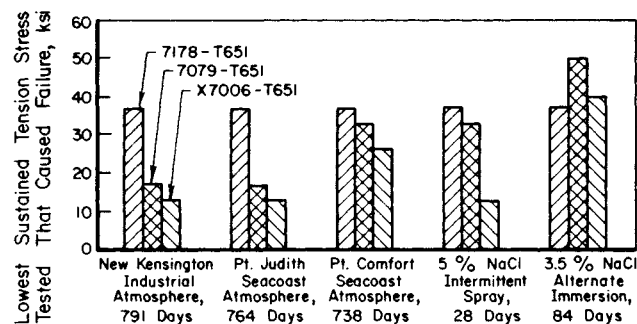


FIGURE 84. RELATIVE RESISTANCE TO STRESS CORROSION CRACKING OF THREE ALUMINUM ALLOYS USING 2.5-INCH-DIAMETER ROLLED ROD SPECIMENS(96)

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The stress levels employed corresponded to 75, 50, and 25 percent of the respective transverse yield strengths.

A plot of the stress-corrosion results for commonly used aluminum alloys is shown in Figure 85.(97) As is evident, the short-transverse samples, taken from plate 2.0 to 7.0 inch thick, were the most susceptible. Special heat treatments have been developed to increase the resistance of high-strength aluminum alloys to stress-corrosion cracking. Several of the alloy-temper combinations shown in Figure 86 have relatively high stress-corrosion-cracking thresholds in the short-transverse direction.

Hunter and Fricke(99) have observed the corrosion behavior in chloride environments of Alloys 7079-T6 and 7039-T6 as compared with the same alloys under stress. Unstressed 7079-T6 was attacked intergranularly on both "former" grain boundaries and fragment boundaries. For 7039-T6, unstressed samples corroded by pitting. Stress-corrosion cracks in 7079-T6, 7039-T6, and 7075-T6 always initiated in "former" grain boundaries perpendicular to the stress. Boundaries between "grains" having considerably different orientation were preferred in many cases. Pits resulting from dissolution of minor constituents, or in the matrices, were not related to crack initiation in 2219-T37, 7075-T6, or 7079-T6, but may be related to the cracking behavior of Alloy 7039-T6.(99)

\*For an overall view of stress-corrosion cracking of aluminum, the reader is referred to DMIC Memorandum 202.(94) Recent European data are reviewed in DMIC Memorandum 240.(95)

Alloy 2219 was found susceptible to stress-corrosion cracking in chloride environments in the T37 but not in the T87 condition. Alloy 7075 is susceptible in the T6 condition but the T73 heat treatment produces a high resistance to stress-corrosion cracking.(100)

Williams, et al.,(101) studied weldments produced by electron-beam welding on 7039-T61. Samples under tensile stresses up to 100 percent of the .02 percent offset yield were exposed to alternate immersion in synthetic seawater. During the 500-hour test, no failures by stress-corrosion cracking were observed. A mild pitting attack occurred in the heat-affected zone and this accounts for the losses for the as-welded specimens (see Table 68).

TABLE 68. EFFECTS OF STRESS-CORROSION TESTING ON THE TENSILE PROPERTIES OF 7039 ALUMINUM PLATE(101)

(Samples were subjected to 500 hours of cyclic immersion in synthetic seawater.)

Condition	Yield Strength, (.02% Offset), ksi	Stress Corrosion Stress Levels(a), ksi	Pre-Stress-Corrosion Ultimate Tensile Strength, ksi	Post-Stress-Corrosion Ultimate Tensile Strength, ksi	Decrease in Ultimate Tensile Strength, percent
Longitudinal welds, welded in T61 condition	28.35	25.5 22.6 19.8	53.6	39.5	26.0
Longitudinal welds, welded in T4 and artificially aged to T61	35.2	31.7 28.2 24.6	51.15	51.15	0
Long-transverse welds, welded in T61 condition	22.85	20.6 18.3 16.0	47.1	40.5	14.0
Long-transverse welds, welded in T61 resolution and artificially aged	41.25	41.25 37.13 33.0	56.15	56.83	0

(a) 100 percent of .02 percent offset.

These examples demonstrate that some of the high-strength alloys can be used in marine environments at a sacrifice in strength. The tensile strength of Alloy 7075 in the T7351 condition is about 10 percent less than that of the same alloy in the T6 condition. Under the circumstances, it may be preferable to use either Alloy 6061-T6 or one of the strain-hardened 5000 series alloys which are more resistant to stress-corrosion cracking and to other forms of corrosion.

5000 Series Alloys. Strength is imparted to the aluminum-magnesium series of alloys by strain hardening. This is usually followed by a partial anneal, with some reduction in strength. Cold working introduces residual stresses, but is also believed to promote intergranular precipitation of a magnesium-aluminum compound during aging. Alloys with higher magnesium content, especially those with more than 4.5 percent (e.g., Alloys 5356 and 5456; see Table 69), tend to form this precipitate more readily. When the intergranular precipitate has developed in these alloys, the combination of a susceptible path and applied or residual tensile stress will accelerate intergranular corrosion cracking of the alloy in the marine environment. Distortion of the grain structure by the strain-hardening process may result in a less direct path.



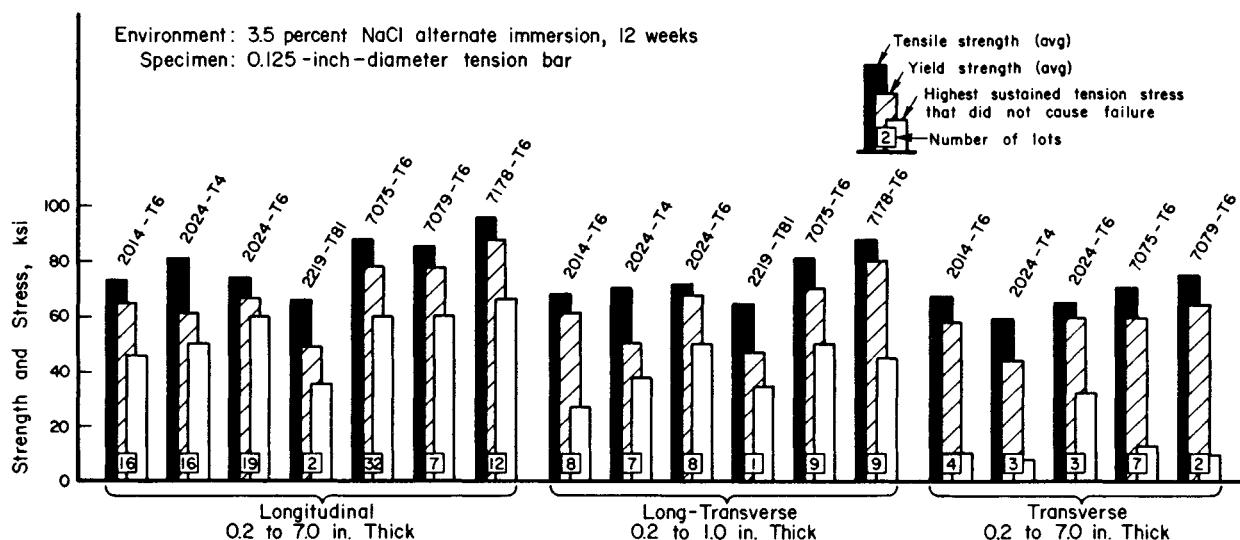


FIGURE 85. COMPARISON OF THE RESISTANCE TO STRESS-CORROSION CRACKING OF ALUMINUM-ALLOY EXTRUSIONS TO SALT WATER<sup>(97)</sup>

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Observe height of white bars.

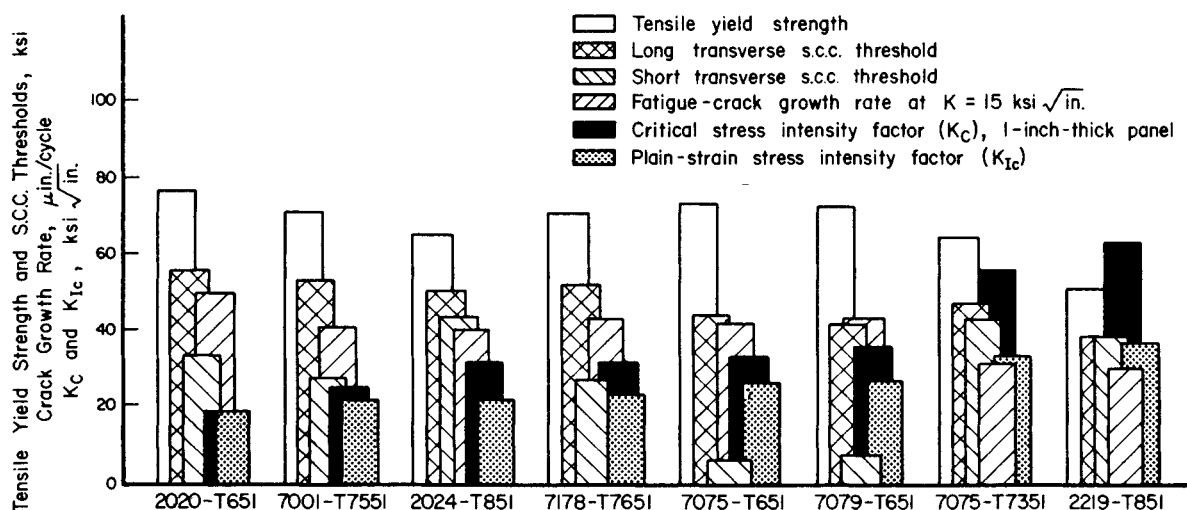


FIGURE 86. COMPARISON OF THE EIGHT ALUMINUM ALLOY-TEMPER COMBINATIONS ON THE BASIS OF TENSILE YIELD STRENGTH, STRESS-CORROSION-CRACKING THRESHOLDS (USING 3.5% NaCl ALTERNATE IMMERSION), FATIGUE-CRACK GROWTH RATES, AND FRACTURE-TOUGHNESS CRITERIA,  $K_{IC}$  AND  $K_{IC}$ <sup>(98)</sup>

Long transverse direction except where noted, 1-3/8 inch plate.



TABLE 69. COMMERCIAL ALLOYS OF THE 5000-SERIES GROUPED BY MAGNESIUM CONTENT(103)

Magnesium Content, %	Alloy Designation
Maximum	
<3.5	5005, 5050, 5052 5454 5357, 5457, 5557
3.5 - 4.5	5154 (3.1 to 3.9 Mg, 0.1 max Mn) 5086 (3.5 to 4.5 Mg, 0.2 to 0.7 Mn)
>4.5	5083 (4.0 to 4.9 Mg, 0.3 to 1.0 Mn) 5155 (3.5 to 5.0 Mg, 0.2 to 0.6 Mn) 5056 (4.5 to 5.6 Mg, 0.05 to .20 Mn) 5356 (4.7 to 5.5 Mg, 0.05 to .20 Mn) 5456 (4.7 to 5.5 Mg, 0.5 to 1.0 Mn)
Nominal	
3.5	5154
4	5086
4.5	5083
5	5356-5456

The effect of nine different tempers on Alloy 5456 with and without sensitization (to simulate welding) was investigated by Niederberger, et al.(102) Failures occurred with the H12, H16, H32, and H36 tempers. No failures occurred in sensitized or unsensitized samples in O, H22, H24, and H321 tempers. Alloy 5456-H32, as well as a series of other magnesium-bearing alloys, showed no signs of stress-corrosion failure after exposure for about 400 days in the deep ocean.(90)

In practice, the use of alloys with the higher magnesium content has been restricted to deckhouses and nonsensitive structural applications. This resulted from experiences with stress-corrosion cracking. It would appear that by the use of suitable strain-hardening and temper combinations and by avoiding fit-up welds, or other sources of residual tensile stresses, the alloys containing higher amounts of magnesium can be used in marine service.

Alloy 6061. Alloy 6061 is one of the aluminum-magnesium silicide types and it may be susceptible to stress-corrosion cracking in the T4 heat-treatment condition if a high heat-treating temperature is employed, followed by a slow quench. In the fully aged condition, T6 temper, the precipitate is present as small discrete particles and the alloy is immune to stress-corrosion cracking.

For marine service, this alloy has a combination of strength and corrosion properties that make it a preferred choice over most of the 2000 or 7000 series of alloys.

#### Marine Applications

The application of aluminum to ocean-going vessels has taken years. On ships, for example, there has been a step-by-step introduction of aluminum-alloy components, first in pleasure boats, then for larger vessels. The Navy is now gaining experience with aluminum-hulled vessels, including some hydrofoil ships.(103)

In practice, aluminum hulls exposed to seawater often are not painted. In the case of a small vessel, sufficient thickness must be provided to allow for pitting. Some fishing boats are unpainted but make use of zinc anodes to control galvanic attack at critical areas such as in the vicinity of the propeller.(104) Biofouling is removed periodically by skin divers.

The major reason for painting aluminum which is exposed to seawater is to prevent biofouling. Antifouling formulations based on toxic organo-tin compounds are safe and effective for aluminum. On the other hand, paints using copper compounds should be avoided since copper ions released from the paint may deposit on exposed aluminum and stimulate pitting. By interspersing a thick coating of anticorrosive primer, this problem has been mitigated to some extent, but with the advent of organo tins, the use of copper-bearing paints no longer can be justified. In no case should an antifouling paint containing mercury compounds be allowed to contact aluminum. Mercury amalgamates with aluminum, and will promote cracking under tensile stress.

Aluminum alloys serve well in the marine atmosphere if properly selected and applied; however, poor workmanship can lead to failures. Welds often are the source of failure.

Where aluminum sheet or plate is to be joined to another metal, the aluminum should be on the weather side so as to act as a flashing, as illustrated in Figure 87. A fitting of another metal should be electrically insulated from the aluminum (see Figure 88). Stainless steel (e.g., Types 304 or 316) fasteners have been used with success on aluminum. Here the area ratio is favorable, i.e., small cathode and large anode. Steel fastenings clad with zinc (galvanized), aluminum (aluminized), or cadmium (electroplated) also have given satisfactory service with aluminum, especially when the entire system is painted. Whether paint is used or not, it is essential that the fasteners be coated, as this will reduce the attack on the adjacent aluminum.

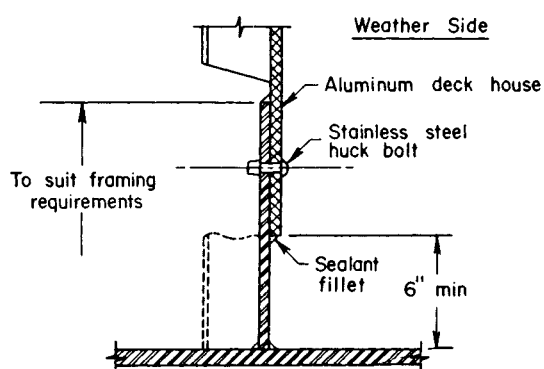


FIGURE 87. ALUMINUM DECKHOUSE JOINT DETAIL(103)  
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#### Beryllium

Although beryllium is resistant to humid air, pitting is apt to occur in the marine atmosphere.

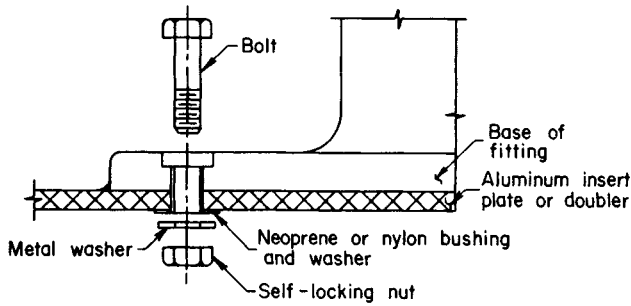


FIGURE 88. TYPICAL INSTALLATION DETAIL OF DISSIMILAR-METAL FITTINGS(103)

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Pitting also occurs in seawater. As shown in Figure 89, the pitting is most intense in synthetic seawater during the first 2 months. Pitting becomes more widespread with time, and pits up to 4 mils deep have been observed. As presented in Table 70, pitting of the same order was obtained in natural seawater at 59 F. Seawater at warmer temperatures than this would normally be expected to have more fouling activity. Beryllium in tropical waters, for example, would typically be covered with marine organisms and this would induce a rate of pitting higher than those reported in Table 70.

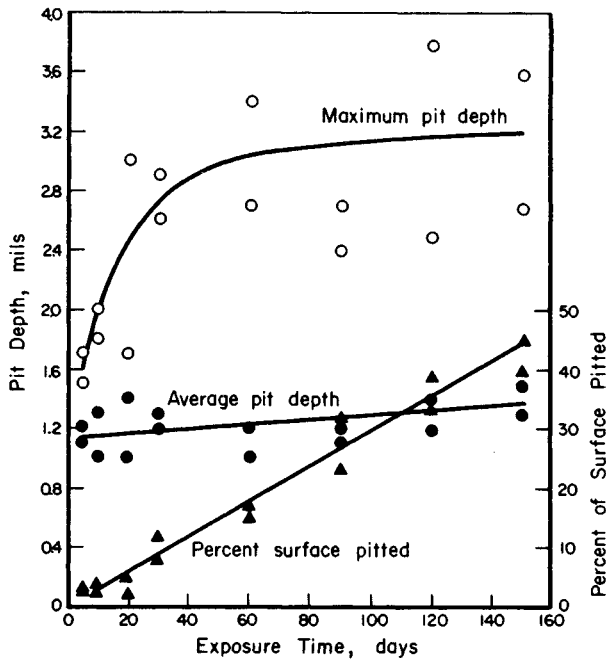


FIGURE 89. PITTING ATTACK OF UNSTRESSED, PICKLED BERYLLIUM SHEET MATERIAL EXPOSED TO SYNTHETIC SEAWATER AT 77 F(105)

Continuous total immersion testing.

The stress-corrosion-cracking behavior of beryllium in salt solutions has been studied by several investigators.(105-108) The results to date have not indicated any susceptibility to stress-corrosion cracking in salt solution or seawater for commercial-purity beryllium. On the other hand, severe pitting that drastically lowered the load-carrying ability of the material has been encountered. There is some evidence to suggest that while no greater incidence of pit density is observed with

stress, certain pits become more active and penetrate the metal rapidly.

TABLE 70. PITTING OF PICKLED BERYLLIUM [CONTINUOUS TOTAL IMMERSION IN 15 C (59 F) NATURAL SEAWATER](106)

Exposure Time, days	Pit Depth, mils		Percent of Surface Pitted
	Avg	Max	
0	Negligible	0.2(a)	Negligible
2	Negligible	1.5	Negligible
3	1.3	1.9	Negligible
5	1.	1.6	1
10	1.2	1.8	2
14	1.4	2.0	3
20	1.4	3.0	5
30	1.2	3.0	12
40	1.0	2.5	15
60	1.2	3.0	20

(a) Resulted from pickling.

Some method of controlling the corrosion is required if beryllium is to be used in marine environments. Anodized coatings sealed with sodium silicate have shown improved stability in saline solutions. A ceramically bonded aluminum coating (Serme Tel W) is also employed on beryllium. The best results are obtained by applying a double coat to a grit-blasted surface, drying at 175 F, and curing at 650 F.(107) In marine atmospheres, this coating can be used above 400 F, but the anodized coatings cannot because they become unstable.

Since information on behavior of beryllium in marine environments is very scanty and the composition of commercial beryllium varies considerably, any consideration of its use should be preceded by an intensive study of the corrosion behavior in the actual environment involved.

## Magnesium

Highly purified distilled magnesium corrodes in seawater at a rate of about 10 mpy, or roughly double the rate of iron. However, commercial magnesium often corrodes at several hundred times that rate, largely because of the presence of impurities such as iron, and the corrosion is accompanied by visible hydrogen evolution. In view of this poor behavior, magnesium and its alloys are not used in seawater. For example, after only 1 year in the Pacific Ocean at Panama, a controlled-purity magnesium alloy (AZ31X) 250 mils thick had a pit 153 mils deep at mean tide.(109) The deep pits were associated with a mollusk infestation. As a sacrificial anode, however, magnesium has had considerable use in seawater, as discussed earlier.

Judging from magnesium's poor behavior in seawater, one might not expect good resistance to marine atmospheres. In the marine atmosphere, however, magnesium is more resistant than iron. The corrosion rate depends on (1) the amount of chlorides reaching the surface and (2) the degree of rainfall, or moisture. Corrosion rates vary, but 1 mpy is fairly typical. For Alloy AZ31, the rate was 0.94 mpy after 16 years at Daytona Beach, Florida, and about 0.9 mpy after 32 months at Daytona

Beach; and 0.57 and 0.5 mpy, respectively, after 4 years at the 80- and 800-foot lots at Kure Beach, N. C. Part of the variation in rate at these four marine sites may be attributed to the aggressiveness of the climate and part probably results from different levels of impurities, such as iron, in the specimens, since they were taken from different heats. The relation between corrosion and exposure time for AZ61X and AZ31X alloys at Cristobal is shown in Figure 90. Note that the higher purity AZ61X alloy has slightly greater resistance.(88) Figure 91 shows the straight-line relation for the corrosion with time for Alloy AZ31A at Battelle's marine site south of Daytona, Florida.

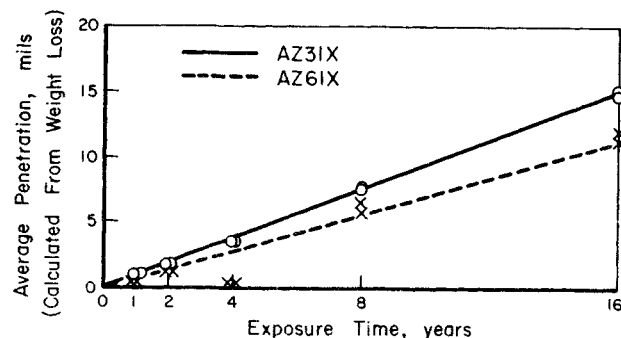


FIGURE 90. CORROSION RATES OF MAGNESIUM AZ61X AFTER 16 YEARS' EXPOSURE IN MARINE ATMOSPHERE ON CARIBBEAN COAST, CANAL ZONE(88)

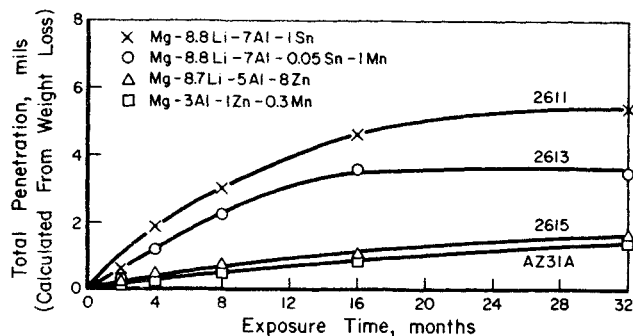


FIGURE 91. MAGNESIUM-ALLOY CORROSION IN MARINE EXPOSURE AT THE 300-FOOT RACKS AT THE BATTELLE EXPOSURE SITE SOUTH OF DAYTONA BEACH, FLORIDA(110)

These examples indicate that unprotected AZ31 of commercial quality has moderately good resistance to marine atmospheres. Some roughening of the surface by pitting is apt to occur, especially with alloys of lesser purity.

Magnesium is not widely used for equipment in marine services. However, aircraft and military gear have used magnesium components. A tremendous effort has gone into the development of protective treatments and coatings for magnesium. DMIC Memorandum 205 discusses surface treatments for magnesium in great detail.(111)

A recommended method of providing protection is as follows: first apply a conversion coating, such as Dow-17 anodize, to the metal surface; then apply an alkali-resistant coating system such as an unpigmented epoxy resin base, and cure by baking. Alkali resistance is important because

magnesium in the presence of moisture develops a strong alkaline reaction at defects in a protective coating.

Zinc chromate pigmented primer often is used in protective systems; this is followed by a top coating of a vinyl, epoxy, acrylic, or a urethane resin type of formulation.

Since magnesium is the most anodic metal in the galvanic series, galvanic coupling to another metal will cause accelerated attack on the magnesium. The other metal in the couple also may deteriorate. For example, when a couple between magnesium and aluminum was exposed at the 80-foot lot, Kure Beach, N. C., anodic attack took place on the magnesium and alkali attack, from the cathodic reaction, developed on the aluminum; both metals corroded more rapidly than when uncoupled.

### Special-Purpose Metals

The refractory metals are used in electronic and instrument applications, which may involve a marine environment. The noble metals, likewise, have electrical, electronic, and other special applications. Zinc is used as a sacrificial anode and as a protective (galvanic) coating. Lead is used as an impressed-current anode. Cadmium is used as a metallic coating over steel, and is very protective. Tin, which is quite resistant to marine environments, is not extensively used as a metal, but is used in alloys.

### Refractory Metals

The refractory metals covered here include tantalum, zirconium, niobium, molybdenum, tungsten, vanadium, hafnium, and chromium. Comparatively few data are available for these metals in marine environments. As a group, however, these metals show an outstanding degree of resistance to attack by a variety of corrosive environments. The chemical properties of these metals have several points in common. Foremost among these is the fact that they all form a tight, thin, passive oxide film on their surface. This feature is related to their good-to-excellent corrosion behavior in saline environments. All of these metals are fouled by marine organisms in ocean waters. However, most of them are sufficiently passive to perform well even in the presence of deposits and fouling.

Tantalum. Of the refractory metals, tantalum is the most corrosion resistant to a wide spectrum of corrosive solutions. This inertness is caused by the presence of a self-healing film of  $Ta_2O_5$ . As shown in Table 71, the corrosion rate for tantalum was only 0.011 mpy after exposure to a 3 percent salt solution at room temperature for 84 days. In seawater, with a pH of 8, tantalum rivals titanium in inertness. After 181 days' exposure in shallow seawater, no measurable change was observed.(92) An alloy of 90Ta-10W also has been found to be completely resistant to ambient seawater.

TABLE 71. CORROSION RATES OF REFRACTORY METALS IN 3 PERCENT NaCl(112)

Temperature, F	Test Period, days	Corrosion Rate, mpy (Calculated From Weight Loss)								
		Ti	Zr	Hf	V	Nb	Ta	Cr	Mo	W
68	7(a)	0	0	0	0.07	0	0	0	0.013	0.015
84	84	0	0.011	0	0.57	0.0069	0.0017	0	0.011	0.0031
212	2	0	0.067	0.022	0.7	0.05	0.03	0	0.04	0.28

(a) Alternate immersion; the other two tests are for continuous immersion.

As shown in Table 71, the corrosion rate of tantalum in a salt solution is an order of magnitude higher at 212 F than at 68 F. Presumably in hot seawater, there also would be an acceleration in the attack. It is also possible that crevice attack in tantalum may become a factor in hot seawater.

Tantalum is also inert as an impressed-current anode in ambient seawater. The tantalum surface, in this application, is normally platinized.

When coupled to such structural metals as steel or aluminum, tantalum may develop nascent hydrogen on its cathodic surface. In acid solutions, this leads to embrittlement of the tantalum.<sup>(112)</sup> However, in alkaline seawater there appears to be less danger of this action taking place. The same rules apply for coupling tantalum as for coupling other metals, such as titanium, to common structural metals.

**Zirconium.** Zirconium is resistant to a wide spectrum of saline solutions. For example, it resists  $\text{CaCl}_2$  solutions up to boiling temperatures and, as shown in Table 71, its corrosion rate in 3 percent  $\text{NaCl}$  is 0.011 mpy at 68 F and 0.067 mpy at the boiling point. In synthetic ocean water, zirconium is fully resistant up to the boiling point. The Navy has reported the seawater behavior of zirconium to resemble that of titanium.<sup>(113)</sup> Seawater with free chlorine present attacks zirconium, and in this respect, zirconium is different from titanium.

Zirconium, from the evidence at hand, can be expected to be completely resistant in marine environments, including the atmosphere, at ambient temperatures.

**Niobium.** Niobium is similar to tantalum and zirconium in its corrosion properties, in that it will resist acids and salt solutions. There are some exceptions. Niobium, as indicated in Table 71, showed the same order of corrosion resistance in 3 percent  $\text{NaCl}$  as did zirconium. Niobium should be resistant to all marine environments. Niobium showed no measurable attack after 181 days of exposure in seawater.<sup>(92)</sup>

**Molybdenum.** Pure molybdenum oxidizes slowly in the marine atmosphere, thus developing a series of interference colors. ASTM tests have shown corrosion rates of 0.1 mpy after 7 years for specimens at the 80- and 800-foot lots at Kure Beach, N. C.<sup>(12)</sup> The maximum pitting was 2.4 mils.

There is some attack under submerged conditions, particularly when the solutions are aerated. In the German work reported in Table 71, the corrosion rate obtained for molybdenum in aerated 3 percent  $\text{NaCl}$  was only 0.011.<sup>(113)</sup> as compared with a rate of 0.4 mpy obtained by the Bureau of Mines.<sup>(115)</sup> Evidently, the aeration of the salt solution was more effective in the Bureau of Mines' experiment. At 95 F, corrosion rates of 0.4 mpy in 3 percent  $\text{NaCl}$  and 0.3 mpy in synthetic ocean water have been obtained.<sup>(114)</sup> At still higher temperatures, the rate of attack increases, e.g., up to 2.1 mpy at 140 F and 3.5 mpy at 212 F for synthetic ocean water.

In seawater at Port Hueneme, California, molybdenum showed uniform corrosion, with a rate of only 0.1 mpy after 181 days.<sup>(92)</sup> Thus, molybdenum is very resistant in ambient seawater, but at elevated temperatures, some attack may be expected.

**TZM** is a dilute molybdenum-base alloy containing about 0.45 percent titanium and 0.10 percent zirconium. **Mo30W**

contains 30 percent tungsten. These two alloys were compared with molybdenum in substitute ocean water as a liquid and as a spray. In the substitute ocean-water test at 140 F, the corrosion rates for molybdenum, TZM, and Mo30W were 2.1, 1.7, and 1.4 mpy, respectively. In the spray test, the rates, in the same order, were 0.4, 1.1, and 0.5 mpy. All specimens developed a thin black deposit with very slight corrosion.<sup>(115)</sup> These results would suggest that the two alloys have marine resistance of the same order as that for unalloyed molybdenum.

**Tungsten.** Tungsten, like molybdenum, resists attack in marine atmospheres (see Table 71). In synthetic seawater, corrosion rates of 0.2 mpy (95 F), 0.3 (140 F), and 0.7 mpy (212 F) are reported.<sup>(114)</sup> In live seawater, a corrosion rate of 0.3 mpy after 181 days was obtained. These results are similar to those for molybdenum.

**Vanadium** Vanadium shows good resistance to sodium chloride (see Table 71) and to synthetic seawater. In air-saturated  $\text{NaCl}$  solutions at 95 F, corrosion rates of 0.4 mpy were obtained. In live seawater, vanadium corrodes at 3 mpy.<sup>(46)</sup> From this evidence, one would expect vanadium to be less resistant to marine environment than are titanium and tantalum, but to have a resistance similar to that of molybdenum.

**Hafnium.** Hafnium, for which no marine data were found, would be expected to resemble zirconium in resistance to marine corrosion. In stagnant 20 percent  $\text{NaCl}$  solution at 95 F, hafnium corrodes at 0.08 mpy.<sup>(116)</sup> (See also Table 71.)

**Chromium.** Chromium, as a metal sheet, is not attacked by  $\text{NaCl}$  solution (see Table 71) at temperatures up to the boiling point. In this environment it was as resistant as titanium. In seawater, the strong passive film should be resistant, and local attack should be less likely than in the case of the stainless steels.

Chromium, as an electroplate over a nickel coating confers good resistance to the basic metal, e.g., steel, brass, or zinc-base die castings, in marine atmospheres.<sup>(46)</sup>

## Noble Metals

Platinum is the most resistant of the precious metals in the group consisting of platinum, palladium, gold, and silver.

Platinum is completely resistant to marine atmospheres and to seawater. In the latter, its main application is as impressed-current anodes. Platinum is more often used with another metal as a backing, such as platinized titanium or tantalum. It also is an essential part of the lead-platinum anode system. All types of platinum impressed-current anodes have been highly successful. On titanium or tantalum, for example, a platinum coating 100 microinches thick will provide for impressed currents as high as 100 amp/ft<sup>2</sup>. The oxidation loss of platinum in seawater anode applications is taken as 6 mg/amp-yr.<sup>(117)</sup>

Palladium resembles platinum in marine resistance. In seawater as an anode, palladium also is resistant, but less so than



Gold is completely resistant to the marine atmosphere and to seawater. It has been used to protect electrical contacts from tarnishing and corrosion in a marine atmosphere. Gold also has been used as a coating to protect a magnetic diaphragm exposed directly to seawater.

Silver has good corrosion resistance to marine environments, but will tarnish in a marine atmosphere, especially if sulfur compounds are present. After 2.6 years at Kure Beach, N. C., the corrosion rate of silver in seawater was 0.5 mpy.(46) Silver's main use in the marine field is in electrical and electronic equipment such as radar waveguides.(26) On electrical contacts, a thin coating of palladium or gold is sometimes used to retard tarnishing. Lead-silver alloys are used for impressed-current anodes.(118)

#### Lead, Zinc, Cadmium and Tin

**Lead.** Lead is resistant to the marine atmosphere. At Cristobal, Canal Zone, corrosion rates of 0.1 mpy were recorded for an 8-year exposure.(119) The corrosion was uniform, and as shown in Figure 92 is proportional with time. Even lower rates were found at La Jolla, California, namely, 0.016 mpy after 10 years. Although lead is cathodic to steel, it does confer protection as a metal coating. For thicker coatings of say 1 mil or more, lead corrosion products tend to plug damaged areas such as at a scratch. Protection is improved if the marine atmosphere is polluted.

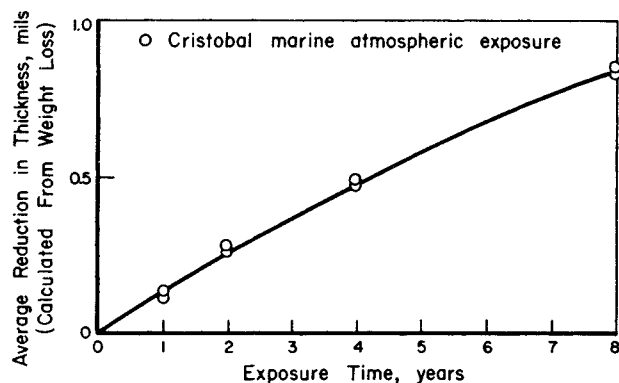


FIGURE 92. RELATION BETWEEN CORROSION AND EXPOSURE TIME FOR LEAD EXPOSED TO MARINE ATMOSPHERE IN PANAMA CANAL ZONE(120)

The corrosion of lead is 0.3 mpy after 16 years in the Pacific Ocean.(120) A comparison of lead with other metals (Figure 93) indicates that its corrosion rate stabilizes at about the same rate as that for Monel, and is somewhat less than that of zinc.(109) Pitting was observed in this exposure and was ascribed to local cell attack under marine fouling. It may be that  $H_2S$  generation from decaying organisms, in the lowest layer of marine fouling, modifies the corrosion of lead.

There seems to be little variation in the corrosion behavior of lead in the seawater at different geographical sites. Typical rates for lead and lead alloys are presented in Table 72.

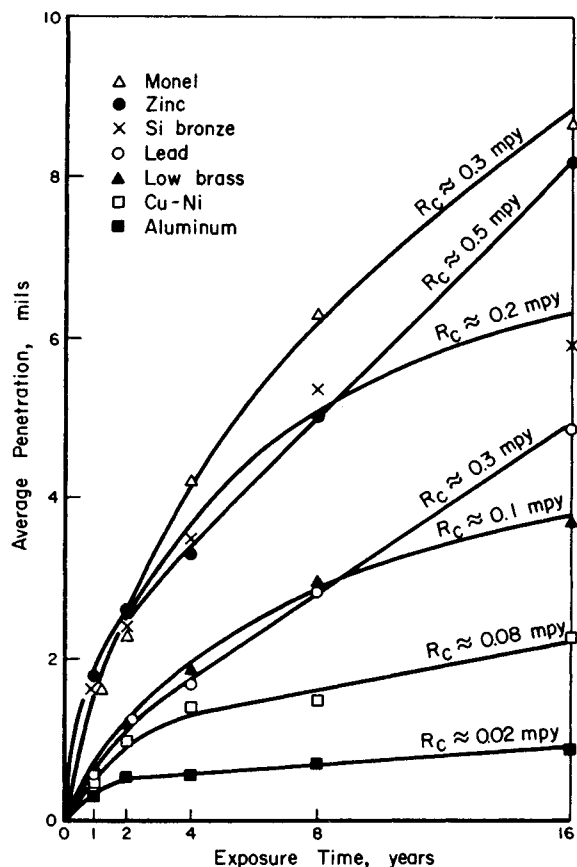


FIGURE 93. COMPARISON OF AVERAGE PENETRATION OF WROUGHT NONFERROUS METALS AFTER 16 YEARS' CONTINUOUS IMMERSION IN SEAWATER(109)

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TABLE 72. CORROSION OF LEAD IN SEAWATER(121)

Specimen	Form	Exposure Time, years	Corrosion Rate		Location
			Mdd	Mpy	
99.96% Pb	Bar	4	4.0	0.5	Weston super Mare
1.6% Sb/Pb	Bar	4	3.0	0.4	Weston super Mare
Chemical lead	Sheet	0.5	3.1	0.4	San Francisco Harbour
Lead	Plate	1.7	4.7	0.6	Kure Beach

Information from a variety of exposures indicates that the rate of attack for lead and lead alloys in seawater is about 0.5 mpy.(121) However, recent tests in shallow- and deep-ocean environments showed rates ranging as high as 1.2 mpy for several types of lead (see Table 73). The attack was uniform for exposures of up to about 6 months. After longer periods of time, the attack would be expected to diminish. It is of interest to note that the 67Pb-33Sn solder reported in Table 73 showed rates similar to that of lead in the deep ocean, but 3.7 mpy in shallow seawater.(92)

The main use of lead in seawater has been as a protective sheath for submerged communications cables. The excellent resistance of the sheath is an indication that lead will endure in both seawater and the bottom sediments.



TABLE 73. CORROSION OF LEAD, SOLDER, TIN, AND ZINC IN SEAWATER(92)

Metal	Days	Depth, ft	weight loss mpy	Pit Depth, mils	Remarks
Chemical lead(a)	181	5	1.2	—	Uniform attack
	197	2340	0.3	—	Ditto
	123	5640	0.8	—	"
Tellurium lead(b)	181	5	1.0	—	"
	197	2340	0.3	—	"
	123	5640	1.1	—	"
Antimonial lead(c)	181	5	1.2	—	"
	197	2340	0.3	—	"
	123	5640	0.8	—	"
Solder(d)	181	5	3.7	—	"
	197	2340	0.5	—	"
	123	5640	0.5	—	"
Tin(e)	181	5	8.3	30	Perforated
	197	2340	1.8	2	Crevice attack
	123	5640	0.5	—	General attack
Zinc(f)	181	5	4.5	5	Pitting
	197	2340	2.3	2	Ditto
	123	5640	6.7	13	"

(a) 99.9 Pb.

(b) 99+ Pb, 0.04 Te.

(c) 94.0 Pb, 6.0 Sb.

(d) 67 Pb -33 Sn.

(e) 99.9 Sn.

(f) 0.01 Fe, 0.09 Pb.

Zinc. Although zinc is used mainly as a galvanic coating to protect steel in the marine atmosphere, it is of interest to examine the corrosion rates of zinc itself. During the first few years, zinc corrosion tends to diminish and stabilize at a steady rate. By way of illustration, after 10 and 20 years at the marine-atmospheric-exposure site at La Jolla, California, rolled zinc had reached a steady rate of 0.069 mpy.(122) At Key West, Florida, an even lower rate 0.022 mpy was obtained. Comparative data from four sites are presented in Table 74. In the rural, mildly corrosive atmosphere at State College, Pennsylvania, for example, the rate is double that of Key West and two-thirds that at La Jolla.

The corrosion of zinc varies some with time of year first exposed. Other corrosion experience with zinc suggested that purity might be a factor in the marine environment. However, as shown in Table 75, in 1-year tests, iron contamination up to 0.011 percent did not adversely affect the corrosion behavior.

The excellent corrosion resistance of zinc in the marine atmosphere helps explain its usefulness as a coating to protect iron. At Key West, exposure tests in an aggressive marine

TABLE 74. ASTM DATA ON ZINC(122)

Location	Penetration, mpy	
	10 Yr	20 Yr
Key West	0.019	0.022
Sandy Hook	0.059	0.073
La Jolla	0.068	0.069
State College	0.040	0.044

TABLE 75. KURE BEACH TESTS ON IRON-CONTAINING ROLLED ZINC(122)

Iron, %	Penetration, mpy			
	80-Foot Rack		800-Foot Rack	
	6 Months	1 Year	6 Months	1 Year
0.0003	0.4	0.4	0.3	0.2
0.0008	0.45	0.3	0.3	0.2
0.0014	0.5	0.4	0.3	0.2
0.0021	0.5	0.4	0.3	0.2
0.006	0.45	0.4	0.3	0.2
0.011	0.45	0.6(a)	0.3	0.2

(a) 0.2 and 1 mil/year on duplicate panels.

environment are being conducted. Galvanized 22-gauge steel panels (with zinc coatings ranging from 1.5 to 2.6 oz/ft<sup>2</sup>) coated on both sides have gone more than 32 years without any rust appearing. At the present rate of attack, it is estimated that the 2-ounce coating\* will last 79 years.(122) However, higher corrosion rates would be expected where actual seawater splash strikes the galvanized surface.

In seawater, the corrosion rate of sheet zinc is usually 1 to 2 mpy(122), although some recent data indicate higher rates. After 3 years' exposure at Eastport, Maine, a rate of 1.0 mpy was obtained. Similar rates are reported for zinc exposure in the Pacific Ocean off the Panama Canal Zone. Corrosion rates in flowing seawater at Kure Beach for special high-grade zinc are given below.(122)

Exposure Time, yr	Corrosion Rate, mpy
0.5	1.9
4	0.8

Corrosion rates ranging from 2.3 to 6.7 mpy were obtained for zinc specimens containing 0.01 percent iron and 0.09 percent lead in Pacific waters.(92) These data are presented in Table 73. Pits as deep as 13 mils were reported. On the other hand, in experiments conducted at Harbor Island, North Carolina, zinc with as much as 0.011 percent iron showed a rate of only 1.4 mpy. These data are listed in Table 76 along with tidal and low-velocity data. Note the good behavior of zinc in the tide zone and the increase in attack with a velocity of only 2 fps.

Even though zinc usually corrodes at a rate lower than that of iron, it is not recommended as a metal for service in seawater. There has been little actual use of metallic zinc in seawater, partly because of poor physical properties and partly because of its susceptibility to localized attack.(46) Zinc's major contribution is as a sacrificial anode in seawater, as discussed elsewhere. Zinc is also used as a galvanic coating on

The excellent corrosion resistance of zinc in the marine atmosphere helps explain its usefulness as a coating to protect iron. At Key West, exposure tests in an aggressive marine

\*A 1-ounce coating is about 1.8 mils thick and, therefore, a 2-ounce coating would be 3.6 mils thick.

steel. Galvanized-steel piping is used on board ship to handle seawater lines used for fire fighting. The limited oxygen present in the stagnant seawater inside the pipe no doubt is a factor in the low rate of corrosion observed.

TABLE 76. SEAWATER CORROSION OF IRON-CONTAINING ZINC<sup>(122)</sup>

Iron, %	Corrosion Rate(a), mpy		
	Total Immersion	Tidal Zone	2 FPS Flow
0.0003	1.4	0.8	3.0
0.0008	0.8	0.8	2.0
0.0014	0.8	0.9	2.0
0.0021	0.8	0.9	2.0
0.006	0.8	0.8	2.0
0.011	1.4	0.9	2.0

(a) Average of two 1 x 4 x 1/2-inch specimens exposed 1 year.

Cadmium. Cadmium is used as a metal coating over steel in marine applications. In the marine atmosphere, zinc is usually preferred, but if the local conditions are very corrosive, cadmium may be better by a substantial margin, as illustrated by Figure 94.

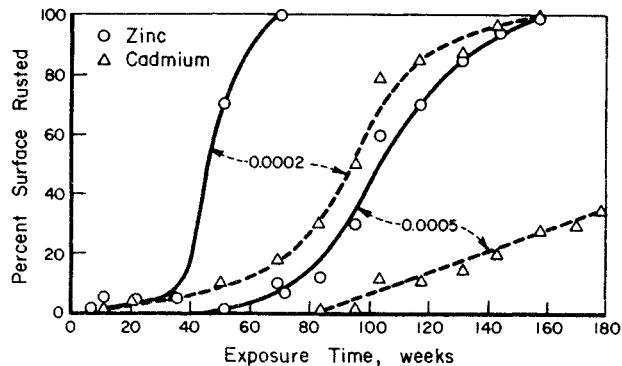


FIGURE 94. COMPARISON OF PROGRESSIVE DEVELOPMENT OF RUST ON ZINC- AND CADMIUM-PLATED STEEL PANELS AT 80 FOOT LOT, KURE BEACH, N.C.<sup>(123)</sup>

Coating thicknesses 0.0002 and 0.0005 inch.

Tin. Tin is resistant to marine atmospheres and could be used in some special applications. After 10 years at a marine location, tin showed a weight gain of 0.11 mdd.<sup>(4)</sup> When the deposit was removed, the penetration (calculated from the weight loss) was found to be 0.089 mpy.

Recent results for tin in seawater are given in Table 73. Weight-loss penetrations of 1.8 and 0.5 mpy were obtained for two deep-ocean exposures. The 30-mil-thick sample in the surface exposure perforated in 181 days, and the correspondingly high penetration figure based on weight loss is only approximate.<sup>(92)</sup> Although the older results suggested that tin was resistant to seawater, the new information does not bear

this out. The tendency of tin to pit as well as its susceptibility to crevice attack and to local corrosion under biofouling and deposits would predate against using tin in seawater. Tin is about 0.25 volt cathodic to iron and, therefore, will not serve as a practical coating system for the protection of steel alloys in seawater.

### Cathodic Protection

The corrosion of many metallic structures immersed in seawater can be reduced to a low value by the application of cathodic protection. Protection is achieved when the potential of the steel, for example, is brought to about -0.80 volt with reference to the saturated calomel half cell. For submerged structures, cathodic protection is widely used, together with coatings, to restrict corrosion.

### Mechanism

There are a number of ways of explaining the mechanism of cathodic protection. Simply stated, a metal tends to develop local anodes and cathodes when first immersed in an electrolyte like seawater. These arise because of compositional or other variations on the surface. When an external cathodic current is applied, the local cathodes tend to polarize to the potential of the local anodes. Once this potential is achieved, corrosion currents no longer flow. The quantity of electricity to be supplied to achieve this condition will vary, depending on the metal and the depolarizing characteristics of the environment.

### Major Parameters

In seawater, the major parameters that affect cathodic polarization are resistivity, oxygen content, and velocity of the seawater, and the deposition of a calcareous scale. If the metal is coated, the integrity of paint film will affect the current required for polarization.

Resistivity decreases with increase in salinity; for seawater of constant salinity, the resistivity decreases as the temperature is raised. In ordinary seawater, the resistivity may vary from 35 ohm-cm in arctic waters to 16 ohm-cm in tropic waters.<sup>(124)</sup> Resistivity will tend to increase considerably in harbors and estuaries where there is freshwater dilution. Thus, for maintaining polarization on a ship moving in and out of waters of varying resistivity, a cathodic protective system responsive to the changes in environment is required.

Oxygen is the principal depolarizer in seawater. An increase in the oxygen content will promote greater depolarization of the cathodic reaction and a corresponding increase in current will be required to maintain polarization.

An increase in the velocity of the seawater causes the products of the cathodic reaction to be removed more rapidly. The amount of oxygen arriving at the cathode surface per unit of time also will increase. These combined actions will increase the current demand for polarization. For example, as shown in Figure 95, increasing the velocity from stagnant to 13 fps would increase tenfold the current density required to maintain polarization on bare steel in seawater. For offshore platforms, the movement or vibration of the structure may have to be taken into account to the velocity effect of the ocean currents sweeping by to arriving at some estimate of the increased cathodic-current demand for polarization.

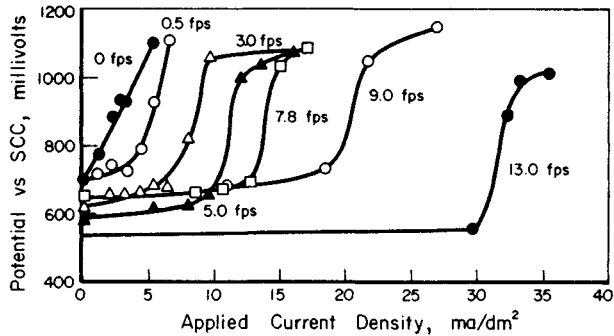


FIGURE 95. CATHODIC POLARIZATION OF MILD STEEL IN SEAWATER FLOWING AT DIFFERENT VELOCITIES AT 26 C(124)

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Temperature also may affect the degree of polarization. An increase in temperature decreases the solubility of oxygen but increases the rate of diffusion. In a particular situation, these factors may tend to balance out.

Calcareous Coating

The application of cathodic current promotes the formation of hydroxyl ions at cathodic areas. Also, the concentration of calcium and magnesium ions tends to increase in the film of seawater over the cathode. As a result of these changes, the solubility of calcium carbonate and magnesium hydroxide is exceeded and a calcareous coating is deposited. The development of this coating can be accelerated by using somewhat higher current density than that normally employed for polarization in practice. For electrocoating, 50 to 350 ma/ft<sup>2</sup> gives satisfactory coatings.(125) The most dense deposits tend to form at 100 to 200 ma/ft<sup>2</sup> and are found to contain equal parts of calcium carbonate and magnesium hydroxide.(125) At high current densities, above 200 ma/ft<sup>2</sup>, the deposit is quite soft. The current density-time requirements for the formation of calcareous films that result in low current requirements for protection are summarized in Table 77. It will be seen that at high current densities, films can be formed in a few days, after which a much lower current density is required for continued protection. This fact is further illustrated by an experiment conducted on prefilmed steel panels by the Dow Chemical Company. As shown in Figure 96, their work suggests that once a calcareous deposit has been formed, only 3 ma/ft<sup>2</sup> is required for protection. For these conditions, higher current densities do not offer any additional protection. Current densities below 3 ma/ft<sup>2</sup> were not sufficient to maintain complete protection.

In practice, steel structures are polarized initially at higher current densities than are required for continued protection, in order to take advantage of the calcareous coating. Such a technique can result in a considerable saving in current requirements. For example, if a current of 50 ma/ft<sup>2</sup> is applied to a structure for the first 5 days or so, polarization can then be maintained with a current of about 3 ma/ft<sup>2</sup>, as mentioned above. Ampere-hour savings of as much as 40 percent can be achieved during the first year of protection by this rapid polarization procedure.(125)

There appears to be less tendency for the calcareous scale to form in the deep ocean. In an experiment conducted by the Navy, galvanic anodes were found effective in providing cathodic protection to bare steel in the ocean at 5,600 feet.(75) However, the anodes were found to have been

consumed more rapidly than would be expected if the experiment were conducted at the surface. Since the pH is lower at great depths, and the calcium carbonate concentration is below saturation, higher currents apparently are required to achieve polarization.

TABLE 77. POLARIZATION OF BARE STEEL IN SEAWATER(125)

Initial Current Density, ma/ft <sup>2</sup>	Exposure Time	Film	Current Density Required for Continued Protection, ma/ft <sup>2</sup>
200	1 day	Soft, with high magnesium content	2-3
100	2-3 days	Fairly hard	2-3
50	5-6 days	Hard, mainly calcareous	2-3
20	20-30 days	Medium thickness, hard	3-4
10	2-3 months	Medium thickness, hard	4
6	Up to 6 months if at all	Light, hard	4-5

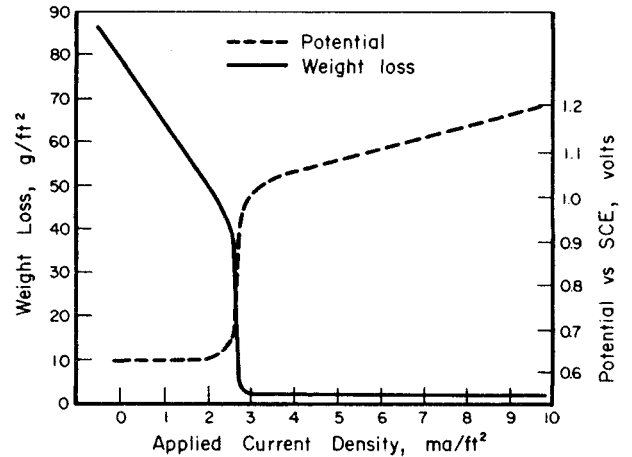


FIGURE 96. STEEL PANELS, FIRST COATED WITH CALCAREOUS SCALE (COX COATING) THEN CATHODICALLY PROTECTED FOR 1 YEAR IN SEAWATER, SHOWING WEIGHT LOSS AND POTENTIAL AS RELATED TO CURRENT DENSITY(125)

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Current Requirements

It is pointed out that the discussion on the amount of current required to prevent corrosion of steel is based primarily on relatively quiet seawater conditions. At some geographical locations, the current requirements are often higher, for example, 5 to 10 ma/ft<sup>2</sup>, depending on the velocity and other factors. In Cook Inlet, Alaska, where ocean currents are particularly strong, a current density of as much as 15 ma/ft<sup>2</sup> may be required to achieve complete protection.

For steel in seawater, it is more typical to apply a protective alkali-resistant paint over the surface. This, in combination with cathodic protection, results in an effective method of corrosion control. Current requirements are much lower than for bare steel since it is necessary to provide protection only at the damaged areas in the paint coating. These, in turn, will be polarized more rapidly by the calcareous scale. The net effect is to promote more uniform polarization of the entire structure, since damaged areas closest to the anode will be "repaired" first, forcing the current to travel to more distant coating defects (holidays). Cathodic protection does not interfere with the performance of antifouling coatings.

#### Overprotection Effects

In seawater, steel structures can be protected at a potential of about -0.80 volt or higher versus the saturated calomel reference cell. At higher cathodic voltages, for example, -1.10 volt or greater, there is danger of damaging effects from the excessive hydroxyl-ion formation and from the large volumes of hydrogen gas generated. Amphoteric metals and some protective organic coatings are sensitive to alkali. Blistering of paint films may result from endosmosis effects or from hydrogen developed under the film. These effects frequently are observed on that portion of the metal structure nearest the anode. Nascent hydrogen can damage steel, especially the high-strength low-alloy steels. On carbon steels, hydrogen damage in seawater usually is not observed under cathodic protection. With excessive cathodic protection, the hydrogen liberated can promote catastrophic cracking with high-yield-strength steels (e.g., above 150,000 psi) when under tensile stress (hydrogen-stress cracking).

One of the "poisons" that tend to promote hydrogen penetration into the metal is sulfide. Sulfides are present in seawater that is polluted and also in waters at the bottom where the mud may have sulfate-reducing bacteria.

#### Selection of Anodes

Two types of anode systems are employed in cathodic protection. The anodes may be (1) the sacrificial type or (2) the impressed-current "insoluble" type.

**Sacrificial Type.** Use of sacrificial anodes dates back to Faraday. Their major advantage is simplicity and little need for supervision.

The sacrificial-type anodes being used for seawater applications include zinc, aluminum, and magnesium. The characteristics of these are given in Table 78.

**Zinc.** Cathodic protection systems employing zinc anodes have been very successful. The design is simple, anodes of high current efficiency are available, and the inherent self-regulating characteristic is a distinct advantage. Zinc anodes need to employ a low resistance circuit so that the anode can develop the necessary current needed to maintain the facility at polarization. Zinc anodes have a high ampere-hour capability per unit volume. The protective coating or paint system on the marine structure is not subjected to local high potential, as may occur with magnesium anodes in some installations.

When zinc is employed in the cathodic protection of a steel ship's hull, the lesser volume of the zinc anodes compared with that of magnesium or aluminum can be an advantage from the hydrodynamics involved. A general rule of thumb for a steel hull is to employ one 22-lb anode, 6 x 12 x 1.25 inches (or equivalent), for each 100 square feet of painted surface. In addition, one such anode is provided for each 5 square feet of cathodic metal, such as the bronze propeller, bearings, shafts, etc. These extra anodes are installed close to the sites where the cathodic metals are located. Anode life is only 1 to 2 years following this rule. Extra anodes can be installed if it is desired

TABLE 78. CHARACTERISTICS OF COMMERCIALY AVAILABLE SACRIFICIAL ANODES IN SEAWATER SERVICE(75,124,126-129)

Anode	Description	Max Structure Potential, volt	Solution Potential, volt	Current Efficiency, percent	Ampere-hours per Pound	Pounds per 1 Amp-Year	Notes
Magnesium	0.03 Cu (max), 0.003 Fe (max), and 0.10 Mn (min)	-1.15	-1.50(a)	50	500	17.5	
Zinc	—	-0.90	-1.05(a) -1.10(c)	95	354	24.7	
Al-Zn-Hg	99.9% purity Al + 0.045 Hg + 0.45 Zn	-1.00	-1.05(b) -1.1(c)	95	1280	6.1	No heat treatment required — good efficiency
Al-Zn-Sn	See Table 80	—	—	85(d)	1150	7.6	Requires precise control of heat treatment

(a) Closed-circuit potential referred to Ag/AgCl electrode.

(b) Closed-circuit potential referred to saturated calomel electrode.

(c) Closed-circuit potential referred to Cu-CuSO<sub>4</sub> electrode.

(d) Efficiencies as low as 32 percent have been reported with improper heat treatment.

to extend the time between replacement. When anodes are mounted directly on the hull or structure, an anode shield, usually of plastic, is employed to insure proper current distribution.

The performance of zinc anodes depends upon the control of impurities in the zinc. The presence of very small amounts of certain impurities promotes the formation of a dense adherent skin of corrosion product which polarizes the anodes. The major harmful impurity is iron which, in amounts as little as 15 ppm, seriously impairs anode efficiency. This adverse effect of iron can be counteracted by additions of silicon, aluminum, and cadmium. Zinc anodes which meet Military Specification MIL-18001G, presented in Table 79, are considered entirely dependable and generate current at close to 100 percent efficiency.

TABLE 79. COMPOSITION OF ANODE ZINC (MIL-18001G)(127)

Composition, percent	
Al	0.10 -0.50
Cd	0.025-0.15
Pb	0.006 max
Si	0.125 max
Cu	0.005 max
Fe	0.005 max
Zn	(balance)

Aluminum. Although aluminum anodes have been available for many years, it is only during the last decade that they have found extensive application in the marine field. The first anode developed for marine service was the Al3Zn (3% Zn) alloy. The newer anode types are tertiary alloys of aluminum-zinc-tin and aluminum-zinc-mercury. Their characteristics are given in Table 80.

TABLE 80. NOMINAL CHEMICAL COMPOSITIONS AND EFFICIENCIES OF SEVERAL PROPRIETARY ALUMINUM-ALLOY ANODES(91)

	Chemical Composition, percent						Galvanic Efficiency, percent
	Zn	Sn	Hg	B	Fe	Al(b)	
A	4.66	0.22	Not detected(a)	—	0.08	Balance	84-87
B	6.85	0.14	Ditto	0.02	0.05	Balance	45-80
C	4.36	0.13	"	—	0.07	Balance	60-85
D	1.65	0.08	"	—	0.07	Balance	31-69
E	0.60	—	0.04	—	0.07	Balance	95

(a) Spectrographically.

(b) Minus the common impurities such as Si.

As in the case with zinc anodes, control of impurities for aluminum anodes is essential for best performance. In addition, however, the Al-Zn-Sn alloy anode also requires a closely controlled heat treatment to develop the desired electrochemical properties. Because of the reactive nature of mercury, special processing is also involved in obtaining the desired electrochemical characteristics in the Al-Zn-Hg alloy anode. As shown in Figure 97, the current output of the Al-Zn-Hg anodes compares favorably with zinc in a 255-day test. According to Schreiber and Reding(130) the Al-Zn-Hg alloy not only has high current capacity, but reproducibility of performance, and

stable potential. The current efficiency is high for a wide range of current demand, as illustrated by the results in Figure 98.

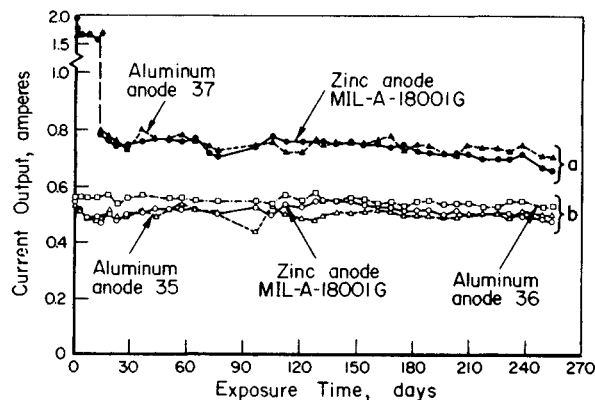


FIGURE 97. COMPARISON OF CURRENT OUTPUT IN SEAWATER OF ALUMINUM-ZINC-MERCURY TYPE ANODES AND ZINC ANODES(91)

Current was controlled by (a) 0.01 ohm shunt and (b) 0.5 ohm shunts, respectively, to a steel cathode which was unpolarized.

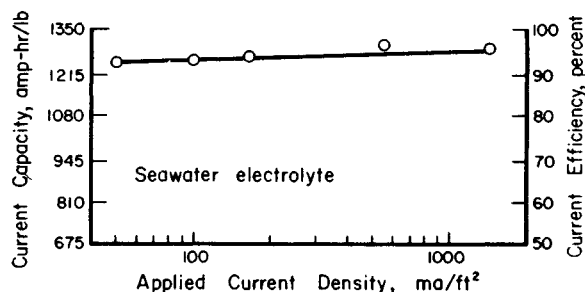


FIGURE 98. CURRENT CAPACITY AND EFFICIENCY AS RELATED TO CURRENT DENSITY FOR A NOMINAL Al0.045Hg-0.45Zn ALLOY(130)

If the aluminum-zinc-tin alloy is carefully controlled as to composition and heat treatment, it too will provide high current and stable potential. Aluminum anodes can be used wherever protection with the magnesium type would be a problem.

Magnesium. With the advent of the high-purity zinc anode and, more recently, the ternary-alloy aluminum anodes, the use of magnesium anodes for service in seawater has declined markedly. However, magnesium is still used for some special applications. The alloy preferred for marine service is Mg-6Al-3Zn, with careful control of iron and nickel to less than 0.003 percent each and copper to less than 0.10 percent. Its higher driving potential and lower density can be an advantage, even at 50 percent current efficiency, in some special applications. For example, a 200-pound anode has been developed to provide 6 amperes' output for a life of 2 years. It is suspended from, and grounded to, the marine structure to be protected by a wire cable.(127)

In one anode of recent development, 20 pounds of magnesium is cast over a 375-pound anode of zinc.(127) This type



of anode should provide higher polarizing currents during the initial period when the calcareous scale is being formed. After that, the zinc takes over and maintains polarization.

**Impressed-Current Type.** For many installations involving seawater, an impressed-current system, which requires a local power source, is now preferred. In this system, direct current from a low-voltage source is introduced into the seawater at a suitable distance from the object to be protected using insoluble anodes of the type indicated in Table 81. An advantage of the impressed-current anode system is that the amount of current supplied can be adjusted to meet changing demands resulting from such factors as velocity, resistivity, oxygen level, and damage to protective paints.

Impressed-current anodes normally are secured to the hull, in the case of a ship, and may be fastened directly to a structure. Fewer anodes are used than would be the case with the galvanic type. Since greater distances are involved to insure coverage, these anodes must be driven at a higher voltage. Thus, a shield (usually plastic), about 3 or 4 feet square, must be applied to the surface around the anode to avoid damage to the paint and structure immediately adjacent to the anode. Alternatively, the anode can be mounted several yards from the nearest metal in the structure.

TABLE 81. IMPRESSED CURRENT ANODES USED IN SEAWATER APPLICATIONS(117,127,131)

Anode	Description	Characteristics	Notes
Platinum	Used as thin sheets with support, e.g., 0.005-inch-thick disk with a cast polyester plaster, plus glass-fiber backing	No restrictions on anode current density.	
Platinized titanium	Very thin film of platinum on titanium; 0.00001-inch film, for example, on rod or disk copper core for electrical conductivity; anode to cathode voltage about 12 volts	A current density of 100 amp/ft <sup>2</sup> , can be employed. Some pitting may occur at higher current densities	
Platinized tantalum (or niobium)	(Similar to above)	Higher voltage can be used than with platinized titanium	
Lead/Silver	Dark-brown coating is formed to make anode "insoluble" Alloys: 93Pb-6Sb-1Ag or 98Pb-2Ag	Once coating is developed, anode must be handled with care. Breakage is a problem	Electrical lead attachment can be a problem
Graphite	Double-boiled linseed oil used to impregnate graphite	Chlorine and oxygen generated in seawater seems to attack impregnant. Poor mechanical properties	Leads are factory installed following design plans of installation
Silicon/Iron	Brittle alloys with 14%Si, 3%Mo, rest Fe or 14% Si, 5Cr, 1Mn, rest Fe	Performance variable in seawater. Does better in brackish water than in seawater. Poor mechanical properties. Local failure by pitting in seawater	Ditto

## UPDATE 1977

## The Ocean Environment

Factors Affecting the  
Corrosivity of Seawater

The effect of oxygen concentration in seawater on the corrosion of 181 metals and alloys has been evaluated at the Naval Civil Engineering Laboratory.<sup>(132)</sup> Linear regression analyses were performed on the results of deep-ocean tests conducted for 1 year at 1.5, 760, and 1830 meters depth (5.75, 0.4, and 1.35 ml O<sub>2</sub>/l seawater, respectively). The corrosion rates of the following alloys increased linearly with oxygen concentration in the seawater: carbon and low alloy steels, cast iron, copper alloys (except Muntz metal and Manganese Bronze A), Type 410 stainless steel, Ni-200, Monel 400, Inconel 600 and X-750, Ni-30Mo-2Fe, and lead. The corrosion rates of many other alloys increased with temperature but not linearly or uniformly. Many of the alloys were not corroded at any of the 3 oxygen levels after 1 year's exposure. This group included silicon cast irons, several 18 Cr-8 Ni stainless steels, several Ni-Cr-Fe and Ni-Cr-Mo alloys, titanium alloys, columbium, and tantalum.

The effect of aerobic marine bacteria on the corrosion of metals has been studied by the University of Miami and the Office of Saline Water.<sup>(133)</sup> Specimens were exposed to untreated aerated seawater from a tidal channel and to the same water passed through a Millipore filter to remove living microbiota. Corrosion rates obtained by polarization resistance methods in these studies are summarized below:

	Corrosion Rate, mils/yr	
	Bacteria Water	Bacteria-Free Water
Steel	6.7	7.4
5052 Aluminum	0.2 to 0.48	0.12 to 0.35
Type 316 Stainless Steel	0.1	0.01

A chemical engineer's guide to seawater has been prepared by the Dow Chemical Company.<sup>(134)</sup> Information in the papers on seawater covers average monthly temperature and salinity at various locations off the U.S. coast, chemical composition, physical properties at concentrations varying from that of fresh water to four times normal seawater, foaming and turbidity characteristics, deposition of solids, and marine life.

## Forms of Corrosion

The electrochemical potentials of high-purity metals have been determined in quiescent seawater by the Naval Research Laboratory.<sup>(135)</sup> The electrochemical potentials of many metals varied with time. Those of tin and bismuth were relatively stable in full-strength seawater, but were less stable in dilute seawater. The potential for high-purity aluminum was quite negative, suggesting that it might find application as a galvanic anode. A galvanic series, prepared based on the median of the values obtained over 69 days' exposure, is presented in Table 82.

Some cavitation-erosion experiments were described on steels (HY 80, HY 120, and SAE 1020), aluminum alloys, and copper in synthetic seawater as well as distilled water.<sup>(136)</sup> Various intensities of erosion were applied using the standard ASTM vibratory apparatus. In general, the corrosive seawater environment increased the maximum erosion rates, decreased the exposure period needed to attain the maximum rates, and decreased the erosion strength of these materials.

TABLE 82. GALVANIC SERIES FOR HIGH-PURITY METALS<sup>(135)</sup> (69 DAYS IN SEAWATER AT KEY WEST, FLORIDA)

Metal	Metal Purity, percent,	Median Potential, SCE Reference volts
Palladium	99.99+	+0.308
Platinum	99.99+	+0.295
Titanium	Iodide (zone refined)	+0.200
Tantalum	99.9	+0.195
Gold	99.97+	+0.175
Columbium	99.9	+0.110
Zirconium	99.9	+0.010
Silver	99.95	-0.025
Nickel	99.99+ (zone refined)	-0.038
Silver	99.999	-0.115
Copper	99.99+ (zone refined)	-0.141
Nickel	99.99+ (zone refined)	-0.172
Tantalum	99.99+ (zone refined)	-0.172
Molybdenum	99.9	-0.173
Vanadium	99.99+ (zone refined)	-0.209
Tungsten	99.9	-0.240
Bismuth	99.9	-0.248
Indium	99.999 (spectrographic grade)	-0.368
Tin	Rerun 99.999 (spectrographic grade)	-0.525 -0.671
Iron	99.9+ (electrolytic grade)	-0.749
Aluminum	99.99+ (zone refined)	-1.472
	99.99+ (ingot)	-1.455

## Corrosion of Carbon and Low-Alloy Steels

## Splash, Tide, and Submerged

Much of the current knowledge involving the corrosion of steel piling in seawater has been presented in a literature survey prepared by the Army Coastal Engineering Research Center.<sup>(137)</sup> Included in the report are the causes of corrosion, effects of environmental conditions, corrosion rates of bare steel, test results on protective coatings, the use of cathodic protection, and the use of concrete jackets for protection. The survey indicated that flame-sprayed zinc sealed with Saran or vinyl is possibly the best coating system tested; properly designed and constructed concrete jackets are very effective; cathodic protection is also effective; and combinations of cathodic protection with coatings or concrete jackets may be advantageous.

The effect of alloying additions on the corrosion behavior of steel in seawater at velocities to 2 m/sec and temperatures to 20 to 55 °C has been studied by Sumitomo in Japan.<sup>(138)</sup> Chromium, molybdenum, manganese, copper, and aluminum additions were beneficial in reducing corrosion rates. A more seawater-resistant steel alloy was developed that contains 2 percent chromium and 0.2 percent molybdenum. Compared with mild steel, this new alloy is two times better in flowing aerated seawater and ten times better in flowing deaerated seawater.

The use of a Monel weld inlay to extend the fatigue life of nickel-steel propeller shafts in seawater has been studied at the Naval Ship Research and Development Center.<sup>(139)</sup> A Monel inlaid six-foot-long shaft was rotated at 600 rpm at 10 ksi stress level in Severn River water. The test facility was shut down overnight and on weekends, at which time there was no load on the shaft, but the inlaid area was covered with seawater. Fatigue failure occurred after 15,500,000 cycles which was about normal for a regular nickel-steel shaft and the Monel inlay, as installed, evidently did not prolong the fatigue life of the propeller shaft.

#### Stress Corrosion Cracking

U.S. Steel has studied the effects of prior uniform plastic strain (to 5 percent) on the mechanical and environmental properties of HY-80, HY-130, 12Ni-5Cr-3Mo maraging steel, and 10Ni-Cr-Mo-Co quenched and tempered steel.<sup>(140)</sup> Precracked cantilever beam specimens were used to determine  $K_{IX}$  and  $K_{ISCC}$  values in air and synthetic seawater, respectively. The results showed that prior plastic strain improved the mechanical properties and that  $K_{IX}$  decreased in a consistent manner depending on the yield strength and the level of strain. However, the apparent  $K_{ISCC}$  value did not follow a consistent behavior pattern. The  $K_{ISCC}$  value of HY-80 (immune to SCC) was not affected by plastic strain, while that of 12Ni-5Cr-3Mo maraging steel was increased and those for HY-130 and 10Ni-Cr-Mo-Co Q & T were decreased a moderate amount.

The susceptibility of gun steel (4337 modified) to stress-corrosion cracking has been studied at Watervliet Arsenal, using precracked cantilever-beam specimens, in air at 100 percent relative humidity, distilled water, and 3 percent NaCl solution.<sup>(141)</sup> The susceptibility to cracking increased in the order of environments given. Increasing the yield strength of the gun steel from 142 to 200 ksi increased the susceptibility to cracking.

The stress-corrosion cracking behavior of cold worked A-286 has been investigated at the George C. Marshall Space Flight Center.<sup>(142)</sup> No stress-corrosion cracks were detected in specimens cold worked to 53 percent reduction and exposed 180 days to a 3.5 percent NaCl solution in alternate immersion testing.

The stress corrosion cracking behavior of 200 ksi yield strength 4340 steel has been explored in a 3.5 NaCl solution under conditions of anodic and cathodic polarization.<sup>(143)</sup> Both anodically and cathodically charged specimens exhibited cracking. Time to cracking increased as the specimens were made cathodic and decreased as the potential was made more negative. These results were rationalized in terms of hydrogen liberation.

In studies at U.S. Steel, precracked weld specimens of the HY-80 and HY-130 steels were found to be susceptible to both stress corrosion cracking and hydrogen embrittlement in a 3 percent NaCl solution whereas in the absence of a fatigue crack, neither alloy was susceptible.<sup>(144)</sup>

The corrosion-fatigue crack-growth behavior of steels above and below  $K_{ISCC}$  has been studied at the University of Illinois.<sup>(145)</sup>

AISI 4340 (220 ksi yield strength) steel was selected for the above- $K_{ISCC}$  study while HY-80 was selected for the below- $K_{ISCC}$  study. The former is known to be highly susceptible to stress-corrosion cracking, while the latter is known to have high resistance to stress-corrosion cracking. The vacuum fatigue crack-propagation rate was only slightly lower for the HY-80 steel than for the 4340 steel. The fatigue crack-propagation rate for 4340 steel in 3.5 percent NaCl was constant at frequencies lower than 0.5 Hz indicating that the environmental attack controls the crack-growth rate. On the other hand, the cyclic crack-propagation rate of HY-80 in 3.5 percent NaCl solution increased with decrease in loading frequency from 10 to 0.1 Hz indicating an increase in environmental attack that was due to attack of fresh surface areas generated by the fatigue loading. Applying cathodic protection to both materials increased the cracking rates above those of the freely corroding rates, thus indicating that hydrogen embrittlement was the mechanism of environmental attack.

Additional fatigue crack-propagation studies have been conducted by the Naval Research Laboratory in support of the development of advanced surface ships such as hydrofoils and surface-effect ships.<sup>(146)</sup> Single-edge-notch cantilever specimens of HY-130 steel, 17-4PH steel, Ti-6Al-2Cu-1Ta-0.8Mo, and 5456-H116 aluminum were fatigue tested in air and in seawater with and without applied potentials. Both seawater and negative potential accelerated crack-growth rates in the ferrous alloys. Neither seawater nor negative potential affected crack-growth rates in the titanium alloy. Seawater caused a moderate increase in crack-growth rates in the aluminum alloy, but both negative and positive potentials were beneficial.

Additional corrosion-fatigue crack-propagation studies on the HY-130 alloy have been reported elsewhere.<sup>(147)</sup> Also, the effect of load shedding (partial or full removal of load) on the SCC of D6 ac steel has been described.<sup>(148)</sup>

#### Corrosion of Stainless Steels

##### Splash, Tide, and Submerged

Additional data from the extensive Naval test program at Port Hueneme, California, have been reported.<sup>(149)</sup> In all, a total of 1,750 specimens of 57 different stainless steels were exposed in seawater at the surface and at depths of 2500 and 6000 feet in the Pacific Ocean for times from 123 to 1064 days. Corrosion rates, type of corrosion, pit depths, and stress corrosion cracking resistance were among the parameters evaluated. Representative data for a selected group of these alloys are given in Table 83.

In general, corrosion at the surface was more severe than at depths of 2500 or 6000 feet or in the sediments at these depths. A cast Fe-23Ni-21Cr-5Mo-1Si alloy was uncorroded. Types 317 and 319 were attacked only by incipient (<1 mil deep) crevice corrosion; 20 Cr-3 was attacked by both incipient crevice and incipient pitting; Type 325 exhibited general surface attack; all other stainless steels investigated in the AISI 200, 300, 400, and 600 series were attacked by pitting, tunneling, and crevice corrosion ranging from 1 mil in depth to complete penetration (greater than 100 mils). Sensitization of Types 304 and 316 decreased their corrosion resistance. Precipitation hardening stainless steels which failed by stress corrosion cracking included 630-H925, 631-TH1050, 631-RH1050, 632-RH1100, 15-7AMV-Annealed, -RH950, and RH1150, and PH14-8Mo-SRH950. Stainless steel wire ropes of the Type 304, 316, 18Cr-14Mn, and the Cr-Ni-Mo-Cu, Cr-Ni-Mo-Si-N, Cr-Ni-V-N, and Cr-Ni-Si compositions were also attacked by the pitting and crevice types of corrosion.

TABLE 83. DEEP OCEAN BEHAVIOR OF STAINLESS STEELS<sup>(149)</sup>

Alloy	Environment <sup>(a)</sup>	Exposure, days	Depth, feet	Corrosion Rate, mpy	Max. Pit Depth, mils <sup>(b)</sup>
201	W	366	5	0.6	0
	W	402	2370	<0.1	0
	S	402	2370	<0.1	0
	W	1064	5300	<0.1	0
	S	1064	5300	0.5	50P
310	W	366	5	0.1	0
	W	402	2370	<0.1	0
	S	402	2370	<0.1	0
	W	1064	5300	<0.1	0
	S	1064	5300	<0.1	0
347	W	366	5	0.7	50P
	W	402	2370	<0.1	0
	S	402	2370	<0.1	0
	W	1064	5300	<0.1	1
	S	1064	5300	<0.1	0
446	W	366	5	0.6	50P
	W	402	2370	<0.1	0
	S	402	2370	<0.1	0
	W	1064	5300	<0.1	0
	S	1064	5300	<0.1	0
PH14-8Mo, SRH950	W	181	5	1.7, 3.1	120P, 120P
	W	402	2370	<0.1, 0.5	1, 1
	S	402	2370	<0.1, 0.3	1, 120P
	W	403	6780	<0.1, 0.4	1, 1
	S	403	6780	<0.1, 0.2	1, 120P
15-7 AMV, Ann.	W	402	2370	0.5	48P
	S	402	2370	0.5	48P
	W	1064	5300	3.0	48P
	S	1064	5300	0.9	48P
	W	366	5	2.6	50P
18Cr-14Mn-0.5N	W	402	2370	0.8, 1.1	115P, 0
	S	402	2370	<0.1, 1	0, 115P
	W	1064	5300	<0.1, 0.2	0, 0
	S	1064	5300	0.3, 0.4	115P, 62P

(a) W and S represent specimens exposed in water and partially in bottom sediment, respectively.

(b) P designates perforated and I designates incipient.

In another program, specimens from a 1250-foot length of Type 304 stainless steel wire rope were examined after 34 months' continuous immersion in the Gulf of Mexico.<sup>(150)</sup> The absence of corrosion on the top 1000 feet of the stainless steel wire rope was attributed to the beneficial effects of a retained lubricant, to cathodic protection from a steel anode located above the rope, and to probable inadvertent cathodic protection from the 6062-T6 aluminum surface buoy. Relatively severe corrosion was observed on the bottom 250 feet of the rope where it was shielded from cathodic protection because it had been jacketed with Neoprene to prevent abrasion of the synthetic rope used for the lower section of the mooring system.

The corrosion behavior of 18 Ni (180) and 18 Ni (200) maraging steels in seawater has been studied by International Nickel.<sup>(151)</sup> General corrosion rates were about half those of 4340 and HY-80 steels. The  $K_{Isc}$  values in seawater were 130 and 94 ksi $\sqrt{\text{in.}}$  for the Ni 18 (180) and Ni 18 (200) alloys, respectively.

The corrosion behavior in seawater of 190 ksi yield strength 10Ni-2Cr-1Mo-8Co steel has been evaluated by the Naval Ship Research and Development Laboratory.<sup>(152)</sup> The alloy corroded uniformly at a rate of 6 mils/yr in a one-year test and exhibited moderate crevice corrosion at the edge of a crevice with a maximum depth of 9 mils after one years' exposure. Precracked cantilever beam tests indicated a threshold stress intensity  $K_{Isc}$  of 135 ksi $\sqrt{\text{in.}}$  in seawater.

In other seawater studies, the corrosion behavior of Nitronic 50 (Fe-22Cr-13Ni-5Mn-2Mo) has been investigated at the Naval Ship Research and Development Center.<sup>(153)</sup> One-inch base plate and gas-metal-arc weldments were exposed to air and Severn River

water. The alloy demonstrated satisfactory stress-corrosion resistance and excellent fatigue resistance in seawater —  $K_{II}/YS$  was 1.38  $\sqrt{\text{in.}}$  after 1300 hours in seawater which was a reduction of only 15 percent when compared with air values.

The mechanical, corrosion, and fatigue properties of 15-5PH stainless steel, Inconel 718, and Rene 41 have been studied at the Naval Ship Research and Development Center as candidates for hydrofoil applications.<sup>(154)</sup> Fatigue tests were conducted in Severn River water on smooth specimens at 1450 cpm in fully reversed bending. General corrosion, crevice corrosion, and bent beam and WOL loaded stress-corrosion tests were conducted in seawater at Wrightsville Beach, North Carolina. The 15-5PH and Inconel 718 exhibited crevice attack (more severe on the 15-5PH) and stress corrosion tests were invalidated because of specimen relaxation due to crevice corrosion. The Rene 41 did not exhibit any corrosion attack. No stress-corrosion failures were observed, and two WOL specimens loaded to 59.5 and 77.6 ksi  $\sqrt{\text{in.}}$  showed no crack extension after a 1-year exposure. Because of the difficulty in machining and welding thick sections of Rene 41 and Inconel 718, the 15-5PH steel was considered the best overall candidate for the hydrofoil applications.

#### Crevice Corrosion

The crevice corrosion of selected stainless steels in seawater has been studied by the Naval Research Laboratory.<sup>(155)</sup> Specimens were tested unprotected or bolted to zinc or steel for up to 550 days in Florida tidal and pumped natural seawater. None of the stainless steels tested (24Ni-20Cr-6.5Mo, 26Cr-1Mo, 22Cr-13Ni-5Mn, and Type 216) was completely immune to crevice corrosion except for several specimens of the 24Ni-20Cr-6.5Mo alloy. Cathodic protection from mild steel or zinc protected the stainless steels against crevice corrosion, but edge attack and general corrosion were observed on some of these specimens.

Studies of the crevice corrosion of Type 304 stainless steel in 3.5 percent NaCl solution indicated that intermittent applications of cathodic protection were sufficient to prevent crevice corrosion.<sup>(156)</sup>

The factors contributing to crevice corrosion of 13Cr stainless steel in seawater have been reviewed by Soviet investigators.<sup>(157)</sup> In agreement with earlier studies in the Western World, these workers observed that no passive film formed, and crevice corrosion occurred when the dissolved oxygen content in the seawater was 0.07 ppm or less.

In Japanese have developed a new duplex stainless steel (26Cr-6Ni-0.4Cu-3Mo plus W and N) with improved resistance to crevice attack in seawater.<sup>(158)</sup> In their studies, they also have developed a new laboratory crevice-corrosion test method which consists of immersing the alloy in a solution of 3 percent NaCl-0.05M Na<sub>2</sub>SO<sub>4</sub>-activated charcoal. The accelerated laboratory test results correlated well with field experience.

#### Stress Corrosion Cracking

Stress-corrosion-cracking test results have been included in the Battelle-Columbus evaluation of newly developed materials of interest to the Air Force for potential weapons system usage.<sup>(159,160)</sup> Four-point loaded beams stressed to 80 percent of yield strength were exposed 1000 hours to 3.5 percent NaCl solution under alternate immersion conditions (10 minutes in, 50 minutes out). No stress-corrosion cracks were observed in 7 replicate specimens of each of the following materials: 15-5PH (H1025) forged bar; HP9Ni-4Co-0.20C forged bar; PH13-8Mo



(H1000) forged bar; 7049-T76 extrusion; Ti-6Al-2Sn-4Zr-6Mo sheet; Inconel 702 sheet (aged); Inconel 706 forged bar (creep-rupture heat treatment); 17-4PH (H900) ESR bar; Udimet 710 forged bar; X7050-T7E56 hand forging; 2214-T351 (Alcoa 417 Process) plate; and Ti-6Al-4V (DBHT) diffusion bonded component.

Additional  $K_{Isc}$  data for high-strength steels are summarized in a report issued by the Naval Research Laboratory.<sup>(161)</sup> Most data were obtained in 3.5 percent NaCl solution for 1-inch plate with a through-the-thickness direction of crack propagation (WT and RT).  $K_{Isc}$ , yield strength, and  $K_{Ic}$  or  $K_{Ix}$  data are plotted for AISI 4340, 9Ni-4Co, 12Ni Maraging, 18Ni Maraging, and PH13-8Mo steels. A limited study of specimen orientation revealed little or no effect of the direction of crack propagation on  $K_{Isc}$ , as shown in Table 84.

TABLE 84. EFFECTS OF SPECIMEN ORIENTATION WITH RESPECT TO WROUGHT TEXTURE ON  $K_{Isc}$  OBTAINED ON PRECRACKED CANTILEVER BEAM SPECIMENS IN 3.5 PERCENT NaCl SOLUTION<sup>(161)</sup>

Alloy	$K_{Isc}$ , ksi $\sqrt{\text{in.}}$			
	RT(a)	WT(a)	WR(a)	RW(a)
9Ni-4Co-0.2C	—	115	104	—
18Ni-180	—	125	145	—
12Ni-5Cr-3Mo	—	19	19	25
12Ni-5Cr-3Mo	70	60	—	—
12Ni-5Cr-3Mo	—	105	103	—
4340 (200 YS)	—	—	11	10

(a) Convention is that of ASTM Committee E-24.

The effect of impurity additions of sulfur, phosphorus, carbon, chromium, and silicon + manganese on the fracture toughness and stress-corrosion cracking (SCC) of 18Ni (300 grade) maraging steels have been studied in 3.5 weight percent NaCl solution with the following results:<sup>(162)</sup>

Variable	Fracture Toughness	Resistance to SCC
High-purity heat (<0.005C)	Increase	None
0.01 to 0.06 carbon	Decrease	Slight increase
Up to 0.03 phosphorus additions	None	Slight increase
0.24 chromium addition	None	Decrease
Up to 0.03 sulfur additions	None	None
Silicon + manganese additions	Decrease	None

Five other stress corrosion cracking studies have been conducted which have involved the determination of  $K_{Isc}$  values for stainless steels in a 3.5 percent NaCl solution. The materials involved and the respective references to these investigations are given as follows: 17-4PH<sup>(163)</sup>, Type 420SS<sup>(164)</sup>, AFC77<sup>(165)</sup>, and 18Ni maraging steel.<sup>(166,167)</sup> Similarly, corrosion fatigue studies in seawater have been reported for 17-4PH<sup>(168,169)</sup>, 15-5PH<sup>(169)</sup>, and 18 Ni.<sup>(170)</sup>

Finally, research results on the pH and analysis of the corroded in stress corrosion cracks of the following steels (after exposure in a 3.5 percent NaCl solution) have also been reported<sup>(171)</sup>: 0.45C, 4340, 9Ni-4Co-0.2C, 17-4PH, and 12Ni-5Cr-3Mo, 18Ni, 13Cr-9Ni-Mo maraging steels.

## Corrosion of Nickel-Base Alloys

The corrosion of 22 commercially available nickel alloys in quiet and low velocity (2 fps) seawater have been studied by the Naval Ship Research and Development Laboratory.<sup>(172)</sup> General, crevice, and stress corrosion were investigated in exposures of two years' duration. No stress-corrosion cracking was observed in any of the alloys (U-bend specimens). Alloys containing  $\geq 54$  nickel  $\geq 16$  chromium  $\geq 9$  molybdenum were resistant to general, pitting, and crevice attack. Other nickel-chromium-molybdenum alloys exhibited no general corrosion, little or no pitting on boldly exposed surfaces, and varying degrees of crevice attack. Nickel-chromium-iron alloys, as well as 60Ni-19Cr-17Co and 97Ni-2Be, exhibited no general corrosion, but experienced moderate to severe pitting on boldly exposed surfaces and in crevices. General corrosion plus moderate localized corrosion was found on 65Ni-27Mo, 65Ni-35Cu, 60Ni-40Cu, 45Ni-55Cu, and 65Ni-30Cu-3Al specimens.

The corrosion behavior of Multiphase Alloy MP35N (35Ni-35Co-20Cr-10Mo) has been investigated by Standard Pressed Steel.<sup>(173)</sup> The alloy is an extremely noble metal with a potential of +0.056 (versus Ag-AgCl) in seawater. It is cathodic to most materials and caused galvanic corrosion of K-Monel, Type 316 stainless steel, and carbon steel in couple tests conducted in seawater. No galvanic corrosion was noted in similar tests conducted with titanium-MP35N couples. Wire-rope samples made of MP35N alloy have shown no evidence of attack after 2.5 years' exposure in the mud, seawater, tidal zone, splash zone, or marine atmosphere.

The excellent resistance of Inconel 702 and 706 and Udimet 710 to stress corrosion cracking in tests at Battelle-Columbus has been cited previously.<sup>(159,160)</sup>

## Corrosion of Copper and Copper-Base Alloys

A 5-year study on fouling and corrosion in seawater has been conducted at the Inco Laboratory at Wrightsville Beach, North Carolina.<sup>(174)</sup> Highly corrodible materials such as steel fouled readily, but the fouling could be removed easily and sloughed off periodically with the corrosion product. Passive alloys such as aluminum fouled readily, and the fouling was tightly adherent. Crevice corrosion beneath the fouling caused pitting on these alloys. Toxic alloys such as beryllium and lead were not completely resistant to fouling. The copper alloys possessed fouling resistance because they formed cuprous oxide corrosion products that are toxic to the organisms. An overlayer of cupric hydroxylchloride often forms on these alloys which is not toxic and leads to fouling, but the fouling can be easily removed. Pure copper, 90-10 Cu-Ni and 70-30 Cu-Ni were equally resistant to fouling. Copper alloys did not provide fouling protection to adjacent materials, thus indicating that the toxicity does not result from the release of poisonous ions to the seawater.

The influence of chromium on the corrosion behavior of copper-nickel alloys in flowing seawater has also been explored by this same Inco Laboratory.<sup>(175)</sup> This work showed that chromium additions of 0.5 to 3 percent were effective for both strengthening and increasing seawater velocity limitations (up to 40 m/s) limitations for turbulent flow conditions without adversely affecting other properties of this alloy system. Selected corrosion data illustrating this effect are given in Table 85.

Copper-nickel alloys for use at even greater seawater velocities have also been evaluated by the Navy.<sup>(176)</sup> Efforts to include velocities up to 120 FPS (36 m/s) resulted in new approaches and

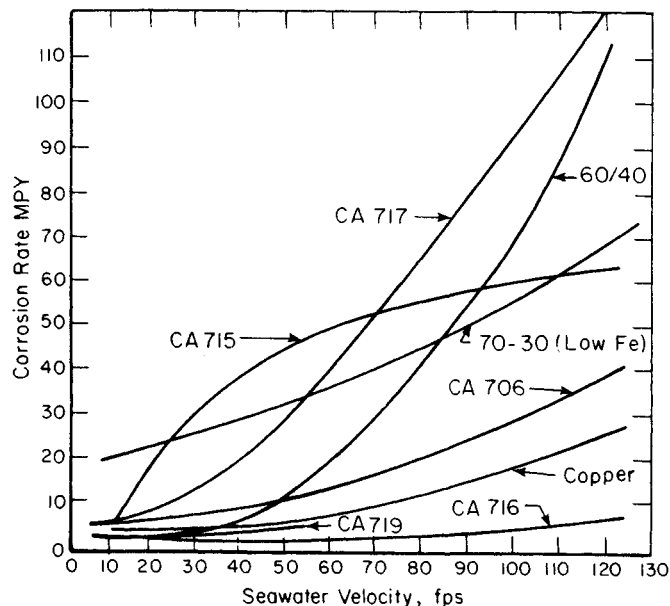


TABLE 85. SUMMARY OF PARALLEL FLOW SEA WATER CORROSION TESTS<sup>(175)</sup>

Alloy	Avg. Sea Water Temp., C	Localized Attack <sup>(a)</sup> -- mm			
		3 m/s (10 FPS)	6 m/s (20 FPS)	11 m/s (35 FPS)	15 m/s (50 FPS)
CA-706	10	.10	.10	.08	.08
CA-715	10	.03	.03	.08	.13
IN-838	20	<.03	.03	.10	.13
Cu-70Ni-3Cr	10	<.03	<.03	<.03	<.03

(a) 30 day exposures.

a reassessment of available test techniques. Four different test techniques were employed, including two rotating specimen tests, one impingement, and one multivelocity jet tests. Some of the results are summarized in Figure 99 which illustrates the benefit of iron and chromium additions to copper-nickel in increasing their resistance to corrosion-erosion and impingement damage.

FIGURE 99. RESULTS OF MULTIVELOCITY AND HIGH VELOCITY JET TESTS ON COPPER AND COPPER ALLOYS<sup>(176)</sup>

CA706: Cu-10.6Ni-1.5Fe-0.44Mn

CA715: Cu-31.4Ni-0.6Fe-0.72Mn

CA716: Cu-29.6Ni-5.4Fe-0.08Mn

CA717: Cu-32.6Ni-0.75Fe-0.55Mn-0.58Be

CA719: Cu-29.7Ni-0.21Fe-0.58Mn-3.1Cr

## Corrosion of Titanium and Titanium-Base Alloys

The corrosion of several alloys at various depths (7, 27, 42, and 80 meters) in the Black Sea has been reported by Russian scientists.<sup>(177)</sup> Titanium was resistant at all depths with a corrosion rate of  $<0.001\text{g/m}^2\text{-hr}$ . 18Cr-9Ni stainless steel pitted (2.8 mm deep after 21 months of exposure), but corrosion performance improved with depth, and at 80 meters, only slight

crevice attack was observed. The improved performance was attributed to lower temperature and lower dissolved oxygen at depth. Carbon steel exhibited a minimum in attack at 27 meters ( $0.039\text{ g/m}^2\text{-hr}$ ) that was attributed to heavier marine growth at this level. The corrosion of copper alloys increased with depth ( $0.042\text{ g/m}^2\text{-hr}$  at 80 meters) and this was attributed to the formation of nonprotective corrosion films in the absence of light.

A modest amount of effort in the past 7 years has been devoted to laboratory studies of the stress corrosion cracking of various titanium alloys in the presence of either seawater or a 3.5 percent NaCl solution. The Ti-6Al-4V alloy has received most of the attention with individual studies being reported on the effects of specimen thickness<sup>(178)</sup>, sample orientation<sup>(179)</sup>, and heat treatment<sup>(180)</sup> on stress-corrosion cracking behavior. Similar stress-corrosion cracking studies have also been reported for the Ti-6Al-6V-2Sn<sup>(179)</sup>, Ti-3Cu<sup>(180)</sup>, Ti-7Al-21b-1Ta<sup>(181)</sup>, and Ti-8Al-8Mo-2Fe-3Al<sup>(182)</sup> alloys.

The fatigue crack growth of Ti-6Al-2Cb-1Ta-0.8Mo alloy in air and natural seawater has been investigated at the Naval Research Laboratory.<sup>(183)</sup> Single-edge-notched (SEN), side-grooved specimens were tested in zero-to-tension loading. The alloy showed no evidence of environmental sensitivity on fatigue cracking in seawater at its free corrosion potential or at cathodic-protection potentials of -800 or -1050 mV versus Ag/AgCl reference cell. The fatigue crack growth rate of this alloy was later compared with that for several other high strength alloys in follow-on work by this same laboratory.<sup>(184)</sup> Environments were seawater at the free corrosion potential and several hundred millivolts more negative than the free corrosion potential. Compared with results in air:

- Seawater or negative potential had no effect on Ti-6Al-2Cb-1Ta-0.8Mo (114.5 ksi YS)
- Deleterious effect of seawater and no effect of negative potential on 17-4PH VM steel (153.6 ksi YS)
- Deleterious effect of seawater and negative potential on 17-4PH OAM steel (135 and 163 ksi YS)
- Deleterious effect of seawater and negative potential on HY-130 steel (147.2 ksi YS)
- Deleterious effect of seawater and beneficial effect of negative potential on 5456-H116 aluminum (31.1 ksi YS).

The excellent resistance to SCC of the Ti-6Al-4V and Ti-6Al-2Sn-4Zr-6Mo alloys has been cited previously.<sup>(159,160)</sup>

## Corrosion of Aluminum Alloys

Atmosphere, Splash, Tide, and Submerged

Seven aluminum alloys and panels of high-purity aluminum were evaluated after exposure for ten years in seawater at Wrightsville Beach, N.C. in half-tide immersion and full immersion.<sup>(185)</sup> All panels were heavily fouled with barnacles and other marine growth for all exposure periods. The fouling had little apparent effect on the pitting depth of the aluminum in tidal immersion, but generated heavy etching on some alloys during the 5 to 10 year exposure interval.

Little change in tensile properties after ten years' exposure was noted for any of the test alloys. Tensile losses reported for several alloys after full immersion include: 5086-0 (3.7 percent), 5154-H38 (5.1 percent), and 5457-H34 (5.2 percent). The high-purity 1199 and alloys 5154-H38, 5456-0, and 5456-H321 showed losses of 16 to 27 percent in elongation while the change in elongation for the 5086-0 was a decrease of about 6 percent.

Confirming other work, the corrosion rates were found to be greater for the full seawater immersion than for the tidal immersion. The lowest ten-year corrosion rate in the half-tide location was 0.014 mpy (mils per year) and the 5456-0, and the highest rate for the aluminum-magnesium 5000 series was 0.051 mpy for the 5456-H321 alloy. In full-immersion tests, the lowest rate was 0.064. For comparison, the rates for the 1199 alloy were 0.036 mpy in tidal and 0.061 mpy in full immersion. Corrosion weight losses and depth of pitting had reduced rates of growth over the interval between five years and ten years. Maximum depth of pitting for an alloy was generally at least four times the magnitude of average of the twenty deepest pits. Maximum pitting depths for each of the materials tested in half-tide and full immersion are given in Table 86.

TABLE 86. PITTING BEHAVIOR OF ALUMINUM ALLOYS AFTER 10 YEARS EXPOSURE<sup>(185)</sup>

Alloy	Half-Tide Exposure		Full Immersion	
	Rating(a)	Max. Pit Depth, mils	Rating(a)	Max. Pit Depth, mils
5154-H38	5	19.5	2-1/2	15.2
1199	4	39.0	2-1/2	12.7
5457-H34	1	22.0	2-1/2	12.0
5086-0	2	27.0	2-1/2	18.1
5083-0	6	38.0	5	24.0
5454-H34	3	19.9	6	20.0
5456-H321	8	72.0	7	45.3
5456-0	7	68.5	8	131.0

(a) Based on average of 20 deepest pits; number 1 is best.

Additional marine corrosion behavior on three of these same alloys (5086, 5083, and 5456) in the H116 and H117 tempers have also been reported.<sup>(186)</sup> Panels were exposed for 2 years to the marine atmosphere, at the splash and spray zone, and fully submerged in seawater at Wrightsville Beach, North Carolina. No exfoliation attack occurred on any specimen, although some slight pitting and edge attack were observed. Aging the H-116 and H-117 tempers 1 week at 100°C prior to exposure caused increased pitting and edge attack but did not appear to pose a long-term corrosion problem.

The effect of exposure conditions on the corrosion of 6061-T6 aluminum in seawater has been studied by the Naval Research Laboratory.<sup>(187)</sup> Specimens exposed 730 days under a pier at Key West, Florida, exhibited random shallow pitting not associated with intentional crevice areas. In laboratory static corrosion cells and in a flume at 3/4 fps velocity, corrosion in the intentional crevice was far more severe than on the exposed surfaces. Attack in the crevice was severe for the flume specimens which were found to be completely penetrated (0.16 cm) after 730 days of exposure.

The results of corrosion studies with 5086-H32 and 6061-T6 aluminum alloys in seawater and in the Potomac River have been reported.<sup>(188)</sup> Exposures ranged to 3.5 years. The 5086-H32 alloy was corrosion-resistant to both waters. Severe galvanic corrosion occurred in both waters (Potomac River was most severe)

when the alloy was coupled to 90-10 copper nickel, yellow brass, Type 304 stainless steel, or mild steel. The galvanic corrosion could not be completely prevented by cathodic protection. The 6061-T6 aluminum was severely corroded when immersed in quiescent seawater or Potomac River water. The best overall protection to both aluminum alloys was a vinyl anticorrosive barrier with a tributyl tin toxicant (for antifouling) and cathodic protection.

Corrosion, stress-corrosion, and corrosion fatigue have been determined by Alcoa for fifty-one lots of 7050-T76 sheet, 7050-T73651 plate, 7050-T73652 hand forgings, 7050-T736 die forgings, and 7050-T76511 extruded shapes.<sup>(189)</sup> All products showed a high order of resistance to exfoliation in accelerated corrosion tests. No stress-corrosion cracking (SCC) failures occurred in tensile specimens of sheet, plate, and hand forgings in tests to 605 days in a seacoast atmosphere and to 763 days in an industrial atmosphere. SCC failures have occurred in four of ten 7053-T736 die forgings stressed at 35 ksi and two of four 7050-T76511 extruded shapes stressed at 25 ksi. In the industrial atmosphere, only one specimen of a die forging failed at 45 ksi. Fatigue crack propagation in humid air and salt fog tended to be two or three times that in dry air. The fatigue strengths of the 7050 plate, hand forgings, and extruded shapes were about the same in salt fog, but were somewhat lower than values reported for 7475-T761 sheet, 2124-T851 plate, and 7049-T73 and 7175-T736 hand forgings.

#### Galvanic Attack and Velocity Effects

Galvanic couples of Alodine 600 coated 7075, 6061, or 2024 aluminum to Ti-6Al-4V or Type 304 stainless steel have been studied at Rockwell International Science Center.<sup>(190)</sup> Galvanic corrosion current and weight-loss data were obtained in 3.5 percent NaCl solution at room temperature. The Alodine 600 coating greatly reduced the dissolution rates of the aluminum alloys. Damage to bare or coated aluminum alloys was greater when coupled to the Type 304 stainless steel. Dissolution rates obtained from galvanic current data were lower than those calculated from weight-loss data. However, with appropriate correction factors, the continuous recording of galvanic current data could be used to obtain instantaneous corrosion rates which could be used to extrapolate to long-term rates.

In later work by the same laboratory the galvanic corrosion behavior of 1100, 2024, 2219, 6061, and 7075 aluminum alloys coupled to copper, Type 304L stainless steel, Ti-6Al-4V, 4130 steel, or zinc were studied.<sup>(191)</sup> Electrochemical- and weight-loss data were obtained in several environments. In 3.5 percent NaCl, the dissolution rates of aluminum alloys in couples decreased in the order of copper > 4130 steel > 304L > Ti-6Al-4V.

The effect of velocity on the seawater corrosion behavior of high-performance ship materials has been studied by Bell Aerospace and Ocean City Research.<sup>(192)</sup> A water wheel was used to obtain velocities to 90 knots in ambient seawater. General corrosion rates of aluminum alloys 5086-H117 and 5456-H117 were less than 0.1 mpy at zero velocity and increased to about .12 mpy at 90 knots. The general corrosion rates for Inconel 625, 17-4PH stainless steel, and Ti-6Al-4V were less than 0.1 mpy at zero velocity and increased to 0.5 to 1.5 mpy at 90 knots. The galvanic corrosion rates of the aluminum alloys were less than 0.6 mpy at zero velocity and increased to as high as 59 mpy at 90 knots. Coupling to Ti-6Al-4V had less effect on the galvanic corrosion of the aluminum than did coupling to 17-4PH or Inconel 625.

In an extension of this work, the relationship between electrode potential and the velocity of seawater on the pitting behavior

of aluminum alloys has been reported in a paper jointly prepared by Bell Aerospace Textron and Ocean City Research Corporation.<sup>(193)</sup> Aluminum alloys 1100 and 5456-H117 were exposed to seawater velocities ranging from 0 to 60 knots. Potentiostatic techniques were used to obtain critical pitting potentials, protection potentials, and corrosion potentials. The results indicated that all three of these potentials became more active (negative) as velocity increased except for a discontinuous shift in the noble (positive) direction between 15 and 30 knots. The extent of pitting decreased with increasing seawater velocity.

#### Stress Corrosion

A modest effort has been exerted over the past 7 years in obtaining a better understanding of stress corrosion cracking of the 2014<sup>(194,195)</sup>, 2024<sup>(194,196)</sup>, and 6061<sup>(194)</sup> alloys in seawater and saline solutions. A Navy study on forgings of all three of these alloy plus 7075 is representative of these programs.<sup>(194)</sup> In this work, smooth and precracked cantilever beam specimens were exposed to natural sea water. The  $K_{ISCC}$  values for the short-transverse orientation of these specimens were:

Alloy	Forging Size, inches	$K_{ISCC}$ ksi $\sqrt{\text{in.}}$
6061-T652	9 x 24 x 24	24
6061-T652	6 x 12 x 24	26
2024-T352	6 x 12 x 24	23
2024-T852	6 x 12 x 24	14
7075-T7352	6 x 12 x 24	18
2014-T6	8 x 16 x 19	16

In general, the alloys with low  $K_{ISCC}$  values failed early in the smooth-specimen tests. Notable exceptions were the smooth specimens of 2024-T852 which appeared to outlast 2024-T352, even though the latter had a higher  $K_{ISCC}$  value.

However, most of the emphasis in recent studies on SCC in aluminum alloys has been centered on the high strength 7000 series alloys, particularly of the 7075 type. In 1972, for example, Alcoa published the results of studying the effects of alloying additions or substitutions on the SCC behavior of this prominent Al-Zn-Mg-Mn alloy's composition.<sup>(197)</sup>

Short-transverse constant-strain tensile specimens were exposed to the alternate immersion 3.5 percent NaCl test and to the industrial atmosphere at New Kensington, Pennsylvania. The effects of the various additions are summarized below:

Element	Stress-Corrosion Resistance	Strength
Silver	Marginal Increase	No Increase
Zirconium or manganese substituted for chromium	Decrease	Increase
Increased zinc	Increase	—
Increased copper in chromium free alloys	Increase	Increase

In another program, aimed at the development of a high-strength aluminum alloy with improved resistance to SCC in short transverse direction, the alloys studied included a 7175 control and variations of 5.8 to 7.4 percent zinc, 2.0 to 2.5 percent magnesium, and 2.1 to 2.7 percent copper, with either separate or combined additions of zirconium, manganese, and chromium.<sup>(198)</sup> All the alloys developed more attractive combinations of strength and

hardenability than the 7175 control and exhibited equivalent or better resistance to stress-corrosion cracking. The alloys with the optimum combination of properties contained

Element	Percent
Zinc	5.75 to 6.25
Magnesium	2.0 to 2.5
Copper	2.1 to 2.6
Zirconium	0.09 to 0.15
Silicon	0.10 max
Iron	0.12 max

The culmination of this effort was the development of Alcoa's MA15 alloy.<sup>(199)</sup> This material has longitudinal yield strength of 61 ksi and good resistance to stress-corrosion cracking at 25 ksi stress in the short transverse direction, based on 30 days' exposure in the 3.5 percent NaCl alternate immersion test. The alloy with optimum strength and stress-corrosion resistance contains 5.5 to 6.5 zinc, 1.9 to 2.4 magnesium, 2.25 to 2.75 copper, 0.08 to 0.14 zirconium, 0.12 maximum iron, 0.10 maximum silicon, and 0.04 maximum titanium. However, long-term tests (84 days) in 3.5 percent NaCl produced erratic results, and caution was recommended in evaluating this alloy until the results are obtained for long-time atmospheric tests. The corrosion and mechanical properties of three tempers of commercially fabricated 1- to 6-inch plate of this aluminum alloy (MA15) have been evaluated by Alcoa in later property comparisons of this alloy with 7075-T651, 7075-T7351, 7079-T651, and 2024-T351.<sup>(200)</sup> Compared at equal strengths, the MA15 alloy developed higher resistance to exfoliation corrosion and stress-corrosion cracking, higher toughness, and better fatigue performance than the established commercial alloys. Compared at equal resistance to stress-corrosion cracking, MA15 developed higher strength than the established commercial alloys.

Earlier, the mechanical, fracture, fatigue, and stress-corrosion properties of a Boeing-recommended aluminum alloy (Alloy 21) had been evaluated by Boeing.<sup>(201)</sup> The alloy contains 6.4 zinc, 2.5 magnesium, 1.1 copper, 0.13 iron, 0.10 manganese, and 0.13 zirconium. A T6 + 35 hour at 325 F heat treatment achieved a 25-ksi short-transverse stress-corrosion threshold for smooth specimens. The mechanical properties of the Alloy 21 were comparable to those of 7049-T73. The fracture toughness was as good, or better than, that of other high-strength aluminum alloys. The smooth and notched-axial (tension-tension) fatigue properties were comparable to those of 7075-T6 and 7075-T73.

Two other extensive evaluation programs have been reported which included exposure of high strength aluminum alloys in marine atmospheres. One of these included studies of exfoliation corrosion and SCC of the 7075-T6, -T73, 7078-T7, and 7178-T6 compositions.<sup>(202)</sup> The other was concerned with determinations of the SCC of 7075, 7475, 7050, and 7049 alloy plates in several tempers.<sup>(203)</sup>

Corrosion fatigue and fatigue crack growth in aluminum alloys in seawater and saline solutions have also been the object of study in four other programs. Two of these were devoted to the 5456-H117<sup>(204)</sup> and 7075<sup>(205)</sup> alloys exclusively. Another program<sup>(206)</sup> covered the 2024 and 7075 alloys in several tempers while the fourth program<sup>(207)</sup> embraced the 2014, 7075, 7079, X7080, and CH70 compositions.

Finally, Alcoa has reported the results of a 4-year study on comparing stress-corrosion cracking behavior using fracture mechanics techniques and conventional smooth specimen procedures.<sup>(208)</sup> Commercial plate and rolled or forged bars 2 to 2.5 inches thick of 13 aluminum alloys, 13 precipitation hardening stainless steels, and 2 titanium alloys were studied. Bolt loaded



precracked compact tension specimens and axially loaded smooth tensile specimens were exposed to 3.5 percent NaCl (alternate immersion), a seacoast atmosphere, and an inland industrial atmosphere. Aluminum specimens with a low threshold stress for smooth specimens also exhibited a low threshold stress-intensity factor  $K_{ISCC}$  for precracked specimens. Similar correlation was found for high threshold stress levels and high  $K_{ISCC}$ . However, most of the precipitation hardening steels and the titanium alloys exhibited a low  $K_{ISCC}$  and high SCC growth rate even though the threshold stress level for smooth specimens was high.

#### Corrosion of Fasteners

In studying hydrofoil craft, the Naval Ship Research and Development Center has investigated the seawater corrosion of fasteners installed in various structural materials.<sup>(209)</sup> Seven bolt materials were inserted in five panel materials with and without a sealant (Coast Pro-Seal 800-B-2). The bolt materials were 2024 aluminum, ASTM Grade 5 steel, Types 304, 316, and A-286 stainless steels, MP35N Multiphase, and Ti-6Al-4V. The panel materials were fiberglass, 5456-H117 aluminum, HY-130 steel, Ti-6Al-4V, and 17-4PH stainless steel. Specimens were completely immersed in natural seawater at Wrightsville Beach, North Carolina, commencing in June, 1974. The MP35N and Ti-6Al-4V bolts did not corrode in any structure tested. Unpainted steel fasteners corroded, bare aluminum fasteners pitted, and bare stainless steel fasteners exhibited crevice corrosion. Sealant was required in the fiberglass panels to minimize crevice corrosion and on the aluminum and steel panels to minimize galvanic corrosion. Sealant was not necessary to minimize corrosion in the titanium panels. Sealant was detrimental in 17-4PH stainless steel panels, apparently because it produced a tighter crevice and increased the severity of crevice attack.

The results of the third and fourth years' program to develop a full temperature range (-65 to 325 F) protective system for fastener areas of carrier-based Navy aircraft have been reported by Lockheed-Georgia.<sup>(210)</sup> Screening tests on coating systems included thermal stability at 350 F, tensile and elongation properties at -65 F, bend and impact tests on coated panels at -65 F, and seacoast exposure of coated panels. Final evaluations were based on fatigue tests that simulated five cycles of simulated flight spectrum on coated titanium and aluminum specimens which had a typical aircraft joint with eight fasteners. The most effective coating combinations were three-layer systems composed of MIL-P-23377 epoxy-polyamide primer, an aliphatic linear polyurethane topcoat and intermediate coats of elastomeric polyurethane or inhibited polysulfides. These systems were applied to A-7 carrier-based Navy aircraft in 1975 and will be inspected periodically for 3 years.

The corrosion behavior of high-strength fastener materials has been evaluated by Standard Pressed Steel.<sup>(211)</sup> The behavior in crevices, stress-corrosion cracking, hydrogen embrittlement, and the simulated service environment was compared for some but not all material combinations. The materials (and minimum tensile strengths) were: Custom 455 (220 ksi), PH13-8Mo (220 ksi), PH12-9Mo (220 ksi), Inconel 718 (220 ksi), H11 (220 and 260 ksi), Multiphase MP35N (260 ksi), and Marage-300 (260 ksi). In general, the results showed that the ferrous alloys were susceptible to crevice corrosion, the alloys were not very susceptible to stress-corrosion (bolts torqued to 75 percent of yield and exposed to 3.5 NaCl alternate immersion), and hydrogen embrittlement could be a problem.

Corrosion-resistant fastener selection for marine applications has been described in an article prepared by ITT Harper.<sup>(212)</sup> Tabular data are presented for fasteners to be used above or below

water line for attaching each of the following materials to itself or to any of the other materials: wood, fiberglass, rubber, plastic (Nylon), aluminum, steel, galvanized steel, copper, brass, nickel, stainless steel, and Monel.

#### Corrosion of Composites and Miscellaneous Materials

The saltwater corrosion behavior of aluminum graphite composites has been studied by the Aerospace Corporation.<sup>(213)</sup> Exposed to 3.5 percent NaCl were aluminum/graphite and aluminum/boron composites, AZ31B magnesium, A356 aluminum, and these two alloys coupled to block graphite or 4340 steel. Based on test results, the corrosion performance of the alloys was rated as follows (1 is most resistant, 4 is least resistant):

- (1) A356 aluminum alloy  
Aluminum/boron composite
- (2) Aluminum/graphite composite
- (3) A356/4340 couple  
A356/graphite couple
- (4) AZ31B magnesium alloy  
AZ31B/4340 couple  
AZ31B/graphite couple.

The aluminum/graphite couple exhibited a slightly greater corrosion rate than the A356 aluminum presumably because of the galvanic coupling effect. Boron is nonconductive and, thus, produced no galvanic effects in the aluminum/boron composite.

The galvanic corrosion of aluminum coupled to graphite-epoxy composite materials has also been studied at the Naval Air Development Center.<sup>(214)</sup> Electrochemical measurements in 3.5 percent NaCl solution revealed a 1-volt potential difference between the graphite-epoxy and 7075-T6 or 7075-T651 aluminum and 0.3 volt difference between the composite the Ti-6Al-4V. Corrosion current measurements showed that aluminum alloys, cadmium plate, and cadmium plate plus chromate conversion coating are much more reactive than Ti-6Al-4V when coupled to the graphite-epoxy composite. Posttest tensile results after 2 weeks of exposure to salt spray and synthetic seawater +SO<sub>2</sub> spray indicated significant strength losses in graphite-epoxy-aluminum honeycomb structures, but little or no loss if the composite were made without the aluminum. Galvanic coupling the graphite-epoxy composite to 7075-T651 aluminum had no effect on the stress-corrosion cracking of the alloy but did increase its general corrosion rate.

Information on the deterioration of materials and undersea-system components in seawater is compiled in a report issued by the Naval Research Laboratory.<sup>(215)</sup> Materials included are metals, plastics and composites, ceramics, paper, and natural fibers. Components included photographic materials, magnetic tape, electronic components, propellants, and explosives.

#### Corrosion of Coated Structural Metals

##### Coatings for Steel

Coated, unscored steel panels prepared by the Wisconsin Protective Coating Corporation were exposed 2 and 7 years in the atmosphere, splash zone, half submerged and fully submerged in a partially shielded area south of Long Island, New York.<sup>(216)</sup> Of the primers studied, inorganic and organic zinc primers were effective at 2-1/2 to 3-1/2 mils thickness; the optimum thickness

of organic epoxy-type primers was 8 mils; and vinyl primers were suitable only for vinyl systems. The projected film thickness needed for ten-year life in this area was 2-1/2 to 3-1/2 mils of inorganic zinc primer without topcoat for atmospheric exposure 100 and 1000 feet from the shore. In other systems the recommended thicknesses were:

System	Atmospheric	Thickness, mils Splash Zone	Immersed
Epoxy (chalking)	10	12	10
Vinyl and vinyl acrylics	7	9	7
2-1/2 to 3 mils zinc-rich primer plus topcoat	7 (topcoat)	7 (topcoat)	7 (topcoat)

Grit blasting to near white metal was sufficient surface preparation for these systems.

Zinc coatings on steel have also been evaluated in the marine atmosphere at the NASA Kennedy Space Center and by Metco. The NASA program compared the results of an 18-month exposure of fifty-nine commercially available zinc-rich coatings and forty-seven topcoat materials as applied to carbon steel.<sup>(217)</sup> The inorganic (Type I) classes of zinc-rich coatings were far superior to the organic (Type II) classes in the seacoast atmosphere. The inorganic coatings were effective at 3-mil film thickness whereas 4 to 6 mils was required for the organic coatings to survive 12 months' exposure. Topcoat systems adversely affected the performance of the zinc-rich systems. Panels sheltered from the environments deteriorated at about the same rate as unsheltered panels.

The Metco work covered 18 years of testing of flame-sprayed zinc and aluminum (sealed and unsealed) on low carbon steel panels exposed to sea water at mean tide and below low tide levels at two different locations.<sup>(218)</sup> Panels were also exposed to atmospheric conditions at six different locations including rural, industrial, salt air and salt spray environments.

The results were consistent with the above described experiences and indicated that low carbon steel can be protected from the corrosive effects of these environments for eighteen years or more by the application of flame sprayed zinc or aluminum coatings.

Seven different paint coating systems were tested on structural steels, high-strength stainless steels, and aluminum alloys in the deep Pacific and Atlantic Oceans.<sup>(219)</sup> The Pacific specimens were placed on the bottom in 5900 ft of water for six months while the Atlantic specimens were on the bottom at 4050 ft for more than four years.

The epoxy paint system provided good to excellent corrosion protection at both test locations.

The inorganic zinc coating provided adequate protection to the steel specimens for six months in the Pacific Ocean, but would have to be at least 0.010 to 0.020 in. thick to be effective for up to one year.

The two stainless steels Almar 362 and Carpenter 455 were highly susceptible to crevice corrosion when not coated. Uncoated specimens suffered from crevice attack in the same manner as types 302, 303, and 304 stainless steel.

302, 303, and 304 stainless steel.

The maintenance painting of steel structures for underwater and splash zones has also been reviewed by Drisko and Brouillette.<sup>(220)</sup>

Electroplated chromium-over-nickel coatings on steel have been tested at and near the coast and in a rain forest in the Panama Canal Zone.<sup>(221)</sup> After 9 months' exposure at the tropical marine site, coatings 40 microns thick provided effective protection while those 20 microns thick did not. After 35 months' exposure only 40 micron-thick coatings protected against severe attack of the base metal.

Diffusion coatings for improving the seawater erosion resistance of steel and other metals have also been studied.<sup>(222)</sup> The diffusion coatings were applied by the molten salt electrolytic process as indicated below:

Beryllium into: Monel, nickel, 1018 steel, copper, cupronickels, Cu-6Al

Boron into: Nickel, 4340 steel, 1018 steel, and 1018 coated with nickel electrodeposit or molybdenum spray

Chromium into: 4340 steel, 1018 steel.

The erosion tests were carried out in synthetic seawater using an ultrasonic horn at 20 kc and 1 mil displacement to produce cavitation. Only the beryllium coatings on the copper-base alloys showed good resistance to erosion. Their performance was comparable with that of Alloy 718 and superior to that of Type 316 stainless steel.

#### Coatings for Aluminum Alloys

Six different experimental claddings for corrosion protection of 7075-T6 aluminum have been studied by the Air Force Materials Laboratory.<sup>(223)</sup> Claddings tested were 1199, 5457, 7004, 7039, 7072, and 7472 aluminum. Exposures were conducted for periods of up to 24 months in tropical, semitropical, and inland industrial sites at Panama, Cape Kennedy, Florida, and McCook, Illinois, respectively. Cladding alloys 1199 (99.99 Al), 5457 (0.9 Mg), 7004 (4.4 Zn, 1.7 Mg, 0.3 Mn, 0.14 Cr), and 7472 (1.6 Zn, 1.2 Mg) were superior from a corrosion standpoint to the 7072 alloy now in use. Alloy 1199 had the best overall corrosion performance and alloy 5457 was a close second.

Sea atmosphere corrosion experiences have also been described for the Alclad 2024-T81<sup>(224)</sup> and Alclad 7050-T76<sup>(225)</sup> alloys.

Lockheed-Georgia also has investigated a variety of organic coatings for improving the resistance of aluminum to stress-corrosion cracking.<sup>(226)</sup> Alternate immersion tests were conducted in 3.5 percent NaCl on tensile specimens coated with acrylic and butyl rubber, polysulfides, aluminum foil, polyester film, and polyurethanes. A three-layer system composed of an inhibited polysulfide primer, aluminum foil or Mylar intermediate coat, and an aliphatic linear polyurethane topcoat prevented SCC for 24 months in the test media but was considered impractical because of difficulties associated with applying the intermediate films of aluminum or Mylar. Substitution of an elastomeric polyurethane for the intermediate coat resulted in a more practical system that provided protection for more than 10 months in the 3.5 percent NaCl solution.



## Desalination Experiences

As noted earlier, this section on Desalination Experiences was a new feature of Update 1977. This is not meant to imply that DMIC Report 245, "Corrosion of Metals in Marine Environments", omitted mention of desalination applications for metals. Rather, in the earlier report these experiences were presented separately in the various sections dealing with the individual metals and alloys, e.g., seawater distillation experiences with copper alloys were described in the "Submerged, Heat-Exchanger-Corrosion" section under "Copper and Copper-Base Alloys".

One important event since the issuance of DMIC Report 245 was the publication of a very extensive bibliography covering desalination experiences over this earlier time period. Thus, from December, 1968, through June, 1972, the Oak Ridge National Laboratory prepared and issued a 15 volume set of an indexed bibliography on the corrosion and performance of materials in saline water conversion processes. Each volume carries an identical title, differing only by the volume number.<sup>(227)</sup> The volumes contain abstracts for 870 publications taken from the computerized storage and retrieval system for the Materials Information Center of the Office of Saline Water. The abstracts are grouped in 33 categories relating to the various stages and aspects of saline water conversion. Because of their vintage, no effort was made to incorporate information from any of these 870 references into this review. Rather, Update 1977 has concentrated on desalination experiences since June, 1972, which are summarized in the paragraphs which follow.

## Galvanic Attack

The potentials of sixteen metals in aerated seawater at 30 to 200 C (86 to 392 F) have been determined at the Rosenstiel School of Marine and Applied Science.<sup>(228)</sup> In general, all metals became more electronegative as the temperature was increased. The most active metals at 30 C were carbon steel, aluminum alloys, and zinc. At 200 C, carbon steel shifted to more noble potentials leaving only aluminum and zinc in the most active group. The galvanic series for these metals in aerated seawater at 200 C was in the order (positive to negative):

- (1) Inconel 625
- (2) Titanium-6Al-4V
- (3) Hastelloy C
- (4) 316 stainless steel
- (5) Monel K-500
- (6) 70-30 Cu-Ni
- (7) CDA 194
- (8) 90-10 Cu-Ni
- (9) Aluminum Brass
- (10) Arsenical Admiralty Brass
- (11) Yellow Brass
- (12) Nickel 270
- (13) 1016 Steel
- (14) 1100 Aluminum
- (15) 5086 Aluminum
- (16) Zinc.

The corrosion in closed seawater systems of aluminum-base alloys coupled to Monel 400, brass, titanium, and stainless steel has also been investigated by scientists from Battelle-Columbus, Pennsylvania State University, and the Environmental Protection Agency.<sup>(229)</sup> Galvanic corrosion of aluminum in aerated seawater was severe when coupled to Monel 400, less severe when coupled to hard anodized aluminum, and least severe when coupled to titanium or stainless steel. The removal of dissolved oxygen was the

most effective method of preventing corrosion. This procedure greatly lowered the magnitude of the attack, but did not completely eliminate corrosion. Conventional inhibitors were not entirely effective in eliminating attack on the aluminum when coupled to Monel 400.

## Carbon and Low Alloy Steels

The Dow Chemical Company has issued a summary report on corrosion studies conducted for the OSW that were related to the desalination of seawater.<sup>(230)</sup> Among the results of the study are: the pitting tendency for stainless steels is suppressed at seawater pH greater than 6.7; aluminum alloys pit in 220 F high salinity seawater at pH 6.1 but not at pH 7.0; 15 to 20 ppm bicarbonate seawater alkalinity increases the pitting and corrosion resistance of aluminum alloys, but an 8-ppm bicarbonate level gives only partial pitting resistance; mild steel, COR-TEN, and Copper Alloy 122 show acceptable rates in aerated softened seawater at pH 9 to 9.5 and 290 to 320 F. The report also describes techniques and apparatus to study pitting, determine bimetallic corrosion rates, determine critical velocity, determine heat-transfer coefficients, analyze dissolved oxygen and carbon dioxide, and determine total alkalinity in seawater.

An earlier Dow report described similar evaluations on a variety of other types of steel and some aluminum alloys.<sup>(231)</sup> It was shown that the corrosion performance of copper-bearing steel (ASTM A-242) was about 30 percent better than that of mild steel. Both of these steels performed well with 5 ppb oxygen in the seawater, but had high corrosion rates with greater than 100 ppb oxygen in the water. Steels containing 4 to 8 percent nickel and 3.5 percent chromium also exhibited high corrosion rates in hot water containing 125 ppb oxygen, but were not tested at the lower oxygen levels. The pitting and crevice corrosion behavior of wrought stainless steels were not consistent; preliminary ratings of stainless steel types in descending order of merit were: 316, 304, 409, and 430. Cast stainless steels CF-8, CF-8M, and CA-15 showed highly localized attack with 125 ppb oxygen in the water, but had greatly improved performance with 5 ppb oxygen in the water.

Additional studies at Dow compared the performance of carbon, low alloy, Alloy 20, Type 304 and Type 311 steels, aluminum alloys, and copper alloys.<sup>(232)</sup> Oxygen was the primary cause of attack in all alloys studied. Low-alloy steels were better than mild steels, particularly at high velocities. Attack rates on the steels doubled between 82 and 120 C (180 and 250 F). Aluminum alloys were unaffected by oxygen under 1 ppm and temperatures to 120 C had no effect, but they were sensitive to galvanic, velocity, and scavenging effects (plating out of heavy metal ions).

## Stainless Steel

Electrochemical and in-plant corrosion studies have been made by Westinghouse on ferritic stainless steels for use in desalination plants.<sup>(233)</sup> The results revealed that many high-purity stainless steels are resistant to deaerated seawater at 250 F (120 C). However, as the dissolved oxygen content of the water was increased, the chromium-plus-molybdenum concentration of the steels had to be increased to maintain adequate corrosion resistance. Ferritic stainless steels containing 21 to 23 weight percent chromium and 3 to 5 weight percent molybdenum were resistant to 250 F seawater containing 200 to 500 ppb dissolved oxygen.

The corrosion behavior of austenitic stainless steels in Baltic seawater (3200 to 3900 ppm chloride) has been studied in Sweden.<sup>(234)</sup> Tests were conducted for times up to two years on tubes in heat exchangers in a test loop at 50 C (122 F) and

0.1 and 10 meters/sec (0.33 and 33 feet/sec) velocity. Pitting was observed wherever there were crevices. All unwelded, fully exposed specimens were resistant at both water velocities. A study devoted specifically to the effect of seawater on the corrosion behavior of Type 304 stainless steel at elevated temperatures has also been reported.<sup>(235)</sup>

Designing with stainless steels for service in a variety of seawater environments has been discussed in a paper by Moller of the International Nickel Company.<sup>(236)</sup> Conditions conducive to the stress corrosion cracking of the various kinds of stainless steels are described. Nineteen case histories of SCC failures are described in applications that include boilers, steam lines, salt-water condensers, sour-water heated reboiler, bolts in a distillation column, MEA reboilers, and a seawater desalination plant.

Sandvik Corporation in Sweden has developed a stainless steel that resists stress-corrosion cracking in low-chloride environments.<sup>(237)</sup> Designated 3RE60, the alloy contains 0.03C-18.5Cr-4.7Ni-2.7Mo-1.7Si-1.5Mn and has a minimum yield strength of 45 Kp/mm<sup>2</sup> (about twice that of the usual 18Cr-8Ni stainless steels). The general corrosion resistance of the alloy compares favorably with that of Type 316L stainless steel. Although 3RE60 cracks readily in boiling 42 percent MgCl<sub>2</sub> solution, it has not cracked in a number of low-chloride environments that produced cracking in 18Cr-8Ni alloys. These included water at 295 C (565 F) containing 100 ppm chloride and 8 ppm oxygen, refinery heat exchangers handling 190 C (375 F) water containing 900 ppm chloride, and cooling coils with partial evaporation of Baltic seawater (about 3000 ppm chloride) at 270 C (520 F).

#### Copper-Base Alloys

The incipient corrosion of copper alloys, arising from the use of polluted water in the seawater cooling systems of new construction ships, may proceed in subsequent service leading to early failures.<sup>(238)</sup> To investigate these effects, the Danish Ship Research Laboratory undertook a study to determine how far a pretreatment of copper alloys with a suitable inhibitor solution, accomplished before assembling of the seawater carrying components on board the ship, could prevent initiation of corrosion attack from polluted water.

After a pretreatment in a sodium-dimethyldithiocarbamate solution, heat exchanger tubes from Al-brass, CuNi 90/10 and CuNi 70/30 were simultaneously exposed for a 5 week fitting-out period at selected harbors in more parallels with different surface preparations ("as received" and inhibitor pretreated). It was found that the shop pretreatment of copper alloy components, carried out before mounting of the pipe system, as in these tests, does not provide safe protection of copper alloys during and after the fitting out period. On the contrary, the pretreatment in more instances increased the corrosion in the subsequent operation period. It was also concluded that:

- CuNi 90/10 was the least resistant material toward sulfide polluted seawater in these tests and the intensity of attack increased with the flow velocity.
- Al-brass suffered in general less corrosion than CuNi 90/10.
- CuNi 70/30 was least affected by polluted seawater with a slight tendency to some recognizable corrosion at the lower flow velocities.

Materials problems in salt-water cooling towers have been reviewed by Exxon Research and Engineering Company.<sup>(239)</sup> Specific problems include:

- Silicon bronze bolts are susceptible to corrosion/erosion where falling water droplets impinge, and the attack is aggravated by sulfides in the water
- Sulfides from polluted water or process leakage cause severe corrosion of copper-base alloys
- Sulfides can be countered by use of oxidizing biocides such as chlorine or hypochlorite which oxidize the sulfides to less corrosive sulfates.
- Pitting of Type 316 stainless steel in crevice areas where poor cleanliness or microbiological control is maintained and excellent performance in well-aerated portions.

#### Titanium and Titanium-Base Alloys

Seventeen different heat-exchanger tubing alloys have been evaluated after 15,000 hours of exposure to Baltic seawater (0.4 percent chloride) at 50 C and 2 to 5 m/sec in tests conducted in Sweden.<sup>(240)</sup> In the clean seawater employed, titanium, Alloy 825, and molybdenum-containing austenitic stainless steels were completely resistant to attack even at rolled-in crevices. Intergranular attack occurred adjacent to welds in ferritic-molybdenum stainless steels, but these were found to have been accidentally carburized prior to welding. Aluminum alloys and a number of copper alloys exhibited erosion-corrosion at the velocities studied. The 70-30 Cu-Ni-Fe resisted attack at the 4 to 5 m/sec velocity.

Letvin and Smith have observed that because of its excellent record of performance in salt water, titanium has become a serious candidate for the entire shipboard seawater piping systems.<sup>(241)</sup> Land-based titanium seawater piping in the form of heat exchangers is becoming increasingly used; twenty-one condensers representing a 12,424-megawatt generating capacity in coastal power plants are already installed or on order.<sup>(242)</sup>

The Oak Ridge National Laboratory has issued a compilation of its research efforts on reactions and transport phenomena at surfaces as related to desalination.<sup>(243)</sup> Included are separate articles on the following subjects:

- Kinetics and Pitting Attack of Titanium in Chloride Solutions
- Pitting of Titanium in Saline Waters
- Kinetics of Initiation of Crevice Corrosion of Titanium

#### Aluminum-Base Alloys

Verink and George reported the results of an inspection of aluminum components in the Aluminum Association experimental desalination plant at Freeport, Texas, after approximately 36 months of service.<sup>(244)</sup> Five tubing alloys (1200, 3003, 5050, 5052, and 6063), two plate alloys (5454 and 6061), and one pipe alloy (6061) are being evaluated under conditions likely to be encountered in desalination plants. No significant corrosion has been found on any of the process equipment, including piping, tube sheets, flanges, flash tanks, heat exchanger heads, or support structures. No special corrosive attack under barnacles has been observed and overall plant appearance remains excellent. The minor amount of pitting apparent in several of the heat exchanger tubes after six months service appeared no more severe during the present inspection. This initial pitting was attributed to heavy metal ion scavenging. With the passage of time, the alloy surface apparently became immune to further damage. The relative behavior of the tube alloys in a heat exchanger operating at a water

TABLE 87. EVALUATION OF TUBES FROM THE HEAT RECOVERY UNIT E-22<sup>(244)</sup>

Alloy	Months Tested	Temp., F	First Pass			Remarks
			Max. Pit Depth, Inches	Avg. Pit Depth, Inches	No. of Pits/In <sup>2</sup>	
3003	32	125	0.010	0.002	1	Pitted areas
5052	32	125	0	0	0	Slight etch (one small depression)
6063	32	125	0.008	0.002	1	
5050	20	125	0.018	0.005	0.01	Very few pits, but few deep pits
1200	6	125	0	0	0	Slight etched area, no real pits
Last Pass						
3003	32	210	0	0	0	Excellent appearance, very slight etch
5052	32	210	0	0	0	Excellent appearance, very slight etch
6063	32	210	0	0	0	Excellent appearance, very slight etch
5050	20	210	0.003	0.002	0.1	Few shallow pits, very slight etch
1200	6	210	0	0	0	Excellent appearance, very slight etch

velocity of 5 fps and water temperatures from 125 to 210 F is shown in Table 87.

Alcoa investigators have also reported on an electrochemical study of the corrosion behavior in seawater of 1100-F, 6063-T6, and 5052-H34 aluminum alloys.<sup>(245)</sup> One conclusion was that after a short break-in period, the general corrosion rates of these alloys would be less than 1 mil per year at operating temperatures to 300 F. The 6063 alloy was judged slightly more susceptible to pitting than the 5052 alloy within the 75 to 125 F temperature range if corrosion products were allowed to accumulate. Although the 1100 alloy showed a somewhat lower capability to repassivate pits than the magnesium-containing alloys, it was considered satisfactory for service to 260 F.

Additional corrosion experience with aluminum in three desalting plants has been described by the Resources Conservation Company.<sup>(246)</sup> The plants were a desalination plant in the Virgin Islands, a brine concentrator in El Paso, Texas, and a small OSW test plant at Roswell, New Mexico. Aluminum 3003, 6061, and 6063, and titanium comprised most of the equipment in these plants which operated with acidified water containing 10 to 50 ppb oxygen near atmospheric boiling. In general, the aluminum performed well. Notable exceptions were (1) severe attack with oxygen-saturated intake water at 5 to 6 pH and 21 to 100 C, and (2) severe pitting where copper was present in one feed. The former problem was solved by replacement with fiberglass piping while the latter was solved by raising the pH to 7.5 and allowing the oxygen to rise to 50 ppb.

Finally, Taylor has summarized over seventy publications describing either corrosion studies of aluminum alloys in seawater or actual experience with aluminum components in desalination equipment.<sup>(247)</sup> Experience in a number of areas suggests that alloys containing 1 to 3 percent magnesium (5052, for example) exhibit superior corrosion resistance in a seawater environment. Avoidance of galvanic contact with steel or copper-base alloys is important. Pitting also can be troublesome, especially in water entry areas, when high heavy-metal ion concentrations are present in the water. Methods for reducing pitting problems in such cases through the use of entry screens or heavy-metal traps are described.

In view of their excellent corrosion resistance, low cost, and ease of fabrication, aluminum alloys are prime candidates for the construction of desalination equipment.

#### Cathodic Protection

Two reports have been published which describe experiences with the use of sacrificial Al-Zn-Hg anodes in the cathodic protection of offshore structures<sup>(248,249)</sup> and another which compares the electrochemical characteristics of commercial Al-Zn-Hg, Al-Zn-In, and Al-Zn-Sn alloys in seawater at Key West, Florida.<sup>(250)</sup> The Al-Zn-Hg anode consistently produced the highest efficiency with a minimum of 1250 amp hr/lb. The current capacity of Al-Zn-In anodes was 757 to 900 amp hr/lb at nominal in-service current densities while that of Al-Zn-Sn anodes was 630 to 1000 amp hr/lb with the lowest value being obtained at low current densities. The heat treatable Al-Zn-Sn anodes were not considered to be suitable for galvanic anodes in seawater based on their current outputs and current capacities.

The electrochemical properties of magnesium and zinc anodes, in addition to aluminum alloys, were also reviewed and compared in a comprehensive study by the Navy.<sup>(251)</sup> The principal conclusions from the review are:

1. By using magnesium anodes conforming to MIL-A-21412A, zinc anodes conforming to MIL-A-18001H or aluminum anodes of the proper identity, one can readily obtain dependable electrochemical properties from galvanic anodes for seawater service. Aluminum alloy anodes containing small percentages of zinc and mercury have consistently given satisfactory electrochemical characteristics, but the current capacity may be lowered considerably if the anodes are used in anaerobic muds covered by seawater.
2. The aluminum-zinc-mercury alloy anodes have the lowest relative metal cost per ampere year compared to magnesium, zinc, or other aluminum alloy anodes studied.

Five studies were noted where the major emphasis was on techniques for the cathodic protection of stainless steels. Sacrificial zinc anodes were favored in two of these<sup>(252,253)</sup> while zinc, aluminum, iron and magnesium anodes were evaluated in another.<sup>(254)</sup> One study was confined to the use of impressed currents.<sup>(255)</sup> In another, broad program it was shown that carbon steel was a very effective anode material, protecting stainless steel in excess of 8 years in seawater and through 16 years at mean tide.<sup>(256)</sup>

Researchers at the Shell Development Company have reported on the corrosion of pipeline steels in and near the bottom sediments of the Gulf of Mexico at depths of 50 to 500 feet.<sup>(257)</sup> It was shown that the corrosion of separate, buried steel panels and the cathodic protection current densities required to control this corrosion are less than in the ocean immediately above the mudline. The corrosion rate of unprotected steel panels exposed to seawater above the mud is as high as 11 mpy depending on the time and location of exposure. Unprotected panels below the mudline, however, corrode at rates of 1 to 3 mpy. Pitting corrosion of these panels is also more intense in the water above the mud than buried in the mud. The current density required to reduce the corrosion rate of these panels to  $< 1$  mpy is in excess of  $3.2 \text{ mA/ft}^2$  above the mudline and from  $0.6$  to  $2.5 \text{ mA/ft}^2$  below the mudline. The current density required to control corrosion decreases with increasing depth of burial in the mud.

The corrosion behavior and response to cathodic protection of wire ropes have been studied by the Naval Research Laboratory.<sup>(258)</sup> Wire ropes with and without zinc anodes were exposed partially or completely submerged in seawater at Key West, Florida. Based on 790 days of exposure, Ti-13V-11Cr-3Al, aluminized steel, and a nickel alloy (Ni-22Cr-9Mo-2Fe-3.75Cb+Ta) were suitable for 2 years of exposure without cathodic protection. Phosphor bronze, galvanized steel, and 90/10 copper-nickel clad Type 304L stainless steel were suitable if cathodically protected. Unclad Type 304 and 90/10 copper-nickel clad Type 205 stainless steel exhibited localized corrosion even when cathodically protected.

Six articles on cathodic protection are included in the November, 1973, issue of Materials Protection and Performance.<sup>(259)</sup> The articles discuss protection of ship hulls, Mississippi River docks, buried coaxial cable, and water-tank interiors as well as direct-current concepts and the effect of anode length on anode output.

Experiences with the cathodic protection of marine heat exchangers<sup>(260)</sup> and desalting plants<sup>(261,262)</sup> have also been described. In general, techniques involving impressed currents for cathodic protection are favored.



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## APPENDIX

DESIGNATIONS AND COMPOSITIONS OF  
SELECTED COPPER AND ALUMINUM ALLOYSTABLE A-1. STANDARD COPPER DEVELOPMENT ASSOCIATION DESIGNATIONS  
FOR SELECTED COPPER AND COPPER ALLOYS

CDA No.	Previous Trade Name	Nominal Composition(a), weight percent
<u>Coppers</u>		
102	Oxygen-free	99.95 Cu + Ag
110	Electrolytic tough pitch	99.90 Cu + Ag
122	Phos. deoxidized	.015-.040 P, bal Cu
172	Beryllium-copper	1.8-2 Be, 0.6 (Fe + Ni + Co), bal Cu
192	Iron-phos.-copper	2.1-2.6 Fe, .01-.04 P, bal Cu
<u>Brasses</u>		
230	Red brass, 85%	84-86 Cu, .05 Pb, .05 Fe, bal Zn
240	Low brass	78.5-81.5 Cu, .05 Pb, .05 Fe, bal Zn
260	Cartridge brass, 70%	68.5-71.5 Cu, .07 Pb, .05 Fe, bal Zn
280	Muntz metal, 60%	59-63 Cu, 0.3 Pb, .07 Fe, bal Zn
420	(Tin Brass)	88-91 Cu, 1.5-2 Sn, 0.25 P, bal Zn
442	Admiralty, uninhibited	70-73 Cu, .07 Pb, .06 Fe, 0.8-1.2 Sn, bal Zn
443	Admiralty, arsenical	70-73 Cu, .07 Pb, .06 Fe, 0.8-1.2 Sn, .02-0.1 As, bal Zn
464	Naval Brass, uninhibited	59-62 Cu, 0.2 Pb, 0.1 Fe, 0.5-1 Sn, bal Zn
<u>Bronzes</u>		
505	Phos. bronze, 1.25% E	.05 Pb, 0.1 Fe, 1-1.7 Sn, 0.3 Zn, .03-0.35 P, bal Cu
510	Phos. bronze, 5% A	.05 Pb, 0.1 Fe, 3.5-5.8 Sn, 0.3 Zn, .03-0.35 P, bal Cu
518	Phos. bronze	.02 Pb, 4-6 Sn, 0.1-0.35 P, bal Cu
521	Phos. bronze, 8% C	.05 Pb, 0.1 Fe, 7-9 Sn, 0.2 Zn, .03-0.35 P, bal Cu
608	(Aluminum bronze)	0.1 Pb, 0.1 Fe, 5-6.5 Al, 0.35 As, bal Cu
614	Aluminum Bronze D	1.5-3.5 Fe, 6-8 Al, 1 Mn, bal Cu
637	(Aluminum bronze)	.05 Pb, 0.3 Fe, 0.6 Sn, 1 Zn, 6.5-8.5 Sn, 0.15 As, 1.2-2.2 Si, 0.25 Ni, bal Cu
<u>Miscellaneous Alloys</u>		
655	High-silicon Bronze A	.05 Pb, 0.8 Fe, 1.5 Zn, 1.5 Mn, 2.8-3.8 Si, 0.6 Ni, bal Cu
675	Manganese bronze	57-60 Cu, 0.2 Pb, 0.8-2 Fe, 0.5-1.5 Sn, 0.25 Al, .05-0.5 Mn, bal Zn
687	Aluminum brass, arsenical	76-79 Cu, .07 Pb, .06 Fe, 1.8-2.5 Al, .02-0.1 As, bal Zn
704	Copper-nickel, 5%	.05 Pb, 1.3-1.7 Fe, 1 Zn, 4.8-6.2 Ni, 0.3-0.8 Mn, bal Cu
706	Copper-nickel, 10%	.05 Pb, 1-1.8 Fe, 1 Zn, 9-11 Ni, 1 Mn, bal Cu
707	(Copper-nickel)	.05 Fe, 9.5-10.5 Ni, 0.5 Mn, bal Cu
711	(Copper-nickel)	.05 Pb, 0.1 Fe, 0.2 Zn, 22-24 Ni, 0.15 Mn, bal Cu
715	Copper-nickel 30%	.05 Pb, 0.4-0.7 Fe, 1 Zn, 29-33 Ni, 1 Mn, bal Cu
732	(Nickel-silver)	70 Cu, .05 Pb, 0.6 Fe, 3-6 Zn, 19-23 Ni, 1 Mn
745	Nickel-silver, 65-10	63.5-68.5 Cu, 0.1 Pb, 0.25 Fe, 9-11 Ni, 0.5 Mn, bal Zn
752	Nickel-silver, 65-18	63-65 Cu, 0.1 Pb, 0.25 Fe, 16.5-19.5 Ni, 0.5 Mn, bal Zn

(a) Maximum contents shown unless a range is indicated.

Source: Application Data Sheet, "Standard Designations for Copper and Copper Alloys (Wrought Products Only)", Brochure 107/8, Copper Development Association, Inc., New York, N. Y.



TABLE A-2. COMPOSITION LIMITS FOR SELECTED ALUMINUM ALLOYS

Alloy Designation	Chemical Composition(a), weight percent								
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Others
1100	1 (Si + Fe)		0.2	0.05	—	—	0.1	—	0.15 total
2014	0.5-1.2	1	3.9-5	0.4-1.2	0.2-0.8	0.1	0.25	0.15	—
2024	0.5	0.5	3.8-4.9	0.3-0.9	1.2-1.8	0.1	0.25	—	—
2219	0.2	0.3	5.8-6.8	0.2-0.4	0.02	—	0.1	0.02-0.1	0.05-0.15 V
3003	0.6	0.7	0.2	1-1.5	—	—	0.1	—	0.15 total
3004	0.3	0.7	0.25	1-1.5	0.8-1.3	—	0.25	—	0.15 total
5050	0.4	0.7	0.2	0.1	1-1.8	0.1	0.25	—	0.15 total
5052	0.5 (Si + Fe)		0.1	0.1	2.2-2.8	0.15-0.35	0.1	—	—
5056	0.3	0.4	0.1	0.05-0.2	4.5-5.6	0.05-0.2	0.1	—	0.15 total
5083	0.4	0.4	0.1	0.3-1	4-4.9	0.05-0.25	0.25	0.15	—
5086	0.4	0.5	0.1	0.2-0.7	3.5-4.5	0.05-0.25	0.25	0.15	—
5154	0.45 (Si + Fe)		0.1	0.1	3.1-3.9	0.15-0.35	0.2	0.2	0.15 total
5356	0.5 (Si + Fe)		0.1	0.05-0.2	4.5-5.5	0.05-0.2	0.1	0.06-0.2	—
5454	0.4 (Si + Fe)		0.1	0.5-1	2.4-3	0.05-0.2	0.25	0.2	0.15 total
5456	0.4 (Si + Fe)		0.1	0.5-1	4.7-5.5	0.05-0.2	0.25	0.2	—
6061	0.4-0.8	0.7	0.15-0.4	0.15	0.8-1.2	0.04-0.35	0.25	0.15	—
7001	0.35	0.4	1.6-2.6	0.2	2.6-3.4	0.18-0.4	6.8-8	0.2	—
X7002	0.2	0.4	0.5-1	0.05-0.3	2-3	0.1-0.3	3-4	0.15	—
X7005	0.35 (Si + Fe)		0.1	0.2-0.7	1-1.8	0.06-0.2	4.2-5	0.15	0.08-0.2 Zr
X7006	0.35 (Si + Fe)		0.1	0.5	1.7-2.8	0.3	3.7-4.8	0.15	—
7039	0.3	0.4	0.1	0.1-0.4	2.3-3.3	0.15-0.25	3.5-4.5	0.1	0.15 total
7072	0.7 (Si + Fe)		0.1	0.1	0.1		0.8-1.3	—	0.15 total
7075	0.5	0.7	1.2-2	0.3	2.1-2.9	0.18-0.4	5.1-6.1	0.2	—
7079	0.3	0.4	0.4-0.8	0.1-0.8	2.9-3.7	0.1-0.25	3.8-4.8	0.1	—
7178	0.5	0.7	1.6-2.4	0.3	2.4-3.1	0.18-0.4	6.3-7.3	0.2	—

(a) Maximum values except for ranges indicated.

# **CORROSION OF METALS AND ALLOYS AT VARYING DEPTHS**

Material in the following chapter is from a report by F.M. Reinhart, of the Naval Civil Engineering Laboratory, Port Hueneme, California (ADA-021 279).

## INTRODUCTION

Between 1962 and 1970 the Civil Engineering Laboratory, Naval Construction Battalion Center, Port Hueneme, California, exposed approximately 20,000 specimens of about 475 different alloys in the Pacific Ocean. These specimens were exposed at the surface and at nominal depths of 2,500 and 6,000 feet for periods of time varying from 123 to 1,064 days.

The purpose of these exposures was to provide the Naval Facilities Engineering Command (NAVFAC) with information on the deterioration of materials in deep-ocean environments. Such information was needed to improve techniques, to develop new techniques pertaining to naval material, and to support the increasing interest in the deep ocean as an operating environment.

The Naval Facilities Engineering Command is charged with the responsibility for the construction and maintenance of all fixed Naval facilities; hence, the construction and maintenance of Naval structures at depths in the oceans are but one facet of its overall responsibility. Fundamental to the design, construction, maintenance, and operation of structures and their related facilities is information on the deterioration of materials in a particular environment. Since there was very little published information on the behavior of construction materials in deep-ocean environments, this program was initiated in 1960 to obtain such information.

In-situ testing was chosen because it is not possible to duplicate all the variables and the changes in these variables that prevail in any one environment or location. A test site was considered suitable if the circulation (currents), sedimentation, and bottom conditions were representative of open ocean conditions: (1) the bottom should be reasonably flat, (2) the site should be open and not located in an area of restricted circulation, such as a silled basin, (3) the site should be reasonably close to Port Hueneme for ship operations, and (4) the site should be within the operating range of the more precise navigating and locating techniques.

A Pacific Ocean site meeting these requirements was selected at a nominal depth of 6,000 feet. The ocean bottom at this site is relatively flat in a broad submarine valley southwest of San Miguel Island, California; it is readily accessible to the Civil Engineering Laboratory; and it is subject to the effects of ocean currents. This site, designated Test Site I, is approximately 81 nautical miles southwest of Port Hueneme, latitude  $33^{\circ}44'N$ , longitude  $120^{\circ}45'W$ .

Oceanographic data collected between 1961 and 1963 [1,2] show the presence of an oxygen minimum zone at depths between 2,000 and 3,000 feet. This minimum oxygen zone was present at all sites investigated when the ocean floor was at depths varying between 2,000 and 13,000 feet.

It is well known that the corrosion rates of many materials (e.g., steels) are affected by the concentration of oxygen in the environment. Because of this, it was decided to establish a second test site, Test Site II, in this minimum oxygen concentration zone where, it was thought, much pertinent information could be obtained. Test Site II (nominal depth of 2,500 feet) is 75 nautical miles west of Port Hueneme, latitude  $34^{\circ}06'N$ , longitude  $120^{\circ}42'W$ .

The oceanographic investigations by the Civil Engineering Laboratory also disclosed that the ocean floor at these sites is rather firm and was characterized as sandy, green cohesive mud (partially glauconite) with some rocks. Biological cultures of these bottom sediments showed the presence of sulfate-reducing bacteria in at least the first 6 inches of sediment.

In order to determine the differences between the corrosiveness of seawater at depths and at the surface in the Pacific Ocean, it is desirable to compare deep-ocean corrosion data with surface immersion data. Since surface data from the Pacific Ocean in the vicinity of Port Hueneme were not available in the literature for most of the alloys exposed at depths in the Pacific Ocean, it was decided to establish a surface exposure site to obtain this information. Therefore, a third site, Test Site V, was established at the

Naval Pacific Missile Range, Point Mugu, California, latitude 34°06'N, longitude 119°07'W. Test Site V is about 10 miles east of Port Hueneme.

The specific geographical locations of the test sites and the average characteristics of the seawater 10 feet above the ocean floor at these sites are given in Table 1. Their positions relative to the California coast are shown in Figure 1. The variation of the temperature, pH, salinity and oxygen content of the seawater with depth at the STU sites is shown in Figure 2.

Other naval activities were invited to participate in this program and, if possible, to contribute to the

funding. From 1962 to 1966 the Naval Air Systems Command supplied funds for partial support of the program. Navy contractors and other companies also participated in this program. The participants are listed in Table 2 as well as those who evaluated the materials and whether or not the evaluators, other than CEL, supplied CEL with the results of their evaluations.

This report presents the performance data obtained by CEL and other participants from the seawater exposures at the sites given in Table 1. The performance of the various materials as supported by this data is also discussed.

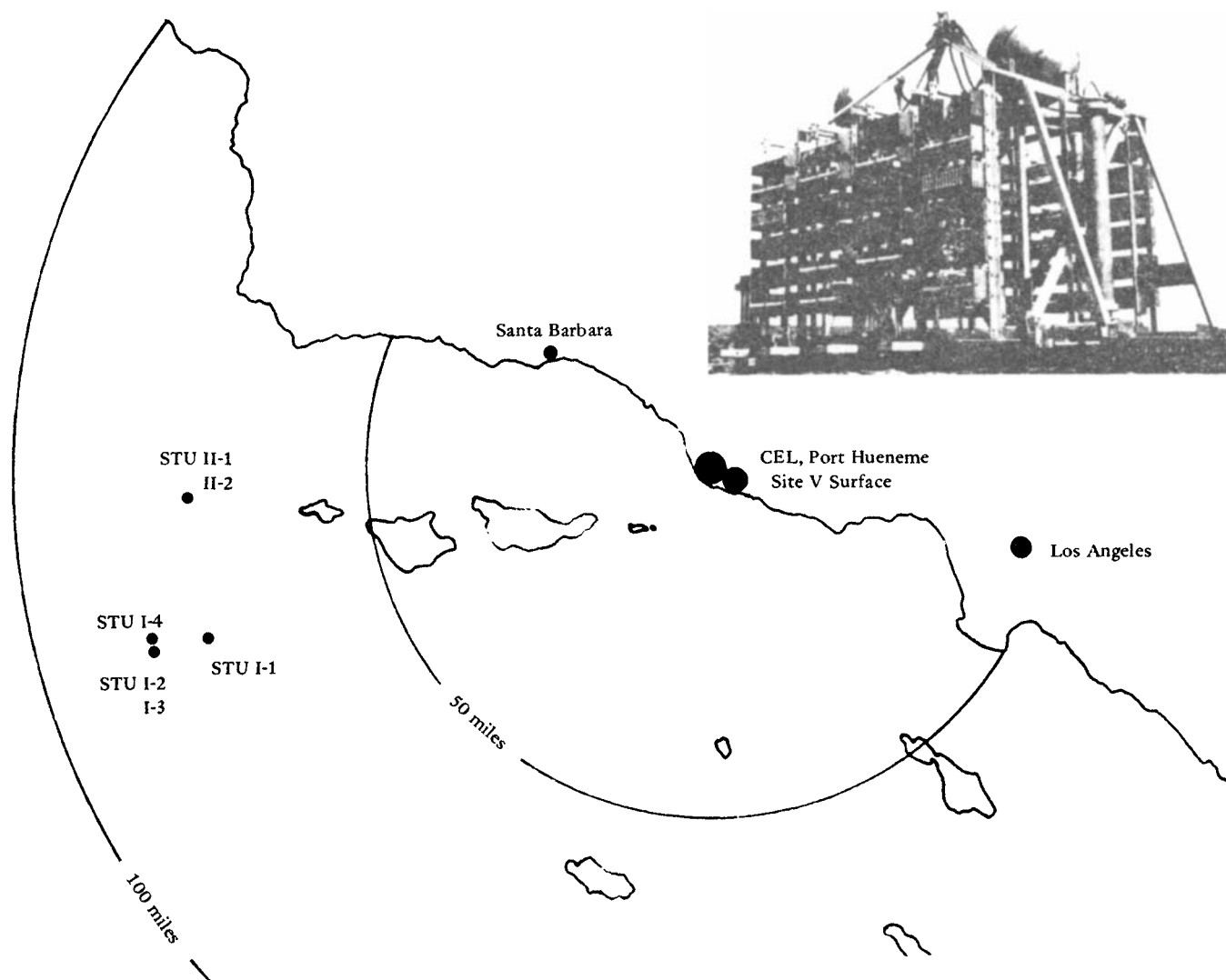


Figure 1. STU sites off the Pacific Coast; STU structure in inset.



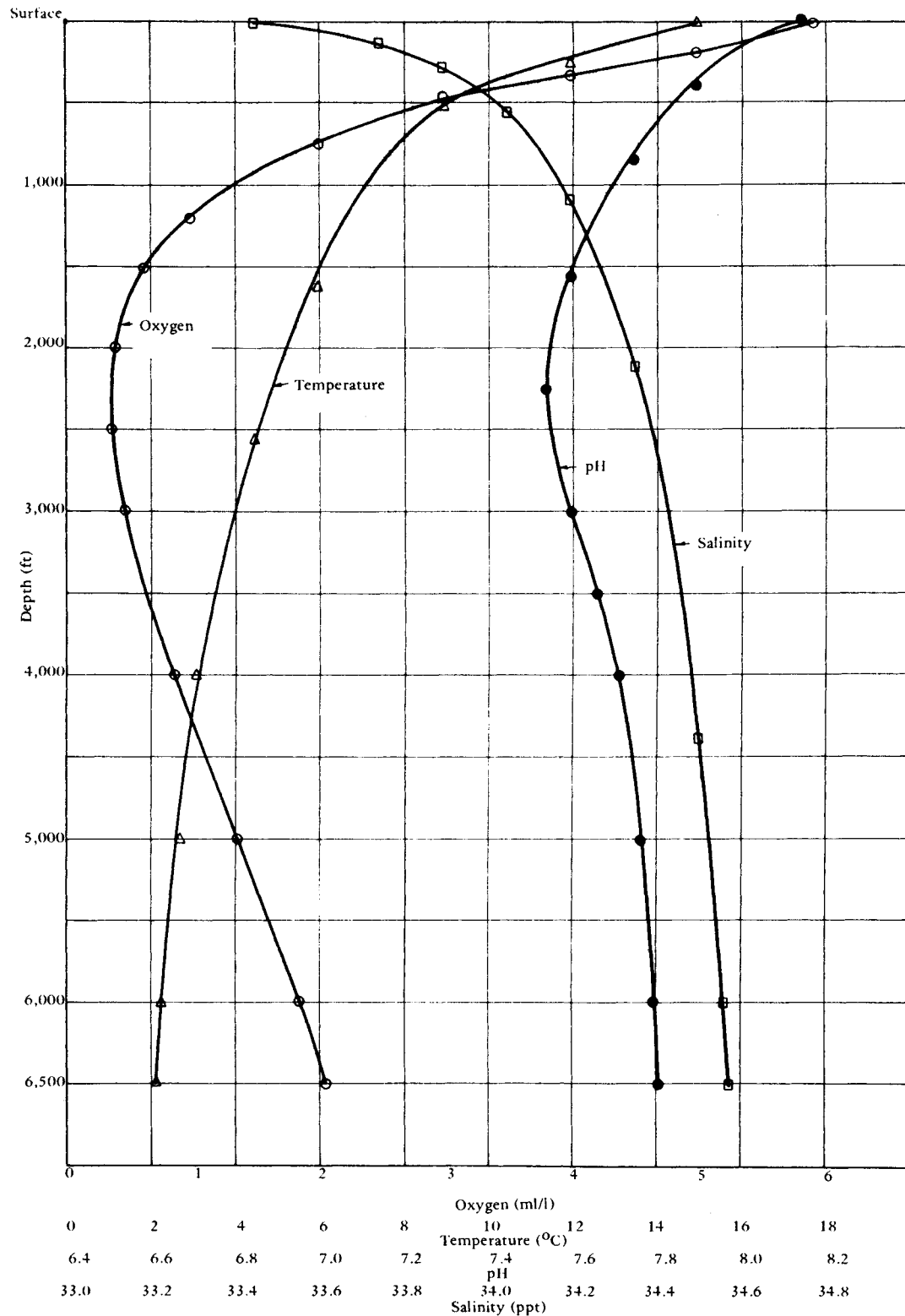


Figure 2. Variation of environment with depth at STU sites.

Table 1. Exposure Site Locations and Seawater Characteristics

Site No.	Latitude N	Longitude W	Depth (ft)	Exposure (day)	Temperature (°C)	Oxygen (ml/l)	Salinity (ppt)	pH	Average Current (knot)
I-1	33°46'	120°37'	5,300	1,064	2.6	1.2	34.51	7.5	0.03
I-2	33°44'	120°45'	5,640	751	2.3	1.3	34.51	7.6	0.03
I-3	33°44'	120°45'	5,640	123	2.3	1.3	34.51	7.6	0.03
I-4	33°46'	120°46'	6,780	403	2.2	1.6	34.40	7.7	0.03
I-5	33°51'	120°35'	5,900	189	2.3	1.6	34.6	7.4	0.03
II-1	34°06'	120°42'	2,340	197	5.0	0.4	34.36	7.5	0.06
II-2	34°06'	120°42'	2,370	402	5.0	0.4	34.36	7.5	0.06
V	34°06'	119°07'	5	181-763	12-19	3.9-6.6	33.51	8.1	variable

Table 2. Participants in Test Program

Name	Materials Evaluated By	Report Submitted to CEL
Aerojet-General Corp.	AGC	no
Aluminum Company of America	CEL	—
Allegheny Ludlum Steel Corp.	CEL	—
American Chain and Cable Co.	CEL	—
American Steel and Wire Div., U.S.S.	CEL	—
Anaconda American Brass Co.	CEL	—
Anaconda Wire and Cable Co.	AWCC	yes
Armco Steel Corp.	CEL	—
Baldt Anchor Chain and Forge Div., Boston Metals Co.	CEL	—
Bell Telephone Laboratories	BTL	yes
Bethlehem Steel Co.	CEL	—
Boeing Co.	Boeing	yes
Brush Beryllium Co.	CEL	—
Carpenter Steel Co.	CEL	—
E. I. Dupont Co.	CEL	—
Elgiloy Co.	CEL	—
Fansteel Metallurgical Corp.	CEL	—
Goodyear Aerospace Corp.	GAC	yes
Haynes Stellite Div., Cabot Corp.	CEL	—
Hooker Chemical Corp.	CEL	—

Continued

Table 2. Continued.

Name	Materials Evaluated By	Report Submitted to CEL
International Nickel Co., Inc.	INCO/CEL	yes/—
Joseph T. Ryerson & Son	CEL	—
Kaiser Aluminum and Chemical Corp.	CEL	—
Kawecki Berylco Industries	CEL	—
Lukens Steel Co.	CEL	—
Menasco Manufacturing Co.	MMC	no
Metco Inc.	CEL	—
Military Consultant Service	CEL	—
Minnesota Mining and Manufacturing Co.	3M	—
Mobay Chemical Co.	CEL	—
Naval Air Development Center	NADC	yes
Naval Air Systems Command	NASC	yes
Naval Electronics Laboratory	NEL	no
NAVFAC, Code 042	CEL	—
Naval Ordnance Test Station	NOTS	no
Naval Pacific Missile Range	CEL	—
Naval Ship Research and Development Center, Annapolis Div.	NSRDC(A) <sup>a</sup>	yes
Naval Underwater Ordnance Station	NUOS	no
Owens Corning Fiberglass Corp.	CEL	—
Reactive Metals Inc.	CEL	—
Republic Steel Corp.	CEL	—
Reynolds Metals Co.	RMC	yes
Scripps Institution of Oceanography	CEL	—
Shell Development Co.	Shell	yes
Standard Pressed Steel Co.	CEL	—
Taylor Fibre Co.	CEL	—
Texas Instruments, Inc.	CEL	—
Titanium Metals Corporation of America	CEL	—
TRW Space Technology Laboratories	TRW	yes
Tube Turns Plastic Co.	CEL	—
U.S. Rubber Co.	CEL	—
U.S. Steel Corp.	USS/CEL	yes/—
Valley Bolt Co.	CEL	—

<sup>a</sup> Formerly Marine Engineering Laboratory (MEL), Annapolis, Maryland.

## STEEL AND CAST IRONS

The data discussed in this section were obtained from the reports given in References 3 through 19. The chemical compositions of the alloys are given in Table 3; their surface conditions and heat treatments, if any, are given in Table 4.

The corrosion rates and types of corrosion of all the alloys are given in Table 5. Inorganic coatings were applied to some steels to evaluate their protective qualities. These coatings and their conditions are given in Table 6. Steels that were exposed in a stressed condition to determine their susceptibility to stress corrosion cracking are given in Table 7.

The effects of corrosion on the mechanical properties of many of the alloys were determined after various periods of exposure; these results are given in Table 8.

Water near the surface in the open sea is quite uniform in its composition throughout the oceans [20]; therefore, the corrosion rates of steels exposed under similar conditions in clean seawater should be comparable. The results of many investigations on the corrosion of structural steels in surface seawater at many locations throughout the world show that after a short period of exposure the corrosion rates are constant and amount to between 3 and 5 mils per year [21,22]. Factors which can cause differences in corrosion rates outside these limits are variations in marine fouling, contamination of the seawater near the shorelines, variations in seawater velocity, and differences in the surface water temperature.

## 2.1. IRONS AND STEELS

The corrosion rates of the irons; mild steels; high-strength low-alloy steels; high-strength steels; other alloy steels; and nickel alloy steels are given in Table 5. Analysis of the corrosion rates of these alloys shows that for all practical purposes their corrosion rates were comparable for any one duration of exposure at any one depth or at the surface. Therefore, these data were treated statistically to obtain one median value for each time of exposure and each

depth. These average data values were used to plot curves to show the general corrosion behavior to be expected from these alloys with regard to duration of exposure, depth in the ocean, and concentration of oxygen in seawater.

### 2.1.1. Duration of Exposure

The effects of the duration of exposure on the corrosion of steels in seawater at the surface and at depth are shown in Figure 3. The corrosion rates of the steels exposed in seawater at nominal depths of 2,500 and 6,000 feet in the Pacific Ocean decreased with increasing duration of exposure and were consistently lower than the surface corrosion rates by a factor of approximately 3. The corrosion rates at the 2,500-foot depth also were lower than those at the 6,000-foot depth. The corrosion rates decreased asymptotically with increasing duration of exposure both at the surface and at the 6,000-foot depth.

The performance of the steels when partially embedded in the bottom sediments at the 2,500- and 6,000-foot depths is shown in Figure 4. Here, also, the average corrosion rates of the steels at the 6,000-foot depth decreased asymptotically with increasing duration of exposure. During the initial exposures the steels corroded at faster rates in seawater than in the bottom sediments at the 6,000-foot depth, but after approximately 2 years of exposure, their average corrosion rates were approximately the same as shown by comparing the curves in Figures 3 and 4. Here, also, the average corrosion rates at the 2,500-foot depth were lower than at the 6,000-foot depth, but they increased with increasing duration of exposure.

### 2.1.2. Depth

The effect of depth of exposure in seawater on the average corrosion rates of the steels is shown in Figure 5. The variation of the concentration of oxygen in seawater with depth is also shown in Figure 5 for comparison purposes. The shape of the curve

for steels shows that corrosion of steels is not affected by depth (pressure), at least to a depth of 6,000 feet (2,700 psi) for a period of 1 year of exposure. The shape of this curve is practically identical to that of the oxygen concentration curve. The identical shape of these curves indicate that the concentration of oxygen in seawater exerts a major influence on the corrosion of steels in this environment.

### 2.1.3. Concentration of Oxygen

The effect of the variation in the concentration of oxygen in seawater on the corrosion of steels after 1 year of exposure is shown in Figure 6. The curve for the average corrosion rates of the steels after 1 year of exposure versus the concentration of oxygen is a straight line. This indicates that the corrosion of steels in seawater is proportional to the concentration of oxygen.

### 2.1.4. Nickel

The effect of the variation of the concentration of nickel on the corrosion of steels is shown in Figure 7. Variations of from 1.5 to 9% in the nickel content were ineffectual with respect to the corrosion of steel both at the surface and at depth. However, the corrosion rates in surface exposures were higher than at depth by about a factor of 7.

### 2.1.5. Type of Corrosion

All the steel, except AISI Type 502, in general, corroded uniformly except for some slight pitting in surface seawater which was caused by fouling. The corrosion rates of AISI Type 502 steel (5% Cr-0.5% Mo) were erratic and higher than those of the other steels. This behavior is attributed to the broad, shallow pitting and the severe crevice corrosion caused by the chromium content of the steel.

### 2.1.6. Metallic Coatings

Zinc, aluminum, sprayed aluminum, titanium-cadmium, cadmium, copper, and nickel-coated steel specimens were exposed at depth.

A 1 oz/sq ft of zinc on galvanized steel sheet exposed at a depth of 2,500 feet protected the steel

for from 3 to 4 months in the seawater and for about 7 months when partially embedded in the bottom sediments.

A 1 oz/sq ft of aluminum on aluminized steel sheet exposed at a depth of 2,500 feet protected the steel for at least 13 months in the seawater and when partially embedded in the bottom sediments.

A 6-mil-thick hot-sprayed aluminum coating over steel, which had been subsequently primed and sprayed with two coats of clear vinyl sealer, protected the underlying steel from corroding for 1,064 days at the 6,000-foot depth. After removal from exposure the aluminum coating was dark gray and speckled with pin-point size areas of white corrosion products. Since no red rust was present, it is evident that this coating would provide added protection to the steel for an additional period of time, possibly another 3 years.

A titanium-cadmium coating on AISI 4130 steel was completely sacrificed, and the underlying steel was covered with a layer of red rust after 402 days of exposure at a depth of 2,500 feet. Such a coating would not provide satisfactory protection for seawater applications.

An electrolytically applied cadmium coating on steels, both stressed and unstressed, did not provide adequate protection for 1 year of exposure at depths of 2,500 and 6,000 feet.

Electrolytically applied copper and nickel coatings on steels, both stressed and unstressed, failed within 6 months after exposure at the 2,500-foot depth and caused galvanic corrosion of the underlying steels.

### 2.1.7. Inorganic Coatings

A few steels were coated with selected paint coatings to determine their performance at depths in the Pacific Ocean. Table 6 shows the results of this test.

The multicoat epoxy systems exhibited, in general, satisfactory performance, while the multicoat polyurethane system behaved erratically, varying from cracked and blistered paint to no paint failures. The single-coat, zinc-rich primer coating did not afford satisfactory protection for a period of 6 months at a depth of 6,000 feet.



### 2.1.8. Cathodic Protection

Sacrificial zinc anodes were attached to AISI Type 1015 steel to determine its effectiveness in providing cathodic protection to a more noble material at these depths.

The sacrificial zinc anodes were effective in reducing the corrosion of the AISI Type 1015 steel. They provided nearly complete protection for 123 days, 50% protection during 751 days of exposure, and 30% during 1,064 days of exposure.

### 2.1.9. Galvanic Corrosion

A few galvanic couples (dissimilar metals) of AISI Type 4130 and AISI Type 4140, 1 x 7-inch steel strips with 1-inch-square pieces of 6061 and 7075-T6 aluminum alloys, AZ31B magnesium alloy, aluminum bronze alloy, titanium metal, and AISI Type 308 stainless steel attached to them were exposed at depths of 2,500 and 6,000 feet for 400 days to determine their compatibilities.

After 400 days of exposure at a depth of 6,000 feet aluminum alloy 6061 attached to AISI Type 4130 steel was moderately corroded with practically no corrosion of the steel; the aluminum alloy 7075-T6 was severely corroded under the same conditions. Magnesium alloy AZ31B was nearly completely sacrificed when attached to AISI Type 4130 steel, but the steel was also corroded because of the insulating layer of magnesium alloy corrosion products which accumulated at the faying surfaces of the two alloys. AISI Type 4130 steel was extensively corroded when in contact with the aluminum bronze.

After 400 days of exposure at a depth of 2,500 feet, AISI Type 4340 steel was rusted considerably from being in contact with titanium metal or AISI Type 308 stainless steel.

### 2.1.10. Stress Corrosion

Some of the steels were exposed in a stressed condition at stresses equivalent to from 30 to 75% of their respective yield strengths. The steels, stresses, depths, days of exposure, and their susceptibility to stress corrosion cracking are given in Table 7.

One-half-inch AISI Type 4140 steel bolts, heat-treated to about 175,000 psi tensile strength, failed

during 400 days of exposure — one in the bottom sediment and two in the seawater at the 2,500-foot depth. Whether these failures were due to stress corrosion or hydrogen embrittlement is not certain. Bolts of such hardness should not be used in deep-sea applications.

One nickel-plated specimen of AISI Type 4130 steel, stressed at 127,000 psi, failed during 197 days of exposure at a depth of 2,500 feet. Since no unplated specimens failed, it is possible that the failure was caused by the nickel plating. Hydrogen absorbed into the metal during the plating process could have caused hydrogen embrittlement, which in turn caused the failure.

Some 18 Ni maraging specimens failed by stress corrosion when stressed at various levels, under different conditions, for different periods of time at different depths. These results indicate that the stress corrosion behavior of this steel is unpredictable and unreliable when used at high stress levels (above about 150,000 psi yield strength) for seawater applications.

The other steels were not susceptible to stress corrosion.

### 2.1.11. Mechanical Properties

The percent changes in the mechanical properties of the steels resulting from corrosion are given in Table 8.

The percent elongation of HSLA No. 5 in thicknesses of 1/4 inch and 1/8 inch was decreased by 77 and 82%, respectively, after 400 days of exposure at the 2,500-foot depth.

The mechanical properties of AISI Type 4130 steel, bare, cadmium, copper, or nickel-plated were affected after 400 days of exposure at the 2,500- and 6,000-foot depths. Cadmium, copper, or nickel plating on AISI Type 4340 steel also caused decreases in the mechanical properties of the steel after exposure for 400 days at the 2,500-foot depth.

Because of pitting corrosion the elongation of AISI Type 502 (5% Cr) steel was decreased from 13 to 38% during all exposures at both depths, except for 197 days at the 2,500-foot depth.

The mechanical properties of the 18 Ni maraging steels were, in general, adversely affected by exposure at depth in the Pacific Ocean.

### 2.1.12. Corrosion Products

The corrosion products from some of the steels were analyzed by X-ray diffraction, spectrographic analysis, quantitative chemical analysis, and infrared spectrophotometry. The constituents found were:

- Alpha iron oxide –  $\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$
- Iron hydroxide  $\text{Fe}(\text{OH})_3$
- Beta iron (III) oxide hydroxide –  $\text{FeOOH}$
- Iron oxide hydrate –  $\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$
- Significant amounts of chloride, sulfate, and phosphate ions.

## 2.2. ANCHOR CHAINS

Two types of 3/4-inch-diameter anchor chains, Dilok and welded stud link, were exposed as shown in Table 9. The chain links were covered with layers of loose, flaky rust which varied from thin to thick as the time of exposure increased. Exposure for as long as 751 days did not decrease the breaking loads of the chains as shown in Table 9. In most cases there was rust in the bottoms of the sockets of the Dilok chain, indicating that seawater had penetrated the sockets. This could be a source of additional corrosion and early failure of this type of chain.

## 2.3. CAST IRONS

The corrosion rates of the cast irons are given in Table 5. Analysis of this data shows that for all practical purposes the corrosion rates of the alloy cast irons (nickel, nickel-chromium No. 1 and 2, and ductile irons No. 1 and 2) are comparable. This is also true of the austenitic cast irons. These average data values were used to plot curves to show the general corrosion behavior to be expected from these alloys with regard to duration of exposure, depth in the ocean, and concentration of oxygen in seawater.

### 2.3.1. Duration of Exposure

The effects of duration of exposure on the corrosion of cast irons in seawater at the surface and at depth are shown in Figure 3.

There was no measurable corrosion of the high silicon and the high silicon-molybdenum cast irons in seawater, either at the surface or at depth.

In all three environments (surface, 2,500-, and 6,000-foot depths), the corrosion rates decreased with increasing duration of exposure and were consistently lower at depth than at the surface. The corrosion rates at the 2,500-foot depth were lower than those at the 6,000-foot depth. At the surface and at the 6,000-foot depth the corrosion rates decreased asymptotically with increasing duration of exposure. At the 6,000-foot depth the corrosion rates of the austenitic cast irons, for the first 400 days of exposure, were lower than those of the gray and alloy cast irons, but they were comparable after longer periods of exposure, about 1 mpy. However, at the 2,500-foot depth, the corrosion rates of the austenitic cast irons were lower than those of the alloy and gray cast irons for exposures of up to 400 days.

The corrosion of the cast irons when partially embedded in the bottom sediments is shown in Figure 4. Here again, there was no measurable corrosion of the high silicon and high silicon-molybdenum cast irons in the bottom sediment at either depth.

The other cast irons behaved essentially the same as in the seawater except that the alloy cast irons initially corroded at slower rates than in the seawater at the 6,000-foot depth. After 2 years of exposure at the 6,000-foot depth in both the seawater and the bottom sediments, all the steels and cast irons corroded at essentially the same rate.

In the sediments at the 2,500-foot depth the corrosion rates of the austenitic cast irons tended to increase very slightly with increasing duration of exposure, while those of the alloy cast irons increased considerably.

### 2.3.2. Depth

The effect of depth of exposure in seawater on the average corrosion rates of the alloy and austenitic cast irons as well as those of the gray and high silicon cast irons is shown in Figure 5. The variation of the concentration of oxygen in seawater with depth is also shown in Figure 5 for comparison purposes. The shapes of the curves for the cast irons show that the corrosion of the cast irons is not directly affected by depth (pressure), at least to a depth of 6,000 feet for a period of 1 year.

### 2.3.3. Concentration of Oxygen

The effect of the variation in the concentration of oxygen in seawater on the corrosion of cast irons after 1 year of exposure is shown in Figure 6. The curves for the average corrosion rates of the gray, alloy, and austenitic cast irons versus the concentration of oxygen are essentially straight lines. This indicates that the corrosion of the cast irons in seawater is proportional to the concentration of oxygen. However, the different slopes of the curves indicate different degrees of influence, the influence being greatest on the alloy cast irons and least on the gray cast irons. Oxygen exerted no influence on the corrosion of high silicon or high silicon-molybdenum cast irons.

### 2.3.4. Type of Corrosion

All the cast irons corroded uniformly both in the seawater and in the bottom sediments. The high

silicon and high silicon-molybdenum cast irons were uncorroded in any of the environments.

### 2.3.5. Mechanical Properties

The percent changes in the mechanical properties of the cast irons due to exposure in seawater are given in Table 8. The mechanical properties of the Type 4 austenitic cast iron were not affected by exposure either at the surface or at the 2,500-foot depth. However, the mechanical properties of the D-2C austenitic cast iron were significantly lowered. About 80% of the surfaces of fracture of the D-2C specimens were black in contrast to the gray surfaces of fracture of unexposed specimens. Metallographic examinations of polished cross sections of the D-2C alloy adjacent to the surfaces of fracture showed that the alloy had been attacked by selective interdendritic corrosion. This selective corrosion was the cause of the decrease in mechanical properties of the alloy.

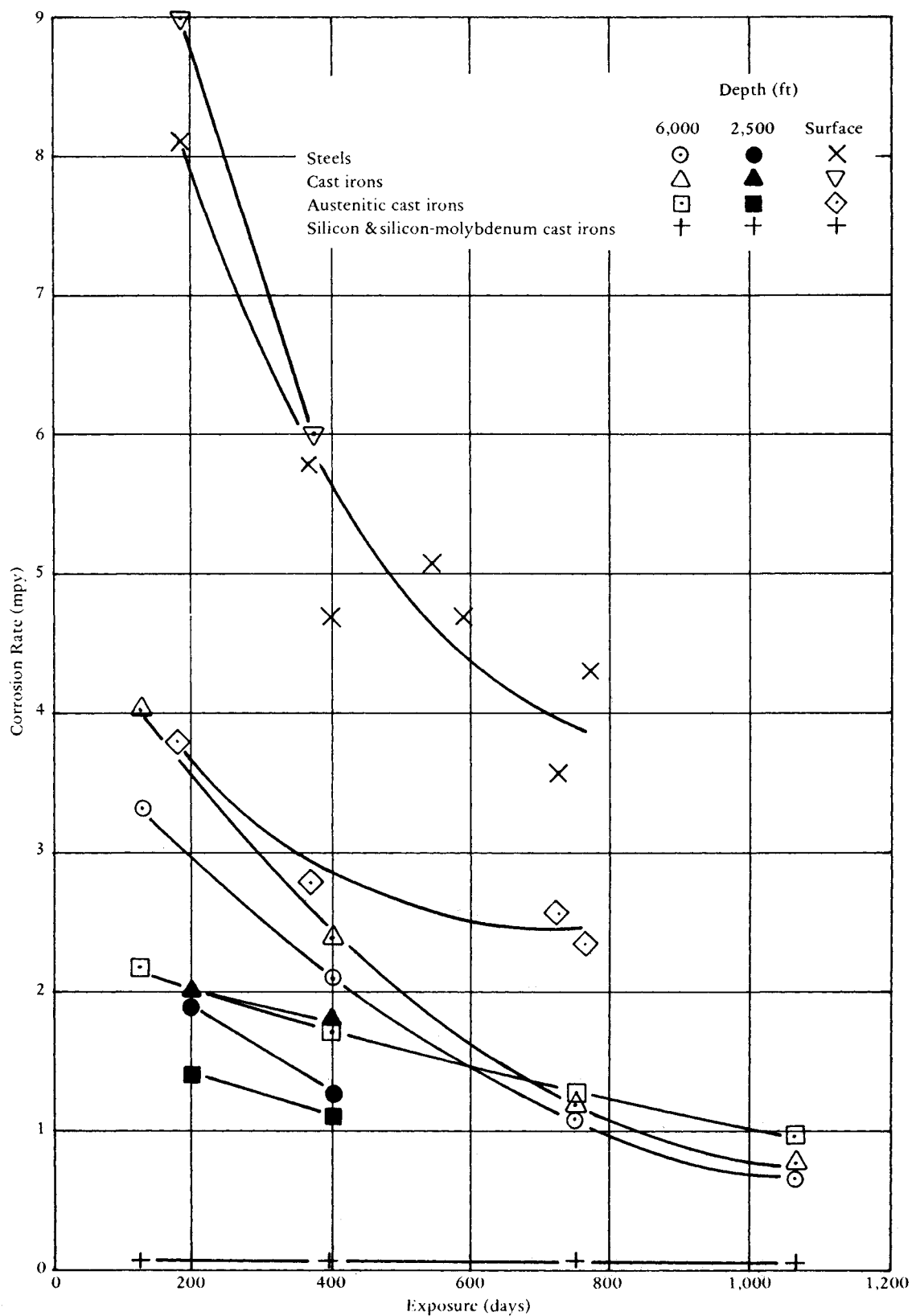


Figure 3. Effect of duration of exposure on corrosion of steels and cast irons.

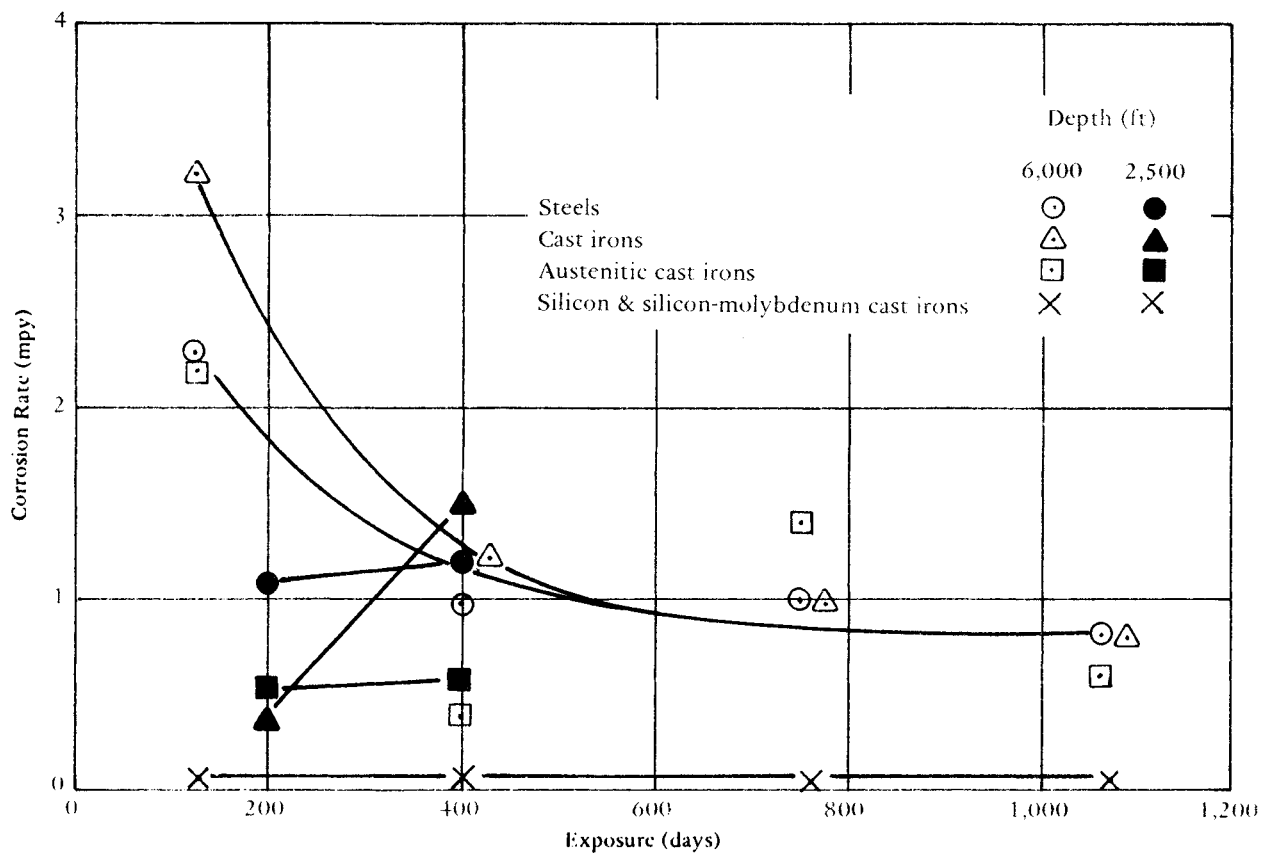


Figure 4. Effect of duration of exposure on corrosion of steels and cast irons in bottom sediments.



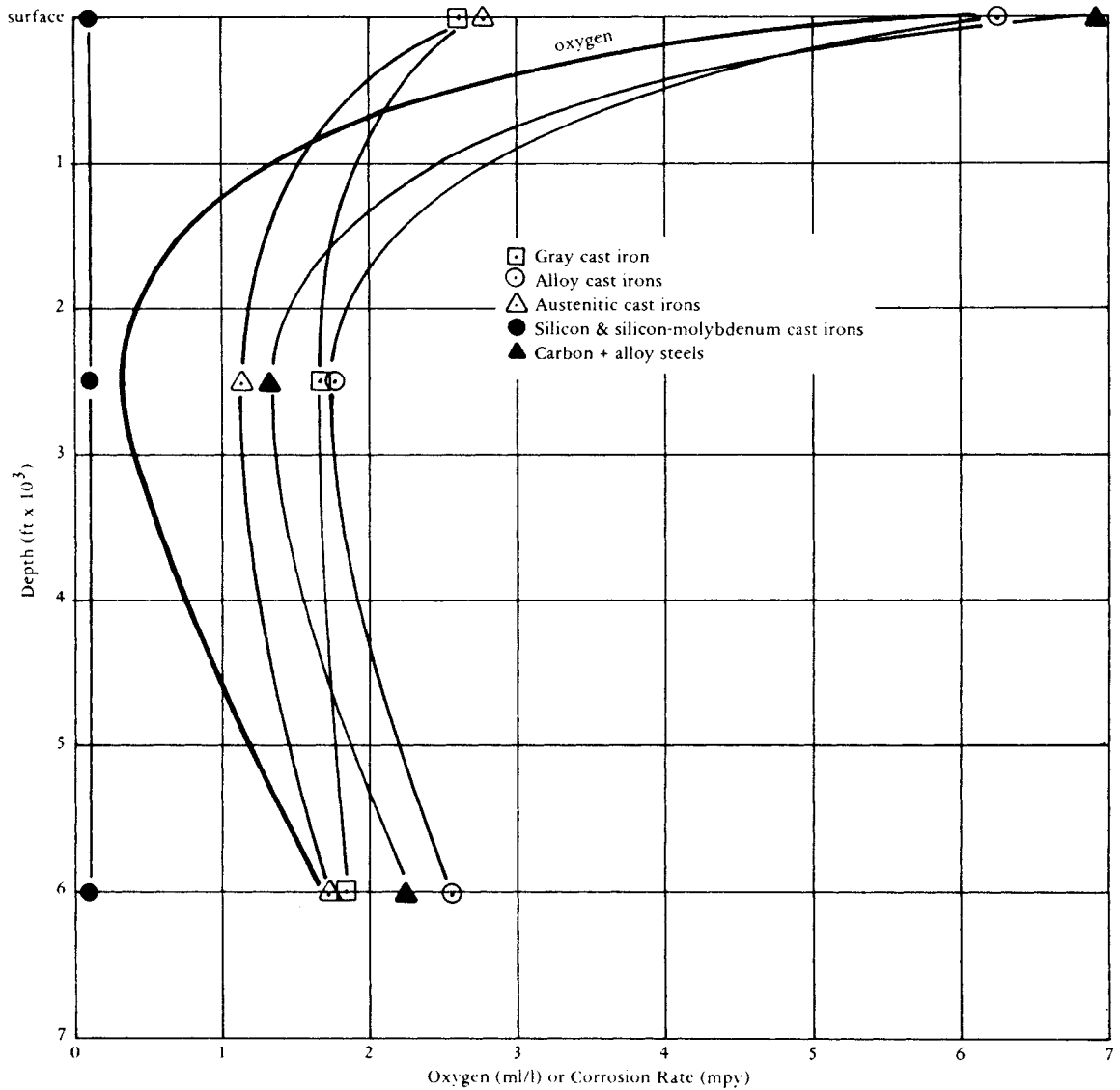


Figure 5. Effect of depth on the corrosion of steels and cast irons after 1 year of exposure in seawater.

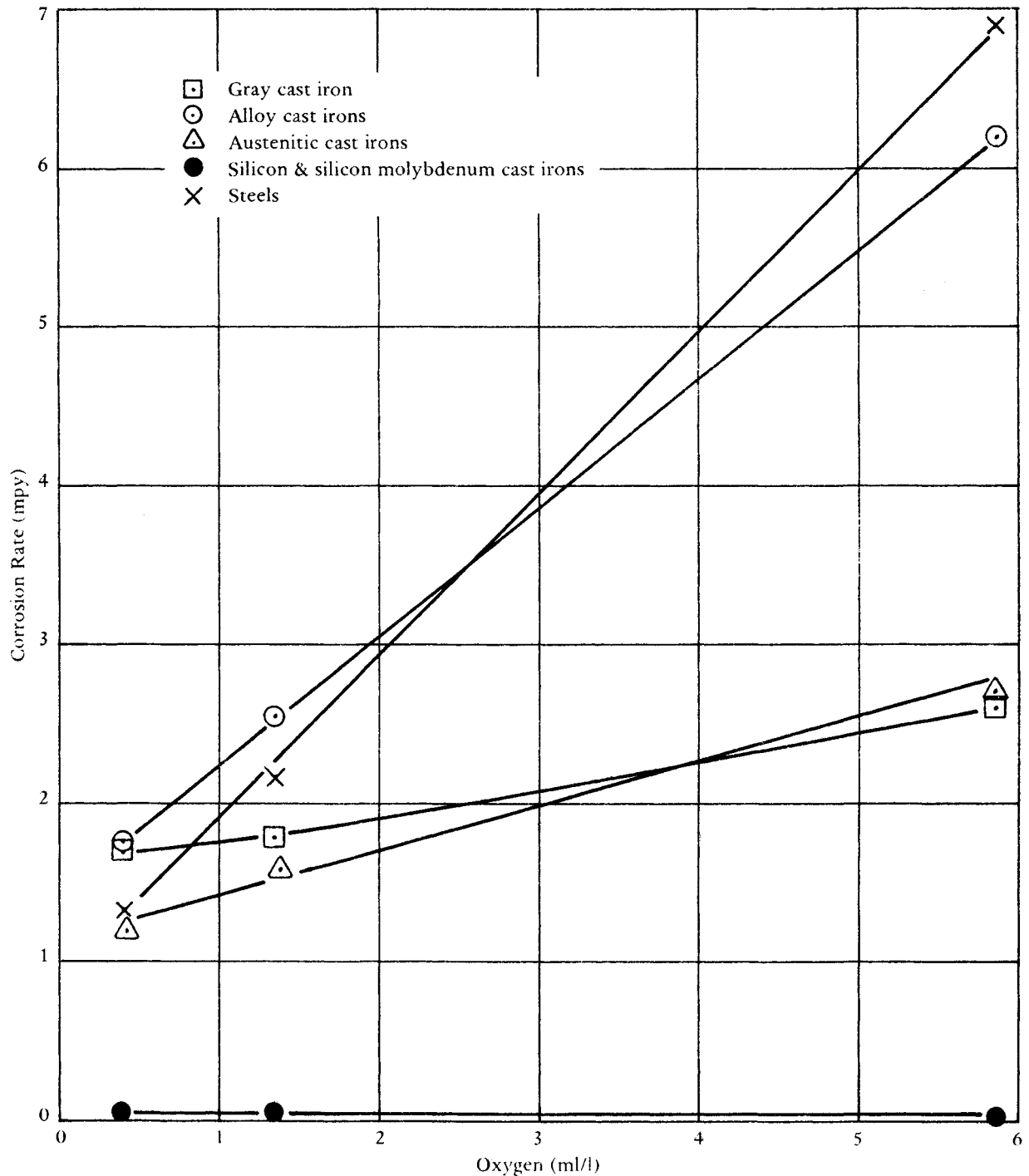


Figure 6. Effect of concentration of oxygen in seawater on the corrosion of steels and cast irons after 1 year of exposure.

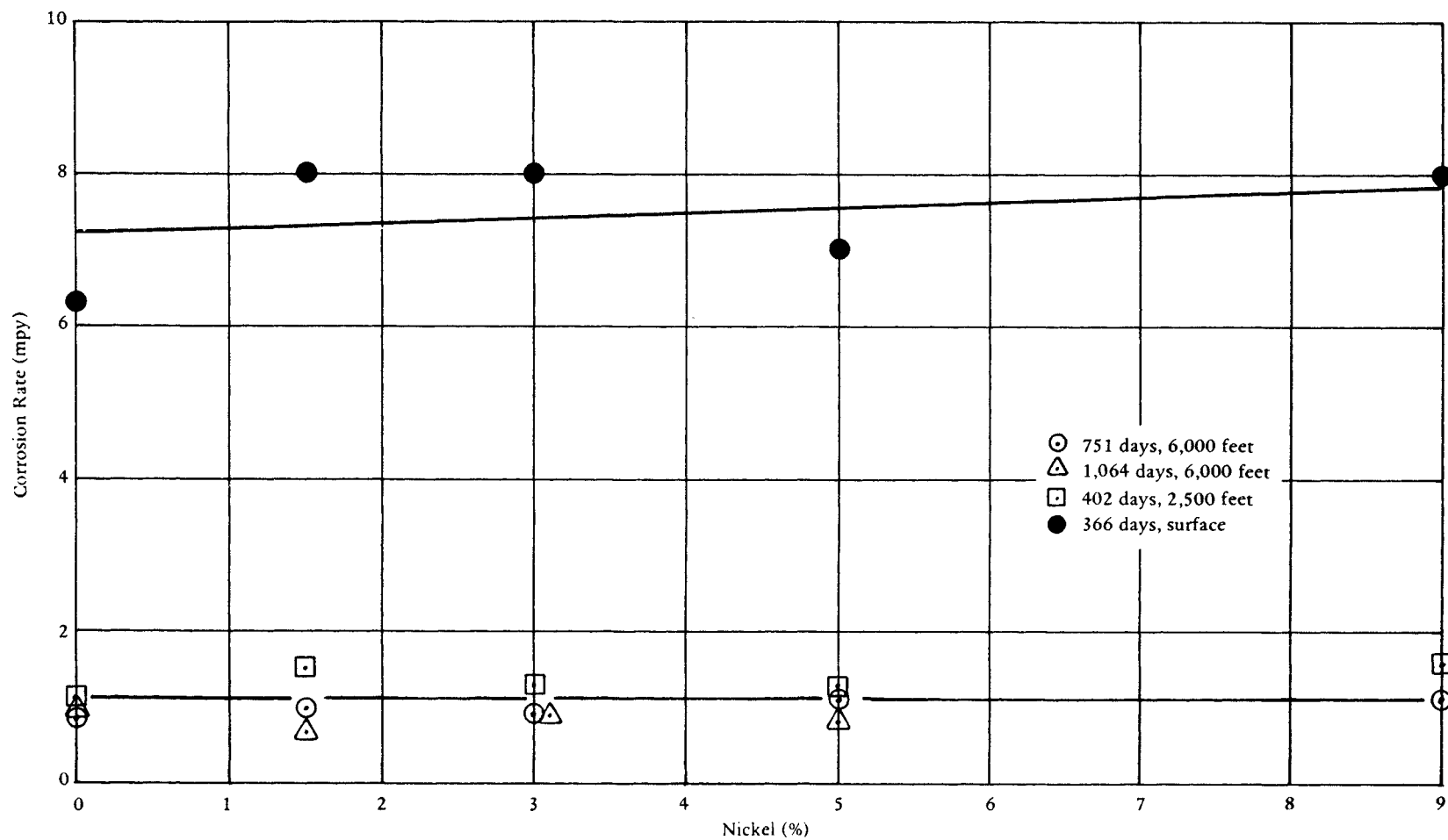


Figure 7. Effect of nickel on the corrosion of steel in seawater.

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

Alloy	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Co	Other	Source <sup>a</sup>
Wrought iron	0.02	0.06	0.13	0.01	0.13	—	—	—	—	—	2.5 slag	CEL (4)
ARMCO iron	—	0.02	—	—	—	—	—	—	—	—	—	INCO (3)
AISI 1010	0.12	0.50	0.004	0.023	0.060	—	—	—	—	—	—	CEL (4)
AISI 1010	0.11	0.52	0.016	0.024	0.048	—	—	—	—	—	—	CEL (4)
AISI 1010	—	0.34	0.01	—	0.02	0.04	0.02	—	0.03	—	—	INCO (3)
AISI 1015	—	—	—	—	—	—	—	—	—	—	—	MEL (5)
Copper steel	—	0.40	0.01	—	0.02	0.01	0.03	—	0.28	—	—	INCO (3)
ASTM A36	0.24	0.70	0.011	0.027	0.055	—	—	—	—	—	—	CEL (4)
ASTM A36	0.20	0.55	0.010	0.020	0.064	—	—	—	—	—	—	CEL (4)
ASTM A387-D	0.06	0.49	0.013	0.021	0.24	—	2.20	1.02	—	—	—	CEL (4)
Plow steel <sup>b</sup>	—	—	—	—	—	—	—	—	—	—	—	CEL (4)
HSLA No. 1 <sup>c</sup>	0.18	0.86	0.014	0.023	0.28	0.05	0.64	0.18	—	—	0.047 V 0.0028 B 0.020 Ti	CEL (4)
HSLA No. 2	0.12	0.30	0.015	0.025	0.27	2.34	1.25	0.20	0.17	—	—	CEL (4)
HSLA No. 3	0.17	0.28	0.020	0.018	0.20	2.96	1.76	0.40	—	—	—	CEL (4)
HSLA No. 3	0.10	0.28	0.014	0.010	0.25	2.91	1.59	0.52	—	—	—	CEL (4)
HSLA No. 3	—	—	—	—	—	—	—	—	—	—	—	Boeing (6)
HSLA No. 4	0.07	0.38	0.11	0.025	0.54	0.31	0.88	—	0.28	—	—	CEL (4)
HSLA No. 4	—	0.36	0.08	—	0.41	0.32	0.72	—	0.38	—	—	INCO (3)
HSLA No. 5	0.14	0.78	0.020	0.025	0.23	0.74	0.56	0.42	0.22	—	0.36 V 0.0041 B	CEL (4)
HSLA No. 5	0.20	0.83	—	0.03	—	0.38	0.54	0.21	0.45	—	0.35 V	NADC (7)
HSLA No. 5 <sup>d</sup>	—	—	—	—	—	—	—	—	—	—	—	INCO (3)
HSLA No. 6	0.26	0.13	0.007	0.008	0.01	3.07	1.43	0.97	—	—	0.07 Cb	CEL (4)
HSLA No. 6	—	—	—	—	—	—	—	—	—	—	—	Boeing (6)
HSLA No. 7	—	0.43	0.12	—	0.13	0.54	—	—	1.0	—	—	INCO (3)
HSLA No. 8	—	0.24	0.03	—	0.004	0.47	0.51	—	0.51	—	—	INCO (3)
HSLA No. 9	—	0.75	0.12	—	0.55	1.00	0.70	—	0.50	—	—	INCO (3)
HSLA No. 10	—	0.63	0.01	—	—	0.99	—	—	1.42	—	—	INCO (3)

Continued

Table 3. Continued.

Alloy	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Co	Other	Source <sup>a</sup>
HSLA No. 11	—	0.69	0.08	—	—	0.50	0.26	—	0.30	—	—	INCO (3)
HSLA No. 12	0.14	0.26	0.011	0.009	0.27	2.60	1.55	0.46	—	—	0.02 V	CEL (4)
HSLA No. 13	0.23	1.18	0.04	0.05	0.30	—	—	—	—	—	0.02 Cb + V 0.015 N	CEL (4)
HS No. 1 <sup>e</sup>	0.11	0.78	0.008	0.006	0.29	5.03	0.56	0.42	—	—	0.05 V	CEL (4)
HS No. 1A	0.12	0.84	0.003	0.005	0.32	4.91	0.56	0.48	—	—	0.07 V 0.021 Al 0.003 O 0.010 N	CEL (4)
HS No. 2	0.002	0.018	0.004	0.005	0.05	12.20	5.07	3.12	—	—	0.21 Ti 0.25 Al	CEL (4)
HS No. 2A	0.032	0.073	0.007	0.013	0.062	12.04	5.04	3.39	—	—	0.24 Ti 0.41 Al 0.008 N	USS (8)
HS No. 3	0.28	0.29	0.005	0.005	0.10	8.26	0.53	0.47	—	3.82	0.15 V	CEL (4)
HS No. 3A	0.24	0.19	0.004	0.010	0.01	8.36	0.47	0.47	—	3.90	0.06 V	CEL (4)
HS No. 4	0.11	0.38	0.006	0.013	0.27	2.76	1.23	0.30	—	—	0.10 V 0.035 Al	CEL (4)
HS No. 5	0.11	0.06	0.005	0.005	0.067	9.91	2.20	0.98	—	8.00	0.003 Al 0.001 O 0.002 N	CEL (4)
HS No. 6	0.18	0.30	0.007	0.004	0.02	9.18	0.77	1.01	0.13	4.39	0.09 V	CEL (4)
12 Ni, maraging	—	—	—	—	—	—	—	—	—	—	—	Boeing (6)
18 Ni, maraging	0.02	0.10	0.005	0.007	0.14	17.92	—	4.78	—	8.75	0.003 B 0.94 Ti 0.17 Al	CEL (4)
18 Ni, maraging	0.02	0.05	0.005	0.010	0.06	18.17	—	4.85	0.10	8.13	0.36 Ti 0.08 Al	CEL (4)
18 Ni, maraging	—	—	—	—	—	18.0	—	5.0	—	7.0	—	INCO (3)
18 Ni, maraging	—	—	—	—	—	18.0	—	4.72	—	7.85	—	NADC (7)
18 Ni, maraging	—	—	—	—	—	—	—	—	—	—	—	Boeing (6)
1.5% Ni	—	—	—	—	—	—	—	—	—	—	—	INCO (3)

Continued



Table 3. Continued.

Alloy	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Co	Other	Source <sup>a</sup>
3% Ni	—	—	—	—	—	—	—	—	—	—	—	INCO (3)
5% Ni	—	—	—	—	—	—	—	—	—	—	—	INCO (3)
9% Ni	—	—	—	—	—	—	—	—	—	—	—	INCO (3)
AISI 4130	0.29	0.42	—	—	—	—	0.90	0.18	—	—	—	NADC (7)
AISI 4140	0.42	0.87	0.016	0.032	0.24	—	0.87	0.22	—	—	—	Shell (9)
AISI 4340	0.40	0.73	0.013	0.014	0.27	1.77	0.82	0.24	—	—	—	CEL (4)
AISI 4340	0.33	0.65	—	—	—	2.0	0.73	0.26	0.11	—	—	NADC (7)
AISI 502	0.06	0.48	0.020	0.010	0.33	—	4.75	0.55	—	—	—	CEL (4)
AISI 502	0.06	0.5	—	—	—	0.4	5.2	0.5	—	—	—	INCO (3)
D6AC	0.45	—	—	—	—	0.6	1.1	1.1	—	—	0.1 V	Boeing (6)
Gray cast iron	—	—	—	—	—	—	—	—	—	—	—	INCO (3)
Ni cast iron	—	0.68	—	—	2.47	1.56	—	—	—	—	—	INCO (3)
Ni-Cr cast iron No. 1	—	0.73	—	—	1.64	1.66	0.60	—	—	—	—	INCO (3)
Ni-Cr cast iron No. 2	—	0.86	—	—	1.99	3.22	0.98	—	—	—	—	INCO (3)
Ductile cast iron No. 1	—	0.35	—	—	2.50	0.91	—	—	—	—	—	INCO (3)
Ductile cast iron No. 2	—	0.34	—	—	2.24	—	—	—	—	—	—	INCO (3)
Si cast iron	—	—	—	—	14.5	—	—	—	—	—	—	INCO (3)
Si-Mo cast iron	—	—	—	—	14.0	—	—	3.0	—	—	—	INCO (3)
Si-Mo cast iron	0.4-1.0	0.4-1.0	—	—	14-17	—	—	3.5	—	—	—	NADC (7)
Austenitic cast iron, Type 1	—	1.4	—	—	2.05	15.8	1.79	—	6.71	—	—	INCO (3)
Austenitic cast iron, Type 2	—	1.01	—	—	2.29	18.2	2.04	—	—	—	—	INCO (3)
Austenitic cast iron, Type 3	—	0.6	—	—	1.15	28.4	2.87	—	—	—	—	INCO (3)
Austenitic cast iron, Type 4	—	0.56	—	—	5.34	29.7	4.94	—	—	—	—	INCO (3)
Austenitic cast iron, Type 4	2.13	0.79	—	—	5.60	29.98	5.02	—	0.16	—	—	CEL (4)
Austenitic cast iron D-2	—	0.94	—	—	3.0	21.4	2.26	—	—	—	—	INCO (3)
Austenitic cast iron D-2b	—	0.96	—	—	2.0	20.8	3.19	—	—	—	—	INCO (3)
Austenitic cast iron D-2c	2.45	2.12	0.017	—	2.38	22.34	0.08	—	—	—	—	CEL (4)
Austenitic cast iron D-3	—	0.5	—	—	1.83	29.8	2.70	—	—	—	—	INCO (3)

Continued

Table 3. Continued.

Alloy	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Co	Other	Source <sup>a</sup>
Austenitic cast iron, hardenable	—	—	—	—	—	—	—	—	—	—	—	INCO (3)
Galvanized steel, 1 oz/ft <sup>2 f</sup>	0.15 max	0.25-0.60	0.040 max	0.050 max	—	—	—	—	—	—	—	CEL (4)
Aluminized steel, Type 2, 1.03 oz/ft <sup>2</sup>	—	—	—	—	—	—	—	—	—	—	—	CEL (4)

<sup>a</sup>Numbers refer to references at end of report.

<sup>b</sup>No composition limits.

<sup>c</sup>High-strength, low-alloy steel.

<sup>d</sup>With mill scale.

<sup>e</sup>High-strength steel.

<sup>f</sup>ASTM Specification A526-64T, 18 gage.

Table 4. Condition of the Steels, As Received

Alloy	Condition
Wrought iron	As fabricated pipe
Armco iron	Mill finish, anodically cleaned
AISI C1010	Hot rolled (mill) and pickled (laboratory)
AISI 1015	Grit blasted
ASTM A36	Hot rolled (mill) and pickled (laboratory)
ASTM A387-D	Hot rolled (mill) and pickled (laboratory)
HSLA No. 1	Water quenched from 1,650°F to 1,750°F and tempered at 1,100°F to 1,275°F (mill), blast cleaned (laboratory)
HSLA No. 2	Hot rolled and pickled
HSLA No. 3	Water quenched from 1,650°F and tempered at 1,150°F to 1,200°F (mill), blast cleaned (laboratory)
HSLA No. 4	Hot rolled (mill) and pickled (laboratory)
HSLA No. 5	Water quenched from 1,650°F to 1,750°F and tempered at 1,150°F to 1,275°F (mill), blast cleaned (laboratory)
HSLA No. 6	Consumable electrode vacuum melt, hot rolled, annealed, cleaned and oiled
HSLA No. 12	Quenched and tempered
HS No. 1	Quenched and tempered
HS No. 2	Solution annealed and aged
HS No. 3	Consumable electrode vacuum melt, hot rolled, annealed, cleaned and oiled
AISI 4130	Quenched and tempered
AISI 4140	Austenized at 1,550°F for 0.7 hr, oil quenched to room temperature, tempered at 900°F for 1 hr, air cooled to room temperature
AISI 4340 (200 ksi)	Oil quenched from 1,550°F, tempered for 1 hr at 750°F, blast cleaned (laboratory)
AISI 4340 (150 ksi)	Oil quenched from 1,550°F, tempered for 1 hr at 1,050°F, blast cleaned (laboratory)
AISI 502	Annealed and pickled, No. 1 sheet finish (mill)
18% Ni, maraging (0.202)	Electric furnace air melt, air cast, annealed, desealed and oiled

Continued

Table 4. Continued.

Alloy	Condition
18% Ni, maraging (0.082)	Electric furnace air melt, air cast, annealed, desealed and oiled (mill); CEL unwelded, aged at 900°F for 3 hr, air cooled, then welded
18% Ni, maraging	Electric furnace air melt, air cast, annealed, aged at 950°F for 3 hr, air cooled, as rolled surfaces
18% Ni, maraging	Electric furnace air melt, air cast, annealed, aged at 950°F for 3 hr, air cooled, surfaces ground to RMS-125
Austenitic cast iron, Type 4	As cast
Nodular austenitic cast iron, Type D-2c	As cast
Galvanized steel, 18 gage	1.0 oz/ft <sup>2</sup>
Aluminized steel, Type 2	Commercial quality, 1.03 oz/ft <sup>2</sup>

Table 5. Corrosion Rates of Irons and Steels

Alloy	Exposure (day)	Depth (ft)	Corrosion Rate (mpy) <sup>a</sup>		Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
			W <sup>b</sup>	M <sup>b</sup>		
Armco iron	123	5,640	3.1	2.4	U	INCO (3)
Armco iron	403	6,780	1.5	0.5 <sup>e</sup>	U	INCO (3)
Armco iron	751	5,640	0.8	0.7	G	INCO (3)
Armco iron	1,064	5,300	0.7	1.9 <sup>e</sup>	U	INCO (3)
Armco iron	197	2,340	1.9	0.9	G	INCO (3)
Armco iron	402	2,370	1.4	1.4	G	INCO (3)
Armco iron	181	5	6.9	—	U, CR <sup>f</sup>	INCO (3)
Armco iron	366	5	7.1	—	G	INCO (3)
Wrought iron	123	5,640	2.6	—	U	CEL (4)
Wrought iron	403	6,780	1.4	1.2	U	CEL (4)
Wrought iron	751	5,640	0.9	—	U	CEL (4)
Wrought iron	1,064	5,300	0.6	—	U	CEL (4)
Wrought iron	197	2,340	2.0	1.2	U	CEL (4)
Wrought iron	402	2,370	1.5	1.5	G	CEL (4)
Wrought iron	181	5	5.3	—	U	CEL (4)
Wrought iron	364	5	4.8	—	G	CEL (4)
Wrought iron	723	5	4.0	—	G	CEL (4)
Wrought iron	763	5	4.8	—	G	CEL (4)
AISI 1010	123	5,640	3.0	2.2	U	CEL (4)
AISI 1010	123	5,640	2.4	1.5	U	INCO (3)
AISI 1010	403	6,780	1.5	1.7	U	CEL (4)
AISI 1010	403	6,780	2.3	0.5	G	INCO (3)
AISI 1010	751	5,640	0.9	—	U	CEL (4)
AISI 1010	751	5,640	0.8	0.6	G	INCO (3)
AISI 1010	1,064	5,300	0.8	—	U	CEL (4)
AISI 1010	1,064	5,300	1.1	1.0	U	CEL (4)
AISI 1010	1,064	5,300	0.9	0.5	U	INCO (3)
AISI 1010	197	2,340	1.5	1.7	U	CEL (4)
AISI 1010	197	2,340	1.7	0.6	G	INCO (3)
AISI 1010	402	2,370	1.2	1.1	U	CEL (4)
AISI 1010	402	2,370	1.1	1.1	G	INCO (3)
AISI 1010	181	5	9.1	—	U	CEL (4)
AISI 1010	181	5	9.0	—	G	INCO (3)
AISI 1010	366	5	8.0	—	G	INCO (3)
AISI 1010	398	5	8.2	—	U	CEL (4)
AISI 1010	588	5	8.9	—	G	CEL (4)
AISI 1015	123	5,640	3.0	—	U	MEL (5)
AISI 1015	751	5,640	1.7	—	U	MEL (5)
AISI 1015	1,064	5,300	0.6	—	U	MEL (5)
AISI 1015 <sup>g</sup>	386	5	5.3	—	G	MEL (5)
Copper steel	123	5,640	1.9	1.6	U	INCO (3)
Copper steel	403	6,780	2.1	0.7	G	INCO (3)
Copper steel	751	5,640	1.4	0.6	G	INCO (3)
Copper steel	1,064	5,300	0.5	0.4	U	INCO (3)
Copper steel	197	2,340	2.0	0.5	G	INCO (3)
Copper steel	402	2,370	1.1	1.2	U	INCO (3)
Copper steel	181	5	9.0	—	G	INCO (3)
Copper steel	366	5	6.0	—	G	INCO (3)

Continued



Table 5. Continued

Alloy	Exposure (day)	Depth (ft)	Corrosion Rate (mpy) <sup>a</sup>		Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
			W <sup>b</sup>	M <sup>b</sup>		
ASTM A36	123	5,640	3.1	2.4	U	CEL (4)
ASTM A36	403	6,780	1.5	1.8	U	CEL (4)
ASTM A36	751	5,640	0.9	—	U	CEL (4)
ASTM A36	1,064	5,300	0.6	—	U	CEL (4)
ASTM A36	197	2,340	1.7	1.7	U	CEL (4)
ASTM A36	402	2,370	1.3	1.5	U	CEL (4)
ASTM A36	181	5	10.7	—	G, C (8)	CEL (4)
ASTM A36	398	5	6.2	—	G	CEL (4)
ASTM A36	540	5	6.3	—	G	CEL (4)
ASTM A36	588	5	5.8	—	G	CEL (4)
ASTM A387-D	123	5,640	3.0	2.3	U	CEL (4)
ASTM A387-D	403	6,780	2.0	1.9	U	CEL (4)
ASTM A387-D	751	5,640	0.9	0.9	U	CEL (4)
ASTM A387-D	197	2,340	1.8	2.0	U	CEL (4)
ASTM A387-D	402	2,370	1.3	1.3	U	CEL (4)
HSLA No. 1	123	5,640	2.9	2.2	U	CEL (4)
HSLA No. 1	403	6,780	2.0	1.2	U	CEL (4)
HSLA No. 1	751	5,640	0.9	—	U	CEL (4)
HSLA No. 1	1,064	5,300	0.6	—	U	CEL (4)
HSLA No. 1	1,064	5,300	0.6	0.7	U	CEL (4)
HSLA No. 1	197	2,340	1.4	1.4	U	CEL (4)
HSLA No. 1	402	2,370	1.0	1.0	U	CEL (4)
HSLA No. 1	181	5	9.7	—	G, P	CEL (4)
HSLA No. 1	398	5	5.2	—	G, P	CEL (4)
HSLA No. 1	588	5	4.7	—	G, P	CEL (4)
HSLA No. 2	123	5,640	4.7	4.3	U	CEL (4)
HSLA No. 2	403	6,780	2.1	2.2	U	CEL (4)
HSLA No. 2	751	5,640	0.9	—	U	CEL (4)
HSLA No. 2	1,064	5,300	0.5	—	U	CEL (4)
HSLA No. 2	197	2,340	1.4	1.4	U	CEL (4)
HSLA No. 2	197	2,340	1.1	—	G	Boeing (6)
HSLA No. 2	402	2,370	1.3	1.1	U	CEL (4)
HSLA No. 2	181	5	6.8	—	G, P	CEL (4)
HSLA No. 2	398	5	4.5	—	U, P	CEL (4)
HSLA No. 2	540	5	4.4	—	G, P	CEL (4)
HSLA No. 3	1,064	5,300	0.7	—	U	CEL (4)
HSLA No. 4	123	5,640	3.6	—	U	CEL (4)
HSLA No. 4	123	5,640	4.3	1.8	U, C (9)	INCO (3)
HSLA No. 4	403	6,780	3.3	2.3	U	CEL (4)
HSLA No. 4	403	6,780	2.1	0.4	G	INCO (3)
HSLA No. 4	751	5,640	1.2	—	U	CEL (4)
HSLA No. 4	751	5,640	0.9	0.7	G	INCO (3)
HSLA No. 4	1,064	5,300	0.3	—	U	CEL (4)
HSLA No. 4	1,064	5,300	1.1	—	U	CEL (4)
HSLA No. 4	1,064	5,300	0.6	0.6	U	INCO (3)
HSLA No. 4	197	2,340	1.4	0.9	U	CEL (4)
HSLA No. 4	197	2,340	2.2	0.7	G	INCO (3)
HSLA No. 4	402	2,370	1.1	1.1	G	CEL (4)

Continued

Table 5. Continued

Alloy	Exposure (day)	Depth (ft)	Corrosion Rate (mpy) <sup>d</sup>		Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
			W <sup>b</sup>	M <sup>b</sup>		
HSLA No. 4	402	2,370	1.3	1.0	G	INCO (3)
HSLA No. 4	181	5	11.0	—	G	INCO (3)
HSLA No. 4	366	5	8.0	—	G	INCO (3)
HSLA No. 5	123	5,640	3.1	1.6	U	CEL (4)
HSLA No. 5	123	5,640	6.0	3.5	E	INCO (3)
HSLA No. 5	403	6,780	2.7	1.8	U	CEL (4)
HSLA No. 5	403	6,780	7.4	0.2	S-E, P (3)	INCO (3)
HSLA No. 5 <sup>b</sup>	403	6,780	3.7	—	G	NADC (7)
HSLA No. 5	751	5,640	1.4	0.9	U	CEL (4)
HSLA No. 5	751	5,640	3.1	3.2	G, S-E	INCO (3)
HSLA No. 5	1,064	5,300	0.9	—	U	CEL (4)
HSLA No. 5	1,064	5,300	0.7	1.0	U	CEL (4)
HSLA No. 5	1,064	5,300	0.9	1.0	U	INCO (3)
HSLA No. 5	197	2,340	1.4	1.5	U	CEL (4)
HSLA No. 5	197	2,340	3.3	0.9	E, I-P	INCO (3)
HSLA No. 5	197	2,340	2.5	—	U	NADC (7)
HSLA No. 5	402	2,370	1.1	1.3	U	CEL (4)
HSLA No. 5	402	2,370	1.4	1.3	U, G	INCO (3)
HSLA No. 5 <sup>b</sup>	402	2,370	1.1	—	G	NADC (7)
HSLA No. 5	181	5	8.9	—	U	CEL (4)
HSLA No. 5	181	5	11.0	—	G	INCO (3)
HSLA No. 5	366	5	8.0	—	G	INCO (3)
HSLA No. 5	398	5	6.0	—	G, P	CEL (4)
HSLA No. 5	540	5	5.4	—	G, P	CEL (4)
HSLA No. 6	197	2,340	1.4	—	G	Boeing (6)
HSLA No. 6	402	2,370	0.9	0.9	U	CFL (4)
HSLA No. 7	123	5,640	3.5	2.1	C (4), U	INCO (3)
HSLA No. 7	403	6,780	1.5	0.3	G	INCO (3)
HSLA No. 7	751	5,640	0.8	1.3	G	INCO (3)
HSLA No. 7	1,064	5,300	0.8	0.6	U	INCO (3)
HSLA No. 7	197	2,340	2.3	0.6	G	INCO (3)
HSLA No. 7	402	2,370	1.4	1.1	G	INCO (3)
HSLA No. 7	181	5	11.0	—	G	INCO (3)
HSLA No. 7	366	5	8.0	—	G	INCO (3)
HSLA No. 8	123	5,640	3.8	2.3	U	INCO (3)
HSLA No. 8	403	6,780	2.3	0.3	G	INCO (3)
HSLA No. 8	751	5,640	1.2	0.8	G	INCO (3)
HSLA No. 8	1,064	5,300	0.7	0.5	U	INCO (3)
HSLA No. 8	197	2,340	1.9	0.7	G	INCO (3)
HSLA No. 9	123	5,640	4.3	2.1	C (10)	INCO (3)
HSLA No. 9	403	6,780	2.5	0.3	G	INCO (3)
HSLA No. 9	751	5,640	1.4	1.0	G	INCO (3)
HSLA No. 9	1,064	5,300	0.6	0.5	U	INCO (3)
HSLA No. 9	197	2,340	1.6	0.6	G	INCO (3)
HSLA No. 10	123	5,640	4.1	2.5	C (9), U	INCO (3)
HSLA No. 10	403	6,780	1.8	0.5	G	INCO (3)
HSLA No. 10	751	5,640	0.9	1.1	G	INCO (3)

Continued

Table 5. Continued

Alloy	Exposure (day)	Depth (ft)	Corrosion Rate (mpy) <sup>d</sup>		Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
			W <sup>b</sup>	M <sup>b</sup>		
HSLA No. 10	1,064	5,300	0.9	0.6	U	INCO (3)
HSLA No. 10	197	2,340	2.1	0.8	G	INCO (3)
HSLA No. 10	402	2,370	1.5	1.2	G	INCO (3)
HSLA No. 10	181	5	11.0	—	G	INCO (3)
HSLA No. 10	366	5	8.0	—	G	INCO (3)
HSLA No. 11	123	5,640	3.4	1.7	U	INCO (3)
HSLA No. 11	403	6,780	2.4	0.4	G	INCO (3)
HSLA No. 11	751	5,640	1.2	0.8	G	INCO (3)
HSLA No. 11	1,064	5,300	0.7	0.5	U	INCO (3)
HSLA No. 11	197	2,340	1.8	0.6	G	INCO (3)
HSLA No. 12	181	5	8.5	—	U, P	CEL (4)
HSLA No. 12	398	5	4.2	—	G, P	CEL (4)
HSLA No. 12	540	5	4.9	—	G, P	CEL (4)
HSLA No. 12	588	5	4.3	—	G, P	CEL (4)
HS No. 1	189	5,900	2.7	1.8	U	CEL (4)
HS No. 1 <sup>i</sup>	189	5,900	2.7	1.8	U	CEL (4)
HS No. 1 <sup>j, k</sup>	189	5,900	2.6	1.6	U	CEL (4)
HS No. 1	181	5	9.9	—	U	CEL (4)
HS No. 1	398	5	4.7	—	G, P	CEL (4)
HS No. 1	540	5	4.5	—	G, P	CEL (4)
HS No. 1	588	5	4.2	—	G, P	CEL (4)
HS No. 2	403	6,780	14.5 max, 9.0 avg <sup>l</sup>		P	USS (8)
HS No. 2, welded	403	6,780				
Base metal			13.5 max, 9.0 avg <sup>l</sup>		P	USS (8)
Weld metal			18.1 max, 13.5 avg <sup>l</sup>		P	USS (8)
HS No. 2	197	2,340	20.4 max, 16.7 avg <sup>l</sup>		P	USS (8)
HS No. 2, welded	197	2,340				
Base metal			29.6 max, 25.9 avg <sup>l</sup>		P	USS (8)
Weld metal			44.5 max, 38.9 avg <sup>l</sup>		P	USS (8)
HS No. 2	181	5	8.2	—	U	CEL (4)
HS No. 2	398	5	3.5	—	G, P	CEL (4)
HS No. 2	588	5	3.3	—	G, P	CEL (4)
HS No. 3	402	2,370	1.7	1.4	G	CEL (4)
HS No. 3	398	5	5.0	—	U, P	CEL (4)
HS No. 3	540	5	3.8	—	G, P	CEL (4)
HS No. 3	588	5	4.6	—	G, P	CEL (4)
HS No. 4	189	5,900	2.9	1.8	U	CEL (4)
HS No. 4 <sup>i</sup>	189	5,900	2.3	1.5	U	CEL (4)
HS No. 4 <sup>j, k</sup>	189	5,900	2.5	1.7	U, P	CEL (4)
HS No. 5	189	5,900	2.3	1.9	U	CEL (4)
HS No. 5 <sup>i</sup>	189	5,900	2.0	1.7	U	CEL (4)
HS No. 5 <sup>j</sup>	189	5,900	1.8	1.6	U	CEL (4)
HS No. 6	189	5,900	2.5	1.6	U	CEL (4)
HS No. 6 <sup>i</sup>	189	5,900	2.8	1.5	U	CEL (4)
HS No. 6 <sup>j</sup>	189	5,900	2.9	2.7	U	CEL (4)

Continued

Table 5. Continued

Alloy	Exposure (day)	Depth (ft)	Corrosion Rate (mpy) <sup>a</sup>		Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
			W <sup>b</sup>	M <sup>b</sup>		
12% Ni, maraging	197	2,340	2.4	—	G	Boeing (6)
18% Ni, maraging	123	5,640	3.6	—	U	NADC (7)
18% Ni, maraging	189	5,900	2.2	1.7	U	CEL (4)
18% Ni, maraging	403	6,780	1.6	—	U	NADC (7)
18% Ni, maraging	197	2,340	1.6	—	G	Boeing (6)
18% Ni, maraging	197	2,340	2.9	—	U	NADC (7)
18% Ni, maraging	402	2,370	1.3	—	U	NADC (7)
18% Ni, maraging	402	2,370	1.3	0.9	G	CEL (4)
18% Ni, maraging	402	2,370	1.5	0.8	G	INCO (3)
18% Ni, maraging (as rolled)	402	2,370	1.4	1.3	G	CEL (4)
18% Ni, maraging (machined)	402	2,370	1.3	1.2	G	CEL (4)
18% Ni, maraging <sup>b</sup>	402	2,370	3.5	2.6	G	CEL (4)
18% Ni, maraging <sup>b</sup>	402	2,370	2.8	1.7	G	CEL (4)
18% Ni, maraging	181	5	5.4	—	U, P	CEL (4)
18% Ni, maraging	181	5	10.0	—	P	INCO (3)
18% Ni, maraging <sup>m</sup>	181	5	5.8	—	U	CEL (4)
18% Ni, maraging <sup>b</sup>	181	5	5.1	—	U	CEL (4)
18% Ni, maraging	366	5	7.0	—	P	INCO (3)
18% Ni, maraging	398	5	3.0	—	U, P	CEL (4)
18% Ni, maraging	588	5	3.1	—	G, C, P	CEL (4)
18% Ni, maraging <sup>m</sup>	364	5	4.0	—	G, P	CEL (4)
18% Ni, maraging <sup>m</sup>	723	5	3.5	—	G, P	CEL (4)
18% Ni, maraging <sup>m</sup>	763	5	4.1	—	G	CEL (4)
18% Ni, maraging <sup>b</sup>	364	5	4.0	—	P, WB(G)	CEL (4)
18% Ni, maraging <sup>b</sup>	723	5	3.3	—	G, P	CEL (4)
18% Ni, maraging <sup>b</sup>	763	5	3.9	—	G	CEL (4)
1.5% Ni steel	123	5,640	3.5	2.7	U	INCO (3)
1.5% Ni steel	403	6,780	1.7	0.8	G	INCO (3)
1.5% Ni steel	751	5,640	1.0	0.5	G	INCO (3)
1.5% Ni steel	1,064	5,300	0.7	0.7	U	INCO (3)
1.5% Ni steel	197	2,340	1.9	0.5	U	INCO (3)
1.5% Ni steel	402	2,370	1.5	1.2	U	INCO (3)
1.5% Ni steel	181	5	11.0	—	G	INCO (3)
1.5% Ni steel	366	5	8.0	—	G	INCO (3)
3% Ni steel	123	5,640	3.4	3.0	U	INCO (3)
3% Ni steel	403	6,780	1.9	0.4	C (2), G	INCO (3)
3% Ni steel	751	5,640	0.9	0.9	G	INCO (3)
3% Ni steel	1,064	5,300	0.9	0.6	U	INCO (3)
3% Ni steel	197	2,340	1.7	0.4	G	INCO (3)
3% Ni steel	402	2,370	1.3	1.0	G	INCO (3)
3% Ni steel	181	5	11.0	—	G	INCO (3)
3% Ni steel	366	5	8.0	—	G	INCO (3)
5% Ni steel	123	5,640	2.8	2.8	U	INCO (3)
5% Ni steel	403	6,780	2.8	0.4	C (6), G	INCO (3)
5% Ni steel	751	5,640	1.1	0.8	G	INCO (3)
5% Ni steel	1,064	5,300	0.7	0.5	U	INCO (3)
5% Ni steel	197	2,340	1.7	0.4	G	INCO (3)
5% Ni steel	402	2,370	1.3	1.1	U	INCO (3)

Continued

Table 5. Continued

Alloy	Exposure (day)	Depth (ft)	Corrosion Rate (mpy) <sup>a</sup>		Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
			W <sup>b</sup>	M <sup>b</sup>		
5% Ni steel	181	5	8.0	—	G	INCO (3)
5% Ni steel	366	5	7.0	—	G	INCO (3)
9% Ni steel	123	5,640	5.6	5.6	U	INCO (3)
9% Ni steel	403	6,780	2.9	0.5	C (9), G	INCO (3)
9% Ni steel	751	5,640	1.1	4.5	G	INCO (3)
9% Ni steel	1,064	5,300	4.6	1.2	U	INCO (3)
9% Ni steel	197	2,340	1.9	0.4	G	INCO (3)
9% Ni steel	402	2,370	1.6	1.3	G	INCO (3)
9% Ni steel	181	5	10.0	—	I-P	INCO (3)
9% Ni steel	366	5	8.0	—	G	INCO (3)
AISI 4130 (100 ksi)	123	5,640	2.3	—	U	NADC (7)
AISI 4130 (160 ksi)	123	5,640	3.1	—	U	NADC (7)
AISI 4130 (100 ksi)	403	6,780	2.7	—	U	NADC (7)
AISI 4130 (100 ksi)	751	5,640	2.2	—	U	NADC (7)
AISI 4130 (100 ksi)	1,064	5,300	1.3	—	U	NADC (7)
AISI 4130 (100 ksi)	197	2,340	2.3	—	U	NADC (7)
AISI 4130 (100 ksi)	402	2,370	1.0	—	U	NADC (7)
AISI 4140	402	2,370	1.4	1.6	G, C (12)	Shell (9)
AISI 4340 (150 ksi)	123	5,640	2.7	—	U	CEL (4)
AISI 4340 (150 ksi)	403	6,780	2.2	1.7	U	CEL (4)
AISI 4340 (150 ksi)	403	6,780	2.2	1.5	U	CEL (4)
AISI 4340	403	6,780	1.6	—	U	NADC (7)
AISI 4340 (150 ksi)	751	5,640	0.8	—	U	CEL (4)
AISI 4340 (150 ksi)	197	2,340	1.9	1.3	U	CEL (4)
AISI 4340 (150 ksi)	197	2,340	1.6	1.8	U	CEL (4)
AISI 4340	197	2,340	4.1	—	U	NADC (7)
AISI 4340	402	2,370	1.0	—	U	NADC (7)
AISI 4340 (150 ksi)	402	2,370	1.2	1.3	U	CEL (4)
AISI 4340 (200 ksi)	123	5,640	2.8	—	U	CEL (4)
AISI 4340 (200 ksi)	403	6,780	2.0	1.9	U	CEL (4)
AISI 4340 (200 ksi)	403	6,780	2.0	1.8	U	CEL (4)
AISI 4340 (200 ksi)	751	5,640	0.9	—	U	CEL (4)
AISI 4340 (200 ksi)	197	2,340	1.4	1.4	U	CEL (4)
AISI 4340 (200 ksi)	197	2,340	2.1	2.2	U	CEL (4)
AISI 4340 (200 ksi)	402	2,370	1.4	1.4	U	CEL (4)
AISI 502	123	5,640	5.9	4.3	P, C (21)	CEL (4)
AISI 502	123	5,640	4.3	4.6	P (12), E, C (24)	INCO (3)
AISI 502	403	6,780	2.3	2.6	C (22)	CEL (4)
AISI 502	403	6,780	13.2	0.4	P, C (35), G	INCO (3)
AISI 502	751	5,640	2.8	—	E, C (50), P (36)	CEL (4)
AISI 502	751	5,640	4.4	2.5	C (PR)	INCO (3)
AISI 502	1,064	5,300	2.6	—	C	CEL (4)
AISI 502	1,064	5,300	1.9	1.7	P, C	CEL (4)
AISI 502	1,064	5,300	3.0	1.1	C (PR)	INCO (3)

Continued

Table 5. Continued

Alloy	Exposure (day)	Depth (ft)	Corrosion Rate (mpy) <sup>d</sup>		Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
			W <sup>b</sup>	M <sup>b</sup>		
AISI 502	197	2,340	1.4	1.2	P, C (23)	CEL (4)
AISI 502	197	2,340	3.1	0.2	E, C (20)	INCO (3)
AISI 502	402	2,370	0.8	0.6	P, C (16)	CEL (4)
AISI 502	402	2,370	3.1	0.1	P, C (PR)	INCO (3)
AISI 502	181	5	7.0	—	P (18)	CEL (4)
AISI 502	181	5	13.0	—	G	INCO (3)
AISI 502	366	5	8.0	—	G	INCO (3)
AISI 502	398	5	4.4	—	G, P (30)	CEL (4)
AISI 502	540	5	4.1	—	G, P	CEL (4)
D6AC	197	2,340	1.5	—	G	Boeing (6)
Gray cast iron	123	5,640	4.2	3.0	U	INCO (3)
Gray cast iron	403	6,780	1.8	1.3	U	INCO (3)
Gray cast iron	751	5,640	1.2	1.0	G	INCO (3)
Gray cast iron	1,064	5,300	0.8	0.5	U	INCO (3)
Gray cast iron	197	2,340	2.0	0.3	G	INCO (3)
Gray cast iron	402	2,370	1.7	2.0	U	INCO (3)
Gray cast iron	366	5	2.6	—	G	INCO (3)
Ni cast iron	123	5,640	4.4	3.4	U	INCO (3)
Ni cast iron	403	6,780	2.9	1.5	U, M	INCO (3)
Ni cast iron	751	5,640	1.4	1.1	G	INCO (3)
Ni cast iron	1,064	5,300	0.9	1.5	G	INCO (3)
Ni cast iron	197	2,340	2.2	0.3	G	INCO (3)
Ni cast iron	402	2,370	1.5	1.5	U	INCO (3)
Ni cast iron	181	5	8.5	—	U	INCO (3)
Ni cast iron	366	5	7.6	—	G	INCO (3)
Ni-Cr cast iron No. 1	123	5,640	4.3	3.3	U	INCO (3)
Ni-Cr cast iron No. 1	403	6,780	1.7	1.2	U	INCO (3)
Ni-Cr cast iron No. 1	751	5,640	1.3	0.9	G	INCO (3)
Ni-Cr cast iron No. 1	1,064	5,300	0.8	0.7	U	INCO (3)
Ni-Cr cast iron No. 1	197	2,340	1.9	0.3	G	INCO (3)
Ni-Cr cast iron No. 1	402	2,370	1.8	1.4	U	INCO (3)
Ni-Cr cast iron No. 1	181	5	6.7	—	U	INCO (3)
Ni-Cr cast iron No. 1	366	5	5.2	—	U	INCO (3)
Ni-Cr cast iron No. 2	123	5,640	4.3	3.7	U	INCO (3)
Ni-Cr cast iron No. 2	403	6,780	1.8	1.4	U	INCO (3)
Ni-Cr cast iron No. 2	751	5,640	1.3	1.1	G	INCO (3)
Ni-Cr cast iron No. 2	1,064	5,300	0.7	0.7	U	INCO (3)
Ni-Cr cast iron No. 2	197	2,340	1.9	0.3	G	INCO (3)
Ni-Cr cast iron No. 2	402	2,370	1.8	1.1	U	INCO (3)
Ni-Cr cast iron No. 2	181	5	8.5	—	U	INCO (3)
Ni-Cr cast iron No. 2	366	5	4.9	—	G	INCO (3)
Ductile cast iron No. 1	123	5,640	3.1	3.0	U	INCO (3)
Ductile cast iron No. 1	403	6,780	3.4	1.0	G	INCO (3)
Ductile cast iron No. 1	751	5,640	1.0	0.9	G	INCO (3)
Ductile cast iron No. 1	1,064	5,300	0.6	0.7	U	INCO (3)
Ductile cast iron No. 1	197	2,340	1.9	0.7	G	INCO (3)
Ductile cast iron No. 1	402	2,370	1.9	1.7	U	INCO (3)

Continued



Table 5. Continued

Alloy	Exposure (day)	Depth (ft)	Corrosion Rate (mpy) <sup>a</sup>		Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
			W <sup>b</sup>	M <sup>b</sup>		
Ductile cast iron No. 1	181	5	10.0	—	U	INCO (3)
Ductile cast iron No. 1	366	5	6.2	—	CR (24)	INCO (3)
Ductile cast iron No. 2	123	5,640	3.9	2.9	U	INCO (3)
Ductile cast iron No. 2	403	6,780	2.9	0.9	G, M	INCO (3)
Ductile cast iron No. 2	751	5,640	1.0	0.8	G	INCO (3)
Ductile cast iron No. 2	1,064	5,300	0.8	0.6	U	INCO (3)
Ductile cast iron No. 2	197	2,340	2.3	0.5	G	INCO (3)
Ductile cast iron No. 2	402	2,370	1.8	1.4	U	INCO (3)
Ductile cast iron No. 2	181	5	10.0	—	U	INCO (3)
Ductile cast iron No. 2	366	5	7.1	—	G	INCO (3)
Silicon cast iron	123	5,640	<0.1	<0.1	NC	INCO (3)
Silicon cast iron	403	6,780	<0.1	<0.1	NC	INCO (3)
Silicon cast iron	751	5,640	<0.1	<0.1	NC	INCO (3)
Silicon cast iron	1,064	5,300	<0.1	<0.1	NC	INCO (3)
Silicon cast iron	197	2,340	<0.1	<0.1	NC	INCO (3)
Silicon cast iron	402	2,370	<0.1	<0.1	NC	INCO (3)
Silicon cast iron	181	5	<0.1	—	E	INCO (3)
Silicon cast iron	366	5	<0.1	—	ET	INCO (3)
Si-Mo cast iron	123	5,640	<0.1	<0.1	NC	INCO (3)
Si-Mo cast iron	403	6,780	<0.1	<0.1	NC	INCO (3)
Si-Mo cast iron	403	6,780	0.1	—	U	NADC (7)
Si-Mo cast iron	751	5,640	<0.1	<0.1	NC	INCO (3)
Si-Mo cast iron	1,064	5,300	<0.1	<0.1	NC	INCO (3)
Si-Mo cast iron	197	2,340	<0.1	<0.1	NC	INCO (3)
Si-Mo cast iron	402	2,370	<0.1	<0.1	NC	INCO (3)
Si-Mo cast iron	402	2,370	<0.1	—	U	NADC (7)
Si-Mo cast iron	181	5	<0.1	—	NC	INCO (3)
Si-Mo cast iron	366	5	<0.1	—	ET	INCO (3)
Austenitic cast iron, Type 1	123	5,640	2.4	2.4	G	INCO (3)
Austenitic cast iron, Type 1	403	6,780	1.0	0.2	U	INCO (3)
Austenitic cast iron, Type 1	751	5,640	0.5	0.8	G	INCO (3)
Austenitic cast iron, Type 1	1,064	5,300	0.5	0.6	U	INCO (3)
Austenitic cast iron, Type 1	197	2,340	1.8	1.1	G	INCO (3)
Austenitic cast iron, Type 1	402	2,370	1.5	0.6	U	INCO (3)
Austenitic cast iron, Type 1	181	5	4.1	—	U	INCO (3)
Austenitic cast iron, Type 1	366	5	2.7	—	U	INCO (3)
Austenitic cast iron, Type 2	123	5,640	2.4	2.2	G	INCO (3)
Austenitic cast iron, Type 2	403	6,780	2.2	0.2	U	INCO (3)
Austenitic cast iron, Type 2	751	5,640	1.5	1.6	G	INCO (3)
Austenitic cast iron, Type 2	1,064	5,300	1.4	1.0	G	INCO (3)
Austenitic cast iron, Type 2	197	2,340	1.3	1.1	G	INCO (3)
Austenitic cast iron, Type 2	402	2,370	1.1	0.7	U	INCO (3)
Austenitic cast iron, Type 2	181	5	5.8	—	U	INCO (3)
Austenitic cast iron, Type 2	366	5	2.9	—	U	INCO (3)
Austenitic cast iron, Type 3	123	5,640	1.9	1.7	G	INCO (3)
Austenitic cast iron, Type 3	403	6,780	1.8	<0.1	U	INCO (3)
Austenitic cast iron, Type 3	751	5,640	1.9	1.9	G	INCO (3)

Continued

Table 5. Continued

Alloy	Exposure (day)	Depth (ft)	Corrosion Rate (mpy) <sup>d</sup>		Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
			W <sup>b</sup>	M <sup>b</sup>		
Austenitic cast iron, Type 3	1,064	5,300	1.2	0.8	U	INCO (3)
Austenitic cast iron, Type 3	197	2,340	0.8	0.7	G	INCO (3)
Austenitic cast iron, Type 3	402	2,370	0.6	0.7	U	INCO (3)
Austenitic cast iron, Type 3	181	5	5.0	—	U	INCO (3)
Austenitic cast iron, Type 3	366	5	2.8	—	U	INCO (3)
Austenitic cast iron, Type 4	123	5,640	1.8	1.6	G	INCO (3)
Austenitic cast iron, Type 4	189	5,900	2.0	1.4	U	CEL (4)
Austenitic cast iron, Type 4	403	6,780	2.0	1.3	U	INCO (3)
Austenitic cast iron, Type 4	751	5,640	1.2	1.5	G	INCO (3)
Austenitic cast iron, Type 4	1,064	5,300	0.9	0.4	U	INCO (3)
Austenitic cast iron, Type 4	197	2,340	0.8	0.4	G	INCO (3)
Austenitic cast iron, Type 4	402	2,370	0.9	0.7	G	CEL (4)
Austenitic cast iron, Type 4	402	2,370	0.8	0.3	U	INCO (3)
Austenitic cast iron, Type 4	181	5	3.8	—	U	CEL (4)
Austenitic cast iron, Type 4	181	5	3.4	—	U	INCO (3)
Austenitic cast iron, Type 4	364	5	2.4	—	G	CEL (4)
Austenitic cast iron, Type 4	366	5	2.4	—	U	INCO (3)
Austenitic cast iron, Type 4	723	5	2.0	—	G	CEL (4)
Austenitic cast iron, Type 4	763	5	2.0	—	G	CEL (4)
Austenitic cast iron, D-2	123	5,640	2.6	2.4	G	INCO (3)
Austenitic cast iron, D-2	403	6,780	1.2	0.2	U	INCO (3)
Austenitic cast iron, D-2	751	5,640	1.3	1.5	G	INCO (3)
Austenitic cast iron, D-2	1,064	5,300	1.1	0.4	U	INCO (3)
Austenitic cast iron, D-2	197	2,340	1.2	0.2	G	INCO (3)
Austenitic cast iron, D-2	402	2,370	1.1	0.5	U	INCO (3)
Austenitic cast iron, D-2	181	5	4.3	—	G	INCO (3)
Austenitic cast iron, D-2	366	5	2.4	—	G	INCO (3)
Austenitic cast iron, D-2b	123	5,640	2.1	2.0	G	INCO (3)
Austenitic cast iron, D-2b	403	6,780	1.6	0.1	U	INCO (3)
Austenitic cast iron, D-2b	751	5,640	1.2	1.3	G	INCO (3)
Austenitic cast iron, D-2b	1,064	5,300	1.0	0.4	G	INCO (3)
Austenitic cast iron, D-2b	197	2,340	1.4	0.1	G	INCO (3)
Austenitic cast iron, D-2b	402	2,370	0.9	0.6	U	INCO (3)
Austenitic cast iron, D-2b	181	5	4.1	—	G	INCO (3)
Austenitic cast iron, D-2b	366	5	2.7	—	G	INCO (3)
Austenitic cast iron, D-2c	189	5,900	3.3	1.5	U	CEL (4)
Austenitic cast iron, D-2c	402	2,370	1.8	1.2	U	CEL (4)
Austenitic cast iron, D-2c	181	5	3.9	—	U	CEL (4)
Austenitic cast iron, D-2c	364	5	3.2	—	G	CEL (4)
Austenitic cast iron, D-2c	723	5	3.1	—	U	CEL (4)
Austenitic cast iron, D-2c	763	5	2.8	—	U	CEL (4)
Austenitic cast iron, D-3	123	5,640	1.9	2.2	G	INCO (3)
Austenitic cast iron, D-3	402	6,780	2.7	0.4	G	INCO (3)
Austenitic cast iron, D-3	751	5,640	2.1	1.9	G	INCO (3)
Austenitic cast iron, D-3	1,064	5,300	1.2	0.7	U	INCO (3)
Austenitic cast iron, D-3	197	2,340	0.9	0.2	G	INCO (3)
Austenitic cast iron, D-3	402	2,370	0.7	0.5	U	INCO (3)
Austenitic cast iron, D-3	181	5	4.3	—	G	INCO (3)

Continued

Table 5. Continued

Alloy	Exposure (day)	Depth (ft)	Corrosion Rate (mpy) <sup>d</sup>		Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
			W <sup>b</sup>	M <sup>b</sup>		
Austenitic cast iron, D-3	366	5	3.2	—	G	INCO (3)
Austenitic cast iron, hardenable	123	5,640	2.5	2.8	G	INCO (3)
Austenitic cast iron, hardenable	403	6,780	1.1	0.4	U	INCO (3)
Austenitic cast iron, hardenable	751	5,640	0.7	0.7	G	INCO (3)
Austenitic cast iron, hardenable	1,064	5,300	0.6	0.7	U	INCO (3)
Austenitic cast iron, hardenable	197	2,340	2.8	0.1	G	INCO (3)
Austenitic cast iron, hardenable	402	2,370	1.8	0.5	U	INCO (3)
Austenitic cast iron, hardenable	181	5	4.2	—	U	INCO (3)
Austenitic cast iron, hardenable	366	5	2.6	—	U	INCO (3)
Galvanized steel, 1 oz/ft <sup>2</sup> <sup>n</sup>	189	5,900	1.9	1.6	U	CEL (4)
Galvanized steel, 1 oz/ft <sup>2</sup>	402	2,370	0.9	0.4	G	CEL (4)
Aluminized steel, 1 oz/ft <sup>2</sup> <sup>o</sup>	189	5,900	0.2	0.2	U	CEL (4)
Aluminized steel, 1 oz/ft <sup>2</sup> <sup>p</sup>	402	2,370	0.0	0.0	G	CEL (4)

<sup>a</sup> mpy = mils penetration per year calculated from weight loss.

<sup>b</sup> W = specimens exposed on sides of structure in seawater; M = specimens exposed in the base of the structure, partially embedded in the bottom sediment.

<sup>c</sup> Symbols signify the following types of corrosion:

C = Crevice	NC = No visible corrosion
CR = Cratering	P = Pitting
E = Edge	PR = Perforation
ET = Etched	S = Severe
G = General	U = Uniform
I = Incipient	WB = Weld bead
M = Corroded at sediment line	

Numbers after symbols refer to maximum depth in mils.

<sup>d</sup> Numbers refer to references at end of report.

<sup>e</sup> Corrosion accelerated below mud line.

<sup>f</sup> Single crater, 12 mils deep.

<sup>g</sup> Surface exposure at Francis L. LaQue Corrosion Laboratory, Wrightsville Beach, N.C.

<sup>h</sup> Welded.

<sup>i</sup> Transverse butt weld, weld bead same as plate.

<sup>j</sup> Circular weld bead, 3-in. diameter, in center of plate.

<sup>k</sup> Pitted, 154 mils maximum, 73.4 average (15 pits), water.

<sup>l</sup> Pitting rate, mpy.

<sup>m</sup> Heat treated 900°F, 3 hr, air cooled.

<sup>n</sup> Zinc coating completely gone.

<sup>o</sup> Aluminum coating 50% gone, mottled, bare steel in places.

<sup>p</sup> W = no rust, 78% aluminum coating remaining; M = no rust, 60% aluminum coating remaining.

Table 6. Inorganic Coatings on Steels

Alloy	Exposure (day)	Depth (ft)	Paint Coating	Condition After Exposure <sup>a</sup>	Source <sup>b</sup>
AISI 4130	123	5,640	Wash primer, MIL-C-8541	NPF	NADC (7)
	403	6,780	Epoxy primer, MIL-P-23377		
	1,064	5,300	Epoxy topcoat, MIL-C-22750		
	197	2,340			
	402	2,370			
AISI 4340	197	2,340	Wash primer, MIL-C-8541	NPF	NADC (7)
	402	2,370	Epoxy primer, MIL-P-23377		
			Epoxy topcoat, MIL-C-22750		
18% Ni, maraging	123	5,640	Wash primer, MIL-C-8541	NPF	NADC (7)
	403	6,780	Epoxy primer, MIL-P-23377		
	197	2,340	Epoxy topcoat, MIL-C-22750		
	402	2,370			
HSLA No. 5	197	2,340	Wash primer, MIL-C-8541 Epoxy primer, MIL-P-23377 Epoxy topcoat, MIL-C-22750	NPF	NADC (7)
HSLA No. 4	189	5,900	Zinc rich primer, 8 mils	RS	CEL (4)
HSLA No. 5	189	5,900	Zinc rich primer, 8 mils	RS	CEL (4)
HSLA No. 13	189	5,900	Zinc rich primer, 8 mils	RS	CEL (4)
HSLA No. 4	189	5,900	Wash primer, MIL-C-8514, 1 mil	NPF	CEL (4)
HSLA No. 5	189	5,900	Zinc rich primer, 8 mils	NPF	CEL (4)
HSLA No. 13	189	5,900	Epoxy topcoat, 6 mils	NPF	CEL (4)
HSLA No. 4	189	5,900	Epoxy tar primer, 8 mils	NPF	CEL (4)
HSLA No. 5	189	5,900	Epoxy tar topcoat, 8 mils	NPF	CEL (4)
HSLA No. 13	189	5,900		NPF	CEL (4)
HSLA No. 4	189	5,900	Epoxy tar primer, 8 mils	RS, IPF	CEL (4)
HSLA No. 5	189	5,900	Epoxy tar topcoat, aluminum pigmented, 8 mils	NPF	CEL (4)
HSLA No. 13	189	5,900		NPF	CEL (4)
HSLA No. 3	197	2,340	Epoxy primer, 162-Y-26, W.P. Fuller Co.	GC	Boeing (6)
HSLA No. 6	197	2,340	Topcoat, Epicote Finish 26-64, Unit	GC	Boeing (6)
12% Ni, maraging	197	2,340	Gull gray, National Lead Co.	FPP	Boeing (6)
18% Ni, maraging	197	2,340		FPP	Boeing (6)
D6AC	197	2,340		GC	Boeing (6)
HSLA No. 3	197	2,340	Polyurethane, laminar X500	PC	Boeing (6)
HSLA No. 6	197	2,340	Primer, 4-G-14, green	PB	Boeing (6)
12% Ni, maraging	197	2,340	Topcoat, 4-W-1A, white	NPF	Boeing (6)
18% Ni, maraging	197	2,340	Magna Coating and Chemical Co.	FPP	Boeing (6)
D6AC	197	2,340		GC	Boeing (6)

<sup>a</sup>Symbols signify the following:

GC = Good condition.

FPP = Few spots of paint failure.

IPF = Incipient paint failure.

NPF = No paint failure.

PC = Paint cracked.

PB = Paint blistered.

RS = Rust stains.

<sup>b</sup>Numbers indicate references at end of report.

Table 7. Stress Corrosion Tests

Alloy	Stress (ksi)	Percent Yield Strength	Exposure (day)	Depth (ft)	Number of Specimens Exposed	Number Failed	Source <sup>a</sup>
0.2% Cu steel	—	33	123	5,640	3	0	NADC (7)
0.2% Cu steel	—	45	123	5,640	3	0	NADC (7)
0.2% Cu steel	—	64	123	5,640	3	0	NADC (7)
AISI 4130	51	30	403	6,780	3	0	NADC (7)
AISI 4130, Cd plated	51	30	403	6,780	3	0	NADC (7)
AISI 4130, Ni plated	51	30	403	6,780	3	0	NADC (7)
AISI 4130, Cu plated	51	30	403	6,780	3	0	NADC (7)
AISI 4130	51	30	751	5,640	3	0	NADC (7)
AISI 4130	51	30	197	2,340	3	0	NADC (7)
AISI 4130	85	50	403	6,780	3	0	NADC (7)
AISI 4130, Cd plated	85	50	463	6,780	3	0	NADC (7)
AISI 4130, Ni plated	85	50	403	6,780	3	0	NADC (7)
AISI 4130, Cu plated	85	50	403	6,780	3	0	NADC (7)
AISI 4130	85	50	751	5,640	3	0	NADC (7)
AISI 4130	127	75	403	6,780	3	0	NADC (7)
AISI 4130, Cd plated	127	75	403	6,780	3	0	NADC (7)
AISI 4130, Ni plated	127	75	403	6,780	3	0	NADC (7)
AISI 4130, Cu plated	127	75	403	6,780	3	0	NADC (7)
AISI 4130	127	75	751	5,640	3	0	NADC (7)
AISI 4130	127	75	197	2,340	3	0	NADC (7)
AISI 4130, Cd plated	127	75	197	2,340	3	0	NADC (7)
AISI 4130, Ni plated	127	75	197	2,340	3	1	NADC (7)
AISI 4130, Cu plated	127	75	197	2,340	3	0	NADC (7)
AISI 4140	120	—	402	2,370	6	0	Shell (9)
AISI 4140, bolts	90	—	402	2,370	6	0	Shell (9)
AISI 4140, bolts	175	—	402	2,370	6	3 <sup>b</sup>	Shell (9)
AISI 4340 (150 ksi)	46	35	123	5,640	3	0	CEL (4)
AISI 4340 (150 ksi)	46	35	403	6,780	3	0	CEL (4)
AISI 4340 (150 ksi)	45	30	403	6,780	3	0	NADC (7)
AISI 4340 (150 ksi), Cd plated	45	30	403	6,780	3	0	NADC (7)
AISI 4340 (150 ksi), Ni plated	45	30	403	6,780	3	0	NADC (7)
AISI 4340 (150 ksi), Cu plated	45	30	403	6,780	3	0	NADC (7)
AISI 4340 (150 ksi)	46	35	751	5,640	3	0	CEL (4)
AISI 4340 (150 ksi)	45	30	751	5,640	3	0	NADC (7)
AISI 4340 (150 ksi)	46	35	197	2,340	3	0	CEL (4)
AISI 4340 (150 ksi)	45	30	197	2,340	3	0	NADC (7)
AISI 4340 (150 ksi)	45	30	403	2,370	3	0	NADC (7)
AISI 4340 (150 ksi), Cd plated	45	30	403	2,370	3	0	NADC (7)
AISI 4340 (150 ksi), Ni plated	45	30	403	2,370	3	0	NADC (7)
AISI 4340 (150 ksi), Cu plated	45	30	403	2,370	3	0	NADC (7)
AISI 4340 (150 ksi)	66	50	123	5,640	3	0	CEL (4)
AISI 4340 (150 ksi)	66	50	403	6,780	3	0	CEL (4)
AISI 4340 (150 ksi)	66	50	403	6,780	3	0	NADC (7)
AISI 4340 (150 ksi), Cd plated	66	50	403	6,780	3	0	NADC (7)
AISI 4340 (150 ksi), Ni plated	66	50	403	6,780	3	0	NADC (7)
AISI 4340 (150 ksi), Cu plated	66	50	403	6,780	3	0	NADC (7)
AISI 4340 (150 ksi)	66	50	751	5,640	3	0	CEL (4)
AISI 4340 (150 ksi)	66	50	751	5,640	3	0	NADC (7)
AISI 4340 (150 ksi)	66	50	197	2,340	3	0	CEL (4)

Continued

Table 7. Continued.

Alloy	Stress (ksi)	Percent Yield Strength	Exposure (day)	Depth (ft)	Number of Specimens Exposed	Number Failed	Source <sup>a</sup>
AISI 4340 (150 ksi)	66	50	402	2,370	3	0	CEL (4)
AISI 4340 (150 ksi)	66	50	402	2,370	3	0	NADC (7)
AISI 4340 (150 ksi), Cd plated	66	50	402	2,370	3	0	NADC (7)
AISI 4340 (150 ksi), Ni plated	66	50	402	2,370	3	0	NADC (7)
AISI 4340 (150 ksi), Cu plated	66	50	402	2,370	3	0	NADC (7)
AISI 4340 (150 ksi)	99	75	123	5,640	3	0	CEL (4)
AISI 4340 (150 ksi)	99	75	403	6,780	3	0	CEL (4)
AISI 4340 (150 ksi)	99	75	403	6,780	3	0	NADC (7)
AISI 4340 (150 ksi), Cd plated	99	75	403	6,780	3	0	NADC (7)
AISI 4340 (150 ksi), Ni plated	99	75	403	6,780	3	0	NADC (7)
AISI 4340 (150 ksi), Cu plated	99	75	403	6,780	3	0	NADC (7)
AISI 4340 (150 ksi)	99	75	751	5,640	3	0	CEL (4)
AISI 4340 (150 ksi)	99	75	751	5,640	3	0	NADC (7)
AISI 4340 (150 ksi)	99	75	197	2,340	3	0	CEL (4)
AISI 4340 (150 ksi)	99	75	197	2,340	3	0	NADC (7)
AISI 4340 (150 ksi), Cd plated	99	75	197	2,340	3	0	NADC (7)
AISI 4340 (150 ksi), Ni plated	99	75	197	2,340	3	0	NADC (7)
AISI 4340 (150 ksi), Cu plated	99	75	197	2,340	3	0	NADC (7)
AISI 4340 (150 ksi)	99	75	402	2,370	3	0	CEL (4)
AISI 4340 (150 ksi)	99	75	402	2,370	3	0	NADC (7)
AISI 4340 (150 ksi), Cd plated	99	75	402	2,370	3	0	NADC (7)
AISI 4340 (150 ksi), Ni plated	99	75	402	2,370	3	0	NADC (7)
AISI 4340 (150 ksi), Cu plated	99	75	402	2,370	3	0	NADC (7)
AISI 4340 (200 ksi)	65	35	123	5,640	3	0	CEL (4)
AISI 4340 (200 ksi)	65	35	403	6,780	2	0	CEL (4)
AISI 4340 (200 ksi)	65	35	751	5,640	3	0	CEL (4)
AISI 4340 (200 ksi)	65	35	197	2,340	3	0	CEL (4)
AISI 4340 (200 ksi)	93	50	123	5,640	3	0	CEL (4)
AISI 4340 (200 ksi)	93	50	403	6,780	2	0	CEL (4)
AISI 4340 (200 ksi)	93	50	751	5,640	3	0	CEL (4)
AISI 4340 (200 ksi)	93	50	197	2,340	3	0	CEL (4)
AISI 4340 (200 ksi)	93	50	402	2,370	3	0	CEL (4)
AISI 4340 (200 ksi)	139	75	123	5,640	3	0	CEL (4)
AISI 4340 (200 ksi)	139	75	403	6,780	2	0	CEL (4)
AISI 4340 (200 ksi)	139	75	751	5,640	3	0	CEL (4)
AISI 4340 (200 ksi)	139	75	197	2,340	3	0	CEL (4)
AISI 4340 (200 ksi)	139	75	402	2,370	3	0	CEL (4)
ASTM A36	20	50	402	2,370	3	0	CEL (4)
ASTM A36	30	75	402	2,370	3	0	CEL (4)
ASTM A387-D	24	50	402	2,370	3	0	CEL (4)
ASTM A387-D	37	75	402	2,370	3	0	CEL (4)
HSLA No. 1 <sup>c</sup>	38	35	197	2,340	3	0	CEL (4)
HSLA No. 1	55	50	197	2,340	3	0	CEL (4)
HSLA No. 1	55	50	402	2,370	3	0	CEL (4)
HSLA No. 1	82	75	197	2,340	3	0	CEL (4)
HSLA No. 1	82	75	402	2,370	3	0	CEL (4)
HSLA No. 4 <sup>d</sup>	—	75	189	5,900	1	0	CEL (4)

Continued



Table 7. Continued.

Alloy	Stress (ksi)	Percent Yield Strength	Exposure (day)	Depth (ft)	Number of Specimens Exposed	Number Failed	Source <sup>a</sup>
HSLA No. 4 <sup>e</sup>	—	75	189	5,900	2	0	CEL (4)
HSLA No. 4 <sup>f</sup>	—	75	189	5,900	1	0	CEL (4)
HSLA No. 5	41	35	197	2,340	3	0	CEL (4)
HSLA No. 5	59	50	197	2,340	3	0	CEL (4)
HSLA No. 5	59	50	402	2,370	3	0	CEL (4)
HSLA No. 5	89	75	197	2,340	3	0	CEL (4)
HSLA No. 5	89	75	402	2,370	3	0	CEL (4)
HSLA No. 5 <sup>d</sup>	—	75	189	5,900	2	0	CEL (4)
HSLA No. 5 <sup>e</sup>	—	75	189	5,900	2	0	CEL (4)
HSLA No. 5 <sup>f</sup>	—	75	189	5,900	1	0	CEL (4)
HSLA No. 13 <sup>d</sup>	—	75	189	5,900	2	0	CEL (4)
HSLA No. 13 <sup>e</sup>	—	75	189	5,900	2	0	CEL (4)
HSLA No. 13 <sup>f</sup>	—	75	189	5,900	1	0	CEL (4)
HS No. 3 <sup>g</sup>	86	50	189	5,900	3	0	CEL (4)
HS No. 3 <sup>b</sup>	86	50	189	5,900	3	0	CEL (4)
HS No. 3	129	75	189	5,900	3	0	CEL (4)
HS No. 3 <sup>b</sup>	129	75	189	5,900	3	0	CEL (4)
HS No. 6	96	50	189	5,900	3	0	CEL (4)
HS No. 6 <sup>b</sup>	96	50	189	5,900	3	0	CEL (4)
HS No. 6	143	75	189	5,900	3	0	CEL (4)
HS No. 6 <sup>b</sup>	143	75	189	5,900	3	0	CEL (4)
HS No. 6 <sup>i</sup>	96	50	189	5,900	3	0	CEL (4)
HS No. 6 <sup>b, i</sup>	96	50	189	5,900	3	0	CEL (4)
HS No. 6 <sup>i</sup>	143	75	189	5,900	3	0	CEL (4)
HS No. 6 <sup>b, i</sup>	143	75	189	5,900	3	0	CEL (4)
AISI 502	18	50	197	2,340	3	0	CEL (4)
AISI 502	18	50	402	2,370	3	0	CEL (4)
AISI 502	27	75	197	2,340	3	0	CEL (4)
AISI 502	27	75	402	2,370	3	0	CEL (4)
18% Ni, maraging	83	33	123	5,640	3	0	NADC (7)
18% Ni, maraging	105	42	123	5,640	3	0	NADC (7)
18% Ni, maraging	158	50	189	5,900	3	0	CEL (4)
18% Ni, maraging <sup>b</sup>	158	50	189	5,900	3	2	CEL (4)
18% Ni, maraging	237	75	189	5,900	3	3	CEL (4)
18% Ni, maraging <sup>b</sup>	237	75	189	5,900	3	3	CEL (4)
18% Ni, maraging	—	75	403	6,780	3	3	NADC (7)
18% Ni, maraging <sup>i, j</sup>	—	75	403	6,780	3	3	NADC (7)
18% Ni, maraging	—	75	751	5,640	3	0	NADC (7)
18% Ni, maraging <sup>i</sup>	70	35	197	2,340	3	0	Boeing (6)
18% Ni, maraging <sup>i</sup>	100	50	197	2,340	3	0	Boeing (6)
18% Ni, maraging <sup>i</sup>	150	75	197	2,340	3	0	Boeing (6)
18% Ni, maraging	75	30	197	2,340	3	0	NADC (7)
18% Ni, maraging	125	50	197	2,340	3	0	NADC (7)
18% Ni, maraging	188	75	197	2,340	3	0	NADC (7)
18% Ni, maraging <sup>i</sup>	75	30	197	2,340	3	0	NADC (7)
18% Ni, maraging <sup>i</sup>	125	50	197	2,340	3	0	NADC (7)
18% Ni, maraging <sup>h, j</sup>	188	75	197	2,340	3	3	NADC (7)

Continued

Table 7. Continued.

Alloy	Stress (ksi)	Percent Yield Strength	Exposure (day)	Depth (ft)	Number of Specimens Exposed	Number Failed	Source <sup>a</sup>
18% Ni, maraging, Cu plated <sup>j</sup>	188	75	197	2,340	3	0	NADC (7)
18% Ni, maraging, Ni plated <sup>j</sup>	188	75	197	2,340	3	0	NADC (7)
18% Ni, maraging	188	75	402	2,370	3	3	NADC (7)
18% Ni, maraging <sup>j</sup>	188	75	402	2,370	3	3	NADC (7)
18% Ni, maraging	109	35	402	2,370	3	0	CEL (4)
18% Ni, maraging	156	50	402	2,370	3	0	CEL (4)
18% Ni, maraging	234	75	402	2,370	3	0	CEL (4)
18% Ni, maraging <sup>j</sup>	109	35	402	2,370	3	0	CEL (4)
18% Ni, maraging <sup>j</sup>	156	50	402	2,370	3	0	CEL (4)
18% Ni, maraging <sup>j</sup>	234	75	402	2,370	3	0	CEL (4)
12% Ni, maraging	63	35	197	2,340	3	0	Boeing (6)
12% Ni, maraging	90	50	197	2,340	3	0	Boeing (6)
12% Ni, maraging	135	75	197	2,340	3	0	Boeing (6)

<sup>a</sup>Numbers refer to references at end of report.

<sup>b</sup>One specimen failed in bottom sediment, two in water.

<sup>c</sup>HSLA = high-strength, low-alloy steel.

<sup>d</sup>Zinc-rich primer, 8 mils.

<sup>e</sup>Zinc-rich primer, 8 mils plus wash primer (MIL-C-8514), 6 mils plus epoxy topcoat, 6 mils.

<sup>f</sup>Epoxy tar primer, 8 mils plus epoxy topcoat, 8 mils.

<sup>g</sup>HS = high-strength steel.

<sup>h</sup>Exposed in bottom sediment.

<sup>i</sup>TIG welded.

<sup>j</sup>Cracked at edge of heat affected zone.

Table 8. Changes in Mechanical Properties of Irons and Steels Due to Corrosion

Alloy	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>a</sup>
			Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
Wrought iron	123	5,640	47	—	30	—	15	—	CEL (4)
Wrought iron	403	6,780	47	+5	30	+2	15	+118	CEL (4)
Wrought iron	751	5,640	47	+6	30	0	15	+154	CEL (4)
Wrought iron	1,064	5,300	47	+6	30	+3	15	+113	CEL (4)
Wrought iron	197	2,340	47	—	30	—	15	—	CEL (4)
Wrought iron	402	2,370	47	+2	30	-25	15	+26	CEL (4)
Wrought iron	181	5	47	+7	30	-8	15	+17	CEL (4)
AISI 1010	123	5,640	54	-1	36	0	42	+1	CEL (4)
AISI 1010	403	6,780	54	+1	36	+6	42	-8	CEL (4)
AISI 1010	751	5,640	54	0	36	+3	42	-3	CEL (4)
AISI 1010	1,064	5,300	54	+6	36	+8	42	-5	CEL (4)
AISI 1010	197	2,340	54	+2	36	+4	42	-4	CEL (4)
AISI 1010	402	2,370	54	-2	36	-4	42	-3	CEL (4)
AISI 1010	181	5	54	+3	36	-1	42	-18	CEL (4)
ASTM A36	123	5,640	66	-1	39	+2	39	+9	CEL (4)
ASTM A36	403	6,780	66	+2	39	+4	39	-11	CEL (4)
ASTM A36	751	5,640	66	+1	39	+6	39	-11	CEL (4)
ASTM A36	1,064	5,300	66	+4	39	+4	39	+14	CEL (4)
ASTM A36	197	2,340	66	+2	39	+4	39	-1	CEL (4)
ASTM A36	402	2,370	66	+1	39	-2	39	-4	CEL (4)
ASTM A36	181	5	66	+1	39	-1	39	-19	CEL (4)
ASTM A387-D	123	5,640	76	+3	49	+4	32	-5	CEL (4)
ASTM A387-D	403	6,780	76	+6	49	+6	32	-16	CEL (4)
ASTM A387-D	751	5,640	76	+7	49	+7	32	-17	CEL (4)
ASTM A387-D	1,064	5,300	76	—	49	—	32	—	CEL (4)
ASTM A387-D	197	2,340	76	+4	49	-2	32	-10	CEL (4)
ASTM A387-D	402	2,370	76	+3	49	+6	32	-10	CEL (4)
HSLA No. 1 <sup>b</sup>	123	5,640	121	0	110	+1	12	+42	CEL (4)
HSLA No. 1	403	6,780	121	+3	110	+3	12	+32	CEL (4)
HSLA No. 1	751	5,640	121	+2	110	+4	12	+31	CEL (4)
HSLA No. 1	1,064	5,300	121	+2	110	+3	12	+32	CEL (4)
HSLA No. 1	197	2,340	121	+2	110	+2	12	+39	CEL (4)
HSLA No. 1	402	2,370	121	+1	110	-1	12	+30	CEL (4)
HSLA No. 1	181	5	121	+1	110	+1	12	+13	CEL (4)

Continued

Table 8. Continued.

Alloy	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>a</sup>
			Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
HSLA No. 2	123	5,640	100	+1	89	-2	28	-12	CEL (4)
HSLA No. 2	403	6,780	100	+4	89	-2	28	-12	CEL (4)
HSLA No. 2	751	5,640	100	+6	89	+4	28	-3	CEL (4)
HSLA No. 2	1,064	5,300	100	+6	89	+4	28	+42	CEL (4)
HSLA No. 2	197	2,340	100	+4	89	+2	28	-9	CEL (4)
HSLA No. 2	402	2,370	100	+2	89	-3	28	-11	CEL (4)
HSLA No. 2	181	5	100	+1	89	+3	28	0	CEL (4)
HSLA No. 3	1,064	5,300	107	+10	88	+4	30	+33	CEL (4)
HSLA No. 4	123	5,640	70	+5	52	+7	32	+24	CEL (4)
HSLA No. 4	403	6,780	70	+4	52	+4	32	+40	CEL (4)
HSLA No. 4	751	5,640	70	+4	52	+7	32	+18	CEL (4)
HSLA No. 4	1,064	5,300	70	+5	52	+6	32	+20	CEL (4)
HSLA No. 4	197	2,340	70	+6	52	+8	32	+36	CEL (4)
HSLA No. 4	402	2,370	70	+3	52	-2	32	-33	CEL (4)
HSLA No. 5	123	5,640	125	+1	118	+2	16	-1	CEL (4)
HSLA No. 5	403	6,780	125	+4	118	+5	16	-11	CEL (4)
HSLA No. 5	751	5,640	125	+6	118	+5	16	-6	CEL (4)
HSLA No. 5	1,064	5,300	125	+6	118	+6	16	-2	CEL (4)
HSLA No. 5	197	2,340	125	+2	118	+2	16	+2	CEL (4)
HSLA No. 5	197	2,340	105	0	123	0	17	-2	NADC (7)
HSLA No. 5	402	2,370	125	+3	118	+4	16	-3	CEL (4)
HSLA No. 5	402	2,370	123	0	105	+12	17	-2	NADC (7)
HSLA No. 5 <sup>c</sup>	402	2,370	123	-1	105	0	17	-77	NADC (7)
HSLA No. 5 <sup>d</sup>	402	2,370	123	+7	105	+13	17	-82	NADC (7)
HSLA No. 5 <sup>e</sup>	402	2,370	123	+3	105	+17	17	-4	NADC (7)
HSLA No. 5 <sup>f</sup>	402	2,370	123	-1	105	+10	17	-2	NADC (7)
HSLA No. 5 <sup>g</sup>	402	2,370	123	-5	105	+4	17	-29	NADC (7)
HSLA No. 6	402	2,370	131	+2	117	-1	16	-10	CEL (4)
HSLA No. 12	181	5	120	0	109	-2	26	+4	CEL (4)
HS No. 1 <sup>b</sup>	181	5	145	-2	140	-3	22	+7	CEL (4)
HS No. 2	181	5	194	-4	186	-5	15	+5	CEL (4)
HS No. 3	402	2,370	169	0	118	-6	14	+8	CEL (4)

Continued

Table 8. Continued.

Alloy	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>a</sup>
			Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
AISI 4130	123	5,640	91	-22	63	-30	30	-13	NADC (7)
AISI 4130	123	5,640	169	-44	—	—	11	0	NADC (7)
AISI 4130	403	6,780	169	0	148	-7	11	-41	NADC (7)
AISI 4130	751	5,640	91	-23	63	-34	30	-22	NADC (7)
AISI 4130	1,064	5,300	91	-27	63	-37	—	-31	NADC (7)
AISI 4130	197	2,340	91	0	63	0	30	-11	NADC (7)
AISI 4130	402	2,370	169	+7	148	-35	11	-41	NADC (7)
AISI 4130	402	2,370	91	-3	63	+43	30	-36	NADC (7)
AISI 4130 <sup>e</sup>	402	2,370	91	-17	63	-21	30	-14	NADC (7)
AISI 4130 <sup>f</sup>	402	2,370	91	-17	63	-23	30	-26	NADC (7)
AISI 4130 <sup>g</sup>	402	2,370	91	-17	63	+6	—	—	NADC (7)
AISI 4340	123	5,640	201	+4	185	+5	8	+43	CEL (4)
AISI 4340	123	5,640	143	+3	132	+4	13	+28	CEL (4)
AISI 4340	402	6,780	201	+4	185	+3	8	+25	CEL (4)
AISI 4340	402	6,780	209	+1	190	+1	8	-2	CEL (4)
AISI 4340	402	6,780	143	-1	132	-3	13	+27	CEL (4)
AISI 4340	402	6,780	147	0	136	-1	14	-6	CEL (4)
AISI 4340	751	5,640	201	+3	185	+10	8	+30	CEL (4)
AISI 4340	751	5,640	143	+3	132	+3	13	+28	CEL (4)
AISI 4340	197	2,340	201	+3	185	+5	8	+49	CEL (4)
AISI 4340	197	2,340	209	-2	190	-1	8	+11	CEL (4)
AISI 4340	197	2,340	143	+5	132	+4	13	+29	CEL (4)
AISI 4340	197	2,340	147	0	136	0	14	-3	CEL (4)
AISI 4340	197	2,340	293	-37	213	-19	9	0	NADC (7)
AISI 4340	402	2,370	209	-2	190	0	8	+3	CEL (4)
AISI 4340	402	2,370	147	-2	136	-3	14	-5	CEL (4)
AISI 4340	402	2,370	200	+1	184	+1	9	—	NADC (7)
AISI 4340 <sup>e</sup>	402	2,370	200	-18	184	-14	9	-27	NADC (7)
AISI 4340 <sup>f</sup>	402	2,370	200	-29	184	—	9	-48	NADC (7)
AISI 4340 <sup>g</sup>	402	2,370	200	-40	184	—	9	-73	NADC (7)
AISI 502	123	5,640	59	-2	36	+5	33	-34	CEL (4)
AISI 502	403	6,780	59	-5	36	+1	33	-17	CEL (4)
AISI 502	751	5,640	59	-8	36	+6	33	-38	CEL (4)
AISI 502	1,064	5,300	59	-3	36	+3	33	-38	CEL (4)
AISI 502	197	2,340	59	-1	36	-4	33	-2	CEL (4)

Continued

Table 8. Continued.

Alloy	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>a</sup>
			Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
AISI 502	402	2,370	59	-1	36	+4	33	-13	CEL (4)
AISI 502	181	5	59	+5	36	0	33	-29	CEL (4)
18 Ni, maraging	123	5,640	245	-38	—	—	5	+122	NADC (7)
18 Ni, maraging	1,064	5,300	245	+8	241	+8	5	-31	NADC (7)
18 Ni, maraging	197	2,340	245	-24	241	-24	5	-2	NADC (7)
18 Ni, maraging	402	2,370	245	-13	241	-15	5	-64	NADC (7)
18 Ni, maraging <sup>i</sup>	402	2,370	321	-6	315	—	3	-16	CEL (4)
18 Ni, maraging <sup>j</sup>	402	2,370	170	-6	151	-1	8	-51	CEL (4)
18 Ni, maraging <sup>j</sup>	402	2,370	254	+6	236	+2	7	+16	CEL (4)
18 Ni, maraging <sup>k</sup>	402	2,370	252	+7	239	+8	7	+4	CEL (4)
Austenitic cast iron, Type 4	402	2,370	23	-4	20	-8	2	-35	CEL (4)
Austenitic cast iron, Type 4	181	5	23	+11	20	+7	2	+30	CEL (4)
Austenitic cast iron, Type D-2C	402	2,370	47	-38	42	-56	5	-36	CEL (4)
Austenitic cast iron, Type D-2C	181	5	47	-18	42	-8	5	-34	CEL (4)
Galvanized steel, 1 oz/ft <sup>2</sup>	402	2,370	49	+3	40	0	38	-6	CEL (4)
Aluminized steel, 1 oz/ft <sup>2</sup>	402	2,370	51	-2	38	-7	28	+3	CEL (4)

<sup>a</sup>Numbers refer to references at end of report.<sup>b</sup>HSLA = high-strength, low-alloy steel.<sup>c</sup>1/4-in. thick.<sup>d</sup>1/8-in. thick.<sup>e</sup>Cadmium plated.<sup>f</sup>Copper plated.<sup>g</sup>Nickel plated.<sup>h</sup>HS = high-strength steel.<sup>i</sup>Welded.<sup>j</sup>Machined, RMS 125.<sup>k</sup>As rolled.



Table 9. Effect of Corrosion on Breaking Strengths of Anchor Chains

(chains degreased, 0.75-inch size)

Designation	Exposure		Breaking Load (lb)		Remarks
	Days	Depth	Original	Final	
Dilok	123	5,640	59,000	58,500	Thin film flaky rust, broke at bottom of socket
Dilok	403	6,780	59,000	64,500	Thin film flaky rust, broke at bottom of socket
Dilok	751	5,640	59,000	71,000	Thin film flaky rust, broke at bottom of socket
Dilok	197	2,340	59,000	76,500	Thin film flaky rust, broke at end of link
Welded stud link	123	5,640	57,500	61,500	Thin film flaky rust, broke at end of link
Welded stud link	403	6,780	57,500	59,500	Thin film flaky rust, broke at end of link
Welded stud link	751	5,640	57,500	59,500	Thin film flaky rust, broke at end of link
Welded stud link	197	2,340	57,500	61,000	Thin film flaky rust, broke at end of link

## COPPER ALLOYS

The excellent corrosion resistance of copper and its alloys is partially due to its being a relatively noble metal. However, in many environments, its satisfactory performance depends on the formation of adherent, relatively thin films of corrosion products. In seawater corrosion, resistance depends on the presence of a surface oxide film through which oxygen must diffuse in order for corrosion to continue. This oxide film adjoining the metal is cuprous oxide covered with a mixture of cupric oxy-chloride, cupric hydroxide, basic cupric carbonate, and calcium sulfate. Since oxygen must diffuse through this film for corrosion to occur, it would be expected that under normal circumstances the corrosion rates would decrease with increase in time of exposure.

Copper alloys corrode uniformly; hence, corrosion rates calculated from weight losses and reported as mils per year reflect the true condition of the alloys. Therefore, corrosion rates for the copper alloys can be used reliably for design purposes. However, this does not apply to those copper base alloys which are susceptible to parting corrosion. (Parting corrosion is defined as the selective attack of one or more of the components of a solid solution alloy.) Examples of parting corrosion are dezincification, dealuminification, denickelification, desiliconification, etc.

The data on the copper alloys were obtained from the reports given in References 3 through 19 and 23. The copper alloys are separated into the different classes of copper alloys (coppers, brasses, bronzes, and copper-nickel alloys) for comparison and discussion purposes.

The chemical compositions, corrosion rates and types of corrosion, stress corrosion characteristics, and changes in mechanical properties due to corrosion of the coppers are given in Tables 10 through 13. The effects of duration of exposure are shown graphically in Figures 8 and 15.

The chemical compositions, corrosion rates and types of corrosion, stress corrosion characteristics, and changes in mechanical properties due to the corrosion of the brasses are given in Tables 14 through 17. The effects of the duration of exposure are shown graphically in Figures 11 and 15.

The chemical compositions, corrosion rates and types of corrosion, stress corrosion characteristics, and changes in mechanical properties due to corrosion of the bronzes are given in Tables 18 through 21. The effects of the duration of exposure are shown graphically in Figures 12 and 15.

The chemical compositions, corrosion rates and types of corrosion, stress corrosion characteristics, and changes in mechanical properties due to corrosion of the copper-nickel alloys are given in Tables 22 through 25. The effects of the duration of exposure are shown graphically in Figures 13 and 15.

The effects of depth and the effect of the concentration of oxygen in seawater on the corrosion of the copper alloys are shown in Figures 9 and 14.

The effect of the iron content on the corrosion of the copper-nickel alloys is shown in Figure 14.

## 3.1. COPPERS

The chemical compositions of the coppers are given in Table 10, their corrosion rates and types of corrosion in Table 11, their resistance to stress corrosion cracking in Table 12, and the changes in their mechanical properties due to corrosion in Table 13.

## 3.1.1. Duration of Exposure

The effects of the duration of exposure on the corrosion of copper in seawater at depth, at the surface, and in the bottom sediments are shown graphically in Figure 8. At the surface and at the 6,000-foot depth, both in the seawater and in the bottom sediment, the corrosion rates decreased with increasing duration of exposure. At the 2,500-foot depth the corrosion rates in the seawater and in the bottom sediment were essentially constant. Also, the corrosion rates were practically the same at depth as at the surface.

The beryllium-copper alloys behaved very similarly to copper, and their corrosion rates were comparable. Beryllium-copper chain corroded at the

same rates and in the same manner as the alloy in sheet form. Welding by either the TIG or MIG processes as well as aging at either 600°F or 800°F did not affect the corrosion behavior of the beryllium-copper alloys.

### 3.1.2. Effect of Depth

The effect of depth on the corrosion of copper is shown in Figure 9. The corrosion of copper was not affected by depth, at least to a depth of 6,000 feet.

### 3.1.3. Effect of Concentration of Oxygen

The effect of the concentration of oxygen in seawater on the corrosion of copper is shown in Figure 10. The corrosion of copper was unaffected by the concentration of oxygen in seawater within the range of 0.4 to 5.75 ppm.

### 3.1.4. Stress Corrosion

Copper and beryllium-coppers were exposed in the seawater while stressed at values equivalent to 30 and 75% of their respective yield strengths for the periods of time and at the depths shown in Table 12. Neither copper nor the beryllium-coppers were susceptible to stress corrosion. Aging at either 600°F or 800°F did not affect the stress corrosion resistance of beryllium-copper (CDA No. 172).

### 3.1.5. Mechanical Properties

The effects of exposure in seawater on their mechanical properties are given in Table 13. The mechanical properties of the copper and the beryllium-coppers were not significantly affected by exposure in seawater at the surface or at depth.

### 3.1.6. Galvanic Corrosion

Dissimilar metal couples consisting of 1 x 2-inch strips of aluminum alloy 7075-T6 fastened to 1 x 6-inch strips of beryllium-copper alloy (CDA No. 175) with plastic fasteners were exposed in seawater at a depth of 2,500 feet for 402 days. After exposure the 7075-T6 was covered with a heavy uniform layer of corrosion products, while there was a thin layer of

corrosion products on the CDA No. 175 alloy. This indicates that the aluminum was corroding galvanically to protect the beryllium-copper from corroding.

## 3.2. BRASSES (Copper-Zinc Alloys)

The chemical compositions of the brasses are given in Table 14, their corrosion rates and types of corrosion in Table 15, their resistance to stress corrosion cracking in Table 16, and the changes in their mechanical properties due to corrosion in Table 17.

### 3.2.1. Duration of Exposure

The effects of the duration of exposure on the corrosion of the brasses in seawater at depth, at the surface, and in the bottom sediments are shown in Figure 11.

Since the corrosion rates of all the brasses, except those of alloys, CDA No. 280 and 675, were so comparable, the average values for any one time, depth, or environment were used to prepare the curves in Figure 11. The corrosion rate values of alloys CDA No. 280 (Muntz Metal) and CDA No. 675 (manganese bronze A) were considerably higher than those of all the other brasses. These high rates were attributed to the severe parting corrosion (dezincification) which had occurred on these two alloys.

The curves in Figure 11 show the effects of the duration of exposure on the corrosion of the brasses in seawater. The corrosion rates of the brasses decreased slightly with increasing duration of exposure at the surface and at depths of 2,500 and 6,000 feet both in seawater and in the bottom sediments. The corrosion of the brasses was the same in the bottom sediments as in the seawater at the 6,000-foot depth, but slower in the bottom sediments than in the seawater at the 2,500-foot depth. The corrosion in seawater was practically the same at the 2,500-foot depth as at the 6,000-foot depth. The brasses corroded slightly slower at depth than at the surface.

### 3.2.2. Parting Corrosion (Dezincification)

The alloys attacked by parting corrosion are shown in Table 15. All the brasses, except Arsenical

Admiralty (CDA No. 443), aluminum brass, and nickel brass, were attacked by parting corrosion in degrees varying from slight to severe. The zinc content varied from 10 to 42% with the severity of parting corrosion generally increasing with the zinc content. Although the Arsenical Admiralty contained about 30% zinc, the addition of about 0.03% arsenic rendered it immune to parting corrosion. Because of the 2% aluminum in aluminum brass and the 8% nickel in the nickel brass, they were also immune to parting corrosion even though they contained 20 and 40% zinc, respectively.

### 3.2.3. Effect of Depth

The effect of depth on the corrosion of the brasses after 1 year of exposure in seawater is shown in Figure 9. Although there was a slight tendency for the brasses to corrode more slowly at depth than at the surface, this slight decrease is not significant.

### 3.2.4. Effect of Concentration of Oxygen

The effect of the concentration of oxygen in seawater on the corrosion of the brasses after 1 year of exposure is shown in Figure 10. The corrosion of the brasses increased linearly, but slightly, with increasing oxygen concentration.

### 3.2.5. Stress Corrosion

Two brasses, CDA No. 280 and 443, were exposed in seawater while stressed at values equivalent to 50 and 75% of their respective yield strengths for the periods of time and at the depths given in Table 16. Neither alloy was susceptible to stress corrosion at either depth, 2,500 or 6,000 feet, after 400 days of exposure.

### 3.2.6. Mechanical Properties

The effects of corrosion on the mechanical properties of three brasses are given in Table 17. The mechanical properties of Arsenical Admiralty were not impaired, while those of Muntz Metal and nickel-manganese bronze were impaired. The degree of impairment increased with the time of exposure at both depths, 2,500 and 6,000 feet. The degree of

impairment in both alloys roughly paralleled the severity of the parting corrosion.

### 3.2.7. Corrosion Products

The corrosion products which formed on cast nickel-manganese bronze during 403 days of exposure at a depth of 6,000 feet were analyzed by X-ray diffraction, spectrographic, infra-red spectrophotometer, and quantitative analyses methods. The corrosion products were composed of cupric chloride ( $\text{CuCl}_2 \cdot 2\text{H}_2\text{O}$ ); copper hydroxychloride ( $\text{Cu}_2(\text{OH})_3\text{Cl}$ ); copper as metal, 35.98%; minor amounts of aluminum, iron, silicon, and sodium; chloride ions as  $\text{Cl}$ , 0.91%; sulfate ions as  $\text{SO}_4$ , 11.53%; small quantities of an organic compound or compounds present due to decomposed algae and vegetative materials.

## 3.3. BRONZES

The chemical compositions of the bronzes are given in Table 18, their corrosion rates and types of corrosion in Table 19, their resistance to stress corrosion in Table 20, and the changes in their mechanical properties due to corrosion in Table 21.

### 3.3.1. Duration of Exposure

The effects of the duration of exposure on the corrosion of the bronzes in seawater at depths, at the surface, and in the bottom sediments are shown in Figure 12.

Since the corrosion rates of all the bronzes, except those of alloys CDA No. 653 and 655 (silicon bronzes), were so comparable, the average values for any one time, depth, or environment were used to prepare the curves in Figure 12. Because the corrosion rates of the silicon bronzes were so much greater than those of the other bronzes, they were not averaged with the others. They are shown in Figure 12 as a separate curve that includes the rates for both depths as well as those for the surface. The average corrosion of the bronzes in seawater and in the bottom sediments was essentially constant with increasing duration of exposure. Also, it was essentially the same at the 2,500-foot depth as at the

6,000-foot depth, both in the seawater and in the bottom sediments. The corrosion of the silicon bronzes was greater than that of the other bronzes at depth and at the surface; it decreased with increasing duration of exposure until it was the same as the other bronzes after 1,064 days of exposure. The average corrosion of the bronzes in surface seawater was greater than at depth, and it decreased with increasing duration of exposure.

### 3.3.2. Parting Corrosion

Parting corrosion was found on all the aluminum bronzes (dealuminification) and on the silicon bronzes (coppering) as shown in Table 19. The parting corrosion was most severe on the cast alloy containing 10, 11, and 13% aluminum. There was much less on the wrought aluminum bronzes with there being very few cases of slight attack on the alloy containing 5% aluminum and more cases on the alloy containing 7% aluminum. The parting corrosion on the silicon bronzes occurred only occasionally, but its rating varied from slight to severe.

### 3.3.3. Effect of Depth

The effect of depth on the corrosion of the bronzes after 1 year of exposure in seawater is shown in Figure 9. The bronzes corroded slightly slower at depth than at the surface, but the difference was not considered to be significant. For practical purposes depth does not influence the corrosion of the bronzes.

### 3.3.4. Effect of Concentration of Oxygen

The effect of the concentration of oxygen in seawater on the corrosion of the bronzes after 1 year of exposure is shown in Figure 10. The corrosion of the bronzes increased linearly, but slightly, with increasing oxygen concentration, and at 5.75 ml/l oxygen they were corroding at the same rate as copper and other copper alloys.

### 3.3.5. Stress Corrosion

Four bronzes, phosphor bronze A, phosphor bronze D, aluminum bronze 5%, and silicon bronze A, were exposed in seawater to determine their

susceptibility to stress corrosion. They were stressed at values equivalent to 35, 50, and 75% of their respective yield strengths as shown in Table 20. They were not susceptible to stress corrosion for periods of exposure of 400 days at either depth.

### 3.3.6. Mechanical Properties

The effects of corrosion on the mechanical properties of four bronzes are given in Table 21. The mechanical properties of the phosphor bronzes A and D were not affected by exposures at depth. The decreases (12, 27, and 29%) in the elongation of the aluminum bronze were attributed to parting corrosion. Also, the decrease in the mechanical properties of silicon bronze A after 403 days of exposure in the bottom sediments at a depth of 6,000 feet was attributed to parting corrosion.

### 3.3.7. Corrosion Products

Chemical analyses of the corrosion products removed from aluminum bronze showed the presence of copper oxy-chloride, cupric chloride; major elements, copper and aluminum; minor elements, iron, magnesium, calcium, and silicon; chloride ion, 0.9%, and sulfate ion, 9.0%.

## 3.4. COPPER-NICKEL ALLOYS

The chemical compositions of the copper-nickel alloys are given in Table 22, their corrosion rates and type of corrosion in Table 23, their resistance to stress corrosion in Table 24, and the changes in their mechanical properties due to corrosion in Table 25.

### 3.4.1. Duration of Exposure

The effects of the duration of exposure on the corrosion of the copper-nickel alloys in seawater at depths, at the surface, and in the bottom sediments are shown in Figure 13.

Because the corrosion rates of all the copper-nickel alloys were comparable, average values for any one time, depth, or environment were used to construct the curves in Figure 13. The average corrosion at the surface and at the 6,000-foot depth, both in seawater and in the bottom sediments, decreased

linearly with increasing duration of exposure, while corrosion attack was constant in seawater and in the bottom sediments with increasing duration of exposure at the 2,500-foot depth. Corrosion at the 2,500-foot depth was slightly less rapid than at the surface or the 6,000-foot depth. Corrosion in surface seawater decreased at a more rapid rate than at depth. The differences in the corrosion rates of the copper-nickel alloys in the different environments were so small that, for practical purposes, they can be considered to be the same.

### 3.4.2. Effect of Depth

The effect of depth on the corrosion of the copper-nickel alloys after 1 year of exposure in seawater is shown in Figure 9. Depth exerted no influence on the corrosion of the copper-nickel alloys during 1 year of exposure, at least to a depth of 6,000 feet.

### 3.4.3. Effect of Concentration of Oxygen

The effect of the concentration of oxygen in seawater on the corrosion of the copper-nickel alloys after 1 year of exposure is shown in Figure 10. The corrosion increased slightly with increasing oxygen concentration during 1 year of exposure.

### 3.4.4. Effect of Iron

Copper-nickel alloys with iron contents varying between 0.03 and 5% were among the alloys in this program. The effects of iron on the corrosion of these alloys after 400 days and 1,064 days of exposure at the 6,000-foot depth are shown in Figure 14. Generally, the rates of corrosion decreased with increasing iron content.

### 3.4.5. Stress Corrosion

Four copper-nickel alloys were exposed in seawater to determine their susceptibility to stress corrosion under the conditions given in Table 24. They were not susceptible to stress corrosion.

### 3.4.6. Mechanical Properties

The effects of corrosion on the mechanical properties of five copper-nickel alloys are given in Table

25. The mechanical properties were not adversely affected during exposure at the depths and during the times of exposure given in Table 25.

### 3.4.7. Corrosion Products

Chemical analyses of the corrosion products removed from 70% copper-30% nickel-5% iron exposed for 751 days at a depth of 6,000 feet showed that they were composed of nickel hydroxide ( $\text{Ni}(\text{OH})_2$ ); cupric chloride ( $\text{CuCl}_2$ ); major elements, copper and nickel; minor elements, iron, magnesium, sodium, and traces of silicon, and manganese; chloride ion as  $\text{Cl}$ , 4.77%; sulfate ions as  $\text{SO}_4$ , 0.80%; copper as metal, 43.63%.

## 3.5. ALL COPPER ALLOYS

The effects of the duration of exposure on the corrosion of all the copper alloys in seawater at the surface and at the 6,000-foot depth are summarized in Figure 15. Their rates of corrosion decreased essentially linearly with increasing duration of exposure. Their rates were also comparable and were essentially the same after 1,064 days of exposure.

The corrosion of all the copper alloys was not affected by depth as shown in Figure 9.

The corrosion of copper and the silicon bronzes was not influenced by changes in the concentration of oxygen in seawater during 1 year of exposure, while that of the other alloys increased with increasing oxygen concentration, as shown in Figure 10.

None of the copper alloys were susceptible to stress corrosion.

The mechanical properties of copper, the beryllium-copper alloys, copper-nickel alloys, phosphor bronzes A and D, and Arsenical Admiralty brass were not adversely affected by exposure in seawater either at the surface or at depth. Those of 5% aluminum bronze, silicon bronze A, Muntz Metal, and nickel-manganese bronze were adversely affected.

Aluminum alloy 7075-T6 was galvanically corroded when in contact with beryllium-copper.

All the brasses containing from 10 to 42% zinc, except Arsenical Admiralty, aluminum brass, nickel brass, all the aluminum bronzes, and the silicon bronzes, were attacked by parting corrosion.



Corrosion products consisted of cupric chloride,  $\text{CuCl}_2 \cdot \text{H}_2\text{O}$ , copper oxychloride,  $\text{Cu}_2(\text{OH}_3\text{Cl})$ , nickel hydroxide,  $\text{Ni}(\text{OH})_2$ , copper, aluminum, nickel, iron, silicon, sodium, magnesium, manganese, calcium, chloride ion, and sulfate ion.

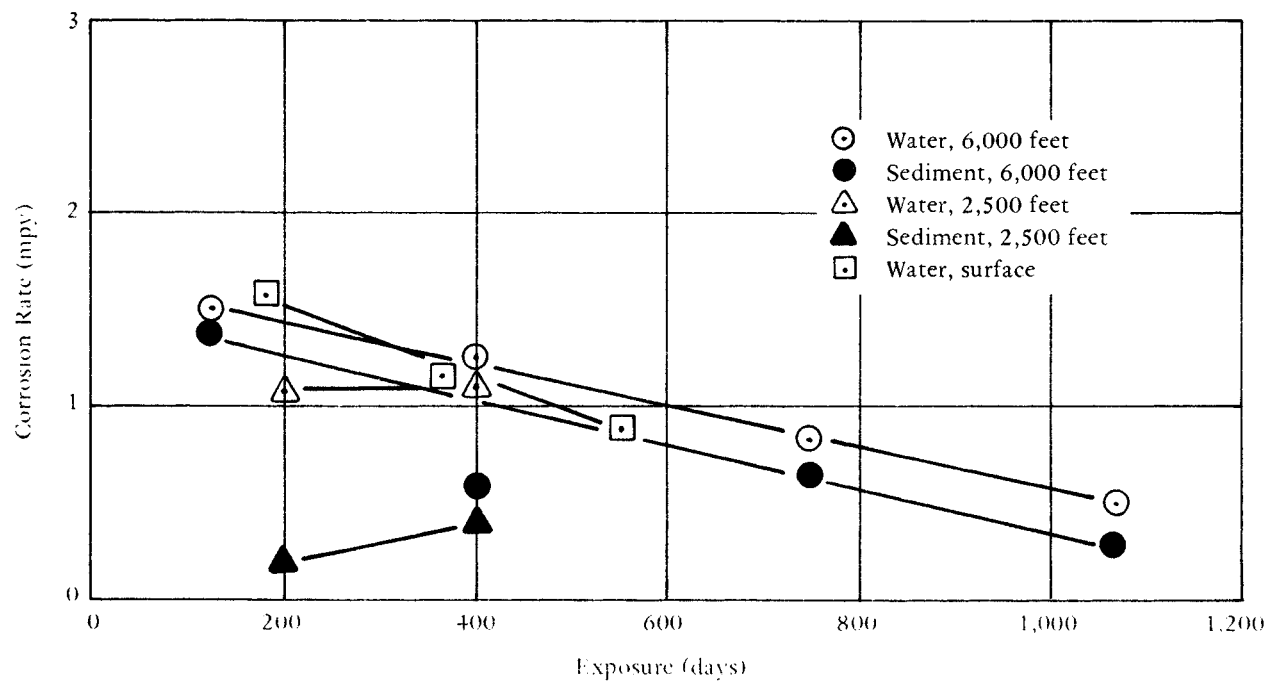


Figure 8. Effect of the duration of exposure on the corrosion of copper in seawater.

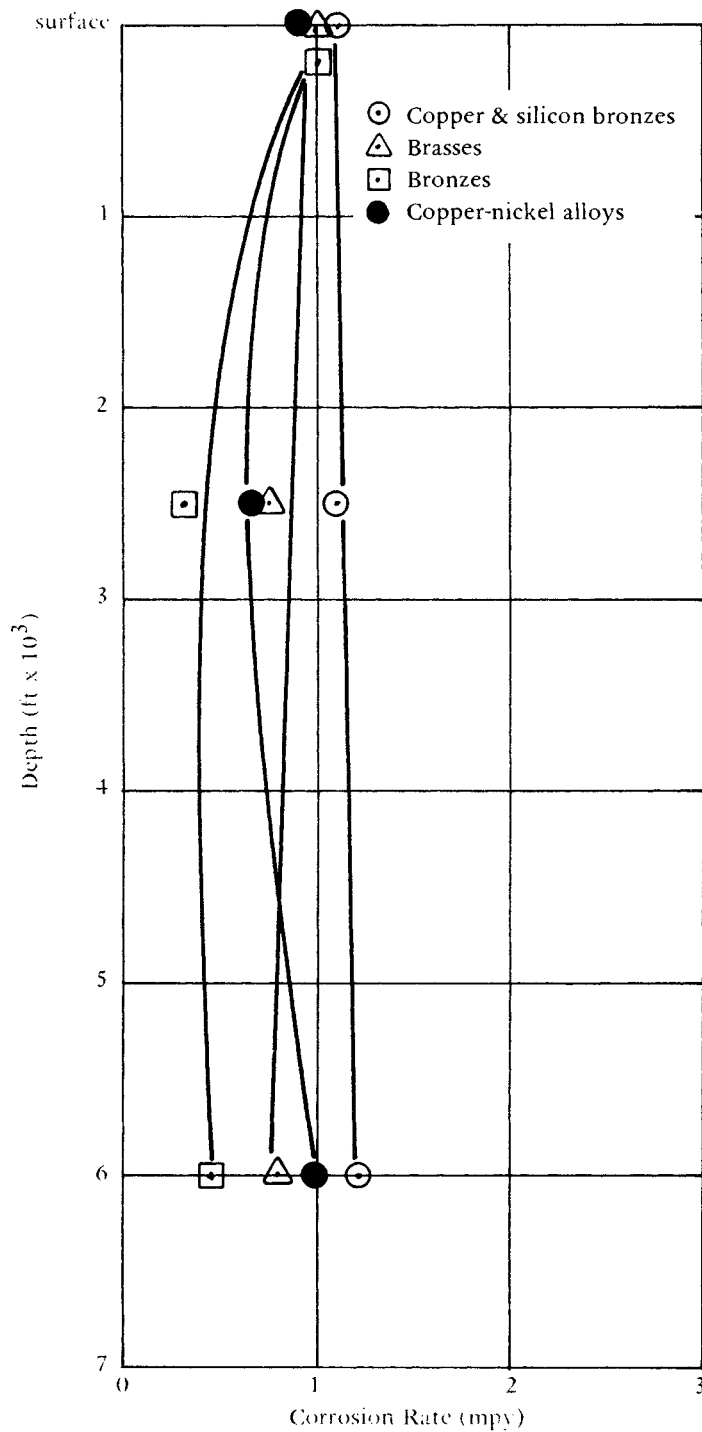


Figure 9. Effect of depth on the corrosion of copper alloys after 1 year of exposure in seawater.

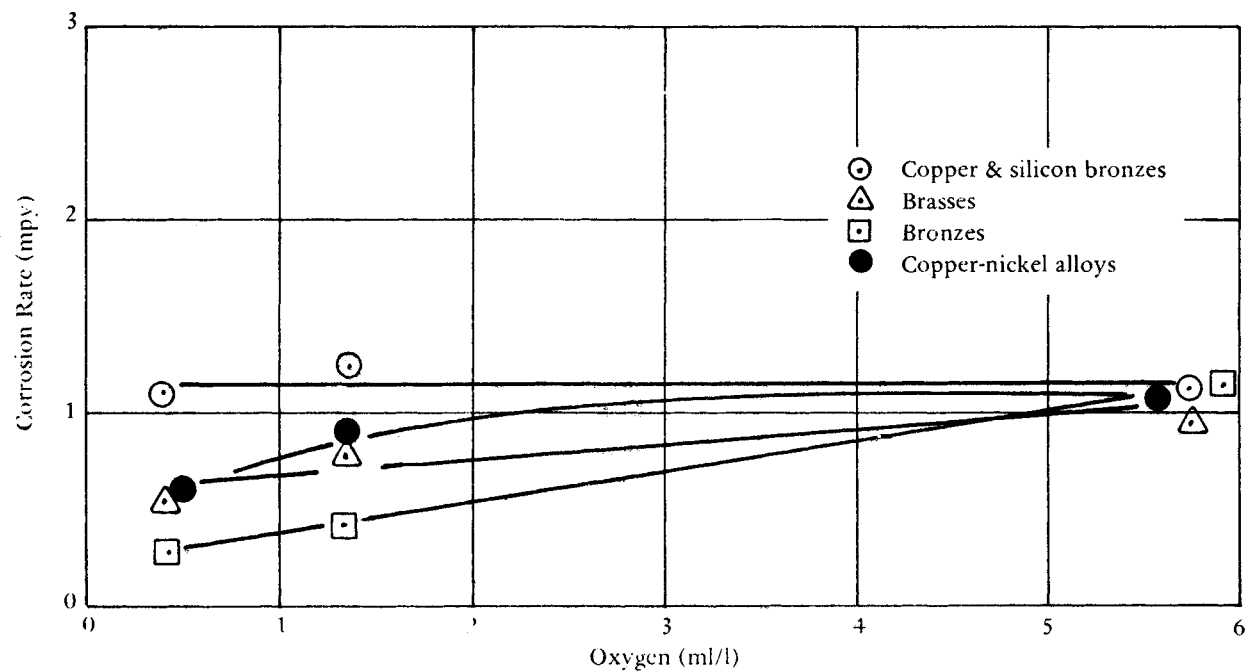


Figure 10. Effect of concentration of oxygen in seawater on the corrosion of copper alloys after 1 year of exposure.

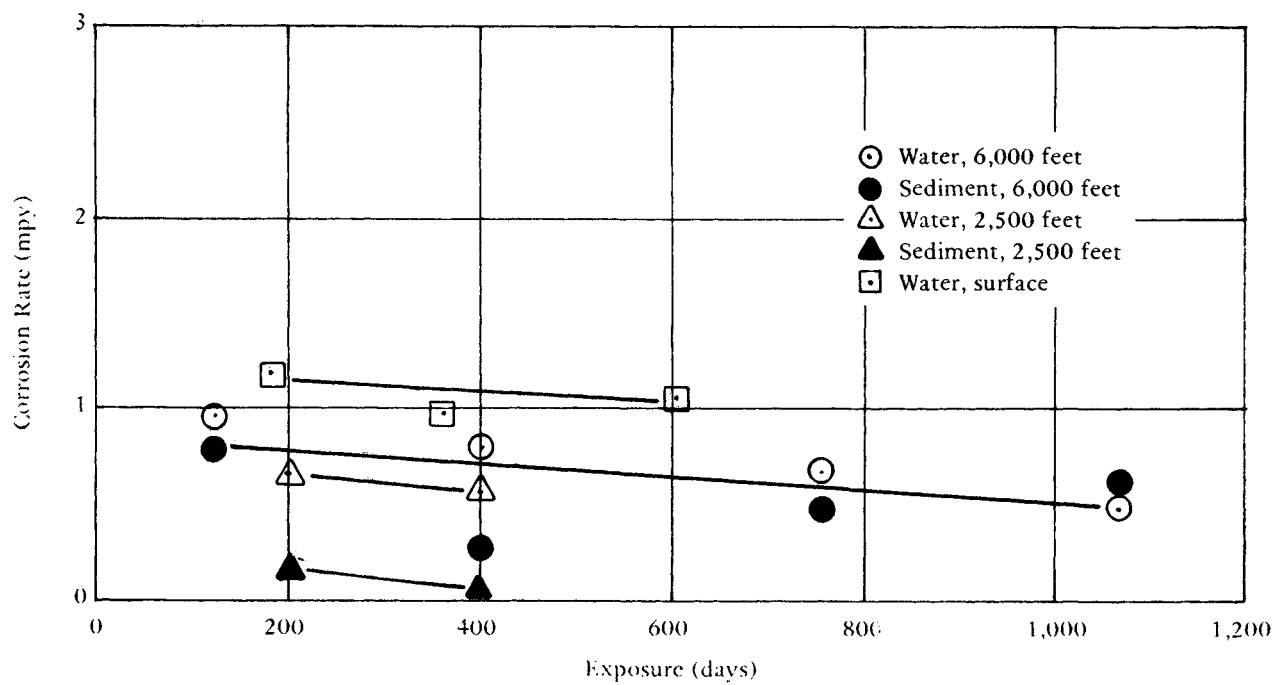


Figure 11. Effect of duration of exposure on the corrosion of brasses in seawater.

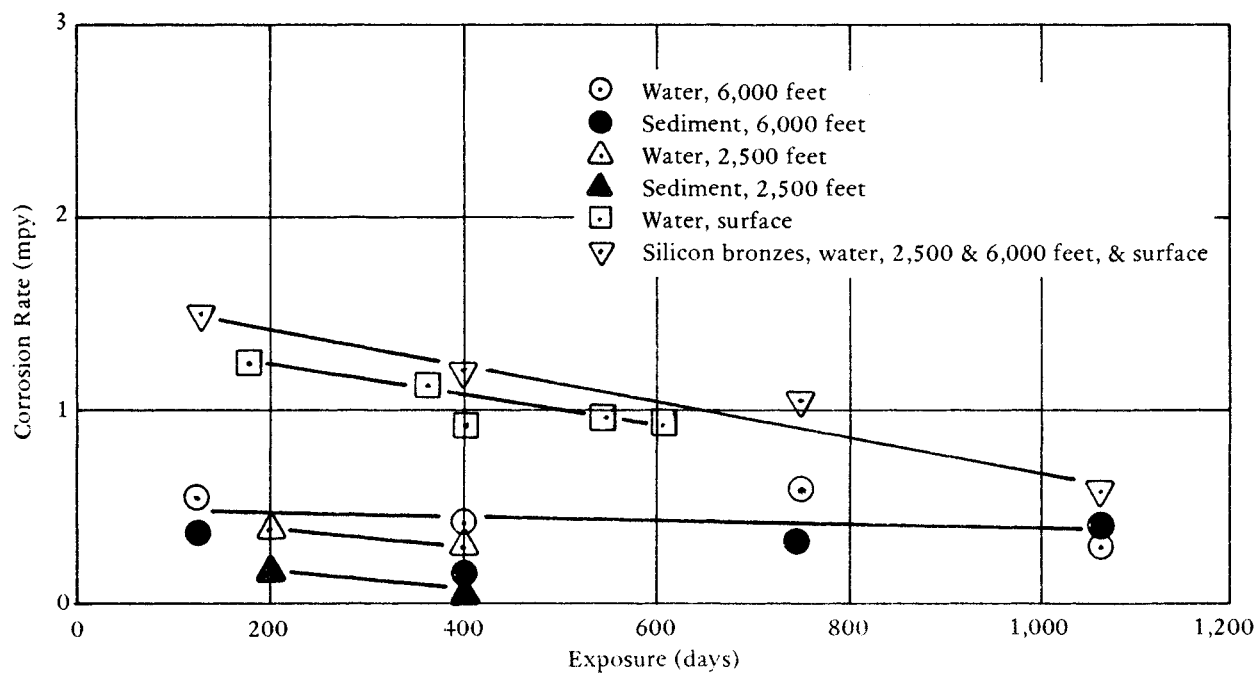


Figure 12. Effect of duration of exposure on the corrosion of bronzes in seawater.



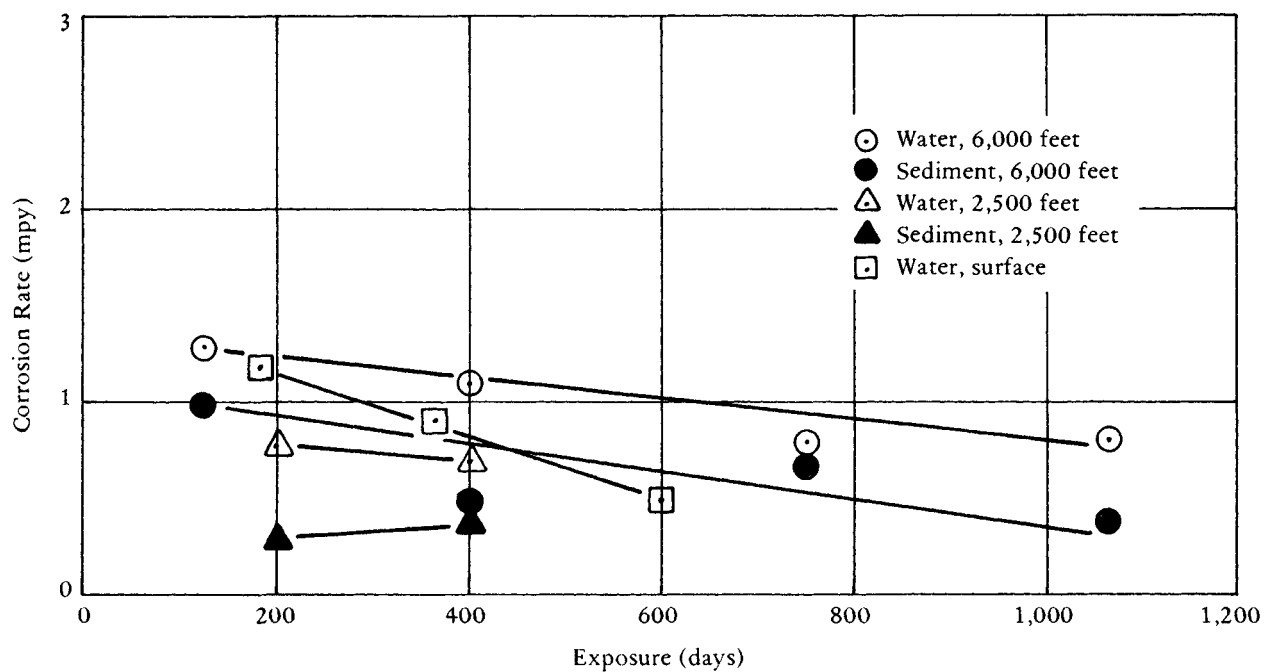


Figure 13. Effect of duration of exposure on the corrosion of copper-nickel alloys in seawater.

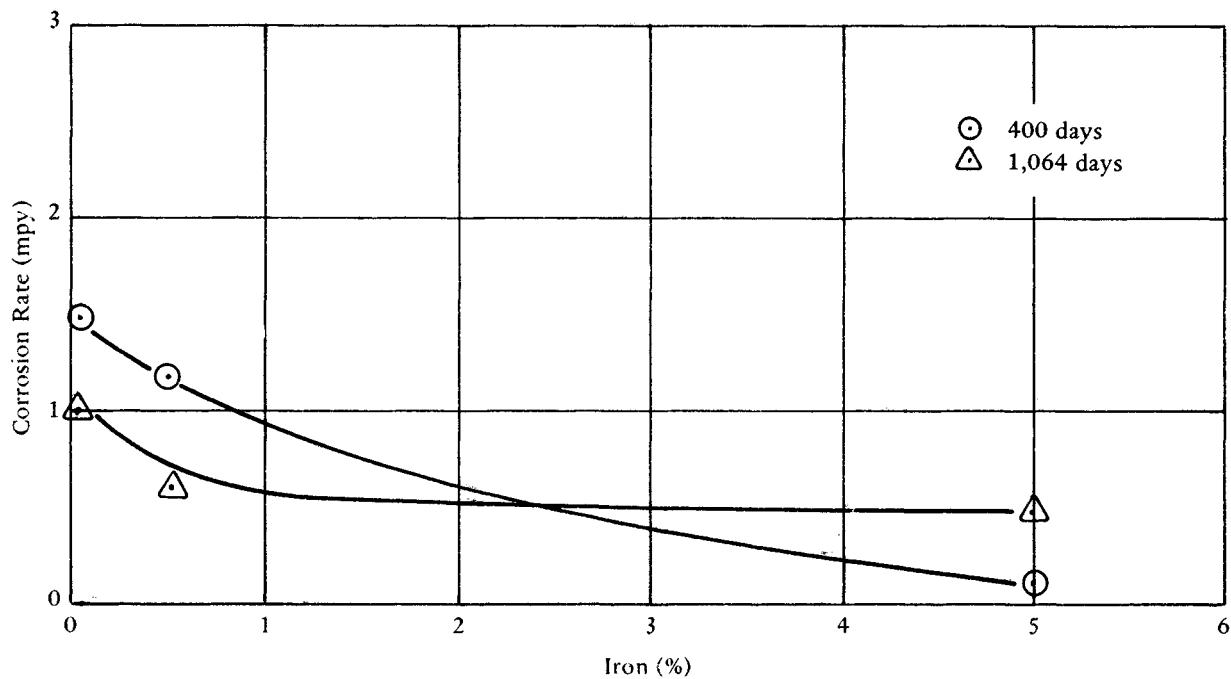


Figure 14. Effect of concentration of iron on the corrosion of the copper-nickel alloys in seawater at the 6,000-foot depth.

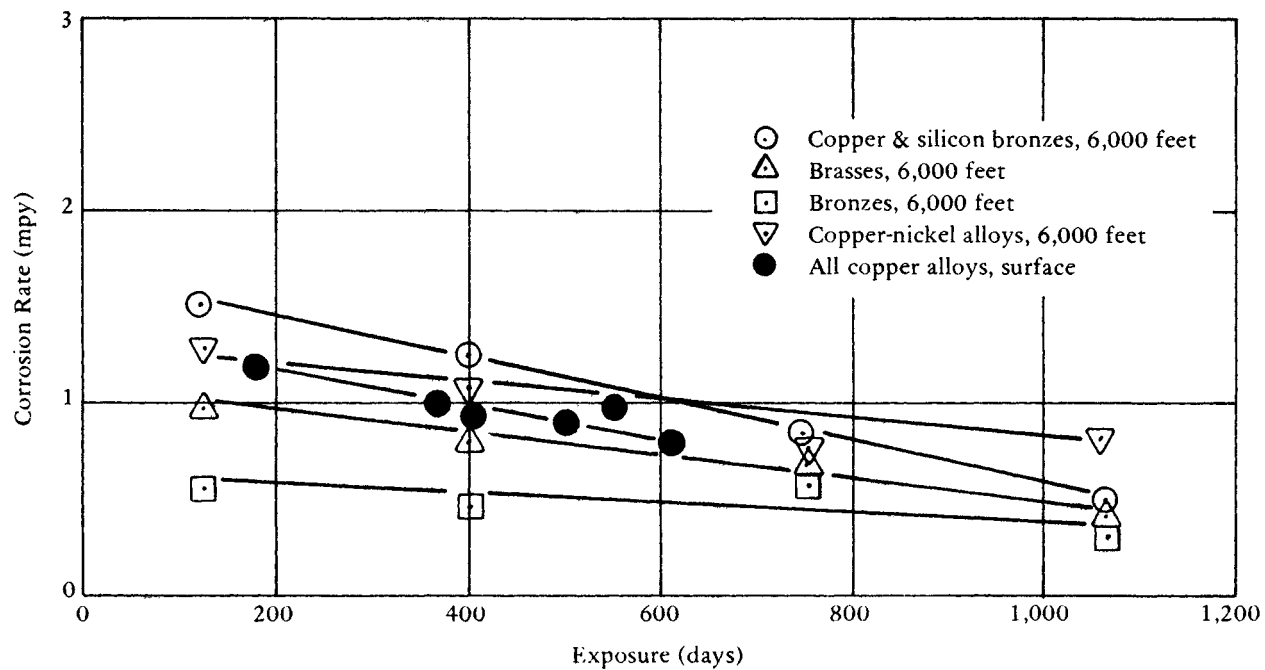


Figure 15. Effect of duration of exposure on the corrosion of copper alloys in seawater.

Table 10. Chemical Composition of Coppers, Percent by Weight

Alloy	CDA No. <sup>a</sup>	Cu	Ni	Be	Co	Source <sup>b</sup>
Copper, O free	102	99.96	—	—	—	CEL (4)
Copper, O free	102	99.9	—	—	—	INCO (3)
Copper, O free	102	99.97	—	—	—	CEL (4)
Copper, O free	102	99.9	—	—	—	MEL (5)
Be-Cu	170	97.06	—	2.02	0.58	NADC (7)
Be-Cu	172	97.42	—	2.02	0.54	NADC (7)
Be-Cu	172	97.80	0.05	1.90	0.25	CEL (4)
Be-Cu	175	97.06	—	0.61	2.4	NADC (7)
Be-Cu chain <sup>c</sup>	825	remainder	—	2.0	0.5	CEL (4)

<sup>a</sup>Copper Development Association alloy number.<sup>b</sup>Numbers refer to references at end of report.<sup>c</sup>Cast alloy.

Table 11. Corrosion Rates and Types of Corrosion of Coppers

Alloy	CDA No. <sup>a</sup>	Environment <sup>b</sup>	Exposure (day)	Depth (ft)	Corrosion Rate (mpy)	Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
Copper, O free	102	W	123	5,640	1.6	U	CEL (4)
Copper, O free	102	W	123	5,640	1.5	U	INCO (3)
Copper, O free	102	S	123	5,640	1.3	U	CEL (4)
Copper, O free	102	S	123	5,640	1.5	U	INCO (3)
Copper, O free	102	W	123	5,640	1.9	U	MEL (5)
Copper, O free	102	W	403	6,780	1.2	U	CEL (4)
Copper, O free	102	W	403	6,780	1.3	U	INCO (3)
Copper, O free	102	S	403	6,780	1.1	U	CEL (4)
Copper, O free	102	S	403	6,780	<0.1	U	INCO (3)
Copper, O free	102	W	751	5,640	0.7	U	CEL (4)
Copper, O free	102	W	751	5,640	1.0	U	INCO (3)
Copper, O free	102	S	751	5,640	0.7	U	INCO (3)
Copper, O free	102	W	751	5,640	0.6	U	MEL (5)
Copper, O free	102	W	1,064	5,300	0.5	U	CEL (4)
Copper, O free	102	W	1,064	5,300	0.5	U	INCO (3)
Copper, O free	102	S	1,064	5,300	0.3	G	INCO (3)
Copper, O free	102	W	1,064	5,300	0.4	U	MEL (5)
Copper, O free	102	W	197	2,340	0.8	U	CEL (4)

Continued

Table 11. Continued

Alloy	CDA No. <sup>a</sup>	Environment <sup>b</sup>	Exposure (day)	Depth (ft)	Corrosion Rate (mpy)	Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
Copper, O free	102	W	197	2,340	1.4	U	INCO (3)
Copper, O free	102	S	197	2,340	0.2	U	CEL (4)
Copper, O free	102	S	197	2,340	0.2	U	INCO (3)
Copper, O free	102	W	402	2,370	0.9	U	CEL (4)
Copper, O free	102	W	402	2,370	1.4	U	INCO (3)
Copper, O free	102	S	402	2,370	0.6	U	CEL (3)
Copper, O free	102	S	402	2,370	0.2	ET	INCO (3)
Copper, O free	102	W	181	5	1.4	P (22m)	CEL (4)
Copper, O free	102	W	181	5	1.8	G	INCO (3)
Copper, O free	102	W	366	5	1.2	G	INCO (3)
Copper, O free <sup>e</sup>	102	W	386	5	0.7	U	MEL (5)
Copper, O free	102	W	398	5	1.1	G, P (37m)	CEL (4)
Copper, O free	102	W	540	5	0.9	G, P (22m)	CEL (4)
Copper, O free	102	W	588	5	0.9	G, P (20m)	CEL (4)
Be-Cu <sup>f</sup>	170	W	123	5,640	0.5	U	NADC (7)
Be-Cu	170	W	751	5,640	0.5	U	NADC (7)
Be-Cu	170	W	197	2,340	0.0	NC	NADC (7)
Be-Cu	170	W	402	2,370	0.6	U	NADC (7)
Be-Cu	172 <sup>g</sup>	W	123	5,640	0.5	U	NADC (7)
Be-Cu	172 <sup>b</sup>	W	123	5,640	0.5	U	NADC (7)
Be-Cu	172 <sup>g</sup>	W	751	5,640	0.5	U	NADC (7)
Be-Cu	172 <sup>b</sup>	W	751	5,640	0.5	U	NADC (7)
Be-Cu	172 <sup>g</sup>	W	197	2,340	0.2	U	NADC (7)
Be-Cu	172 <sup>b</sup>	W	197	2,340	0.2	U	NADC (7)
Be-Cu	172 <sup>g</sup>	W	402	2,370	0.5	U	NADC (7)
Be-Cu	172 <sup>b</sup>	W	402	2,370	0.4	U	NADC (7)
Be-Cu	172	W	402	2,370	0.6	U	CEL (4)
Be-Cu	172	S	402	2,370	0.5	U	CEL (4)
Be-Cu	172	W	181	5	0.1	U	CEL (4)
Be-Cu	172	W	364	5	1.1	U	CEL (4)
Be-Cu	172	W	723	5	0.8	U	CEL (4)
Be-Cu	172	W	763	5	0.8	U	CEL (4)
Be-Cu <sup>i</sup>	172	W	402	2,370	0.5	U <sup>j</sup>	CEL (4)
Be-Cu <sup>i</sup>	172	S	402	2,370	0.5	U <sup>j</sup>	CEL (4)
Be-Cu <sup>i</sup>	172	W	181	5	0.1	U <sup>j</sup>	CEL (4)
Be-Cu <sup>i</sup>	172	W	364	5	1.0	U	CEL (4)
Be-Cu <sup>i</sup>	172	W	723	5	0.7	U	CEL (4)
Be-Cu <sup>i</sup>	172	W	763	5	0.8	U	CEL (4)
Be-Cu <sup>k</sup>	172	W	402	2,370	0.6	ET	CEL (4)
Be-Cu <sup>k</sup>	172	S	402	2,370	0.5	ET	CEL (4)

Continued

Table 11. Continued

Alloy	CDA No. <sup>a</sup>	Environment <sup>b</sup>	Exposure (day)	Depth (ft)	Corrosion Rate (mpy)	Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
Be-Cu <sup>k</sup>	172	W	181	5	0.1	ET	CEL (4)
Be-Cu <sup>k</sup>	172	W	364	5	1.1	U	CEL (4)
Be-Cu <sup>k</sup>	172	W	723	5	0.7	U	CEL (4)
Be-Cu <sup>k</sup>	172	W	763	5	0.7	U	CEL (4)
Be-Cu chain <sup>l</sup>	825	W	402	2,370	0.5	U	CEL (4)
Be-Cu chain <sup>l</sup>	825	S	402	2,370	0.4	U	CEL (4)
Be-Cu chain <sup>l</sup>	825	W	181	5	0.1	U	CEL (4)
Be-Cu chain <sup>l</sup>	825	W	364	5	1.0	U	CEL (4)
Be-Cu chain <sup>l</sup>	825	W	723	5	0.8	U	CEL (4)
Be-Cu chain <sup>l</sup>	825	W	763	5	0.8	P (30.5m), C (7m)	CEL (4)

<sup>a</sup>Copper Development Association alloy numbers.

<sup>b</sup>W = totally exposed in seawater on sides of structure.

S = exposed in base of structure so that the lower portions of the specimens were embedded in the bottom sediments.

<sup>c</sup>Symbols for types of corrosion:

C = Crevice

P = Pitting

ET = Etching

U = Uniform

G = General

NC = No corrosion

Numbers indicate mils (i.e., 20 = 20 mils; 20m = 20 mils maximum)

<sup>d</sup>Numbers refer to references at end of report.

<sup>e</sup>Francis L. LaQue Corrosion Laboratory, INCO, Wrightsville Beach, N.C.

<sup>f</sup>Beryllium-copper

<sup>g</sup>Aged at 600°F

<sup>h</sup>Aged at 800°F

<sup>i</sup>MIG weld

<sup>j</sup>Uniform, weld bead etched

<sup>k</sup>TIG weld

<sup>l</sup>Cast



Table 12. Stress Corrosion of Coppers

Alloy	CDA No. <sup>a</sup>	Stress (ksi)	Yield Strength (%)	Exposure (day)	Depth (ft)	Specimens		Source <sup>b</sup>
						Exposed	Failed	
Copper, O free	102	11	75	197	2,340	3	0	CEL (4)
Copper, O free	102	11	75	402	2,370	3	0	CEL (4)
Be-Cu <sup>c</sup>	170	50	30	403	6,780	3	0	NADC (7)
Be-Cu	170	126	75	403	6,780	3	0	NADC (7)
Be-Cu	170	50	30	402	2,370	3	0	NADC (7)
Be-Cu	170	126	75	402	2,370	3	0	NADC (7)
Be-Cu	172 <sup>d</sup>	53	30	403	6,780	3	0	NADC (7)
Be-Cu	172 <sup>d</sup>	133	75	403	6,780	3	0	NADC (7)
Be-Cu	172 <sup>d</sup>	53	30	402	2,370	3	0	NADC (7)
Be-Cu	172 <sup>d</sup>	133	75	402	2,370	3	0	NADC (7)
Be-Cu	172 <sup>e</sup>	37	30	403	6,780	3	0	NADC (7)
Be-Cu	172 <sup>e</sup>	93	75	403	6,780	3	0	NADC (7)
Be-Cu	172 <sup>e</sup>	37	30	402	2,370	3	0	NADC (7)
Be-Cu	172 <sup>e</sup>	93	75	402	2,370	3	0	NADC (7)
Be-Cu	175	32	30	403	6,780	3	0	NADC (7)
Be-Cu	175	80	75	403	6,780	3	0	NADC (7)
Be-Cu	175	32	30	402	2,370	3	0	NADC (7)
Be-Cu	175	80	75	402	2,370	3	0	NADC (7)

<sup>a</sup>Copper Development Association alloy number.<sup>b</sup>Numbers refer to references at end of report.<sup>c</sup>Beryllium-copper<sup>d</sup>Aged at 600°F<sup>e</sup>Aged at 800°F

Table 13. Changes in Mechanical Properties of Coppers Due to Corrosion

Alloy	CDA No. <sup>a</sup>	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>b</sup>
				Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
Copper, O free	102	123	5,640	33	+2	14	-6	52	-2	CEL (4)
Copper, O free	102	403	6,780	33	0	14	+9	52	-6	CEL (4)
Copper, O free	102	751	5,640	33	+4	14	+11	52	-6	CEL (4)
Copper, O free	102	197	2,340	33	-8	14	-18	52	-4	CEL (4)
Copper, O free	102	402	2,370	33	+2	14	+4	52	-7	CEL (4)
Copper, O free	102	181	5	33	+4	14	+20	52	-14	CEL (4)
Be-Cu <sup>c</sup>	170	123	5,640	188	0	167	0	5	0	NADC (7)
Be-Cu	170	751	5,640	188	-2	167	-2	5	-6	NADC (7)
Be-Cu	170	197	2,340	188	+11	167	+10	5	+4	NADC (7)
Be-Cu	170	402	2,370	188	-7	167	-6	5	0	NADC (7)
Be-Cu	172	402	2,370	176	-9	162	-8	4	-14	CEL (4)
Be-Cu <sup>d</sup>	172	402	2,370	161	-5	158	-2	3	+18	CEL (4)
Be-Cu <sup>e</sup>	172	402	2,370	166	-1	162	-6	3	-17	CEL (4)
Be-Cu	172	181	5	176	-7	162	-6	4	-29	CEL (4)
Be-Cu <sup>d</sup>	172	181	5	158	+3	157	-1	4	-29	CEL (4)
Be-Cu <sup>e</sup>	172	181	5	166	+3	162	-4	3	-17	CEL (4)
Be-Cu <sup>f</sup>	172	123	5,640	196	0	177	0	4	0	NADC (7)
Be-Cu <sup>f</sup>	172	751	5,640	196	-1	177	-2	4	-19	NADC (7)
Be-Cu <sup>f</sup>	172	197	2,340	196	0	177	0	4	0	NADC (7)
Be-Cu <sup>f</sup>	172	402	2,370	196	-8	177	-13	4	-26	NADC (7)
Be-Cu <sup>g</sup>	172	123	5,640	144	-2	124	-7	9	0	NADC (7)
Be-Cu <sup>g</sup>	172	751	5,640	144	-4	124	-10	9	+26	NADC (7)
Be-Cu <sup>g</sup>	172	197	2,340	144	+6	124	+10	9	+25	NADC (7)
Be-Cu <sup>g</sup>	172	402	2,370	144	-6	124	-12	9	+26	NADC (7)
Be-Cu	175	123	5,640	121	0	107	0	15	-20	NADC (7)
Be-Cu	175	751	5,640	121	-4	107	0	15	-13	NADC (7)
Be-Cu	175	197	2,340	121	0	107	0	15	0	NADC (7)
Be-Cu	175	402	2,370	121	-3	107	0	15	-23	NADC (7)

<sup>a</sup>Copper Development Association alloy number.<sup>b</sup>Numbers refer to references at end of report.<sup>c</sup>Beryllium-copper.<sup>d</sup>MIG welded.<sup>e</sup>TIG welded.<sup>f</sup>Aged at 600°F.<sup>g</sup>Aged at 800°F.

Table 14. Chemical Composition of Copper-Zinc Alloys (Brasses), Percent by Weight

Alloy	CDA No. <sup>a</sup>	Cu	Zn	Sn	Ni	Al	Mn	Fe	Other	Source <sup>b</sup>
Commercial bronze	220	90	10	—	—	—	—	—	—	INCO (3)
Red brass	230	85	15	—	—	—	—	—	—	INCO (3)
Red brass	230	85	15	—	—	—	—	—	—	MEL (5)
Commercial brass	268	66.47	33.51	<0.05	—	—	—	0.02	<0.01 Pb	CEL (4)
Yellow brass	270	68.48	31.50	<0.05	—	—	—	0.02	<0.01 Pb	CEL (4)
Yellow brass	270	65.0	35.0	—	—	—	—	—	—	INCO (3)
Muntz metal	280	60.69	39.29	—	—	—	—	<0.02	—	CEL (4)
Muntz metal	280	60.0	40.0	—	—	—	—	—	—	INCO (3)
Arsenical admiralty	443	71.19	27.77	1.00	—	—	—	0.01	0.027 As	CEL (4)
Arsenical admiralty	443	70.0	29.0	1.0	—	—	—	—	0.04 As	INCO (3)
Naval brass	464	60.46	38.74	0.69	—	—	—	0.03	0.08 Pb	CEL (4)
Naval brass	464	60.2	39.8	0.8	—	—	—	—	—	MEL (5)
Tobin bronze	—	58.94	39.07	0.89	nil	<0.10	—	1.10	<0.05 Pb	CEL (4)
Mn bronze A	675	56.0	42.0	—	—	1.0	0.1	1.0	—	INCO (3)
Mn bronze B	670	68.0	21.0	—	—	5.0	4.0	2.0	—	MEL (5)
Ni-Mn bronze <sup>c</sup>	868	54.58	34.48	0.70	3.77	1.73	3.06	1.66	0.02 Pb	CEL (4)
Al brass	—	78.0	20.0	—	—	2.0	—	—	—	INCO (3)
Ni brass	—	50.0	40.0	—	8.0	—	—	2.0	—	INCO (3)

<sup>a</sup>Copper Development Association alloy number.<sup>b</sup>Numbers refer to references at end of report.<sup>c</sup>Cast alloy.

Table 15. Corrosion Rates and Types of Corrosion of Copper-Zinc Alloys (Brasses)

Alloy	CDA No. <sup>a</sup>	Environment <sup>b</sup>	Exposure (day)	Depth (ft)	Corrosion Rate (mpy)	Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
Commercial Bronze	220	W	123	5,640	0.6	U	INCO (3)
Commercial Bronze	220	S	123	5,640	0.3	U	INCO (3)
Commercial Bronze	220	W	403	6,780	0.6	U	INCO (3)
Commercial Bronze	220	S	403	6,780	<0.1	U	INCO (3)
Commercial Bronze	220	W	751	5,640	0.6	C (9)	INCO (3)
Commercial Bronze	220	S	751	5,640	0.4	C (20)	INCO (3)
Commercial Bronze	220	W	1,064	5,300	0.4	C (20)	INCO (3)
Commercial Bronze	220	S	1,064	5,300	0.6	U	INCO (3)
Commercial Bronze	220	W	197	2,340	0.3	U	INCO (3)
Commercial Bronze	220	S	197	2,340	0.1	NU-ET	INCO (3)
Commercial Bronze	220	W	402	2,370	0.2	SL-DZ	INCO (3)
Commercial Bronze	220	S	402	2,370	<0.1	SL-DZ	INCO (3)
Commercial Bronze	220	W	181	5	1.1	U	INCO (3)
Commercial Bronze	220	W	366	5	1.1	P (4)	INCO (3)
Red Brass	230	W	123	5,640	1.3	U	INCO (3)
Red Brass	230	S	123	5,640	1.7	SL-DZ	INCO (3)
Red Brass	230	W	123	5,640	1.9	U	MEL (5)
Red Brass	230	W	403	6,780	1.2	SL-DZ	INCO (3)
Red Brass	230	S	403	6,780	0.4	GBSL	INCO (3)
Red Brass	230	W	751	5,640	0.9	SL-DZ	INCO (3)
Red Brass	230	S	751	5,640	0.7	U	INCO (3)
Red Brass	230	W	751	5,640	0.7	U	MEL (5)
Red Brass	230	W	1,064	5,300	0.6	SL-DZ	INCO (3)
Red Brass	230	S	1,064	5,300	0.3	G	INCO (3)
Red Brass	230	W	1,064	5,300	0.6	U	MEL (5)
Red Brass	230	W	197	2,340	1.0	U	INCO (3)
Red Brass	230	S	197	2,340	0.1	U	INCO (3)
Red Brass	230	W	402	2,370	0.7	U	INCO (3)
Red Brass	230	S	402	2,370	<0.1	ET	INCO (3)
Red Brass	230	W	181	5	1.8	SL-DZ	INCO (3)
Red Brass	230	W	366	5	1.2	CR (6)	INCO (3)
Red Brass <sup>e</sup>	230	W	386	5	0.8	U	MEL (5)
Commercial Brass	268	W	1,064	5,300	0.8	S-DZ	CEL (4)
Yellow Brass	268	W	1,064	5,300	0.6	MO-DZ	CEL (4)
Yellow Brass	270	W	123	5,640	1.4	U	INCO (3)
Yellow Brass	270	S	123	5,640	1.3	U	INCO (3)
Yellow Brass	270	W	403	6,780	1.0	U	INCO (3)
Yellow Brass	270	S	403	6,780	0.2	GBSL	INCO (3)
Yellow Brass	270	W	751	5,640	2.5	SL-DZ	INCO (3)
Yellow Brass	270	S	751	5,640	0.6	SL-DZ	INCO (3)

Continued

Table 15. Continued.

Alloy	CDA No. <sup>a</sup>	Environment <sup>b</sup>	Exposure (day)	Depth (ft)	Corrosion Rate (mpy)	Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
Yellow Brass	270	W	1,064	5,300	0.6	U	INCO (3)
Yellow Brass	270	S	1,064	5,300	0.5	U	INCO (3)
Yellow Brass	270	W	197	2,340	0.9	U	INCO (3)
Yellow Brass	270	S	197	2,340	0.2	NU-ET	INCO (3)
Yellow Brass	270	W	402	2,370	0.9	U	INCO (3)
Yellow Brass	270	S	402	2,370	0.1	ET	INCO (3)
Yellow Brass	270	W	181	5	2.1	U	INCO (3)
Yellow Brass	270	W	366	5	1.3	U	INCO (3)
Muntz Metal	280	W	123	5,640	1.6	SL-DZ	CEL (4)
Muntz Metal	280	W	123	5,640	2.1	U	INCO (3)
Muntz Metal	280	S	123	5,640	1.3	SL-DZ	CEL (4)
Muntz Metal	280	S	123	5,640	1.5	U	INCO (3)
Muntz Metal	280	W	403	6,780	2.6	SL-DZ	CEL (4)
Muntz Metal	280	W	403	6,780	3.3	S-DZ	INCO (3)
Muntz Metal	280	S	403	6,780	1.8	SL-DZ	CEL (4)
Muntz Metal	280	S	403	6,780	0.6	GBSL	INCO (3)
Muntz Metal	280	W	751	5,640	3.2	G-DZ	CEL (4)
Muntz Metal	280	W	751	5,640	4.0	S-DZ	INCO (3)
Muntz Metal	280	S	751	5,640	1.7	S-DZ	INCO (3)
Muntz Metal	280	W	1,064	5,300	2.3	S-DZ	INCO (3)
Muntz Metal	280	S	1,064	5,300	0.8	U	INCO (3)
Muntz Metal	280	W	197	2,340	0.7	SL-DZ; P (10)	CEL (4)
Muntz Metal	280	W	197	2,340	0.7	U	INCO (3)
Muntz Metal	280	S	197	2,340	0.5	SL-DZ; P (5)	CEL (4)
Muntz Metal	280	S	197	2,340	<0.1	SL-DZ <sup>f</sup>	INCO (3)
Muntz Metal	280	W	402	2,370	0.7	SL-DZ	CEL (4)
Muntz Metal	280	W	402	2,370	0.7	SL-DZ	INCO (3)
Muntz Metal	280	S	402	2,370	0.6	SL-DZ	CEL (4)
Muntz Metal	280	S	402	2,370	0.1	ET	INCO (3)
Muntz Metal	280	W	181	5	2.4	DZ	CEL (4)
Muntz Metal	280	W	181	5	3.4	SL-DZ	INCO (3)
Muntz Metal	280	W	366	5	3.7	S-DZ	INCO (3)
Muntz Metal	280	W	398	5	3.1	DZ, P (6)	CEL (4)
Muntz Metal	280	W	540	5	3.4	DZ, I-P	CEL (4)
Muntz Metal	280	W	588	5	3.3	DZ, I-P	CEL (4)
Arsenical Admiralty	443	W	123	5,640	1.0	U	CEL (4)
Arsenical Admiralty	443	W	123	5,640	1.1	U	INCO (3)
Arsenical Admiralty	443	S	123	5,640	1.0	U	CEL (4)
Arsenical Admiralty	443	S	123	5,640	1.0	U	INCO (3)
Arsenical Admiralty	443	W	403	6,780	0.7	U	CEL (4)
Arsenical Admiralty	443	W	403	6,780	0.8	U	INCO (3)

Continued

Table 15. Continued.

Alloy	CDA No. <sup>a</sup>	Environment <sup>b</sup>	Exposure (day)	Depth (ft)	Corrosion Rate (mpy)	Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
Arsenical Admiralty	443	S	403	6,780	0.8	U	CEL (4)
Arsenical Admiralty	443	S	403	6,780	0.2	GBSL	INCO (3)
Arsenical Admiralty	443	W	751	5,640	0.6	U	CEL (4)
Arsenical Admiralty	443	W	751	5,640	0.7	U	INCO (3)
Arsenical Admiralty	443	S	751	5,640	0.4	U	CEL (4)
Arsenical Admiralty	443	S	751	5,640	0.5	U	INCO (3)
Arsenical Admiralty	443	W	1,064	5,300	0.5	U	INCO (3)
Arsenical Admiralty	443	S	1,064	5,300	0.5	U	INCO (3)
Arsenical Admiralty	443	W	197	2,340	0.6	U	CEL (4)
Arsenical Admiralty	443	W	197	2,340	1.0	U	INCO (3)
Arsenical Admiralty	443	S	197	2,340	0.2	U	CEL (4)
Arsenical Admiralty	443	S	197	2,340	<0.1	U	INCO (3)
Arsenical Admiralty	443	W	402	2,370	0.6	U	CEL (4)
Arsenical Admiralty	443	W	402	2,370	0.6	U	INCO (3)
Arsenical Admiralty	443	S	402	2,370	0.4	U	CEL (4)
Arsenical Admiralty	443	S	402	2,370	0.1	ET	INCO (3)
Arsenical Admiralty	443	W	181	5	1.3	U	CEL (4)
Arsenical Admiralty	443	W	181	5	1.8	G	INCO (3)
Arsenical Admiralty	443	W	366	5	1.3	U	INCO (3)
Arsenical Admiralty	443	W	608	5	1.1	U; I-P	CEL (4)
Naval Brass	464	W	123	5,640	1.2	U	MEL (5)
Naval Brass	464	W	751	5,640	0.6	U	MEL (5)
Naval Brass	464	W	1,064	5,300	0.7	U	MEL (5)
Naval Brass	464	W	1,064	5,300	1.0	S-DZ	CEL (4)
Naval Brass <sup>e</sup>	464	W	364	5	0.7	U	MEL (5)
Tobin Bronze	—	W	1,064	5,300	0.9	S-DZ	CEL (4)
Mn Bronze A	675	W	123	5,640	2.9	EX-DZ	INCO (3)
Mn Bronze A	675	S	123	5,640	2.0	EX-DZ	INCO (3)
Mn Bronze A	675	W	403	6,780	2.7	S-DZ	INCO (3)
Mn Bronze A	675	S	403	6,780	0.9	S-DZ	INCO (3)
Mn Bronze A	675	W	751	5,640	7.2	S-DZ	INCO (3)
Mn Bronze A	675	S	751	5,640	2.6	V-S-DZ	INCO (3)
Mn Bronze A	675	W	1,064	5,300	2.0	S-DZ	INCO (3)
Mn Bronze A	675	S	1,064	5,300	1.2	S-DZ	INCO (3)
Mn Bronze A	675	W	197	2,340	1.2	S-DZ	INCO (3)
Mn Bronze A	675	S	197	2,340	0.2	SL-DZ	INCO (3)
Mn Bronze A	675	W	402	2,370	0.8	S-DZ	INCO (3)
Mn Bronze A	675	S	402	2,370	<0.1	SL-DZ	INCO (3)
Mn Bronze A	675	W	181	5	4.8	S-DZ	INCO (3)
Mn Bronze A	675	W	366	5	1.9	S-DZ	INCO (3)

Continued



Table 15. Continued.

Alloy	CDA No. <sup>a</sup>	Environment <sup>b</sup>	Exposure (day)	Depth (ft)	Corrosion Rate (mpy)	Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
Mn Bronze B	670	W	123	5,640	1.5	DZ	MEL (5)
Mn Bronze B	670	W	751	5,640	3.0	DZ	MEL (5)
Ni-Mn Bronze <sup>g</sup>	868	W	123	5,640	0.5	SL-DZ	CEL (4)
Ni-Mn Bronze	868	W	403	6,780	0.4	MD-DZ	CEL (4)
Ni-Mn Bronze	868	S	403	6,780	0.5	MD-DZ	CEL (4)
Ni-Mn Bronze	868	W	751	5,640	2.3	V-S-DZ	CEL (4)
Ni-Mn Bronze	868	W	197	2,340	0.4	SL-DZ	CEL (4)
Ni-Mn Bronze	868	S	197	2,340	0.4	SL-DZ	CEL (4)
Ni-Mn Bronze	868	W	402	2,340	1.6	SL-DZ	CEL (4)
Ni-Mn Bronze	868	S	402	2,340	2.9	SL-DZ	CEL (4)
Ni-Mn Bronze	868	W	181	5	<0.1	SL-DZ	CEL (4)
Ni-Mn Bronze	868	W	364	5	0.7	DZ	CEL (4)
Ni-Mn Bronze	868	W	723	5	2.9	DZ	CEL (4)
Ni-Mn Bronze	868	W	763	5	3.0	DZ	CEL (4)
Al Brass	—	W	123	5,640	0.7	U	INCO (3)
Al Brass	—	S	123	5,640	0.5	U	INCO (3)
Al Brass	—	W	403	6,780	0.4	U	INCO (3)
Al Brass	—	S	403	6,780	0.1	GBSL	INCO (3)
Al Brass	—	W	751	5,640	0.3	U	INCO (3)
Al Brass	—	S	751	5,640	0.1	U	INCO (3)
Al Brass	—	W	1,064	5,300	0.2	U	INCO (3)
Al Brass	—	S	1,064	5,300	0.8	G	INCO (3)
Al Brass	—	W	197	2,340	0.5	U	INCO (3)
Al Brass	—	S	197	2,340	<0.1	U	INCO (3)
Al Brass	—	W	402	2,370	0.3	U	INCO (3)
Al Brass	—	S	402	2,370	0.1	ET	INCO (3)
Al Brass	—	W	181	5	0.8	G	INCO (3)
Al Brass	—	W	366	5	0.4	P (4)	INCO (3)
Ni Brass	—	W	123	5,640	1.3	U	INCO (3)
Ni Brass	—	S	123	5,640	1.1	U	INCO (3)
Ni Brass	—	W	403	6,780	1.3	U	INCO (3)
Ni Brass	—	S	403	6,780	0.2	GBSL	INCO (3)
Ni Brass	—	W	751	5,640	1.0	U	INCO (3)
Ni Brass	—	S	751	5,640	0.7	U	INCO (3)
Ni Brass	—	W	1,064	5,300	0.8	U	INCO (3)
Ni Brass	—	S	1,064	5,300	0.5	U	INCO (3)
Ni Brass	—	W	197	2,340	0.8	U	INCO (3)
Ni Brass	—	S	197	2,340	<0.1	NU-ET	INCO (3)
Ni Brass	—	W	402	2,370	0.7	U	INCO (3)
Ni Brass	—	S	402	2,370	<0.1	ET	INCO (3)

Continued

Table 15. Continued.

Alloy	CDA No. <sup>a</sup>	Environment <sup>b</sup>	Exposure (day)	Depth (ft)	Corrosion Rate (mpy)	Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
Ni Brass	—	W	181	5	1.1	U	INCO (3)
Ni Brass	—	W	366	5	0.9	U	INCO (3)

<sup>a</sup>Copper Development Association alloy number.

<sup>b</sup>W = Totally exposed in seawater on sides of structure; S = Exposed in base of structure so that the lower portions of the specimen were embedded in the bottom sediments.

<sup>c</sup>Symbols for types of corrosion:

C	= Crevice	MD	= Medium
CR	= Cratering	MO	= Moderate
DZ	= Dezincification	NU	= Nonuniform
ET	= Etching	P	= Pitting
EX	= Extensive	S	= Severe
G	= General	SL	= Slight
GBSL	= General below sediment line	U	= Uniform
I	= Incipient	V	= Very

Numbers indicate maximum depth in mils.

<sup>d</sup>Numbers refer to references at end of report.

<sup>e</sup>Francis L. LaQue Corrosion Laboratory, INCO, Wrightsville Beach, N.C.

<sup>f</sup>At spacer.

<sup>g</sup>Cast alloy.

Table 16. Stress Corrosion of Copper-Zinc Alloys (Brasses)

Alloy	CDA No. <sup>a</sup>	Stress (ksi)	Tensile Strength (%)	Exposure (day)	Depth (ft)	Specimens		Source <sup>b</sup>
						Exposed	Failed	
Arsenical admiralty	443	10.0	50	403	6,780	2	0	CEL (4)
Arsenical admiralty	443	14.0	75	403	6,780	2	0	CEL (4)
Arsenical admiralty	443	9.5	50	197	2,340	3	0	CEL (4)
Arsenical admiralty	443	14.3	75	197	2,340	3	0	CEL (4)
Arsenical admiralty	443	9.0	50	402	2,370	3	0	CEL (4)
Arsenical admiralty	443	13.4	75	402	2,370	3	0	CEL (4)
Muntz metal	280	12.0	50	403	6,780	2	0	CEL (4)
Muntz metal	280	18.0	75	403	6,780	2	0	CEL (4)
Muntz metal	280	12.2	50	197	2,340	3	0	CEL (4)
Muntz metal	280	18.3	75	197	2,340	3	0	CEL (4)
Muntz metal	280	17.7	50	402	2,370	3	0	CEL (4)
Muntz metal	280	26.5	75	402	2,370	3	0	CEL (4)

<sup>a</sup>Copper Development Association alloy number.<sup>b</sup>Numbers refer to references at end of report.

Table 17. Changes in Mechanical Properties of Brasses Due to Corrosion

Alloy	CDA No. <sup>a</sup>	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>b</sup>
				Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
Muntz metal	280	123	5,640	56	-4	24	-3	53	-6	CEL (4)
Muntz metal	280	403	6,780	56	-16	24	-12	53	-25	CEL (4)
Muntz metal	280	751	5,640	56	-32	24	-29	53	-31	CEL (4)
Muntz metal	280	197	2,340	56	-6	24	-17	53	-6	CEL (4)
Muntz metal	280	402	2,370	56	-8	24	-10	53	-15	CEL (4)
Muntz metal	280	181	5	56	-7	24	-16	53	-13	CEL (4)
Arsenical admiralty	443	123	5,640	51	0	19	+3	66	-2	CEL (4)
Arsenical admiralty	443	403	6,780	51	-2	19	-5	66	+1	CEL (4)
Arsenical admiralty	443	751	5,680	51	-2	19	-1	66	+1	CEL (4)
Arsenical admiralty	443	197	2,340	51	-6	19	-21	66	-3	CEL (4)
Arsenical admiralty	443	402	2,370	51	-2	19	-3	66	-1	CEL (4)
Arsenical admiralty	443	181	5	51	-2	19	-10	66	-12	CEL (4)
Ni-Mn bronze	868	123	5,640	71	-2	31	-10	20	+25	CEL (4)
Ni-Mn bronze	868	403	6,780	71	-33	31	-8	20	-60	CEL (4)
Ni-Mn bronze	868	751	5,640	71	-40	31	-21	20	-58	CEL (4)
Ni-Mn bronze	868	197	2,340	71	-3	31	-17	20	+16	CEL (4)
Ni-Mn bronze	868	402	2,370	71	-6	31	+53	20	-61	CEL (4)
Ni-Mn bronze	868	181	5	71	-10	31	+14	20	-35	CEL (4)

<sup>a</sup>Copper Development Association alloy number.<sup>b</sup>Numbers refer to references at end of report.

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

Alloy	CDA No. <sup>a</sup>	Cu	Sn	Zn	Ni	Al	Fe	Si	Pb	P	Mn	Source <sup>b</sup>
G bronze <sup>c</sup>	—	88.0	2.0	10.0	—	—	—	—	—	—	—	INCO (3)
Modified G bronze <sup>c</sup>	—	88.0	8.0	4.0	—	—	—	—	—	—	—	INCO (3)
M bronze <sup>c</sup>	—	88.2	6.0	4.0	—	—	—	—	2.0	—	—	INCO (3)
Leaded Sn bronze <sup>c</sup>	—	85.0	5.0	5.0	—	—	—	—	5.0	—	—	INCO (3)
Phosphor bronze A	510	94.64	4.94	<0.10	—	—	<0.05	—	—	0.26	—	CEL (4)
Phosphor bronze A	510	96.0	4.0	—	—	—	—	—	—	0.25	—	INCO (3)
Phosphor bronze A	510	95.62	4.44	<0.10	—	—	<0.05	—	—	0.06	—	CEL (4)
Phosphor bronze D	524	90.00	9.23	<0.10	—	—	<0.05	—	—	0.17	—	CEL (4)
Al bronze, 5%	606	95.0	—	—	—	5.0	—	—	—	—	—	INCO (3)
Al bronze, 5%	606	95.11	—	—	—	4.76	<0.05	—	—	—	—	CEL (4)
Al bronze, 5%	606	—	—	—	—	—	—	—	—	—	—	Boeing (6)
Al bronze, 7%	614	90.11	—	0.15	—	6.59	3.15	—	<0.02	—	—	CEL (4)
Al bronze, 7%	614	90.0	—	—	—	7.0	3.0	—	—	—	—	INCO (3)
Al bronze, 7%	614	88.0	—	—	—	9.0	3.0	—	—	—	—	NADC (7)
Al bronze, 10% <sup>c</sup>	953	89.0	—	—	—	10.0	1.0	—	—	—	—	INCO (3)
Al bronze, 11% <sup>c</sup>	954	86.0	—	—	—	10.0	4.0	—	—	—	—	INCO (3)
Al bronze, 11% <sup>c</sup>	954	86.5	—	—	—	10.0	3.5	—	—	—	—	MEL (5)
Al bronze, 13% <sup>c</sup>	—	83.0	—	—	—	13.0	4.0	—	—	—	—	INCO (3)
Ni-Al bronze	—	83.5	—	—	2.5	10.0	4.0	—	—	—	—	MEL (5)
Ni-Al bronze No. 1	—	80.0	—	—	4.0	11.0	4.0	—	—	—	1.0	INCO (3)
Ni-Al bronze No. 1	—	80.0	—	—	4.0	10.0	4.0	—	—	—	—	MEL (5)
Ni-Al bronze No. 2	—	80.0	—	—	5.0	10.0	4.0	—	—	—	0.5	INCO (3)
Ni-Al bronze No. 3	—	80.0	—	—	5.0	9.0	3.5	—	—	—	3.0	INCO (3)
Si bronze, 3%	653	97.0	—	—	—	—	—	3.0	—	—	—	INCO (3)
Si bronze A	655	95.49	—	—	—	—	<0.02	3.28	—	—	1.18	CEL (4)
Si bronze A	655	95.0	—	—	—	—	—	3.0	—	—	1.0	INCO (3)
Si bronze A	655	96.0	—	—	—	—	—	3.0	—	—	1.0	Boeing (6)
Ni-Vee bronze A <sup>c</sup>	—	88.0	5.0	2.0	5.0	—	—	—	—	—	—	INCO (3)
Ni-Vee bronze B <sup>c</sup>	—	87.0	5.0	2.0	5.0	—	—	1.0	—	—	—	INCO (3)
Ni-Vee bronze C <sup>c</sup>	—	80.0	5.0	5.0	5.0	—	—	5.0	—	—	—	INCO (3)

<sup>a</sup>Copper Development Association alloy number.<sup>b</sup>Numbers refer to references at end of report.<sup>c</sup>Cast alloy.

Table 19. Corrosion Rates and Types of Corrosion of Copper Alloys (Bronzes)

Alloy	CDA No. <sup>a</sup>	Environment <sup>b</sup>	Exposure (day)	Depth (ft)	Corrosion Rate (mpy)	Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
G Bronze <sup>e</sup>	—	W	123	5,640	0.5	U	INCO (3)
G Bronze	—	S	123	5,640	0.3	U	INCO (3)
G Bronze	—	W	403	6,780	0.7	U	INCO (3)
G Bronze	—	S	403	6,780	0.1	GBSL	INCO (3)
G Bronze	—	W	751	5,640	0.7	U	INCO (3)
G Bronze	—	S	751	5,640	0.3	U	INCO (3)
G Bronze	—	W	1,064	5,300	0.3	U	INCO (3)
G Bronze	—	S	1,064	5,300	0.4	U	INCO (3)
G Bronze	—	W	197	2,340	0.2	U	INCO (3)
G Bronze	—	S	197	2,340	<0.1	I-C	INCO (3)
G Bronze	—	W	402	2,370	0.3	U	INCO (3)
G Bronze	—	S	402	2,370	<0.1	ET	INCO (3)
G Bronze	—	W	181	5	1.3	G	INCO (3)
G Bronze	—	W	366	5	1.2	CR (9)	INCO (3)
Modified G Bronze <sup>e</sup>	—	W	123	5,640	0.5	U	INCO (3)
Modified G Bronze	—	S	123	5,640	0.3	U	INCO (3)
Modified G Bronze	—	W	403	6,780	0.4	U	INCO (3)
Modified G Bronze	—	S	403	6,780	<0.1	U	INCO (3)
Modified G Bronze	—	W	751	5,640	0.7	U	INCO (3)
Modified G Bronze	—	S	751	5,640	0.4	C (19)	INCO (3)
Modified G Bronze	—	W	1,064	5,300	0.4	C (18); P	INCO (3)
Modified G Bronze	—	S	1,064	5,300	0.5	U	INCO (3)
Modified G Bronze	—	W	197	2,340	0.3	U	INCO (3)
Modified G Bronze	—	S	197	2,340	0.2	NU-ET	INCO (3)
Modified G Bronze	—	W	402	2,370	0.3	U	INCO (3)
Modified G Bronze	—	S	402	2,370	<0.1	ET	INCO (3)
Modified G Bronze	—	W	181	5	1.3	G	INCO (3)
Modified G Bronze	—	W	366	5	1.0	CR (7)	INCO (3)
M Bronze <sup>e</sup>	—	W	123	5,640	0.5	U	INCO (3)
M Bronze	—	S	123	5,640	0.4	U	INCO (3)
M Bronze	—	W	403	6,780	0.4	U	INCO (3)
M Bronze	—	S	403	6,780	<0.1	U	INCO (3)
M Bronze	—	W	751	5,640	0.7	U	INCO (3)
M Bronze	—	S	751	5,640	0.3	U	INCO (3)
M Bronze	—	W	1,064	5,300	0.4	U	INCO (3)
M Bronze	—	S	1,064	5,300	0.4	U	INCO (3)
M Bronze	—	W	197	2,340	0.4	U	INCO (3)
M Bronze	—	S	197	2,340	0.1	ET	INCO (3)
M Bronze	—	W	402	2,370	0.3	U	INCO (3)
M Bronze	—	S	402	2,370	<0.1	ET	INCO (3)
M Bronze	—	W	181	5	1.6	G	INCO (3)
M Bronze	—	W	366	5	1.1	CR (2)	INCO (3)
Leaded Sn Bronze <sup>e</sup>	—	W	123	5,640	0.4	U	INCO (3)
Leaded Sn Bronze	—	S	123	5,640	0.2	U	INCO (3)
Leaded Sn Bronze	—	W	403	6,780	0.5	U	INCO (3)
Leaded Sn Bronze	—	S	403	6,780	0.1	U	INCO (3)
Leaded Sn Bronze	—	W	751	5,640	0.6	U	INCO (3)
Leaded Sn Bronze	—	S	751	5,640	3.2	S-G	INCO (3)
Leaded Sn Bronze	—	W	1,064	5,300	0.4	U	INCO (3)

Continued



Table 19. Continued.

Alloy	CDA No. <sup>a</sup>	Environment <sup>b</sup>	Exposure (day)	Depth (ft)	Corrosion Rate (mpy)	Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
Leaded Sn Bronze	—	S	1,064	5,300	0.3	U	INCO (3)
Leaded Sn Bronze	—	W	197	2,340	0.5	U	INCO (3)
Leaded Sn Bronze	—	S	197	2,340	<0.1	NU-ET	INCO (3)
Leaded Sn Bronze	—	W	402	2,370	0.5	U	INCO (3)
Leaded Sn Bronze	—	S	402	2,370	<0.1	ET	INCO (3)
Leaded Sn Bronze	—	W	181	5	1.4	G	INCO (3)
Leaded Sn Bronze	—	W	366	5	1.3	CR (5)	INCO (3)
P Bronze A	510	W	123	5,640	0.6	U	CEL (4)
P Bronze A	510	W	123	5,640	0.5	U	INCO (3)
P Bronze A	510	S	123	5,640	0.4	U	CEL (4)
P Bronze A	510	S	123	5,640	0.4	U	INCO (3)
P Bronze A	510	W	403	6,780	0.2	ET	CEL (4)
P Bronze A	510	W	403	6,780	0.3	U	INCO (3)
P Bronze A	510	S	403	6,780	0.3	ET	CEL (4)
P Bronze A	510	S	403	6,780	0.1	GBSL	INCO (3)
P Bronze A	510	W	751	5,640	0.2	ET	CEL (4)
P Bronze A	510	W	751	5,640	0.3	U	INCO (3)
P Bronze A	510	S	751	5,640	0.1	U	INCO (3)
P Bronze A	510	W	1,064	5,300	0.4	U	CEL (4)
P Bronze A	510	W	1,064	5,300	0.2	U	INCO (3)
P Bronze A	510	S	1,064	5,300	0.4	G	INCO (3)
P Bronze A	510	W	197	2,340	0.3	U	CEL (4)
P Bronze A	510	W	197	2,340	0.4	U	INCO (3)
P Bronze A	510	S	197	2,340	0.3	f	CEL (4)
P Bronze A	510	S	197	2,340	<0.1	I-C	INCO (3)
P Bronze A	510	W	402	2,370	0.1	ET	CEL (4)
P Bronze A	510	W	402	2,370	0.2	U	INCO (3)
P Bronze A	510	S	402	2,370	0.2	EWO	CEL (4)
P Bronze A	510	S	402	2,370	0.2	ET	INCO (3)
P Bronze A	510	W	181	5	1.1	U	CEL (4)
P Bronze A	510	W	181	5	1.6	P (4)	INCO (3)
P Bronze A	510	W	366	5	1.3	CR (5)	INCO (3)
P Bronze A	510	W	588	5	1.3	CR (15); C (3)	CEL (4)
P Bronze A	510	W	608	5	1.1	CR (15)	CEL (4)
P Bronze D	524	W	123	5,640	0.5	U	CEL (4)
P Bronze D	524	S	123	5,640	0.4	U	CEL (4)
P Bronze D	524	W	403	6,780	0.2	ET	CEL (4)
P Bronze D	524	S	403	6,780	0.3	ET	CEL (4)
P Bronze D	524	W	751	5,640	0.3	U	CEL (4)
P Bronze D	524	S	751	5,640	0.4	NU	CEL (4)
P Bronze D	524	W	197	2,340	0.4	U	CEL (4)
P Bronze D	524	S	197	2,340	0.2	U	CEL (4)
P Bronze D	524	W	402	2,370	<0.1	U	CEL (4)
P Bronze D	524	S	402	2,370	<0.1	U	CEL (4)
P Bronze D	524	W	181	5	1.1	NU	CEL (4)
P Bronze D	524	W	398	5	0.9	CR (4)	CEL (4)
P Bronze D	524	W	540	5	0.7	CR (2)	CEL (4)
P Bronze D	524	W	608	5	0.7	CR (7); C (5)	CEL (4)
Al Bronze, 5%	606	W	123	5,640	0.6	U	INCO (3)
Al Bronze, 5%	606	S	123	5,640	0.4	U	INCO (3)

Continued

Table 19. Continued.

Alloy	CDA No. <sup>a</sup>	Environment <sup>b</sup>	Exposure (day)	Depth (ft)	Corrosion Rate (mpy)	Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
Al Bronze, 5%	606	W	403	6,780	0.2	SL-DA	INCO (3)
Al Bronze, 5%	606	S	403	6,780	<0.1	U	INCO (3)
Al Bronze, 5%	606	W	751	5,640	0.3	SL-DA	INCO (3)
Al Bronze, 5%	606	S	751	5,640	0.2	V-SL-DA	INCO (3)
Al Bronze, 5%	606	W	1,064	5,300	0.2	NU	CEL (4)
Al Bronze, 5%	606	W	1,064	5,300	0.2	CR (5)	INCO (3)
Al Bronze, 5%	606	S	1,064	5,300	0.5	G	INCO (3)
Al Bronze, 5%	606	W	197	2,340	0.4	U	INCO (3)
Al Bronze, 5%	606	S	197	2,340	0.2	NU-ET	INCO (3)
Al Bronze, 5%	606	W	197	2,340	0.2	U	Boeing (6)
Al Bronze, 5%	606	W	402	2,370	0.2	U	INCO (3)
Al Bronze, 5%	606	S	402	2,370	0.1	ET	INCO (3)
Al Bronze, 5%	606	W	181	5	1.1	G	INCO (3)
Al Bronze, 5%	606	W	366	5	0.7	G	INCO (3)
Al Bronze, 7%	614		123	5,640	0.5	SL-DA	CEL (4)
Al Bronze, 7%	614	W	123	5,640	0.6	U	INCO (3)
Al Bronze, 7%	614	S	123	5,640	0.3	U	CEL (4)
Al Bronze, 7%	614	S	123	5,640	0.4	U	INCO (3)
Al Bronze, 7%	614	W	403	6,780	0.7	SL-DA; C (12); P (12)	CEL (4)
Al Bronze, 7%	614	W	403	6,780	0.2	U	INCO (3)
Al Bronze, 7%	614	S	403	6,780	0.7	SL-DA; C (13); P (16)	CEL (4)
Al Bronze, 7%	614	S	403	6,780	<0.1	SL-DA	INCO (3)
Al Bronze, 7%	614	W	403	6,780	NC	NC	NADC (7)
Al Bronze, 7%	614	W	751	5,640	0.5	MD-DA; C (7); P (12)	CEL (4)
Al Bronze, 7%	614	W	751	5,640	1.5	G	INCO (3)
Al Bronze, 7%	614	S	751	5,640	0.2	V-SL-DA	INCO (3)
Al Bronze, 7%	614	W	1,064	5,300	0.2	CR (7)	INCO (3)
Al Bronze, 7%	614	S	1,064	5,300	0.2	MO-DA	INCO (3)
Al Bronze, 7%	614	W	197	2,340	0.3	U	CEL (4)
Al Bronze, 7%	614	W	197	2,340	0.3	U	INCO (3)
Al Bronze, 7%	614	S	197	2,340	0.1	U	CEL (4)
Al Bronze, 7%	614	S	197	2,340	0.2	ET	INCO (3)
Al Bronze, 7%	614	W	402	2,370	0.2	U	CEL (4)
Al Bronze, 7%	614	W	402	2,370	0.2	ET	INCO (3)
Al Bronze, 7%	614	S	402	2,370	0.2	U	INCO (3)
Al Bronze, 7%	614	S	402	2,370	0.1	SL-DA	INCO (3)
Al Bronze, 7%	614	W	181	5	2.9	NU-DA	CEL (4)
Al Bronze, 7%	614	W	181	5	0.8	G	INCO (3)
Al Bronze, 7%	614	W	366	5	0.6	G	INCO (3)
Al Bronze, 7%	614	W	588	5	0.9	SL-DA; CR (44); C (20)	CEL (4)
Al Bronze, 10% <sup>e</sup>	—	W	123	5,640	0.7	SL-DA	INCO (3)
Al Bronze, 10%	—	S	123	5,640	0.6	SL-DA	INCO (3)
Al Bronze, 10%	—	W	403	6,780	0.7	MO-DA	INCO (3)
Al Bronze, 10%	—	S	403	6,780	<0.1	SL-DA	INCO (3)
Al Bronze, 10%	—	W	751	5,640	2.3	G	INCO (3)
Al Bronze, 10%	—	S	751	5,640	0.9	U; SL-DA	INCO (3)
Al Bronze, 10%	—	W	1,064	5,300	0.2	U	INCO (3)
Al Bronze, 10%	—	S	1,064	5,300	0.4	SL-DA	INCO (3)
Al Bronze, 10%	—	W	197	2,340	0.3	MO-DA	INCO (3)
Al Bronze, 10%	—	S	197	2,340	0.2	MO-DA	INCO (3)

Continued

Table 19. Continued.

Alloy	CDA No. <sup>a</sup>	Environment <sup>b</sup>	Exposure (day)	Depth (ft)	Corrosion Rate (mpy)	Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
Al Bronze, 10%	—	W	402	2,370	0.3	S-DA	INCO (3)
Al Bronze, 10%	—	S	402	2,370	<0.1	MO-DA	INCO (3)
Al Bronze, 10%	—	W	181	5	2.1	MO-DA	INCO (3)
Al Bronze, 10%	—	W	366	5	1.3	MO-DA	INCO (3)
Al Bronze, 11% <sup>e</sup>	—	W	123	5,640	0.4	U	MEL (5)
Al Bronze, 11%	—	W	123	5,640	0.5	V-SL-DA	INCO (3)
Al Bronze, 11%	—	S	123	5,640	0.4	V-SL-DA	INCO (3)
Al Bronze, 11%	—	W	403	6,780	0.1	SL-DA	INCO (3)
Al Bronze, 11%	—	S	403	6,780	<0.1	SL-DA	INCO (3)
Al Bronze, 11%	—	W	751	5,640	0.8	SL-DA	INCO (3)
Al Bronze, 11%	—	W	751	5,640	0.3	U-P	MEL (5)
Al Bronze, 11%	—	S	751	5,640	0.1	V-SL-DA	INCO (3)
Al Bronze, 11%	—	W	1,064	5,300	0.1	SL-DA	INCO (3)
Al Bronze, 11%	—	S	1,064	5,300	0.2	MO-DA	INCO (3)
Al Bronze, 11%	—	W	197	2,340	0.2	SL-DA <sup>g</sup>	INCO (3)
Al Bronze, 11%	—	S	197	2,340	<0.1	SL-DA <sup>b</sup>	INCO (3)
Al Bronze, 11%	—	W	402	2,370	0.2	MO-DA	INCO (3)
Al Bronze, 11%	—	S	402	2,370	<0.1	SL-DA	INCO (3)
Al Bronze, 11%	—	W	366	5	1.1	U	INCO (3)
Al Bronze, 13% <sup>e</sup>	—	W	123	5,640	0.5	V-SL-DA	INCO (3)
Al Bronze, 13%	—	S	123	5,640	0.5	V-SL-DA	INCO (3)
Al Bronze, 13%	—	W	403	6,780	0.6	S-DA	INCO (3)
Al Bronze, 13%	—	S	403	6,780	<0.1	SL-DA	INCO (3)
Al Bronze, 13%	—	W	751	5,640	1.9	S-DA	INCO (3)
Al Bronze, 13%	—	S	751	5,640	0.5	MO-DA	INCO (3)
Al Bronze, 13%	—	W	1,064	5,300	0.6	S-DA	INCO (3)
Al Bronze, 13%	—	S	1,064	5,300	0.3	SL-DA	INCO (3)
Al Bronze, 13%	—	W	197	2,340	0.4	MO-DA	INCO (3)
Al Bronze, 13%	—	S	197	2,340	<0.1	SL-DA	INCO (3)
Al Bronze, 13%	—	W	402	2,370	0.3	MO-DA	INCO (3)
Al Bronze, 13%	—	S	402	2,370	<0.1	SL-DA	INCO (3)
Al Bronze, 13%	—	W	181	5	2.1	S-DA	INCO (3)
Al Bronze, 13%	—	W	366	5	1.9	S-DA	INCO (3)
Ni-Al Bronze	—	W	123	5,640	0.6	P	MEL (5)
Ni-Al Bronze	—	W	751	5,640	0.4	P (21)	MEL (5)
Ni-Al Bronze No. 1	—	W	123	5,640	0.5	U	MEL (5)
Ni-Al Bronze No. 1	—	W	123	5,640	0.4	I-P	INCO (3)
Ni-Al Bronze No. 1	—	S	123	5,640	0.2	I-P	INCO (3)
Ni-Al Bronze No. 1	—	W	403	6,780	0.3	I-P	INCO (3)
Ni-Al Bronze No. 1	—	S	403	6,780	0.1	U	INCO (3)
Ni-Al Bronze No. 1	—	W	751	5,640	1.1	C (16); P	INCO (3)
Ni-Al Bronze No. 1	—	W	751	5,640	0.2	P	MEL (5)
Ni-Al Bronze No. 1	—	S	751	5,640	0.3	P (17)	INCO (3)
Ni-Al Bronze No. 1	—	W	1,064	5,300	0.1	P (8)	INCO (3)
Ni-Al Bronze No. 1	—	S	1,064	5,300	1.2	CR (30)	INCO (3)
Ni-Al Bronze No. 1	—	W	197	2,340	0.3	U	INCO (3)
Ni-Al Bronze No. 1	—	S	197	2,340	<0.1	U-ET	INCO (3)

Continued

Table 19. Continued.

Alloy	CDA No. <sup>a</sup>	Environment <sup>b</sup>	Exposure (day)	Depth (ft)	Corrosion Rate (mpy)	Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
Ni-Al Bronze No. 2	—	W	123	5,640	0.5	U	INCO (3)
Ni-Al Bronze No. 2	—	S	123	5,640	0.3	U	INCO (3)
Ni-Al Bronze No. 2	—	W	403	6,780	0.2	I-P	INCO (3)
Ni-Al Bronze No. 2	—	S	403	6,780	0.1	U	INCO (3)
Ni-Al Bronze No. 2	—	W	751	5,640	0.5	SL-DA	INCO (3)
Ni-Al Bronze No. 2	—	S	751	5,640	0.2	C (13)	INCO (3)
Ni-Al Bronze No. 2	—	W	1,064	5,300	0.2	C (5)	INCO (3)
Ni-Al Bronze No. 2	—	S	1,064	5,300	0.5	CR (21)	INCO (3)
Ni-Al Bronze No. 2	—	W	197	2,340	0.3	U	INCO (3)
Ni-Al Bronze No. 2	—	S	197	2,340	0.1	U	INCO (3)
Ni-Al Bronze No. 2	—	W	402	2,370	0.2	U	INCO (3)
Ni-Al Bronze No. 2	—	S	402	2,370	<0.1	ET	INCO (3)
Ni-Al Bronze No. 2	—	W	181	5	1.0	C (8)	INCO (3)
Ni-Al Bronze No. 2	—	W	366	5	0.4	U	INCO (3)
Ni-Al Bronze No. 3	—	W	123	5,640	0.4	U	INCO (3)
Ni-Al Bronze No. 3	—	S	123	5,640	0.3	U	INCO (3)
Ni-Al Bronze No. 3	—	W	403	6,780	0.2	U	INCO (3)
Ni-Al Bronze No. 3	—	S	403	6,780	<0.1	NU-ET	INCO (3)
Ni-Al Bronze No. 3	—	W	751	5,640	0.2	I-P	INCO (3)
Ni-Al Bronze No. 3	—	S	751	5,640	0.1	U	INCO (3)
Ni-Al Bronze No. 3	—	W	1,064	5,300	<0.1	P (4)	INCO (3)
Ni-Al Bronze No. 3	—	S	1,064	5,300	0.2	CR (10)	INCO (3)
Ni-Al Bronze No. 3	—	W	197	2,340	0.3	U	INCO (3)
Ni-Al Bronze No. 3	—	S	197	2,340	0.2	U	INCO (3)
Si Bronze, 3%	653	W	123	5,640	1.3	U	INCO (3)
Si Bronze, 3%	653	S	123	5,640	1.5	U	INCO (3)
Si Bronze, 3%	653	W	403	6,780	1.2	MO-CO	INCO (3)
Si Bronze, 3%	653	S	403	6,780	0.4	GBSL	INCO (3)
Si Bronze, 3%	653	W	751	5,640	1.0	U	INCO (3)
Si Bronze, 3%	653	S	751	5,640	0.7	U	INCO (3)
Si Bronze, 3%	653	W	1,064	5,300	0.6	MO-CO	INCO (3)
Si Bronze, 3%	653	S	1,064	5,300	0.4	SL-CO	INCO (3)
Si Bronze, 3%	653	W	197	2,340	1.1	U	INCO (3)
Si Bronze, 3%	653	S	197	2,340	0.1	NU-ET	INCO (3)
Si Bronze, 3%	653	W	402	2,370	1.2	U	INCO (3)
Si Bronze, 3%	653	S	402	2,370	0.2	ET	INCO (3)
Si Bronze, 3%	653	W	181	5	1.7	U	INCO (3)
Si Bronze, 3%	653	W	366	5	1.1	G	INCO (3)
Si Bronze A	655	W	123	5,640	1.6	U	CEL (4)
Si Bronze A	655	W	123	5,640	1.4	U	INCO (3)
Si Bronze A	655	S	123	5,640	1.8	U	CEL (4)
Si Bronze A	655	S	123	5,640	1.5	U	INCO (3)
Si Bronze A	655	W	403	6,780	1.2	CO	CEL (4)
Si Bronze A	655	W	403	6,780	1.2	U	INCO (3)
Si Bronze A	655	S	403	6,780	1.8	ET	CEL (4)
Si Bronze A	655	S	403	6,780	0.2	GBSL	INCO (3)
Si Bronze A	655	W	751	5,640	0.8	S-CO	CEL (4)
Si Bronze A	655	W	751	5,640	1.4	U	INCO (3)
Si Bronze A	655	S	751	5,640	0.9	G	INCO (3)

Continued

Table 19. Continued.

Alloy	CDA No. <sup>a</sup>	Environment <sup>b</sup>	Exposure (day)	Depth (ft)	Corrosion Rate (mpy)	Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
Si Bronze A	655	W	1,064	5,300	0.6	SL-CO	INCO (3)
Si Bronze A	655	S	1,064	5,300	0.4	U	INCO (3)
Si Bronze A	655	W	197	2,340	0.8	U	Boeing (6)
Si Bronze A	655	W	197	2,340	0.9	U	CEL (4)
Si Bronze A	655	W	197	2,340	1.1	U	INCO (3)
Si Bronze A	655	S	197	2,340	0.6	U	CEL (4)
Si Bronze A	655	S	197	2,340	0.2	U	INCO (3)
Si Bronze A	655	W	402	2,370	1.0	ET	CEL (4)
Si Bronze A	655	W	402	2,370	0.8	U	INCO (3)
Si Bronze A	655	S	402	2,370	0.8	ET	CEL (4)
Si Bronze A	655	S	402	2,370	0.1	ET	INCO (3)
Si Bronze A	655	W	181	5	1.8	U	CEL (4)
Si Bronze A	655	W	181	5	1.6	G	INCO (3)
Si Bronze A	655	W	366	5	1.2	G	INCO (3)
Si Bronze A	655	W	398	5	1.1	G	CEL (4)
Si Bronze A	655	W	540	5	2.5	CR (30); C (15)	CEL (4)
Si Bronze A	655	W	588	5	0.9	CR (9)	CEL (4)
Ni-Vee Bronze A <sup>e</sup>	—	W	123	5,640	0.7	U	INCO (3)
Ni-Vee Bronze A	—	S	123	5,640	0.5	U	INCO (3)
Ni-Vee Bronze A	—	W	403	6,780	0.6	U	INCO (3)
Ni-Vee Bronze A	—	S	403	6,780	0.3	U	INCO (3)
Ni-Vee Bronze A	—	W	751	5,640	2.6	S <sup>i</sup>	INCO (3)
Ni-Vee Bronze A	—	S	751	5,640	0.4	U	INCO (3)
Ni-Vee Bronze A	—	W	1,064	5,300	2.2	CR (20)	INCO (3)
Ni-Vee Bronze A	—	S	1,064	5,300	0.3	U	INCO (3)
Ni-Vee Bronze A	—	W	197	2,340	0.6	U	INCO (3)
Ni-Vee Bronze A	—	S	197	2,340	<0.1	NU-ET	INCO (3)
Ni-Vee Bronze A	—	W	402	2,370	0.4	U	INCO (3)
Ni-Vee Bronze A	—	S	402	2,370	<0.1	ET	INCO (3)
Ni-Vee Bronze A	—	W	181	5	2.0	P (7)	INCO (3)
Ni-Vee Bronze A	—	W	366	5	1.5	CR (10)	INCO (3)
Ni-Vee Bronze B <sup>e</sup>	—	W	123	5,640	0.6	U	INCO (3)
Ni-Vee Bronze B	—	S	123	5,640	0.4	U	INCO (3)
Ni-Vee Bronze B	—	W	403	6,780	0.5	U	INCO (3)
Ni-Vee Bronze B	—	S	403	6,780	0.1	U	INCO (3)
Ni-Vee Bronze B	—	W	751	5,640	0.5	U	INCO (3)
Ni-Vee Bronze B	—	S	751	5,640	0.3	U	INCO (3)
Ni-Vee Bronze B	—	W	1,064	5,300	0.3	U	INCO (3)
Ni-Vee Bronze B	—	S	1,064	5,300	0.4	U	INCO (3)
Ni-Vee Bronze B	—	W	197	2,340	0.6	U	INCO (3)
Ni-Vee Bronze B	—	S	197	2,340	<0.1	NU-ET	INCO (3)
Ni-Vee Bronze B	—	W	402	2,370	1.2	U	INCO (3)
Ni-Vee Bronze B	—	S	402	2,370	<0.1	ET	INCO (3)
Ni-Vee Bronze B	—	W	181	5	1.8	P (4)	INCO (3)
Ni-Vee Bronze B	—	W	366	5	1.3	CR (6)	INCO (3)
Ni-Vee Bronze C <sup>e</sup>	—	W	123	5,640	0.8	U	INCO (3)
Ni-Vee Bronze C	—	S	123	5,640	0.5	U	INCO (3)
Ni-Vee Bronze C	—	W	403	6,780	0.8	U	INCO (3)
Ni-Vee Bronze C	—	S	403	6,780	0.2	U	INCO (3)
Ni-Vee Bronze C	—	W	751	5,640	2.0	G	INCO (3)

Continued

Table 19. Continued.

Alloy	CDA No. <sup>a</sup>	Environment <sup>b</sup>	Exposure (day)	Depth (ft)	Corrosion Rate (mpy)	Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
Ni-Vee Bronze C	—	S	751	5,640	0.4	U	INCO (3)
Ni-Vee Bronze C	—	W	1,064	5,300	0.5	U	INCO (3)
Ni-Vee Bronze C	—	S	1,064	5,300	0.3	U	INCO (3)
Ni-Vee Bronze C	—	W	197	2,340	0.8	U	INCO (3)
Ni-Vee Bronze C	—	S	197	2,340	<0.1	ET	INCO (3)
Ni-Vee Bronze C	—	W	402	2,370	0.6	U	INCO (3)
Ni-Vee Bronze C	—	S	402	2,370	0.1	ET	INCO (3)
Ni-Vee Bronze C	—	W	181	5	1.8	U	INCO (3)
Ni-Vee Bronze C	—	W	366	5	1.5	CR (5)	INCO (3)

<sup>a</sup>Copper Development Association alloy number.

<sup>b</sup>W = Totally exposed in seawater on sides of structure; S = Exposed in base of structure so that a portion of each specimen was exposed in the bottom sediments.

<sup>c</sup>Symbols for types of corrosion:

C	= Crevice	I	= Incipient
CO	= Coppering, a selective attack where copper appears on surface similar to dezincification	MD	= Medium
CR	= Cratering	MO	= Moderate
DA	= Dealuminification	NU	= Nonuniform
ET	= Etching	P	= Pitting
EWO	= Etched only in the water	S	= Severe
G	= General	SL	= Slight
GBSL	= General below sediment line	U	= Uniform
		V	= Very

Numbers indicate maximum depth in mils.

<sup>d</sup>Numbers refer to references at end of report.

<sup>e</sup>Cast alloy.

<sup>f</sup>Pitting in bottom sediment, 12 mils maximum.

<sup>g</sup>At spacer.

<sup>h</sup>At crevice.

<sup>i</sup>Severe corrosion in small area.



Table 20. Stress Corrosion of Copper Alloys (Bronzes)

Alloy	CDA No. <sup>a</sup>	Stress (ksi)	Tensile Strength (%)	Exposure (day)	Depth (ft)	Specimens		Source <sup>b</sup>
						Exposed	Failed	
Phosphor bronze A	510	12.0	50	403	6,780	2	0	CEL (4)
Phosphor bronze A	510	19.0	75	403	6,780	2	0	CEL (4)
Phosphor bronze A	510	12.5	50	197	2,340	3	0	CEL (4)
Phosphor bronze A	510	18.7	75	197	2,340	3	0	CEL (4)
Phosphor bronze A	510	12.6	50	402	2,370	3	0	CEL (4)
Phosphor bronze A	510	19.0	75	402	2,370	3	0	CEL (4)
Phosphor bronze D	524	10.0	35	403	6,780	2	0	CEL (4)
Phosphor bronze D	524	14.0	50	403	6,780	2	0	CEL (4)
Phosphor bronze D	524	21.0	75	403	6,780	2	0	CEL (4)
Phosphor bronze D	524	9.8	35	197	2,340	3	0	CEL (4)
Phosphor bronze D	524	13.9	50	197	2,340	3	0	CEL (4)
Phosphor bronze D	524	20.9	75	197	2,340	3	0	CEL (4)
Phosphor bronze D	524	16.4	50	402	2,370	3	0	CEL (4)
Phosphor bronze D	524	24.5	75	402	2,370	3	0	CEL (4)
Al bronze, 5%	606	18.0	35	403	6,780	2	0	CEL (4)
Al bronze, 5%	606	26.0	50	403	6,780	2	0	CEL (4)
Al bronze, 5%	606	38.0	75	403	6,780	2	0	CEL (4)
Al bronze, 5%	606	17.9	35	197	2,340	3	0	CEL (4)
Al bronze, 5%	606	25.6	50	197	2,340	3	0	CEL (4)
Al bronze, 5%	606	38.4	75	197	2,340	3	0	CEL (4)
Al bronze, 5%	606	28.3	50	402	2,370	3	0	CEL (4)
Al bronze, 5%	606	42.5	75	402	2,370	3	0	CEL (4)
Si bronze A	655	10.0	35	403	6,780	2	0	CEL (4)
Si bronze A	655	14.0	50	403	6,780	2	0	CEL (4)
Si bronze A	655	21.0	75	403	6,780	2	0	CEL (4)
Si bronze A	655	9.6	35	197	2,340	3	0	CEL (4)
Si bronze A	655	13.8	50	197	2,340	3	0	CEL (4)
Si bronze A	655	20.6	75	197	2,340	3	0	CEL (4)
Si bronze A	655	10.8	50	402	2,370	3	0	CEL (4)
Si bronze A	655	16.2	75	402	2,370	3	0	CEL (4)

<sup>a</sup>Copper Development Association alloy number.<sup>b</sup>Numbers refer to references at end of report.

Table 21. Changes in Mechanical Properties of Copper Alloys (Bronzes) Due to Corrosion

Alloy	CDA No. <sup>a</sup>	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>b</sup>
				Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
Phosphor bronze A	510	123	5,640	51	0	25	-3	64	+3	CEL (4)
Phosphor bronze A	510	403	6,780	51	+1	25	-1	64	+2	CEL (4)
Phosphor bronze A	510	751	5,640	51	+1	25	-1	64	-1	CEL (4)
Phosphor bronze A	510	197	2,340	51	-3	25	-13	64	-1	CEL (4)
Phosphor bronze A	510	402	2,370	51	-1	25	-3	64	-3	CEL (4)
Phosphor bronze A	510	181	5	51	0	25	-7	64	-2	CEL (4)
Phosphor bronze D	524	123	5,640	64	+1	28	0	70	0	CEL (4)
Phosphor bronze D	524	403	6,780	64	+2	28	+1	70	+3	CEL (4)
Phosphor bronze D	524	751	5,640	64	+2	28	+3	70	-1	CEL (4)
Phosphor bronze D	524	197	2,340	64	0	28	-3	70	+3	CEL (4)
Phosphor bronze D	524	402	2,370	64	+1	28	+1	70	-1	CEL (4)
Phosphor bronze D	524	181	5	64	-1	28	+1	70	+4	CEL (4)
Al bronze, 5%	606	123	5,640	85	0	51	+2	45	-9	CEL (4)
Al bronze, 5%	606	403	6,780	85	-1	51	0	45	-29	CEL (4)
Al bronze, 5%	606	751	5,640	85	0	51	+1	45	-27	CEL (4)
Al bronze, 5%	606	197	2,340	85	0	51	-2	45	-7	CEL (4)
Al bronze, 5%	606	402	2,370	85	0	51	0	45	-12	CEL (4)
Al bronze, 5%	606	181	5	85	-3	51	-3	45	-20	CEL (4)
Si bronze A	655	123	5,640	64	+2	28	+4	61	-2	CEL (4)
Si bronze A	655	403	6,780 <sup>c</sup>	64	-1	28	-4	61	-1	CEL (4)
Si bronze A	655	403	6,780 <sup>d</sup>	64	-25	28	-18	61	-40	CEL (4)
Si bronze A	655	751	5,640	64	-1	28	-5	61	-1	CEL (4)
Si bronze A	655	197	2,340	64	-2	28	-14	61	-3	CEL (4)
Si bronze A	655	402	2,370	64	-1	28	-3	61	-2	CEL (4)
Si bronze A	655	181	5	64	-1	28	-7	61	+3	CEL (4)

<sup>a</sup>Copper Development Association alloy number.<sup>b</sup>Numbers refer to references at end of report.<sup>c</sup>Totally exposed in water.<sup>d</sup>Partially embedded in the bottom sediments.

Table 22. Chemical Composition of Copper-Nickel Alloys, Percent by Weight

Alloy	CDA No. <sup>a</sup>	Cu	Ni	Fe	Mn	Zn	Pb	Source <sup>b</sup>
Cu-Ni, 95-5	704	91.98	6.25	1.24	0.53	—	—	CEL (4)
Cu-Ni, 90-10	706	89.04	9.42	1.16	0.38	—	—	CEL (4)
Cu-Ni, 90-10	706	89.0	10.0	1.4	0.5	—	—	INCO (3)
Cu-Ni, 90-10	706	88.7	10.0	1.3	—	—	—	MEL (5)
Cu-Ni, 90-10 <sup>c</sup>	962	86.0	11.0	1.4	1.3	—	—	INCO (3)
Cu-Ni, 80-20	710	78.62	20.41	0.62	0.35	—	—	CEL (4)
Cu-Ni, 80-20	711	80.0	20.0	0.03	0.2	—	—	INCO (3)
Cu-Ni, 70-30	715	68.61	30.53	0.53	0.33	—	—	CEL (4)
Cu-Ni, 70-30	715	69.0	30.0	0.6	0.4	—	—	INCO (3)
Cu-Ni, 70-30	715	69.4	30.0	0.6	—	—	—	MEL (5)
Cu-Ni, 70-30	716	64.02	29.95	5.27	0.75	—	—	CEL (4)
Cu-Ni, 55-45	—	54.0	45.0	0.1	1.0	—	—	INCO (3)
Cu-Ni-Zn-Pb	—	62.0	25.0	—	—	8.0	5.0	INCO (3)
Nickel-silver	752	65.0	18.0	—	—	17.0	—	INCO (3)

<sup>a</sup>Copper Development Association alloy number.<sup>b</sup>Numbers refer to references at end of report.<sup>c</sup>Cast alloy.

Table 23. Corrosion Rates and Types of Corrosion of Copper-Nickel Alloys

Alloy	CDA No. <sup>a</sup>	Environment <sup>b</sup>	Exposure (day)	Depth (ft)	Corrosion Rate (mpy)	Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
Cu-Ni, 95-5	704	W	123	5,640	1.5	U	CEL (4)
Cu-Ni, 95-5	704	S	123	5,640	1.5	U	CEL (4)
Cu-Ni, 95-5	704	W	403	6,780	0.8	U	CEL (4)
Cu-Ni, 95-5	704	S	403	6,780	0.8	U	CEL (4)
Cu-Ni, 95-5	704	W	751	5,640	0.7	U	CEL (4)
Cu-Ni, 95-5	704	S	751	5,640	0.6	U	CEL (4)
Cu-Ni, 95-5	704	W	197	2,340	0.9	U	CEL (4)
Cu-Ni, 95-5	704	S	197	2,340	0.6	U	CEL (4)
Cu-Ni, 95-5	704	W	402	2,370	0.9	U	CEL (4)
Cu-Ni, 95-5	704	S	402	2,370	0.8	U	CEL (4)
Cu-Ni, 90-10	706	W	123	5,640	0.9	U	MEL (5)
Cu-Ni, 90-10	706	W	123	5,640	1.6	U	CEL (4)
Cu-Ni, 90-10	706	W	123	5,640	0.8	U	INCO (3)
Cu-Ni, 90-10	706	S	123	5,640	1.2	U	CEL (4)
Cu-Ni, 90-10	706	S	123	5,640	0.8	U	INCO (3)
Cu-Ni, 90-10	706	W	403	6,780	0.8	U	CEL (4)
Cu-Ni, 90-10	706	W	403	6,780	0.6	U	INCO (3)
Cu-Ni, 90-10	706	S	403	6,780	0.7	U	CEL (4)
Cu-Ni, 90-10	706	S	403	6,780	<0.1	U	INCO (3)
Cu-Ni, 90-10	706	W	751	5,640	0.5	U	MEL (5)
Cu-Ni, 90-10	706	W	751	5,640	0.7	U	CEL (4)
Cu-Ni, 90-10	706	W	751	5,640	0.6	U	INCO (3)
Cu-Ni, 90-10	706	S	751	5,640	0.5	U	INCO (3)
Cu-Ni, 90-10	706	W	1,064	5,300	0.6	U	MEL (5)
Cu-Ni, 90-10	706	W	1,064	5,300	0.7	U	INCO (3)
Cu-Ni, 90-10	706	S	1,064	5,300	0.2	G	INCO (3)
Cu-Ni, 90-10	706	W	197	2,340	0.8	U	CEL (4)
Cu-Ni, 90-10	706	W	197	2,340	0.8	U	INCO (3)
Cu-Ni, 90-10	706	S	197	2,340	0.5	U	CEL (4)
Cu-Ni, 90-10	706	S	197	2,340	<0.1	U	INCO (3)

Continued

Table 23. Continued.

Alloy	CDA No. <sup>a</sup>	Environment <sup>b</sup>	Exposure (day)	Depth (ft)	Corrosion Rate (mpy)	Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
Cu-Ni, 90-10	706	W	402	2,370	0.6	U <sup>e</sup>	CEL (4)
Cu-Ni, 90-10	706	W	402	2,370	0.8	U	INCO (3)
Cu-Ni, 90-10	706	S	402	2,370	0.5	U <sup>e</sup>	CEL (4)
Cu-Ni, 90-10	706	S	402	2,370	0.1	ET	INCO (3)
Cu-Ni, 90-10	706	W	181	5	1.1	NU	CEL (4)
Cu-Ni, 90-10	706	W	181	5	0.9	U	INCO (3)
Cu-Ni, 90-10	706	W	366	5	0.6	U	INCO (3)
Cu-Ni, 90-10 <sup>f</sup>	706	W	386	5	0.3	U	MEL (5)
Cu-Ni, 90-10	706	W	608	5	0.5	U	CEL (4)
Cu-Ni, 90-10 <sup>g</sup>	962	W	402	2,370	0.7	U	INCO (3)
Cu-Ni, 90-10 <sup>g</sup>	962	S	402	2,370	0.1	ET	INCO (3)
Cu-Ni, 90-10 <sup>g</sup>	962	W	181	5	1.1	U	INCO (3)
Cu-Ni, 90-10 <sup>g</sup>	962	W	366	5	0.9	U	INCO (3)
Cu-Ni, 80-20	710	W	123	5,640	1.2	U	CEL (4)
Cu-Ni, 80-20	711	W	123	5,640	1.9	U	INCO (3)
Cu-Ni, 80-20	710	S	123	5,640	1.3	U	CEL (4)
Cu-Ni, 80-20	711	S	123	5,640	1.1	U	INCO (3)
Cu-Ni, 80-20	710	W	403	6,780	1.2	ET	CEL (4)
Cu-Ni, 80-20	711	W	403	6,780	1.5	U	INCO (3)
Cu-Ni, 80-20	710	S	403	6,780	1.0	ET	CEL (4)
Cu-Ni, 80-20	711	S	403	6,780	0.1	EBSL	INCO (3)
Cu-Ni, 80-20	710	W	751	5,640	0.8	U	CEL (4)
Cu-Ni, 80-20	711	W	751	5,640	1.3	U	INCO (3)
Cu-Ni, 80-20	711	S	751	5,640	1.0	U	INCO (3)
Cu-Ni, 80-20	711	W	1,064	5,300	1.0	U	INCO (3)
Cu-Ni, 80-20	711	S	1,064	5,300	0.5	U	INCO (3)
Cu-Ni, 80-20	710	W	197	2,340	0.7	U	CEL (4)
Cu-Ni, 80-20	711	W	197	2,340	1.1	U	INCO (3)
Cu-Ni, 80-20	710	S	197	2,340	0.5	U	CEL (4)

Continued

Table 23. Continued.

Alloy	CDA No. <sup>a</sup>	Environment <sup>b</sup>	Exposure (day)	Depth (ft)	Corrosion Rate (mpy)	Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
Cu-Ni, 80-20	711	S	197	2,340	<0.1	SL-ET	INCO (3)
Cu-Ni, 80-20	710	W	402	2,370	0.6	U	CEL (4)
Cu-Ni, 80-20	711	W	402	2,370	1.1	U	INCO (3)
Cu-Ni, 80-20	710	S	402	2,370	0.5	U <sup>b</sup>	CEL (4)
Cu-Ni, 80-20	711	S	402	2,370	0.2	ET	INCO (3)
Cu-Ni, 80-20	711	W	181	5	2.8	G	INCO (3)
Cu-Ni, 80-20	711	W	366	5	1.9	G	INCO (3)
Cu-Ni, 70-30, 0.5 Fe	715	W	123	5,640	1.0	U	MEL (5)
Cu-Ni, 70-30, 0.5 Fe	715	W	123	5,640	1.2	U	CEL (4)
Cu-Ni, 70-30, 0.5 Fe	715	W	123	5,640	1.3	U	INCO (3)
Cu-Ni, 70-30, 0.5 Fe	715	S	123	5,640	0.8	U	CEL (4)
Cu-Ni, 70-30, 0.5 Fe	715	S	123	5,640	0.9	U	INCO (3)
Cu-Ni, 70-30, 0.5 Fe	715	W	403	6,780	1.2	U	CEL (4)
Cu-Ni, 70-30, 0.5 Fe	715	W	403	6,780	1.2	U	INCO (3)
Cu-Ni, 70-30, 0.5 Fe	715	S	403	6,780	1.1	U	CEL (4)
Cu-Ni, 70-30, 0.5 Fe	715	S	403	6,780	0.2	G	INCO (3)
Cu-Ni, 70-30, 0.5 Fe	715	W	751	5,640	0.4	U	MEL (5)
Cu-Ni, 70-30, 0.5 Fe	715	W	751	5,640	0.7	U	CEL (4)
Cu-Ni, 70-30, 0.5 Fe	715	W	751	5,640	0.9	G	INCO (3)
Cu-Ni, 70-30, 0.5 Fe	715	S	751	5,640	0.7	U	INCO (3)
Cu-Ni, 70-30, 0.5 Fe	715	W	1,064	5,300	0.5	U	MEL (5)
Cu-Ni, 70-30, 0.5 Fe	715	W	1,064	5,300	0.6	U	INCO (3)
Cu-Ni, 70-30, 0.5 Fe	715	S	1,064	5,300	0.5	G	INCO (3)
Cu-Ni, 70-30, 0.5 Fe	715	W	123	2,500	0.6	U	CEL (4)
Cu-Ni, 70-30, 0.5 Fe	715	W	197	2,340	0.7	U	CEL (4)
Cu-Ni, 70-30, 0.5 Fe	715	W	197	2,340	0.9	U	INCO (3)
Cu-Ni, 70-30, 0.5 Fe	715	S	197	2,340	0.2	U	CEL (4)
Cu-Ni, 70-30, 0.5 Fe	715	S	197	2,340	<0.1	SL-ET	INCO (3)
Cu-Ni, 70-30, 0.5 Fe	715	W	402	2,370	0.5	U	CEL (4)
Cu-Ni, 70-30, 0.5 Fe	715	W	402	2,370	0.6	U	INCO (3)

Continued



Table 23. Continued.

Alloy	CDA No. <sup>a</sup>	Environment <sup>b</sup>	Exposure (day)	Depth (ft)	Corrosion Rate (mpy)	Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
Cu-Ni, 70-30, 0.5 Fe	715	S	402	2,370	0.4	U	CEL (4)
Cu-Ni, 70-30, 0.5 Fe	715	S	402	2,370	0.1	ET	INCO (3)
Cu-Ni, 70-30, 0.5 Fe	715	W	181	5	0.5	U	CEL (4)
Cu-Ni, 70-30, 0.5 Fe	715	W	181	5	0.5	G	INCO (3)
Cu-Ni, 70-30, 0.5 Fe	715	W	366	5	0.4	G	INCO (3)
Cu-Ni, 70-30, 0.5 Fe <sup>f</sup>	715	W	386	5	0.2	U	MEL (5)
Cu-Ni, 70-30, 0.5 Fe	715	W	398	5	0.4	P (7)	CEL (4)
Cu-Ni, 70-30, 0.5 Fe	715	W	608	5	0.3	I-P	CEL (4)
Cu-Ni, 70-30, 5.0 Fe	716	W	123	5,640	0.2	U	CEL (4)
Cu-Ni, 70-30, 5.0 Fe	716	S	123	5,640	0.2	U	CEL (4)
Cu-Ni, 70-30, 5.0 Fe	716	W	403	6,780	0.1	ET	CEL (4)
Cu-Ni, 70-30, 5.0 Fe	716	S	403	6,780	0.1	ET	CEL (4)
Cu-Ni, 70-30, 5.0 Fe	716	W	751	5,640	0.5	C (16); NU-P (16); CO	CEL (4)
Cu-Ni, 70-30, 5.0 Fe	716	S	751	5,640	0.2	C (14); NU-P (24); CO	CEL (4)
Cu-Ni, 70-30, 5.0 Fe	716	W	197	2,340	0.1	U	CEL (4)
Cu-Ni, 70-30, 5.0 Fe	716	S	197	2,340	0.1	U	CEL (4)
Cu-Ni, 70-30, 5.0 Fe	716	W	402	2,370	0.1	U	CEL (4)
Cu-Ni, 70-30, 5.0 Fe	716	S	402	2,370	0.1	U	CEL (4)
Cu-Ni, 70-30, 5.0 Fe	716	W	181	5	0.8	I-P; C (5)	CEL (4)
Cu-Ni, 70-30, 5.0 Fe	716	W	398	5	0.7	CR (17); U	CEL (4)
Cu-Ni, 70-30, 5.0 Fe	716	W	608	5	0.6	C (13); CR (18)	CEL (4)
Cu-Ni, 55-45	—	W	123	5,640	0.7	U	INCO (3)
Cu-Ni, 55-45	—	S	123	5,640	0.7	U	INCO (3)
Cu-Ni, 55-45	—	W	403	6,780	1.2	U	INCO (3)
Cu-Ni, 55-45	—	S	403	6,780	<0.1	SL-ET	INCO (3)
Cu-Ni, 55-45	—	W	751	5,640	1.0	U	INCO (3)
Cu-Ni, 55-45	—	S	751	5,640	0.5	U	INCO (3)
Cu-Ni, 55-45	—	W	1,064	5,300	1.0	G	INCO (3)
Cu-Ni, 55-45	—	S	1,064	5,300	0.5	C to PR (50); S-E	INCO (3)

Continued

Table 23. Continued.

Alloy	CDA No. <sup>a</sup>	Environment <sup>b</sup>	Exposure (day)	Depth (ft)	Corrosion Rate (mpy)	Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
Cu-Ni, 55-45	—	W	197	2,340	0.8	U	INCO (3)
Cu-Ni, 55-45	—	S	197	2,340	0.2	I-C; I-P	INCO (3)
Cu-Ni, 55-45	—	W	402	2,370	0.7	U	INCO (3)
Cu-Ni, 55-45	—	S	402	2,370	0.1	ET	INCO (3)
Cu-Ni, 55-45	—	W	181	5	1.8	U	INCO (3)
Cu-Ni, 55-45	—	W	366	5	1.2	U	INCO (3)
Cu-Ni-Zn-Pb	—	W	123	5,640	0.9	U	INCO (3)
Cu-Ni-Zn-Pb	—	S	123	5,640	0.6	U	INCO (3)
Cu-Ni-Zn-Pb	—	W	403	6,780	0.8	U	INCO (3)
Cu-Ni-Zn-Pb	—	S	403	6,780	0.1	GBSL	INCO (3)
Cu-Ni-Zn-Pb	—	W	751	5,640	0.6	U	INCO (3)
Cu-Ni-Zn-Pb	—	S	751	5,640	0.5	U	INCO (3)
Cu-Ni-Zn-Pb	—	W	1,064	5,300	0.5	U	INCO (3)
Cu-Ni-Zn-Pb	—	S	1,064	5,300	0.3	U	INCO (3)
Cu-Ni-Zn-Pb	—	W	197	2,340	0.5	U	INCO (3)
Cu-Ni-Zn-Pb	—	S	197	2,340	<0.1	SL-ET	INCO (3)
Cu-Ni-Zn-Pb	—	W	402	2,370	0.4	U	INCO (3)
Cu-Ni-Zn-Pb	—	S	402	2,370	<0.1	ET	INCO (3)
Cu-Ni-Zn-Pb	—	W	181	5	1.0	U	INCO (3)
Cu-Ni-Zn-Pb	—	W	366	5	0.7	U	INCO (3)
Nickel-Silver	752	W	123	5,640	2.0	U	INCO (3)
Nickel-Silver	752	S	123	5,640	2.6	U	INCO (3)
Nickel-Silver	752	W	403	6,780	1.4	U	INCO (3)
Nickel-Silver	752	S	403	6,780	0.5	GBSL	INCO (3)
Nickel-Silver	752	W	751	5,640	1.5	U	INCO (3)
Nickel-Silver	752	S	751	5,640	0.8	U	INCO (3)
Nickel-Silver	752	W	1,064	5,300	0.6	U	INCO (3)
Nickel-Silver	752	S	1,064	5,300	0.4	G	INCO (3)
Nickel-Silver	752	W	197	2,340	1.0	U	INCO (3)

Continued

Table 23. Continued.

Alloy	CDA No. <sup>a</sup>	Environment <sup>b</sup>	Exposure (day)	Depth (ft)	Corrosion Rate (mpy)	Type of Corrosion <sup>c</sup>	Source <sup>d</sup>
Nickel-Silver	752	S	197	2,340	<0.1	SL-ET	INCO (3)
Nickel-Silver	752	W	402	2,370	1.0	U	INCO (3)
Nickel-Silver	752	S	402	2,370	0.1	ET	INCO (3)
Nickel-Silver	752	W	181	5	1.1	U	INCO (3)
Nickel-Silver	752	W	366	5	0.7	U	INCO (3)

<sup>a</sup>Copper Development Association alloy number.

<sup>b</sup>W = Totally exposed in seawater on sides of structure; S = Exposed in base of structure so that a portion of each specimen was embedded in the bottom sediments.

<sup>c</sup>Symbols for types of corrosion:

C	= Crevice	GBSL	= General below sediment line
CO	= Coppering, a selective attack where copper appears on surface	I	= Incipient
CR	= Cratering	NU	= Nonuniform
E	= Edge	P	= Pitting
ET	= Etching	PR	= Perforation
EBSL	= Etched below sediment line	S	= Severe
G	= General	SL	= Slight
		U	= Uniform

Numbers indicate maximum depth in mils.

<sup>d</sup>Numbers refer to references at end of report.

<sup>e</sup>Much less below sediment line.

<sup>f</sup>Exposed at Francis L. LaQue Corrosion Laboratory, INCO, Wrightsville Beach, N.C.

<sup>g</sup>Cast alloy.

<sup>h</sup>No visible corrosion below sediment line.

Table 24. Stress Corrosion of Copper-Nickel Alloys

Alloy	CDA No. <sup>a</sup>	Stress (ksi)	Tensile Strength (%)	Exposure (day)	Depth (ft)	Specimens		Source <sup>b</sup>
						Exposed	Failed	
Cu-Ni, 95-5	704	16.0	50	403	6,780	2	0	CEL (4)
Cu-Ni, 95-5	704	24.0	75	403	6,780	2	0	CEL (4)
Cu-Ni, 95-5	704	16.0	50	197	2,340	3	0	CEL (4)
Cu-Ni, 95-5	704	24.0	75	197	2,340	3	0	CEL (4)
Cu-Ni, 95-5	704	12.9	50	402	2,370	3	0	CEL (4)
Cu-Ni, 95-5	704	19.3	75	402	2,370	3	0	CEL (4)
Cu-Ni, 90-10	706	34.4	50	402	2,370	3	0	CEL (4)
Cu-Ni, 90-10	706	52.0	75	402	2,370	3	0	CEL (4)
Cu-Ni, 80-20	710	15.0	75	403	6,780	2	0	CEL (4)
Cu-Ni, 80-20	710	15.0	75	197	2,340	3	0	CEL (4)
Cu-Ni, 80-20	710	8.9	50	402	2,370	3	0	CEL (4)
Cu-Ni, 80-20	710	13.3	75	402	2,370	3	0	CEL (4)
Cu-Ni, 70-30, 0.5 Fe	715	13.0	50	403	6,780	2	0	CEL (4)
Cu-Ni, 70-30, 0.5 Fe	715	20.0	75	403	6,780	2	0	CEL (4)
Cu-Ni, 70-30, 0.5 Fe	715	13.2	50	197	2,340	3	0	CEL (4)
Cu-Ni, 70-30, 0.5 Fe	715	19.8	75	197	2,340	3	0	CEL (4)
Cu-Ni, 70-30, 0.5 Fe	715	14.0	50	402	2,370	3	0	CEL (4)
Cu-Ni, 70-30, 0.5 Fe	715	21.0	75	402	2,370	3	0	CEL (4)
Cu-Ni, 70-30, 5.0 Fe	716	14.0	35	403	6,780	2	0	CEL (4)
Cu-Ni, 70-30, 5.0 Fe	716	21.0	50	403	6,780	2	0	CEL (4)
Cu-Ni, 70-30, 5.0 Fe	716	31.0	75	403	6,780	2	0	CEL (4)
Cu-Ni, 70-30, 5.0 Fe	716	14.4	35	197	2,340	3	0	CEL (4)
Cu-Ni, 70-30, 5.0 Fe	716	20.6	50	197	2,340	3	0	CEL (4)
Cu-Ni, 70-30, 5.0 Fe	716	30.9	75	197	2,340	3	0	CEL (4)
Cu-Ni, 70-30, 5.0 Fe	716	26.6	50	402	2,370	3	0	CEL (4)
Cu-Ni, 70-30, 5.0 Fe	716	39.9	75	402	2,370	3	0	CEL (4)

<sup>a</sup>Copper Development Association alloy number.<sup>b</sup>Numbers refer to references at end of report.

Table 25. Changes in Mechanical Properties of Copper-Nickel Alloys Due to Corrosion

[Next Page](#)

Alloy	CDA No. <sup>a</sup>	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>b</sup>
				Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
Cu-Ni, 95-5	704	123	5,640	48	+1	32	+16	33	+2	CEL (4)
Cu-Ni, 95-5	704	403	6,780	48	+2	32	+3	33	-5	CEL (4)
Cu-Ni, 95-5	704	751	5,640	48	-1	32	-3	33	+2	CEL (4)
Cu-Ni, 95-5	704	197	2,340	48	-4	32	-9	33	+7	CEL (4)
Cu-Ni, 95-5	704	402	2,370	48	-1	32	-6	33	+4	CEL (4)
Cu-Ni, 90-10	706	123	5,640	43	+3	16	+11	42	0	CEL (4)
Cu-Ni, 90-10	706	403	6,780	43	+3	16	+6	42	-5	CEL (4)
Cu-Ni, 90-10	706	751	5,640	43	+3	16	+9	42	-2	CEL (4)
Cu-Ni, 90-10	706	197	2,340	43	-1	16	0	42	-2	CEL (4)
Cu-Ni, 90-10	706	402	2,370	43	+4	16	+13	42	-6	CEL (4)
Cu-Ni, 90-10	706	181	5	43	+4	16	+9	42	-18	CEL (4)
Cu-Ni, 80-20	710	123	5,640	49	0	21	-3	44	+2	CEL (4)
Cu-Ni, 80-20	710	403	6,780	49	+2	21	-2	44	-3	CEL (4)
Cu-Ni, 80-20	710	751	5,640	49	+1	21	-2	44	-3	CEL (4)
Cu-Ni, 80-20	710	197	2,340	49	+1	21	-6	44	+1	CEL (4)
Cu-Ni, 80-20	710	402	2,370	49	+1	21	-2	44	-2	CEL (4)
Cu-Ni, 70-30, 0.5 Fe	715	123	5,640	58	+1	26	-2	41	+3	CEL (4)
Cu-Ni, 70-30, 0.5 Fe	715	403	6,780	58	-25	26	-1	41	-3	CEL (4)
Cu-Ni, 70-30, 0.5 Fe	715	751	5,640	58	-25	26	-4	41	-4	CEL (4)
Cu-Ni, 70-30, 0.5 Fe	715	197	2,340	58	-3	26	-14	41	+1	CEL (4)
Cu-Ni, 70-30, 0.5 Fe	715	402	2,370	58	+2	26	-3	41	-3	CEL (4)
Cu-Ni, 70-30, 0.5 Fe	715	181	5	58	+3	26	-9	41	-13	CEL (4)
Cu-Ni, 70-30, 5.0 Fe	716	123	5,640	78	+2	41	+5	35	+1	CEL (4)
Cu-Ni, 70-30, 5.0 Fe	716	403	6,780	78	-1	41	-3	35	-1	CEL (4)
Cu-Ni, 70-30, 5.0 Fe	716	751	5,640	78	+3	41	+5	35	-9	CEL (4)
Cu-Ni, 70-30, 5.0 Fe	716	197	2,340	78	+1	41	-4	35	0	CEL (4)
Cu-Ni, 70-30, 5.0 Fe	716	402	2,370	78	+7	41	+10	35	-8	CEL (4)
Cu-Ni, 70-30, 5.0 Fe	716	181	5	78	+3	41	+6	35	-18	CEL (4)

<sup>a</sup>Copper Development Association alloy number.<sup>b</sup>Numbers refer to references at end of report.

## NICKEL AND NICKEL ALLOYS

Nickel and its alloys are passive in moving seawater, but are subject to pitting and concentration cell (crevice) corrosion in stagnant seawater. Their passivity is due to the presence of an impervious oxide layer on their surfaces which breaks down under certain conditions. Fouling organisms, deposits, and crevices which restrict the availability of oxygen to localized areas cause such breakdowns. Where sufficient oxygen is not available to repair the breaks in the protective film, pitting and crevice (concentration cell) corrosion occur. Thus, in seawater, pitting and crevice corrosion are the most prevalent modes of attack.

Corrosion rates calculated from weight losses due to localized corrosion are meaningless because they present an untrue picture of the corrosion behavior of the alloy. Corrosion rates such as mils-per-year connote a uniform thickness of metal lost over a period of time, assuming uniform corrosion. Hence, a very low corrosion rate resulting from a few deep pits or crevice corrosion in one area will present a very misleading picture of the corrosion behavior of an alloy in that particular environment.

The data on the nickel alloys were obtained from the reports given in References 3 through 19 and 23. They are separated into different groups (nickels, nickel-copper-alloys, and nickel alloys) for comparison and discussion purposes.

The chemical compositions, corrosion rates and types of corrosion, and changes in mechanical properties due to corrosion of the nickels are given in Tables 26 to 28; those of the nickel-copper alloys in Tables 29 to 31; those of the nickel alloys in Tables 32 to 34; and the resistance to stress corrosion in Table 35.

The effects of depth and the effect of the concentration of oxygen in seawater on the corrosion of the nickels, the nickel-copper alloys, and the nickel alloys are shown in Figures 15 and 16.

### 4.1. NICKELS

The chemical compositions of the nickels are given in Table 26, their corrosion rates and types of

corrosion in Table 27, and the changes in their mechanical properties due to corrosion in Table 28.

#### 4.1.1. Duration of Exposure

The corrosion rates and types of corrosion of the seven nickels (94% minimum nickel) are given in Table 27. Pitting, crevice, and edge (on the sheared ends) localized types of corrosion were responsible for practically all the corrosion. The edge corrosion was caused by microcracks and microcrevices that formed during the shearing operation; this illustrates dramatically the corrosion damage that can be caused by this fabricating procedure. Lateral penetration, initiated at a sheared edge, of as much as an inch during 6 months of exposure was found. To prevent this type of corrosion, all deformed metal created during shearing or punching operations must be removed by machining, grinding, or reaming.

Because the corrosion of the nickels was localized, no definite correlation with duration of exposure was possible. However, the severity of pitting and crevice corrosion increased with increasing time of exposure at depth as well as at the surface. Corrosion rates increased with duration of exposure at the 6,000-foot depth, although they were neither progressive nor constant. In some cases corrosion rates were considerably higher during shorter times of exposure than after longer times of exposure. Corrosion rates at the 2,500-foot depth were constant with increasing time of exposure.

#### 4.1.2. Effect of Depth

The severity and frequency of pitting and crevice corrosion were much greater at the surface than at depth. Also, the average corrosion rates were greater at the surface than at depth, although they did not decrease progressively with increasing depth as shown in Figure 16. The curves in Figure 16 are based on average values for each group of alloys.



#### 4.1.3. Effect of Concentration of Oxygen

The severity and frequency of pitting and crevice corrosion, in general, increased with increasing concentration of oxygen in seawater. The average corrosion rates increased progressively, but not constantly, with increasing concentration of oxygen in seawater as shown in Figure 17.

#### 4.1.4. Effect of Welding

The weld beads were preferentially corroded when nickel Ni-200 was welded by manual shielded metal-arc welding using welding electrode 141, and by TIG welding using filler metal 61. The weld beads were severely pitted when welded with electrode 141. The weld beads and heat-affected zones were perforated when welded with filler metal 61. This preferential attack of the weld bead materials indicates that they were anodic to the parent sheet metal.

#### 4.1.5. Mechanical Properties

The effect of exposure on the mechanical properties of nickel Ni-200 is shown in Table 28. The mechanical properties were not affected by exposure at depth for 1,064 days or for 181 days at the surface.

### 4.2. NICKEL-COPPER ALLOYS

The chemical compositions of the nickel-copper alloys are given in Table 29, their corrosion rates and types of corrosion in Table 30, and the changes in their mechanical properties due to corrosion in Table 31.

#### 4.2.1. Duration of Exposure

The corrosion rates and types of corrosion of seven nickel-copper alloys are given in Table 30. Except for the cast alloys 410 and 505, the predominant types of corrosion were pitting and crevice. At the 6,000-foot depth there was an overall tendency for the corrosion rates of the cast alloys to decrease with increasing duration of exposure, but

this tendency was neither progressive nor constant. Because the corrosion of the other nickel-copper alloys was localized (pitting and crevice corrosion), no definite correlation with duration of exposure was possible either at depth or at the surface. However, the intensity of pitting and crevice corrosion, in general, increased with increasing duration of exposure both at depth and at the surface.

#### 4.2.2. Effect of Depth

The severity and frequency of pitting and crevice corrosion were much greater at the surface than at depth. Also, the average corrosion rates were greater at the surface than at depth, although they did not decrease progressively or constantly with increasing depth, as shown in Figure 16. Although these corrosion rates are unreliable because they are based upon localized corrosion weight losses, they do substantiate the conclusion based upon the frequency and severity of pitting and crevice corrosion.

#### 4.2.3. Effect of Concentration of Oxygen

The severity and frequency of pitting and crevice corrosion, in general, increased with increasing concentration of oxygen in seawater. Even though pitting and crevice corrosion were the predominant types for these alloys in seawater, their average corrosion rates calculated from weight losses increased linearly with increasing concentration of oxygen, as shown in Figure 17.

#### 4.2.4. Effect of Welding

When Ni-Cu 400 alloy was welded with filler metal 60 by the TIG welding process, the weld beads were severely pitted both in the seawater and in the bottom sediment after exposure for 402 days at a depth of 2,500 feet, but they were corroded uniformly after 181 days of exposure at the surface. Butt welds in Ni-Cu 400 alloy made by the manual shielded metal-arc process with electrode 190 were attacked by incipient pitting corrosion both in the seawater and in the bottom sediment after 189 days of exposure at a depth of 5,900 feet and by crater corrosion of the weld bead after 540 days of exposure at the surface. Three-inch-diameter, unrelieved,

circular welds in Ni-Cu 400 alloy by the manual shielded metal-arc process with electrode 190 corroded uniformly both in the seawater and in the bottom sediment after 189 days of exposure at a depth of 5,900 feet. The unrelieved circular welds were tested to determine whether welding stresses would cause any corrosion-induced cracking. When Ni-Cu 400 alloy was welded by the manual shielded metal-arc process with electrodes 130 and 180, the weld beads were corroded uniformly after 181 days of exposure at the surface and after 402 days of exposure at the 2,500-foot depth. There was no preferential corrosion when Ni-Cu 400 was TIG welded with electrode 167 after 402 days of exposure at the 2,500-foot depth, but the weld bead was selectively attacked and was covered with a deposit of copper after 403 days of exposure at the 6,000-foot depth [7].

The weld beads in Ni-Cu K-500 alloy made by the manual shielded metal-arc process with electrode 134 were attacked by pitting corrosion of the weld bead and the heat-affected zone after 181 days of exposure at the surface, by crater corrosion of the weld bead after 540 days of exposure at the surface, and by line corrosion at the edge of the weld bead after 402 days of exposure at the 2,500-foot depth. When Ni-Cu K-500 alloy was TIG welded with filler metal 64, the weld beads were uniformly corroded after 181 days of exposure at the surface and 402 days of exposure at the 2,500-foot depth, and the weld beads and the heat-affected zones were attacked by pitting corrosion after 540 days of exposure at the surface.

#### 4.2.5. Galvanic Corrosion

When AISI 4130 steel was fastened to Ni-Cu 400 alloy in a surface area ratio of 1:2, the AISI 4130 was severely corroded and the Ni-Cu 400 was uncorroded after 403 days of exposure at the 6,000-foot depth [7]. This shows that the steel was being sacrificed to protect the nickel-copper alloy.

#### 4.2.6. Crevice Corrosion

Ni-Cu 400 alloy hardware was attacked by crevice corrosion after 751 days of exposure at the 6,000-foot depth when in contact with fiberglass [13].

#### 4.2.7. Corrosion Products

X-ray diffraction, spectrochemical, and chemical analyses of corrosion products removed from nickel-copper alloys 400 and K-500 showed that they were composed of cupric oxide ( $\text{CuO}$ ), nickel oxide ( $\text{NiO}$ ), nickel hydroxide ( $\text{Ni(OH)}_2$ ), cupric chloride ( $\text{CuCl}_2$ ), copper-oxy-chloride ( $\text{CuCl}_2 \cdot 3\text{CuO} \cdot 4\text{H}_2\text{O}$ ), a trace of nickel sulfide ( $\text{NiS}$ ), and phosphate, chloride, and sulfate ions.

#### 4.2.8. Mechanical Properties

The effects of exposure on the mechanical properties of Ni-Cu 400 and K-500 alloys are shown in Table 31. There were no significant changes due to corrosion of either unwelded or welded alloys.

### 4.3. NICKEL ALLOYS

The chemical compositions of the nickel alloys are given in Table 32, their corrosion rates and types of corrosion in Table 33, and the changes in their mechanical properties due to corrosion in Table 34.

There were no significant weight losses (none greater than 0.1 mpy) or any visible corrosion on any of the following alloys:

Ni-Cr-Fe 718, unwelded and welded

Ni-Cr-Mo 625, unwelded and welded

Ni-Mo-Cr C and 3

Ni-Cr-Fe-Mo F and G

Ni-Cr-Co 41

There were no significant weight losses (none greater than 0.1 mpy) and only some cases of incipient crevice corrosion on the following alloys:

Ni-Fe-Cr 804, 825Cb, and 901

Ni-Co-Cr 700

Ni-Cr-Fe-Mo X

The corrosion resistance of Ni-Fe-Cr 825Cb was better than that of its counterparts 825 and 825S (sensitized). Alloy 825 was attacked by both pitting and crevice corrosion, and 825S had only one case of

crevice corrosion. Thus, the addition of small amounts of columbium to alloy 825 improves its corrosion resistance, at least in seawater.

All the nickel alloys corroded essentially the same in the bottom sediments as in the seawater above them.

#### 4.3.1. Duration of Exposure

The corrosion rates and types of corrosion of the nickel alloys are given in Table 33. Except for the 12 alloys above, 13 of the remaining 16 alloys were attacked by crevice and pitting corrosion with crevice corrosion being considerably more predominant. Ni-Be alloy was attacked by pitting corrosion on the ends of the bars. Ni-Mo-Fe alloys B and 2 were attacked by general corrosion. Because of the crevice and pitting types of corrosion, corrosion rates were meaningless for determining effects of duration of exposure on the corrosion behavior of these alloys. These 14 alloys were: Ni-Cr-Fe alloys 600, 610, X-750, and 88, Ni-Fe-Cr alloys 800, 825, 825S, and 902, Ni-Sn-Zn 23, Ni-Cr alloys 65-35, 75, and 80-20, Ni-Si alloy D, and Ni-Be.

#### 4.3.2. Effect of Depth

The severity and frequency of crevice and pitting corrosion, in general, of the 16 alloys given in the previous paragraph were much greater at the surface than at depth. Also, the average corrosion rates were greater at the surface than at depth, although they did not decrease progressively or constantly with increasing depth, as shown in Figure 16. Although these corrosion rates are unreliable because they are based upon localized corrosion weight losses, they do substantiate the conclusion based upon the frequency and severity of pitting and crevice corrosion.

#### 4.3.3. Effect of Concentration of Oxygen

The severity and frequency of crevice and pitting corrosion of the nickel alloys which corroded significantly, in general, increased with increasing concentration of oxygen in seawater. Their average corrosion rates calculated from weight losses increased asymptotically with increasing concentration of oxygen, as shown in Figure 17.

#### 4.3.4. Effect of Welding

The weld beads in Ni-Cr-Fe 600 alloy, made by the TIG welding process using filler metal 62, were perforated by line corrosion along their edges after 402 days of exposure at the 2,500-foot depth, and 540 days of exposure at the surface; the weld bead was attacked by incipient pitting corrosion after 181 days of exposure at the surface.

When Ni-Cr-Fe 600 alloy was TIG welded with filler metal 82, the weld beads and heat-affected zones were perforated after 402 days of exposure at the 2,500-foot depth; the weld bead was pitted after 540 days of exposure at the surface; and the weld bead was slightly etched after 181 days of exposure at the surface.

The weld beads in Ni-Cr-Fe 600 alloy, made by the manual shielded metal-arc process using electrode 132, were perforated after 402 days of exposure at the 2,500-foot depth and after 540 days of exposure at the surface. The weld beads were also attacked by tunnel corrosion after 540 days of exposure at the surface.

Weld beads in Ni-Cr-Fe 600 alloy, made by the manual shielded metal-arc process using electrode 182, were perforated after 181 days of exposure at the surface, but were only etched after 402 days of exposure at the 2,500-foot depth.

Butt welds in Ni-Cr-Fe 718 alloy, made by the TIG process using filler metal 718, were uncorroded after 189 days of exposure in both seawater and bottom sediment at the 6,000-foot depth, in seawater after 402 days of exposure at the 2,500-foot depth, and after 540 days of exposure at the surface. Also, 3-inch-diameter, unrelieved, circular weld beads made by the same process were etched after 189 days of exposure in seawater and in the bottom sediment at the 6,000-foot depth.

The weld beads in Ni-Cr-Fe X-750 alloy, made by the TIG process using filler metal 69, were etched after 402 days of exposure at the 2,500-foot depth, but both the weld beads and heat-affected zones were attacked by crater corrosion after 540 days of exposure at the surface. Weld beads in Ni-Cr-Fe X-750 alloy, made by the manual shielded metal-arc process, were perforated and the heat-affected zone was attacked by tunnel corrosion after 402 days of exposure at the 2,500-foot depth; the heat-affected

zone was perforated by crater corrosion after 540 days of exposure at the surface.

Weld beads in Ni-Fe-Cr 800 alloy, made by the TIG process with filler metal 82, were perforated by line corrosion along their edges after 402 days of exposure at the 2,500-foot depth, and both the weld beads and heat-affected zones were attacked by tunnel corrosion after 540 days of exposure at the surface. There was line corrosion along the edge of the weld beads when Ni-Fe-Cr 800 alloy was welded by the manual shielded metal-arc process using electrode 138 after 402 days of exposure at the 2,500-foot depth. Both the weld beads and heat-affected zones were perforated by corrosion after 540 days of exposure at the surface when Ni-Fe-Cr 800 alloy was welded by the manual shielded metal-arc process using electrode 182.

Weld beads in Ni-Fe-Cr 825 alloy, made by the TIG welding process with filler metal 65, were uncorroded after 402 days of exposure at the 2,500-foot depth and after 181 days of exposure at the surface; the weld beads and heat-affected zones were attacked by incipient pitting corrosion after 540 days of exposure at the surface. When butt welds were made by the manual shielded metal-arc process using electrode 135, the weld beads were uncorroded after 181 days of exposure at the surface and 189 days of exposure in the bottom sediment at the 6,000-foot depth; there was incipient pitting of the weld bead after 189 days of exposure in the seawater at the 6,000-foot depth; one end of the weld bead was corroded after 402 days of exposure at the 2,500-foot depth; and there was crater corrosion of the heat-affected zone after 540 days of exposure at the surface. When the weld beads were 3-inch-diameter unrelieved circles made by the manual shielded metal-arc process, they were uncorroded after 189 days of exposure in seawater and in the bottom sediment at the 6,000-foot depth.

Butt welds and 3-inch-diameter, unrelieved circular welds in Ni-Cr-Mo 625 alloy, made by the TIG welding process using filler metal 625, were uncorroded after 189 days of exposure at the 6,000-foot depth and after 588 days of exposure at the surface.

#### 4.3.5. Galvanic Corrosion

When AISI 4130 steel was fastened to Ni-Cr-Fe 600 alloy in a surface area ratio of 1:2, the 4130 was severely corroded and the Ni-Cr-Fe 600 alloy was uncorroded after 403 days of exposure at the 6,000-foot depth [7]. This shows that the 4130 steel was the anodic member of the couple and was being sacrificed to protect the cathodic nickel alloy. When Ni-Be alloy was fastened to Ni-Cr-Fe 600 alloy in a surface area ratio of 1:2, the Ni-Be was severely attacked with there being a much lesser amount of corrosion on the Ni-Cr-Fe 600 alloy.

#### 4.3.6. Mechanical Properties

The effects of exposure on the mechanical properties of five of the nickel alloys are given in Table 34. The mechanical properties of Ni-Fe-Cr 825 and Ni-Mo-Cr C alloys were not affected. However, there were significant decreases in the elongations of alloys Ni-Cr-Fe 600, Ni-Fe-Cr 902, and Ni-Be, 1/2HT.

### 4.4. STRESS CORROSION

The susceptibility of some of the nickel alloys to stress corrosion is given in Table 35. None of the alloys tested were susceptible to stress corrosion cracking at both the 2,500-foot and 6,000-foot depths for exposures of at least 400 days duration.

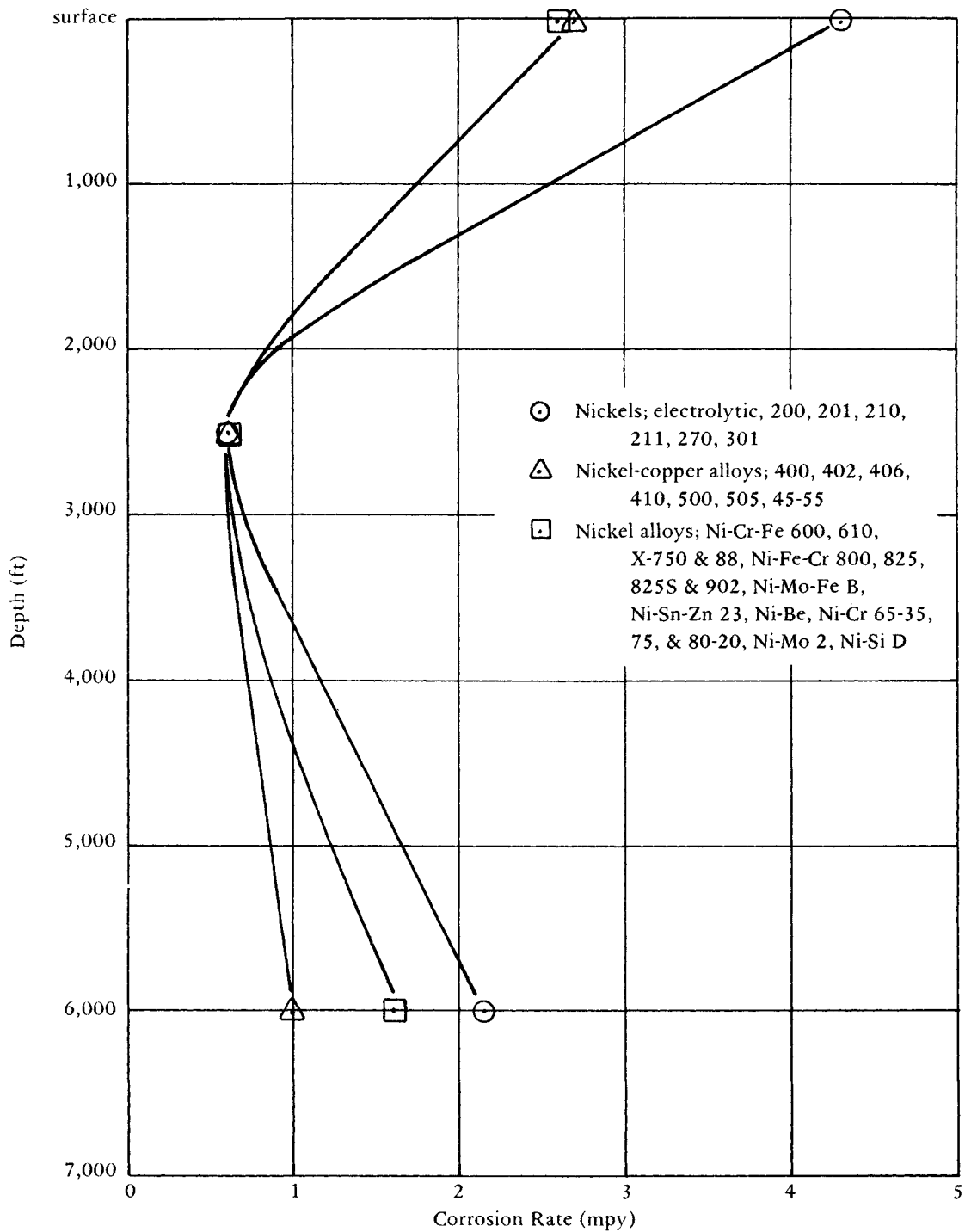


Figure 16. Effect of depth on the corrosion of nickel alloys after 1 year of exposure.

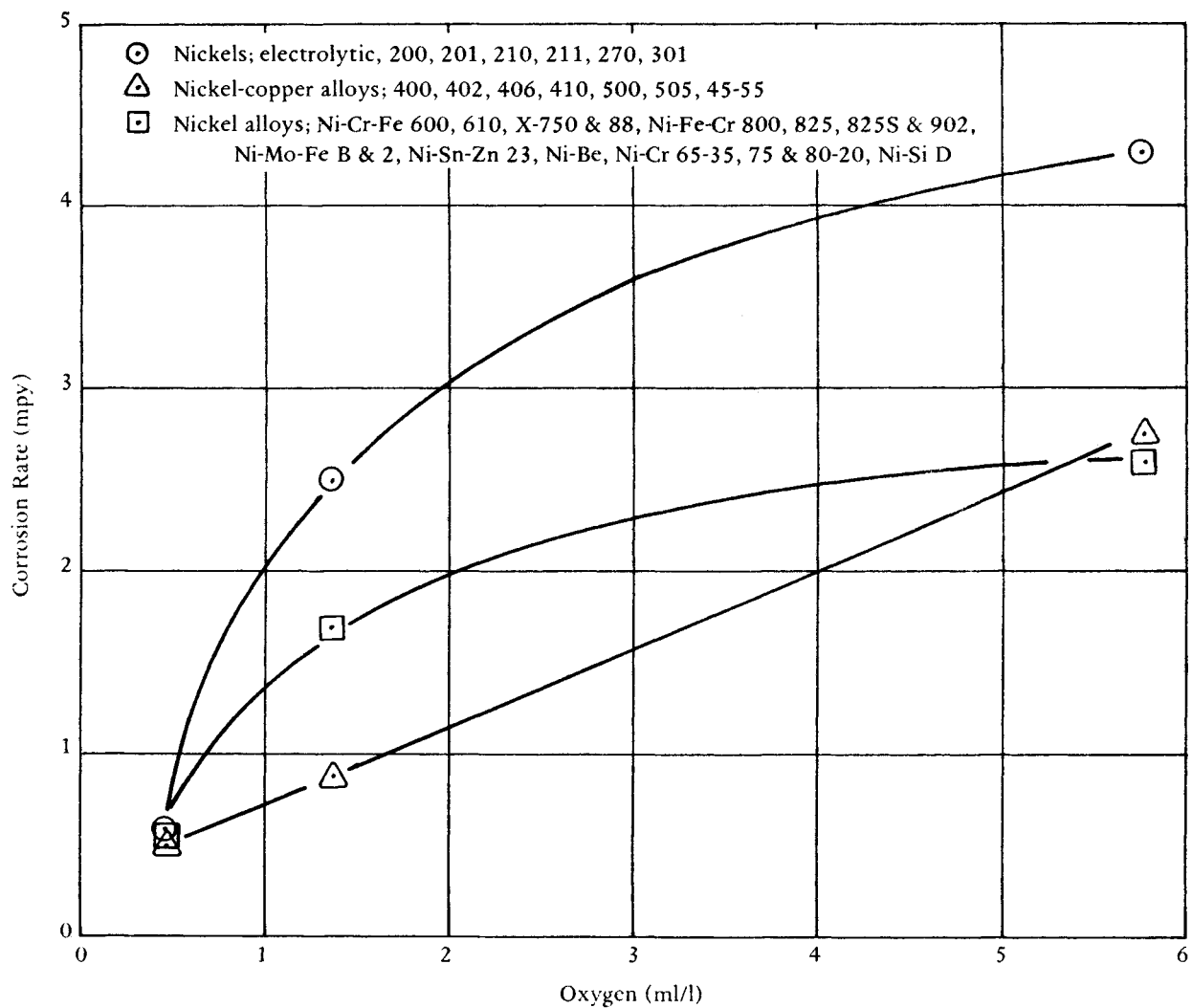


Figure 17. Effect of concentration of oxygen in seawater on the corrosion of nickel alloys after 1 year of exposure.



Table 26. Chemical Composition of Nickels, Percent by Weight

Alloy	Ni	C	Mn	Fe	S	Si	Cu	Ti	Other	Source <sup>a</sup>
Electrolytic Ni	99.97 + Co	—	—	—	—	—	—	—	—	INCO (3)
Ni-200	99.5	0.05	0.29	0.04	0.006	0.07	0.02	—	—	CEL (4)
Ni-200	99.5	0.06	0.25	0.15	0.005	0.05	0.05	—	—	CEL (4)
Ni-200	99.5	0.06	—	—	—	—	—	—	—	INCO (3)
Ni-201	99.5	0.01	—	—	—	—	—	—	—	INCO (3)
Ni-211	95.0	—	5.0	—	—	—	—	—	—	INCO (3)
Ni-270	99.97	—	—	—	—	—	—	—	—	INCO (3)
Ni-210, cast	95.6	—	1.0	—	—	2.0	—	—	—	INCO (3)
Ni-301	94.0	—	—	—	—	—	—	—	4.5 Al	INCO (3)
Filler metal 61	96.0	0.06	0.30	0.10	0.005	0.40	0.02	3.0	—	CEL (4)
Electrode 141	96.0	0.05	0.25	0.30	0.005	0.60	0.05	2.2	0.25 Al	CEL (4)

<sup>a</sup>Numbers refer to references at end of report.

Table 27. Corrosion Rates and Types of Corrosion of Nickels

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mil)	Crevice Depth (mil)	Type <sup>b</sup>	Weld <sup>b</sup>	
Electrolytic Ni	W	123	5,640	<0.1	—	3	C	—	INCO (3)
Electrolytic Ni	S	123	5,640	0.3	—	4	C	—	INCO (3)
Electrolytic Ni	W	403	6,780	1.2	—	20	C	—	INCO (3)
Electrolytic Ni	S	403	6,780	0.1	—	19	C	—	INCO (3)
Electrolytic Ni	W	751	5,640	0.5	—	50	C (PR)	—	INCO (3)
Electrolytic Ni	S	751	5,640	0.1	—	25	C	—	INCO (3)
Electrolytic Ni	W	1,064	5,300	0.7	50	—	P (PR)	—	INCO (3)
Electrolytic Ni	S	1,064	5,300	0.4	50	50	C (PR); P (PR)	—	INCO (3)
Electrolytic Ni	W	197	2,340	0.4	—	50	C (PR); P	—	INCO (3)
Electrolytic Ni	S	197	2,340	0.1	—	—	NU-ET	—	INCO (3)
Electrolytic Ni	W	402	2,370	0.6	—	50	C (PR)	—	INCO (3)
Electrolytic Ni	S	402	2,370	0.2	—	—	I-C; I-P	—	INCO (3)
Electrolytic Ni	W	181	5	4.5	30	30	C (PR); P (PR)	—	INCO (3)
Electrolytic Ni	W	366	5	6.9	30	30	C (PR); P (PR)	—	INCO (3)
Ni-200	W	123	5,640	0.7	—	SL	SL-C; EX-E <sup>d</sup>	—	CEL (4)
Ni-200	W	123	5,640	<0.1	—	2	C	—	INCO (3)
Ni-200	S	123	5,640	1.6	—	SL	SL-C; EX-E <sup>d</sup>	—	CEL (4)
Ni-200	S	123	5,640	0.3	—	22	C	—	INCO (3)
Ni-200	W	403	6,780	1.6	—	79	C; T (PR123)	—	CEL (4)
Ni-200	W	403	6,780	0.6	—	50	C (PR)	—	INCO (3)
Ni-200	S	403	6,780	1.7	—	29	C; T (PR123)	—	CEL (4)
Ni-200	S	403	6,780	0.4	38	—	P <sup>e</sup>	—	INCO (3)
Ni-200	W	751	5,640	1.8	—	116	C; T	—	CEL (4)
Ni-200	W	751	5,640	1.6	50	50	C (PR); P (PR)	—	INCO (3)
Ni-200	S	751	5,640	0.1	—	30	C; P	—	INCO (3)
Ni-200	W	1,064	5,300	1.2	—	8	C; EX-E <sup>d</sup>	—	CEL (4)
Ni-200	W	1,064	5,300	1.1	50	50	C (PR); P (PR)	—	INCO (3)
Ni-200	S	1,064	5,300	1.0	—	123	C (PR); EX-E <sup>d</sup>	—	CEL (4)
Ni-200	S	1,064	5,300	0.6	—	50	C (PR); EX-E <sup>d</sup>	—	INCO (3)
Ni-200	W	197	2,340	0.5	—	43	C; EX-E <sup>d</sup>	—	INCO (3)
Ni-200	W	197	2,340	0.5	—	10	C; P	—	INCO (3)

Continued

Table 27. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mil)	Crevice Depth (mil)	Type <sup>b</sup>	Weld <sup>b</sup>	
Ni-200	S	197	2,340	0.5	—	—	EX-E <sup>d</sup>	—	CEL (4)
Ni-200	S	197	2,340	<0.1	—	—	NU-ET	—	INCO (3)
Ni-200	W	402	2,370	0.6	—	3	C; S-ET	—	CEL (4)
Ni-200	W	402	2,370	0.6	—	50	C (PR)	—	INCO (3)
Ni-200, welded, electrode 141	W	402	2,370	0.8	—	—	ET; I-P	S-P	CEL (4)
Ni-200, welded, filler metal 61	W	402	2,370	0.6	—	—	ET; I-P	P (PR)	CEL (4)
Ni-200	S	402	2,370	0.5	—	—	U <sup>f</sup>	—	CEL (4)
Ni-200	S	402	2,370	0.2	—	—	I-C; I-P	—	INCO (3)
Ni-200, welded, filler metal 61	S	402	2,370	0.7	—	—	U <sup>f</sup>	—	INCO (3)
Ni-200	W	181	5	1.9	45	50	C; P	—	CEL (4)
Ni-200	W	181	5	7.2	50	50	C (PR); P (PR)	—	INCO (3)
Ni-200	W	366	5	4.5	40	40	C (PR); P (PR)	—	INCO (3)
Ni-200	W	398	5	1.9	125	—	P (PR); T	—	CEL (4)
Ni-200	W	540	5	1.5	125	—	P (PR); T	—	CEL (4)
Ni-200, welded, filler metal 61	W	540	5	1.9	125	—	P (PR); T	WB (PR); HAZ (PR)	CEL (4)
Ni-200	W	588	5	1.5	125	—	P (PR); T	—	CEL (4)
Ni-201	W	123	5,640	0.5	50	—	P (PR)	—	INCO (3)
Ni-201	S	123	5,640	1.3	50	—	P (PR)	—	INCO (3)
Ni-201	W	403	6,780	0.7	50	50	C (PR); P (PR)	—	INCO (3)
Ni-201	S	403	6,780	0.2	—	20	C	—	INCO (3)
Ni-201	W	751	5,640	1.1	30	30	C (PR); P (PR)	—	INCO (3)
Ni-201	S	751	5,640	0.2	30	30	C (PR); P (PR)	—	INCO (3)
Ni-201	W	1,064	5,300	0.8	50	50	C (PR); P (PR)	—	INCO (3)
Ni-201	S	1,064	5,300	0.3	50	50	C (PR); P (PR)	—	INCO (3)
Ni-201	W	197	2,340	0.5	—	50	C (PR); P <sup>g</sup>	—	INCO (3)
Ni-201	S	197	2,340	<0.1	—	—	I-C	—	INCO (3)
Ni-201	W	402	2,370	0.6	50	50	C (PR); P (PR)	—	INCO (3)
Ni-201	W	181	5	6.7	50	50	C (PR); P (PR)	—	INCO (3)
Ni-201	W	366	5	3.6	50	50	C (PR); P (PR)	—	INCO (3)
Ni-210, cast	W	123	5,640	2.0	8	—	P	—	INCO (3)
Ni-210, cast	S	123	5,640	1.1	23	—	P	—	INCO (3)
Ni-210, cast	W	403	6,780	7.2	—	70	C	—	INCO (3)
Ni-210, cast	S	403	6,780	0.3	—	—	U	—	INCO (3)
Ni-210, cast	W	751	5,640	3.3	—	75	C	—	INCO (3)

Continued

Table 27. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mil)	Crevice Depth (mil)	Type <sup>b</sup>	Weld <sup>b</sup>	
Ni-210, cast	S	751	5,640	1.7	—	67	C; P	—	INCO (3)
Ni-210, cast	W	1,064	5,300	1.5	50	—	P	—	INCO (3)
Ni-210, cast	S	1,064	5,300	0.9	12	16	C; P	—	INCO (3)
Ni-210, cast	W	197	2,340	0.6	—	—	I-C; I-P	—	INCO (3)
Ni-210, cast	S	197	2,340	<0.1	—	—	SL-ET	—	INCO (3)
Ni-210, cast	W	402	2,370	0.7	—	16	C	—	INCO (3)
Ni-210, cast	S	402	2,370	0.3	—	—	G	—	INCO (3)
Ni-210, cast	W	181	5	5.0	30	12	C; P	—	INCO (3)
Ni-210, cast	W	366	5	3.4	68	32	C; P	—	INCO (3)
Ni-211	W	123	5,640	0.3	—	22	C	—	INCO (3)
Ni-211	S	123	5,640	0.8	—	28	C; P	—	INCO (3)
Ni-211	W	403	6,780	0.8	50	50	C (PR); P (PR)	—	INCO (3)
Ni-211	S	403	6,780	0.2	—	29	C	—	INCO (3)
Ni-211	W	751	5,640	1.3	—	30	C (PR)	—	INCO (3)
Ni-211	S	751	5,640	0.3	—	30	C (PR)	—	INCO (3)
Ni-211	W	1,064	5,300	1.0	50	50	C (PR); P (PR)	—	INCO (3)
Ni-211	S	1,064	5,300	0.7	50	50	C (PR); P (PR)	—	INCO (3)
Ni-211	W	197	2,340	0.5	—	32	C (PR)	—	INCO (3)
Ni-211	S	197	2,340	<0.1	—	—	I-C	—	INCO (3)
Ni-211	W	402	2,370	0.6	—	50	C (PR)	—	INCO (3)
Ni-211	S	402	2,370	0.2	—	—	I-C; I-P	—	INCO (3)
Ni-211	W	181	5	5.0	50	50	C (PR); P (PR)	—	INCO (3)
Ni-211	W	366	5	4.5	50	50	C (PR); P (PR)	—	INCO (3)
Ni-270	W	402	2,370	0.6	—	50	C (PR)	—	INCO (3)
Ni-270	S	402	2,370	0.3	—	—	I-C; I-P	—	INCO (3)
Ni-270	W	181	5	6.5	10	21	C; P	—	INCO (3)
Ni-270	W	366	5	4.5	40	40	C (PR); P (PR)	—	INCO (3)
Ni-301	W	123	5,640	2.8	—	50	C (PR)	—	INCO (3)
Ni-301	S	123	5,640	3.1	—	50	C (PR)	—	INCO (3)
Ni-301	W	403	6,780	4.1	—	50	C (PR)	—	INCO (3)
Ni-301	S	403	6,780	1.0	—	40	C (PR)	—	INCO (3)
Ni-301	W	751	5,640	3.3	—	50	C (PR)	—	INCO (3)
Ni-301	S	751	5,640	2.7	—	50	C (PR)	—	INCO (3)

Continued

Table 27. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mil)	Crevice Depth (mil)	Type <sup>b</sup>	Weld <sup>b</sup>	
Ni-301	W	1,064	5,300	1.8	—	50	C (PR)	—	INCO (3)
Ni-301	S	1,064	5,300	1.1	35	50	C (PR); P	—	INCO (3)
Ni-301	W	197	2,340	1.1	—	50	C (PR)	—	INCO (3)
Ni-301	S	197	2,340	<0.1	—	—	I-C	—	INCO (3)
Ni-301	W	402	2,370	0.7	—	—	SL-E	—	INCO (3)
Ni-301	S	402	2,370	0.2	—	35	C (PR)	—	INCO (3)
Ni-301	W	181	5	3.8	18	—	P	—	INCO (3)
Ni-301	W	366	5	4.1	40	40	C (PR); P (PR)	—	INCO (3)

<sup>a</sup>W = Totally exposed in seawater on sides of structure; S = Exposed in base of structure so that a portion of each specimen was embedded in the bottom sediments.

<sup>b</sup>Symbols for types of corrosion:

C = Crevice	P = Pitting
E = Edge	PR = Perforated
ET = Etched	S = Severe
EX = Extensive	SL = Slight
G = General	T = Tunnel
HAZ = Heat affected zone	U = Uniform
I = Incipient	V = Very
NC = No visible corrosion	W = Weld bead
NU = Nonuniform	

Numbers indicate maximum depth in mils.

<sup>c</sup>Numbers refer to references at end of report.

<sup>d</sup>Sheared edges only.

<sup>e</sup>One pit only.

<sup>f</sup>Portion in sediment bright, uncorroded.

<sup>g</sup>Elongated pits.

Table 28. Changes in Mechanical Properties of Nickel-200 Due to Corrosion

Alloy	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>a</sup>
			Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
Ni-200	123	5,640	65	-1	18	-16	46	0	CEL (4)
Ni-200	403	6,780	65	+2	18	+1	46	-1	CEL (4)
Ni-200	751	5,640	65	+1	18	+1	46	-4	CEL (4)
Ni-200	1,064	5,300	65	0	18	-10	46	-13	CEL (4)
Ni-200	197	2,340	65	0	18	-10	46	-4	CEL (4)
Ni-200	402	2,370	65	+1	18	+4	46	-5	CEL (4)
Ni-200	181	5	65	+1	18	+10	46	-4	CEL (4)

<sup>a</sup>Numbers refer to references at end of report.

Table 29. Chemical Composition of Nickel-Copper Alloys, Percent by Weight

Alloy	Ni	Cu	C	Mn	Fe	S	Si	Ti	Other	Source <sup>a</sup>
Ni-Cu 400	65.17	32.62	0.11	1.06	0.90	0.007	0.10	—	—	CEL (4)
Ni-Cu 400	66.00	31.50	0.12	0.90	1.35	0.005	0.15	—	—	CEL (4)
Ni-Cu 400	68.02	29.25	0.12	0.99	1.52	0.010	<0.05	—	<0.10 Al	CEL (4)
Ni-Cu 400	65.90	31.75	0.14	0.94	1.07	0.010	0.19	—	<0.10 Al	CEL (4)
Ni-Cu 400	66.00	32.00	—	0.90	1.40	—	0.20	—	—	INCO (3)
Filler metal 60	66.00	30.50	0.03	0.35	0.10	0.005	0.50	2.20	—	CEL (4)
Electrode 130	68.00	27.00	0.15	2.50	0.50	0.005	0.40	0.30	1.00 Al	CEL (4)
Electrode 180	63.00	28.00	0.03	5.00	0.25	0.005	0.75	0.70	0.30 Al 1.50 Cb	CEL (4)
Ni-Cu 402	58.00	40.00	—	0.90	1.20	—	0.10	—	—	INCO (3)
Ni-Cu 406	84.00	13.00	—	0.90	1.40	—	0.20	—	—	INCO (3)
Ni-Cu 410 <sup>b</sup>	66.00	31.00	—	0.80	1.00	—	1.60	—	—	INCO (3)
Ni-Cu K-500	65.00	29.50	0.15	0.60	1.00	0.005	0.15	0.50	2.80 Al	CEL (4)
Ni-Cu K-500	65.00	30.00	—	0.60	1.00	—	0.20	—	2.80 Al	INCO (3)
Ni-Cu 505 <sup>b</sup>	64.00	29.00	—	0.80	2.00	—	4.00	—	—	INCO (3)
Filler metal 64	65.00	29.50	0.15	0.60	1.00	0.005	0.15	0.50	2.80 Al	CEL (4)
Electrode 134	66.00	27.00	0.25	2.50	1.00	0.005	0.40	0.30	2.00 Al	CEL (4)
Ni-Cu 60	65.00	30.00	—	0.90	2.00	—	1.00	—	1.00 Al	INCO (3)

<sup>a</sup>Numbers refer to references at end of report.

<sup>b</sup>Cast alloy.



Table 30. Corrosion Rates and Types of Corrosion of the Nickel-Copper Alloys

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mil)	Crevice Depth (mil)	Type <sup>b</sup>	Weld <sup>b</sup>	
Ni-Cu 400	W	123	5,640	0.8	—	—	U	—	CEL (4)
Ni-Cu 400	W	123	5,640	0.4	—	—	U	—	INCO (3)
Ni-Cu 400	W	123	5,640	0.5	—	—	ET; I-C	—	MEL (5)
Ni-Cu 400	S	123	5,640	0.5	—	—	U	—	CEL (4)
Ni-Cu 400	S	123	5,640	0.4	—	5	C; U	—	INCO (3)
Ni-Cu 400	W	189	5,900	0.4	—	5	C; I-P	—	CEL (4)
Ni-Cu 400	S	189	5,900	0.3	1	—	I-C; I-P	—	CEL (4)
Ni-Cu 400, long. butt weld, electrode 190	W	189	5,900	0.4	—	—	I-P	I-P	CEL (4)
Ni-Cu 400, long. butt weld, electrode 190	S	189	5,900	0.4	—	—	I-P	I-P	CEL (4)
Ni-Cu 400, 3-in. circular weld, electrode 190	W	189	5,900	0.3	—	—	U	U	CEL (4)
Ni-Cu 400, 3-in. circular weld, electrode 190	S	189	5,900	0.3	—	—	U	U	CEL (4)
Ni-Cu 400	W	403	6,780	0.5	20	10	C; P; E	—	CEL (4)
Ni-Cu 400	W	403	6,780	0.8	—	40	C (PR); U	—	INCO (3)
Ni-Cu 400	S	403	6,780	0.4	18	10	C; P; E	—	CEL (4)
Ni-Cu 400	S	403	6,780	0.1	—	2	C; U	—	INCO (3)
Ni-Cu 400	W	751	5,640	1.0	45	45	C; P; E	—	CEL (4)
Ni-Cu 400	W	751	5,640	3.1	—	40	C (PR); P	—	INCO (3)
Ni-Cu 400	W	751	5,640	0.1	—	13	C; ET	—	MEL (5)
Ni-Cu 400	S	751	5,640	1.3	—	40	C (PR)	—	INCO (3)
Ni-Cu 400	W	1,064	5,300	0.8	—	6	C; E	—	CEL (4)
Ni-Cu 400	W	1,064	5,300	0.5	—	40	C (PR); P	—	INCO (3)
Ni-Cu 400	S	1,064	5,300	0.6	47	125	C (PR); P	—	CEL (4)
Ni-Cu 400	S	1,064	5,300	0.6	—	40	C (PR); CR	—	INCO (3)
Ni-Cu 400	W	197	2,340	0.4	10	11	C; P	—	CEL (4)
Ni-Cu 400	W	197	2,340	0.4	—	7	C	—	INCO (3)
Ni-Cu 400	W	197	2,340	1.0	—	—	U	—	NADC (7)
Ni-Cu 400	S	197	2,340	0.3	—	—	U	—	CEL (4)
Ni-Cu 400	S	197	2,340	0.2	—	4	C	—	INCO (3)
Ni-Cu 400	W	402	2,370	0.4	20	—	P	—	CEL (4)
Ni-Cu 400	W	402	2,370	0.8	—	40	C (PR); P	—	INCO (3)
Ni-Cu 400	S	402	2,370	0.3	—	—	E; I-P	—	CEL (4)
Ni-Cu 400	S	402	2,370	0.1	—	—	ET	—	INCO (3)
Ni-Cu 400, welded, electrode 130	W	402	2,370	0.5	—	—	I-P	U	CEL (4)
Ni-Cu 400, welded, electrode 180	W	402	2,370	0.5	—	—	I-P	U	CEL (4)
Ni-Cu 400, welded, filler metal 60	W	402	2,370	0.4	—	—	I-P	S-P	CEL (4)

Continued

Table 30. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mil)	Crevice Depth (mil)	Type <sup>b</sup>	Weld <sup>b</sup>	
Ni-Cu 400, welded, filler metal 60	S	402	2,370	0.4	—	—	E	S-P	CEL (4)
Ni-Cu 400	W	181	5	0.6	28	15	C; P	—	CEL (4)
Ni-Cu 400	W	181	5	5.8	12	40	C (PR); P	—	INCO (3)
Ni-Cu 400, welded, electrode 180	W	181	5	0.7	11	—	P	U	CEL (4)
Ni-Cu 400, welded, filler metal 60	W	181	5	0.5	12	—	P	U	CEL (4)
Ni-Cu 400	W	366	5	2.4	16	40	C (PR); P	—	INCO (3)
Ni-Cu 400	W	386 <sup>d</sup>	5	1.3	20	63	C (PR); P	—	MEL (5)
Ni-Cu 400	W	398	5	0.8	39	—	P	—	CEL (4)
Ni-Cu 400	W	540	5	0.9	17	—	P; E	—	CEL (4)
Ni-Cu 400, welded, electrode 190	W	540	5	1.2	28	—	P; CR	WB (CR)	CEL (4)
Ni-Cu 400	W	588	5	0.8	29	—	P	—	CEL (4)
Ni-Cu 402	W	123	5,640	0.3	—	—	U	—	INCO (3)
Ni-Cu 402	S	123	5,640	0.3	—	—	U	—	INCO (3)
Ni-Cu 402	W	403	6,780	0.7	—	—	U	—	INCO (3)
Ni-Cu 402	S	403	6,780	1.3	—	—	I-C	—	INCO (3)
Ni-Cu 402	W	751	5,640	0.5	—	14	C; P	—	INCO (3)
Ni-Cu 402	S	751	5,640	0.3	—	7	C	—	INCO (3)
Ni-Cu 402	W	1,064	5,300	0.3	—	12	C	—	INCO (3)
Ni-Cu 402	S	1,064	5,300	1.0	—	50	C (PR); CR	—	INCO (3)
Ni-Cu 402	W	197	2,340	0.4	—	—	U	—	INCO (3)
Ni-Cu 402	S	197	2,340	<0.1	—	—	I-C	—	INCO (3)
Ni-Cu 402	W	402	2,370	0.7	—	32	C (PR); P	—	INCO (3)
Ni-Cu 402	S	402	2,370	<0.1	—	—	I-C	—	INCO (3)
Ni-Cu 402	W	181	5	3.6	9	13	C; P	—	INCO (3)
Ni-Cu 402	W	366	5	2.3	30	30	C (PR); P (PR)	—	INCO (3)
Ni-Cu 406	W	123	5,640	0.2	—	8	C	—	INCO (3)
Ni-Cu 406	S	123	5,640	0.4	—	50	C (PR)	—	INCO (3)
Ni-Cu 406	W	403	6,780	0.5	—	50	C (PR)	—	INCO (3)
Ni-Cu 406	S	403	6,780	<0.1	—	—	I-C	—	INCO (3)
Ni-Cu 406	W	751	5,640	0.7	—	40	C (PR)	—	INCO (3)
Ni-Cu 406	S	751	5,640	0.3	—	40	C (PR)	—	INCO (3)
Ni-Cu 406	W	1,064	5,300	0.8	—	50	C (PR)	—	INCO (3)
Ni-Cu 406	S	1,064	5,300	1.0	—	50	C (PR)	—	INCO (3)
Ni-Cu 406	W	197	2,340	0.5	—	23	C	—	INCO (3)

Continued

Table 30. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mil)	Crevice Depth (mil)	Type <sup>b</sup>	Weld <sup>b</sup>	
Ni-Cu 406	S	197	2,340	<0.1	—	—	U-ET	—	INCO (3)
Ni-Cu 406	W	402	2,370	0.6	—	50	C (PR)	—	INCO (3)
Ni-Cu 406	S	402	2,370	0.1	—	30	C	—	INCO (3)
Ni-Cu 406	W	181	5	7.5	50	50	C (PR); P (PR)	—	INCO (3)
Ni-Cu 406	W	366	5	6.0	50	50	C (PR); P (PR)	—	INCO (3)
Ni-Cu 410, cast	W	123	5,640	0.8	—	—	U	—	INCO (3)
Ni-Cu 410, cast	S	123	5,640	0.5	—	—	U	—	INCO (3)
Ni-Cu 410, cast	W	403	6,780	1.1	—	—	U	—	INCO (3)
Ni-Cu 410, cast	S	403	6,780	<0.1	—	—	EBSL	—	INCO (3)
Ni-Cu 410, cast	W	751	5,640	0.9	—	—	U	—	INCO (3)
Ni-Cu 410, cast	S	751	5,640	0.5	—	—	U	—	INCO (3)
Ni-Cu 410, cast	W	1,064	5,300	0.5	—	—	G	—	INCO (3)
Ni-Cu 410, cast	S	1,064	5,300	0.4	—	—	G	—	INCO (3)
Ni-Cu 410, cast	W	197	2,340	0.6	—	—	U	—	INCO (3)
Ni-Cu 410, cast	S	197	2,340	0.2	—	—	U	—	INCO (3)
Ni-Cu 410, cast	W	402	2,370	0.4	—	—	G	—	INCO (3)
Ni-Cu 410, cast	S	402	2,370	0.1	—	—	I-P	—	INCO (3)
Ni-Cu 410, cast	W	181	5	1.3	16	14	C; P	—	INCO (3)
Ni-Cu 410, cast	W	366	5	3.1	19	30	C; P	—	INCO (3)
Ni-Cu K-500	W	123	5,640	0.4	—	9	C	—	INCO (3)
Ni-Cu K-500	W	123	5,640	0.7	—	11	ET; C	—	MEL (5)
Ni-Cu K-500	S	123	5,640	0.7	—	11	C	—	INCO (3)
Ni-Cu K-500	W	187	5,900	0.1	9	16	C; P	—	CEL (4)
Ni-Cu K-500	S	187	5,900	0.2	11	26	C; P	—	CEL (4)
Ni-Cu K-500	W	403	6,780	0.3	—	18	C	—	INCO (3)
Ni-Cu K-500	S	403	6,780	<0.1	—	2	C	—	INCO (3)
Ni-Cu K-500	W	751	5,640	3.6	—	30	C (PR)	—	INCO (3)
Ni-Cu K-500	W	751	5,640	0.4	8	63	C (PR); P (PR)	—	MEL (5)
Ni-Cu K-500	S	751	5,640	1.5	—	30	C (PR)	—	INCO (3)
Ni-Cu K-500	W	1,064	5,300	0.9	—	30	C (PR)	—	INCO (3)
Ni-Cu K-500	S	1,064	5,300	0.7	—	—	CR (PR30)	—	INCO (3)
Ni-Cu K-500	W	197	2,340	0.4	—	—	U	—	INCO (3)
Ni-Cu K-500	S	197	2,340	0.2	—	—	U	—	INCO (3)
Ni-Cu K-500	W	402	2,370	0.6	38	46	C; P	—	CEL (4)

Continued

Table 30. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mil)	Crevice Depth (mil)	Type <sup>b</sup>	Weld <sup>b</sup>	
Ni-Cu K-500	W	402	2,370	0.6	—	30	C (PR)	—	INCO (3)
Ni-Cu K-500	W	402	2,370	0.6	—	30	C	—	Shell (9)
Ni-Cu K-500	S	402	2,370	0.3	—	7	C	—	Shell (9)
Ni-Cu K-500	S	402	2,370	0.3	48	37	C; P	—	CEL (4)
Ni-Cu K-500	S	402	2,370	<0.1	—	—	ET	—	INCO (3)
Ni-Cu K-500, welded, electrode 134	W	402	2,370	0.6	14	—	P	U <sup>e</sup>	CEL (4)
Ni-Cu K-500, welded, electrode 64	W	402	2,370	0.5	21	—	P	U	CEL (4)
Ni-Cu K-500	W	181	5	1.0	8	12	C; P	—	CEL (4)
Ni-Cu K-500	W	181	5	6.4	30	30	C (PR); P (PR)	—	INCO (3)
Ni-Cu K-500, welded, electrode 134	W	181	5	0.9	12	—	P	P (HAZ)(WB)	CEL (4)
Ni-Cu K-500, welded, filler metal 64	W	181	5	1.1	8	—	P	U	CEL (4)
Ni-Cu K-500	W	366	5	3.6	30	30	C (PR); P (PR)	—	INCO (3)
Ni-Cu K-500	W	386 <sup>d</sup>	5	1.4	33	63	C (PR); P	—	MEL (5)
Ni-Cu K-500, welded, electrode 134	W	540	5	1.1	20	—	P	WB (CR)	CEL (4)
Ni-Cu K-500, welded, filler metal 64	W	540	5	0.9	13	—	P	P (WB)(HAZ)	CEL (4)
Ni-Cu 505, cast	W	123	5,640	1.4	—	—	U	—	INCO (3)
Ni-Cu 505, cast	S	123	5,640	2.4	—	—	U	—	INCO (3)
Ni-Cu 505, cast	W	403	6,780	1.9	—	—	U	—	INCO (3)
Ni-Cu 505, cast	S	403	6,780	<0.1	—	—	I-C	—	INCO (3)
Ni-Cu 505, cast	W	751	5,640	1.0	—	—	U	—	INCO (3)
Ni-Cu 505, cast	S	751	5,640	2.1	—	—	U	—	INCO (3)
Ni-Cu 505, cast	W	1,064	5,300	1.0	—	—	G	—	INCO (3)
Ni-Cu 505, cast	S	1,064	5,300	0.5	—	—	G	—	INCO (3)
Ni-Cu 505, cast	W	197	2,340	0.3	—	—	U	—	INCO (3)
Ni-Cu 505, cast	S	197	2,340	0.2	—	—	U	—	INCO (3)
Ni-Cu 505, cast	W	402	2,370	0.3	—	—	G	—	INCO (3)
Ni-Cu 505, cast	S	402	2,370	<0.1	—	—	ET	—	INCO (3)
Ni-Cu 505, cast	W	181	5	0.7	—	—	NU	—	INCO (3)
Ni-Cu 505, cast	W	366	5	1.1	13	—	P	—	INCO (3)
Ni-Cu 60	W	123	5,640	3.0	—	50	C (PR)	—	INCO (3)
Ni-Cu 60	S	123	5,640	2.1	—	24	C	—	INCO (3)
Ni-Cu 60	W	403	6,780	3.0	—	50	C (PR)	—	INCO (3)
Ni-Cu 60	S	403	6,780	<0.1	—	—	I-C	—	INCO (3)
Ni-Cu 60	W	751	5,640	4.9	—	62	C (PR)	—	INCO (3)

Continued

Table 30. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mil)	Crevice Depth (mil)	Type <sup>b</sup>	Weld <sup>b</sup>	
Ni-Cu 60	S	751	5,640	1.3	—	62	C (PR)	—	INCO (3)
Ni-Cu 60	W	1,064	5,300	1.4	—	62	C (PR)	—	INCO (3)
Ni-Cu 60	S	1,064	5,300	0.9	—	33	C; CR	—	INCO (3)
Ni-Cu 60	W	197	2,340	0.5	—	17	C	—	INCO (3)
Ni-Cu 60	S	197	2,340	0.1	—	—	U	—	INCO (3)

<sup>a</sup>W = Totally exposed in seawater on sides of structure; S = Exposed in base of structure so that the lower portions of the specimen were embedded in the bottom sediments.

<sup>b</sup>Symbols for types of corrosion:

C	= Crevice	I	= Incipient
CR	= Cratering	NU	= Nonuniform
E	= Edge	P	= Pitting
EBSL	= Etched below sediment line	PR	= Perforation
ET	= Etched	S	= Severe
G	= General	U	= Uniform
HAZ	= Heat affected zone	WB	= Weld bead

Numbers indicate maximum depth in mils.

<sup>c</sup>Numbers refer to References at end of report.

<sup>d</sup>Francis L. LaQue Corrosion Laboratory, INCO, Wrightsville Beach, N.C.

<sup>e</sup>Line corrosion at edge of weld bead.

Table 31. Changes in Mechanical Properties of Nickel-Copper Alloys Due to Corrosion

Alloy	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>a</sup>
			Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
Ni-Cu 400	123	5,640	75	+2	29	+1	44	+1	CEL (4)
Ni-Cu 400	403	6,780	75	+2	29	+2	44	+2	CEL (4)
Ni-Cu 400	751	5,640	75	-2	29	-2	44	-22	CEL (4)
Ni-Cu 400	1,064	5,300	75	+3	29	+5	44	-3	CEL (4)
Ni-Cu 400	197	2,340	75	+2	29	+1	44	-1	CEL (4)
Ni-Cu 400	197	2,340	82	0	41	+11	40	-14	NADC (7)
Ni-Cu 400	402	2,370	82	-1	41	-2	40	-25	NADC (7)
Ni-Cu 400	402	2,370	75	+3	29	+6	44	-1	CEL (4)
Ni-Cu 400	402	2,370	77	0	29	0	44	0	CEL (4)
Ni-Cu 400, welded, filler metal 60	402	2,370	77	-3	29	+17	44	-34 <sup>b</sup>	CEL (4)
Ni-Cu 400, welded, filler metal 60 <sup>c</sup>	402	2,370	77	+1	29	+14	44	-26 <sup>b</sup>	CEL (4)
Ni-Cu 400, welded, electrode 130	402	2,370	77	0	29	+14	44	-15 <sup>b</sup>	CEL (4)
Ni-Cu 400, welded, electrode 180	402	2,370	77	0	29	+16	44	-25 <sup>b</sup>	CEL (4)
Ni-Cu 400	181	5	75	+2	29	+1	44	-11	CEL (4)
Ni-Cu K-500	402	2,370	98	+1	43	+4	37	+1	CEL (4)

<sup>a</sup>Numbers refer to references at end of report.<sup>b</sup>Broke in weld.<sup>c</sup>Partially embedded in bottom sediment.

Table 32. Chemical Composition of Other Nickel Alloys, Percent by Weight

Alloy	Ni	C	Mn	Fe	S	Si	Cu	Cr	Ti	Mo	Cb	Other	Source <sup>a</sup>
Ni-Cr-Fe 600	76.00	0.04	0.20	7.20	0.007	0.20	0.10	15.8	—	—	—	—	CEL (4)
Ni-Cr-Fe 600	75.26	0.06	0.18	7.25	0.008	0.27	0.38	16.0	—	—	—	—	CEL (4)
Ni-Cr-Fe 600	76.0	—	—	7.0	—	—	—	16.0	—	—	—	—	INCO (3)
Ni-Cr-Fe 610	71.0	—	—	9.0	—	2.0	—	16.0	—	—	—	—	INCO (3)
Ni-Cr-Fe 718	52.5	0.04	0.20	18.0	0.007	0.20	0.10	19.0	0.80	3.0	5.2	0.60 Al	CEL (4)
Ni-Cr-Fe X750	73.41	0.08	0.55	6.90	0.003	0.36	0.09	14.50	2.40	—	0.90	0.81 Al	CEL (4)
Ni-Cr-Fe X750	73.0	—	—	7.0	—	—	—	15.0	2.5	—	—	—	INCO (3)
Ni-Cr-Fe X750	73.0	0.04	0.70	6.75	0.007	0.30	0.05	15.0	2.50	—	0.85	0.80 Al	CEL (4)
Ni-Fe-Cr 800	32.0	—	1.0	46.0	—	—	—	20.0	—	—	—	—	INCO (3)
Ni-Fe-Cr 800	32.0	0.04	0.75	46.0	0.007	0.35	0.30	20.5	—	—	—	—	CEL (4)
Ni-Fe-Cr 804	43.0	—	—	25.0	—	—	—	29.0	—	—	—	—	INCO (3)
Ni-Fe-Cr 825	41.12	0.05	0.82	30.86	0.01	0.31	1.61	21.12	1.00	2.94	—	0.14 Al	CEL (4)
Ni-Fe-Cr 825	41.8	0.03	0.65	30.0	0.007	0.35	1.80	21.5	0.90	3.0	—	0.15 Al	CEL (4)
Ni-Fe-Cr 825	42.0	—	—	30.0	—	—	2.0	22.0	—	3.0	—	—	INCO (3)
Ni-Fe-Cr 825Cb	42.0	—	—	30.0	—	—	2.0	22.0	—	3.0	—	—	INCO (3)
Ni-Fe-Cr 901	43.0	—	—	34.0	—	—	—	14.0	—	—	—	—	INCO (3)
Ni-Fe-Cr 902	42.0	0.02	0.40	48.5	0.008	0.50	0.05	5.4	2.40	—	—	0.65 Al	CEL (4)
Ni-Cr-Mo 103 <sup>c</sup>	67.0	0.02	—	—	—	—	—	18.0	—	14.0	0.5	—	CEL (4)
Ni-Cr-Mo 625	61.0	0.05	0.15	3.00	0.007	0.30	0.10	22.0	—	9.0	4.0	—	CEL (4)
Ni-Cr-Mo 625	63.0	—	—	—	—	—	—	22.0	—	9.0	—	—	INCO (3)
Ni-Mo-Cr "C"	55.68	0.05	0.52	6.32	0.009	0.62	—	15.33	—	16.71	—	3.53 W 0.96 Co 0.26 V 0.010 P	CEL (4)
Ni-Mo-Cr "C"	60.0	—	—	5.0	—	—	—	15.0	—	16.0	—	4.0 W	INCO (3)
Ni-Mo-Cr 3	58.0	—	—	3.00	—	—	—	19.0	—	19.0	—	—	INCO (3)
Ni-Co-Cr 700	46.0	—	—	1.0	—	—	—	15.0	—	3.75	—	28.5 Co 3.0 Al	INCO (3)
Ni-Cr-Co "41"	55.29	0.11	<0.01	0.33	—	0.07	—	19.08	3.34	9.72	—	11.47 Co	CEL (4)
Ni-Mo-Fe "B"	60.0	—	—	5.0	—	—	—	—	—	26.0	—	—	INCO (3)
Ni-Mo-Fe 2	66.0	—	—	2.0	—	—	—	—	—	30.0	—	—	INCO (3)
Ni-Co-Cr-Mo <sup>b</sup>	35.0	—	—	—	—	—	—	19.84	—	10.0	—	35.0 Co	CEL (4)
Co-Cr-Ni-Fe-Mo <sup>c</sup>	14.96	0.05	1.96	14.60	—	0.74	—	19.84	—	7.14	—	0.058 Al 40.46 Co 0.07 Be	CEL (4)
Ni-Cr-Fe-Mo "F"	46.0	—	—	21.0	—	—	—	22.0	—	7.0	—	—	INCO (3)
Ni-Cr-Fe-Mo "G"	45.0	—	—	20.0	—	—	2.00	21.0	—	7.0	—	2.5 Co 1.0 W	INCO (3)
Ni-Cr-Fe-Mo "X"	60.0	—	—	19.0	—	—	—	22.0	—	9.0	—	—	INCO (3)
Ni-Cr-Fe 88	71.0	—	—	7.0	—	—	—	10.0	—	—	—	5.0 Sn 3.0 Bi	INCO (3)
Ni-Sn-Zn 23	79.0	—	2.0	—	—	—	—	—	—	—	—	8.0 Sn 7.0 Zn 4.0 Pb	INCO (3)
Ni-Be	97.55	—	—	—	—	—	—	—	—	—	—	1.95 Be	CEL (4)

Continued



Table 32. Continued.

Alloy	Ni	C	Mn	Fe	S	Si	Cu	Cr	Ti	Mo	Cb	Other	Source <sup>a</sup>
Ni-Cr 65-35	65.0	—	—	—	—	—	—	35.0	—	—	—	—	INCO (3)
Ni-Cr 75	78.0	—	—	—	—	—	—	20.0	—	—	—	—	INCO (3)
Ni-Cr 80-20	80.0	—	—	—	—	—	—	20.0	—	—	—	—	INCO (3)
Ni-Si "D"	86.0	—	—	—	—	10.0	3.0	—	—	—	—	—	INCO (3)
Filler metal 62	73.5	0.04	0.20	7.50	0.007	0.30	0.03	16.0	—	—	2.3	—	CEL (4)
Filler metal 65	42.0	0.03	0.80	30.0	0.008	0.30	1.70	21.0	0.90	3.0	—	—	CEL (4)
Filler metal 69	72.8	0.04	0.70	6.80	0.007	0.30	0.05	15.2	2.40	—	0.85	0.80 Al	CEL (4)
Filler metal 82	72.0	0.02	3.00	1.00	0.007	0.20	0.02	20.0	0.5	—	2.5	—	CEL (4)
Electrode 132	74.0	0.05	0.75	8.50	0.005	0.20	0.10	14.0	—	—	2.0	0.1 Ce	CEL (4)
Electrode 135	38.0	0.05	0.50	31.0	0.008	0.40	1.80	19.0	—	5.5	1.0	—	CEL (4)
Electrode 138	38.0	0.16	1.90	27.0	0.008	0.40	0.40	28.0	—	3.60	—	1.0 W	CEL (4)
Electrode 182	68.0	0.05	7.50	7.50	0.005	0.60	0.10	14.0	—	—	2.0	0.1 Ce	CEL (4)
Filler metal 718	52.5	0.04	0.20	18.0	0.007	0.20	0.10	19.0	0.80	3.0	—	—	CEL (4)

<sup>a</sup>Numbers refer to references at end of report.

<sup>b</sup>Wire rope and bolts.

<sup>c</sup>Wire rope.

Table 33. Corrosion Rates and Types of Corrosion of Nickel Alloys

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mil)	Crevice Depth (mil)	Type <sup>b</sup>	Weld <sup>b</sup>	
Ni-Cr-Fe 600	W	123	5,640	<0.1	—	4	C	—	INCO (3)
Ni-Cr-Fe 600	S	123	5,640	<0.1	—	3	C	—	INCO (3)
Ni-Cr-Fe 600	W	189	5,900	<0.1	—	39	C	—	CEL (4)
Ni-Cr-Fe 600	S	189	5,900	0.0	—	—	I-C	—	CEL (4)
Ni-Cr-Fe 600	W	403	6,780	0.1	—	23	C	—	INCO (3)
Ni-Cr-Fe 600	S	403	6,780	0.3	—	—	I-C	—	INCO (3)
Ni-Cr-Fe 600	W	751	5,640	<0.1	—	33	C	—	INCO (3)
Ni-Cr-Fe 600	S	751	5,640	<0.1	—	4	C; P	—	INCO (3)
Ni-Cr-Fe 600	W	1,064	5,300	0.1	—	35	C (PR)	—	INCO (3)
Ni-Cr-Fe 600	W	1,064	5,300	0.5	—	51	C; P	—	CEL (4)
Ni-Cr-Fe 600	S	1,064	5,300	<0.1	—	2	C	—	INCO (3)
Ni-Cr-Fe 600	W	197	2,340	0.2	—	15	C	—	INCO (3)
Ni-Cr-Fe 600	S	197	2,340	0.1	—	10	C	—	INCO (3)
Ni-Cr-Fe 600	W	402	2,370	0.0	—	—	SL-ET; I-P	—	CEL (4)
Ni-Cr-Fe 600	W	402	2,370	0.1	—	28	C	—	INCO (3)
Ni-Cr-Fe 600, welded, filler metal 62	W	402	2,370	0.4	—	—	U	WB (PR) <sup>d</sup>	CEL (4)
Ni-Cr-Fe 600, welded, filler metal 82	W	402	2,370	0.3	—	—	U	WB (PR); T (PR)(HAZ) <sup>d</sup>	CEL (4)
Ni-Cr-Fe 600, welded, electrode 132	W	402	2,370	0.3	—	—	ET	WB (PR)	CEL (4)
Ni-Cr-Fe 600, welded, electrode 182	W	402	2,370	<0.1	—	—	ET	ET	CEL (4)
Ni-Cr-Fe 600	S	402	2,370	0.1	—	—	ET; T (PR125)	—	CEL (4)
Ni-Cr-Fe 600	S	402	2,370	<0.1	—	—	I-C	—	INCO (3)
Ni-Cr-Fe 600	W	181	5	0.2	105	—	E; P <sup>e</sup>	—	CEL (4)
Ni-Cr-Fe 600	W	181	5	1.7	50	50	C (PR); P (PR)	—	INCO (3)
Ni-Cr-Fe 600, welded, filler metal 62	W	181	5	<0.1	—	—	U	I-P	CEL (4)
Ni-Cr-Fe 600, welded, filler metal 82	W	181	5	<0.1	—	—	U	SL-ET	CEL (4)
Ni-Cr-Fe 600, welded, electrode 182	W	181	5	1.3	—	—	U	WB (PR)	CEL (4)
Ni-Cr-Fe 600	W	366	5	0.6	50	50	C (PR); P (PR)	—	INCO (3)
Ni-Cr-Fe 600	W	540	5	0.5	67	—	P	—	CEL (4)

Continued

Table 33. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mil)	Crevice Depth (mil)	Type <sup>b</sup>	Weld <sup>b</sup>	
Ni-Cr-Fe 600, welded, filler metal 62	W	540	5	0.7	88	—	P	WB (PR125)	CEL (4)
Ni-Cr-Fe 600, welded, filler metal 82	W	540	5	0.6	77	—	P	P	CEL (4)
Ni-Cr-Fe 600, welded, electrode 132	W	540	5	0.9	60	—	P	WB (PR); T	CEL (4)
Ni-Cr-Fe 600, welded, electrode 182	W	540	5	0.9	50	—	P	WB (PR)	CEL (4)
Ni-Cr-Fe 610, cast	W	123	5,640	0.3	—	4	C	—	INCO (3)
Ni-Cr-Fe 610, cast	S	123	5,640	0.1	—	2	C	—	INCO (3)
Ni-Cr-Fe 610, cast	W	403	6,780	<0.1	—	—	I-C	—	INCO (3)
Ni-Cr-Fe 610, cast	S	403	6,780	0.1	—	—	I-C	—	INCO (3)
Ni-Cr-Fe 610, cast	W	751	5,640	0.6	—	83	C	—	INCO (3)
Ni-Cr-Fe 610, cast	S	751	5,640	0.3	—	5	C	—	INCO (3)
Ni-Cr-Fe 610, cast	W	1,064	5,300	0.9	—	—	I-P	—	INCO (3)
Ni-Cr-Fe 610, cast	S	1,064	5,300	<0.1	—	13	C	—	INCO (3)
Ni-Cr-Fe 610, cast	W	197	2,340	0.2	—	2	C	—	INCO (3)
Ni-Cr-Fe 610, cast	S	197	2,340	<0.1	—	3	C	—	INCO (3)
Ni-Cr-Fe 610, cast	W	402	2,370	0.3	—	18	C	—	INCO (3)
Ni-Cr-Fe 610, cast	S	402	2,370	<0.1	—	—	I-C	—	INCO (3)
Ni-Cr-Fe 610, cast	W	181	5	1.8	180	23	C; P(PR)	—	INCO (3)
Ni-Cr-Fe 610, cast	W	366	5	1.3	55	24	C; P	—	INCO (3)
Ni-Cr-Fe 718	W	189	5,900	0.0	—	—	NC	—	CEL (4)
Ni-Cr-Fe 718	S	189	5,900	<0.1	—	—	NC	—	CEL (4)
Ni-Cr-Fe 718, longitudinal butt weld, electrode 718	W	189	5,900	<0.1	—	—	NC	—	CEL (4)
Ni-Cr-Fe 718, longitudinal butt weld, electrode 718	S	189	5,900	<0.1	—	—	NC	—	CEL (4)
Ni-Cr-Fe 718, 3-in. circular weld, electrode 718	W	189	5,900	<0.1	—	—	NC	ET	CEL (4)
Ni-Cr-Fe 718, 3-in. circular weld, electrode 718	S	189	5,900	<0.1	—	—	NC	ET	CEL (4)
Ni-Cr-Fe 718	W	402	2,370	<0.1	—	—	NC	—	CEL (4)

Continued

Table 33. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mil)	Crevice Depth (mil)	Type <sup>b</sup>	Weld <sup>b</sup>	
Ni-Cr-Fe 718, welded, electrode 718	W	402	2,370	0.0	—	—	NC	NC	CEL (4)
Ni-Cr-Fe 718	W	181	5	<0.1	—	—	NC	—	CEL (4)
Ni-Cr-Fe 718	W	540	5	0.0	—	—	NC	—	CEL (4)
Ni-Cr-Fe 718, welded, electrode 718	W	540	5	0.0	—	—	NC	NC	CEL (4)
Ni-Cr-Fe X750	W	123	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe X750	S	123	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe X750	W	403	6,780	0.2	—	35	C (PR)	—	INCO (3)
Ni-Cr-Fe X750	S	403	6,780	<0.1	—	3	C	—	INCO (3)
Ni-Cr-Fe X750	W	751	5,640	0.4	—	40	C (PR)	—	INCO (3)
Ni-Cr-Fe X750	S	751	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe X750	W	1,064	5,300	0.1	25	40	C (PR); P	—	INCO (3)
Ni-Cr-Fe X750	W	1,064	5,300	0.1	—	47	C	—	INCO (3)
Ni-Cr-Fe X750	S	1,064	5,300	<0.1	—	9	C	—	INCO (3)
Ni-Cr-Fe X750	W	197	2,340	0.4	—	18	C	—	INCO (3)
Ni-Cr-Fe X750	S	197	2,340	<0.1	—	7	C	—	INCO (3)
Ni-Cr-Fe X750	W	402	2,370	0.1	—	16	C	—	Shell (9)
Ni-Cr-Fe X750	W	402	2,370	0.1	—	17	C	—	INCO (3)
Ni-Cr-Fe X750	W	402	2,370	0.1	—	—	T	—	CEL (4)
Ni-Cr-Fe X750, welded, filler metal 69	W	402	2,370	0.3	—	—	ET	ET	CEL (4)
Ni-Cr-Fe X750, welded, electrode 718	W	402	2,370	0.2	—	—	U	T (HAZ55); WB; E (PR)	CEL (4)
Ni-Cr-Fe X750	S	402	2,370	0.4	—	16	C	—	Shell (9)
Ni-Cr-Fe X750	S	402	2,370	<0.1	—	4	C	—	INCO (3)
Ni-Cr-Fe X750	S	402	2,370	<0.1	—	—	ET	—	CEL (4)
Ni-Cr-Fe X750	W	181	5	1.4	50	50	C (PR); P (PR)	—	INCO (3)
Ni-Cr-Fe X750	W	366	5	0.9	50	50	C (PR); P (PR)	—	INCO (3)
Ni-Cr-Fe X750	W	540	5	0.3	130	130	C (PR); P (PR)	—	CEL (4)
Ni-Cr-Fe X750, welded, filler metal 69	W	540	5	0.5	130	—	P (PR)	CR (WB&HAZ)	CEL (4)
Ni-Cr-Fe X750, welded, electrode 718	W	540	5	0.5	130	130	C (PR); P (PR)	CR (PR; HAZ)	CEL (4)

Continued

Table 33. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mil)	Crevice Depth (mil)	Type <sup>b</sup>	Weld <sup>b</sup>	
Ni-Fe-Cr 800	W	123	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 800	S	123	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 800	W	403	6,780	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 800	S	403	6,780	<0.1	—	1	C	—	INCO (3)
Ni-Fe-Cr 800	W	751	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 800	S	751	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 800	W	1,064	5,300	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 800	S	1,064	5,300	<0.1	—	6	C	—	INCO (3)
Ni-Fe-Cr 800	W	197	2,340	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 800	S	197	2,340	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 800	W	402	2,370	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 800	W	402	2,370	0.0	—	—	NC	—	CEL (4)
Ni-Fe-Cr 800, welded, filler metal 82	W	402	2,370	<0.1	—	—	NC	WB; E (PR)	CEL (4)
Ni-Fe-Cr 800, welded, electrode 138	W	402	2,370	<0.1	—	—	NC	WB (E) <sup>d</sup>	CEL (4)
Ni-Fe-Cr 800	S	402	2,370	<0.1	—	—	ET	—	CEL (4)
Ni-Fe-Cr 800	S	402	2,370	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 800	W	181	5	<0.1	—	—	NC	—	CEL (4)
Ni-Fe-Cr 800	W	181	5	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 800	W	366	5	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 800	W	540	5	0.3	128	—	P (PR)	—	CEL (4)
Ni-Fe-Cr 800, welded, filler metal 82	W	540	5	0.4	128	—	P (PR)	T (WB&HAZ)	CEL (4)
Ni-Fe-Cr 800, welded, electrode 182	W	540	5	0.7	128	—	P (PR)	WB&HAZ (PR)	CEL (4)
Ni-Fe-Cr 804	W	123	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 804	S	123	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 804	W	403	6,780	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 804	S	403	6,780	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 804	W	751	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 804	S	751	5,640	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 804	W	1,064	5,300	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 804	S	1,064	5,300	<0.1	—	—	I-C	—	INCO (3)

Continued

Table 33. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mil)	Crevice Depth (mil)	Type <sup>b</sup>	Weld <sup>b</sup>	
Ni-Fe-Cr 804	W	197	2,340	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 804	S	197	2,340	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 804	W	402	2,370	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 804	S	402	2,370	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 804	W	181	5	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 804	W	366	5	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 825	W	123	5,640	0.0	—	—	NC	—	CEL (4)
Ni-Fe-Cr 825	W	123	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 825	W	123	5,640	0.1	—	—	NC; I-C	—	MEL (5)
Ni-Fe-Cr 825	S	123	5,640	<0.1	—	—	NC	—	CEL (4)
Ni-Fe-Cr 825	S	123	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 825	W	189	5,900	<0.1	—	—	NC	—	CEL (4)
Ni-Fe-Cr 825	S	189	5,900	<0.1	—	—	NC	—	CEL (4)
Ni-Fe-Cr 825, longitudinal butt weld, electrode 135	W	189	5,900	<0.1	—	—	NC	WB (I-P)	CEL (4)
Ni-Fe-Cr 825, longitudinal butt weld, electrode 135	S	189	5,900	<0.1	—	—	NC	NC	CEL (4)
Ni-Fe-Cr 825, 3-in. circular weld, electrode 135	W	189	5,900	0.0	—	—	NC	NC	CEL (4)
Ni-Fe-Cr 825, 3-in. circular weld, electrode 135	S	189	5,900	<0.1	—	—	NC	NC	CEL (4)
Ni-Fe-Cr 825	W	403	6,780	0.0	—	—	NC	—	CEL (4)
Ni-Fe-Cr 825	W	403	6,780	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 825	S	403	6,780	0.0	—	—	NC	—	CEL (4)
Ni-Fe-Cr 825	S	403	6,780	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 825	W	751	5,640	<0.1	—	22	C	—	CEL (4)
Ni-Fe-Cr 825	W	751	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 825	W	751	5,640	0.4	1	63	C (PR); P	—	MEL (5)
Ni-Fe-Cr 825	S	751	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 825	W	1,064	5,300	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 825	S	1,064	5,300	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 825	W	197	2,340	0.0	—	—	NC	—	CEL (4)
Ni-Fe-Cr 825	W	197	2,340	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 825	S	197	2,340	<0.1	—	8	C	—	CEL (4)

Continued

Table 33. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mil)	Crevice Depth (mil)	Type <sup>b</sup>	Weld <sup>b</sup>	
Ni-Fe-Cr 825	S	197	2,340	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 825	W	402	2,370	<0.1	—	15	C; ET	—	CEL (4)
Ni-Fe-Cr 825	W	402	2,370	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 825, welded, filler metal 65	W	402	2,370	<0.1	—	—	NC	NC	CEL (4)
Ni-Fe-Cr 825, welded, electrode 135	W	402	2,370	<0.1	—	—	NC	WB <sup>f</sup>	CEL (4)
Ni-Fe-Cr 825	S	402	2,370	<0.1	—	8	C	—	CEL (4)
Ni-Fe-Cr 825	S	402	2,370	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 825	W	181	5	<0.1	44 <sup>g</sup>	33	C; P	—	CEL (4)
Ni-Fe-Cr 825	W	181	5	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 825, welded, filler metal 65	W	181	5	<0.1	—	—	NC	NC	CEL (4)
Ni-Fe-Cr 825, welded, electrode 135	W	181	5	<0.1	—	—	NC	NC	CEL (4)
Ni-Fe-Cr 825	W	366	5	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 825	W	386 <sup>b</sup>	5	<0.1	2	57	C; P	—	MEL (5)
Ni-Fe-Cr 825	W	398	5	<0.1	—	—	NC	—	CEL (4)
Ni-Fe-Cr 825	W	540	5	<0.1	43	24	C; P	—	CEL (4)
Ni-Fe-Cr 825, welded, filler metal 65	W	540	5	<0.1	4	—	P	I-P (WB&HAZ)	CEL (4)
Ni-Fe-Cr 825, welded, electrode 135	W	540	5	<0.1	6	—	I-C; P	CR (HAZ)	CEL (4)
Ni-Fe-Cr 825	W	588	5	<0.1	18	—	P	—	CEL (4)
Ni-Fe-Cr 825	W	608	5	<0.1	54	—	P	—	CEL (4)
Ni-Fe-Cr 825S <sup>i</sup>	W	123	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 825S	S	123	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 825S	W	403	6,780	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 825S	S	403	6,780	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 825S	W	751	5,640	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 825S	S	751	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 825S	W	1,064	5,300	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 825S	S	1,064	5,300	<0.1	—	4	C	—	INCO (3)
Ni-Fe-Cr 825S	W	197	2,340	<0.1	—	—	I-C; I-P	—	INCO (3)

Continued



Table 33. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mil)	Crevice Depth (mil)	Type <sup>b</sup>	Weld <sup>b</sup>	
Ni-Fe-Cr 825S	S	197	2,340	<0.1	—	—	I-C; I-P	—	INCO (3)
Ni-Fe-Cr 825S	W	402	2,370	<0.1	—	—	I-C; I-P	—	INCO (3)
Ni-Fe-Cr 825S	S	402	2,370	<0.1	—	—	I-C; I-P	—	INCO (3)
Ni-Fe-Cr 825S	W	181	5	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 825S	W	366	5	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 825Cb	W	123	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 825Cb	S	123	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 825Cb	W	403	6,780	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 825Cb	S	403	6,780	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 825Cb	W	751	5,640	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 825Cb	S	751	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 825Cb	W	1,064	5,300	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 825Cb	S	1,064	5,300	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 825Cb	W	197	2,340	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 825Cb	S	197	2,340	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 825Cb	W	402	2,370	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 825Cb	S	402	2,370	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 825Cb	W	181	5	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 825Cb	W	366	5	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 901	W	123	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 901	S	123	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 901	W	403	6,780	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 901	S	403	6,780	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 901	W	751	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 901	S	751	5,640	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 901	W	1,064	5,300	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 901	S	1,064	5,300	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 901	W	197	2,340	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 901	S	197	2,340	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 901	W	402	2,370	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 901	S	402	2,370	<0.1	—	—	I-C	—	INCO (3)
Ni-Fe-Cr 901	W	181	5	<0.1	—	—	NC	—	INCO (3)
Ni-Fe-Cr 901	W	366	5	<0.1	—	—	I-C	—	INCO (3)

Continued

Table 33. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mil)	Crevice Depth (mil)	Type <sup>b</sup>	Weld <sup>b</sup>	
Ni-Fe-Cr 902	W	402	2,370	1.4	—	35	C; I-P	—	CEL (4)
Ni-Fe-Cr 902	S	402	2,370	1.0	—	20	C; I-P	—	CEL (4)
Ni-Fe-Cr 902	W	181	5	2.2	—	26	C	—	CEL (4)
Ni-Fe-Cr 902	W	364	5	2.5	—	41	C	—	CEL (4)
Ni-Fe-Cr 902	W	723	5	1.7	—	40	C	—	CEL (4)
Ni-Fe-Cr 902	W	763	5	1.5	73	125	C (PR); P	—	CEL (4)
Ni-Cr-Mo 625	W	189	5,900	0.0	—	—	NC	—	CEL (4)
Ni-Cr-Mo 625	S	189	5,900	0.0	—	—	NC	—	CEL (4)
Ni-Cr-Mo 625, longitudinal butt weld, electrode 625	W	189	5,900	0.0	—	—	NC	NC	CEL (4)
Ni-Cr-Mo 625, longitudinal butt weld, electrode 625	S	189	5,900	0.0	—	—	NC	NC	CEL (4)
Ni-Cr-Mo 625, 3-in. circular weld, electrode 625	W	189	5,900	0.0	—	—	NC	NC	CEL (4)
Ni-Cr-Mo 625, 3-in. circular weld, electrode 625	S	189	5,900	0.0	—	—	NC	NC	CEL (4)
Ni-Cr-Mo 625	W	402	2,370	<0.1	—	—	NC	—	CEL (4)
Ni-Cr-Mo 625	W	402	2,370	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Mo 625	S	402	2,370	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Mo 625	W	181	5	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Mo 625	W	366	5	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Mo 625	W	398	5	0.0	—	—	NC	—	CEL (4)
Ni-Cr-Mo 625, welded, electrode 625	W	398	5	0.0	—	—	NC	NC	CEL (4)
Ni-Cr-Mo 625	W	540	5	0.0	—	—	NC	—	CEL (4)
Ni-Cr-Mo 625, welded, filler metal 625	W	540	5	0.0	—	—	NC	NC	CEL (4)
Ni-Cr-Mo 625, welded, electrode 625	W	540	5	0.0	—	—	NC	NC	CEL (4)
Ni-Cr-Mo 625	W	588	5	0.0	—	—	NC	—	CEL (4)
Ni-Cr-Mo 625, welded, electrode 625	W	588	5	0.0	—	—	NC	NC	CEL (4)
Ni-Mo-Cr C	W	123	5,640	<0.1	—	—	NC	—	CEL (4)
Ni-Mo-Cr C	W	123	5,640	<0.1	—	—	NC	—	INCO (3)

Continued

Table 33. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mil)	Crevice Depth (mil)	Type <sup>b</sup>	Weld <sup>b</sup>	
Ni-Mo-Cr C	W	123	5,640	<0.1	—	—	NC	—	MEL (5)
Ni-Mo-Cr C	S	123	5,640	<0.1	—	—	NC	—	CEL (4)
Ni-Mo-Cr C	S	123	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Mo-Cr C	W	403	6,780	0.0	—	—	NC	—	CEL (4)
Ni-Mo-Cr C	W	403	6,780	<0.1	—	—	NC	—	INCO (3)
Ni-Mo-Cr C	S	403	6,780	0.0	—	—	NC	—	CEL (4)
Ni-Mo-Cr C	S	403	6,780	<0.1	—	—	NC	—	INCO (3)
Ni-Mo-Cr C	W	751	5,640	0.0	—	—	NC	—	CEL (4)
Ni-Mo-Cr C	W	751	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Mo-Cr C	W	751	5,640	<0.1	—	—	NC	—	MEL (5)
Ni-Mo-Cr C	S	751	5,640	0.0	—	—	NC	—	CEL (4)
Ni-Mo-Cr C	S	751	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Mo-Cr C	W	1,064	5,300	0.0	—	—	NC	—	CEL (4)
Ni-Mo-Cr C	W	1,064	5,300	<0.1	—	—	NC	—	INCO (3)
Ni-Mo-Cr C	S	1,064	5,300	0.0	—	—	NC	—	CEL (4)
Ni-Mo-Cr C	S	1,064	5,300	<0.1	—	—	NC	—	INCO (3)
Ni-Mo-Cr C	W	197	2,340	0.0	—	—	NC	—	CEL (4)
Ni-Mo-Cr C	W	197	2,340	<0.1	—	—	NC	—	INCO (3)
Ni-Mo-Cr C	S	197	2,340	0.0	—	—	NC	—	CEL (4)
Ni-Mo-Cr C	S	197	2,340	<0.1	—	—	NC	—	INCO (3)
Ni-Mo-Cr C	W	402	2,370	0.0	—	—	NC	—	CEL (4)
Ni-Mo-Cr C	W	402	2,370	<0.1	—	—	NC	—	INCO (3)
Ni-Mo-Cr C	S	402	2,370	0.0	—	—	NC	—	CEL (4)
Ni-Mo-Cr C	S	402	2,370	<0.1	—	—	NC	—	INCO (3)
Ni-Mo-Cr C	W	181	5	<0.1	—	—	NC	—	CEL (4)
Ni-Mo-Cr C	W	181	5	<0.1	—	—	NC	—	INCO (3)
Ni-Mo-Cr C	W	366	5	<0.1	—	—	NC	—	INCO (3)
Ni-Mo-Cr C	W	398	5	<0.1	—	—	NC	—	CEL (4)
Ni-Mo-Cr C	W	608	5	0.0	—	—	NC	—	CEL (4)
Ni-Mo-Cr 3	W	123	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Mo-Cr 3	S	123	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Mo-Cr 3	W	403	6,780	<0.1	—	—	NC	—	INCO (3)
Ni-Mo-Cr 3	S	403	6,780	<0.1	—	—	NC	—	INCO (3)
Ni-Mo-Cr 3	W	751	5,640	<0.1	—	—	NC	—	INCO (3)

Continued

Table 33. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mil)	Crevice Depth (mil)	Type <sup>b</sup>	Weld <sup>b</sup>	
Ni-Mo-Cr 3	S	751	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Mo-Cr 3	W	1,064	5,300	<0.1	—	—	NC	—	INCO (3)
Ni-Mo-Cr 3	S	1,064	5,300	<0.1	—	—	NC	—	INCO (3)
Ni-Mo-Cr 3	W	197	2,340	<0.1	—	—	NC	—	INCO (3)
Ni-Mo-Cr 3	S	197	2,340	<0.1	—	—	NC	—	INCO (3)
Ni-Mo-Cr 3	W	402	2,370	<0.1	—	—	NC	—	INCO (3)
Ni-Mo-Cr 3	S	402	2,370	<0.1	—	—	NC	—	INCO (3)
Ni-Mo-Cr 3	W	181	5	<0.1	—	—	NC	—	INCO (3)
Ni-Mo-Cr 3	W	366	5	<0.1	—	—	NC	—	INCO (3)
Ni-Co-Cr 700	W	123	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Co-Cr 700	S	123	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Co-Cr 700	W	403	6,780	<0.1	—	—	NC	—	INCO (3)
Ni-Co-Cr 700	S	403	6,780	<0.1	—	—	NC	—	INCO (3)
Ni-Co-Cr 700	W	751	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Co-Cr 700	S	751	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Co-Cr 700	W	1,064	5,300	<0.1	—	—	NC	—	INCO (3)
Ni-Co-Cr 700	S	1,064	5,300	<0.1	—	—	I-C	—	INCO (3)
Ni-Co-Cr 700	W	197	2,340	<0.1	—	—	NC	—	INCO (3)
Ni-Co-Cr 700	S	197	2,340	<0.1	—	—	NC	—	INCO (3)
Ni-Co-Cr 700	W	402	2,370	<0.1	—	—	I-C	—	INCO (3)
Ni-Co-Cr 700	S	402	2,370	<0.1	—	—	I-C	—	INCO (3)
Ni-Co-Cr 700	W	181	5	<0.1	—	—	NC	—	INCO (3)
Ni-Co-Cr 700	W	366	5	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Co 41	W	1,064	5,300	0.0	—	—	NC	—	CEL (4)
Ni-Mo-Fe B	W	123	5,640	2.3	—	—	U	—	INCO (3)
Ni-Mo-Fe B	S	123	5,640	2.2	—	—	U	—	INCO (3)
Ni-Mo-Fe B	W	403	6,780	4.0	—	—	U	—	INCO (3)
Ni-Mo-Fe B	S	403	6,780	0.6	—	—	U <sup>j</sup>	—	INCO (3)
Ni-Mo-Fe B	W	751	5,640	2.9	—	—	G	—	INCO (3)
Ni-Mo-Fe B	S	751	5,640	1.8	—	—	G	—	INCO (3)
Ni-Mo-Fe B	W	1,064	5,300	1.5	—	—	G	—	INCO (3)
Ni-Mo-Fe B	S	1,064	5,300	0.3	—	—	NU	—	INCO (3)
Ni-Mo-Fe B	W	197	2,340	<0.1	—	—	NU-ET	—	INCO (3)

Continued

Table 33. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mil)	Crevice Depth (mil)	Type <sup>b</sup>	Weld <sup>b</sup>	
Ni-Mo-Fe B	S	197	2,340	<0.1	—	—	I-C; I-P	—	INCO (3)
Ni-Mo-Fe B	W	402	2,370	1.2	—	—	G	—	INCO (3)
Ni-Mo-Fe B	S	402	2,370	0.2	—	—	U	—	INCO (3)
Ni-Mo-Fe B	W	181	5	7.9	—	—	G	—	INCO (3)
Ni-Mo-Fe B	W	366	5	6.4	—	—	G	—	INCO (3)
Ni-Mo-Fe 2	W	123	5,640	1.2	—	—	G	—	INCO (3)
Ni-Mo-Fe 2	S	123	5,640	1.1	—	—	G	—	INCO (3)
Ni-Mo-Fe 2	W	403	6,780	2.2	—	—	G	—	INCO (3)
Ni-Mo-Fe 2	S	403	6,780	0.3	—	—	G	—	INCO (3)
Ni-Mo-Fe 2	W	751	5,640	6.8	—	—	G	—	INCO (3)
Ni-Mo-Fe 2	S	751	5,640	1.6	—	—	G	—	INCO (3)
Ni-Mo-Fe 2	W	1,064	5,300	3.2	—	—	G	—	INCO (3)
Ni-Mo-Fe 2	S	1,064	5,300	1.8	—	—	G	—	INCO (3)
Ni-Mo-Fe 2	W	197	2,340	1.0	—	—	G	—	INCO (3)
Ni-Mo-Fe 2	S	197	2,340	0.2	—	—	G	—	INCO (3)
Ni-Mo-Fe 2	W	402	2,370	1.6	—	—	G	—	INCO (3)
Ni-Mo-Fe 2	S	402	2,370	0.3	—	—	ET	—	INCO (3)
Ni-Mo-Fe 2	W	181	5	4.7	5	—	P	—	INCO (3)
Ni-Mo-Fe 2	W	366	5	4.7	12	—	P	—	INCO (3)
Ni-Cr-Fe-Mo F	W	123	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe-Mo F	S	123	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe-Mo F	W	403	6,780	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe-Mo F	S	403	6,780	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe-Mo F	W	751	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe-Mo F	S	751	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe-Mo F	W	1,064	5,300	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe-Mo F	S	1,064	5,300	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe-Mo F	W	197	2,340	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe-Mo F	S	197	2,340	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe-Mo F	W	402	2,370	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe-Mo F	S	402	2,370	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe-Mo F	W	181	5	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe-Mo F	W	366	5	<0.1	—	—	NC	—	INCO (3)

Continued

Table 33. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mil)	Crevice Depth (mil)	Type <sup>b</sup>	Weld <sup>b</sup>	
Ni-Cr-Fe-Mo G	W	402	2,370	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe-Mo G	S	402	2,370	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe-Mo G	W	181	5	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe-Mo G	W	366	5	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe-Mo X	W	123	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe-Mo X	S	123	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe-Mo X	W	403	6,780	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe-Mo X	S	403	6,780	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe-Mo X	W	751	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe-Mo X	S	751	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe-Mo X	W	1,064	5,300	<0.1	—	—	SL-ET	—	INCO (3)
Ni-Cr-Fe-Mo X	S	1,064	5,300	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe-Mo X	W	197	2,340	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe-Mo X	S	197	2,340	<0.1	—	—	I-C	—	INCO (3)
Ni-Cr-Fe-Mo X	W	402	2,370	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe-Mo X	S	402	2,370	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe-Mo X	W	181	5	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe-Mo X	W	366	5	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe 88	W	123	5,640	0.1	—	4	C	—	INCO (3)
Ni-Cr-Fe 88	S	123	5,640	0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe 88	W	403	6,780	<0.1	—	5	C	—	INCO (3)
Ni-Cr-Fe 88	S	403	6,780	<0.1	—	—	NC	—	INCO (3)
Ni-Cr-Fe 88	W	751	5,640	<0.1	—	—	I-C	—	INCO (3)
Ni-Cr-Fe 88	S	751	5,640	1.3	180	—	P (PR) <sup>k</sup>	—	INCO (3)
Ni-Cr-Fe 88	W	1,064	5,300	<0.1	—	67	C	—	INCO (3)
Ni-Cr-Fe 88	S	1,064	5,300	<0.1	—	5	C	—	INCO (3)
Ni-Cr-Fe 88	W	197	2,340	0.3	—	17	C; P	—	INCO (3)
Ni-Cr-Fe 88	S	197	2,340	<0.1	—	—	I-C	—	INCO (3)
Ni-Cr-Fe 88	W	402	2,370	0.4	—	52	C; P	—	INCO (3)
Ni-Cr-Fe 88	S	402	2,370	<0.1	—	—	I-C	—	INCO (3)
Ni-Cr-Fe 88	W	181	5	1.1	108	17	C; P	—	INCO (3)
Ni-Cr-Fe 88	W	366	5	1.0	150	—	P	—	INCO (3)

Continued

Table 33. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mil)	Crevice Depth (mil)	Type <sup>b</sup>	Weld <sup>b</sup>	
Ni-Sn-Zn 23	W	123	5,640	2.6	—	25	C	—	INCO (3)
Ni-Sn-Zn 23	S	123	5,640	1.8	—	14	C	—	INCO (3)
Ni-Sn-Zn 23	W	403	6,780	8.4	—	36	C; P	—	INCO (3)
Ni-Sn-Zn 23	S	403	6,780	<0.1	—	—	NC	—	INCO (3)
Ni-Sn-Zn 23	W	751	5,640	3.5	—	56	C; P	—	INCO (3)
Ni-Sn-Zn 23	S	751	5,640	2.1	—	52	C; P	—	INCO (3)
Ni-Sn-Zn 23	W	1,064	5,300	1.7	—	50	C; P	—	INCO (3)
Ni-Sn-Zn 23	S	1,064	5,300	1.0	35	—	P	—	INCO (3)
Ni-Sn-Zn 23	W	197	2,340	0.5	—	15	C	—	INCO (3)
Ni-Sn-Zn 23	S	197	2,340	<0.1	—	—	I-C	—	INCO (3)
Ni-Sn-Zn 23	W	402	2,370	0.9	—	29	C	—	INCO (3)
Ni-Sn-Zn 23	S	402	2,370	0.1	—	—	I-C	—	INCO (3)
Ni-Sn-Zn 23	W	181	5	3.7	37	27	C; P	—	INCO (3)
Ni-Sn-Zn 23	W	366	5	4.5	37	37	C; P	—	INCO (3)
Ni-Be	W	402	2,370	1.1	17	—	ET; P <sup>I</sup>	—	CEL (4)
Ni-Be	S	402	2,370	0.7	8	—	ET; P <sup>I</sup>	—	CEL (4)
Ni-Be	W	364	5	5.4	152	—	ET; P <sup>I</sup>	—	CEL (4)
Ni-Be	W	763	5	4.9	345	—	CR (43); P <sup>I</sup>	—	CEL (4)
Ni-Cr, 65-35	W	123	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Cr, 65-35	S	123	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Cr, 65-35	W	403	6,780	<0.1	—	35	C (PR)	—	INCO (3)
Ni-Cr, 65-35	S	403	6,780	<0.1	—	—	I-C	—	INCO (3)
Ni-Cr, 65-35	W	751	5,640	<0.1	—	20	C	—	INCO (3)
Ni-Cr, 65-35	S	751	5,640	<0.1	—	—	I-C	—	INCO (3)
Ni-Cr, 65-35	W	1,064	5,300	<0.1	—	5	C	—	INCO (3)
Ni-Cr, 65-35	S	1,064	5,300	0.1	—	50	C (PR)	—	INCO (3)
Ni-Cr, 65-35	W	197	2,340	0.3	—	24	C	—	INCO (3)
Ni-Cr, 65-35	S	197	2,340	<0.1	—	—	I-C	—	INCO (3)
Ni-Cr, 65-35	W	402	2,370	0.1	—	6	C	—	INCO (3)
Ni-Cr, 65-35	S	402	2,370	<0.1	—	—	I-C	—	INCO (3)
Ni-Cr, 65-35	W	181	5	2.4	50	50	C (PR); P (PR)	—	INCO (3)
Ni-Cr, 65-35	W	366	5	1.9	30	30	C (PR); P (PR)	—	INCO (3)

Continued



Table 33. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mil)	Crevice Depth (mil)	Type <sup>b</sup>	Weld <sup>b</sup>	
Ni-Cr, 75	W	123	5,640	<0.1	—	—	I-C	—	INCO (3)
Ni-Cr, 75	S	123	5,640	<0.1	—	—	NC	—	INCO (3)
Ni-Cr, 75	W	403	6,780	0.4	—	40	C (PR)	—	INCO (3)
Ni-Cr, 75	S	403	6,780	<0.1	—	—	I-C	—	INCO (3)
Ni-Cr, 75	W	751	5,640	0.5	—	40	C (PR); P	—	INCO (3)
Ni-Cr, 75	S	751	5,640	<0.1	—	2	C	—	INCO (3)
Ni-Cr, 75	W	1,064	5,300	<0.1	—	—	I-C	—	INCO (3)
Ni-Cr, 75	S	1,064	5,300	<0.1	—	12	C	—	INCO (3)
Ni-Cr, 75	W	197	2,340	0.3	—	40	C (PR)	—	INCO (3)
Ni-Cr, 75	S	197	2,340	<0.1	—	5	C	—	INCO (3)
Ni-Cr, 75	W	402	2,370	0.4	—	40	C (PR)	—	INCO (3)
Ni-Cr, 75	S	402	2,370	<0.1	—	—	I-C	—	INCO (3)
Ni-Cr, 75	W	181	5	1.5	50	50	C (PR); P (PR)	—	INCO (3)
Ni-Cr, 75	W	366	5	1.2	50	50	C (PR); P (PR)	—	INCO (3)
Ni-Cr, 80-20	W	123	5,640	<0.1	—	2	C	—	INCO (3)
Ni-Cr, 80-20	S	123	5,640	<0.1	—	—	I-C	—	INCO (3)
Ni-Cr, 80-20	W	403	6,780	0.2	—	11	C	—	INCO (3)
Ni-Cr, 80-20	S	403	6,780	<0.1	—	—	I-C	—	INCO (3)
Ni-Cr, 80-20	W	751	5,640	0.4	—	32	C (PR)	—	INCO (3)
Ni-Cr, 80-20	S	751	5,640	<0.1	—	—	I-C	—	INCO (3)
Ni-Cr, 80-20	W	1,064	5,300	<0.1	—	5	C	—	INCO (3)
Ni-Cr, 80-20	S	1,064	5,300	0.1	—	50	C (PR)	—	INCO (3)
Ni-Cr, 80-20	W	197	2,340	0.2	—	32	C (PR)	—	INCO (3)
Ni-Cr, 80-20	S	197	2,340	<0.1	—	—	I-C; E	—	INCO (3)
Ni-Cr, 80-20	W	402	2,370	0.2	—	18	C; P	—	INCO (3)
Ni-Cr, 80-20	S	402	2,370	<0.1	—	—	I-C	—	INCO (3)
Ni-Cr, 80-20	W	181	5	2.6	50	50	C (PR); P (PR)	—	INCO (3)
Ni-Cr, 80-20	W	366	5	1.6	30	30	C (PR); P (PR)	—	INCO (3)
Ni-Si D	W	123	5,640	1.3	—	12	C	—	INCO (3)
Ni-Si D	S	123	5,640	1.4	—	10	C	—	INCO (3)
Ni-Si D	W	403	6,780	2.4	—	5	C; P	—	INCO (3)
Ni-Si D	S	403	6,780	1.4	—	14	C	—	INCO (3)
Ni-Si D	W	751	5,640	1.7	—	29	C	—	INCO (3)
Ni-Si D	S	751	5,640	1.5	—	6	C; P	—	INCO (3)

Continued

Table 33. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mil)	Crevice Depth (mil)	Type <sup>b</sup>	Weld <sup>b</sup>	
Ni-Si D	W	1,064	5,300	1.6	38	42	C; P	—	INCO (3)
Ni-Si D	S	1,064	5,300	1.1	20	25	C; P	—	INCO (3)
Ni-Si D	W	197	2,340	0.2	—	—	I-C	—	INCO (3)
Ni-Si D	S	197	2,340	<0.1	—	—	I-C	—	INCO (3)
Ni-Si D	W	402	2,370	0.5	—	14	C	—	INCO (3)
Ni-Si D	S	402	2,370	0.2	—	—	ET	—	INCO (3)
Ni-Si D	W	181	5	2.5	19	25	C; P	—	INCO (3)
Ni-Si D	W	366	5	1.9	37	33	C; P	—	INCO (3)

<sup>a</sup>W = Totally exposed in seawater on sides of structure; S = Exposed in base of structure so that the lower portions of the specimen were embedded in the bottom sediments.

<sup>b</sup>Symbols for types of corrosion:

C = Crevice	NU = Nonuniform
CR = Cratering	P = Pitting
E = Edge	PR = Perforation
ET = Etched	SL = Slight
G = General	T = Tunneling
HAZ = Heat affected zone	U = Uniform
I = Incipient	WB = Weld bead
NC = No visible corrosion	

Numbers indicate maximum depth in mils.

<sup>c</sup>Numbers refer to references at end of report.

<sup>d</sup>Line corrosion at edge of weld bead.

<sup>e</sup>Only two deep pits.

<sup>f</sup>One end corroded.

<sup>g</sup>Under barnacles.

<sup>h</sup>Francis L. LaQue Corrosion Laboratory, INCO, Wrightsville Beach, N.C.

<sup>i</sup>Sensitized by heating 1 hour at 1,200°F and then air cooling.

<sup>j</sup>Groove at mud line.

<sup>k</sup>Only one pit.

<sup>l</sup>Pitting only on ends of bars.

Table 34. Changes in Mechanical Properties of Nickel Alloys Due to Corrosion

Alloy	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>a</sup>
			Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
Ni-Cr-Fe 600	197	2,340	111	0	51	+7	51	-30	NADC (7)
Ni-Cr-Fe 600	403	2,370	111	-10	51	-14	51	-15	NADC (7)
Ni-Fe-Cr 825	123	5,640	108	0	52	+4	38	0	CEL (4)
Ni-Fe-Cr 825	403	6,780	108	0	52	+3	38	-4	CEL (4)
Ni-Fe-Cr 825	751	5,640	108	+2	52	+5	38	-3	CEL (4)
Ni-Fe-Cr 825	197	2,340	108	0	52	+4	38	-6	CEL (4)
Ni-Fe-Cr 825	402	2,370	108	+1	52	+4	38	-3	CEL (4)
Ni-Fe-Cr 825	181	5	108	+1	52	-2	38	-7	CEL (4)
Ni-Fe-Cr 902	402	2,370	99	-2	40	-8	43	-49	CEL (4)
Ni-Fe-Cr 902	181	5	99	-1	40	+6	43	-50	CEL (4)
Ni-Mo-Cr C	123	5,640	121	+3	60	+5	43	-1	CEL (4)
Ni-Mo-Cr C	403	6,780	121	+5	60	+1	43	+15	CEL (4)
Ni-Mo-Cr C	751	5,640	121	+4	60	0	43	+15	CEL (4)
Ni-Mo-Cr C	1,064	5,300	121	+3	60	-7	43	+15	CEL (4)
Ni-Mo-Cr C	197	2,340	121	+3	60	-1	43	+18	CEL (4)
Ni-Mo-Cr C	402	2,370	121	+3	60	+3	43	+12	CEL (4)
Ni-Mo-Cr C	181	5	121	+3	60	-1	43	+15	CEL (4)
Ni-Be, 1/2 H <sup>b</sup>	197	2,340	134	-2	124	0	12	0	NADC (7)
Ni-Be, 1/2 H	402	2,370	134	-3	124	-2	12	-14	NADC (7)
Ni-Be, 1/2 HT <sup>c</sup>	197	2,340	248	-2	200	0	9	-33	NADC (7)
Ni-Be, 1/2 HT	402	2,370	248	-5	200	-	9	-60	NADC (7)

<sup>a</sup>Numbers refer to references at end of report.<sup>b</sup>Age hardened.<sup>c</sup>Age hardened and cold worked.

Table 35. Stress Corrosion of Nickel Alloys

Alloy	Stress (ksi)	Percent Yield Strength	Exposure (day)	Depth (ft)	Number of Specimens Exposed	Number Failed	Source <sup>a</sup>
Ni-200	13	50	402	2,370	3	0	CEL (4)
Ni-200	19	75	402	2,370	3	0	CEL (4)
Ni-Cu 400	14	50	402	2,370	3	0	CEL (4)
Ni-Cu 400	22	75	402	2,370	3	0	CEL (4)
Ni-Cu 400	12	30	403	6,780	3	0	NADC (7)
Ni-Cu 400	31	75	403	6,780	3	0	NADC (7)
Ni-Cu 400	12	30	197	2,340	3	0	NADC (7)
Ni-Cu 400	31	75	197	2,340	3	0	NADC (7)
Ni-Cu 400	12	30	402	2,370	3	0	NADC (7)
Ni-Cu 400	31	75	402	2,370	3	0	NADC (7)
Ni-Cu K-500	120	—	402	2,370	3	0	Shell (9)
Ni-Cr-Fe 600	15	30	403	6,780	3	0	NADC (7)
Ni-Cr-Fe 600	38	75	403	6,780	3	0	NADC (7)
Ni-Cr-Fe 600	15	30	197	2,340	3	0	NADC (7)
Ni-Cr-Fe 600	38	75	197	2,340	3	0	NADC (7)
Ni-Cr-Fe 600	15	30	402	2,370	3	0	NADC (7)
Ni-Cr-Fe 600	38	75	402	2,370	3	0	NADC (7)
Ni-Cr-Fe X-750	120	—	402	2,370	3	0	Shell (9)
Ni-Mo-Cr C	21	35	123	5,640	3	0	CEL (4)
Ni-Mo-Cr C	30	50	123	5,640	3	0	CEL (4)
Ni-Mo-Cr C	45	75	123	5,640	3	0	CEL (4)
Ni-Mo-Cr C	21	35	403	6,780	3	0	CEL (4)
Ni-Mo-Cr C	30	50	403	6,780	3	0	CEL (4)
Ni-Mo-Cr C	45	75	403	6,780	3	0	CEL (4)
Ni-Mo-Cr C	21	35	751	5,640	3	0	CEL (4)
Ni-Mo-Cr C	30	50	751	5,640	3	0	CEL (4)
Ni-Mo-Cr C	45	75	751	5,640	3	0	CEL (4)
Ni-Mo-Cr C	21	35	197	2,340	3	0	CEL (4)
Ni-Mo-Cr C	30	50	197	2,340	3	0	CEL (4)
Ni-Mo-Cr C	45	75	197	2,340	3	0	CEL (4)
Ni-Mo-Cr C	30	50	402	2,370	3	0	CEL (4)
Ni-Mo-Cr C	45	75	402	2,370	3	0	CEL (4)
Ni-Fe-Cr 825	26	50	402	2,370	3	0	CEL (4)
Ni-Fe-Cr 825	39	75	402	2,370	3	0	CEL (4)
Ni-Be, 1/2 H	37	30	403	6,780	3	0	NADC (7)
Ni-Be, 1/2 H	93	75	403	6,780	3	0	NADC (7)
Ni-Be, 1/2 H	37	30	197	2,340	3	0	NADC (7)

Continued

Table 35. Continued.

Alloy	Stress (ksi)	Percent Yield Strength	Exposure (day)	Depth (ft)	Number of Specimens Exposed	Number Failed	Source <sup>a</sup>
Ni-Be, 1/2 H	93	75	197	2,340	3	0	NADC (7)
Ni-Be, 1/2 H	37	30	402	2,370	3	0	NADC (7)
Ni-Be, 1/2 H	93	75	402	2,370	3	0	NADC (7)
Ni-Be, 1/2 HT	60	30	403	6,780	3	0	NADC (7)
Ni-Be, 1/2 HT	60	30	197	2,340 <sup>b</sup>	3	0	NADC (7)
Ni-Be, 1/2 HT	60	30	402	2,370	3	0	NADC (7)

<sup>a</sup>Numbers refer to references at end of report.

<sup>b</sup>Severe corrosion at sheared edges indicating possible susceptibility to stress corrosion cracking.

## STAINLESS STEELS

The corrosion resistance of stainless steels is attributed to a very thin, stable oxide film on the surface of the alloy which results from the alloying of carbon steels with chromium. Chromium, being a passive metal (corrosion resistant), imparts its passivity to steel when alloyed with it in amounts of 12% or greater. These iron-chromium alloys are very corrosion-resistant in oxidizing environments because the passive film is maintained in most environments when a sufficient amount of oxidizing agent or oxygen is present to repair any breaks in the protective film.

The corrosion resistance of stainless steels is further enhanced by the addition of nickel to the iron-chromium alloys. This group of alloys is popularly known as the 18-8 (18% chromium -- 8% nickel) stainless steels.

In general, oxidizing conditions favor passivity (corrosion resistance), while reducing conditions destroy it. Chloride ions are particularly aggressive in destroying this passivity.

Stainless steels usually corrode by pitting and crevice corrosion in seawater. Pits begin by breakdown of the passive film at weak spots or at non-homogeneities. The breakdown is followed by the formation of an electrolytic cell, the anode of which is a minute area of active metal and the cathode of which is a considerable area of passive metal. The large potential difference characteristic of this "passive-active" cell accounts for considerable flow of current with attendant rapid corrosion (pitting) at the small anode.

Pitting is most likely to occur in the presence of chloride ions (for example, seawater), combined with such depolarizers as oxygen or oxidizing salts. An oxidizing environment is usually necessary for preservation of passivity with accompanying high corrosion resistance; but, unfortunately, it is also a favorable condition for pitting. The oxidizer can often act as a depolarizer for passive-active cells that were established by breakdown of passivity at a specific point or area. The chloride ion in particular can accomplish this breakdown.

Stainless steels can and do pit in aerated seawater (near neutral chloride solution). Pitting is less pronounced in rapidly moving seawater (aerated solution) as compared with partially aerated, stagnant seawater. The flow of seawater carries away corrosion products which would otherwise accumulate at crevices or cracks. It also insures uniform passivity through free access of dissolved oxygen.

As discussed above, stainless steels generally corrode in seawater by pitting and crevice corrosion; therefore, as much as 90 to 95% of the exposed surface can be uncorroded. With such low percentages of the total exposed area affected, corrosion calculated from loss in weight as mils penetration per year (mpy) can give a very misleading picture. The mpy implies a uniform decrease in thickness, which, for stainless steels, is not the case.

A manifestation of pitting corrosion, whose presence and extent is often overlooked, is tunnel corrosion. Tunnel corrosion is also classified by some as edge, honeycomb, or underfilm corrosion. Tunnel corrosion is insidious because of its nature and because many times it is not apparent from the outside surfaces of the object. It starts as a pit on the surface or on an edge and propagates laterally through the material, many times leaving thin films of uncorroded metal on the exposed surfaces.

Another manifestation of localized attack in stainless steels is oxygen concentration cell corrosion in crevices (usually known as crevice corrosion). This type of corrosion occurs underneath deposits of any kind on the metal surface, underneath barnacles, and at the faying surfaces of a joint. The area of stainless steel that is shielded from the surrounding solution becomes deficient in oxygen, thus creating a difference in oxygen concentration between the shielded and unshielded areas. An electrolytic cell is created, with a difference of potential being generated between the high and low oxygen concentration areas (the low oxygen concentration area becomes the anode of the cell).

Low weight losses and corrosion rates accompany these manifestations of corrosion. Thus, the integrity

of a stainless steel structure can be jeopardized if designed solely on the basis of corrosion rates calculated from weight losses rather than on the basis of measured depths of pits, lengths of tunnel corrosion, and depths of crevice corrosion. Pitting, tunneling, and crevice corrosion, can and do penetrate stainless steel rapidly, thus rendering it useless in short periods of time.

Therefore, corrosion rates expressed as mpy calculated from weight losses, maximum pit depths, maximum lengths of tunnel corrosion, maximum depths of crevice corrosion, and types of corrosion are tabulated to provide an overall picture of the corrosion of the stainless steels.

### 5.1. AISI 200 SERIES STAINLESS STEELS

The chemical compositions of the AISI 200 Series stainless steels are given in Table 36, their corrosion rates and types of corrosion in Table 37, their stress corrosion behavior in Table 38, and the effect of exposure on their mechanical properties in Table 39.

The AISI 200 Series stainless steels are 300 Series stainless steels modified by substituting manganese for about one-half of the nickel. This modification does not adversely affect the corrosion resistance of iron-chromium-nickel alloys in many environments.

#### 5.1.1. Duration of Exposure

The AISI 201 and 202 alloys were attacked by crevice and pitting types of corrosion both at the surface and at depths in the seawater. There was a tendency for both alloys to be more severely corroded after longer periods of exposure both at the surface and at depth. The bottom sediments were about as corrosive as the seawater above them.

#### 5.1.2. Effect of Depth

The corrosion of AISI 201 was approximately the same at the surface as at depth, while that of AISI 202 was less severe at depth than at the surface. However, it was concluded that depth had no definite influence on the corrosion of the AISI 200 Series stainless steels.

#### 5.1.3. Effect of Concentration of Oxygen

The effect of changes in the concentration of oxygen in seawater on the corrosion of both AISI 201 and 202 stainless steels was nonuniform. In general, crevice and pitting corrosion were more rapid and severe at the surface than at depth, but there was no definite correlation between corrosion and oxygen concentration.

As is well known, oxygen can and does play a dual role in the corrosion of stainless steels in electrolytes (for example, seawater). An oxidizing environment (presence of oxygen or other oxidizers) is necessary for maintaining the passivity of stainless steels. However, this same oxidizing environment is necessary to initiate and maintain pitting in stainless steels. Oxygen often acts as the depolarizer for passive-active cells created by the breakdown of passivity at a specific point or area. The chloride ion (present in abundance in seawater) is singularly efficient in accomplishing this breakdown. Therefore, this dual role of oxygen can be used to explain the inconsistent and erratic corrosion behavior of stainless steels in seawater.

#### 5.1.4. Stress Corrosion

AISI 201 stainless steel was exposed at the depths and for the times shown in Table 38 when stressed at values equivalent to 30 and 75% of its yield strength to determine its susceptibility to stress corrosion. AISI 201 stainless steel was not susceptible to stress corrosion under the above conditions of test.

#### 5.1.5. Mechanical Properties

The effects of exposure on the mechanical properties of AISI 201 and 202 stainless steels are given in Table 39. The mechanical properties were not adversely affected.

### 5.2. AISI 300 SERIES STAINLESS STEELS

The chemical compositions of the AISI 300 Series stainless steels are given in Table 40, their corrosion rates and types of corrosion in Table 41, their stress



corrosion behavior in Table 42, and the effect of exposure on their mechanical properties in Table 43.

The corrosion of the AISI 300 Series stainless steels was very erratic and unpredictable. They were attacked by crevice, pitting, and tunnel types of corrosion, in varying degrees of severity ranging from incipient to perforation of the thickness of the specimens and tunnels extending laterally for a distance of 11 inches (11,000 mils) through the specimen. Comparing the intensities of these types of localized corrosion with the corresponding corrosion rates indicates no definite correlation between them.

Two alloys, AISI 317 and 329, were attacked only by incipient crevice corrosion during exposures at all three depths (surface, 2,500, and 6,000 feet) in seawater for periods ranging from 366 days at the surface to 1,064 days at the 6,000-foot depth.

Sensitization (heating for 1 hour at 1,200°F and cooling in air) rendered AISI 304 and 316 stainless steels more susceptible to corrosion than their unsensitized counterparts.

#### 5.2.1. Duration of Exposure

Examination of the data in Table 41 shows that there is no definite or consistent correlation between severity of corrosion or corrosion rates and duration of exposure. For example, at the 6,000-foot depth in seawater the intensities of pitting and tunnel corrosion were greater after 403 days than after 1,064 days of exposure, the intensity of crevice corrosion was greater after 1,064 days than after 403 days of exposure, and the maximum corrosion rate was greater after 1,064 days than after 403 days of exposure.

#### 5.2.2. Effect of Depth

The data in Table 41 show, in general, that the intensities of crevice, pitting, and tunnel corrosion were either about the same or greater at the surface than at the depth. The corrosion rates are in agreement with this conclusion in that those of most of the alloys were greater at the surface than at depth. Based on these data and the above statements, it is concluded that depth in the ocean exerts no significant influence on the corrosion of AISI 300 Series stainless steels.

#### 5.2.3. Effect of Concentration of Oxygen

There was no definite correlation between the intensities of pitting, tunnel, and crevice corrosion of the AISI 300 Series stainless steels and changes in the concentration of oxygen in seawater after 1 year of exposure. On the basis of corrosion rates for those alloys which had definite weight losses, the rates increased with increasing concentration of oxygen, but not uniformly.

These data indicate that the corrosion of the AISI 300 Series stainless steels is not proportional to changes in the concentration of oxygen in seawater. The dual role oxygen plays in the corrosion of stainless steels in seawater, as discussed previously, also applies here as an explanation for the erratic behavior of AISI 300 Series stainless steels.

#### 5.2.4. Stress Corrosion

Some of the AISI 300 Series stainless steels were stressed at values ranging from 30 to 80% of their respective yield strengths. They were exposed in the seawater at depths of 2,500 and 6,000 feet for various periods of time to determine their susceptibility to stress corrosion cracking. These data are given in Table 42.

None of the steels were susceptible to stress corrosion under the conditions of these tests.

#### 5.2.5. Mechanical Properties

The effects of exposure on the mechanical properties of some of the 300 Series stainless steels are given in Table 43.

In only two cases were the mechanical properties adversely affected: (1) After 1,064 days of exposure at the 6,000-foot depth, the tensile and yield strengths and the elongation of AISI 304L were reduced by about 30%. This is attributed to the perforation of the specimen by both crevice and pitting corrosion, and edge and tunnel corrosion. (2) After 402 days of exposure at the 2,500-foot depth, the tensile and yield strengths of welded, sensitized AISI 316 were reduced by 45%. These reductions are attributed to the effects of welding.

### 5.3. AISI 400 SERIES STAINLESS STEELS

The chemical compositions of the AISI 400 Series stainless steels are given in Table 44, their corrosion rates and type of corrosion in Table 45, their stress corrosion behavior in Table 46, and the effect of exposure on their mechanical properties in Table 47.

The AISI 400 Series stainless steels are those which nominally contain 11 to 27% chromium. The 400 Series stainless steels are further divided into ferritic and martensitic steels. The ferritic steels are nonhardenable by heat treatment; those in this category in this program were AISI 405, 430, and 446. The martensitic steels are hardenable by heat treatment, and the one in this category in this program was AISI 410.

The corrosion of the AISI 400 Series stainless steels was erratic and was characterized by the localized types of corrosion (crevice, pitting, and tunnel). The intensities of these types varied from none to complete perforation of the thickness of the specimens for the crevice and pitting types and tunnel corrosion extending laterally the entire 12-inch (12,000 mils) length of specimens. There was no correlation between the intensities of these types of localized corrosion and the corresponding corrosion rates calculated from weight losses. The frequencies and intensities of these types of corrosion were also greater for the AISI 400 Series stainless steels than for the AISI 300 Series stainless steels.

#### 5.3.1. Duration of Exposure

The data in Table 45 show no correlation between either intensities of the localized types of corrosion or corrosion rates and duration of exposure. Neither one decreased or increased continuously with increasing duration of exposure.

#### 5.3.2. Effect of Depth

Depth had no uniform or gradual effect on the corrosion rates of the AISI 400 Series stainless steels, although the rates were lower at depth than at the surface. However, these corrosion rates did not decrease with increasing depth, i.e., they were lower at the 2,500-foot depth than at the 6,000-foot depth for two of the four steels. The intensities of the

localized types of corrosion were either the same or greater at the surface as at depth.

Depth had no definite influence on the corrosion of the AISI 400 Series stainless steels.

#### 5.3.3. Effect of Concentration of Oxygen

In general, the corrosion rates of the AISI 400 Series stainless steels were higher at the highest concentration of oxygen (at the surface) than at the lower concentrations. However, the increases were not proportional to the increase in the oxygen concentration except for AISI 410 after 1 year of exposure. The intensities of the localized types of corrosion were not influenced by changes in the concentration of oxygen in the seawater.

In general, changes in the concentration of oxygen in seawater did not exert a major influence on the corrosion of the AISI 400 Series stainless steels.

#### 5.3.4. Stress Corrosion

The AISI 400 Series stainless steels were stressed at values ranging from 30 to 75% of their respective yield strengths. They were exposed in seawater at the 2,500- and 6,000-foot depths for various periods of time to determine their susceptibilities to stress corrosion cracking. These data are given in Table 46.

None of the AISI 400 Series stainless steels were susceptible to stress corrosion under the conditions of these tests.

#### 5.3.5. Mechanical Properties

The effects of exposure on the mechanical properties of the AISI 400 Series stainless steels are given in Table 47.

In only two cases were the mechanical properties seriously impaired: (1) After 403 days of exposure at the 6,000-foot depth, the tensile and yield strengths and the elongation of AISI 405 were seriously reduced. (2) After 751 days of exposure at the 6,000-foot depth, the tensile and yield strengths and the elongation of AISI 430 were completely destroyed.

In all other exposures and for the other steels there was no impairment of the mechanical properties.

### 5.3.6. Corrosion Products

The corrosion products taken from one of the corrosion tunnels in AISI Type 430 stainless steel were analyzed by X-ray diffraction, spectrographic analysis, quantitative chemical analysis, and infra-red spectrophotometry and were found to contain amorphous ferric oxide ( $\text{Fe}_2\text{O}_3 \cdot \text{XH}_2\text{O}$ ), Fe, Cr, Mn, Si, trace of Ni, 1.41% chloride ion, 2.12% sulfate ion, and a significant amount of phosphate ion.

## 5.4. PRECIPITATION-HARDENING STAINLESS STEEL

The chemical compositions of the precipitation-hardening stainless steels are given in Table 48, their corrosion rates and types of corrosion in Table 49, their stress corrosion behavior in Tables 50 and 51, and the effect of exposure on their mechanical properties in Table 52.

The precipitation-hardening stainless steels differ from the conventional stainless steels (AISI Series 200, 300, and 400) in that they can be hardened to very high strength levels by heating the annealed steels to temperatures in the 900 to 1,200°F range and then cooling in air.

The corrosion of the precipitation-hardening stainless steels was erratic and was of the crevice, pitting, and tunnel types of localized corrosion with some edge attack. There was no correlation between the intensities of these types of localized corrosion and the corresponding corrosion rates calculated from weight losses. The frequencies and intensities of these types of corrosion were greater for the precipitation-hardening stainless steels than for the AISI 300 Series stainless steels.

The 15-7AMV steels corroded at extremely rapid rates by crevice, pitting, tunnel, and edge corrosion. In many instances, large portions of the specimens had been lost due to corrosion; in other cases tunnel corrosion had extended laterally through the specimens for distances of 11 or 12 inches within a year of exposure. They were considerably more susceptible to corrosion than were the other precipitation-hardening stainless steels.

Alloy 17Cr-14Ni-Cu-Mo was nearly free of corrosion after exposure for 366 days at the surface, 402 days at 2,500 feet, and 1,064 days at 6,000 feet.

There was one case of pitting to a depth of 3 mils after 181 days of exposure at the surface. There was incipient crevice corrosion at the surface and at depth except for pitting to a depth of 3 mils after 1,064 days of exposure in the bottom sediment at the 6,000-foot depth.

### 5.4.1. Duration of Exposure

The data in Table 49 show that there was no correlation between the intensities of the localized types of corrosion and duration of exposure. Also, there was no correlation between corrosion rates calculated from weight losses and duration of exposure except for the 15-7AMV steels for which the corrosion rates increased with increasing time of exposure.

### 5.4.2. Effect of Depth

In general, depth had no effect on the corrosion of the precipitation-hardening stainless steels.

### 5.4.3. Effect of Concentration of Oxygen

Changes in the concentration of oxygen in seawater exerted no definite or major influence on the corrosion behavior of the precipitation-hardening stainless steels.

### 5.4.4. Effect of Welding

A 3-inch-diameter circular, unrelieved weld was made in the center of the 6 x 12-inch specimens of some of the alloys to impose residual stresses in the specimens. Others had a 6-inch-long transverse, unrelieved butt weld across the center of the 6 x 12-inch specimens. These welds were to determine whether welding affected the corrosion behavior and stress corrosion susceptibilities of the alloys.

Welding did not affect the corrosion behavior of the precipitation-hardening stainless steels.

The effects of residual stresses imposed by welding will be discussed under 5.4.5.

### 5.4.5. Stress Corrosion

The precipitation-hardening stainless steels were stressed at values ranging from 35 to 85% of their

respective yield strengths. They were exposed in seawater at the surface, 2,500-, and 6,000-foot depths for various periods of time to determine their susceptibilities to stress corrosion. Their data are given in Table 50. A 3-inch-diameter circular, unrelieved weld was made in the center of the 6 x 12-inch specimens of some alloys to impose residual stresses in them. Transverse, unrelieved butt welds were made in other specimens for the purpose of simulating stresses induced during construction or fabrication. These residual stresses were multiaxial rather than uniaxial as was the case with the specimens with calculated stresses. In addition, values of these residual stresses were indeterminable. These specimens were exposed in seawater under the same conditions as those above. Their data are given in Table 51.

Alloy AISI 630, H925 with a transverse butt weld did not fail by stress corrosion when stressed to 75% of its yield strength either at the surface or at depth. However, it did fail due to the unrelieved stresses imposed by the circular weld after 403 days of exposure at the 6,000-foot depth. The crack propagated across the weld bead.

Specimens of transverse, butt-welded AISI 631, TH1050 failed when stressed to 50% of its yield strength and exposed both at the surface and at depth. Specimens with circular welds also failed when exposed at the surface and at depth. At the surface the cracks extended radially from a point inside the circle to the circular weld bead. At depth the crack extended across and around the outside edge of the weld bead.

Specimens of transverse, butt-welded AISI 631, RH1050 failed when stressed to 75% of its yield strength and exposed at the 2,500-foot depth. Specimens with circular weld beads also failed when exposed at depth. The cracks originated at the outside edge of the weld beads and propagated circumferentially in both directions either at the edge of the weld bead or in the heat-affected zone.

Specimens of alloy AISI 632, RH100 with a transverse butt weld did not fail by stress corrosion when stressed to 75% of its yield strength and exposed either at the surface or at depth. However, a specimen with a circular weld failed during 402 days of exposure at the 2,500-foot depth. The origin of the crack was on the outside edge of the weld bead, and it propagated circumferentially in both directions in the heat-affected zone.

Alloys AISI 634, CRT; AISI 635; ASTM XM16, H950 and H1050; AL362, H950 and H1050; and alloy 18Cr-14Mn-0.5N were not susceptible to stress corrosion under the conditions of these tests.

Alloy PH14-8Mo, SRH950 with a transverse butt weld failed by stress corrosion cracking when stressed to 50% of its yield strength and exposed at depth.

Specimens of 15-7AMV in the A, RH1150, and RH950 tempers failed by stress corrosion cracking when stressed at 35, 50, and 75% of their respective yield strengths and exposed at depth. Alloy 15-7AMV, RH1150 failed when exposed at depth due to the stresses imposed by it being squeezed between insulators such that it was slightly bowed. Alloys of 15-7AMV, RH1150 and RH950 failed by stress corrosion when exposed at depth; the cracks originated at unreamed, drilled holes in the specimens.

#### 5.4.6. Mechanical Properties

The effects of exposure on the mechanical properties of the precipitating-hardening stainless steels are given in Table 52. Generally, the mechanical properties of the precipitation-hardening stainless steels were adversely affected by exposure in seawater both at the surface and at depth.

### 5.5. MISCELLANEOUS STAINLESS STEELS

Included in this category are the case and specialty stainless steels which could not be included in the other classifications. Their higher nickel contents and the addition of molybdenum are to increase the range of protection of their passive films and to increase their resistance to pitting corrosion. Because these passive films are so much more resistant to destruction, any corrosion is localized in the form of crevice and pitting.

The chemical compositions of the miscellaneous stainless steels are given in Table 53, their corrosion rates and types of corrosion in Table 54, their stress corrosion behavior in Table 55, and the effect of exposure on their mechanical properties in Table 56.

These alloys were considerably more resistant to corrosion than the other alloys. There were two cases of crevice corrosion at depth of alloy 20Cb, with the deepest attack being 102 mils. There were also two

cases each of crevice and pitting attack during surface exposure; 21 mils maximum for crevice corrosion, and 24 mils maximum for pitting corrosion.

Alloy 20Cb-3, a modified version of 20Cb (4% higher nickel content), was more resistant to corrosion by seawater and the bottom sediments than 20Cb. There was only one case of crevice corrosion (40 mils deep) at depth.

The corrosion of two cast versions of 20Cb, Ni-Cr-Cu-Mo numbers 1 and 2, was very similar to that of the 20Cb. There were isolated cases of crevice corrosion, the maximum depth of attack being 27 mils.

There was only incipient crevice corrosion on cast alloy Ni-Cr-Mo during exposure at the surface and at depth.

Cast alloy Ni-Cr-Mo-Si was not susceptible to cor-

rosion by seawater during exposure either at the surface or at depth.

Cast alloy RL-35-100 was attacked by general and uniform types rather than by the localized types of corrosion. The corrosion rates were rather low, the maximum being 0.7 mil per year after 3 years of exposure at the 6,000-foot depth.

The corrosion behavior of these alloys was not affected by duration of exposure, depth of exposure, or changes in the concentration of oxygen in seawater.

As shown in Table 55, alloy 20Cb was not susceptible to stress corrosion in seawater at depth.

The effects of exposure in seawater on the mechanical properties of alloy 20Cb are given in Table 56. The mechanical properties were not affected.

Table 36. Chemical Compositions of 200 Series Stainless Steels, Percent by Weight

Alloy	C	Mn	P	S	Si	Ni	Cr	Fe <sup>a</sup>	Source <sup>b</sup>
AISI 201	0.08	6.8	—	—	—	4.0	17.1	R	INCO (3)
AISI 201	0.14	7.0	—	0.009	—	4.5	16.5	R	NADC (7)
AISI 202	0.09	7.6	—	—	—	4.5	17.8	R	INCO (3)
AISI 202	0.13	7.9	—	0.007	—	5.2	17.0	R	NADC (7)

<sup>a</sup>R = remainder.<sup>b</sup>Numbers refer to references at end of report.

Table 37. Corrosion Rates and Types of Corrosion of 200 Series Stainless Steels

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion				Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mils)	Crevice Depth <sup>b</sup> (mils)	Type <sup>b</sup>	
AISI 201	W	123	5,640	<0.1	0	I	I-C	INCO (3)
AISI 201	W	123	5,640	<0.1	0	0	NC	NADC (7)
AISI 201	S	123	5,640	<0.1	0	0	NC	INCO (3)
AISI 201	W	403	6,780	<0.1	0	I	I-C	INCO (3)
AISI 201	W	403	6,780	—	—	S	S-C	NADC (7)
AISI 201 <sup>d</sup>	W	403	6,780	—	—	—	WB (NC)	NADC (7)
AISI 201	S	403	6,780	<0.1	0	2	C	INCO (3)
AISI 201	W	751	5,640	<0.1	0	I	I-C	INCO (3)
AISI 201	W	751	5,640	—	—	S	S-C	NADC (7)
AISI 201	S	751	5,640	<0.1	0	0	NC	INCO (3)
AISI 201	W	1,064	5,300	<0.1	0	I	I-C	INCO (3)
AISI 201	S	1,064	5,300	0.5	50	I	I-C; P (PR)	INCO (3)
AISI 201	W	197	2,340	<0.1	0	4	C	INCO (3)
AISI 201	W	197	2,340	—	—	S	S-C	NADC (7)
AISI 201	S	197	2,340	<0.1	0	3	C	INCO (3)
AISI 201	W	402	2,370	<0.1	0	1	C	INCO (3)
AISI 201	W	402	2,370	—	—	S	S-C; WB (S-C)	NADC (7)
AISI 201	S	402	2,370	<0.1	0	2	C	INCO (3)
AISI 201	W	182	5	<0.1	0	I	I-C	INCO (3)
AISI 201	W	366	5	0.6	0	0	S-E	INCO (3)
AISI 202	W	123	5,640	<0.1	0	0	NC	INCO (3)
AISI 202	W	123	5,640	<0.1	—	—	NC	NADC (7)
AISI 202	S	123	5,640	<0.1	0	0	NC	INCO (3)
AISI 202	W	403	6,780	<0.1	0	I	I-C	INCO (3)
AISI 202	S	403	6,780	<0.1	0	I	I-C	INCO (3)
AISI 202	W	751	5,640	<0.1	0	I	I-C	INCO (3)
AISI 202	S	751	5,640	<0.1	0	I	I-C	INCO (3)

Continued

Table 37. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion				Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mils)	Crevice Depth <sup>b</sup> (mils)	Type <sup>b</sup>	
AISI 202	W	1,064	5,300	<0.1		0	NC	INCO (3)
AISI 202	S	1,064	5,300	<0.1	0	50	C (PR)	INCO (3)
AISI 202	W	197	2,340	<0.1	0	1	I-C	INCO (3)
AISI 202	S	197	2,340	<0.1	0	1	I-C	INCO (3)
AISI 202	W	402	2,370	<0.1	0	17	C	INCO (3)
AISI 202	S	402	2,370	<0.1	17	0	P	INCO (3)
AISI 202	W	182	5	0.6	50	50	C (PR); P (PR)	INCO (3)
AISI 202	W	366	5	0.5	50	50	C (PR); P (PR)	INCO (3)

<sup>a</sup>W = Totally exposed in seawater on sides of structure; S = Exposed in base of structure so that the lower portions of the specimen were embedded in the bottom sediments.

<sup>b</sup>Symbols for types of corrosion:

- C = Crevice
- I = Incipient
- NC = No visible corrosion
- P = Pitting
- PR = Perforated
- S = Severe
- WB = Weld bead

<sup>c</sup>Numbers refer to references at end of report.

<sup>d</sup>Welded.

Table 38. Stress Corrosion of 200 Series Stainless Steels

Alloy	Stress (ksi)	Percent Yield Strength	Exposure (day)	Depth (ft)	Number of Specimens Exposed	Number Failed	Source <sup>a</sup>
AISI 201	22	30	403	6,780	3	0	NADC (7)
AISI 201	55	75	403	6,780	3	0	NADC (7)
AISI 201, sensitized	55	75	403	6,780	3	0	NADC (7)
AISI 201	22	30	197	2,340	3	0	NADC (7)
AISI 201	55	75	197	2,340	3	0	NADC (7)
AISI 201, sensitized	55	75	197	2,340	3	0	NADC (7)
AISI 201	22	30	402	2,370	3	0	NADC (7)
AISI 201	55	75	402	2,370	3	0	NADC (7)
AISI 201, sensitized	22	30	402	2,370	3	0	NADC (7)
AISI 201, sensitized	55	75	402	2,370	3	0	NADC (7)

<sup>a</sup>Numbers refer to references at end of report.



Table 39. Changes in the Mechanical Properties of 200 Series Stainless Steels Due to Corrosion

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>b</sup>
				Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
AISI 201	W	123	5,640	120	+3	73	0	48	+6	NADC (7)
AISI 201	W	751	5,640	120	+2	73	-10	48	+4	NADC (7)
AISI 201	W	197	2,340	120	0	73	-4	48	-8	NADC (7)
AISI 201	W	402	2,370	120	-7	73	-34	48	+35	NADC (7)
AISI 201, welded	W	402	2,370	120	-6	73	-32	48	+29	NADC (7)
AISI 201, sensitized	W	402	2,370		-8		-34		+33	NADC (7)
AISI 202	W	123	5,640	106	+6	—	0	55	0	NADC (7)
AISI 202	W	751	5,640	106	-8	—	-31	—	—	NADC (7)

<sup>a</sup>W = Totally exposed in seawater on sides of structure; S = Exposed in base of structure so that the lower portions of the specimen were embedded in the bottom sediments.

<sup>b</sup>Numbers refer to references at end of report.

Table 40. Chemical Compositions of 300 Series Stainless Steels, Percent by Weight

Alloy	C	Mn	P	S	Si	Ni	Cr	Mo	Other	Fe <sup>a</sup>	Source <sup>b</sup>
AISI 301	0.11	1.17	0.025	0.021	0.34	6.73	17.4	—	—	R	CEL (4)
AISI 301	0.08	1.00	—	0.008	—	7.50	17.50	—	—	R	NADC (7)
AISI 302	0.06	1.05	0.020	0.013	0.60	9.33	18.21	—	—	R	CEL (4)
AISI 302	0.11	1.36	—	—	—	9.9	17.3	0.12	0.26 Cu	R	INCO (3)
AISI 304	0.06	1.73	0.024	0.013	0.43	10.0	18.8	—	—	R	CEL (4)
AISI 304	0.05	1.73	0.020	0.012	0.52	9.55	18.2	0.18	—	R	CEL (4)
AISI 304	0.06	1.46	—	—	—	9.5	18.2	0.34	0.16 Cu	R	INCO (3)
AISI 304	—	—	—	—	—	10.0	19.0	—	—	R	MEL (5)
AISI 304	0.07	—	—	0.019	—	8.90	18.2	0.30	0.19 Cu	R	NADC (7)
AISI 304L	0.03	1.24	0.028	0.023	0.68	10.20	18.7	—	—	R	CEL (4)
AISI 304L	0.02	1.45	—	—	—	9.5	17.9	—	—	R	INCO (3)
AISI 304L	0.03	1.80	—	0.015	—	10.00	18.90	—	0.2 V	R	NADC (7)
AISI 309	0.1	1.60	—	—	—	12.7	23.3	—	—	R	INCO (3)
AISI 310	0.04	1.78	—	—	—	20.9	25.3	—	—	R	INCO (3)
AISI 311	0.2	2.0	—	—	—	19.0	25.0	—	—	R	INCO (3)
AISI 316	0.06	1.61	0.021	0.016	0.40	13.60	18.3	2.41	—	R	CEL (4)
AISI 316	0.05	1.73	—	—	—	13.2	17.2	2.60	—	R	INCO (3)
AISI 316	0.05	1.40	0.01	—	—	12.90	16.40	2.15	—	R	NADC (7)
AISI 316L	0.03	1.29	0.015	0.019	0.51	13.10	17.5	2.32	—	R	CEL (4)
AISI 316L	0.02	1.31	0.013	0.015	0.47	13.70	17.9	2.76	—	R	CEL (4)
AISI 316L	0.02	1.78	—	—	—	13.6	17.7	2.15	—	R	INCO (3)
AISI 316L <sup>c</sup>											NADC (7)
AISI 317	0.05	1.61	—	—	—	13.6	18.7	3.3	—	R	INCO (3)
AISI 321	0.06	2.0	—	—	—	10.5	18.5	—	—	R	INCO (3)
AISI 321	—	1.37	—	—	—	9.85	17.12	—	—	R	NADC (7)
AISI 325	0.03	0.7	—	—	—	23.5	9.0	—	—	R	INCO (3)
AISI 329	0.07	0.46	—	—	—	4.4	27.0	1.40	—	R	INCO (3)
AISI 330	0.20	—	—	—	—	34.5	15.0	—	—	R	INCO (3)
AISI 347	0.04	1.19	—	—	—	11.3	18.1	—	—	R	INCO (3)
AISI 347	—	1.77	—	—	—	10.97	18.00	0.24	—	R	NADC (7)

<sup>a</sup>R = remainder.<sup>b</sup>Numbers refer to references at end of report.<sup>c</sup>No values given.

Table 41. Corrosion Rates and Types of Corrosion of 300 Series Stainless Steels

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mils)	Crevice Depth <sup>b</sup> (mils)	Maximum Tunnel Length (mils)	Type <sup>b</sup>	
AISI 301	W	123	5,640	0.3	0	SL	1,200	SL-C; T	CEL (4)
AISI 301	W	123	5,640	<0.1	0	SL	—	SL-C	NADC (7)
AISI 301	S	123	5,640	0.7	0	SL	750	SL-C; T	CEL (4)
AISI 301	W	403	6,780	1.4	103	15	2,450	C; T; P (PR)	CEL (4)
AISI 301	S	403	6,780	1.6	103	25	4,000	C; T; P (PR)	CEL (4)
AISI 301	W	751	5,640	1.7	103	0	6,000	E; T; P (PR)	CEL (4)
AISI 301	S	751	5,640	1.0	103	0	10,500	E; T; P (PR)	CEL (4)
AISI 301	W	1,064	5,300	0.4	103	0	11,000	E; T; P (PR)	CEL (4)
AISI 301	S	1,064	5,300	1.0	103	0	6,500	E; T; P (PR)	CEL (4)
AISI 301	W	197	2,340	0.3	0	SL	1,250	SL-C; T	CEL (4)
AISI 301	S	197	2,340	0.3	0	SL	1,400	SL-C; T	CEL (4)
AISI 301	W	402	2,370	0.5	103	0	2,500	T; P (PR)	CEL (4)
AISI 301	S	402	2,370	0.6	103	0	2,500	T; P (PR)	CEL (4)
AISI 301	W	181	5	1.9	103	0	2,200	S-E; T; P (PR)	CEL (4)
AISI 301	W	398	5	2.3	103	0	1,150	T; P (PR)	CEL (4)
AISI 301	W	588	5	1.7	103	50	1,500	C; T; P (PR)	CEL (4)
AISI 302	W	123	5,640	<0.1	0	SL	0	SL-C	CEL (4)
AISI 302	W	123	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 302	S	123	5,640	<0.1	0	SL	0	SL-C	CEL (4)
AISI 302	S	123	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 302	W	403	6,780	<0.1	0	18	0	C	CEL (4)
AISI 302	W	403	6,780	<0.1	0	I	—	I-C	INCO (3)
AISI 302	S	403	6,780	<0.1	0	23	0	C	CEL (4)
AISI 302	S	403	6,780	<0.1	0	I	—	I-C	INCO (3)
AISI 302	W	751	5,640	<0.1	0	21	0	C	CEL (4)
AISI 302	W	751	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 302	S	751	5,640	<0.1	0	I	6,000	I-C; E; T	CEL (4)

Continued

Table 41. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mils)	Crevice Depth <sup>b</sup> (mils)	Maximum Tunnel Length (mils)	Type <sup>b</sup>	
AISI 302	S	751	5,640	<0.1	0	I	—	I-C	INCO (3)
AISI 302	W	1,064	5,300	<0.1	0	0	—	NC	INCO (3)
AISI 302	S	1,064	5,300	<0.1	50	50	—	C (PR); P (PR)	INCO (3)
AISI 302	W	197	2,340	<0.1	53	53	1,375	C;(PR); P (PR); T	CEL (4)
AISI 302	W	197	2,340	<0.1	0	I	—	I-C	INCO (3)
AISI 302	S	197	2,340	<0.1	0	20	250	C-T	CEL (4)
AISI 302	S	197	2,340	<0.1	0	I	—	I-C	INCO (3)
AISI 302	W	402	2,370	<0.1	0	18	6,000	C-T	CEL (4)
AISI 302	W	402	2,370	<0.1	0	I	—	I-C	INCO (3)
AISI 302	S	402	2,370	<0.1	0	53	0	C	CEL (4)
AISI 302	S	402	2,370	<0.1	0	I	—	I-C	INCO (3)
AISI 302	W	181	5	0.9	53	0	4,950	E; P (PR); T	CEL (4)
AISI 302	W	181	5	<0.1	15	7	—	C; P	INCO (3)
AISI 302	W	366	5	<0.1	I	I	—	I-C; I-P	INCO (3)
AISI 302	W	398	5	0.4	53	53	5,400	C (PR); E; P (PR); T	CEL (4)
AISI 302	W	588	5	0.5	53	53	5,500	C (PR); P (PR); T	CEL (4)
AISI 304	W	123	5,640	<0.1	0	0	450	T	CEL (4)
AISI 304	W	123	5,640	<0.1	0	I	—	I-C	INCO (3)
AISI 304	W	123	5,640	1.1	0	31	—	C	MEL (5)
AISI 304	S	123	5,640	<0.1	0	0	0	NC	CEL (4)
AISI 304	S	123	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 304	W	403	6,780	0.5	210	0	2,000	E; P (PR); T	CEL (4)
AISI 304	W	403	6,780	<0.1	0	I	—	I-C	INCO (3)
AISI 304	W	403	6,780	—	—	—	—	S-C; WB (NC)	NADC (7)
AISI 304	S	403	6,780	<0.1	0	0	0	SL-F	CEL (4)
AISI 304	S	403	6,780	<0.1	0	I	—	I-C	INCO (3)
AISI 304	W	751	5,640	0.5	210	0	1,600	P (PR); T	CEL (4)

Continued

Table 41. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mils)	Crevice Depth <sup>b</sup> (mils)	Maximum Tunnel Length (mils)	Type <sup>b</sup>	
AISI 304	W	751	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 304	W	751	5,640	1.6	S	125	—	C (PR); E; S-P	MEL (5)
AISI 304	S	751	5,640	<0.1	0	13	—	C	INCO (3)
AISI 304	W	1,064	5,300	<0.1	13	74	1,750	C; E; P; T	CEL (4)
AISI 304	W	1,064	5,300	<0.1	0	I	—	I-C	INCO (3)
AISI 304	W	1,064	5,300	1.0	S	125	—	C (PR); S-E; S-P	MEL (5)
AISI 304	W	1,064	5,300	—	—	—	—	S-C; S-T	NADC (7)
AISI 304	S	1,064	5,300	<0.1	210	29	1,500	C; E; P (PR); T	CEL (4)
AISI 304	S	1,064	5,300	<0.1	0	50	—	C (PR)	INCO (3)
AISI 304	W	197	2,340	0.3	0	11	950	C; E; T	CEL (4)
AISI 304	W	197	2,340	<0.1	0	I	—	I-C	INCO (3)
AISI 304	W	197	2,340	—	—	—	—	S-C	NADC (7)
AISI 304	S	197	2,340	<0.1	0	SL	1,000	SL-C; E; T	CEL (4)
AISI 304	S	197	2,340	<0.1	0	I	—	I-C	INCO (3)
AISI 304	W	402	2,370	0.4	210	0	2,000	E; P (PR); T	CEL (4)
AISI 304	W	402	2,370	<0.1	0	13	—	C	INCO (3)
AISI 304	W	402	2,370	—	—	—	—	S-C; S-T; WB (NC)	NADC (7)
AISI 304	S	402	2,370	0.1	0	0	1,250	S-E; T	CEL (4)
AISI 304	S	402	2,370	<0.1	0	4	—	C	INCO (3)
AISI 304	W	181	5	1.8	210	0	500	E; P (PR); T	CEL (4)
AISI 304	W	181	5	1.3	45	20	—	C; P	INCO (3)
AISI 304	W	366	5	0.4	34	33	—	C; P	INCO (3)
AISI 304	W	386 <sup>d</sup>	5	0.6	63	63	—	C (PR); E; P (PR)	MEL (5)
AISI 304	W	540	5	0.7	42	103	180	C; P; T	CEL (4)
AISI 304	W	588	5	0.5	0	138	110	C; T	CEL (4)
AISI 304 <sup>e</sup>	W	123	5,640	0.7	0	50	—	C (PR)	INCO (3)
AISI 304 <sup>e</sup>	S	123	5,640	0.8	0	37	—	C	INCO (3)

Continued

Table 41. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mils)	Crevice Depth <sup>b</sup> (mils)	Maximum Tunnel Length (mils)	Type <sup>b</sup>	
AISI 304 <sup>e</sup>	W	403	6,780	0.7	0	50	—	C (PR)	INCO (3)
AISI 304 <sup>e</sup>	W	403	6,780	—	—	—	—	S-C; S-T; WB (NC)	NADC (7)
AISI 304 <sup>e</sup>	S	403	6,780	0.4	0	2	—	C	INCO (3)
AISI 304 <sup>e</sup>	W	751	5,640	0.5	50	50	—	C (PR); P (PR)	INCO (3)
AISI 304 <sup>e</sup>	S	751	5,640	0.2	0	50	—	C (PR)	INCO (3)
AISI 304 <sup>e</sup>	W	1,064	5,300	0.4	50	50	—	C (PR); P (PR)	INCO (3)
AISI 304 <sup>e</sup>	W	1,064	5,300	—	—	—	—	S-C; S-T	NADC (7)
AISI 304 <sup>e</sup>	S	1,064	5,300	0.2	50	50	—	C (PR); P (PR)	INCO (3)
AISI 304 <sup>e</sup>	W	197	2,340	0.6	0	50	—	C (PR)	INCO (3)
AISI 304 <sup>e</sup>	W	197	2,340	—	—	—	—	S-C	NADC (7)
AISI 304 <sup>e</sup>	S	197	2,340	<0.1	0	1	—	I-C	INCO (3)
AISI 304 <sup>e</sup>	W	402	2,370	0.3	0	50	—	C (PR)	INCO (3)
AISI 304 <sup>e</sup>	W	402	2,370	—	—	—	—	S-C; S-T; WB (NC)	NADC (7)
AISI 304 <sup>e</sup>	S	402	2,370	<0.1	0	17	—	C	INCO (3)
AISI 304 <sup>e</sup>	W	181	5	1.1	50	50	—	C (PR); P (PR)	INCO (3)
AISI 304 <sup>e</sup>	W	366	5	1.2	50	50	—	C (PR); P (PR)	INCO (3)
AISI 304L	W	123	5,640	0.2	0	SL	200	SL-C; T	CEL (4)
AISI 304L	W	123	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 304L	S	123	5,640	<0.1	0	SL	0	SL-C; T	CEL (4)
AISI 304L	S	123	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 304L	W	403	6,780	<0.1	115	12	4,850	C; E; P (PR); T	CEL (4)
AISI 304L	W	403	6,780	<0.1	0	1	—	I-C	INCO (3)
AISI 304L	W	403	6,780	—	—	—	—	S-C; S-T; WB (NC)	NADC (7)
AISI 304L	S	403	6,780	0.1	0	29	1,000	C; E; T	CEL (4)
AISI 304L	S	403	6,780	<0.1	0	2	—	C	INCO (3)
AISI 304L	W	751	5,640	0.3	115	0	4,000	P (PR); T	CEL (4)
AISI 304L	W	751	5,640	<0.1	0	0	—	NC	INCO (3)

Continued

Table 41. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mils)	Crevice Depth <sup>b</sup> (mils)	Maximum Tunnel Length (mils)	Type <sup>b</sup>	
AISI 304L	S	751	5,640	0.6	0	45	1,000	C; T	CEL (4)
AISI 304L	S	751	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 304L	W	1,064	5,300	0.2	115	115	4,000	C (PR); E; P (PR); T	CEL (4)
AISI 304L	W	1,064	5,300	<0.1	0	I	—	I-C	INCO (3)
AISI 304L	W	1,064	5,300	—	—	—	—	SL-R	NADC (7)
AISI 304L	S	1,064	5,300	0.1	115	0	3,000	P (PR); T	CEL (4)
AISI 304L	S	1,064	5,300	0.2	50	50	—	C (PR); P (PR)	INCO (3)
AISI 304L	W	197	2,340	0.2	0	8	800	C; T	CEL (4)
AISI 304L	W	197	2,340	<0.1	0	I	—	I-C	INCO (3)
AISI 304L	W	197	2,340	—	—	—	—	S-C	NADC (7)
AISI 304L	S	197	2,340	0.1	0	18	0	C	CEL (4)
AISI 304L	S	197	2,340	<0.1	0	I	—	I-C	INCO (3)
AISI 304L	W	402	2,370	0.4	115	0	3,000	P (PR); T	CEL (4)
AISI 304L	W	402	2,370	<0.1	0	I	—	I-C	INCO (3)
AISI 304L	W	402	2,370	—	—	—	—	SL-C; SL-R; WB (L); HAZ (R&T)	NADC (7)
AISI 304L	S	402	2,370	0.2	0	0	1,000	T	CEL (4)
AISI 304L	S	402	2,370	<0.1	0	I	—	I-C	INCO (3)
AISI 304L	W	181	5	0.7	97	0	400	E; P; T	CEL (4)
AISI 304L	W	181	5	<0.1	0	I	—	I-C	INCO (3)
AISI 304L	W	366	5	0.5	50	0	—	P (PR)	INCO (3)
AISI 304L	W	398	5	1.0	115	0	1,100	E; P (PR); T	CEL (4)
AISI 304L	W	540	5	0.7	115	115	1,500	C (PR); E; P (PR); T	CEL (4)
AISI 309	W	123	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 309	S	123	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 309	W	403	6,780	<0.1	0	I	—	I-C	INCO (3)

Continued



Table 41. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mils)	Crevice Depth <sup>b</sup> (mils)	Maximum Tunnel Length (mils)	Type <sup>b</sup>	
AISI 309	S	403	6,780	<0.1	0	1	—	I-C	INCO (3)
AISI 309	W	751	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 309	S	751	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 309	W	1,064	5,300	<0.1	0	1	—	I-C	INCO (3)
AISI 309	S	1,064	5,300	<0.1	0	1	—	I-C	INCO (3)
AISI 309	W	197	2,340	<0.1	0	1	—	I-C	INCO (3)
AISI 309	S	197	2,340	<0.1	0	1	—	I-C	INCO (3)
AISI 309	W	402	2,370	<0.1	0	1	—	I-C	INCO (3)
AISI 309	S	402	2,370	<0.1	0	1	—	I-C	INCO (3)
AISI 309	W	181	5	<0.1	0	33	—	C	INCO (3)
AISI 309	W	366	5	<0.1	0	1	—	I-C	INCO (3)
AISI 310	W	123	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 310	S	123	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 310	W	403	6,780	<0.1	0	1	—	I-C	INCO (3)
AISI 310	S	403	6,780	<0.1	0	1	—	I-C	INCO (3)
AISI 310	W	751	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 310	S	751	5,640	<0.1	0	1	—	I-C	INCO (3)
AISI 310	W	1,064	5,300	<0.1	0	1	—	I-C	INCO (3)
AISI 310	S	1,064	5,300	<0.1	0	1	—	I-C	INCO (3)
AISI 310	W	197	2,340	<0.1	0	1	—	I-C	INCO (3)
AISI 310	S	197	2,340	<0.1	0	1	—	I-C	INCO (3)
AISI 310	W	402	2,370	<0.1	0	14	—	C	INCO (3)
AISI 310	S	402	2,370	<0.1	0	2	—	C	INCO (3)
AISI 310	W	181	5	<0.1	0	1	—	I-C	INCO (3)
AISI 310	W	366	5	<0.1	0	50	—	C (PR)	INCO (3)
AISI 311	W	123	5,640	<0.1	0	0	—	NC	INCO (3)

Continued

Table 41. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mils)	Crevice Depth <sup>b</sup> (mils)	Maximum Tunnel Length (mils)	Type <sup>b</sup>	
AISI 311	S	123	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 311	W	403	6,780	<0.1	0	1	—	I-C	INCO (3)
AISI 311	S	403	6,780	<0.1	0	1	—	I-C	INCO (3)
AISI 311	W	751	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 311	S	751	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 311	W	1,064	5,300	<0.1	0	1	—	I-C	INCO (3)
AISI 311	S	1,064	5,300	<0.1	0	5	—	C	INCO (3)
AISI 311	W	197	2,340	<0.1	0	1	—	I-C	INCO (3)
AISI 311	S	197	2,340	<0.1	0	2	—	C	INCO (3)
AISI 311	W	402	2,370	<0.1	0	6	—	C	INCO (3)
AISI 311	S	402	2,370	<0.1	0	1	—	I-C	INCO (3)
AISI 311	W	181	5	0.5	28	50	—	C (PR); P	INCO (3)
AISI 311	W	366	5	<0.1	1	1	—	I-C; I-P	INCO (3)
AISI 316	W	123	5,640	<0.1	0	0	10	SL-E; SL-T	CEL (4)
AISI 316	W	123	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 316	S	123	5,640	<0.1	0	0	0	SL-E	CEL (4)
AISI 316	S	123	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 316	W	403	6,780	<0.1	0	0	0	NC	CEL (4)
AISI 316	W	403	6,780	<0.1	0	1	—	I-C	INCO (3)
AISI 316	W	403	6,780	—	—	—	—	C; WB (NC)	NADC (7)
AISI 316	S	403	6,780	<0.1	0	5	0	C	CEL (4)
AISI 316	S	403	6,780	<0.1	0	1	—	I-C	INCO (3)
AISI 316	W	751	5,640	<0.1	0	0	0	NC	CEL (4)
AISI 316	W	751	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 316	S	751	5,640	<0.1	0	0	0	NC	CEL (4)
AISI 316	S	751	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 316	W	1,064	5,300	0.2	21	0	0	P	CEL (4)

Continued

Table 41. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mils)	Crevice Depth <sup>b</sup> (mils)	Maximum Tunnel Length (mils)	Type <sup>b</sup>	
AISI 316	W	1,064	5,300	<0.1	0	1	—	C	INCO (3)
AISI 316	S	1,064	5,300	0.2	0	1	0	I-C	CEL (4)
AISI 316	S	1,064	5,300	<0.1	0	1	—	I-C	INCO (3)
AISI 316	W	197	2,340	<0.1	0	0	0	NC	CEL (4)
AISI 316	W	197	2,340	<0.1	0	0	—	NC	INCO (3)
AISI 316	W	197	2,340	0.1	0	SL	0	SL-C; SL-R (WB&HAZ)	NADC (7)
AISI 316	S	197	2,340	<0.1	0	0	0	NC	CEL (4)
AISI 316	S	197	2,340	<0.1	0	1	—	I-C	INCO (3)
AISI 316	W	402	2,370	0.1	230	0	500	E; P (PR); T	CEL (4)
AISI 316	W	402	2,370	<0.1	0	1	—	I-C	INCO (3)
AISI 316	W	402	2,370	0.1	—	—	—	S-C; SC-P; WB (NC)	NADC (7)
AISI 316	S	402	2,370	<0.1	1	0	0	I-P	CEL (4)
AISI 316	S	402	2,370	<0.1	0	1	—	I-C	INCO (3)
AISI 316	W	181	5	1.3	230	0	1,250	E; P (PR); T	CEL (4)
AISI 316	W	181	5	<0.1	0	1	—	I-C	INCO (3)
AISI 316	W	366	5	<0.1	0	0	—	NC	INCO (3)
AISI 316	W	398	5	0.4	154	20	1,350	C; E; P; T	CEL (4)
AISI 316	W	540	5	0.3	0	63	70	C; T	CEL (4)
AISI 316	W	588	5	0.2	0	130	1,500	C; T (PR)	CEL (4)
AISI 316 <sup>e</sup>	W	123	5,640	<0.1	0	1	—	I-C	INCO (3)
AISI 316 <sup>e</sup>	S	123	5,640	0.1	0	21	—	C	INCO (3)
AISI 316 <sup>e</sup>	W	403	6,780	<0.1	0	1	—	I-C	INCO (3)
AISI 316 <sup>e</sup>	W	403	6,780	—	—	—	—	MD-C; WB (NC)	NADC (7)
AISI 316 <sup>e</sup>	S	403	6,780	<0.1	0	2	—	C	INCO (3)
AISI 316 <sup>e</sup>	W	751	5,640	1.5	50	50	—	C (PR); P (PR)	INCO (3)
AISI 316 <sup>e</sup>	S	751	5,640	0.3	0	50	—	C (PR)	INCO (3)
AISI 316 <sup>e</sup>	W	1,064	5,300	<0.1	0	15	—	C	INCO (3)

Continued

Table 41. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mils)	Crevice Depth <sup>b</sup> (mils)	Maximum Tunnel Length (mils)	Type <sup>b</sup>	
AISI 316 <sup>e</sup>	S	1,064	5,300	<0.1	0	6	—	C	INCO (3)
AISI 316 <sup>e</sup>	W	197	2,340	<0.1	0	8	—	C	INCO (3)
AISI 316 <sup>e</sup>	S	197	2,340	<0.1	0	1	—	I-C	INCO (3)
AISI 316 <sup>e</sup>	W	402	2,370	<0.1	0	8	—	C	INCO (3)
AISI 316 <sup>e</sup>	W	402	2,370	0.1	—	—	—	S-C; SC-P; WB (NC)	NADC (7)
AISI 316 <sup>e</sup>	S	402	2,370	<0.1	0	1	—	I-C	INCO (3)
AISI 316 <sup>e</sup>	W	181	5	0.8	7	38	—	C; P	INCO (3)
AISI 316 <sup>e</sup>	W	366	5	0.6	50	50	—	C (PR); P (PR)	INCO (3)
AISI 316L	W	123	5,640	<0.1	0	SL	0	SL-C	CEL (4)
AISI 316L	W	123	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 316L	S	123	5,640	<0.1	0	SL	0	SL-C	CEL (4)
AISI 316L	S	123	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 316L	W	403	6,780	<0.1	0	0	0	NC	CEL (4)
AISI 316L	W	403	6,780	<0.1	0	1	—	I-C	INCO (3)
AISI 316L	W	403	6,780	<0.1	—	—	—	C; SL-R; WB (NC)	NADC (7)
AISI 316L	S	403	6,780	<0.1	0	0	0	NC	CEL (4)
AISI 316L	S	403	6,780	<0.1	0	1	—	I-C	INCO (3)
AISI 316L	W	751	5,640	<0.1	0	13	0	C	CEL (4)
AISI 316L	W	751	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 316L	S	751	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 316L	W	1,064	5,300	<0.1	0	25	0	C	CEL (4)
AISI 316L	W	1,064	5,300	<0.1	0	1	—	I-C	INCO (3)
AISI 316L	S	1,064	5,300	<0.1	0	20	0	C	CEL (4)
AISI 316L	S	1,064	5,300	<0.1	0	1	—	I-C	INCO (3)
AISI 316L	W	197	2,340	<0.1	0	18	0	C	CEL (4)
AISI 316L	W	197	2,340	<0.1	0	8	—	C	INCO (3)
AISI 316L	S	197	2,340	<0.1	0	12	0	C	CEL (4)

Continued

Table 41. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mils)	Crevice Depth <sup>b</sup> (mils)	Maximum Tunnel Length (mils)	Type <sup>b</sup>	
AISI 316L	S	197	2,340	<0.1	0	I	—	I-C	INCO (3)
AISI 316L	W	402	2,370	<0.1	0	0	0	NC	CEL (4)
AISI 316L	W	402	2,370	<0.1	0	I	—	I-C	INCO (3)
AISI 316L	W	402	2,370	—	—	—	—	G; WB (S-L; T)	NADC (7)
AISI 316L	S	402	2,370	<0.1	0	45	0	C	CEL (4)
AISI 316L	S	402	2,370	<0.1	0	I	—	I-C	INCO (3)
AISI 316L	W	181	5	0.3	125	0	1,400	E; P (PR); T	CEL (4)
AISI 316L	W	181	5	<0.1	0	25	—	C	INCO (3)
AISI 316L	W	366	5	<0.1	0	I	—	I-C	INCO (3)
AISI 316L	W	398	5	<0.1	0	0	0	SL-E	CEL (4)
AISI 317	W	123	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 317	S	123	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 317	W	403	6,780	<0.1	0	I	—	I-C	INCO (3)
AISI 317	S	403	6,780	<0.1	0	I	—	I-C	INCO (3)
AISI 317	W	751	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 317	S	751	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 317	W	1,064	5,300	<0.1	0	I	—	I-C	INCO (3)
AISI 317	S	1,064	5,300	<0.1	0	0	—	NC	INCO (3)
AISI 317	W	197	2,340	<0.1	0	I	—	I-C	INCO (3)
AISI 317	S	197	2,340	<0.1	0	I	—	I-C	INCO (3)
AISI 317	W	402	2,370	<0.1	0	I	—	I-C	INCO (3)
AISI 317	S	402	2,370	<0.1	0	I	—	I-C	INCO (3)
AISI 317	W	181	5	<0.1	0	0	—	NC	INCO (3)
AISI 317	W	366	5	<0.1	0	I	—	I-C	INCO (3)
AISI 321	W	123	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 321	W	123	5,640	<0.1	0	0	—	NC	NADC (7)

Continued

Table 41. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mils)	Crevice Depth <sup>b</sup> (mils)	Maximum Tunnel Length (mils)	Type <sup>b</sup>	
AISI 321	S	123	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 321	W	403	6,780	<0.1	0	1	—	I-C	INCO (3)
AISI 321	W	403	6,780	<0.1	—	—	—	T; HAZ	NADC (7)
AISI 321	S	403	6,780	<0.1	0	1	—	I-C	INCO (3)
AISI 321	W	751	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 321	W	751	5,640	1.5	—	—	—	SL-C; SC-R	NADC (7)
AISI 321	S	751	5,640	<0.1	0	1	—	I-C	INCO (3)
AISI 321	W	1,064	5,300	<0.1	0	1	—	I-C	INCO (3)
AISI 321	W	1,064	5,300	<0.1	—	—	—	SL-C; SC-R	NADC (7)
AISI 321	S	1,064	5,300	<0.1	0	0	—	NC	INCO (3)
AISI 321	W	197	2,340	<0.1	0	1	—	I-C	INCO (3)
AISI 321	W	197	2,340	0.2	—	—	—	S-C; SL-P; S-T	NADC (7)
AISI 321	S	197	2,340	<0.1	0	2	—	C	INCO (3)
AISI 321	W	402	2,370	0.2	0	30	—	C (PR)	INCO (3)
AISI 321	W	402	2,370	—	—	—	—	SL-C; SL-R; HAZ (P)	NADC (7)
AISI 321	S	402	2,370	<0.1	0	1	—	I-C	INCO (3)
AISI 321	W	181	5	<0.1	0	2	—	C	INCO (3)
AISI 321	W	366	5	<0.1	22	0	—	P	INCO (3)
AISI 325	W	123	5,640	4.2	11	0	—	P	INCO (3)
AISI 325	S	123	5,640	3.3	13	0	—	P	INCO (3)
AISI 325	W	403	6,780	4.6	14	0	—	P	INCO (3)
AISI 325	S	403	6,780	1.3	0	3	—	C	INCO (3)
AISI 325	W	751	5,640	2.1	0	0	—	G	INCO (3)
AISI 325	S	751	5,640	3.5	0	0	—	NU	INCO (3)
AISI 325	W	1,064	5,300	1.1	0	0	—	G	INCO (3)
AISI 325	S	1,064	5,300	1.3	0	0	—	G	INCO (3)
AISI 325	W	197	2,340	2.8	12	0	—	P	INCO (3)

Continued

Table 41. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mils)	Crevice Depth <sup>b</sup> (mils)	Maximum Tunnel Length (mils)	Type <sup>b</sup>	
AISI 325	S	197	2,340	<0.1	0	2	—	C	INCO (3)
AISI 325	W	402	2,370	1.9	0	0	—	G	INCO (3)
AISI 325	S	402	2,370	0.3	0	0	—	G	INCO (3)
AISI 325	W	181	5	10.0	0	0	—	G	INCO (3)
AISI 325	W	366	5	6.3	16	12	—	C; P	INCO (3)
AISI 329	W	123	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 329	S	123	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 329	W	403	6,780	<0.1	0	0	—	NC	INCO (3)
AISI 329	S	403	6,780	<0.1	0	I	—	I-C	INCO (3)
AISI 329	W	751	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 329	S	751	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 329	W	1,064	5,300	<0.1	0	0	—	NC	INCO (3)
AISI 329	S	1,064	5,300	<0.1	0	0	—	NC	INCO (3)
AISI 329	W	197	2,340	<0.1	0	0	—	NC	INCO (3)
AISI 329	S	197	2,340	<0.1	0	0	—	NC	INCO (3)
AISI 329	W	402	2,370	<0.1	0	0	—	NC	INCO (3)
AISI 329	S	402	2,370	<0.1	0	0	—	NC	INCO (3)
AISI 329	W	181	5	<0.1	0	I	—	I-C	INCO (3)
AISI 329	W	366	5	<0.1	0	I	—	I-C	INCO (3)
AISI 330	W	123	5,640	<0.1	0	I	—	I-C	INCO (3)
AISI 330	S	123	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 330	W	403	6,780	<0.1	0	I	—	I-C	INCO (3)
AISI 330	S	403	6,780	<0.1	0	I	—	I-C	INCO (3)
AISI 330	W	751	5,640	<0.1	0	I	—	I-C	INCO (3)
AISI 330	S	751	5,640	<0.1	0	I	—	I-C	INCO (3)
AISI 330	W	1,064	5,300	<0.1	0	I	—	I-C	INCO (3)

Continued



Table 41. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mils)	Crevice Depth <sup>b</sup> (mils)	Maximum Tunnel Length (mils)	Type <sup>b</sup>	
AISI 330	S	1,064	5,300	<0.1	0	3	—	C	INCO (3)
AISI 330	W	197	2,340	<0.1	0	1	—	I-C	INCO (3)
AISI 330	S	197	2,340	<0.1	0	1	—	I-C	INCO (3)
AISI 330	W	402	2,370	<0.1	0	30	—	C (PR)	INCO (3)
AISI 330	S	402	2,370	<0.1	0	2	—	C	INCO (3)
AISI 330	W	181	5	0.8	50	50	—	C (PR); P (PR)	INCO (3)
AISI 330	W	366	5	0.4	50	0	—	P (PR)	INCO (3)
AISI 347	W	123	5,640	<0.1	0	10	—	C	INCO (3)
AISI 347	W	123	5,640	<0.1	—	—	—	NC	NADC (7)
AISI 347	S	123	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 347	W	403	6,780	<0.1	0	1	—	I-C	INCO (3)
AISI 347	W	403	6,780	—	—	—	—	SL-R; WB (SL-R)	NADC (7)
AISI 347	S	403	6,780	<0.1	0	3	—	C	INCO (3)
AISI 347	W	751	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 347	W	751	5,640	—	—	—	—	SL-R	NADC (7)
AISI 347	S	751	5,640	<0.1	0	29	—	C	INCO (3)
AISI 347	W	1,064	5,300	<0.1	I	I	—	I-C; I-P	INCO (3)
AISI 347	S	1,064	5,300	<0.1	0	50	—	C (PR)	INCO (3)
AISI 347	W	197	2,340	<0.1	0	0	—	NC	INCO (3)
AISI 347	W	197	2,340	—	—	—	—	S-C; SL-R (WB&HAZ)	NADC (7)
AISI 347	S	197	2,340	<0.1	0	1	—	I-C	INCO (3)
AISI 347	W	402	2,370	<0.1	0	1	—	I-C	INCO (3)
AISI 347	W	402	2,370	—	—	—	—	SL-C; SL-R	NADC (7)
AISI 347	S	402	2,370	<0.1	0	2	—	C	INCO (3)
AISI 347	W	181	5	0.8	50	50	—	C (PR); P (PR)	INCO (3)
AISI 347	W	366	5	0.7	50	50	—	C (PR); P (PR)	INCO (3)

Continued

Table 41. Continued.

<sup>a</sup>W = Totally exposed in seawater on sides of structure; S = Exposed in base of structure so that the lower portions of the specimens were embedded in the bottom sediments.

<sup>b</sup>Symbols for types of corrosion:

C	= Crevice	P	= Pitting
E	= Edge	PR	= Perforation
HAZ	= Heat-affected zone	R	= Rust
I	= Incipient	S	= Severe
L	= Line	SC	= Scattered
MD	= Medium	SL	= Slight
NC	= No visible corrosion	T	= Tunnel
NU	= Nonuniform	WB	= Weld Bead

Numbers indicate maximum depth or length in mils.

<sup>c</sup>Numbers refer to references at end of report.

<sup>d</sup>Francis L. LaQue Corrosion Laboratory, INCO, Wrightsville Beach, NC

<sup>e</sup>Sensitized, heated 1 hr at 1,200°F, air cooled.

Table 42. Stress Corrosion of 300 Series Stainless Steels

Alloy	Stress (ksi)	Percent Yield Strength	Exposure (day)	Depth (ft)	Number of Specimens Exposed	Number Failed	Source <sup>a</sup>
AISI 301	24	62	123	5,640	3	0	NADC (7)
AISI 301	32	82	123	5,640	3	0	NADC (7)
AISI 301	62	50	402	2,370	3	0	CEL (4)
AISI 301	94	75	402	2,370	3	0	CEL (4)
AISI 302	22	50	402	2,370	3	0	CEL (4)
AISI 302	33	75	402	2,370	3	0	CEL (4)
AISI 304	14	30	403	6,780	3	0	NADC (7)
AISI 304	35	75	403	6,780	3	0	NADC (7)
AISI 304, sensitized	14	30	403	6,780	3	0	NADC (7)
AISI 304, sensitized	35	75	403	6,780	3	0	NADC (7)
AISI 304	14	30	197	2,340	3	0	NADC (7)
AISI 304	35	75	197	2,340	3	0	NADC (7)
AISI 304, sensitized	35	75	197	2,340	3	0	NADC (7)
AISI 304	14	30	402	2,370	3	0	NADC (7)
AISI 304, sensitized	14	30	402	2,370	3	0	NADC (7)
AISI 304	16	50	402	2,370	3	0	CEL (4)
AISI 304	35	75	402	2,370	3	0	NADC (7)
AISI 304, sensitized	35	75	402	2,370	3	0	NADC (7)
AISI 304	25	75	402	2,370	3	0	CEL (4)
AISI 304L	14	35	123	5,640	3	0	CEL (4)
AISI 304L	20	50	123	5,640	3	0	CEL (4)
AISI 304L	30	75	123	5,640	3	0	CEL (4)
AISI 304L	13	30	403	6,780	3	0	NADC (7)
AISI 304L, sensitized	13	30	403	6,780	3	0	NADC (7)
AISI 304L	20	50	403	6,780	3	0	CEL (4)
AISI 304L	32	75	403	6,780	3	0	NADC (7)
AISI 304L, sensitized	32	75	403	6,780	3	0	NADC (7)
AISI 304L	30	75	403	6,780	3	0	CEL (4)
AISI 304L	14	35	751	5,640	3	0	CEL (4)
AISI 304L	20	50	751	5,640	3	0	CEL (4)
AISI 304L	30	75	751	5,640	3	0	CEL (4)
AISI 304L	13	30	197	2,340	3	0	NADC (7)
AISI 304L	20	50	197	2,340	3	0	CEL (4)
AISI 304L	32	75	197	2,340	3	0	NADC (7)
AISI 304L, sensitized	32	75	197	2,340	3	0	NADC (7)
AISI 304L	30	75	197	2,340	3	0	CEL (4)
AISI 304L	13	30	402	2,370	3	0	NADC (7)
AISI 304L	20	50	402	2,370	3	0	CEL (4)
AISI 304L	32	75	402	2,370	3	0	NADC (7)
AISI 304L, sensitized	32	75	402	2,370	3	0	NADC (7)
AISI 304L	30	75	402	2,370	3	0	CEL (4)

Continued

Table 42. Continued.

Alloy	Stress (ksi)	Percent Yield Strength	Exposure (day)	Depth (ft)	Number of Specimens Exposed	Number Failed	Source <sup>a</sup>
AISI 316	14	30	403	6,780	3	0	NADC (7)
AISI 316, sensitized	14	30	403	6,780	3	0	NADC (7)
AISI 316	35	75	403	6,780	3	0	NADC (7)
AISI 316, sensitized	35	75	403	6,780	3	0	NADC (7)
AISI 316	14	30	197	2,340	3	0	NADC (7)
AISI 316	35	75	197	2,340	3	0	NADC (7)
AISI 316, sensitized	35	75	197	2,340	3	0	NADC (7)
AISI 316	14	30	402	2,370	3	0	NADC (7)
AISI 316, sensitized	14	30	402	2,370	3	0	NADC (7)
AISI 316	18	50	402	2,370	3	0	CEL (4)
AISI 316	35	75	402	2,370	3	0	NADC (7)
AISI 316, sensitized	35	75	402	2,370	3	0	NADC (7)
AISI 316	27	75	402	2,370	3	0	CEL (4)
AISI 316L	17	35	123	5,640	3	0	CEL (4)
AISI 316L	24	50	123	5,640	3	0	CEL (4)
AISI 316L	36	75	123	5,640	3	0	CEL (4)
AISI 316L	14	30	403	6,780	3	0	NADC (7)
AISI 316L	17	35	403	6,780	3	0	CEL (4)
AISI 316L	24	50	403	6,780	3	0	CEL (4)
AISI 316L	35	75	403	6,780	3	0	NADC (7)
AISI 316L, sensitized	35	75	403	6,780	3	0	NADC (7)
AISI 316L	36	75	403	6,780	3	0	CEL (4)
AISI 316L	17	35	751	5,640	3	0	CEL (4)
AISI 316L	24	50	751	5,640	3	0	CEL (4)
AISI 316L	36	75	751	5,640	3	0	CEL (4)
AISI 316L	17	35	197	2,340	3	0	CEL (4)
AISI 316L	24	50	197	2,340	3	0	CEL (4)
AISI 316L	36	75	197	2,340	3	0	CEL (4)
AISI 316L	24	50	402	2,370	3	0	CEL (4)
AISI 316L	36	75	402	2,370	3	0	CEL (4)
AISI 321	10	30	403	6,780	3	0	NADC (7)
AISI 321	25	75	403	6,780	3	0	NADC (7)
AISI 321, sensitized	25	75	403	6,780	3	0	NADC (7)
AISI 321	10	30	197	2,340	3	0	NADC (7)
AISI 321	25	75	197	2,340	3	0	NADC (7)
AISI 321, sensitized	25	75	197	2,340	3	0	NADC (7)
AISI 321	10	30	402	2,370	3	0	NADC (7)
AISI 321	25	75	402	2,370	3	0	NADC (7)
AISI 321, sensitized	25	75	402	2,370	3	0	NADC (7)

Continued

Table 42. Continued

Alloy	Stress (ksi)	Percent Yield Strength	Exposure (day)	Depth (ft)	Number of Specimens Exposed	Number Failed	Source <sup>a</sup>
AISI 347	—	30	403	6,780	3	0	NADC (7)
AISI 347	—	75	403	6,780	3	0	NADC (7)
AISI 347, sensitized	—	75	403	6,780	3	0	NADC (7)
AISI 347	—	30	197	2,340	3	0	NADC (7)
AISI 347	—	75	197	2,340	3	0	NADC (7)
AISI 347, sensitized	—	75	197	2,340	3	0	NADC (7)
AISI 347	—	30	402	2,340	3	0	NADC (7)
AISI 347	—	75	402	2,370	3	0	NADC (7)
AISI 347, sensitized	—	75	402	2,370	3	0	NADC (7)

<sup>a</sup>Numbers refer to references at end of report.

Table 43. Changes in Mechanical Properties of the 300 Series Stainless Steels Due to Corrosion

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>b</sup>
				Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
AISI 301	W	123	5,640	113	+8	—	0	57	+5	NADC (7)
AISI 301	S	123	5,640	175	+1	125	+7	27	+19	CEL (4)
AISI 301	W	403	6,780	175	0	125	0	27	-4	CEL (4)
AISI 301	S	403	6,780	175	+1	125	+1	27	-5	CEL (4)
AISI 301	W	751	5,640	175	-17	125	-16	27	-19	CEL (4)
AISI 301	S	751	5,640	175	-1	125	0	27	-3	CEL (4)
AISI 301	W	1,064	5,300	175	-3	125	-2	27	-10	CEL (4)
AISI 301	S	1,064	5,300	175	+1	125	+9	27	-16	CEL (4)
AISI 301	W	197	2,340	175	-1	125	-7	27	-16	CEL (4)
AISI 301	S	197	2,340	175	+1	125	-8	27	-4	CEL (4)
AISI 301	W	402	2,370	175	+1	125	-2	27	-5	CEL (4)
AISI 301	S	402	2,370	175	+3	125	-3	27	0	CEL (4)
AISI 301	W	181	5	175	-5	125	-1	27	-10	CEL (4)
AISI 301	W	365	5	175	-5	125	-2	27	+10	CEL (4)
AISI 302	S	123	5,640	93	+4	44	-4	54	+4	CEL (4)
AISI 302	W	403	6,780	93	+2	44	0	54	-3	CEL (4)
AISI 302	S	403	6,780	93	+4	44	+1	54	-3	CEL (4)
AISI 302	W	751	5,640	93	+3	44	+1	54	-3	CEL (4)
AISI 302	S	751	5,640	93	+3	44	-2	54	-2	CEL (4)
AISI 302	W	197	2,340	93	-3	44	-10	54	-3	CEL (4)
AISI 302	S	197	2,340	93	-4	44	-10	54	-2	CEL (4)
AISI 302	W	402	2,370	93	+1	44	0	54	-5	CEL (4)
AISI 302	S	402	2,370	93	+1	44	+1	54	-7	CEL (4)
AISI 302	W	181	5	93	0	44	-5	54	-11	CEL (4)
AISI 302	S	365	5	93	+4	44	+2	54	+3	CEL (4)
AISI 304	W	123	5,640	86	+2	36	+1	60	+8	CEL (4)
AISI 304	W	403	6,780	86	+1	36	+6	60	-8	CEL (4)
AISI 304	S	403	6,780	86	+1	36	+5	60	-3	CEL (4)
AISI 304	W	751	5,640	86	-1	36	+6	60	-4	CEL (4)
AISI 304	W	1,064	5,300	86	0	36	+3	60	-5	CEL (4)
AISI 304	S	1,064	5,300	86	-1	36	+2	60	-6	CEL (4)
AISI 304	W	197	2,340	91	+8	47	+4	50	0	NADC (7)
AISI 304	W	197	2,340	86	+1	36	+7	60	-4	CEL (4)
AISI 304	S	197	2,340	86	+1	36	+4	60	-3	CEL (4)

Continued

Table 43. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>b</sup>
				Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
AISI 304, welded	W	402	2,370	91	+3	47	—	50	+2	NADC (7)
AISI 304	W	402	2,370	86	0	36	+6	60	-5	CEL (4)
AISI 304	S	402	2,370	86	-1	36	+2	60	-5	CEL (4)
AISI 304	W	181	5	86	-1	36	+2	60	-13	CEL (4)
AISI 304L	S	123	5,640	81	+5	40	+5	56	+8	CEL (4)
AISI 304L	W	403	6,780	81	-5	40	+6	56	-29	CEL (4)
AISI 304L	S	403	6,780	81	+3	40	+6	56	-2	CEL (4)
AISI 304L	W	751	5,640	81	+3	40	+4	56	-1	CEL (4)
AISI 304L	S	751	5,640	81	+4	40	+6	56	+2	CEL (4)
AISI 304L	W	1,064	5,300	81	-32	40	-30	56	-35	CEL (4)
AISI 304L	S	1,064	5,300	81	+3	40	+8	56	-6	CEL (4)
AISI 304L	W	197	2,340	79	+3	42	-12	55	-6	NADC (7)
AISI 304L	W	197	2,340	81	+1	40	+3	56	-4	CEL (4)
AISI 304L	S	197	2,340	81	-2	40	-9	56	+2	CEL (4)
AISI 304L, welded	W	402	2,370	—	-10	42	—	—	—	NADC (7)
AISI 304L, sensitized	W	402	2,370	—	-9	—	-2	—	—	NADC (7)
AISI 304L	W	402	2,370	81	+4	40	+14	56	-4	CEL (4)
AISI 304L	S	402	2,370	81	+4	40	+8	56	-6	CEL (4)
AISI 304L	W	181	5	81	+1	40	+3	56	-7	CEL (4)
AISI 304L	W	365	5	81	-1	40	+4	56	-17	CEL (4)
AISI 316	S	123	5,640	82	0	37	0	55	0	CEL (4)
AISI 316	W	403	6,780	82	+1	37	+9	55	-5	CEL (4)
AISI 316	S	403	6,780	82	+1	37	+10	55	-7	CEL (4)
AISI 316	W	751	5,640	82	+1	37	+10	55	-4	CEL (4)
AISI 316	S	751	5,640	82	+2	37	+12	55	-6	CEL (4)
AISI 316	W	1,064	5,300	82	+2	37	+9	55	-5	CEL (4)
AISI 316	W	1,064	5,300	81	+1	48	-9	52	-5	CEL (4)
AISI 316	S	1,064	5,300	82	+2	37	+7	55	-7	CEL (4)
AISI 316	S	1,064	5,300	81	+1	48	-11	52	0	CEL (4)
AISI 316	W	197	2,340	84	+1	47	+4	46	0	NADC (7)
AISI 316	W	197	2,340	82	0	37	+13	55	-4	CEL (4)
AISI 316	S	197	2,340	82	+3	37	+9	55	-2	CEL (4)
AISI 316, sensitized <sup>c</sup>	W	402	2,370	84	-44	47	-47	46	+9	NADC (7)
AISI 316	W	402	2,370	82	+2	37	+7	55	-6	CEL (4)
AISI 316	S	402	2,370	82	+2	37	+10	55	-6	CEL (4)

Continued



Table 43. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>b</sup>
				Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
AISI 316	W	181	5	82	+2	37	+14	55	-8	CEL (4)
AISI 316	W	365	5	82	+1	37	+9	55	+1	CEL (4)
AISI 316L	S	123	5,640	86	-1	48	-2	48	+2	CEL (4)
AISI 316L	W	403	6,780	86	+1	48	0	48	-1	CEL (4)
AISI 316L	S	403	6,780	86	+1	48	+5	48	-1	CEL (4)
AISI 316L	W	751	5,640	86	+1	48	+1	48	+3	CEL (4)
AISI 316L	S	751	5,640	86	0	48	0	48	0	CEL (4)
AISI 316L	W	197	2,340	86	+1	48	-3	48	+2	CEL (4)
AISI 316L	S	197	2,340	86	+1	48	-2	48	+1	CEL (4)
AISI 316L, welded	W	402	2,370	—	-9	—	-9	—	—	NADC (7)
AISI 316L, sensitized	W	402	2,370	—	0	—	0	—	0	NADC (7)
AISI 316L	W	402	2,370	86	0	48	-1	48	-4	CEL (4)
AISI 316L	S	402	2,370	86	+1	48	+2	48	-4	CEL (4)
AISI 316L	W	181	5	86	0	48	-2	48	-8	CEL (4)
AISI 316L	W	365	5	86	+2	48	+3	48	+5	CEL (4)
AISI 321	W	123	5,640	83	-1	—	0	50	0	NADC (7)
AISI 321	W	1,064	5,300	83	-37	—	-61	50	+18	NADC (7)
AISI 321	W	1,064	5,300	80	+13	33	+3	53	+6	NADC (7)
AISI 321	W	197	2,340	80	+8	33	+15	53	-9	NADC (7)
AISI 347	W	123	5,640	94	0	—	0	46	+9	NADC (7)
AISI 347	W	751	5,640	94	+2	—	—	46	0	NADC (7)

<sup>a</sup>W = Totally exposed in seawater on sides of structure; S = Exposed in base of structure so that the lower portions of the specimen were embedded in the bottom sediments.

<sup>b</sup>Numbers refer to references at end of report.

<sup>c</sup>Welded and then sensitized.

Table 44. Chemical Compositions of 400 Series Stainless Steels, Percent by Weight

Alloy	C	Mn	P	S	Si	Ni	Cr	Mo	Al	Other	Fe <sup>a</sup>	Source <sup>b</sup>
AISI 405	0.06	0.41	0.025	0.019	0.56	—	12.6	—	0.26	—	R	CEL (4)
AISI 405	0.05	0.85	0.017	0.015	0.57	—	12.46	—	0.21	—	R	CEL (4)
AISI 405	0.05	0.62	0.014	0.011	0.27	—	14.5	—	0.27	—	R	CEL (4)
AISI 410	0.13	0.43	0.019	0.005	0.45	0.010	12.30	—	—	—	R	CEL (4)
AISI 410	0.13	0.4	—	—	—	0.2	12.1	—	—	—	R	INCO (3)
AISI 410	0.15	0.30	—	—	—	—	12.10	0.03	—	<0.09 V	R	NADC (7)
AISI 430	0.07	0.47	0.029	0.011	0.36	—	16.4	—	—	—	R	CEL (4)
AISI 430	0.05	0.46	0.012	0.010	0.36	0.12	16.5	—	—	—	R	CEL (4)
AISI 430	0.06	0.4	—	—	—	—	17.7	—	—	—	R	INCO (3)
AISI 430	0.06	0.40	—	0.013	—	<0.25	15.00	—	—	<0.20 V	R	NADC (7)
AISI 446	0.15	0.8	—	—	—	0.2	30.0	—	—	—	R	INCO (3)

<sup>a</sup>R = remainder.<sup>b</sup>Numbers refer to references at end of report.

Table 45. Corrosion Rates and Types of Corrosion of 400 Series Stainless Steels

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mils)	Crevice Depth <sup>b</sup> (mils)	Maximum Tunnel Length (mils)	Type <sup>b</sup>	
AISI 405	W	123	5,640	2.4	0	0	—	E; T	CEL (4)
AISI 405	S	123	5,640	2.0	0	0	—	E; T	CEL (4)
AISI 405	W	403	6,780	3.9	0	0	2,000	E; T	CEL (4)
AISI 405	S	403	6,780	2.4	0	0	2,500	E; T	CEL (4)
AISI 405	W	751	5,640	2.8	262	0	500	E; P (PR); T	CEL (4)
AISI 405	W	1,064	5,300	1.5	262	262	12,000	C (PR); P (PR); T	CEL (4)
AISI 405	S	1,064	5,300	1.1	262	262	6,250	C (PR); P (PR); T	CEL (4)
AISI 405	W	197	2,340	2.1	0	0	125	E; T	CEL (4)
AISI 405	S	197	2,340	1.4	0	0	380	E; T	CEL (4)
AISI 405	W	402	2,370	1.8	40	15	0	C; P	CEL (4)
AISI 405	S	402	2,370	2.0	52	11	0	C; P	CEL (4)
AISI 405	W	588	5	4.5	124	250	0	C (PR); P	CEL (4)
AISI 410	W	123	5,640	0.2	40	SL	2,950	SL-C; P (PR); T	CEL (4)
AISI 410	W	123	5,640	3.1	50	0	—	P (PR)	INCO (3)
AISI 410	W	123	5,640	<0.1	—	SL	—	SL-C	NADC (7)
AISI 410	S	123	5,640	0.3	40	SL	1,600	SL-C; P (PR); T	CEL (4)
AISI 410	S	123	5,640	2.3	50	0	—	C (PR)	INCO (3)
AISI 410	W	403	6,780	0.2	40	40	6,000	C (PR); P (PR); T	CEL (4)
AISI 410	W	403	6,780	1.9	50	50	—	C (PR); P (PR)	INCO (3)
AISI 410	W	403	6,780	—	—	S	EX	S-C; EX-T	NADC (7)
AISI 410	S	403	6,780	1.0	40	40	8,850	C (PR); P (PR); T	CEL (4)
AISI 410	S	403	6,780	<0.1	0	6	—	C	INCO (3)
AISI 410	W	751	5,640	0.5	40	40	10,000	C (PR); P (PR); T	CEL (4)
AISI 410	W	751	5,640	4.4	50	50	—	C (PR); P (PR)	INCO (3)
AISI 410	W	751	5,640	—	—	S	EX	S-C; EX-T	NADC (7)
AISI 410	S	751	5,640	0.4	40	40	12,000	C (PR); P (PR); T	CEL (4)
AISI 410	W	1,064	5,300	1.7	50	50	—	C (PR); P (PR)	INCO (3)
AISI 410	S	1,064	5,300	0.9	50	50	—	C (PR); P (PR)	INCO (3)
AISI 410	W	197	2,340	0.3	0	10	7,000	C; T	CEL (4)
AISI 410	W	197	2,340	1.3	50	0	—	C (PR)	INCO (3)
AISI 410	W	197	2,340	—	—	S	3,500	S-C; T	NADC (7)
AISI 410	S	197	2,340	0.2	0	15	7,000	C; E; T	CEL (4)
AISI 410	S	197	2,340	0.2	0	18	—	C	INCO (3)
AISI 410	W	402	2,370	0.5	40	40	6,400	C (PR); P (PR); T	CEL (4)

Continued

Table 45. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mils)	Crevice Depth <sup>b</sup> (mils)	Maximum Tunnel Length (mils)	Type <sup>b</sup>	
AISI 410	W	402	2,370	0.8	50	50	—	C (PR); P (PR)	INCO (3)
AISI 410	W	402	2,370	—	—	S	EX	S-C; EX-T	NADC (7)
AISI 410	W	402	2,370	1.2	—	I	1,500	I-C; P; T	Shell (9)
AISI 410	S	402	2,370	0.4	40	40	12,000	C (PR); P (PR); T	CEL (4)
AISI 410	S	402	2,370	0.2	0	50	—	C (PR)	INCO (3)
AISI 410	S	402	2,370	2.5	1	35	1,500	C; P; T	Shell (9)
AISI 410	W	181	5	2.1	40	40	1,000	C (PR); E; P (PR); T	CEL (4)
AISI 410	W	181	5	3.4	50	50	—	C (PR); P (PR)	INCO (3)
AISI 410	W	366	5	3.0	50	50	—	C (PR); P (PR)	INCO (3)
AISI 430	W	123	5,640	0.5	0	10	1,000	C; T	CEL (4)
AISI 430	W	123	5,640	<0.1	0	I	—	I-C	INCO (3)
AISI 430	S	123	5,640	0.1	0	10	2,000	C; T	CEL (4)
AISI 430	S	123	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 430	W	403	6,780	0.2	137	30	3,750	C; P (PR); T	CEL (4)
AISI 430	W	403	6,780	<0.1	0	I	—	I-C	INCO (3)
AISI 430	W	403	6,780	—	—	S	—	S-C; S-T	NADC (7)
AISI 430	S	403	6,780	0.3	137	34	4,500	C; P (PR); T	CEL (4)
AISI 430	S	403	6,780	<0.1	0	I	—	I-C	INCO (3)
AISI 430	W	751	5,640	0.6	137	30	5,000	C; P (PR); T	CEL (4)
AISI 430	W	751	5,640	0.2	0	23	—	C	INCO (3)
AISI 430	S	751	5,640	0.1	50	50	9,000	C (PR); P (PR); T	CEL (4)
AISI 430	S	751	5,640	<0.1	0	50	—	C (PR)	INCO (3)
AISI 430	W	1,064	5,300	0.8	137	97	7,200	C; E; P (PR); T	CEL (4)
AISI 430	W	1,064	5,300	<0.1	0	I	—	I-C	INCO (3)
AISI 430	S	1,064	5,300	0.7	0	40	6,500	C; T	CEL (4)
AISI 430	S	1,064	5,300	0.2	30	30	—	C (PR); P (PR)	INCO (3)
AISI 430	W	197	2,340	0.5	0	17	2,375	C; T	CEL (4)
AISI 430	W	197	2,340	0.4	30	30	—	C (PR); P (PR)	INCO (3)
AISI 430	W	197	2,340	—	—	PR	PR	C (PR); T (PR)	NADC (7)
AISI 430	S	197	2,340	0.3	0	19	2,000	C; T	CEL (4)
AISI 430	S	197	2,340	<0.1	0	3	—	C	INCO (3)
AISI 430	W	402	2,370	0.6	137	20	6,000	C; E; P (PR); T	CEL (4)
AISI 430	W	402	2,370	0.8	30	30	—	C (PR); P (PR)	INCO (3)
AISI 430	W	402	2,370	—	—	S	S	S-C; S-T	NADC (7)

Continued

Table 45. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mils)	Crevice Depth <sup>b</sup> (mils)	Maximum Tunnel Length (mils)	Type <sup>b</sup>	
AISI 430	S	402	2,370	0.4	137	0	11,500	E; P (PR); T	CEL (4)
AISI 430	S	402	2,370	0.2	0	8	—	C	INCO (3)
AISI 430	W	181	5	1.7	50	50	—	C (PR); P (PR)	INCO (3)
AISI 430	W	366	5	1.1	50	50	—	C (PR); P (PR)	INCO (3)
AISI 430	W	540	5	0.7	50	50	4,450	C (PR); P (PR); T	CEL (4)
AISI 430	W	588	5	0.9	50	50	3,900	C (PR); P (PR); T	CEL (4)
AISI 446	W	123	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 446	S	123	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 446	W	403	6,780	<0.1	0	0	—	NC	INCO (3)
AISI 446	S	403	6,780	<0.1	0	1	—	I-C	INCO (3)
AISI 446	W	751	5,640	<0.1	0	0	—	SL-ET	INCO (3)
AISI 446	S	751	5,640	<0.1	0	0	—	NC	INCO (3)
AISI 446	W	1,064	5,300	<0.1	0	0	—	NC	INCO (3)
AISI 446	S	1,064	5,300	<0.1	0	1	—	I-C	INCO (3)
AISI 446	W	197	2,340	<0.1	0	1	—	I-C	INCO (3)
AISI 446	S	197	2,340	<0.1	0	2	—	C	INCO (3)
AISI 446	W	402	2,370	<0.1	0	1	—	I-C	INCO (3)
AISI 446	S	402	2,370	<0.1	0	2	—	C	INCO (3)
AISI 446	W	181	5	0.3	50	50	—	C (PR); P (PR)	INCO (3)
AISI 446	W	366	5	0.6	50	50	—	C (PR); P (PR)	INCO (3)

<sup>a</sup>W = Totally exposed in seawater on sides of structure; S= Exposed in base of structure so that the lower portions of the specimen were embedded in the bottom sediments.

<sup>b</sup>Symbols for types of corrosion:

C	= Crevice	P	= Pitting
E	= Edge	PR	= Perforated
ET	= Etched	S	= Severe
EX	= Extensive	SL	= Slight
I	= Incipient	T	= Tunnel
NC	= No visible corrosion		

<sup>c</sup>Numbers refer to references at end of report.

Table 46. Stress Corrosion of 400 Series Stainless Steels

Alloy	Stress (ksi)	Percent Yield Strength	Exposure (day)	Depth (ft)	Number of Specimens Exposed	Number Failed	Source <sup>a</sup>
AISI 405	43	75	403	6,780	3	0	CEL (4)
AISI 405	20	35	197	2,340	3	0	CEL (4)
AISI 405	29	50	197	2,340	3	0	CEL (4)
AISI 405	43	75	197	2,340	3	0	CEL (4)
AISI 405	43	75	402	2,340	3	0	CEL (4)
AISI 410	47	30	403	6,780	3	0	NADC (7)
AISI 410	116	75	403	6,780	3	0	NADC (7)
AISI 410	47	30	197	2,340	3	0	NADC (7)
AISI 410	116	75	197	2,340	3	0	NADC (7)
AISI 410	47	30	402	2,370	3	0	NADC (7)
AISI 410	24	50	402	2,370	3	0	CEL (4)
AISI 410	116	75	402	2,370	3	0	NADC (7)
AISI 410	36	75	402	2,370	3	0	CEL (4)
AISI 410	120	—	402	2,370	3	0	NADC (7)
AISI 430	—	30	403	6,780	3	0	NADC (7)
AISI 430	—	75	403	6,780	3	0	NADC (7)
AISI 430	—	30	197	2,340	3	0	NADC (7)
AISI 430	—	75	197	2,340	3	0	NADC (7)
AISI 430	—	30	402	2,370	3	0	NADC (7)
AISI 430	27	50	402	2,370	3	0	CEL (4)
AISI 430	—	75	402	2,370	3	0	NADC (7)
AISI 430	41	75	402	2,370	3	0	CEL (4)

<sup>a</sup>Numbers refer to references at end of report.

Table 47. Changes in Mechanical Properties of 400 Series Stainless Steels Due to Corrosion

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>b</sup>
				Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
AISI 405	S	123	5,640	77	+1	59	-2	25	+3	CEL (4)
AISI 405	W	403	6,780	77	-33	59	-25	25	-61	CEL (4)
AISI 405	S	403	6,780	77	+2	59	-2	25	-7	CEL (4)
AISI 405	W	751	5,640	77	0	59	-3	25	-13	CEL (4)
AISI 405	W	197	2,340	77	+2	59	-1	25	-1	CEL (4)
AISI 405	S	197	2,340	77	+2	59	-2	25	-2	CEL (4)
AISI 405	W	402	2,370	77	-21	59	-9	25	-39	CEL (4)
AISI 405	S	402	2,370	77	+3	59	-1	25	-3	CEL (4)
AISI 410	W	123	5,640	183	-52	155	0	15	0	NADC (7)
AISI 410	S	123	5,640	80	0	49	-3	31	+8	CEL (4)
AISI 410	W	403	6,780	80	+2	49	+2	31	-8	CEL (4)
AISI 410	S	403	6,780	80	+2	49	-2	31	-4	CEL (4)
AISI 410	W	751	5,640	80	+4	49	-4	31	-8	CEL (4)
AISI 410	S	751	5,640	80	+2	49	-5	31	-3	CEL (4)
AISI 410	W	197	2,340	201	-26	155	+8	9	-11	NADC (7)
AISI 410	W	197	2,340	80	+1	49	-4	31	-3	CEL (4)
AISI 410	S	197	2,340	80	+1	49	-3	31	-3	CEL (4)
AISI 410	W	402	2,370	201	0	155	-	9	+3	NADC (7)
AISI 410	W	402	2,370	80	+1	49	-2	31	-9	CEL (4)
AISI 410	S	402	2,370	80	+1	49	-2	31	-7	CEL (4)
AISI 410	W	181	5	80	+2	49	-9	31	-13	CEL (4)
AISI 430	W	123	5,640	72	+5	54	-4	29	-6	CEL (4)
AISI 430	W	123	5,640	73	-1	55	-2	28	-1	CEL (4)
AISI 430	W	403	6,780	72	+12	54	+6	29	-22	CEL (4)
AISI 430	S	403	6,780	72	+9	54	0	29	-6	CEL (4)
AISI 430	W	751	5,640	72	-75	54	-100	29	-100	CEL (4)
AISI 430	W	1,064	5,300	72	+10	54	+4	29	-16	CEL (4)
AISI 430	S	1,064	5,300	72	-4	54	0	29	-42	CEL (4)
AISI 430	W	197	2,340	72	+4	54	+1	29	-8	CEL (4)
AISI 430	S	197	2,340	72	+6	54	+3	29	-15	CEL (4)
AISI 430	W	197	2,340	73	+3	55	+3	28	-10	CEL (4)
AISI 430	S	197	2,340	73	+3	55	0	28	-9	CEL (4)
AISI 430	W	402	2,370	72	+5	54	+5	29	-18	CEL (4)
AISI 430	W	402	2,370	73	+3	55	+2	28	-20	CEL (4)
AISI 430	S	402	2,370	73	+3	55	+1	28	-18	CEL (4)

<sup>a</sup>W = Totally exposed in seawater on sides of structure; S = Exposed in base of structure so that the lower portions of the specimen were embedded in the bottom sediment.

<sup>b</sup>Numbers refer to references at end of report.



Table 48. Chemical Compositions of Precipitation-Hardening Stainless Steels, Percent by Weight

Alloy	C	Mn	P	S	Si	Ni	Cr	Mo	Al	Cu	Other	Fe <sup>a</sup>	Source <sup>b</sup>
AISI 630	0.03	0.24	0.017	0.011	0.59	4.17	15.92	—	—	3.23	0.24 Cb	R	CEL (4)
AISI 630	—	1.00	—	—	—	4.00	17.30	—	—	3.00	<0.04 V	R	NADC (7)
AISI 631	0.07	0.48	0.017	0.018	0.42	7.42	17.12	—	1.19	—	—	R	CEL (4)
AISI 631	—	0.69	—	—	—	7.70	17.40	0.30	—	—	—	R	NADC (7)
AISI 632	0.07	0.50	0.016	0.016	0.28	7.19	15.05	2.19	1.11	—	—	R	CEL (4)
AISI 632 <sup>c</sup>	—	—	—	—	—	—	—	—	—	—	—	R	NADC (7)
AISI 633	—	—	—	—	—	4.0	17.0	3.0	—	—	—	R	INCO (3)
AISI 633	—	—	—	—	—	4.0	14.0	3.0	—	—	—	R	MEL (5)
AISI 634	0.12	0.77	0.021	0.009	0.34	6.42	15.35	2.73	—	—	0.095 N	R	CEL (4)
AISI 635	0.05	0.54	0.011	0.006	0.57	6.89	16.8	—	0.14	—	0.64 Ti	R	CEL (4)
AISI 635	0.05	0.56	0.026	0.009	0.74	6.80	16.8	—	0.09	—	0.79 Ti	R	CEL (4)
AISI XM16	0.03	0.50	—	—	0.50	8.50	12.00	—	—	1.50	1.15 Ti 0.50 Cb + Ta	R	CEL (4)
PH14-8 Mo	0.04	0.36	0.004	0.002	0.34	8.12	14.71	2.25	1.21	—	—	R	CEL (4)
15-7 AMV	0.27	0.67	0.020	0.012	0.84	7.4	15.0	2.42	1.55	—	0.16 V	R	CEL (4)
AL362	0.03	0.30	0.015	0.015	0.20	6.50	14.50	—	—	—	0.80 Ti	R	CEL (4)
17Cr-14Ni-Cu-Mo	—	—	—	—	—	14.0	16.0	2.0	—	3.0	—	R	INCO (3)
18Cr-14Mn-0.5N	0.07	14.3	0.021	0.03	0.67	0.27	18.4	—	—	—	0.48 N	R	CEL (4)
18Cr-14Mn-0.5N	—	15.0	—	—	—	0.5	18.0	—	—	—	0.5 N	R	INCO (3)

<sup>a</sup>R = remainder.<sup>b</sup>Numbers refer to references at end of report.<sup>c</sup>No values given.

Table 49. Corrosion Rates and Types of Corrosion of Precipitation-Hardening Stainless Steels

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion						Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mils)	Crevice Depth <sup>b</sup> (mils)	Maximum Tunnel Length (mils)	Type <sup>b</sup>	Weld <sup>b</sup>	
AISI 630, A	W	197	2,340	0.4	—	—	—	NU	—	Boeing (6)
AISI 630, H925 <sup>d</sup>	W	403	6,780	<0.1	0	0	0	NC	NC	CEL (4)
AISI 630, H925 <sup>e</sup>	W	403	6,780	<0.1	0	0	0	NC	T; WB (PR)	CEL (4)
AISI 630, H925 <sup>d</sup>	S	403	6,780	0.4	0	0	4,500	T	T; WB (PR)	CEL (4)
AISI 630, H925 <sup>e</sup>	S	403	6,780	<0.1	0	0	1,000	T	T; HAZ (PR)	CEL (4)
AISI 630, H925 <sup>d</sup>	W	197	2,340	0.1	0	0	0	NC	NC	CEL (4)
AISI 630, H925 <sup>e</sup>	W	197	2,340	<0.1	0	0	0	NC	NC	CEL (4)
AISI 630, H925 <sup>d</sup>	S	197	2,340	0.2	0	0	0	NC	WB (U)	CEL (4)
AISI 630, H925 <sup>e</sup>	S	197	2,340	0.2	0	0	1,200	T	NC	CEL (4)
AISI 630, H925 <sup>d</sup>	W	402	2,370	<0.1	0	0	0	NC	NC	CEL (4)
AISI 630, H925 <sup>e</sup>	W	402	2,370	<0.1	0	0	0	NC	NC	CEL (4)
AISI 630, H925 <sup>d</sup>	S	402	2,370	0.6	112	0	1,750	E; P (PR); T	NC	CEL (4)
AISI 630, H925 <sup>e</sup>	S	402	2,370	<0.1	0	0	0	NC	NC	CEL (4)
AISI 630, H925 <sup>d</sup>	W	181	5	3.0	112	112	1,800	C (PR); E; P (PR); T	NC	CEL (4)
AISI 630, H925 <sup>e</sup>	W	181	5	3.2	112	112	1,000	C (PR); E; P (PR); T	NC	CEL (4)
AISI 630, H925 <sup>e</sup>	W	398	5	1.4	112	112	0	C (PR); E; P (PR)	T; WB&HAZ (PR)	CEL (4)
AISI 631, A	W	123	5,640	—	—	—	—	SC-P	—	NADC (7)
AISI 631, TH1050 <sup>d</sup>	W	403	6,780	0.2	0	0	1,750	E; T	NC	CEL (4)
AISI 631, TH1050 <sup>e</sup>	W	403	6,780	1.1	125	0	1,000	E; P (PR); T	T; WB (PR)	CEL (4)
AISI 631, TH1050 <sup>d</sup>	S	403	6,780	0.6	125	0	1,500	P (PR); T	SCC	CEL (4)
AISI 631, TH1050 <sup>e</sup>	S	403	6,780	1.6	0	125	4,000	C (PR); S-E; T	NC	CEL (4)
AISI 631, TH1050 <sup>d</sup>	W	197	2,340	0.4	125	125	1,250	C (PR); P (PR); T	NC	CEL (4)
AISI 631, TH1050 <sup>e</sup>	W	197	2,340	0.1	125	125	750	C (PR); P (PR); T	NC	CEL (4)
AISI 631, A	W	197	2,340	—	—	S	S	S C; S-T	—	NADC (7)
AISI 631, TH1050 <sup>d</sup>	S	197	2,340	0.3	125	125	1,500	C (PR); P (PR); T	NC	CEL (4)
AISI 631, TH1050 <sup>e</sup>	S	197	2,340	<0.1	125	125	375	C (PR); P (PR); T	NC	CEL (4)
AISI 631, TH1050 <sup>d</sup>	W	402	2,370	0.4	125	0	3,750	E; P (PR); T	I-P	CEL (4)
AISI 631, TH1050 <sup>e</sup>	W	402	2,370	0.6	125	0	3,250	E; P (PR); T	I-P	CEL (4)
AISI 631, TH1050 <sup>d</sup>	S	402	2,370	0.6	125	0	3,500	E; P (PR); T	I-P	CEL (4)
AISI 631, TH1050 <sup>e</sup>	S	402	2,370	0.5	125	0	4,250	E; P (PR); T	I-P	CEL (4)
AISI 631, TH1050 <sup>d</sup>	W	181	5	4.4	125	125	4,000	C (PR); E; P (PR); T	NC	CEL (4)
AISI 631, TH1050 <sup>e</sup>	W	181	5	2.7	125	125	1,000	C (PR); E; P (PR); T	WB&HAZ (PR)	CEL (4)
AISI 631, TH1050 <sup>d</sup>	W	398	5	1.9	125	125	2,600	C (PR); P (PR); T	SCC	CEL (4)

Continued

Table 49. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion						Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mils)	Crevice Depth <sup>b</sup> (mils)	Maximum Tunnel Length (mils)	Type <sup>b</sup>	Weld <sup>b</sup>	
AISI 631, RH1050 <sup>d</sup>	W	403	6,780	0.4	125	125	3,000	C (PR); P (PR); T	SCC	CEL (4)
AISI 631, RH1050 <sup>e</sup>	W	403	6,780	1.0	1	125	2,000	C (PR); I-P; T	I-P	CEL (4)
AISI 631, RH1050 <sup>d</sup>	S	403	6,780	1.3	1	125	6,000	C (PR); S-E; I-P; T; X	I-P	CEL (4)
AISI 631, RH1050 <sup>e</sup>	S	403	6,780	0.8	125	0	1,500	P (PR); T; X	I-P	CEL (4)
AISI 631, RH1050 <sup>d</sup>	W	197	2,340	0.3	1	0	1,375	I-P; T; SCC	SCC	CEL (4)
AISI 631, RH1050 <sup>e</sup>	W	197	2,340	0.6	125	0	1,500	P (PR); T	T; HAZ (PR)	CEL (4)
AISI 631, RH1050 <sup>d</sup>	S	197	2,340	0.6	0	125	1,000	C (PR); T	NC	CEL (4)
AISI 631, RH1050 <sup>e</sup>	S	197	2,340	0.3	125	0	1,250	P (PR); T	NC	CEL (4)
AISI 631, RH1050 <sup>d</sup>	W	402	2,370	<0.1	1	0	1,250	I-P; T	I-P	CEL (4)
AISI 631, RH1050 <sup>e</sup>	W	402	2,370	0.7	125	0	2,500	P (PR); T	I-P	CEL (4)
AISI 631, RH1050 <sup>d</sup>	S	402	2,370	<0.1	125	0	3,000	P (PR); T	SCC	CEL (4)
AISI 631, RH1050 <sup>e</sup>	S	402	2,370	0.5	125	0	5,800	P (PR); T	T; HAZ (PR)	CEL (4)
AISI 631, RH1050 <sup>d</sup>	W	181	5	2.9	125	125	2,500	C (PR); S-E; P (PR); T	NC	CEL (4)
AISI 631, RH1050 <sup>e</sup>	W	181	5	3.3	125	125	1,000	C (PR); S-E; P (PR); T	NC	CEL (4)
AISI 632, RH1100 <sup>d</sup>	W	403	6,780	2.1	125	125	2,850	C (PR); P (PR); T	NC	CEL (4)
AISI 632, RH1100 <sup>e</sup>	W	403	6,780	1.5	125	125	2,000	C (PR); P (PR); T	NC	CEL (4)
AISI 632, RH1100 <sup>d</sup>	S	403	6,780	1.1	125	125	2,100	C (PR); P (PR); T	NC	CEL (4)
AISI 632, RH1100 <sup>e</sup>	S	403	6,780	1.2	125	125	5,500	C (PR); P (PR); T	NC	CEL (4)
AISI 632, RH1100 <sup>d</sup>	W	197	2,340	0.6	125	96	750	C; P (PR); T	NC	CEL (4)
AISI 632, RH1100 <sup>e</sup>	W	197	2,340	0.2	125	0	500	E; P (PR); T	NC	CEL (4)
AISI 632, RH1100 <sup>d</sup>	S	197	2,340	0.5	125	0	750	E; P (PR); T	NC	CEL (4)
AISI 632, RH1100 <sup>e</sup>	S	197	2,340	0.3	125	0	650	E; P (PR); T	NC	CEL (4)
AISI 632, RH1100 <sup>d</sup>	W	402	2,370	0.9	125	0	1,400	P (PR); T	I-P	CEL (4)
AISI 632, RH1100 <sup>e</sup>	W	402	2,370	0.7	125	0	1,000	P (PR); T	NC	CEL (4)
AISI 632, RH1100 <sup>d</sup>	S	402	2,370	0.7	1	0	1,000	I-P; T	SCC	CEL (4)
AISI 632, RH1100 <sup>e</sup>	S	402	2,370	0.6	125	0	1,000	P (PR); T	I-P; HAZ (T)	CEL (4)
AISI 632, RH1100 <sup>d</sup>	W	181	5	3.7	125	0	1,150	S-E; P (PR); T	NC	CEL (4)
AISI 632, RH1100 <sup>e</sup>	W	181	5	3.7	125	0	1,000	S-E; P (PR); T	NC	CEL (4)
AISI 632, RH1100 <sup>e</sup>	W	398	5	1.8	125	125	750	C (PR); P (PR); T	NC	CEL (4)
AISI 633	W	123	5,640	<0.1	0	0	—	NC	—	INCO (3)
AISI 633	W	123	5,640	1.4	0	43	—	C	—	MEL (5)
AISI 633	S	123	5,640	<0.1	0	0	—	NC	—	INCO (3)
AISI 633	W	403	6,780	<0.1	0	1	—	I-C	—	INCO (3)

Continued

Table 49. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion						Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mils)	Crevice Depth <sup>b</sup> (mils)	Maximum Tunnel Length (mils)	Type <sup>b</sup>	Weld <sup>b</sup>	
AISI 633	S	403	6,780	<0.1	0	0	—	NC	—	INCO (3)
AISI 633	W	751	5,640	<0.1	0	0	—	NC	—	INCO (3)
AISI 633	W	751	5,640	6.3	0	63	—	C (PR)	—	MEL (5)
AISI 633	S	751	5,640	<0.1	0	1	—	I-C	—	INCO (3)
AISI 633	W	1,064	5,300	<0.1	0	0	—	NC	—	INCO (3)
AISI 633	W	1,064	5,300	2.8	0	63	—	C (PR)	—	MEL (5)
AISI 633	S	1,064	5,300	<0.1	0	1	—	C	—	INCO (3)
AISI 633	W	197	2,340	<0.1	0	1	—	I-C	—	INCO (3)
AISI 633	S	197	2,340	<0.1	0	1	—	I-C	—	INCO (3)
AISI 633	W	402	2,370	<0.1	0	1	—	I-C	—	INCO (3)
AISI 633	S	402	2,370	<0.1	0	1	—	I-C	—	INCO (3)
AISI 633	W	181	5	<0.1	0	1	—	I-C	—	INCO (3)
AISI 633	W	366	5	<0.1	0	1	—	I-C	—	INCO (3)
AISI 634, CRT	W	123	5,640	<0.1	0	0	0	NC	—	CEL (4)
AISI 634, CRT	W	403	6,780	0.2	0	50	0	C	—	CEL (4)
AISI 634, CRT	S	403	6,780	<0.1	0	30	0	C	—	CEL (4)
AISI 634, CRT	W	751	5,640	0.0	0	0	0	NC	—	CEL (4)
AISI 634, CRT	W	197	2,340	0.2	1	1	0	I-C; I-P	—	CEL (4)
AISI 634, CRT	S	197	2,340	<0.1	1	0	0	I-P	—	CEL (4)
AISI 634, CRT	W	402	2,370	0.4	1	38	0	C; I-P	—	CEL (4)
AISI 634, CRT	S	402	2,370	0.1	1	20	0	C; I-P	—	CEL (4)
AISI 635	W	123	5,640	<0.1	0	SL	0	SL-C	—	CEL (4)
AISI 635	S	123	5,640	<0.1	0	0	0	NC	—	CEL (4)
AISI 635	W	403	6,780	0.2	0	20	0	C	—	CEL (4)
AISI 635	S	403	6,780	0.1	0	11	0	C	—	CEL (4)
AISI 635	W	751	5,640	<0.1	0	0	0	NC	—	CEL (4)
AISI 635	W	1,064	5,300	<0.1	0	50	0	C	—	CEL (4)
AISI 635	S	1,064	5,300	<0.1	0	0	0	NC	—	CEL (4)
AISI 635	W	197	2,340	<0.1	0	0	0	NC	—	CEL (4)
AISI 635	S	197	2,340	<0.1	0	0	0	NC	—	CEL (4)
AISI 635	W	402	2,370	0.3	0	275	0	C (PR)	—	CEL (4)
AISI 635	S	402	2,370	<0.1	0	0	0	NC	—	CEL (4)
AISI 635	W	181	5	0.9	40	275	1,000	C (PR); E; P; T	—	CEL (4)

Continued<sup>d</sup>

Table 49. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion						Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mils)	Crevice Depth <sup>b</sup> (mils)	Maximum Tunnel Length (mils)	Type <sup>b</sup>	Weld <sup>b</sup>	
AISI 635	W	398	5	0.6	40	40	1,200	C; E; P; T	—	CEL (4)
ASTM XM16, H950	W	189	5,900	—	—	—	—	I-C; SPP	—	CEL (4)
ASTM XM16, H950 <sup>d</sup>	W	189	5,900	—	—	—	—	I-C; SPP	SC-P	CEL (4)
ASTM XM16, H1050	W	189	5,900	—	—	—	—	I-C; SPP	—	CEL (4)
ASTM XM16, H1050 <sup>d</sup>	W	189	5,900	—	—	—	—	I-C; SPP	F-P (WB)	CEL (4)
PH14-8Mo, SRH950 <sup>d</sup>	W	403	6,780	0.4	I	0	3,000	I-P; T	I-P	CEL (4)
PH14-8Mo, SRH950 <sup>e</sup>	W	403	6,780	<0.1	I	0	0	I-P	I-P	CEL (4)
PH14-8Mo, SRH950 <sup>d</sup>	S	403	6,780	0.2	120	0	2,000	P (PR); T	HAZ (PR120)	CEL (4)
PH14-8Mo, SRH950 <sup>e</sup>	S	403	6,780	<0.1	I	0	0	I-P	I-P	CEL (4)
PH14-8Mo, SRH950 <sup>d</sup>	W	197	2,340	0.3	0	I	500	I-C; T	NC	CEL (4)
PH14-8Mo, SRH950 <sup>e</sup>	W	197	2,340	<0.1	I	0	0	I-P	NC	CEL (4)
PH14-8Mo, SRH950 <sup>d</sup>	S	197	2,340	<0.1	0	I	0	I-C	NC	CEL (4)
PH14-8Mo, SRH950 <sup>e</sup>	S	197	2,340	<0.1	0	0	0	NC	NC	CEL (4)
PH14-8Mo, SRH950 <sup>d</sup>	W	402	2,370	0.5	I	120	2,000	C (PR); I-P; T	I-P	CEL (4)
PH14-8Mo, SRH950 <sup>e</sup>	W	402	2,370	<0.1	I	0	0	I-P	I-P	CEL (4)
PH14-8Mo, SRH950 <sup>d</sup>	S	402	2,370	0.3	120	0	3,000	P (PR); T	I-P	CEL (4)
PH14-8Mo, SRH950 <sup>e</sup>	S	402	2,370	<0.1	I	0	0	I-P	I-P	CEL (4)
PH14-8Mo, SRH950 <sup>d</sup>	W	181	5	3.1	120	0	2,400	S-E; P (PR); T	NC	CEL (4)
PH14-8Mo, SRH950 <sup>e</sup>	W	181	5	1.7	120	0	1,400	S-E; P (PR); T	WB (PR90)	CEL (4)
15-7 AMV, A	W	123	5,640	<0.1	48	48	750	C (PR); P (PR); T	—	CEL (4)
15-7 AMV, A	S	123	5,640	0.4	48	48	1,800	C (PR); P (PR); T	—	CEL (4)
15-7 AMV, A	W	403	6,780	1.2	48	48	4,000	C (PR); P (PR); T; X	—	CEL (4)
15-7 AMV, A	S	403	6,780	0.8	48	48	2,500	C (PR); P (PR); T; X	—	CEL (4)
15-7 AMV, A	W	751	5,640	2.7	48	48	6,000	C (PR); P (PR); T; X	—	CEL (4)
15-7 AMV, A	S	751	5,640	2.4	48	48	6,000	C (PR); P (PR); T; X	—	CEL (4)
15-7 AMV, A	W	1,064	5,300	3.0	48	48	0	C (PR); P (PR); X	—	CEL (4)
15-7 AMV, A	S	1,064	5,300	0.9	48	48	0	C (PR); P (PR); X	—	CEL (4)
15-7 AMV, A	W	197	2,340	0.4	48	48	2,000	C (PR); E; P (PR); T	—	CEL (4)
15-7 AMV, A	S	197	2,340	0.3	48	48	4,000	C (PR); E; P (PR); T	—	CEL (4)
15-7 AMV, A	W	402	2,370	0.5	48	48	7,300	C (PR); E; P (PR); T	—	CEL (4)
15-7 AMV, A	S	402	2,370	0.5	48	48	13,800	C (PR); E; P (PR); T; X	—	CEL (4)

Continued

Table 49. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion						Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mils)	Crevice Depth <sup>b</sup> (mils)	Maximum Tunnel Length (mils)	Type <sup>b</sup>	Weld <sup>b</sup>	
15-7 AMV, RH1150	W	123	5,640	0.1	45	45	0	C (PR); P (PR)	—	CEL (4)
15-7 AMV, RH1150	S	123	5,640	0.1	45	45	1,150	C (PR); P (PR); T	—	CEL (4)
15-7 AMV, RH1150	W	403	6,780	1.2	45	45	5,750	C (PR); P (PR); T	—	CEL (4)
15-7 AMV, RH1150	S	403	6,780	1.2	45	45	4,500	C (PR); P (PR); T	—	CEL (4)
15-7 AMV, RH1150	W	751	5,640	1.5	45	45	6,000	C (PR); P (PR); T; X	—	CEL (4)
15-7 AMV, RH1150	S	751	5,640	1.2	45	45	6,000	C (PR); P (PR); T; X	—	CEL (4)
15-7 AMV, RH1150	W	1,064	5,300	1.1	45	45	5,000	C (PR); P (PR); T	—	CEL (4)
15-7 AMV, RH1150	S	1,064	5,300	0.9	45	45	6,000	C (PR); P (PR); T	—	CEL (4)
15-7 AMV, RH1150	W	197	2,340	0.4	45	45	3,300	C (PR); P (PR); T	—	CEL (4)
15-7 AMV, RH1150	S	197	2,340	0.7	45	45	1,150	C (PR); P (PR); T	—	CEL (4)
15-7 AMV, RH1150	W	402	2,370	1.0	45	45	8,750	C (PR); E; P (PR); T; X	—	CEL (4)
15-7 AMV, RH1150	S	402	2,370	0.7	45	45	4,000	C (PR); E; P (PR); T	—	CEL (4)
15-7 AMV, RH950	W	123	5,640	0.7	48	48	0	C (PR); P (PR)	—	CEL (4)
15-7 AMV, RH950	S	123	5,640	1.3	48	48	2,900	C (PR); P (PR); T; X	—	CEL (4)
15-7 AMV, RH950	W	403	6,780	1.0	48	48	3,750	C (PR); P (PR); T; X	—	CEL (4)
15-7 AMV, RH950	S	403	6,780	1.2	48	48	5,000	C (PR); P (PR); T; X	—	CEL (4)
15-7 AMV, RH950	W	751	5,640	1.6	48	48	6,000	C (PR); E; P (PR); T	—	CEL (4)
15-7 AMV, RH950	W	1,064	5,300	2.0	48	48	6,000	C (PR); P (PR); T; X	—	CEL (4)
15-7 AMV, RH950	S	1,064	5,300	0.9	48	48	6,000	C (PR); P (PR); T; X	—	CEL (4)
15-7 AMV, RH950	W	197	2,340	0.8	48	48	1,000	C (PR); E; P (PR); T	—	CEL (4)
15-7 AMV, RH950	S	197	2,340	0.7	48	48	1,750	C (PR); E; P (PR); T	—	CEL (4)
15-7 AMV, RH950	W	402	2,370	0.6	48	48	4,650	C (PR); E; P (PR); T	—	CEL (4)
15-7 AMV, RH950	S	402	2,370	0.6	48	48	6,000	C (PR); E; P (PR); T	—	CEL (4)
AL362, H950	W	189	5,900	—	—	—	—	I-C; SPP	—	CEL (4)
AL362, H950 <sup>d</sup>	W	189	5,900	—	—	—	—	I-C; SPP	SPP (WB)	CEL (4)
AL362, H1050	W	189	5,900	—	—	—	—	I-C; SPP	—	CEL (4)
AL362, H1050 <sup>d</sup>	W	189	5,900	—	—	—	—	S-C; SPP	D-P (WB)	CEL (4)
17Cr-14Ni-Cu-Mo	W	123	5,640	<0.1	0	0	—	NC	—	INCO (3)
17Cr-14Ni-Cu-Mo	S	123	5,640	<0.1	0	0	—	NC	—	INCO (3)
17Cr-14Ni-Cu-Mo	W	403	6,780	<0.1	0	1	—	I-C	—	INCO (3)
17Cr-14Ni-Cu-Mo	S	403	6,780	<0.1	0	1	—	I-C	—	INCO (3)
17Cr-14Ni-Cu-Mo	W	751	5,640	<0.1	0	1	—	I-C	—	INCO (3)

Continued

Table 49. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion						Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mils)	Crevice Depth <sup>b</sup> (mils)	Maximum Tunnel Length (mils)	Type <sup>b</sup>	Weld <sup>b</sup>	
17Cr-14Ni-Cu-Mo	S	751	5,640	<0.1	0	1	—	I-C	—	INCO (3)
17Cr-14Ni-Cu-Mo	W	1,064	5,300	<0.1	0	1	—	I-C	—	INCO (3)
17Cr-14Ni-Cu-Mo	S	1,064	5,300	<0.1	0	3	—	C	—	INCO (3)
17Cr-14Ni-Cu-Mo	W	197	2,340	<0.1	0	1	—	I-C	—	INCO (3)
17Cr-14Ni-Cu-Mo	S	197	2,340	<0.1	0	1	—	I-C	—	INCO (3)
17Cr-14Ni-Cu-Mo	W	402	2,370	<0.1	0	1	—	I-C	—	INCO (3)
17Cr-14Ni-Cu-Mo	S	402	2,370	<0.1	0	1	—	I-C	—	INCO (3)
17Cr-14Ni-Cu-Mo	W	181	5	<0.1	3	0	—	P	—	INCO (3)
17Cr-14Ni-Cu-Mo	W	366	5	<0.1	0	1	—	I-C	—	INCO (3)
18Cr-14Mn-0.5N	W	123	5,640	<0.1	0	0	0	NC	—	CEL (4)
18Cr-14Mn-0.5N	W	123	5,640	<0.1	0	0	—	NC	—	INCO (3)
18Cr-14Mn-0.5N	S	123	5,640	0.3	0	115	0	C (PR)	—	CEL (4)
18Cr-14Mn-0.5N	S	123	5,640	<0.1	0	0	—	NC	—	INCO (3)
18Cr-14Mn-0.5N	W	403	6,780	0.5	115	0	2,750	P (PR); T	—	CEL (4)
18Cr-14Mn-0.5N	W	403	6,780	<0.1	0	1	—	I-C	—	INCO (3)
18Cr-14Mn-0.5N	S	403	6,780	0.6	115	115	2,000	C (PR); P (PR); T	—	CEL (4)
18Cr-14Mn-0.5N	S	403	6,780	<0.1	0	3	—	C	—	INCO (3)
18Cr-14Mn-0.5N	W	751	5,640	0.2	115	24	2,800	C; P (PR); T	—	CEL (4)
18Cr-14Mn-0.5N	W	751	5,640	<0.1	0	0	—	NC	—	INCO (3)
18Cr-14Mn-0.5N	S	751	5,640	<0.1	0	0	0	NC	—	CEL (4)
18Cr-14Mn-0.5N	S	751	5,640	<0.1	0	3	—	C	—	INCO (3)
18Cr-14Mn-0.5N	W	1,064	5,300	0.2	115	0	2,250	P (PR); T	—	CEL (4)
18Cr-14Mn-0.5N	W	1,064	5,300	<0.1	0	0	—	NC	—	INCO (3)
18Cr-14Mn-0.5N	S	1,064	5,300	0.3	115	0	4,000	P (PR); T	—	CEL (4)
18Cr-14Mn-0.5N	S	1,064	5,300	0.4	62	62	—	C (PR); P (PR)	—	INCO (3)
18Cr-14Mn-0.5N	W	197	2,340	0.8	115	109	1,250	C; P (PR); T	—	CEL (4)
18Cr-14Mn-0.5N	W	197	2,340	<0.1	0	1	—	I-C	—	INCO (3)
18Cr-14Mn-0.5N	S	197	2,340	0.4	115	21	1,000	C; P (PR); T	—	CEL (4)
18Cr-14Mn-0.5N	S	197	2,340	<0.1	0	13	—	C	—	INCO (3)
18Cr-14Mn-0.5N	W	402	2,370	0.8	115	0	2,000	P (PR); T	—	CEL (4)
18Cr-14Mn-0.5N	W	402	2,370	1.1	0	62	—	C (PR)	—	INCO (3)
18Cr-14Mn-0.5N	S	402	2,370	1.0	115	0	3,000	P (PR); T	—	CEL (4)
18Cr-14Mn-0.5N	S	402	2,370	<0.1	0	1	—	I-C	—	INCO (3)

Continued



Table 49. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion						Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mils)	Crevice Depth <sup>b</sup> (mils)	Maximum Tunnel Length (mils)	Type <sup>b</sup>	Weld <sup>b</sup>	
18Cr-14Mn-0.5N	W	181	5	4.9	50	50	—	C (PR); P (PR)	—	INCO (3)
18Cr-14Mn-0.5N	W	366	5	2.6	50	50	—	C (PR); P (PR)	—	INCO (3)

<sup>a</sup>W = Totally exposed in seawater on sides of structure; S = Exposed in base of structure so that the lower portions of the specimens were embedded in the bottom sediments.

<sup>b</sup>Symbols for types of corrosion:

C = Crevice	S = Severe
D = Deep	SC = Scattered
E = Edge	SCC = Stress corrosion cracked
F = Few	SL = Slight
HAZ = Heat-affected zone	SPP = Scattered pinpoint pitting
I = Incipient	T = Tunnel
NC = No visible corrosion	U = Uniform
NU = Nonuniform	WB = Weld bead
P = Pitting	X = Portion of specimens missing due to corrosion
PR = Perforated	

<sup>c</sup>Numbers refer to references at end of report.

<sup>d</sup>Three-inch-diameter circular weld in center of specimen.

<sup>e</sup>Transverse butt weld.

Table 50. Stress Corrosion of Precipitation-Hardening Stainless Steels, Calculated Stresses

Alloy	Stress (ksi)	Percent Yield Strength	Exposure (day)	Depth (ft)	Number of Specimens Exposed	Number Failed <sup>a</sup>	Source <sup>b</sup>
AISI 630, H925 <sup>c</sup>	65	35	403	6,780	2	0	CEL (4)
AISI 630, H925 <sup>c</sup>	93	50	403	6,780	2	0	CEL (4)
AISI 630, H925 <sup>c</sup>	139	75	403	6,780	2	0	CEL (4)
AISI 630, H925 <sup>c</sup>	65	35	197	2,340	2	0	CEL (4)
AISI 630, H925 <sup>c</sup>	93	50	197	2,340	2	0	CEL (4)
AISI 630, H925 <sup>c</sup>	139	75	197	2,340	2	0	CEL (4)
AISI 630, H925 <sup>c</sup>	93	50	402	2,370	3	0	CEL (4)
AISI 630, H925 <sup>c</sup>	139	75	402	2,370	3	0	CEL (4)
AISI 630, H925 <sup>c</sup>	65	35	70	5	3	3 <sup>d</sup>	CEL (4)
AISI 630, H925 <sup>c</sup>	93	50	364	5	3	1 (89) <sup>d</sup>	CEL (4)
AISI 630, H925 <sup>c</sup>	139	75	364	5	3	2 (70, 233) <sup>d</sup>	CEL (4)
AISI 630, RH950	61	39	123	5,640	3	0	NADC (7)
AISI 630, RH950	86	55	123	5,640	3	0	NADC (7)
AISI 630, RH950	134	86	123	5,640	3	0	NADC (7)
AISI 631, TH1050 <sup>c</sup>	66	35	403	6,780	2	0	CEL (4)
AISI 631, TH1050 <sup>c</sup>	94	50	403	6,780	2	1	CEL (4)
AISI 631, TH1050 <sup>c</sup>	141	75	403	6,780	2	1	CEL (4)
AISI 631, TH1050 <sup>c</sup>	66	35	197	2,340	2	0	CEL (4)
AISI 631, TH1050 <sup>c</sup>	94	50	197	2,340	2	0	CEL (4)
AISI 631, TH1050 <sup>c</sup>	141	75	197	2,340	2	0	CEL (4)
AISI 631, TH1050 <sup>c</sup>	94	50	402	2,370	3	0	CEL (4)
AISI 631, TH1050 <sup>c</sup>	141	75	402	2,370	3	1	CEL (4)
AISI 631, TH1050 <sup>c</sup>	66	35	364	5	3	0	CEL (4)
AISI 631, TH1050 <sup>c</sup>	94	50	364	5	3	1 (253) <sup>e</sup>	CEL (4)
AISI 631, TH1050 <sup>c</sup>	141	75	364	5	3	1 (253) <sup>f</sup>	CEL (4)
AISI 631, RH1050 <sup>c</sup>	69	35	403	6,780	2	0	CEL (4)
AISI 631, RH1050 <sup>c</sup>	98	50	403	6,780	2	0	CEL (4)
AISI 631, RH1050 <sup>c</sup>	147	75	403	6,780	2	1 <sup>d</sup>	CEL (4)
AISI 631, RH1050 <sup>c</sup>	69	35	197	2,340	2	0	CEL (4)
AISI 631, RH1050 <sup>c</sup>	98	50	197	2,340	2	0	CEL (4)
AISI 631, RH1050 <sup>c</sup>	147	75	197	2,340	2	0	CEL (4)
AISI 631, RH1050 <sup>c</sup>	98	50	402	2,370	3	0	CEL (4)
AISI 631, RH1050 <sup>c</sup>	147	75	402	2,370	3	2	CEL (4)
AISI 631, RH1050 <sup>c</sup>	69	35	364	5	3	0	CEL (4)
AISI 631, RH1050 <sup>c</sup>	98	50	364	5	3	0	CEL (4)
AISI 631, RH1050 <sup>c</sup>	147	75	364	5	3	1 (90) <sup>d</sup>	CEL (4)
AISI 632, RH1100 <sup>c</sup>	64	35	403	6,780	2	0	CEL (4)
AISI 632, RH1100 <sup>c</sup>	92	50	403	6,780	2	0	CEL (4)
AISI 632, RH1100 <sup>c</sup>	138	75	403	6,780	2	0	CEL (4)
AISI 632, RH1100 <sup>c</sup>	64	35	197	2,340	2	0	CEL (4)
AISI 632, RH1100 <sup>c</sup>	92	50	197	2,340	2	0	CEL (4)
AISI 632, RH1100 <sup>c</sup>	138	75	197	2,340	2	0	CEL (4)
AISI 632, RH1100 <sup>c</sup>	92	50	402	2,370	3	0	CEL (4)
AISI 632, RH1100 <sup>c</sup>	138	75	402	2,370	3	0	CEL (4)
AISI 632, RH1100 <sup>c</sup>	64	35	364	5	3	0	CEL (4)
AISI 632, RH1100 <sup>c</sup>	92	50	364	5	3	1 (322) <sup>g</sup>	CEL (4)
AISI 632, RH1100 <sup>c</sup>	138	75	364	5	3	3 (56, 70, 133) <sup>g</sup>	CEL (4)

Continued

Table 50. Continued.

Alloy	Stress (ksi)	Percent Yield Strength	Exposure (day)	Depth (ft)	Number of Specimens Exposed	Number Failed <sup>a</sup>	Source <sup>b</sup>
AISI 634, CRT	108	50	402	2,370	3	0	CEL (4)
AISI 634, CRT	162	75	402	2,370	3	0	CEL (4)
AISI 635	68	35	197	2,340	3	0	CEL (4)
AISI 635	97	50	197	2,340	3	0	CEL (4)
AISI 635	145	75	197	2,340	3	0	CEL (4)
AISI 635	92	50	402	2,370	3	0	CEL (4)
AISI 635	138	75	402	2,370	3	0	CEL (4)
ASTM XM16, H950	—	75	189	5,900	2	0	CEL (4)
ASTM XM16, H1050	—	75	189	5,900	1	0	CEL (4)
ASTM XM16, H1050 <sup>b</sup>	—	75	189	5,900	1	0	CEL (4)
PH14-8Mo, SRH950 <sup>c</sup>	75	35	403	6,780	2	0	CEL (4)
PH14-8Mo, SRH950 <sup>c</sup>	107	50	403	6,780	2	0	CEL (4)
PH14-8Mo, SRH950 <sup>c</sup>	161	75	403	6,780	2	1	CEL (4)
PH14-8Mo, SRH950 <sup>c</sup>	75	35	197	2,340	2	0	CEL (4)
PH14-8Mo, SRH950 <sup>c</sup>	107	50	197	2,340	2	0	CEL (4)
PH14-8Mo, SRH950 <sup>c</sup>	161	75	197	2,340	2	0	CEL (4)
PH14-8Mo, SRH950 <sup>c</sup>	107	50	402	2,370	3	1	CEL (4)
PH14-8Mo, SRH950 <sup>c</sup>	161	75	402	2,370	3	1	CEL (4)
PH14-8Mo, SRH950 <sup>c</sup>	75	35	364	5	3	3 (322) <sup>d</sup>	CEL (4)
PH14-8Mo, SRH950 <sup>c</sup>	107	50	364	5	3	3 (322) <sup>d</sup>	CEL (4)
PH14-8Mo, SRH950 <sup>c</sup>	161	75	364	5	3	0	CEL (4)
15-7 AMV, A	20	35	403	6,780	2	0	CEL (4)
15-7 AMV, A	29	50	403	6,780	2	0	CEL (4)
15-7 AMV, A	43	75	403	6,780	2	1	CEL (4)
15-7 AMV, A	20	35	197	2,340	3	0	CEL (4)
15-7 AMV, A	29	50	197	2,340	3	0	CEL (4)
15-7 AMV, A	43	75	197	2,340	3	0	CEL (4)
15-7 AMV, A	29	50	402	2,370	3	0	CEL (4)
15-7 AMV, A	43	75	402	2,370	3	0	CEL (4)
15-7 AMV, RH1150	55	35	123	5,640	3	0	CEL (4)
15-7 AMV, RH1150	79	50	123	5,640	3	0	CEL (4)
15-7 AMV, RH1150	119	75	123	5,640	3	0	CEL (4)
15-7 AMV, RH1150	55	35	403	6,780	2	0	CEL (4)
15-7 AMV, RH1150	79	50	403	6,780	2	0	CEL (4)
15-7 AMV, RH1150	119	75	403	6,780	2	0	CEL (4)
15-7 AMV, RH1150	55	35	751	5,640	3	3 <sup>i</sup>	CEL (4)
15-7 AMV, RH1150	79	50	751	5,640	3	3 <sup>i</sup>	CEL (4)
15-7 AMV, RH1150	119	75	751	5,640	3	3 <sup>i</sup>	CEL (4)
15-7 AMV, RH1150	79	50	197	2,340	3	2	CEL (4)
15-7 AMV, RH1150	119	75	197	2,340	3	3	CEL (4)
15-7 AMV, RH1150	79	50	402	2,370	3	1	CEL (4)
15-7 AMV, RH1150	119	75	402	2,370	3	1	CEL (4)
15-7 AMV, RH950	77	35	123	5,640	3	1 <sup>j</sup>	CEL (4)
15-7 AMV, RH950	110	50	123	5,640	3	3	CEL (4)
15-7 AMV, RH950	165	75	123	5,640	3	3 <sup>k</sup>	CEL (4)
15-7 AMV, RH950	77	35	403	6,780	2	0	CEL (4)
15-7 AMV, RH950	110	50	403	6,780	2	0	CEL (4)
15-7 AMV, RH950	165	75	403	6,780	2	2	CEL (4)

Continued

Table 50. Continued.

Alloy	Stress (ksi)	Percent Yield Strength	Exposure (day)	Depth (ft)	Number of Specimens Exposed	Number Failed <sup>a</sup>	Source <sup>b</sup>
15-7 AMV, RH950	77	35	751	5,640	3	0	CEL (4)
15-7 AMV, RH950	110	50	751	5,640	3	3	CEL (4)
15-7 AMV, RH950	165	75	751	5,640	3	3	CEL (4)
15-7 AMV, RH950	77	35	197	2,340	3	0	CEL (4)
15-7 AMV, RH950	110	50	197	2,340	3	2 <sup>j</sup>	CEL (4)
15-7 AMV, RH950	165	75	197	2,340	3	2	CEL (4)
15-7 AMV, RH950	110	50	402	2,370	3	0	CEL (4)
15-7 AMV, RH950	165	75	402	2,370	3	3	CEL (4)
AL362, H950	—	75	189	5,900	3	0	CEL (4)
AL362, H950 <sup>b</sup>	—	75	189	5,900	6	0	CEL (4)
AL362, H1050	—	75	189	5,900	5	0	CEL (4)
AL362, H1050 <sup>b</sup>	—	75	189	5,900	6	0	CEL (4)
AL362, H1050 <sup>l</sup>	—	75	189	5,900	1	0	CEL (4)
AL362, H1050 <sup>m</sup>	—	75	189	5,900	1	0	CEL (4)
18Cr-14Mn-0.5N	41	50	402	2,370	3	0	CEL (4)
18Cr-14Mn-0.5N	61	75	402	2,370	3	0	CEL (4)

<sup>a</sup>Numbers in parentheses indicate days to failure.

<sup>b</sup>Numbers refer to references at end of report.

<sup>c</sup>Transverse butt weld at midlength of specimens.

<sup>d</sup>Failed by crevice corrosion at anvils of stress jig.

<sup>e</sup>Broke at edge of weld bead.

<sup>f</sup>Broke at junction of heat-affected zone and sheet metal.

<sup>g</sup>Crevice corrosion at bolt hole, released tension.

<sup>h</sup>Painted, zinc-rich primer, 8 mils.

<sup>i</sup>Specimens were missing when structure was retrieved.

<sup>j</sup>Incipient crack in one specimen.

<sup>k</sup>One specimen broke prior to exposure in the seawater.

<sup>l</sup>Painted, wash primer (MIL-C-8514) + red lead epoxy primer + epoxy topcoat, 7 mils.

<sup>m</sup>Painted, wash primer (MIL-C-8514) + epoxy primer + epoxy topcoat, 7 mils.

Table 51. Stress Corrosion of Precipitation-Hardening Stainless Steels, Residual Stresses

Alloy	Exposure (day)	Depth (ft)	Type of Residual Stress	Remarks
AISI 630, H925	403	6,780	Unrelieved circular weld	SCC <sup>a</sup> propagated across weld bead
AISI 631, TH1050	398	5	Unrelieved circular weld	SCC radially in three directions to circular weld bead
AISI 631, TH1050	403	6,780	Unrelieved circular weld	SCC propagated across and around weld bead
AISI 631, RH1050	197	2,340	Unrelieved circular weld	SCC, origin on outside of weld bead, propagated into heat-affected zone, circumferentially in both directions around weld
AISI 631, RH1050	402	2,370	Unrelieved circular weld	SCC, origin on outside of weld bead, propagation in both directions around weld bead at edge of heat-affected zone
AISI 631, RH1050	403	6,780	Unrelieved circular weld	SCC, origin on outside of weld bead and propagated in both directions around outside of weld bead
AISI 632, RH1100	402	2,370	Unrelieved circular weld	SCC, origin on outside edge of weld bead, propagated in both directions around weld in heat-affected zone
15-7 AMV, RH1150	123	5,640	Imposed by insulator	SCC due to squeeze by insulators on sides of panel
15-7 AMV, RH1150	1,064	5,300	Unreamed drilled hole	SCC, origin at unreamed hole, not deburred
15-7 AMV, RH950	1,064	5,300	Unreamed drilled hole	SCC, origin at unreamed hole, not deburred

<sup>a</sup>SCC = stress corrosion cracking failure.

Table 52. Changes in Mechanical Properties of the Precipitation-Hardening Stainless Steels Due to Corrosion

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>b</sup>
				Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
AISI 630, H925 <sup>c</sup>	W	403	6,780	192	-6	185	-6	3	-17	CEL (4)
AISI 630, H925 <sup>c</sup>	S	403	6,780	192	-9	185	-7	3	-33	CEL (4)
AISI 630, H925 <sup>c</sup>	W	402	2,370	192	-8	185	-11	3	-17	CEL (4)
AISI 630, H925 <sup>c</sup>	S	402	2,370	192	-7	185	-9	3	-27	CEL (4)
AISI 630, H925 <sup>c</sup>	W	181	5	192	-7	185	-11	3	+7	CEL (4)
AISI 630, H925 <sup>c,d</sup>	W	365	5	192	-	185	-	3	-	CEL (4)
AISI 631, A	W	197	2,340	134	-8	58	-22	37	-3	NADC (7)
AISI 631, TH1050 <sup>c</sup>	W	403	6,780	197	-25	188	-60	3	+77	CEL (4)
AISI 631, TH1050 <sup>c</sup>	S	403	6,780	197	-24	188	-54	3	+57	CEL (4)
AISI 631, TH1050 <sup>c</sup>	W	402	2,370	197	-22	188	-56	3	+40	CEL (4)
AISI 631, TH1050 <sup>c</sup>	S	402	2,370	197	-21	188	-57	3	+57	CEL (4)
AISI 631, RH1050 <sup>c</sup>	W	403	6,780	207	-29	197	-59	5	-7	CEL (4)
AISI 631, RH1050 <sup>c</sup>	S	403	6,780	207	-21	197	-54	5	+9	CEL (4)
AISI 631, RH1050 <sup>c</sup>	W	402	2,370	207	-24	197	-60	5	-7	CEL (4)
AISI 632, RH1100 <sup>c</sup>	W	403	6,780	192	-22	183	-53	3	+33	CEL (4)
AISI 632, RH1100 <sup>c</sup>	S	403	6,780	192	-24	183	-54	3	+43	CEL (4)
AISI 632, RH1100 <sup>c</sup>	W	402	2,370	192	-20	183	-55	3	+43	CEL (4)
AISI 632, RH1100 <sup>c</sup>	S	402	2,370	192	-19	183	-54	3	+5	CEL (4)
AISI 632, RH1100 <sup>c</sup>	W	181	5	192	-15	183	-54	3	+73	CEL (4)
AISI 632, RH1100 <sup>c</sup>	W	365	5	192	-15	183	-54	3	+72	CEL (4)
AISI 634, CRT	W	123	5,640	229	+4	215	-11	19	-1	CEL (4)
AISI 634, CRT	W	403	6,780	229	+4	215	-11	19	+2	CEL (4)
AISI 634, CRT	S	403	6,780	229	+4	215	-8	19	+4	CEL (4)
AISI 634, CRT	W	751	5,640	229	+8	215	-7	19	+4	CEL (4)
AISI 634, CRT	W	197	2,340	229	+3	215	-11	19	+4	CEL (4)
AISI 634, CRT	S	197	2,340	229	+3	215	-9	19	+4	CEL (4)
AISI 635	W	123	5,640	191	+11	184	+11	14	+7	CEL (4)
AISI 635	W	403	6,780	191	+12	184	+12	14	-32	CEL (4)
AISI 635	S	403	6,780	191	+11	184	+10	14	-33	CEL (4)
AISI 635	W	751	5,640	191	+8	184	+8	14	-26	CEL (4)
AISI 635	W	1,064	5,300	199	+2	193	+2	9	-26	CEL (4)
AISI 635	S	1,064	5,300	199	+4	193	+5	9	-24	CEL (4)
AISI 635	W	197	2,340	191	+1	184	+2	14	-18	CEL (4)

Continued

Table 52. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>b</sup>
				Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
AISI 635	S	197	2,340	191	+2	184	+4	14	-20	CEL (4)
AISI 635	W	402	2,370	191	-2	184	-6	14	-7	CEL (4)
AISI 635	S	402	2,370	191	+7	184	+5	14	-30	CEL (4)
AISI 635	W	181	5	191	+4	184	+5	14	-38	CEL (4)
AISI 635	W	365	5	191	+1	184	+2	14	-5	CEL (4)
PH14-8Mo, SRH950 <sup>c</sup>	W	403	6,780	229	-32	214	-53	2	+40	CEL (4)
PH14-8Mo, SRH950 <sup>c</sup>	S	403	6,780	229	-30	214	-49	2	+150	CEL (4)
PH14-8Mo, SRH950 <sup>c</sup>	W	402	2,370	229	-30	214	-54	2	+100	CEL (4)
PH14-8Mo, SRH950 <sup>c</sup>	S	402	2,370	229	-32	214	-57	2	+50	CEL (4)
PH14-8Mo, SRH950 <sup>c</sup>	W	181	5	229	-23	214	-52	2	+100	CEL (4)
15-7 AMV, A	W	123	5,640	129	-8	57	+3	27	-50	CEL (4)
15-7 AMV, A	W	403	6,780	129	+9	57	-2	27	+38	CEL (4)
15-7 AMV, A	S	403	6,780	129	+10	57	0	27	+64	CEL (4)
15-7 AMV, A	W	751	5,640	129	+6	57	+2	27	+2	CEL (4)
15-7 AMV, A	S	751	5,640	129	+4	57	+5	27	+3	CEL (4)
15-7 AMV, A	W	197	2,340	129	0	57	-10	27	+39	CEL (4)
15-7 AMV, A	S	197	2,340	129	0	57	-10	27	+43	CEL (4)
15-7 AMV, A	W	402	2,370	129	+8	57	+1	27	+34	CEL (4)
15-7 AMV, A	S	402	2,370	129	+8	57	+1	27	+44	CEL (4)
15-7 AMV, RH1150	S	123	5,640	190	-2	158	+1	8	-16	CEL (4)
15-7 AMV, RH1150	W	403	6,780	190	+4	158	+7	8	-50	CEL (4)
15-7 AMV, RH1150	S	403	6,780	190	+3	158	+9	8	-37	CEL (4)
15-7 AMV, RH1150	W	751	5,640	190	-3	158	-28	8	-31	CEL (4)
15-7 AMV, RH1150	S	751	5,640	190	+5	158	+8	8	-4	CEL (4)
15-7 AMV, RH1150	W	1,064	5,300	196	+2	166	+2	8	-10	CEL (4)
15-7 AMV, RH1150	S	1,064	5,300	196	+2	166	+3	8	-3	CEL (4)
15-7 AMV, RH1150	W	197	2,340	190	+2	158	+3	8	-1	CEL (4)
15-7 AMV, RH1150	S	197	2,340	190	+2	158	+5	8	-10	CEL (4)
15-7 AMV, RH1150	W	402	2,370	190	+5	158	+8	8	-7	CEL (4)
15-7 AMV, RH1150	S	402	2,370	190	+4	158	+4	8	-4	CEL (4)
15-7 AMV, RH950	S	123	5,640	248	-19	220	-	2	-4	CEL (4)
15-7 AMV, RH950	W	403	6,780	248	-9	220	+1	2	-100	CEL (4)
15-7 AMV, RH950	S	403	6,780	248	-2	220	+5	2	-88	CEL (4)
15-7 AMV, RH950	W	751	5,640	248	-1	220	+2	2	-	CEL (4)

Continued



Table 52. Continued

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>b</sup>
				Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
15-7 AMV, RH950	W	197	2,340	248	-3	220	0	2	-18	CEL (4)
15-7 AMV, RH950	S	197	2,340	248	-2	220	+2	2	-18	CEL (4)
15-7 AMV, RH950	W	402	2,370	248	+2	220	+2	2	-32	CEL (4)
15-7 AMV, RH950	S	402	2,370	248	-2	220	+1	2	-18	CEL (4)
18Cr-14Mn-0.5N	S	123	5,640	126	0	81	-3	52	+6	CEL (4)
18Cr-14Mn-0.5N	W	403	6,780	126	+2	81	+6	52	-3	CEL (4)
18Cr-14Mn-0.5N	S	403	6,780	126	0	81	+2	52	-1	CEL (4)
18Cr-14Mn-0.5N	W	751	5,640	126	0	81	+5	52	-2	CEL (4)
18Cr-14Mn-0.5N	S	751	5,640	126	-1	81	+1	52	-2	CEL (4)
18Cr-14Mn-0.5N	W	1,064	5,300	126	-2	81	+4	52	-4	CEL (4)
18Cr-14Mn-0.5N	S	1,064	5,300	126	-27	81	-31	52	-36	CEL (4)
18Cr-14Mn-0.5N	W	197	2,340	126	-2	81	+5	52	-4	CEL (4)
18Cr-14Mn-0.5N	S	197	2,340	126	-1	81	+3	52	+2	CEL (4)
18Cr-14Mn-0.5N	W	402	2,370	126	+1	81	+5	52	-11	CEL (4)
18Cr-14Mn-0.5N	S	402	2,370	126	-1	81	+3	52	-9	CEL (4)

<sup>a</sup>W = Totally exposed in seawater on sides of structure; S = Exposed in base of structure so that the lower portions of the specimen were embedded in the bottom sediments.

<sup>b</sup>Numbers refer to references at end of report.

<sup>c</sup>Transverse butt weld at center of 12-inch length.

<sup>d</sup>Too badly corroded to obtain tensile specimens.

Table 53. Chemical Compositions of Miscellaneous Stainless Steels, Percent by Weight

Alloy	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Other	Fe <sup>a</sup>	Source <sup>b</sup>
20 Cb	0.04	0.79	0.018	0.004	0.67	28.38	19.80	2.06	3.11	0.77 Cb + Ta	R	CEL (4)
20 Cb	0.05	0.82	—	—	0.70	28.43	20.09	2.32	3.37	0.83 Cb + Ta	R	CEL (4)
20 Cb	—	—	—	—	—	33.0	20.0	2.5	3.5	—	R	INCO (3)
20 Cb-3 <sup>c</sup>	0.07	2.0	0.035	0.035	1.0	34.0	20.0	2.5	3.5	Cb + Ta, 8XC	R	CEL (4)
20 Cb-3	—	—	—	—	—	34.0	20.0	2.3	3.4	—	R	INCO (3)
Ni-Cr-Cu-Mo No. 1, cast	—	—	—	—	—	30.0	20.0	2.5	4.0	—	R	INCO (3)
Ni-Cr-Cu-Mo No. 2, cast	—	—	—	—	—	30.0	20.0	2.5	3.5	—	R	INCO (3)
Ni-Cr-Mo, cast	—	—	—	—	—	24.0	19.0	3.0	—	—	R	INCO (3)
Ni-Cr-Mo-Si, cast	—	—	—	—	1.0	23.0	21.0	5.0	—	—	R	INCO (3)
RL-35-100, cast	—	1.0	—	—	—	31.0	23.0	9.0	—	—	R	INCO (3)

<sup>a</sup>R = remainder.<sup>b</sup>Numbers refer to references at end of report.<sup>c</sup>Typical analysis.

Table 54. Corrosion Rates and Types of Corrosion of Miscellaneous Stainless Steels

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion				Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mils)	Crevice Depth <sup>b</sup> (mils)	Type <sup>b</sup>	
20 Cb	W	123	5,640	0	0	0	NC	CEL (4)
20 Cb	S	123	5,640	0	0	0	NC	CEL (4)
20 Cb	W	403	6,780	0	0	0	NC	CEL (4)
20 Cb	S	403	6,780	<0.1	0	102	C	CEL (4)
20 Cb	W	751	5,640	<0.1	0	26	C	CEL (4)
20 Cb	S	751	5,640	0	0	0	NC	CEL (4)
20 Cb	W	1,064	5,300	0	0	0	NC	CEL (4)
20 Cb	S	1,064	5,300	0	0	0	NC	CEL (4)
20 Cb	W	197	2,340	<0.1	0	1	I-C	CEL (4)
20 Cb	S	197	2,340	<0.1	0	1	I-C	CEL (4)
20 Cb	W	402	2,370	<0.1	0	0	NC	CEL (4)
20 Cb	S	402	2,370	<0.1	0	0	NC	CEL (4)
20 Cb	W	181	5	<0.1	0	5	C; SL-E	CEL (4)
20 Cb	W	398	5	<0.1	14	0	SL-E; P	CEL (4)
20 Cb	W	540	5	<0.1	24	0	P	CEL (4)
20 Cb	W	588	5	<0.1	0	21	C	CEL (4)
20 Cb-3	W	123	5,640	<0.1	0	0	NC	INCO (3)
20 Cb-3	S	123	5,640	<0.1	0	0	NC	INCO (3)
20 Cb-3	W	189	5,900	<0.1	1	1	I-C; I-P	CEL (4)
20 Cb-3	S	189	5,900	<0.1	0	40	C	CEL (4)

Continued

Table 54. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion				Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mils)	Crevice Depth <sup>b</sup> (mils)	Type <sup>b</sup>	
20 Cb-3	W	403	6,780	<0.1	0	1	I-C	INCO (3)
20 Cb-3	S	403	6,780	<0.1	0	1	I-C	INCO (3)
20 Cb-3	W	751	5,640	<0.1	0	0	NC	INCO (3)
20 Cb-3	S	751	5,640	<0.1	0	0	NC	INCO (3)
20 Cb-3	W	1,064	5,300	<0.1	0	1	I-C	INCO (3)
20 Cb-3	S	1,064	5,300	<0.1	0	1	I-C	INCO (3)
20 Cb-3	W	197	2,340	<0.1	0	1	I-C	INCO (3)
20 Cb-3	S	197	2,340	<0.1	0	1	I-C	INCO (3)
20 Cb-3	W	402	2,370	<0.1	1	0	I-P	INCO (3)
20 Cb-3	S	402	2,370	<0.1	0	1	I-C	INCO (3)
20 Cb-3	W	181	5	<0.1	0	1	I-C	INCO (3)
20 Cb-3	W	366	5	<0.1	0	0	NC	INCO (3)
Ni-Cr-Cu-Mo No. 1, cast	W	123	5,640	<0.1	0	0	NC	INCO (3)
Ni-Cr-Cu-Mo No. 1, cast	S	123	5,640	<0.1	0	0	NC	INCO (3)
Ni-Cr-Cu-Mo No. 1, cast	W	403	5,640	<0.1	0	0	NC	INCO (3)
Ni-Cr-Cu-Mo No. 1, cast	S	403	6,780	<0.1	0	0	NC	INCO (3)
Ni-Cr-Cu-Mo No. 1, cast	W	751	5,640	<0.1	0	0	NC	INCO (3)
Ni-Cr-Cu-Mo No. 1, cast	S	751	5,640	<0.1	0	0	NC	INCO (3)
Ni-Cr-Cu-Mo No. 1, cast	W	1,064	5,300	<0.1	0	1	I-C	INCO (3)
Ni-Cr-Cu-Mo No. 1, cast	S	1,064	5,300	<0.1	0	0	NC	INCO (3)
Ni-Cr-Cu-Mo No. 1, cast	W	197	2,340	<0.1	0	0	NC	INCO (3)
Ni-Cr-Cu-Mo No. 1, cast	S	197	2,340	<0.1	0	1	I-C	INCO (3)
Ni-Cr-Cu-Mo No. 1, cast	W	402	2,370	<0.1	0	8	C	INCO (3)
Ni-Cr-Cu-Mo No. 1, cast	S	402	2,370	<0.1	0	0	NC	INCO (3)
Ni-Cr-Cu-Mo No. 1, cast	W	181	5	0.5	0	20	C	INCO (3)
Ni-Cr-Cu-Mo No. 1, cast	W	366	5	<0.1	0	1	I-C	INCO (3)
Ni-Cr-Cu-Mo No. 2, cast	W	123	5,640	<0.1	0	0	NC	INCO (3)
Ni-Cr-Cu-Mo No. 2, cast	S	123	5,640	<0.1	0	0	NC	INCO (3)
Ni-Cr-Cu-Mo No. 2, cast	W	403	6,780	<0.1	0	0	NC	INCO (3)
Ni-Cr-Cu-Mo No. 2, cast	S	403	6,780	<0.1	0	1	I-C	INCO (3)
Ni-Cr-Cu-Mo No. 2, cast	W	751	5,640	<0.1	0	1	I-C	INCO (3)
Ni-Cr-Cu-Mo No. 2, cast	S	751	5,640	<0.1	0	0	NC	INCO (3)
Ni-Cr-Cu-Mo No. 2, cast	W	1,064	5,300	0.1	0	3	C	INCO (3)
Ni-Cr-Cu-Mo No. 2, cast	S	1,064	5,300	0.1	0	5	C	INCO (3)
Ni-Cr-Cu-Mo No. 2, cast	W	197	2,340	0.1	0	1	I-C	INCO (3)
Ni-Cr-Cu-Mo No. 2, cast	S	197	2,340	<0.1	0	1	I-C	INCO (3)
Ni-Cr-Cu-Mo No. 2, cast	W	402	2,370	0.2	3	0	P	INCO (3)
Ni-Cr-Cu-Mo No. 2, cast	S	402	2,370	<0.1	0	1	I-C	INCO (3)
Ni-Cr-Cu-Mo No. 2, cast	W	181	5	0.1	0	18	C	INCO (3)
Ni-Cr-Cu-Mo No. 2, cast	W	366	5	0.1	0	27	C	INCO (3)
Ni-Cr-Mo, cast	W	123	5,640	<0.1	0	0	NC	INCO (3)
Ni-Cr-Mo, cast	S	123	5,640	<0.1	0	0	NC	INCO (3)
Ni-Cr-Mo, cast	W	403	6,780	<0.1	0	1	I-C	INCO (3)
Ni-Cr-Mo, cast	S	403	6,780	<0.1	0	1	I-C	INCO (3)
Ni-Cr-Mo, cast	W	751	5,640	<0.1	0	0	NC	INCO (3)
Ni-Cr-Mo, cast	S	751	5,640	<0.1	0	0	NC	INCO (3)
Ni-Cr-Mo, cast	W	1,064	5,300	<0.1	0	0	NC	INCO (3)

Continued

Table 54. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion				Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mils)	Crevice Depth <sup>b</sup> (mils)	Type <sup>b</sup>	
Ni-Cr-Mo, cast	S	1,064	5,300	<0.1	0	0	NC	INCO (3)
Ni-Cr-Mo, cast	W	197	2,340	<0.1	0	0	NC	INCO (3)
Ni-Cr-Mo, cast	S	197	2,340	<0.1	0	1	I-C	INCO (3)
Ni-Cr-Mo, cast	W	402	2,370	<0.1	0	1	I-C	INCO (3)
Ni-Cr-Mo, cast	S	402	2,370	<0.1	0	1	I-C	INCO (3)
Ni-Cr-Mo, cast	W	181	5	<0.1	0	0	NC	INCO (3)
Ni-Cr-Mo, cast	W	366	5	<0.1	0	0	NC	INCO (3)
Ni-Cr-Mo-Si, cast	W	123	5,640	<0.1	0	0	NC	INCO (3)
Ni-Cr-Mo-Si, cast	S	123	5,640	<0.1	0	0	NC	INCO (3)
Ni-Cr-Mo-Si, cast	W	403	6,780	<0.1	0	0	NC	INCO (3)
Ni-Cr-Mo-Si, cast	S	403	6,780	<0.1	0	0	NC	INCO (3)
Ni-Cr-Mo-Si, cast	W	751	5,640	<0.1	0	0	NC	INCO (3)
Ni-Cr-Mo-Si, cast	S	751	5,640	<0.1	0	0	NC	INCO (3)
Ni-Cr-Mo-Si, cast	W	1,064	5,300	<0.1	0	0	NC	INCO (3)
Ni-Cr-Mo-Si, cast	S	1,064	5,300	<0.1	0	0	NC	INCO (3)
Ni-Cr-Mo-Si, cast	W	197	2,340	<0.1	0	0	NC	INCO (3)
Ni-Cr-Mo-Si, cast	S	197	2,340	<0.1	0	0	NC	INCO (3)
Ni-Cr-Mo-Si, cast	W	402	2,370	<0.1	0	0	NC	INCO (3)
Ni-Cr-Mo-Si, cast	S	402	2,370	<0.1	0	0	NC	INCO (3)
Ni-Cr-Mo-Si, cast	W	181	5	<0.1	0	0	NC	INCO (3)
Ni-Cr-Mo-Si, cast	S	366	5	<0.1	0	0	NC	INCO (3)
RL-35-100, cast	W	123	5,640	0.3	0	0	G	INCO (3)
RL-35-100, cast	S	123	5,640	0.5	0	0	G	INCO (3)
RL-35-100, cast	W	403	6,780	<0.1	0	0	G	INCO (3)
RL-35-100, cast	S	403	6,780	0.3	0	0	G	INCO (3)
RL-35-100, cast	W	751	5,640	<0.1	0	0	U-ET	INCO (3)
RL-35-100, cast	S	751	5,640	0.3	0	0	ET	INCO (3)
RL-35-100, cast	W	1,064	5,300	0.7	0	0	G	INCO (3)
RL-35-100, cast	S	1,064	5,300	0.1	0	0	G	INCO (3)
RL-35-100, cast	W	197	2,340	<0.1	0	0	NC	INCO (3)
RL-35-100, cast	S	197	2,340	<0.1	0	0	NU-ET	INCO (3)

<sup>a</sup>W = Totally exposed in seawater on sides of structure; S = Exposed in base of structure so that the lower portions of the specimen were embedded in the bottom sediments.

<sup>b</sup>Symbols for types of corrosion:

C = Crevice	NC = No visible corrosion
E = Edge	NU = Nonuniform
ET = Etched	P = Pitted
G = General	SL = Slight
I = Incipient	U = Uniform

<sup>c</sup>Numbers refer to references at end of report.

Table 55. Stress Corrosion of Miscellaneous Stainless Steels

Alloy	Stress (ksi)	Percent Yield Strength	Exposure (day)	Depth (ft)	Number of Specimens Exposed	Number Failed	Source <sup>a</sup>
20 Cb	16	35	123	5,640	3	0	CEL (4)
20 Cb	24	50	123	5,640	3	0	CEL (4)
20 Cb	35	75	123	5,640	3	0	CEL (4)
20 Cb	24	50	403	6,780	2	0	CEL (4)
20 Cb	35	75	403	6,780	2	0	CEL (4)
20 Cb	16	35	751	5,640	3	0	CEL (4)
20 Cb	24	50	751	5,640	3	0	CEL (4)
20 Cb	35	75	751	5,640	3	0	CEL (4)
20 Cb	24	50	197	2,340	3	0	CEL (4)
20 Cb	35	75	197	2,340	3	0	CEL (4)
20 Cb	24	50	402	2,370	3	0	CEL (4)
20 Cb	35	75	402	2,370	3	0	CEL (4)

<sup>a</sup>Numbers refer to references at end of report.

Table 56. Changes in Mechanical Properties of Miscellaneous Stainless Steels

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>b</sup>
				Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
20 Cb	S	123	5,640	92	+5	47	+19	40	-5	CEL (4)
20 Cb	W	403	6,780	92	+2	47	+4	40	-3	CEL (4)
20 Cb	S	403	6,780	92	+1	47	+1	40	-2	CEL (4)
20 Cb	W	751	5,640	92	+1	47	0	40	-2	CEL (4)
20 Cb	S	751	5,640	92	+2	47	+6	40	-5	CEL (4)
20 Cb	S	1,064	5,300	92	+4	47	+9	40	-3	CEL (4)
20 Cb	W	197	2,340	92	-1	47	-1	40	+4	CEL (4)
20 Cb	S	197	2,340	92	0	47	+1	40	-5	CEL (4)
20 Cb	W	402	2,370	92	0	47	-1	40	-7	CEL (4)
20 Cb	S	402	2,370	92	+4	47	+11	40	-12	CEL (4)
20 Cb	W	181	5	92	+2	47	+5	40	-4	CEL (4)
20 Cb	W	365	5	92	-2	47	-4	40	+1	CEL (4)

<sup>a</sup>W = Totally exposed in seawater on sides of structure; S = Exposed in base of structure so that the lower portions of the specimen were embedded in the bottom sediments.

<sup>b</sup>Numbers refer to references at end of report.

## ALUMINUM ALLOYS

The resistance of aluminum and its alloys to corrosion is due to a relatively chemically inert film of aluminum oxide which forms on its surface. As long as this oxide film remains intact the good corrosion resistance is preserved. In oxidizing environments where a sufficient amount of oxidizing agent or oxygen is present to repair any breaks in this protective film, the corrosion resistance of the aluminum alloys is maintained. The usual corrosion protection (passive) film that forms on aluminum in waters at temperatures below 70°C is bayerite ( $\beta\text{-Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$ ).

In general, oxidizing conditions favor the preservation of this passive film, while reducing conditions destroy it. Chloride ions are particularly aggressive in destroying this passive film.

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 seawater this naturally formed protective film breaks down more readily, and its repair and growth are retarded by the chloride ion.

The corrosion of aluminum alloys in seawater is usually of the pitting and crevice types. Pits begin by breakdown of the protective film at weak spots or at nonhomogeneities. The breakdown is followed by the formation of an electrolytic cell, the anode of which is a minute area of active metal and the cathode of which is a considerable area of passive metal. The large potential difference of this "passive-active" cell accounts for the considerable flow of current with its attendant rapid corrosion at the small anode (pitting).

Pitting is most likely to occur in the presence of chloride ions (for example, in seawater), combined with such cathodic depolarizers as oxygen or oxidizing salts. An oxidizing environment is usually necessary for preservation of a passive protective film with accompanying high corrosion resistance, but, unfortunately, it is also a condition for the occurrence of pitting. The oxidizer can often act as a depolarizer for "passive-active" cells established by

the breakdown of passivity at a specific point or area. The chloride ion in particular can accomplish this breakdown.

As discussed above, aluminum alloys generally corrode in seawater by pitting and crevice corrosion; therefore, as much as 90 to 95% of the exposed surface can be uncorroded. With such low percentages of the total exposed area affected, corrosion rates calculated from weight losses as mils penetration per year (mpy) can give a very misleading picture. The mpy implies an uniform decrease in thickness, which for aluminum alloys is not the case.

Another manifestation of localized attack in aluminum alloys is oxygen concentration cell corrosion in crevices (usually known as crevice corrosion). This type of corrosion occurs underneath deposits of any kind on the metal surface, underneath barnacles, and at the faying surfaces of joints. The area of the aluminum alloys which is shielded from the surrounding solution becomes deficient in oxygen, thus creating a difference in oxygen concentration between the shielded and unshielded areas. An electrolytic cell is created with a difference in electrical potential being generated between the high and low oxygen concentration areas; the low concentration area becomes the anode of the cell. Corrosion occurs at the small anodic area and, because the cathodic area is much larger, the rate of attack is considerably greater than if no such cell were present.

There are two other types of localized corrosion often found in aluminum alloys: intergranular and exfoliation. Intergranular (intercrystalline) attack is selective corrosion of grain boundaries or closely adjacent regions without appreciable attack of the grains or crystals themselves. Exfoliation is a lamellar form of corrosion, resulting from a rapid lateral attack along grain boundaries or striations within the grains parallel to the metal surface. This directional attack results in a leafing action, aggravated by the voluminous corrosion products that causes the uncorroded strata to be split apart.

Low weight losses and low corrosion rates accompany these manifestations of localized

corrosion. Thus, the integrity of an aluminum alloy structure will be jeopardized if designed solely on the basis of corrosion rates calculated from weight losses rather than on the basis of measured depths of pits and depths of crevice corrosion. Pitting and crevice corrosion can, and do, penetrate aluminum alloys rapidly in seawater, thus rendering them useless in short periods of time.

Therefore, corrosion rates expressed as mils penetration per year calculated from weight losses, maximum pit depths, maximum depths of crevice corrosion and other type of corrosion are tabulated to provide an overall picture of the corrosion of the aluminum alloys.

### **6.1. 1000 SERIES ALUMINUM ALLOYS (99.00% MINIMUM ALUMINUM)**

The chemical compositions of the 1000 Series aluminum alloys are given in Table 57, their corrosion rates and type of corrosion in Table 58, their stress corrosion behavior in Table 59, and the effect of exposure on their mechanical properties in Table 60.

The 1000 Series aluminum alloys contain a minimum of 99% aluminum and are considered unalloyed aluminums.

The 1000 Series aluminum alloys corroded by the localized types of corrosion, pitting, and crevice.

#### **6.1.1. Duration of Exposure**

The corrosion rates of 1100 alloy decreased with increasing duration of exposure at the surface, in seawater at the 2,500-foot depth, and in the bottom sediments at the 6,000-foot depth, while the reverse occurred in the bottom sediments at the 2,500-foot depth and in the seawater at the 6,000-foot depth. There was no correlation between the severity of crevice corrosion and duration of exposure. The same was true for the severity of pitting corrosion, except at the surface where the maximum depth of pitting corrosion increased with increasing duration of exposure over a period of 1 year.

The corrosion of 1180 alloy was comparable to that of the 1100 alloy.

#### **6.1.2. Effect of Depth**

The corrosion rates of 1100 alloy increased with increasing depth after 1 year of exposure. However, there were no correlations between maximum depths of pitting and crevice corrosion and corrosion rates. In general, pitting and crevice corrosion were more severe at depth than at the surface.

There was no definite effect of depth on the corrosion of 1000 Series aluminum alloys.

#### **6.1.3. Effect of Concentration of Oxygen**

Changes in the concentration of oxygen in seawater had no definite or consistent effect on the corrosion of 1100 aluminum alloy. In general, after 1 year of exposure the corrosion rates and severity of crevice corrosion were greater at the lower oxygen concentrations, while the severity of pitting corrosion was greatest at the highest oxygen concentration.

#### **6.1.4. Stress Corrosion**

Alloys 1100 and 1180 were exposed at the 2,500-foot depth for 402 days when stressed at values equivalent to 50 and 75% of their respective yield strengths (Table 59) to determine their susceptibilities to stress corrosion. They were not susceptible to stress corrosion under the conditions of the test.

#### **6.1.5. Mechanical Properties**

The effects of exposure on the mechanical properties of 1100 and 1180 alloys are given in Table 60. Their mechanical properties were not affected by exposure in seawater at the 2,500-foot depth for 402 days.

### **6.2. 2000 SERIES ALUMINUM ALLOYS (ALUMINUM-COPPER ALLOYS)**

The chemical compositions of the 2000 Series aluminum alloys are given in Table 61, their corrosion rates and type of corrosion in Table 62, their stress corrosion behavior in Table 63, and the effect of exposure on their mechanical properties in Table 64.



The 2000 Series aluminum alloys contain copper as the chief alloying element. Copper is one of the most important alloying metals for aluminum because of its appreciable solubility and its strengthening effect.

The 2000 Series alloys corroded by pitting, crevice, intergranular, and exfoliation types of corrosion.

#### 6.2.1. Duration of Exposure

There was no definite or consistent correlation between corrosion rates and types of corrosion of the 2000 Series alloys and duration of exposure.

#### 6.2.2. Effect of Depth

In general, corrosion rates were greater, and pitting, crevice, and intergranular corrosion were more severe at depth than at the surface after 1 year of exposure. Thus, seawater at depth is more aggressive to the 2000 Series aluminum alloys than is seawater at the surface.

#### 6.2.3. Effect of Concentration of Oxygen

The effect of changes in the concentration of oxygen in seawater on the corrosion behavior of the 2000 Series alloys was inconsistent and erratic except for alloy 2219-T81. The corrosion rates, maximum depths of pits, and maximum depths of crevice corrosion decreased with increasing oxygen concentration, but not linearly, after 1 year of exposure. This behavior of alloy 2219-T81 shows that the concentration of oxygen in seawater exerts considerable influence on the corrosion of this alloy.

#### 6.2.4. Stress Corrosion

The 2000 Series aluminum alloys were exposed at the depths and for the times shown in Table 63 when stressed at values equivalent to 30, 50, or 75% of their respective yield strengths to determine their susceptibilities to stress corrosion. They were not susceptible to stress corrosion under the test conditions.

#### 6.2.5. Other Types of Corrosion

Alloys 2014-T3, 2014-T6, 2024-T3, 2024-T81, 2219-T81, and 2219-T87 were attacked by intergranular corrosion. Alloys 2014-T3, 2024-T3, 2024-T6, 2024-T81, and 2219-T81 were attacked by the exfoliation type of corrosion.

#### 6.2.6. Welding

Welding did not affect the corrosion behavior of aluminum alloys 2024-T3 and 2219-T81.

#### 6.2.7. Mechanical Properties

The effects of exposure on the mechanical properties of the 2000 Series aluminum alloys are given in Table 64. The mechanical properties of the 2000 Series alloys were impaired except for those of alloy Alclad 2024-T3.

### 6.3. 3000 SERIES ALUMINUM ALLOYS (ALUMINUM-MANGANESE ALLOYS)

The chemical compositions of the 3000 Series aluminum alloys are given in Table 65, their corrosion rates and types of corrosion in Table 66, their stress corrosion behavior in Table 67, and the effect of exposure on their mechanical properties in Table 68.

The chief alloying element of the 3000 Series aluminum alloys is manganese. Manganese is added to aluminum in amounts above 1% to increase its strength.

The 3000 Series alloys corroded chiefly by the crevice and pitting types of localized corrosion. There was also some blistering of the Alclad 3003 alloy.

#### 6.3.1. Duration of Exposure

The corrosion rates of alloys 3003 and Alclad 3003 neither increased nor decreased uniformly with increasing duration of exposure, except for Alclad 3003 at the 2,500-foot depth. At this depth the corrosion rates decreased with increasing duration of exposure. In general, the severity of pitting and crevice corrosion was greater after the longer times of exposure.

The corrosion behavior of the 3000 Series alloys was erratic and unpredictable with regard to duration of exposure.

### 6.3.2. Effect of Depth

After 1 year of exposure the corrosion rates and maximum depths of pits increased with increasing depth, but not linearly. Alclad 3003 did not behave in this manner. In other words, the corrosion behavior of alloy 3003 appears to be depth (pressure) dependent in that it increased in severity with increasing depth.

### 6.3.3. Effect of Concentration of Oxygen

The corrosion rates, maximum pit depths, and maximum depths of crevice corrosion on alloys 3003 and Alclad 3003 due to changes in the concentration of oxygen in seawater were erratic.

### 6.3.4. Stress Corrosion

Alloy 3003-H14 was not susceptible to stress corrosion when stressed at values equivalent to 50 and 75% of its yield strength and exposed at the 2,500-foot depth for 402 days as given in Table 67.

### 6.3.5. Corrosion Products

Corrosion products from alloy 3003-H14 were analyzed by X-ray diffraction, spectrographic analysis, quantitative chemical analysis, and infra-red spectrophotometry. The qualitative results were: amorphous  $\text{Al}_2\text{O}_3 \cdot \text{XH}_2\text{O}$ , NaCl,  $\text{SiO}_2$ , Al, Na, Si, Mg, Fe, Cu, Ca, Mn, 3.58% chloride ion, 18.77% sulfate ion, and considerable phosphate ion.

### 6.3.6. Mechanical Properties

The effects of exposure on the mechanical properties of alloys 3003-H14, Alclad 3003-H12, and Alclad 3003-H14 are given in Table 68. In general, the mechanical properties of alloys 3003-H14 and Alclad 3003-H12 were adversely affected by exposure at depth.

## 6.4. 5000 SERIES ALUMINUM ALLOYS (ALUMINUM-MAGNESIUM ALLOYS)

The chemical compositions of the 5000 Series aluminum alloys are given in Table 69, their corrosion rates and types of corrosion in Table 70, their stress corrosion behavior in Table 71, and the effect of exposure on their mechanical properties in Table 72.

Aluminum is alloyed with magnesium to form an important class of nonheat-treatable alloys (5000 Series). Their utility and importance are based on their resistance to corrosion, high strength without heat treatment, and good weldability.

The 5000 Series aluminum alloys corroded chiefly by the crevice and pitting types of localized corrosion. Other types of corrosion found were: blistering, crater, edge, intergranular, line, and exfoliation.

### 6.4.1. Duration of Exposure

The general effect of duration of exposure on the corrosion of the 5000 Series alloys was erratic and nonuniform. The corrosion rates and the maximum depths of pitting or crevice corrosion neither increased nor decreased consistently with increasing duration of exposure; in many cases, the behavior was erratic.

### 6.4.2. Effect of Depth

After 1 year of exposure the average corrosion rates of all the 5000 Series alloys increased with depth, but not linearly. Also, the maximum depths of pits of all the alloys increased linearly with depth. The maximum depth of crevice corrosion of all the alloys increased with depth, but not consistently. The corrosion behavior of the 5000 Series aluminum alloys appears to be more uniformly affected by depth than by duration of exposure or changes in the concentration of oxygen in seawater.

### 6.4.3. Effect of Concentration of Oxygen

The corrosion rates of alloy 5086-H34 increased linearly with increasing concentration of oxygen in

seawater, but the slope of the line was very small (1 to 25). However, such relationships were not found for the maximum depths of pitting and crevice corrosion. The pit depths were a maximum at the highest oxygen concentration, and the maximum depth of crevice corrosion was at the intermediate oxygen concentration.

The corrosion rates of alloy 5456-H321 decreased linearly with increasing concentration of oxygen in seawater, but the slope of the line was very small (1 to 10). However, no correlations were possible between maximum depth of pitting and crevice corrosion.

The corrosion rates and changes in the maximum depths of pits and crevice corrosion of the other 5000 Series aluminum alloys were erratic and inconsistent with respect to changes in the concentration of oxygen in seawater. Changes in the concentration of oxygen in seawater did not exert a constant or uniform influence on the corrosion behavior of the 5000 Series aluminum alloys. This behavior, like that of the stainless steels and some nickel alloys, can be attributed to the dual role oxygen can play with regard to alloys which depend upon passive films for their corrosion resistance.

#### 6.4.4. Stress Corrosion

Some 5000 Series aluminum alloys were exposed at the depths and for the times given in Table 71 when stressed at values equivalent to 30, 50, or 75% of their respective yield strengths to determine their susceptibilities to stress corrosion. They were not susceptible to stress corrosion under the test conditions.

#### 6.4.5. Other Types of Corrosion

Alloys 5052-H32 and 5456-H34 were attacked by the exfoliation type of corrosion. Alloys 5083-H113, 5086-H32, and 5086-H34 were attacked by intergranular corrosion.

#### 6.4.6. Welding

Welding did not affect the corrosion behavior of alloys 5083-H113, 5086-H34, and 5454-H32.

#### 6.4.7. Corrosion Products

Corrosion products from alloy 5086 were analyzed by X-ray diffraction, spectrographic analysis, quantitative chemical analysis, and infra-red spectrophotometry. The qualitative results were: amorphous  $\text{Al}_2\text{O}_3 \cdot x\text{H}_2\text{O}$ , NaCl,  $\text{SiO}_2$ , Al, Na, Mg, Cu, Fe, Si, Ti, 5.8% chloride ion, 26.2% sulfate ion, and considerable phosphate ion.

#### 6.4.8. Mechanical Properties

The effects of exposure on the mechanical properties of the 5000 Series aluminum alloys are given in Table 72. The mechanical properties of the following alloys were adversely affected by exposure: 5456-H321 after 123 days of exposure at the 6,000-foot depth; 5052-H32, 5083-H113, and 5456-H34 after 403 days of exposure at the 6,000-foot depth; and 5456-H321 and 5456-H34 after 751 days of exposure at the 6,000-foot depth. The mechanical properties of the above alloys after exposures for different times at different depths and of the other alloys were not adversely affected by exposure at depth in the seawater.

### 6.5. 6000 SERIES ALUMINUM ALLOYS (ALUMINUM-MAGNESIUM-SILICON ALLOYS)

The chemical compositions of the 6000 Series aluminum alloys are given in Table 73, their corrosion rates and types of corrosion in Table 74, their stress corrosion behavior in Table 75, and the effects of exposure on their mechanical properties in Table 76.

The aluminum-magnesium-silicon system is the basis for a major class of heat-treatable aluminum-base alloys. They combine many desirable characteristics, including moderately high strength and good resistance to corrosion.

There was only one 6000 Series alloy (6061) in this program. Alloy 6061 corroded chiefly by the crevice and pitting types of localized corrosion. Also, there was some intergranular corrosion.

#### 6.5.1. Duration of Exposure

The corrosion rates of 6061 at the surface and at the 6,000-foot depth decreased with duration of

exposure, but not uniformly, while those at the 2,500-foot depth increased with duration of exposure. However, the maximum depths of pitting and crevice corrosion increased with increasing duration of exposure at the surface and at depths of 2,500 and 6,000 feet.

#### 6.5.2. Effect of Depth

Although the corrosion rates and the maximum depths of pitting and crevice corrosion were greater at depth than at the surface, these increases did not increase uniformly with increasing depth. Depth exerted no uniform influence on the corrosion behavior of alloy 6061.

#### 6.5.3. Effect of Concentration of Oxygen

The corrosion rates and maximum depths of pitting and crevice corrosion decreased with increasing concentration of oxygen in seawater. The maximum depths of crevice corrosion decreased linearly with increasing oxygen concentration. The corrosion rates and maximum depths of pitting decreased constantly, but not uniformly, with depth.

#### 6.5.4. Stress Corrosion

Alloy 6061-T6 was exposed at the depths and for the times given in Table 75 when stressed at values equivalent to 30 and 75% of its yield strength to determine its susceptibility to stress corrosion. Alloy 6061-T6 was not susceptible to stress corrosion under the test conditions.

#### 6.5.5. Welding

The corrosion of alloy 6061-T6 was adversely affected by welding. Alloy 6061 was attacked by intergranular corrosion in the "as-welded" condition.

#### 6.5.6. Mechanical Properties

The effects of exposure on the mechanical properties of alloy 6061-T6 are given in Table 76. The mechanical properties of 6061-T6 were adversely affected by exposure in seawater. Those specimens which had been welded and which had been attacked by intergranular corrosion were the most seriously affected.

### 6.6. 7000 SERIES ALUMINUM ALLOYS (ALUMINUM-ZINC-MAGNESIUM ALLOYS)

The chemical compositions of the 7000 Series aluminum alloys are given in Table 77, their corrosion rates and types of corrosion in Table 78, their stress corrosion behavior in Table 79, and the effect of exposure on their mechanical properties in Table 80.

Combinations of zinc and magnesium in aluminum provide a class of heat-treatable alloys, some of which develop the highest strengths presently known for commercial aluminum-base alloys. The addition of copper to the aluminum-zinc-magnesium system, together with small but important amounts of chromium and manganese, results in the highest strength, heat-treatable, aluminum-base alloys commercially available.

The 7000 Series alloys were attacked by crevice, edge, exfoliation, intergranular, and pitting types of corrosion. Corrosion of the Alclad alloys was by shallow pitting and crevice corrosion, slight blistering, and general corrosion.

Because of the erratic behavior of the 7000 Series aluminum alloys during exposure in seawater at depth, it was impossible to find any correlation between their corrosion behavior and duration of exposure, effect of depth, or the effect of changes in the concentration of oxygen in seawater.

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 1-3 after 123 days of exposure, the buoy, which was 300 feet below the surface, was found to be corroded. White corrosion products on the bottom hemisphere covered 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 0.75 inch high with a hole in the top of each blister. The hole in the top of the blister indicates the origin of the failure: originally a pinhole in the cladding alloy existed where seawater gained access to the interface between the cladding alloy and the core alloy. When this blister was sectioned to inspect the corrosion underneath, it was found to be filled with white crystalline aluminum oxide corrosion products. It appeared that seawater 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. 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.

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 seawater 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.

Wei [15] 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

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

#### 6.6.1. Stress Corrosion

The 7000 Series aluminum alloys were exposed at the depths and for the times given in Table 79 when stressed at values equivalent to 30, 50, and 75% of their respective yield strengths to determine their susceptibilities to stress corrosion. Alloys 7075-T6, 7079-T6, Alclad 7079-T6, and 7178-T6, failed by stress corrosion cracking.

#### 6.6.2. Corrosion Products

Corrosion products from alloy 7079-T6 were analyzed by X-ray diffraction, spectrophotographic analysis, quantitative chemical analysis, and infra-red spectrophotometry. The qualitative results were: amorphous  $\text{Al}_2\text{O}_3 \cdot \text{XH}_2\text{O}$ , NaCl, Al metal, Al, Cu, Mg, Mn, Zn, Na, Ca, traces of Ti and Ni, 2.82% chloride ion, 16.7% sulfate ion, and considerable phosphate ion.

#### 6.6.3. Mechanical Properties

The effects of exposure on the mechanical properties of the 7000 Series aluminum alloys are given in Table 80. The mechanical properties of alloys 7002-T6, 7039-T6, 7075-T6, 7075-T64, 7075-T73, 7079-T6, and 7178-T6 were adversely affected.

Table 57. Chemical Composition of 1000 Series Aluminum Alloys, Percent by Weight

Alloy	Gage (in.)	Si	Fe	Cu	Mn	Zn	Al <sup>a</sup>
1100	—	—	—	—	—	—	99.0
1100-0	—	<i>b</i>	<i>b</i>	0.14	0.03	—	R
1100-H14	0.050	0.14	0.55	0.14	—	0.06	R
1180	0.050	0.06	0.08	0.002	0.002	—	R

<sup>a</sup>R = remainder.<sup>b</sup>Si + Fe = 0.57

Table 58. Corrosion Rates and Types of Corrosion of 1000 Series Aluminum Alloys

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion				Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth (mils)	Crevice Depth <sup>b</sup> (mils)	Type <sup>b</sup>	
1100-H14	W	123	5,640	2.0	39	0	P	INCO (3)
1100-H14	S	123	5,640	3.1	41	0	P	INCO (3)
1100-H14	W	403	6,780	4.2	0	62	C (PR)	INCO (3)
1100-H14	S	403	6,780	1.3	62	62	C (PR); P (PR)	INCO (3)
1100-H14	W	751	5,640	4.5	0	62	C (PR)	INCO (3)
1100-H14	S	751	5,640	2.0	0	62	C (PR)	INCO (3)
1100-H14	W	1,064	5,300	3.0	0	62	C (PR)	INCO (3)
1100-H14	W	1,064	5,300	1.8	S-P	S-C	S-C; S-P	CEL (4)
1100-H14	S	1,064	5,300	1.0	0	62	C (PR)	INCO (3)
1100-H14	W	197	2,340	5.6	0	62	C (PR)	INCO (3)
1100-H14	W	197	2,340	<0.1	23	0	E; P	REY (14)
1100-H14	S	197	2,340	<0.1	1	1	I-C; I-P	INCO (3)
1100-H14	W	402	2,340	1.6	0	62	C (PR)	INCO (3)
1100-H14	W	402	2,370	0.9	1	50	C (PR); I-P	CEL (4)
1100-H14	S	402	2,370	0.5	26	26	C; P	INCO (3)
1100-H14	S	402	2,370	0.5	1	50	C (PR); I-P	CEL (4)
1100-H14	W	181	5	1.4	0	S	S-C	INCO (3)
1100-H14	W	366	5	0.6	13	13	C; P	INCO (3)
1180-H14	W	402	2,370	1.0	1	50	C (PR); I-P	CEL (4)
1180	W	402	2,370	<0.1	41	0	E; S-P	REY (14)
1180-H14	S	402	2,370	0.8	1	50	C (PR); I-P	CEL (4)

<sup>a</sup>W = Totally exposed in seawater on sides of structure; S = Exposed in base of structure so that the lower portions of the specimen were embedded in the bottom sediments.<sup>b</sup>Symbols for types of corrosion:

C	= Crevice	P	= Pitting
E	= Edge	PR	= Perforated
I	= Incipient	S	= Severe

<sup>c</sup>Numbers refer to references at end of report.

Table 59. Stress Corrosion of 1000 Series Aluminum Alloys

Alloy	Stress (ksi)	Percent Yield Strength	Exposure (day)	Depth (ft)	Number of Specimens Exposed	Number Failed	Source <sup>a</sup>
1100-H14	8	50	402	2,370	3	0	CEL (4)
1100-H14	12	75	402	2,370	3	0	CEL (4)
1180	6	50	402	2,370	3	0	CEL (4)
1180	10	75	402	2,370	3	0	CEL (4)

<sup>a</sup>Numbers refer to references at end of report.

Table 60. Changes in Mechanical Properties of 1000 Series Aluminum Alloys Due to Corrosion

Alloy	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>a</sup>
			Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
1100-H14	402	2,370	19	-2	18	+3	7	+14	CEL (4)
1180	402	2,370	15	+1	14	+4	11	+1	CEL (4)

<sup>a</sup>Numbers refer to references at end of report.

Table 61. Chemical Composition of 2000 Series Aluminum Alloys, Percent by Weight

Alloy	Gage (in.)	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Other	Al <sup>d</sup>
2014-Tc	—	0.80	0.34	3.90	0.70	0.50	0.01	0.01	0.03	—	—	R
2014-T6	0.050	0.91	0.53	4.23	0.80	0.32	0.03	0.01	0.08	0.02	—	R
2014-T6	—	0.84	0.35	4.43	0.80	0.66	—	—	—	—	—	R
2024	0.064	—	—	4.3	0.6	1.5	—	—	—	—	—	R
2024-T3+T81	—	0.20	0.20	4.50	0.80	1.50	0.02	0.04	0.06	0.01	—	R
Alclad 2024-T3 <sup>b</sup>	—	—	—	—	—	—	—	—	—	—	—	—
2219-T81	0.064	0.20	0.30	6.3	0.30	<0.02	—	—	0.10	0.06	0.10 V 0.17 Zr	R
2219-T81	—	0.05	0.15	4.00	0.10	0.05	0.05	0.10	0.05	0.05	—	R
2219-T87	0.040	0.08	0.12	6.54	0.26	<0.02	<0.02	<0.02	0.03	0.02	0.10 V 0.15 Zr	R
2219-T87	0.040	—	—	6.3	0.30	—	—	—	—	0.06	—	R

<sup>a</sup>R = remainder.<sup>b</sup>No analysis given.



Table 62. Corrosion Rates and Types of Corrosion of 2000 Series Aluminum Alloys

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth <sup>b</sup> (mils)	Crevice Depth <sup>b</sup> (mils)	Type <sup>b</sup>	Weld <sup>b</sup>	
2014-T3	W	123	5,640	—	7	0	B; IG; P; XF	—	NADC (7)
2014-T3	W	751	5,640	—	PR	0	P (PR)	—	NADC (7)
2014-T6	W	403	6,780	—	S	S	S-C; S-P	—	NADC (7)
2014-T6	W	1,064	5,300	—	S	SH	SH-C; S-P	—	NADC (7)
2014-T6	S	1,064	5,300	—	PR	—	P (PR)	—	NADC (7)
2014-T6	W	197	2,340	—	10	0	IG; U-P; L	—	NADC (7)
2014-T6	W	197	2,340	<0.1	20	0	P	—	REY (14)
2014-T6	W	402	2,370	5.4	27	50	C (PR); IG; P	—	CEL (4)
2014-T6	S	402	2,370	3.5	25	50	C (PR); IG; P	—	CEL (4)
2024-0	W	123	5,640	5.2	28	0	P	—	INCO (3)
2024-0	S	123	5,640	3.4	27	0	P	—	INCO (3)
2024-0	W	403	6,780	6.2	62	0	P (PR)	—	INCO (3)
2024-0	S	403	6,780	1.2	0	55	S-C	—	INCO (3)
2024-0	W	751	5,640	2.8	65	65	C (PR); P (PR)	—	INCO (3)
2024-0	S	751	5,640	2.6	65	0	P (PR)	—	INCO (3)
2024-0	W	1,064	5,300	1.9	62	62	C (PR); P (PR)	—	INCO (3)
2024-0	S	1,064	5,300	1.6	55	0	S-P	—	INCO (3)
2024-0	W	197	2,340	3.1	19	0	S-E; P	—	INCO (3)
2024-0	S	197	2,340	<0.1	I	I	I-C; I-P	—	INCO (3)
2024-0	W	402	2,370	3.0	62	62	C (PR); P (PR)	—	INCO (3)
2024-0	S	402	2,370	0.8	0	0	E	—	INCO (3)
2024-0	W	181	5	3.8	32	32	C; P	—	INCO (3)
2024-0	W	366	5	4.1	34	34	C; P	—	INCO (3)
2024-T3	W	403	6,780	—	39	0	S-E; S-P	—	NADC (7)
2024-T3, anodized	W	751	5,640	—	0	0	G	—	NADC (7)
2024-T3	W	1,064	5,300	1.9	—	—	C; P; XF	—	CEL (4)
2024-T3 <sup>e</sup>	W	197	2,340	—	30	0	SL-B; IG; U-P	HAZ (IG)	NADC (7)
2024-T3	W	402	2,370	—	39	0	E; L; P	—	NADC (7)
Alclad 2024-T3	W	123	5,640	—	I	0	I-P	—	NADC (7)
Alclad 2024-T3	W	751	5,640	—	0	0	G	—	NADC (7)
2024-T6	W	403	6,780	—	—	—	L; D-P; XF	—	NADC (7)

Continued

Table 62. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion					Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth <sup>b</sup> (mils)	Crevice Depth <sup>b</sup> (mils)	Type <sup>b</sup>	Weld <sup>b</sup>	
2024-T81	W	123	5,640	—	40	0	B; EX-IG; CR; P	—	NADC (7)
2024-T81	W	403	6,780	—	62	0	S-P	—	NADC (7)
2024-T81, anodized	W	403	6,780	—	0	0	XF	—	NADC (7)
2024-T81, painted	W	403	6,780	—	0	0	NPF	—	NADC (7)
2024-T81	W	402	2,370	—	39	S	S-C; E; D-P; EX-XF	—	NADC (7)
2024-T81, anodized	W	402	2,370	—	0	MD	MD-C; EX-XF	—	NADC (7)
2219-T81	W	123	5,640	2.0	16	15	C; IG; G-P	—	CEL (4)
2219-T81 <sup>d</sup>	W	123	5,640	—	40	0	EX-IG; P; XF	NC	NADC (7)
2219-T81	S	123	5,640	1.9	20	10	C; IG; G-P	—	CEL (4)
2219-T81	W	403	6,780	3.6	35	38	C; E; IG; G-P	—	CEL (4)
2219-T81	S	403	6,780	3.1	62	34	C; E; IG; P (PR)	—	CEL (4)
2219-T81	W	751	5,640	2.4	30	24	C; E; IG; G-P	—	CEL (4)
2219-T81 <sup>d</sup>	W	751	5,640	—	PR	0	P (PR)	NC	NADC (7)
2219-T81	W	1,064	5,300	1.6	47	47	C; SL-E; IG; G-P	—	CEL (4)
2219-T81	S	1,064	5,300	1.5	48	0	IG; G-P	—	CEL (4)
2219-T81	W	197	2,340	2.6	25	0	SL-E; IG; G-P	—	CEL (4)
2219-T81	S	197	2,340	2.0	32	0	E; IG; G-P	—	CEL (4)
2219-T81	W	402	2,370	4.5	78	69	S-C; S-E; IG; S-P	—	CEL (4)
2219-T81	S	402	2,370	2.0	50	66	S-C; S-E; IG; S-P	—	CEL (4)
2219-T81	W	181	5	3.5	24	0	IG; G-P	—	CEL (4)
2219-T81	W	398	5	2.5	26	0	P	—	CEL (4)
2219-T81	W	540	5	1.4	48	32	C; P	—	CEL (4)
2219-T81	W	588	5	4.4	62	43	C; E; P	—	CEL (4)
2219-T87	W	197	2,340	<0.1	12	0	P	—	REY (14)
2219-T87	W	402	2,370	1.7	20	40	C (PR); IG; U-P	—	CEL (4)
2219-T87	S	402	2,370	1.1	16	40	C (PR); IG; U-P	—	CEL (4)

<sup>a</sup>W = Totally exposed in seawater on sides of structure; S= Exposed in base of structure so that the lower portions of the specimens were embedded in the bottom sediments.

<sup>b</sup>Symbols for types of corrosion:

B = Blisters	G = General	NC = No visible corrosion	SL = Slight
C = Crevice	HAZ = Heat-affected zone	NPF = No paint failure	U = Uniform
CR = Crater	I = Incipient	P = Pitting	XF = Exfoliation
D = Deep	IG = Intergranular	PR = Perforated	
E = Edge	L = Line	S = Severe	
EX = Extensive	MD = Moderate	SH = Shallow	

<sup>c</sup>Numbers refer to references at end of report.

<sup>d</sup>Welded with 2319 rod by the TIG process.

<sup>e</sup>Welded.

Table 63. Stress Corrosion of 2000 Series Aluminum Alloys

Alloy	Stress (ksi)	Percent Yield Strength	Exposure (day)	Depth (ft)	Number of Specimens Exposed	Number Failed	Source <sup>a</sup>
2014-T6	17	30	197	2,340	3	0	NADC (7)
2014-T6	41	75	197	2,340	3	0	NADC (7)
2014-T6	31	50	402	2,370	3	0	CEL (4)
2014-T6	46	75	402	2,370	3	0	CEL (4)
2024-T3	15	30	403	6,780	3	<i>b</i>	NADC (7)
2024-T3	38	75	403	6,780	3	<i>b</i>	NADC (7)
2024-T3	15	30	197	2,340	3	0	NADC (7)
2024-T3	38	75	197	2,340	3	0	NADC (7)
2024-T81	15	30	402	2,370	3	0	NADC (7)
2024-T81	38	75	402	2,370	3	0	NADC (7)
2024-T81, anodized	15	30	402	2,370	3	0	NADC (7)
2024-T81, anodized	38	75	402	2,370	3	0	NADC (7)
2219-T81	25	50	402	2,370	3	0	CEL (4)
2219-T81	38	75	402	2,370	3	0	CEL (4)
2219-T87	25	50	402	2,370	3	0	CEL (4)
2219-T87	38	75	402	2,370	3	0	CEL (4)

<sup>a</sup>Numbers refer to references at end of report.<sup>b</sup>Specimens lost at sea during exposure.

Table 64. Changes in Mechanical Properties of 2000 Series Aluminum Alloys Due to Corrosion

Alloy	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>a</sup>
			Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
2014-T3	123	5,640	65	-54	—	—	20	-90	NADC (7)
2014-T6	123	5,640	72	-16	55	+8	20	-90	NADC (7)
2014-T6	751	5,640	72	-39	55	-22	20	-94	NADC (7)
2014-T6	1,064	5,300	72	-19	55	-40	20	-95	NADC (7)
2014-T6	197	2,340	72	-20	55	-4	20	-91	NADC (7)
2014-T6	402	2,370	68	-38	62	-28	11	-92	CEL (4)
2024-T3	403	6,780	62	-35	42	-10	17	-89	NADC (7)
2024-T3	751	5,640	62	+3	42	-4	17	-24	NADC (7)
2024-T3 <sup>b</sup>	197	2,340	62	-100	42	-100	17	-100	NADC (7)
2024-T3	402	2,370	62	-26	42	-3	17	-96	NADC (7)
Alclad 2024-T3	123	5,640	62	0	42	0	17	+12	NADC (7)
2024-T81	123	5,640	72	-49	—	—	10	-95	NADC (7)
2024-T81	403	6,780	72	-10	—	—	10	-58	NADC (7)
2024-T81	402	2,370	72	-3	—	—	10	-55	NADC (7)
2219-T81 <sup>c,d</sup>	123	5,640	62	+5	50	+2	8	+38	NADC (7)
2219-T81	123	5,640	66	-3	50	-1	11	-42	CEL (4)
2219-T81	403	6,780	66	-19	50	-12	11	-52	CEL (4)
2219-T81	751	5,640	66	-18	50	-14	11	-62	CEL (4)
2219-T81	1,064	5,300	66	-22	50	-16	11	-57	CEL (4)
2219-T81	197	2,340	66	-5	50	-6	11	-30	CEL (4)
2219-T81	402	2,370	66	-15	50	-14	11	-62	CEL (4)
2219-T81	181	5	65	-17	50	-13	12	-62	CEL (4)
2219-T87	402	2,370	61	-27	51	-29	10	-77	CEL (4)

<sup>a</sup>Numbers refer to references at end of report.<sup>b</sup>Too severely corroded to machine into tensile specimens.<sup>c</sup>Welded, 2319 electrode, TIG process.<sup>d</sup>Transverse properties.

Table 65. Chemical Composition of 3000 Series Aluminum Alloys, Percent by Weight

Alloy	Gage (in.)	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Al <sup>a</sup>
3003	—	—	—	—	1.2	—	—	—	—	—	R
3003	—	0.15	0.45	0.15	1.25	—	—	—	0.05	—	R
3003-H12 & H14	—	0.10	0.20	0.05	1.10	0.03	0.01	0.01	0.02	0.01	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-H14	0.063	0.15	0.50	0.10	1.30	0.02	—	—	0.07	—	R
3003-H24	—	0.10	0.48	0.16	1.10	—	—	—	0.08	—	R
Alclad 3003-H12	0.125										
Core		0.06	0.70	0.20	1.25	—	—	—	0.10	—	R
Cladding		<sup>b</sup>	<sup>b</sup>	0.10	0.10	0.10	—	—	1.0	—	R
Alclad 3003-H14	—	0.10	0.20	0.05	1.10	0.03	0.01	0.01	0.02	0.01	R

<sup>a</sup> R = remainder.<sup>b</sup> Si + Fe = 0.70.

Table 66. Corrosion Rates and Types of Corrosion of 3000 Series Aluminum Alloys

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion				Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth <sup>b</sup> (mils)	Crevice Depth <sup>b</sup> (mils)	Type <sup>b</sup>	
3003-H14	W	123	5,640	0.5	27	32	C; P	CEL (4)
3003	W	123	5,640	0.6	0	28	C	INCO (3)
3003-H14	S	123	5,640	1.9	55	68	C; E; P	CEL (4)
3003	S	123	5,640	3.6	0	50	C (PR)	INCO (3)
3003-H14	W	403	6,780	3.9	125	66	S-C; P (PR)	CEL (4)
3003	W	403	6,780	3.8	0	50	C (PR)	INCO (3)
3003-H14	S	403	6,780	3.7	125	52	S-C; P (PR)	CEL (4)
3003	S	403	6,780	1.3	0	50	C (PR)	INCO (3)
3003-H14	W	751	5,640	2.3	125	125	C (PR); P (PR)	CEL (4)
3003	W	751	5,640	3.0	0	40	C (PR)	INCO (3)
3003-H14	S	751	5,640	2.5	125	125	C (PR); P (PR)	CEL (4)
3003	S	751	5,640	1.8	0	40	C (PR)	INCO (3)
3003-H14	W	1,064	5,300	2.0	125	125	C (PR); S-E; P (PR)	CEL (4)
3003	W	1,064	5,300	2.8	—	—	d	INCO (3)
3003-H14	S	1,064	5,300	1.9	125	0	EX-E; P (PR)	CEL (4)
3003	S	1,064	5,300	1.0	0	50	C (PR)	INCO (3)
3003-H14	W	197	2,340	<0.1	17	0	E; P	REY (14)
3003-H14	W	197	2,340	2.4	48	28	C; S-E; P	CEL (4)
3003	W	197	2,340	1.4	0	40	C (PR)	INCO (3)
3003-H14	S	197	2,340	1.6	55	25	C; E; S-P	CEL (4)
3003	S	197	2,340	<0.1	1	1	I-C; I-P	INCO (3)
3003-H14	W	402	2,370	1.4	91	93	S-C; S-E; D-P	CEL (4)
3003	W	402	2,370	1.1	0	40	C (PR)	INCO (3)
3003-H14	S	402	2,370	1.7	115	70	S-C; D-P	CEL (4)
3003	S	402	2,370	0.5	0	50	C (PR)	INCO (3)
3003-H14	W	181	5	1.1	33	0	E; P	CEL (4)
3003	W	181	5	1.0	1	0	I-P	INCO (3)
3003	W	366	5	0.6	1	0	I-P	INCO (3)
3003-H14	W	398	5	1.0	21	0	P	CEL (4)
3003-H14	W	540	5	0.3	34	75	C; P	CEL (4)
3003-H14	W	588	5	2.0	65	0	P	CEL (4)
Alclad 3003-H14	W	123	5,640	—	1	0	I-P	NADC (7)
Alclad 3003-H12	W	123	5,640	0.2	18	15	B; C; SL-E; P <sup>e</sup>	CEL (4)
Alclad 3003	W	123	5,640	2.7	0	0	G	INCO (3)
Alclad 3003-H12	S	123	5,640	2.8	20	0	B; C; SL-E <sup>e</sup>	CEL (4)
Alclad 3003	S	123	5,640	2.6	0	0	G	INCO (3)
Alclad 3003-H12	W	403	6,780	0.4	13	14	C; SL-E; P	CEL (4)
Alclad 3003	W	403	6,780	2.5	0	0	G	INCO (3)
Alclad 3003-H12	S	403	6,780	0.2	14	13	C; SL-E; P	CEL (4)
Alclad 3003	S	403	6,780	0.4	0	0	f	INCO (3)
Alclad 3003-H14	W	751	5,640	—	0	0	SL-G	NADC (7)
Alclad 3003-H12	W	751	5,640	0.3	13	13	C; E; P	CEL (4)
Alclad 3003	W	751	5,640	1.4	0	0	G	INCO (3)
Alclad 3003-H12	S	751	5,640	2.4	14	14	C; E; P <sup>e</sup>	CEL (4)
Alclad 3003	S	751	5,640	1.5	0	0	U	INCO (3)
Alclad 3003-H12	W	1,064	5,300	0.5	20	13	C; P <sup>g</sup>	CEL (4)
Alclad 3003	W	1,064	5,300	1.5	0	0	U	INCO (3)

Continued

Table 66. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion				Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth <sup>b</sup> (mils)	Crevice Depth <sup>b</sup> (mils)	Type <sup>b</sup>	
Alclad 3003-H12	S	1,064	5,300	0.8	16	13	C; P <sup>b</sup>	CEL (4)
Alclad 3003	S	1,064	5,300	0.6	0	0	U	INCO (3)
Alclad 3003-H12	W	197	2,340	2.2	15	13	C; P <sup>e</sup>	CEL (4)
Alclad 3003	W	197	2,340	2.3	0	0	G	INCO (3)
Alclad 3003-H12	S	197	2,340	1.1	14	13	C; P <sup>i</sup>	CEL (4)
Alclad 3003	S	197	2,340	<0.1	2	2	C; P;	INCO (3)
Alclad 3003-H12	W	402	2,370	2.2	14	15	C; P <sup>j</sup>	CEL (4)
Alclad 3003	W	402	2,370	1.6	0	0	k	INCO (3)
Alclad 3003-H12	S	402	2,370	1.8	13	14	C; P <sup>l</sup>	CEL (4)
Alclad 3003	S	402	2,370	0.4	0	0	m	INCO (3)
Alclad 3003-H12	W	181	5	1.0	1	0	I-P	CEL (4)
Alclad 3003	W	181	5	1.0	2	0	N-P	INCO (3)
Alclad 3003	W	366	5	0.5	2	0	N-P	INCO (3)
Alclad 3003-H12	W	398	5	1.1	16	0	P	CEL (4)
Alclad 3003-H12	W	540	5	0.3	16	0	P	CEL (4)
Alclad 3003-H12	W	588	5	1.8	17	0	P	CEL (4)

<sup>a</sup>W = Totally exposed in seawater on sides of structure; S = Exposed in base of structure so that the lower portions of the specimens were embedded in the bottom sediments.

<sup>b</sup>Symbols for types of corrosion:

B	= Blisters	N	= Numerous
C	= Crevice	P	= Pitting
D	= Deep	PR	= Perforated
E	= Edge	S	= Severe
EX	= Extensive	SL	= Slight
G	= General	U	= Uniform
I	= Incipient		

<sup>c</sup>Numbers refer to references at end of report.

<sup>d</sup>About 40% of specimen missing.

<sup>e</sup>Large area of cladding gone.

<sup>f</sup>Nonuniform cladding loss.

<sup>g</sup>Nonuniform cladding loss, 18% gone, one area 7 sq. in.

<sup>h</sup>Nonuniform cladding loss, 13% gone, one area 5 sq. in.

<sup>i</sup>One 7-sq.-in. area of cladding gone from portion in water; cladding gone on 2-in.-high strip across bottom portion in bottom sediment.

<sup>j</sup>20% cladding gone and incipient pitting in denuded area.

<sup>k</sup>60% of cladding gone.

<sup>l</sup>18% of cladding gone, incipient pitting in denuded area; cladding gone on 2-in.-high strip across bottom portion embedded in bottom sediment.

<sup>m</sup>20% of cladding gone.



Table 67. Stress Corrosion of 3000 Series Aluminum Alloys

Alloy	Stress (ksi)	Percent Yield Strength	Exposure (day)	Depth (ft)	Number of Specimens Exposed	Number Failed	Source <sup>a</sup>
3003-H14	6	50	402	2,370	3	0	CEL (4)
3003-H14	9	75	402	2,370	3	0	CEL (4)

<sup>a</sup>Numbers refer to references at end of report.

Table 68. Changes in Mechanical Properties of 3000 Series Aluminum Alloys Due to Corrosion

Alloy	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>a</sup>
			Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
3003-H14	123	5,640	22	-4	20	-8	13	-43	CEL (4)
3003-H14	403	6,780	22	-48	20	-50	13	-77	CEL (4)
3003-H14	751	5,640	21	-20	21	-11	4	+25	NADC (7)
3003-H14	751	5,640	22	-24	20	-26	13	-72	CEL (4)
3003-H14	1,064	5,300	22	-3	20	-18	13	-20	CEL (4)
3003-H14	197	2,340	22	-6	20	-10	13	+15	CEL (4)
3003-H14	402	2,370	22	+6	20	+11	13	+5	CEL (4)
3003-H14	181	5	23	+4	21	-1	18	-1	CEL (4)
Alclad 3003-H12	123	5,640	19	-2	18	-1	14	-42	CEL (4)
Alclad 3003-H12	403	6,780	19	+3	18	-1	14	0	CEL (4)
Alclad 3003-H12	751	5,640	19	-3	18	-4	14	-19	CEL (4)
Alclad 3003-H12	1,064	5,300	19	+3	18	+1	14	-12	CEL (4)
Alclad 3003-H12	197	2,340	19	+1	18	+2	14	+7	CEL (4)
Alclad 3003-H12	402	2,370	19	+1	18	0	14	-14	CEL (4)
Alclad 3003-H12	181	5	19	+4	18	+1	14	+2	CEL (4)
Alclad 3003-H14	123	5,640	21	0	-	-	4	+100	NADC (7)

<sup>a</sup>Numbers refer to references at end of report.

Table 69. Chemical Composition of 5000 Series Aluminum Alloys, Percent by Weight

Alloy	Gage (in.)	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Al <sup>a</sup>
5050-H34	0.050	0.18	0.64	0.04	—	1.19	—	—	—	—	R
5052	—	—	—	—	—	2.5	0.25	—	—	—	R
5052-0, H32, H34	—	0.10	0.17	0.02	0.03	2.20	0.22	—	—	0.01	R
5052-H22	—	<i>b</i>	<i>b</i>	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
5083	—	—	—	0.15	0.6	4.5	—	—	—	—	R
5083-H113	0.500	0.40	0.40	0.10	0.65	4.5	0.15	—	0.25	0.15	R
5454	—	—	—	—	0.03	1.0	0.02	—	—	—	R
5454-H32	0.162	<i>c</i>	<i>c</i>	0.10	0.75	2.7	0.13	—	0.25	0.20	R
BA28-1/4 H (5456)	0.050	0.18	0.32	0.036	0.26	5.08	<0.02	<0.02	0.05	—	R
5456-H321 + H343	0.125	<i>c</i>	<i>c</i>	0.10	0.75	5.0	0.13	—	0.25	0.20	R
5456-H321	—	—	—	0.15	0.7	5.0	0.15	—	—	—	R
5456-H327 + H343	—	0.10	0.16	0.10	0.80	5.0	0.07	—	0.01	0.05	R
5456-H34	—	0.10	0.30	0.08	0.77	5.0	0.07	—	—	—	R
5086	—	—	—	—	0.3	4.0	0.15	—	—	—	R
5086-H112	3 in. x 3 in. x 1/2 in. L	—	—	—	0.45	4.0	0.15	—	—	—	R
5086-H32	0.500	0.15	0.25	0.05	0.32	3.75	0.12	—	0.12	0.01	R
5086-H34	0.125	0.40	0.50	0.10	0.45	4.0	0.15	—	0.25	0.15	R
5086-H34	—	0.70	0.10	0.12	0.90	4.00	0.05	0.10	0.04	0.01	R

<sup>a</sup>R = remainder.<sup>b</sup>Si + Fe = 0.23<sup>c</sup>Si + Fe = 0.40

Table 70. Corrosion Rates and Types of Corrosion of 5000 Series Aluminum Alloys

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion				Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth <sup>b</sup> (mils)	Crevice Depth <sup>b</sup> (mils)	Type <sup>b</sup>	
5050-H34	W	402	2,370	<0.1	4	0	P	REY (14)
5050-H34	W	402	2,370	0.1	I	31	C; I-P	CEL (4)
5050-H34	S	402	2,370	0.2	I	31	C; I-P	CEL (4)
5052-0	W	123	5,640	3.7	0	65	C (PR)	INCO (3)
5052-0	S	123	5,640	4.0	0	65	C (PR)	INCO (3)
5052-0	W	403	6,780	4.5	0	62	C (PR)	INCO (3)
5052-0	S	403	6,780	1.2	0	62	C (PR)	INCO (3)
5052-0	W	751	5,640	2.2	65	65	C (PR); P (PR)	INCO (3)
5052-0	S	751	5,640	3.2	0	62	C (PR)	INCO (3)
5052-0	W	1,064	5,300	3.1	0	65	C (PR)	INCO (3)
5052-0	S	1,064	5,300	1.5	0	62	C (PR)	INCO (3)
5052-0	W	197	2,340	1.8	0	65	C (PR)	INCO (3)
5052-0	S	197	2,340	<0.1	I	I	I-C; I-P	INCO (3)
5052-0	W	402	2,370	0.4	0	20	C	INCO (3)
5052-0	S	402	2,370	0.3	0	0	S-B at C	INCO (3)
5052-0	W	181	5	1.2	I	0	I-P	INCO (3)
5052-0	W	366	5	0.6	5	5	C; P	INCO (3)
5052-H22	W	1,064	5,300	0.4	—	—	—	CEL (4)
5052-H32	W	403	6,780	—	39	0	E-XF; P	NADC (7)
5052-H32	W	197	2,340	—	U	0	U-P	NADC (7)
5052-H32	S	197	2,340	<0.1	26	0	L-P	NADC (7)
5052-H32	W	402	2,370	—	F	0	E-XF; L; F-D-P	NADC (7)
5052-H34	W	123	5,640	<0.1	S	0	S-P	NADC (7)
5052-H34	W	123	5,640	—	PP	MO	MO-C; PP	Bell (13)
5052-H34	W	751	5,640	—	0	0	SH-CR	NADC (7)
5052-H34	W	751	5,640	—	SH	MO	MO-C; SH-P	Bell (13)
5052-H34	S	751	5,640	—	SH	S	S-C; SH-P	Bell (13)
5052-H34	W	197	2,340	<0.1	12	0	P	REY (14)
5052-H34	W	402	2,370	0.2	I	34	C; I-P	CEL (4)
5052-H34	S	402	2,370	0.2	I	50	C (PR); I-P	CEL (4)
5083-H113 <sup>d</sup>	W	123	5,640	<0.1	28	0	P <sup>e</sup>	CEL (4)
5083-H113 <sup>d</sup>	S	123	5,640	0.9	65	0	F-P	CEL (4)

Continued

Table 70. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion				Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth <sup>b</sup> (mils)	Crevice Depth <sup>b</sup> (mils)	Type <sup>b</sup>	
5083-H113	W	189	5,900	0.1	1	30	C; I-P	CEL (4)
5083-H113 <sup>e</sup>	W	189	5,900	0.1	4	3	SL-P	CEL (4)
5083-H113	S	189	5,900	0.3	20	11	C; P	CEL (4)
5083-H113 <sup>f</sup>	S	189	5,900	0.2	4	1	I-C; SC-P <sup>g</sup>	CEL (4)
5083-H113	W	403	6,780	4.0	59	0	S-E; P	CEL (4)
5083-H113 <sup>d</sup>	W	403	6,780	2.1	92	0	SL-E; P	CEL (4)
5083-H113	S	403	6,780	0.7	68	0	E; P	CEL (4)
5083-H113 <sup>d</sup>	S	403	6,780	1.1	66	0	SL-E; P	CEL (4)
5083-H113 <sup>d</sup>	W	751	5,640	1.6	83	0	E; P	CEL (4)
5083-H113	W	197	2,340	0.5	23	0	E; P <sup>b</sup>	CEL (4)
5083-H113 <sup>d</sup>	W	197	2,340	0.3	57	0	P	CEL (4)
5083-H113	S	197	2,340	0.6	14	0	E; P <sup>e</sup>	CEL (4)
5083-H113 <sup>d</sup>	S	197	2,340	0.7	55	0	P	CEL (4)
5083-H113	W	402	2,370	0.6	1	52	S-C; I-P	CEL (4)
5083	W	402	2,370	1.0	0	31	C	INCO (3)
5083-H113 <sup>d</sup>	W	402	2,370	0.8	58	0	E; P	CEL (4)
5083-H113	S	402	2,370	0.6	1	57	S-C; I-P	CEL (4)
5083	S	402	2,370	0.4	17	0	P	INCO (3)
5083-H113 <sup>d</sup>	S	402	2,370	0.8	48	0	E; S-P; WB (P) <sup>i</sup>	CEL (4)
5083-H113	W	181	5	1.2	1	3	C; IG (E); I-P	CEL (4)
5083	W	181	5	1.0	0	0	ET	INCO (3)
5083-H113 <sup>f</sup>	W	181	5	0.9	0	0	ET	CEL (4)
5083	W	366	5	0.6	0	0	ET	INCO (3)
5083-H113	W	398	5	0.4	0	0	ET	CEL (4)
5083-H113 <sup>f</sup>	W	398	5	0.5	34	1	I-C; P	CEL (4)
5083-H113	W	540	5	0.7	36	114	S-C; P	CEL (4)
5083-H113 <sup>f</sup>	W	540	5	0.3	4	0	P	CEL (4)
5083-H113	W	588	5	0.3	11	1	I-C; P	CEL (4)
5083-H113 <sup>f</sup>	W	588	5	0.3	9	0	P	CEL (4)
5086	W	402	2,370	0.8	0	35	C (PR)	INCO (3)
5086	S	402	2,370	0.7	0	35	C (PR)	INCO (3)
5086	W	181	5	1.2	1	0	I-P	INCO (3)
5086	W	366	5	0.5	5	5	C; P	INCO (3)

Continued

Table 70. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion				Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth <sup>b</sup> (mils)	Crevice Depth <sup>b</sup> (mils)	Type <sup>b</sup>	
5086-H32	W	189	5,900	0.1	33	15	C; SC-P	CEL (4)
5086-H32	S	189	5,900	0.2	23	4	C; SC-P	CEL (4)
5086-H32 <sup>j</sup>	W	360	4,200	0.1	47	0	E; P	CEL (4)
5086-H32 <sup>j</sup>	S	360	4,200	<0.1	29	0	B; P	CEL (4)
5086-H32	W	197	2,340	<0.1	5	0	P	REY (14)
5086-H32	W	402	2,370	0.4	1	18	C; I-P	CEL (4)
5086-H32	S	402	2,370	0.5	1	18	C; I-P	CEL (4)
5086-H32	W	181	5	1.0	1	0	IG (E); I-P	CEL (4)
5086-H32	W	398	5	0.4	20	0	P	CEL (4)
5086-H32	W	588	5	0.2	22	1	I-C; P	CEL (4)
5086-H34	W	123	5,640	0.1	0	0	ET	CEL (4)
5086-H34 <sup>k</sup>	W	123	5,640	—	—	—	NC-SD	NADC (7)
5086-H34	S	123	5,640	1.4	13	50	S-C; E; P	CEL (4)
5086-H34	W	189	5,900	0.2	3	0	SL-P	CEL (4)
5086-H34	S	189	5,900	0.7	55	126	C (PR); E; S-P	CEL (4)
5086-H34	W	403	6,780	0.6	1	53	S-C; I-P	CEL (4)
5086-H34	S	403	6,780	0.8	4	48	S-C; P	CEL (4)
5086-H34	W	751	5,640	2.0	72	60	S-C; E; S-P	CEL (4)
5086-H34 <sup>k</sup>	W	751	5,640	—	PR	0	P (PR); L (HAZ&WB)	NADC (7)
5086-H34	W	1,064	5,300	0.9	73	69	S-C; S-E; S-P	CEL (4)
5086-H34	S	1,064	5,300	1.2	75	50	S-C; S-E; S-P <sup>l</sup>	CEL (4)
5086-H34 <sup>k</sup>	W	360	4,200	<0.1	47	0	E; P	CEL (4)
5086-H34 <sup>k</sup>	S	360	4,200	<0.1	51	0	E; P <sup>m</sup>	CEL (4)
5086-H34	W	197	2,340	0.7	29	1	I-C; SL-E; F-P	CEL (4)
5086-H34	S	197	2,340	1.1	53	38	S-C; S-E; S-P	CEL (4)
5086-H34	W	402	2,370	0.6	1	5	C; I-P	CEL (4)
5086-H34	S	402	2,370	1.3	17	48	S-C; P	CEL (4)
5086-H34	W	181	5	1.2	6	0	IG; P	CEL (4)
5086-H34	W	398	5	0.8	27	1	I-C; P	CEL (4)
5086-H34	W	540	5	0.3	0	1	I-C; ET	CEL (4)
5086-H34	W	588	5	1.6	47	43	S-C; S-P	CEL (4)
5086-H112 <sup>n</sup>	S	189	5,900	0.1	21	32	C; SC-P	CEL (4)
5086-H112 <sup>n,j</sup>	W	360	4,200	0.1	20	117	S-C; P	CEL (4)

Continued

Table 70. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion				Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth <sup>b</sup> (mils)	Crevice Depth <sup>b</sup> (mils)	Type <sup>b</sup>	
5086-H112 <sup>n,j</sup>	S	360	4,200	<0.1	20	64	S-C; P	CEL (4)
5086-H112 <sup>n</sup>	W	181	5	1.1	1	0	I-P	CEL (4)
5454	W	402	2,370	0.4	0	28	C	INCO (3)
5454	S	402	2,370	0.6	0	80	C (PR)	INCO (3)
5454	W	181	5	1.0	1	0	I-P	INCO (3)
5454	W	366	5	0.5	0	0	ET	INCO (3)
5454-H32 <sup>d</sup>	W	123	5,640	0.1	7	0	p <sup>p</sup>	CEL (4)
5454-H32 <sup>d</sup>	S	123	5,640	1.1	49	0	E; S-P; SL (WB)	CEL (4)
5454-H32	W	403	6,780	0.9	38	0	MO-E; MO-P	CEL (4)
5454-H32 <sup>d</sup>	W	403	6,780	1.7	64	0	E; P; L (HAZ)	CEL (4)
5454-H32	S	403	6,780	0.5	37	0	MO-E; MO-P	CEL (4)
5454-H32 <sup>d</sup>	S	403	6,780	0.6	42	0	E; P; L (HAZ)	CEL (4)
5454-H32 <sup>d</sup>	W	751	5,640	0.9	65	0	E; D-P; SL (WB)	CEL (4)
5454-H32	W	197	2,340	0.7	24	0	SL-E; P	CEL (4)
5454-H32 <sup>d</sup>	W	197	2,340	0.3	41	0	MO-P; P (HAZ)	CEL (4)
5454-H32	S	197	2,340	0.6	16	0	SL-E; P	CEL (4)
5454-H32 <sup>d</sup>	S	197	2,340	0.6	49	S	S-C; MO-P; P (HAZ)	CEL (4)
5454-H32	W	402	2,370	0.3	1	39	C; I-P	CEL (4)
5454-H32 <sup>d</sup>	W	402	2,370	0.6	42	0	P; P (WB) <sup>q</sup>	CEL (4)
5454-H32	S	402	2,370	0.3	1	33	C; I-P	CEL (4)
5454-H32 <sup>d</sup>	S	402	2,370	0.7	22	0	P <sup>r</sup>	CEL (4)
5454-H32 <sup>d</sup>	W	398	5	0.5	8	0	P	CEL (4)
5454-H32 <sup>d</sup>	W	540	5	0.3	1	0	I-P	CEL (4)
5454-H32 <sup>d</sup>	W	588	5	0.7	39	0	P; P (WB&HAZ)	CEL (4)
BA28-1/4 H (5456)	W	197	2,340	<0.1	2	0	P	REY (14)
5456-H32	W	402	2,370	0.6	0	5	C; E	CEL (4)
5456-H32	S	402	2,370	0.7	0	21	C; E	CEL (4)
5456-H321	W	123	5,640	<0.1	0	SL	SL-C; SL-ET	CEL (4)
5456-H321	W	123	5,640	1.3	5	5	C; P	MEL (5)
5456-H321	S	123	5,640	2.1	49	33	C; E; S-P	CEL (4)
5456-H321	W	403	6,780	1.0	1	50	S-C; E; I-P	CEL (4)
5456-H321	S	403	6,780	0.8	44	32	C; E; F-P	CEL (4)

Continued

Table 70. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion				Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth <sup>b</sup> (mils)	Crevice Depth <sup>b</sup> (mils)	Type <sup>b</sup>	
5456-H321	W	751	5,640	2.0	53	25	C; E; F-D-P	CEL (4)
5456-H321	W	751	5,640	2.2	17	23	C; EX-E; P	CEL (4)
5456-H321	S	751	5,640	2.2	50	45	S-C; E; F-D-P	CEL (4)
5456-H321	W	1,064	5,300	1.0	43	37	C; EX-E; F-D-P	CEL (4)
5456-H321	S	1,064	5,300	1.5	36	46	S-C; EX-E; F-P	CEL (4)
5456-H321	W	197	2,340	2.7	17	36	C; E; F-P	CEL (4)
5456-H321	S	197	2,340	2.6	43	18	C; E; F-D-P	CEL (4)
5456-H321	W	402	2,370	1.1	41	44	S-C; E; D-P	CEL (4)
5456-H321	S	402	2,370	1.2	14	32	C; E; P	CEL (4)
5456-H321	W	181	5	1.2	12	0	P	CEL (4)
5456-H321	W	398	5	0.6	16	0	P	CEL (4)
5456-H321	W	540	5	0.9	14	8	C; P	CEL (4)
5456-H34	W	123	5,640	—	31	0	CR (PR); S-E; P	NADC (7)
5456-H34	W	403	6,780	—	PR	0	P (PR); CR	NADC (7)
5456-H34	S	403	6,780	—	—	—	XF	NADC (7)
5456-H34	W	751	5,640	—	PR	—	CR; P (PR); XF; WB (C; S-CR; XF)	NADC (7)
5456-H34	W	1,064	5,300	—	32	PR	C (PR); P; S-XF	NADC (7)
5456-H34	W	1,064	5,300	—	63	I	I-C; E; D-P	CEL (4)
5456-H34	S	197	2,340	<0.1	12	S	S-C; CR (PR); E; P	NADC (7)
5456-H343	W	123	5,640	1.0	25	I	I-C; P	CEL (4)
5456-H343	W	123	5,640	—	S	0	S-E; CR (30); S-P	CEL (4)
5456-H343	W	403	6,780	0.2	I	28	C; I-P	CEL (4)
5456-H343	S	403	6,780	0.2	I	28	C; I-P	CEL (4)
5456-H343	W	751	5,640	1.1	0	64	C (PR); SL-E	CEL (4)
5456-H343	W	1,064	5,300	0.1	35	35	C; E; F-P	CEL (4)
5456-H343	W	197	2,340	0.4	0	I	I-C; E	CEL (4)
5456-H343	S	197	2,340	0.3	0	I	I-C; E	CEL (4)

<sup>a</sup>W = Totally exposed in seawater on sides of structure; S = Exposed in base of structure so that the lower portions of the specimens were embedded in the bottom sediments.

<sup>b</sup>Symbols for types of corrosion:

B = Blisters  
C = Crevice  
CR = Crater

I = Incipient  
IG = Intergranular  
L = Line

SC = Scattered  
SD = Scattered discoloration  
SH = Shallow

Continued



Table 70. Continued.

D = Deep	MO = Moderate	SL = Slight
E = Edge	NC = No visible corrosion	U = Uniform
ET = Etched	P = Pitting	WB = Weld bead
EX = Extensive	PP = Pin-point pitting	XF = Exfoliated
F = Few	PR = Perforated	
HAZ = Heat-affected zone	S = Severe	

Numbers in parentheses indicate maximum depth in mils.

<sup>c</sup>Numbers refer to references at end of report.

<sup>d</sup>Welded with 5052 rod.

<sup>e</sup>Two measurable pits.

<sup>f</sup>Transverse butt weld, 5183 wire, MIG process.

<sup>g</sup>Scattered pitting, heavier in sediment than in water; shallow interconnected pitting in heat-affected zone parallel to weld bead.

<sup>h</sup>One measurable pit.

<sup>i</sup>Line of pits at edge of weld bead; 8 sq. in. area in bottom sediment reduced in thickness from 250 to 71 mils.

<sup>j</sup>Tongue-of-the Ocean, Atlantic Ocean, 4.5°C, 5.18 ml/l oxygen.

<sup>k</sup>Welded, 5566 rod, TIG process.

<sup>l</sup>6-sq.-in. area in sediment reduced in thickness by 60 mils.

<sup>m</sup>0.5-in.-wide undercut pits.

<sup>n</sup>3 x 3 x 1/2-in. angle

<sup>p</sup>Six measurable pits.

<sup>q</sup>Cracked in weld bead.

<sup>r</sup>4-sq.-in. area in sediment reduced in thickness by 94 mils.

Table 71. Stress Corrosion of 5000 Series Aluminum Alloys

Alloy	Stress (ksi)	Percent Yield Strength	Exposure (day)	Depth (ft)	Number of Specimens Exposed	Number Failed	Source <sup>a</sup>
5050-H34	11	50	402	2,370	3	0	CEL (4)
5050-H34	17	75	402	2,370	3	0	CEL (4)
5052-H32	8	30	403	6,780	3	0	NADC (7)
5052-H32	21	75	403	6,780	3	0	NADC (7)
5052-H32	8	30	197	2,340	3	0	NADC (7)
5052-H32	21	75	197	2,340	3	0	NADC (7)
5052-H32	8	30	402	2,370	3	0	NADC (7)
5052-H32	21	75	402	2,370	3	0	NADC (7)
5052-H34	15	50	402	2,370	3	0	CEL (4)
5052-H34	22	75	402	2,370	3	0	CEL (4)
5083-H113 <sup>b</sup>	15	75	403	6,780	3	0	CEL (4)
5083-H113 <sup>b</sup>	15	75	197	6,780	3	0	CEL (4)
5083-H113 <sup>b</sup>	15	75	402	6,780	3	0	CEL (4)
5086-H32	15	50	402	2,370	3	0	CEL (4)
5086-H32	23	75	402	2,370	3	0	CEL (4)
5454-H32 <sup>b</sup>	12	75	403	6,780	2	0	CEL (4)
5454-H32 <sup>b</sup>	12	75	197	2,340	3	0	CEL (4)
5454-H32 <sup>b</sup>	12	75	402	2,370	3	0	CEL (4)
5456-H32	20	50	402	2,370	3	0	CEL (4)
5456-H32	30	75	402	2,370	3	0	CEL (4)

<sup>a</sup>Numbers refer to references at end of report.<sup>b</sup>Transverse butt weld with 5052 rod.

Table 72. Changes in Mechanical Properties of 5000 Series Aluminum Alloys Due to Corrosion

Alloy	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>a</sup>
			Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
5050-H34	402	2,370	28	+2	22	+11	8	+25	CEL (4)
5052-H32	403	6,780	34	0	27	-4	11	-54	NADC (7)
5052-H32	197	2,340	34	-3	27	0	11	-3	NADC (7)
5052-H32	402	2,370	34	0	27	-4	11	-18	NADC (7)
5052-H34 <sup>b</sup>	123	5,640	35	0	26	+3	11	+9	NADC (7)
5052-H34	751	5,640	34	-64	27	-58	11	+95	NADC (7)
5052-H34	402	2,370	37	+4	30	+7	9	+34	CEL (4)
5083-H113 <sup>c</sup>	123	5,640	42	+4	20	-1	13	+26	CEL (4)
5083-H113	403	6,780	50	-15	38	-6	14	-30	CEL (4)
5083-H113 <sup>c</sup>	403	6,780	42	+4	20	-5	13	+23	CEL (4)
5083-H113 <sup>c</sup>	751	5,640	42	+5	20	-8	13	+32	CEL (4)
5083-H113	197	2,340	50	-1	38	-1	14	+3	CEL (4)
5083-H113 <sup>c</sup>	197	2,340	42	+6	20	0	13	+21	CEL (4)
5083-H113	402	2,370	50	-1	38	0	14	+37	CEL (4)
5083-H113 <sup>c</sup>	402	2,370	42	+2	20	-1	13	+17	CEL (4)
5083-H113	181	5	48	-2	35	-11	19	+16	CEL (4)
5083-H113 <sup>c</sup>	181	5	41	+9	22	+11	13	+8	CEL (4)
5086-H32	402	2,370	44	-5	30	-6	14	+33	CEL (4)
5086-H32	181	5	46	-4	32	0	17	+41	CEL (4)
5086-H34 <sup>d,e</sup>	123	5,640	49	-3	35	+8	13	-23	NADC (7)
5086-H34	123	5,640	48	-1	37	+2	12	-1	CEL (4)
5086-H34	403	6,780	48	0	37	-1	12	-5	CEL (4)
5086-H34	751	5,640	48	-7	37	-5	12	-9	CEL (4)
5086-H34	1,064	5,300	48	-2	37	-4	12	-3	CEL (4)
5086-H34	197	2,340	48	-5	37	-6	12	+4	CEL (4)
5086-H34	402	2,370	48	-3	37	-2	12	-3	CEL (4)
5086-H34	181	5	48	0	37	+2	12	-9	CEL (4)
5086-H112 <sup>f</sup>	181	5	47	0	29	-3	16	-2	CEL (4)
5454-H32 <sup>c</sup>	123	5,640	35	-1	16	+10	14	-11	CEL (4)
5454-H32	403	6,780	41	-2	31	-1	13	-22	CEL (4)
5454-H32 <sup>c</sup>	403	6,780	35	-2	16	+23	14	-7	CEL (4)
5454-H32 <sup>c</sup>	751	5,640	35	-16	16	+19	14	-36	CEL (4)
5454-H32	197	2,340	41	0	31	-1	13	-3	CEL (4)
5454-H32 <sup>c</sup>	197	2,340	35	-3	16	-7	14	-3	CEL (4)
5454-H32	402	2,370	41	+4	31	+2	13	+27	CEL (4)
5454-H32	402	2,370	35	-4	16	+6	14	-6	CEL (4)
5456	402	2,370	50	-7	36	+1	15	-7	CEL (4)
5456-H321	123	5,640	56	-10	39	-5	14	-24	CEL (4)
5456-H321	403	6,780	56	-1	39	-6	14	+22	CEL (4)
5456-H321	751	5,640	56	-21	39	-33	14	-30	CEL (4)
5456-H321	1,064	5,300	56	-4	39	-8	14	-6	CEL (4)
5456-H321	197	2,340	56	-4	39	-10	14	0	CEL (4)
5456-H321	402	2,370	56	-1	39	-5	14	+9	CEL (4)
5456-H321	181	5	56	-1	39	-6	14	+9	CEL (4)

Continued

Table 72. Continued.

Alloy	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>a</sup>
			Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
5456-H34	123	5,640	61	-6	43	+5	13	-34	NADC (7)
5456-H34	403	6,780	58	-14	50	-21	3	-80	NADC (7)
5456-H34	751	5,640	58	-14	50	-44	3	-71	NADC (7)
5456-H34	1,064	5,300	58	-14	50	-14	3	+94	NADC (7)
5456-H34	197	2,340	58	-14	50	-8	3	+170	NADC (7)
5454-H34 <sup>g</sup>	403	6,780	58	-11	50	-14	3	+196	NADC (7)
5456-H343	123	5,640	34	+10	—	—	6	+33	NADC (7)
5456-H343	123	5,640	58	0	46	+2	9	+27	CEL (4)
5456-H343	403	6,780	58	-2	46	-6	9	+54	CEL (4)
5456-H343	751	5,640	58	-2	40	-1	9	+27	CEL (4)
5456-H343	1,064	5,300	58	-1	40	-3	9	+30	CEL (4)
5456-H343	197	2,340	58	-3	40	-1	9	+22	CEL (4)

<sup>a</sup>Numbers refer to references at end of report.<sup>b</sup>Transverse properties.<sup>c</sup>Transverse butt weld with 5052 rod.<sup>d</sup>Transverse butt weld, 5566 electrode, TIG process.<sup>e</sup>Mechanical properties transverse to direction of weld.<sup>f</sup>3 in. x 3 in. x 1/2 in. angle.<sup>g</sup>Anodized.

Table 73. Chemical Composition of 6000 Series Aluminum Alloys, Percent by Weight

Alloy	Gage (in.)	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Al <sup>a</sup>
6061	—	—	—	0.25	—	1.0	0.28	—	—	—	R
6061-T6	0.125	0.60	0.70	0.27	0.15	1.0	0.25	—	0.25	0.15	R
6061-T6	—	0.6	—	0.25	—	1.0	0.25	—	—	—	R
6061-T6	—	0.50	0.30	0.20	0.05	0.95	0.15	—	0.06	0.04	R

<sup>a</sup>R = remainder.

Table 74. Corrosion Rates and Types of Corrosion of 6000 Series Aluminum Alloys

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion				Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth <sup>b</sup> (mils)	Crevice Depth <sup>b</sup> (mils)	Type <sup>b</sup>	
6061	W	402	2,370	1.2	0	32	C (PR)	INCO (3)
6061	S	402	2,370	0.7	0	32	C (PR)	INCO (3)
6061	W	181	5	1.2	5	0	P	INCO (3)
6061	W	366	5	0.9	11	11	C; P	INCO (3)
6061-T6	W	123	5,640	<0.1	5	10	C; P <sup>d</sup>	CEL (4)
6061-T6 <sup>e</sup>	W	123	5,640	—	13	0	EX-IG; SC-P	NADC (7)
6061-T6 <sup>e,f</sup>	W	123	5,640	—	SH	0	SH-P; WB&HAZ (B; EX-IG; P (30))	NADC (7)
6061-T6	W	123	5,640	5.2	27	21	C; P	MEL (5)
6061-T6 <sup>g</sup>	W	123	5,640	—	—	—	F-PP	BELL (13)
6061-T6 <sup>h</sup>	W	123	5,640	0	0	0	NC	BELL (13)
6061-T6	S	123	5,640	1.3	32	32	C; P	CEL (4)
6061-T6	W	189	5,900	0.1	3	0	SC-P	CEL (4)
6061-T6	S	189	5,900	0.1	33	18	C; SC-P <sup>i</sup>	CEL (4)
6061-T6	W	403	6,780	1.0	58	55	S-C; S-P	CEL (4)
6061-T6	W	403	6,780	—	—	—	MO-CR	NADC (7)
6061-T6	S	403	6,780	0.7	60	51	S-C; S-P	CEL (4)
6061-T6	W	751	5,640	1.1	65	65	S-C; E; S-P	CEL (4)
6061-T6 <sup>e</sup>	W	751	5,640	—	—	—	CR (PR)	NADC (7)
6061-T6	W	751	5,640	2.6	63	63	C (PR); S-E; P (PR)	MEL (5)
6061-T6 <sup>g</sup>	W	751	5,640	—	PR	0	P (PR); HAZ (PR)	BELL (13)
6061-T6 <sup>h</sup>	W	751	5,640	—	PR	0	P (PR)	BELL (13)
6061-T6	S	751	5,640	1.6	72	75	S-C; E; S-P	CEL (4)
6061-T6	W	1,064	5,300	0.8	77	66	S-C; E; S-P	CEL (4)
6061-T6	S	1,064	5,300	1.0	77	0	E; S-P	CEL (4)
6061-T6	W	197	2,340	1.2	47	42	C; P	CEL (4)
6061-T6 <sup>e</sup>	W	197	2,340	—	36	0	IG; P	NADC (7)
6061-T6	S	197	2,340	1.3	46	1	I-C; P	CEL (4)

Continued

Table 74. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion				Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth <sup>b</sup> (mils)	Crevice Depth <sup>b</sup> (mils)	Type <sup>b</sup>	
6061-T6	W	402	2,370	2.0	75	66	S-C; S-P	CEL (4)
6061-T6	W	402	2,370	—	S	0	S-P	NADC (7)
6061-T6	S	402	2,370	1.2	76	60	S-C; S-P	CEL (4)
6061-T6	W	181	5	1.0	1	8	C; I-P	CEL (4)
6061-T6	W	398	5	0.7	16	0	E; P	CEL (4)
6061-T6	W	540	5	0.3	23	1	I-C; P	CEL (4)

<sup>a</sup>W = Totally exposed in seawater on sides of structure; S = Exposed in base of structure so that the lower portions of the specimens were embedded in the bottom sediments.

<sup>b</sup>Symbols for types of corrosion:

B = Blisters	MO = Moderate
C = Crevice	NC = No visible corrosion
CR = Crater	P = Pitting
E = Edge	PR = Perforated
EX = Extensive	S = Severe
F = Few	SC = Scattered
HAZ = Heat-affected zone	SH = Shallow
I = Incipient	WB = Weld Bead
IG = Intergranular	

<sup>c</sup>Numbers refer to references at end of report.

<sup>d</sup>Six measurable pits.

<sup>e</sup>Welded, 6061 rod, TIG process.

<sup>f</sup>Re-heat treated after welding to T6 condition.

<sup>g</sup>Lap-welded, 4043 rod.

<sup>h</sup>Butt-welded, 4043 rod.

<sup>i</sup>Interconnected pits in portion in sediment.

Table 75. Stress Corrosion of 6000 Series Aluminum Alloys

Alloy	Stress (ksi)	Percent Yield Strength	Exposure (day)	Depth (ft)	Number of Specimens Exposed	Number Failed	Source <sup>a</sup>
6061-T6	12	30	403	6,780	3	0	NADC (7)
6061-T6	30	75	403	6,780	3	0	NADC (7)
6061-T6	12	30	197	2,340	3	0	NADC (7)
6061-T6	30	75	197	2,340	3	0	NADC (7)
6061-T6	12	30	402	2,370	3	0	NADC (7)
6061-T6	30	75	402	2,370	3	0	NADC (7)

<sup>a</sup>Numbers refer to references at end of report.

Table 76. Changes in Mechanical Properties of 6000 Series Aluminum Alloys Due to Corrosion

Alloy	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>a</sup>
			Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
6061-T6	123	5,640	48	-7	41	-2	17	-58	CEL (4)
6061-T6 <sup>b</sup>	123	5,640	44	-43	38	-43	12	-85	NADC (7)
6061-T6 <sup>b,c</sup>	123	5,640	44	-100	38	-100	12	-100	NADC (7)
6061-T6	403	6,780	48	-11	41	-19	17	-58	CEL (4)
6061-T6	751	5,640	48	-24	41	-41	17	-73	CEL (4)
6061-T6	1,064	5,300	48	-11	41	-9	17	-61	CEL (4)
6061-T6	197	2,340	48	-5	41	0	17	-42	CEL (4)
6061-T6	197	2,340	44	-2	38	+3	12	-57	NADC (7)
6061-T6	402	2,370	48	-15	41	-9	17	-70	CEL (4)
6061-T6	181	5	48	0	41	+2	17	-9	CEL (4)

<sup>a</sup>Numbers refer to references at end of report.

<sup>b</sup>Transverse butt weld, 6061 electrode, TIG process.

<sup>c</sup>Transverse welds excessively corroded; not possible to obtain tensile specimens.



Table 77. Chemical Composition of 7000 Series Aluminum Alloys, Percent by Weight

Alloy	Gage (in.)	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Al <sup>d</sup>
7002-T6	0.063	0.11	0.17	0.78	0.17	2.73	0.19	<0.02	3.76	0.04	R
X7002-T6	0.063	0.20	0.40	0.75	0.15	2.50	0.15	—	3.5	—	R
7002-T6	—	0.40	0.15	1.00	0.17	2.30	0.20	—	3.80	0.02	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
7-75-T6, T6A	—	0.10	0.14	1.40	0.08	2.10	0.30	—	5.10	0.07	R
7075-T73	—	0.10	0.14	1.20	0.02	2.20	0.20	—	5.10	0.02	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)		<sup>b</sup>	<sup>b</sup>	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	—	4.3	0.03	R
7079-T6	—	—	—	0.6	0.2	3.3	0.2	—	4.3	—	R
Alclad 7079-T6	0.063										
Core (7079)		—	—	0.6	0.2	3.3	0.17	—	4.3	—	R
Cladding (7072)		—	—	—	—	—	—	—	1.0	—	R
7106-W51 <sup>c</sup>											
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
7178-T6	—	0.10	0.20	1.00	0.05	2.50	0.18	—	7.10	0.03	R
XAP001-T6 <sup>d</sup>											

<sup>a</sup>R = remainder.<sup>c</sup>No analysis given.<sup>b</sup>Si + Fe = 0.39.<sup>d</sup>Experimental metal compact.

Table 78. Corrosion Rates and Types of Corrosion of 7000 Series Aluminum Alloys

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion				Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth <sup>b</sup> (mils)	Crevice Depth <sup>b</sup> (mils)	Type <sup>b</sup>	
7002-T6	W	123	5,640	—	13	0	E; IG; SH-P; XF	NADC (7)
7002-T6, welded <sup>d</sup>	W	123	5,640	—	PR	0	S-E; MO-IG; SH-P; WB (PR); XF	NADC (7)
7002-T6 <sup>d,e</sup>	W	123	5,640	—	PR	0	E; IG; SH-P; WB (PR); XF	NADC (7)
7002-T6	W	403	6,780	1.2	62	0	E; P (PR)	CEL (4)
7002-T6	W	403	6,780	—	1	0	I-P	NADC (7)
7002-T6	S	403	6,780	3.2	62	0	E; P (PR)	CEL (4)
7002-T6	W	751	5,640	—	0	0	NC	NADC (7)
7002-T6, anodized	W	751	5,640	—	0	0	E	NADC (7)
7002-T6, welded <sup>d</sup>	W	751	5,640	—	0	0	WB (HC)	NADC (7)
7002-T6, welded <sup>d</sup>	W	197	2,340	—	0	0	E; IG; U; WB (S; IG)	NADC (7)
7002-T6	W	197	2,340	<0.1	15	0	P; XF	REY (14)
7002-T6	W	197	2,340	<0.1	0	0	NC	Boeing (6)
7002-T6	W	402	2,370	1.6	30	62	C (PR); P	CEL (4)
7002-T6, welded <sup>d</sup>	W	402	2,370	—	SH	0	E; SH-P; WB&HAZ (S)	NADC (7)
7002-T6	S	402	2,370	1.9	5	62	C (PR); P <sup>j</sup>	CEL (4)
Alclad 7002-T6	W	403	6,780	1.4	5	0	p <sup>g</sup>	CEL (4)
Alclad 7002-T6	W	403	6,780	—	0	0	G	NADC (7)
Alclad 7002-T6	W	403	6,780	0.2	4	0	p <sup>h</sup>	CEL (4)
Alclad 7002-T6	W	751	5,640	—	0	0	G	NADC (7)
Alclad 7002-T6	W	197	2,340	<0.1	6	0	P <sup>i</sup>	REY (14)
Alclad 7002-T6	W	402	2,370	0.8	5	5	C; P	CEL (4)
Alclad 7002-T6	W	402	2,370	—	0	0	SL-B	NADC (7)
Alclad 7002-T6	S	402	2,370	1.0	5	5	C; p <sup>j</sup>	CEL (4)
7106	W	197	2,340	<0.1	0	0	NC	Boeing (6)
X7106-W51, welded <sup>k</sup>	W	197	2,340	—	—	—	NC	Boeing (6)
7039-T6	W	123	5,640	0.7	3	0	P; XF	CEL (4)
7039-T6	S	123	5,640	2.1	38	2	C; P; XF	CEL (4)
7039-T6	W	403	6,780	—	—	—	EX-XF	CEL (4)
7039-T6	S	403	6,780	—	—	—	EX-XF	CEL (4)
7039-T6	W	751	5,640	—	—	—	EX-XF	CEL (4)
7039-T6	S	751	5,640	—	—	—	EX-XF	CEL (4)
7039-T6	W	197	2,340	1.9	27	0	P; XF	CEL (4)

Continued

Table 78. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion				Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth <sup>b</sup> (mils)	Crevice Depth <sup>b</sup> (mils)	Type <sup>b</sup>	
7039	W	197	2,340	<0.1	0	0	NC	Boeing (6)
7039-T6	S	197	2,340	1.2	61	0	D-P; XF	CEL (4)
7039-T6	W	402	2,370	—	—	—	EX-XF	CEL (4)
7039-T6	S	402	2,370	—	—	—	EX-XF	CEL (4)
7039-T64	W	189	5,900	0.2	1	14	C; I-P	CEL (4)
7039-T64, welded <sup>l</sup>	W	189	5,900	0.3	41	1	I-C; P; L (HAZ)	CEL (4)
7039-T64	S	189	5,900	0.3	40	45	C; SC-P	CEL (4)
7039-T64, welded <sup>l</sup>	S	189	5,900	0.3	47	1	I-C; P; P (HAZ)	CEL (4)
7039-T64	W	181	5	1.1	0	0	ET	CEL (4)
7039-T64, welded <sup>l</sup>	W	181	5	1.2	1	0	I-P	CEL (4)
7039-T64	W	398	5	1.1	22	1	I-C; P	CEL (4)
7039-T64, welded <sup>l</sup>	W	398	5	0.5	0	0	P (WB&HAZ)	CEL (4)
7039-T64	W	540	5	0.3	6	3	C; P	CEL (4)
7039-T64, welded <sup>l</sup>	W	540	5	0.3	18	1	I-C; P (HAZ)	CEL (4)
7039-T64, welded <sup>l</sup>	W	588	5	0.3	26	1	I-C; P (HAZ)	CEL (4)
7075-T6	W	123	5,640	—	8	0	E; IG; L; G-P	NADC (7)
7075-T6	W	403	6,780	—	PR	0	P (PR)	NADC (7)
7075-T6	S	403	6,780	—	PR	0	P (PR)	NADC (7)
7075-T6A	W	403	6,780	—	PR	0	P (PR); XF (E)	NADC (7)
7075-T6	W	751	5,640	—	PR	—	C; P (PR); XF (E)	NADC (7)
7075-T6A	W	751	5,640	—	PR	0	P (PR); XF (E)	NADC (7)
7075-T6	W	1,064	5,300	—	PR	0	P (PR); S-XF (E)	NADC (7)
7075-T6A	W	1,064	5,300	—	PR	0	P (PR); XF (E)	NADC (7)
7075-T6	W	197	2,340	—	31	—	C; IG; P; S-XF (E)	NADC (7)
7075-T6	S	197	2,340	—	SL	—	C; IG; SL-P; XF (E)	NADC (7)
7075-T6A	W	197	2,340	—	44	0	SL-IG; SC-P	NADC (7)
7075-T6A	S	197	2,340	—	44	0	SL-IG; N-P	NADC (7)
7075-T6	W	402	2,370	—	SL	0	S-E; SL-P	NADC (7)
7075-T6	S	402	2,370	—	SL	0	S-E; SL-P	NADC (7)
7075-T6A	W	402	2,370	—	PR	0	P (PR)	NADC (7)
7075-T6A	S	402	2,370	—	PR	0	P (PR)	NADC (7)

Continued

Table 78. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion				Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth <sup>b</sup> (mils)	Crevice Depth <sup>b</sup> (mils)	Type <sup>b</sup>	
7075-T64	W	123	5,640	—	40	0	EX-P	NADC (7)
7075-T73	W	123	5,640	—	20	0	SC-P	NADC (7)
7075-T73	W	403	6,780	—	SH	0	SH-P; SL-XF (E)	NADC (7)
7075-T73	S	403	6,780	—	SH	0	SH-P; SL-XF (E)	NADC (7)
7075-T73	W	751	5,640	—	PR	0	P (PR)	NADC (7)
7075-T73	W	197	2,340	—	0	—	C; E; SL-IG	NADC (7)
7075-T73	W	402	2,370	—	31	0	B (E); P; XF(E)	NADC (7)
7075-T73	S	402	2,370	—	0	0	B	NADC (7)
Alclad 7075-0	W	1,064	5,300	—	—	—	U	CEL (4)
Alclad 7075-T6	W	123	5,640	—	—	—	B; I-IG	NADC (7)
7079-T6	W	123	5,640	5.2	79	36	C; E; P (PR); XF	CEL (4)
7079-T6	W	123	5,640	0.7	4	9	C; P	MEL (5)
7079-T6	S	123	5,640	3.0	77	32	C; E; P (PR); XF	CEL (4)
7079-T6	W	403	6,780	5.1	77	36	C; S-E; P (PR)	CEL (4)
7079-T6	S	403	6,780	3.4	57	38	C; S-E; P	CEL (4)
7079-T6	W	751	5,640	2.8	79	79	C (PR); P (PR); XF	CEL (4)
7079-T6	W	751	5,640	2.2	41	80	S-C; P	MEL (5)
7079-T6	S	751	5,640	2.7	77	77	C (PR); P (PR); XF	CEL (4)
7079-T6	W	197	2,340	4.7	77	46	C; E; P (PR); XF	CEL (4)
7079-T6	S	197	2,340	3.0	49	55	C; E; P; XF	CEL (4)
7079-T6	W	402	2,370	1.6	16	35	C; S-E; P	CEL (4)
7079-T6	S	402	2,370	1.4	21	27	C; S-E; P	CEL (4)
Alclad 7079-T6	W	197	2,340	<0.1	3	0	p <sup>m</sup>	REY (14)
7178-T6	W	123	5,640	4.1	43	0	P; XF	CEL (4)
7178-T6	W	123	5,640	—	63	0	P (PR); S-IG	NADC (7)
7178-T6	W	403	6,780	4.9	15	35	C; S-E; P; XF	CEL (4)
7178-T6	W	403	6,780	—	PR	0	S-E; P (PR)	NADC (7)
7178-T6	S	403	6,780	4.4	25	30	C; S-E; P; XF	CEL (4)
7178-T6	W	751	5,640	1.5	36	30	C; S-E; P; XF	CEL (4)
7178-T6	W	751	5,640	—	PR	0	S-E; P (PR)	NADC (7)
7178-T6	W	1,064	5,300	1.4	45	39	C; S-E; P; XF	CEL (4)

Continued

Table 78. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion				Source <sup>c</sup>
				Rate (mpy)	Maximum Pit Depth <sup>b</sup> (mils)	Crevice Depth <sup>b</sup> (mils)	Type <sup>b</sup>	
7178-T6	W	197	2,340	3.2	0	—	C; XF	CEL (4)
7178-T6	W	197	2,340	0.2	50	0	P (PR)	REY (14)
7178-T6	W	197	2,340	—	31	—	C; IG; P; S-XF (E)	NADC (7)
7178-T6	S	197	2,340	—	SL	—	C; IG; SL-P; XF (E)	NADC (7)
7178-T6	S	197	2,340	2.4	0	—	C; XF	CEL (4)
7178-T6	W	402	2,370	3.3	34	34	C; E; P; XF	CEL (4)
7178-T6	W	402	2,370	—	82	0	S-E; P (PR)	NADC (7)
7178-T6	S	402	2,370	—	—	0	E; P	NADC (7)
7178-T6	S	402	2,370	1.8	31	34	C; E; P; XF	CEL (4)
Alclad 7178-T6	W	751	5,640	—	PR	0	P (PR)	NADC (7)

<sup>a</sup>W = Totally exposed in seawater on sides of structure; S = Exposed in base of structure so that the lower portions of the specimens were embedded in the bottom sediments.

<sup>b</sup>Symbols for types of corrosion:

B = Blisters	HC = Honeycomb	PR = Perforated
C = Crevice	I = Incipient	S = Severe
D = Deep	IG = Intergranular	SC = Scattered
E = Edge	L = Line	SH = Shallow
ET = Etched	MO = Moderate	SL = Slight
EX = Extensive	N = Numerous	U = Uniform
G = General	NC = No visible corrosion	WB = Weld Bead
HAZ = Heat-affected zone	P = Pitting	XF = Exfoliated (delaminated)

<sup>c</sup>Numbers refer to references at end of report.

<sup>k</sup>Welded by the TIG process and aged.

<sup>d</sup>Transverse butt weld, MRD 7-5 electrode, TIG process.

<sup>l</sup>Transverse butt welded, 7039 wire, MIG process.

<sup>e</sup>Reheat treated to T6 condition after welding.

<sup>m</sup>2.6-mil-thick cladding.

<sup>f</sup>Part of one specimen missing.

<sup>g</sup>80% of cladding gone.

<sup>h</sup>10% of cladding gone.

<sup>i</sup>3.1-mil-thick cladding.

<sup>j</sup>15% of cladding gone.

Table 79. Stress Corrosion of 7000 Series Aluminum Alloys

Alloy	Stress (ksi)	Percent Yield Strength	Exposure (day)	Depth (ft)	Number of Specimens Exposed	Number Failed	Source <sup>a</sup>
7002-T6	18	30	403	6,780	3	0	NADC (7)
7002-T6	45	75	403	6,780	3	0	NADC (7)
7002-T6	18	30	402	2,370	3	0	NADC (7)
7002-T6	30	50	402	2,370	3	0	CEL (4)
7002-T6	45	75	402	2,370	3	0	NADC (7)
7002-T6	45	75	402	2,370	3	0	CEL (4)
Alclad 7002-T6	18	30	403	6,780	3	0	NADC (7)
Alclad 7002-T6	45	75	403	6,780	3	0	NADC (7)
Alclad 7002-T6	18	30	402	2,370	3	0	NADC (7)
Alclad 7002-T6	29	50	402	2,370	3	0	CEL (4)
Alclad 7002-T6	45	75	402	2,370	3	0	NADC (7)
Alclad 7002-T6	43	75	402	2,370	3	0	CEL (4)
7075-T6	22	30	403	6,780	3	1	NADC (7)
7075-T6	55	75	403	6,780	3	<i>b</i>	NADC (7)
7075-T6	22	30	197	2,340	3	0	NADC (7)
7075-T6	55	75	197	2,340	3	2	NADC (7)
7075-T6	22	30	402	2,370	3	0	NADC (7)
7075-T6	55	75	402	2,370	3	2	NADC (7)
7075-T6A <sup>c</sup>	12	30	403	6,780	3	<i>b</i>	NADC (7)
7075-T6A <sup>c</sup>	30	75	403	6,780	3	<i>b</i>	NADC (7)
7075-T6A <sup>c</sup>	12	30	197	2,340	3	0	NADC (7)
7075-T6A <sup>c</sup>	30	75	197	2,340	3	0	NADC (7)
7075-T6A <sup>c</sup>	12	30	402	2,370	3	0	NADC (7)
7075-T6A <sup>c</sup>	30	75	402	2,370	3	0	NADC (7)
7075-T73	24	30	403	6,780	3	0	NADC (7)
7075-T73	51	75	403	6,780	3	0	NADC (7)
7075-T73	24	30	197	2,340	3	0	NADC (7)
7075-T73	51	75	197	2,340	3	0	NADC (7)
7075-T73	24	30	402	2,370	3	0	NADC (7)
7075-T73	51	75	402	2,370	3	0	NADC (7)
7079-T6	34	50	402	2,370	3	2	CEL (4)
7079-T6	50	75	402	2,370	3	3	CEL (4)
Alclad 7079-T6	35	50	402	2,370	3	1	CEL (4)
Alclad 7079-T6	53	75	402	2,370	3	2	CEL (4)
7178-T6	19	30	403	6,780	3	0	NADC (7)
7178-T6	49	75	403	6,780	3	<i>b</i>	NADC (7)
7178-T6	19	30	197	2,340	3	0	NADC (7)
7178-T6	49	75	197	2,340	3	0	NADC (7)
7178-T6	19	30	402	2,370	3	0	NADC (7)
7178-T6	41	50	402	2,370	3	0	CEL (4)
7178-T6	49	75	402	2,370	3	3	NADC (7)
7178-T6	61	75	402	2,370	3	3	CEL (4)
XAP001-T6	6	30	403	6,780	3	<i>b</i>	NADC (7)
XAP001-T6	15	75	403	6,780	3	0	NADC (7)

<sup>a</sup>Numbers refer to references at end of report.<sup>b</sup>Missing when STU was recovered.<sup>c</sup>Alloy 7076-T6 heated 8 hours at 350°F, air cooled.

Table 80. Changes in Mechanical Properties of 7000 Series Aluminum Alloys Due to Corrosion

Alloy	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>a</sup>
			Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
7002-T6	123	5,640	76	-10	68	-12	12	-8	NADC (7)
7002-T6 <sup>b</sup>	123	5,640	33	-32	—	—	2	-100	NADC (7)
7002-T6 <sup>b,c,d</sup>	123	5,640	—	-100	—	-100	—	-100	NADC (7)
7002-T6	403	6,780	70	-62	58	-71	14	-91	CEL (4)
7002-T6	403	6,780	76	-12	68	-15	12	-8	NADC (7)
7002-T6	751	5,640	76	-8	68	-12	12	+17	NADC (7)
7002-T6 <sup>b,d</sup>	197	2,340	—	-100	—	-100	—	-100	NADC (7)
7002-T6	402	2,370	70	-1	58	0	14	0	CEL (4)
7002-T6	402	2,370	76	-10	68	-16	12	-14	NADC (7)
Alclad 7002-T6	403	6,780	65	-1	54	+3	15	-14	CEL (4)
Alclad 7002-T6	402	2,370	65	-3	54	0	15	-10	CEL (4)
7039-T6	123	5,640	69	-4	60	-3	14	-16	CEL (4)
7039-T6 <sup>d</sup>	403	6,780	69	-100	60	-100	14	-100	CEL (4)
7039-T6 <sup>d</sup>	751	5,640	69	-100	60	-100	14	-100	CEL (4)
7039-T6	197	2,340	69	-2	60	-2	14	-2	CEL (4)
7039-T6 <sup>d</sup>	402	2,370	69	-100	60	-100	14	-100	CEL (4)
7039-T64	181	5	63	+2	53	+6	16	+13	CEL (4)
7039-T64 <sup>e</sup>	181	5	63	+17	53	+4	16	+67	CEL (4)
7075-T6	123	5,640	83	0	76	+1	11	-5	NADC (7)
7075-T6	403	6,780	83	-37	76	-28	11	-94	NADC (7)
7075-T6	751	5,640	83	-13	76	-9	11	-84	NADC (7)
7075-T6	1,064	5,300	83	-13	76	-10	11	-52	NADC (7)
7075-T6	197	2,340	83	-8	76	-4	11	-55	NADC (7)
7075-T6	402	2,370	83	-20	76	—	11	-91	NADC (7)
7075-T6 <sup>f</sup>	197	2,340	71	-22	61	-18	10	-10	NADC (7)
7075-T6 <sup>f</sup>	402	2,370	71	+7	61	-10	10	-20	NADC (7)
7075-T64	123	5,640	71	-41	61	-31	10	-100	NADC (7)
7075-T73	123	5,640	72	0	62	0	10	+10	NADC (7)
7075-T73	403	6,780	72	-11	62	-3	10	-75	NADC (7)
7075-T73	751	5,640	72	-8	62	-8	10	0	NADC (7)
7075-T73	197	2,340	72	-3	62	0	10	+10	NADC (7)
7075-T73	402	2,370	72	0	62	+9	10	-70	NADC (7)
Alclad 7075-T6	123	5,640	76	0	68	0	10	-10	NADC (7)
7079-T6	123	5,640	76	-66	67	-63	11	-74	CEL (4)
7079-T6	403	6,780	76	-43	67	-52	11	-70	CEL (4)
7079-T6 <sup>d</sup>	751	5,640	76	-100	67	-100	11	-100	CEL (4)
7079-T6	197	2,340	76	-17	67	-4	11	-23	CEL (4)
7079-T6	402	2,370	76	-1	67	0	11	-22	CEL (4)
Alclad 7079-T6	402	2,370	78	-2	69	-1	12	+4	CEL (4)
7178-T6	123	5,640	88	-19	80	-16	10	-16	CEL (4)
7178-T6 <sup>g</sup>	123	5,640	89	-49	65	—	11	-91	NADC (7)
7178-T6	403	6,780	88	-41	80	-41	10	-82	CEL (4)
7178-T6	403	6,780	89	-56	65	—	11	-91	NADC (7)

Continued



Table 80. Continued.

Alloy	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>a</sup>
			Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
7178-T6	751	5,640	88	-48	80	-64	10	-58	CEL (4)
7178-T6	751	5,640	89	-90	65	—	11	-91	NADC (7)
7178-T6	1,064	5,300	88	-4	80	-33	10	+12	CEL (4)
7178-T6	197	2,340	88	-19	80	-37	10	-52	CEL (4)
7178-T6	197	2,340	89	-17	65	0	11	-10	NADC (7)
7178-T6	402	2,370	88	-24	80	-21	10	-80	CEL (4)
7178-T6	402	2,370	89	-58	65	—	11	-100	NADC (7)

<sup>a</sup>Numbers refer to references at end of report.

<sup>b</sup>Welded, MDR 7-5 electrode, TIG process.

<sup>c</sup>Reheat treated to T6 condition after welding.

<sup>d</sup>Specimens too corroded (exfoliated) to machine into tensile specimens.

<sup>e</sup>Transverse butt weld, 7039 wire, MIG process.

<sup>f</sup>Alloy 7075-T6 heated for 8 hours at 350°F, air cooled.

<sup>g</sup>Properties transverse to the direction of rolling.

## TITANIUM ALLOYS

Titanium and titanium alloys owe their corrosion resistance to a protective oxide film. This film resists attack by oxidizing solutions, in particular those containing chloride ions. It has outstanding resistance to corrosion and pitting in marine environments and other chloride salt solutions.

The chemical compositions of the titanium alloys are given in Table 81, their corrosion rates and types of corrosion in Table 82, their susceptibility to stress corrosion in Table 83, and the effects of exposure on their mechanical properties in Table 84.

### 7.1. CORROSION

The corrosion rates and type of corrosion of the titanium alloys are given in Table 82.

Except for two alloys, there was no corrosion of any of the titanium alloys during exposures in surface seawater or at depths of 2,500 and 6,000 feet. Reference 15 reported a corrosion rate of 0.19 mpy for unalloyed titanium and of 0.18 mpy for 6Al-4V after 123 days of exposure at the 6,000-foot depth, but no corrosion of these same alloys after 751 days of exposure at the 6,000-foot depth. Also, no visible corrosion was reported. For practical purposes these values are considered to be inconsequential. DeLuccia, Reference 17, reported cracking in the heat-affected zone parallel to the weld bead in alloy 6Al-4V after 197 days of exposure at the 2,500-foot depth. Investigation of the weldments showed that the welds had been made under improper conditions and were contaminated with oxygen which made them brittle.

Alloys 75A, 0.15Pd, 5Al-2.5Sn, 6Al-4V, 7Al-2Cb-1Ta, 6Al-2Cb-1Ta-1Mo, and 13V-11Cr-3Al were both unwelded and welded. They were fusion-welded by the inert-gas shielded arc, nonconsumable tungsten electrode process (TIG). There were transverse butt welds across the 6-inch dimension of the specimens and 3-inch-diameter ring welds in the centers of 6 x 12-inch specimens. The welded specimens were intentionally not stress relieved in order to

simulate the conditions present in a welded structure, i.e., to retain the maximum residual internal welding stresses. The process of placing a circular weld in a specimen imposes very high residual stresses in the specimen. Such circular welds simulate multiaxial stresses imposed in structures or parts fabricated by welding. There was no visible corrosion of these welded alloys except for stress corrosion cracking of alloy 13V-11Cr-3Al. This will be discussed under 7.2.

Alloy 6Al-4V was also exposed as:

- (1) Wire, 0.020- 0.045-, and 0.063-inch diameter.
- (2) Cables, 1/16-inch (1 x 19), 1/4-inch (6 x 19), 1/4-inch (6 x 19) with Type 304 stainless steel swaged ends, and 1/4-inch (6 x 19) with ends tied with mild steel wire.
- (3) Flash-welded tube.
- (4) Flash-welded sphere.
- (5) Piece from broken sphere.
- (6) Welded rings 9.625-inch OD x 1.125-inch wide x 8.75-inch ID. One ring was unstressed and the others were stressed up to a maximum of 60,000 psi.

There was no visible corrosion on any of the above specimens except for the AISI Type 304 swaged fittings and the mild steel wire. The faying surfaces of the Type 304 stainless steel fittings were severely attacked by crevice corrosion. The rate of this crevice corrosion was probably increased by the galvanic couple formed by the two dissimilar metals, with the stainless steel being the anode of the couple. The mild steel wire used to tie the end of one titanium cable was corroded almost through by galvanic corrosion; the mild steel wire was anodic to the titanium cable.

### 7.2. STRESS CORROSION

Specimens of the alloys were stressed in various ways and to values equivalent to 30, 35, 50, and 75%

of their respective yield strengths at the surface and at depths of 2,500 and 6,000 feet for different periods of time.

The majority of the specimens were deformed by bowing to obtain the desired tensile stress in the central 2-inch length of the outer surface of the specimen. Many of these specimens, butt-welded by the TIG process, were positioned such that the transverse weld bead was at the apex of the bow in the 2-inch length. Other specimens, 6 x 12-inch, had a 3-inch-diameter circular weld bead placed in the center. The stresses induced by the welding operation were not relieved in order to retain the maximum residual stresses in the specimens. Still other specimens were in the shape of welded rings, 9-5/8 inches outside diameter, which were deformed different amounts in order to induce tensile stresses in the periphery at the ends of the restraining rods.

The results of the stress corrosion tests are given in Table 83. There were no stress corrosion cracking failures of any of the alloys, both unwelded and butt-welded, stressed at values equivalent to as high as 75% of their respective yield strengths for 180 days of exposure at the surface, 402 days at the 2,500-foot depth, and 751 days at the 6,000-foot depth, except for the butt-welded 13V-11Cr-3Al alloy. The unrelieved butt-welded 13V-11Cr-3Al alloy failed by stress corrosion cracking when stressed at values equivalent to 75% (94,500 psi) of its yield strength after 35, 77, and 105 days of exposure at the surface in the Pacific Ocean. The stress corrosion cracks were in the heat-affected zones at the edges of and parallel to the weld beads.

The butt-welded 6 x 12-inch specimens of 13V-11Cr-3Al alloy failed by stress corrosion during 398, 540, and 588 days of exposure at the surface due to the unrelieved residual welding stresses. The stress corrosion cracks were perpendicular to and extended across the weld beads from side to side.

The 6Al-4V alloy rings stressed as high as 60,000 psi (approximately 50% of its yield strength) did not fail by stress corrosion cracking during 402 days of exposure at the 2,500-foot depth.

Alloys 75A, 0.15Pd, 5Al-2.5Sn, 7Al-2Cb-1Ta, 6Al-2Cb-1Ta-1Mo, 6Al-4V, and 13V-11Cr-3Al were exposed with an unrelieved 3-inch-diameter circular weld bead in the center of 6 x 12-inch specimens. Only the 13V-11Cr-3Al alloy failed by stress corrosion cracking because of the residual welding stresses. Failure by stress corrosion cracking occurred first after 181 days of exposure at the surface. Thereafter, failures first occurred during 189 days of exposure when partially embedded in the bottom sediments and during 751 days of exposure in the seawater at the 6,000-foot depth. At the 2,500-foot depth the first failure occurred during 402 days of exposure in the seawater. The cracks in all cases extended radially across the weld beads. In some cases, the cracks changed direction by 90° and propagated circumferentially around the outside of the weld bead. In general, the 13V-11Cr-3Al alloy was more susceptible to stress corrosion cracking in seawater at the surface than at depth in the Pacific Ocean.

### 7.3. MECHANICAL PROPERTIES

The effects of exposure in seawater on the mechanical properties of the titanium alloys are given in Table 84. The mechanical properties of the titanium alloys were not adversely affected.

Table 81. Chemical Composition of Titanium Alloys

Alloy	C	Fe	N	H	O	Al	V	Cr	Other	Ti <sup>a</sup>	Source <sup>a</sup>
Titanium	<0.1	—	0.02	—	—	—	—	—	—	R	INCO (3)
75A	0.027	0.20	0.026	0.004	—	—	—	—	—	R	CEL (4)
75A	0.025	0.13	0.016	0.003	0.28	—	—	—	—	R	CEL (4)
75A	0.025	0.14	0.017	0.003	0.32	—	—	—	—	R	CEL (4)
0.15Pd	0.022	0.06	0.009	0.003	0.15	—	—	—	0.15 Pd	R	CEL (4)
0.15Pd	0.022	0.05	0.012	0.004	—	—	—	—	0.15 Pd	R	CEL (4)
5Al-2.5Sn	0.025	0.34	0.014	0.011	—	5.1	—	—	2.2 Sn	R	CEL (4)
5Al-2.5Sn	0.022	0.27	0.013	0.006	0.18	5.1	—	—	2.4 Sn	R	CEL (4)
5Al-2.5 Sn	0.025	0.35	0.013	0.008	0.17	5.1	—	—	2.5 Sn	R	CEL (4)
7Al-2Cb-1Ta	0.023	0.06	0.006	0.002	0.07	7.0	—	—	1.0 Ta	R	CEL (4)
4Al-3Mo-1V	—	—	—	—	—	4.30	0.95	—	2.91 Mo	R	NADC (7)
4Al-3Mo-1V <sup>c</sup>	0.08	0.25	0.05	0.15	—	4.25	1.0	—	3.0 Mo	R	CEL (4)
4Al-3Mo-1V	—	0.1	—	—	—	4.5	0.9	0.2	3.7 Mo	R	CEL (4)
8Mn <sup>c</sup>	0.20	—	0.07	0.15	—	—	—	—	8.0 Mn	R	CEL (4)
140A	—	1.9	—	—	—	<0.1	< 0.1	2.1	1.9 Mo	R	CEL (4)
6Al-4V	—	—	—	—	—	5.61	4.13	—	—	R	NADC (7)
6Al-4V	0.023	0.15	0.015	0.007	—	6.0	3.9	—	—	R	CEL (4)
6Al-4V	0.025	0.13	0.015	0.007	—	5.9	4.0	—	—	R	CEL (4)
6Al-4V	0.022	0.08	0.013	0.007	0.11	5.8	4.0	—	—	R	CEL (4)
6Al-4V	—	0.1	—	—	—	7.2	5.2	< 0.1	—	R	CEL (4)
7Al-12Zr	—	—	—	—	—	5.93	—	—	11.27 Zr	R	NADC (7)
6Al-2Cb-1Ta-1Mo	0.02	0.06	0.006	0.002	0.077	6.1	—	—	2.2 Cb 1.1 Ta 0.74 Mo	R	CEL (4)
13V-11Cr-3Al	0.027	0.17	0.027	0.008	—	3.1	13.4	11.4	—	R	CEL (4)
13V-11Cr-3Al	0.021	0.14	0.027	0.010	0.12	3.0	13.6	10.9	—	R	CEL (4)

<sup>a</sup>R = remainder.<sup>b</sup>Numbers refer to references at end of report.<sup>c</sup>Nominal compositions.

Table 82. Corrosion Rates and Types of Corrosion of Titanium Alloys

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion		Source <sup>c</sup>
				Rate (mpy)	Type <sup>b</sup>	
Titanium	W	123	5,640	<0.1	NC	INCO (3)
Titanium	W	123	5,640	0.19	NC	MEL (5)
Titanium	S	123	5,640	<0.1	NC	INCO (3)
Titanium	W	403	6,780	<0.1	NC	INCO (3)
Titanium	S	403	6,780	<0.1	NC	INCO (3)
Titanium	W	751	5,640	<0.1	NC	INCO (3)
Titanium	W	751	5,640	<0.1	NC	MEL (5)
Titanium	S	751	5,640	<0.1	NC	INCO (3)
Titanium	W	1,064	5,300	<0.1	NC	INCO (3)
Titanium	S	1,064	5,300	<0.1	NC	INCO (3)
Titanium	W	197	2,340	<0.1	NC	INCO (3)
Titanium	W	197	2,340	<0.1	NC	Boeing (6)
Titanium	S	197	2,340	<0.1	NC	INCO (3)
Titanium	W	402	2,370	<0.1	NC	INCO (3)
Titanium	S	402	2,370	<0.1	NC	INCO (3)
Titanium	W	181	5	<0.1	NC	INCO (3)
Titanium	W	366	5	<0.1	NC	INCO (3)
75A	W	123	5,640	0.0	NC	CEL (4)
75A	S	123	5,640	0.0	NC	CEL (4)
75A <sup>d</sup>	W	189	5,900	0.0	NC	CEL (4)
75A <sup>e</sup>	W	189	5,900	0.0	NC	CEL (4)
75A <sup>d</sup>	S	189	5,900	0.0	NC; BD	CEL (4)
75A <sup>e</sup>	S	189	5,900	0.0	NC; BD	CEL (4)
75A	W	403	6,780	0.0	NC	CEL (4)
75A	S	403	6,780	0.0	NC	CEL (4)
75A	W	751	5,640	0.0	NC	CEL (4)
75A	W	197	2,340	0.0	NC	CEL (4)
75A	S	197	2,340	0.0	NC	CEL (4)
75A	W	402	2,370	0.0	NC	CEL (4)
75A	S	402	2,370	0.0	NC	CEL (4)
75A	W	181	5	0.0	NC; FS	CEL (4)
75A <sup>d</sup>	W	181	5	0.0	NC; FS	CEL (4)
75A <sup>e</sup>	W	181	5	0.0	NC; FS	CEL (4)
75A	W	398	5	0.0	NC	CEL (4)
75A <sup>d</sup>	W	398	5	0.0	NC	CEL (4)
75A <sup>e</sup>	W	398	5	0.0	NC	CEL (4)
75A	W	540	5	0.0	NC	CEL (4)
75A <sup>d</sup>	W	540	5	0.0	NC	CEL (4)
75A <sup>e</sup>	W	540	5	0.0	NC	CEL (4)

Continued

Table 82. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion		Source <sup>c</sup>
				Rate (mpy)	Type <sup>b</sup>	
75A	W	588	5	0.0	NC	CEL (4)
75A <sup>d</sup>	W	588	5	0.0	NC	CEL (4)
75A <sup>e</sup>	W	588	5	0.0	NC	CEL (4)
0.15 Pd <sup>d</sup>	W	189	5,900	0.0	NC	CEL (4)
0.15 Pd <sup>e</sup>	W	189	5,900	0.0	NC	CEL (4)
0.15 Pd <sup>d</sup>	S	189	5,900	0.0	NC; BD	CEL (4)
0.15 Pd <sup>e</sup>	S	189	5,900	0.0	NC; BD	CEL (4)
0.15 Pd <sup>d</sup>	W	181	5	0.0	NC; FS	CEL (4)
0.15 Pd <sup>e</sup>	W	181	5	0.0	NC; FS	CEL (4)
0.15 Pd <sup>d</sup>	W	398	5	0.0	NC	CEL (4)
0.15 Pd <sup>e</sup>	W	398	5	0.0	NC	CEL (4)
0.15 Pd <sup>d</sup>	W	540	5	0.0	NC	CEL (4)
0.15 Pd <sup>e</sup>	W	540	5	0.0	NC	CEL (4)
0.15 Pd <sup>d</sup>	W	588	5	0.0	NC	CEL (4)
0.15 Pd <sup>e</sup>	W	588	5	0.0	NC	CEL (4)
5Al-2.5Sn <sup>d</sup>	W	123	5,640	<0.1	NC	CEL (4)
5Al-2.5Sn <sup>e</sup>	W	123	5,640	0.0	NC	CEL (4)
5Al-2.5Sn <sup>d</sup>	S	123	5,640	<0.1	NC	CEL (4)
5Al-2.5Sn <sup>e</sup>	S	123	5,640	0.0	NC	CEL (4)
5Al-2.5Sn <sup>d</sup>	W	189	5,900	0.0	NC	CEL (4)
5Al-2.5Sn <sup>e</sup>	W	189	5,900	0.0	NC	CEL (4)
5Al-2.5Sn <sup>d</sup>	S	189	5,900	0.0	NC; BD	CEL (4)
5Al-2.5Sn <sup>e</sup>	S	189	5,900	0.0	NC; BD	CEL (4)
5Al-2.5Sn <sup>d</sup>	W	403	6,780	0.0	NC	CEL (4)
5Al-2.5Sn <sup>e</sup>	W	403	6,780	0.0	NC	CEL (4)
5Al-2.5Sn <sup>d</sup>	S	403	6,780	0.0	NC	CEL (4)
5Al-2.5Sn <sup>e</sup>	S	403	6,780	0.0	NC	CEL (4)
5Al-2.5Sn <sup>d</sup>	W	751	5,640	0.0	NC	CEL (4)
5Al-2.5Sn <sup>e</sup>	W	751	5,640	0.0	NC	CEL (4)
5Al-2.5Sn <sup>d</sup>	W	197	2,340	0.0	NC	CEL (4)
5Al-2.5Sn <sup>e</sup>	W	197	2,340	0.0	NC	CEL (4)
5Al-2.5Sn <sup>d</sup>	S	197	2,340	0.0	NC	CEL (4)
5Al-2.5Sn <sup>e</sup>	S	197	2,340	0.0	NC	CEL (4)
5Al-2.5Sn <sup>d</sup>	W	402	2,370	0.0	NC	CEL (4)
5Al-2.5Sn <sup>e</sup>	W	402	2,370	0.0	NC	CEL (4)
5Al-2.5Sn <sup>d</sup>	S	402	2,370	0.0	NC	CEL (4)
5Al-2.5Sn <sup>e</sup>	S	402	2,370	0.0	NC	CEL (4)
5Al-2.5Sn <sup>d</sup>	W	181	5	0.0	NC; FS	CEL (4)
5Al-2.5Sn <sup>e</sup>	W	181	5	0.0	NC; FS	CEL (4)

Continued

Table 82. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion		Source <sup>c</sup>
				Rate (mpy)	Type <sup>b</sup>	
5Al-2.5Sn <sup>d</sup>	W	398	5	0.0	NC	CEL (4)
5Al-2.5Sn <sup>e</sup>	W	398	5	0.0	NC	CEL (4)
5Al-2.5Sn <sup>d</sup>	W	540	5	0.0	NC	CEL (4)
5Al-2.5Sn <sup>e</sup>	W	540	5	0.0	NC	CEL (4)
5Al-2.5Sn <sup>d</sup>	W	588	5	0.0	NC	CEL (4)
7Al-2Cb-1Ta <sup>d</sup>	W	189	5,900	0.0	NC	CEL (4)
7Al-2Cb-1Ta <sup>e</sup>	W	189	5,900	0.0	NC	CEL (4)
7Al-2Cb-1Ta <sup>d</sup>	S	189	5,900	0.0	NC; BD	CEL (4)
7Al-2Cb-1Ta <sup>e</sup>	S	189	5,900	0.0	NC; BD	CEL (4)
7Al-2Cb-1Ta <sup>d</sup>	W	181	5	0.0	NC; FS	CEL (4)
7Al-2Cb-1Ta <sup>e</sup>	W	181	5	0.0	NC; FS	CEL (4)
7Al-2Cb-1Ta <sup>d</sup>	W	398	5	0.0	NC	CEL (4)
7Al-2Cb-1Ta <sup>e</sup>	W	398	5	0.0	NC	CEL (4)
7Al-2Cb-1Ta <sup>d</sup>	W	540	5	0.0	NC	CEL (4)
7Al-2Cb-1Ta <sup>e</sup>	W	540	5	0.0	NC	CEL (4)
7Al-2Cb-1Ta <sup>d</sup>	W	588	5	0.0	NC	CEL (4)
7Al-2Cb-1Ta <sup>e</sup>	W	588	5	0.0	NC	CEL (4)
4Al-3Mo-1V	W	123	5,640	0.0	NC	NADC (7)
4Al-3Mo-1V	W	403	6,780	0.0	NC	NADC (7)
4Al-3Mo-1V	S	403	6,780	0.0	NC; BD	NADC (7)
4Al-3Mo-1V	W	751	5,640	0.0	NC	NADC (7)
4Al-3Mo-1V	S	751	5,640	0.0	NC; BD	NADC (7)
4Al-3Mo-1V	W	1,064	5,300	0.0	NC	CEL (4)
4Al-3Mo-1V	W	1,064	5,300	0.0	NC	NADC (7)
4Al-3Mo-1V	S	1,064	5,300	0.0	NC; BD	NADC (7)
4Al-3Mo-1V	W	197	2,340	0.0	NC	NADC (7)
4Al-3Mo-1V	S	197	2,340	0.0	NC; BD	NADC (7)
4Al-3Mo-1V	W	402	2,370	0.0	NC	CEL (4)
4Al-3Mo-1V	S	402	2,370	0.0	NC	CEL (4)
8 Mn	W	402	2,370	0.0	NC	CEL (4)
8 Mn	S	402	2,370	0.0	NC	CEL (4)
140A	W	1,064	5,300	0.0	NC	CEL (4)
7Al-12Zr	W	123	5,300	<0.1	NC	NADC (7)
6Al-4V	W	123	5,640	<0.1	NC	NADC (7)
6Al-4V	W	123	5,640	0.18	NC	MEL (5)
6Al-4V	W	123	5,640	0.0	NC	CEL (4)
6Al-4V <sup>d</sup>	W	123	5,640	0.0	NC	CEL (4)

Continued



Table 82. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion		Source <sup>c</sup>
				Rate (mpy)	Type <sup>b</sup>	
6Al-4V <sup>e</sup>	W	123	5,640	0.0	NC	CEL (4)
6Al-4V	S	123	5,640	0.0	NC	CEL (4)
6Al-4V <sup>d</sup>	S	123	5,640	0.0	NC	CEL (4)
6Al-4V <sup>e</sup>	S	123	5,640	0.0	NC	CEL (4)
6Al-4V <sup>d</sup>	W	189	5,900	0.0	NC	CEL (4)
6Al-4V <sup>e</sup>	W	189	5,900	0.0	NC	CEL (4)
6Al-4V <sup>d</sup>	S	189	5,900	0.0	NC; BD	CEL (4)
6Al-4V <sup>e</sup>	S	189	5,900	0.0	NC; BD	CEL (4)
6Al-4V	W	403	6,780	0.0	NC	NADC (7)
6Al-4V <sup>f</sup>	W	403	6,780	0.0	NC	NADC (7)
6Al-4V	W	403	6,780	0.0	NC	CEL (4)
6Al-4V <sup>d</sup>	W	403	6,780	0.0	NC	CEL (4)
6Al-4V <sup>e</sup>	W	403	6,780	0.0	NC	CEL (4)
6Al-4V	S	403	6,780	0.0	NC	CEL (4)
6Al-4V <sup>d</sup>	S	403	6,780	0.0	NC	CEL (4)
6Al-4V <sup>e</sup>	S	403	6,780	0.0	NC	CEL (4)
6Al-4V	W	751	5,640	0.0	NC	NADC (7)
6Al-4V	W	751	5,640	<0.1	NC	MEL (5)
6Al-4V	W	751	5,640	0.0	NC	CEL (4)
6Al-4V <sup>d</sup>	W	751	5,640	0.0	NC	CEL (4)
6Al-4V <sup>e</sup>	W	751	5,640	0.0	NC	CEL (4)
6Al-4V	W	1,064	5,300	0.0	NC	CEL (4)
6Al-4V	W	197	2,340	0.0	NC	NADC (7)
6Al-4V <sup>f</sup>	W	197	2,340	0.0	HAZ (CR) <sup>g</sup>	NADC (7)
6Al-4V	W	197	2,340	0.0	NC	CEL (4)
6Al-4V <sup>d</sup>	W	197	2,340	0.0	NC	CEL (4)
6Al-4V <sup>e</sup>	W	197	2,340	0.0	NC	CEL (4)
6Al-4V	S	197	2,340	0.0	NC; BD	NADC (7)
6Al-4V	S	197	2,340	0.0	NC	CEL (4)
6Al-4V <sup>d</sup>	S	197	2,340	0.0	NC	CEL (4)
6Al-4V <sup>e</sup>	S	197	2,340	0.0	NC	CEL (4)
6Al-4V	W	402	2,370	0.0	NC	NADC (7)
6Al-4V	W	402	2,370	0.0	NC	CEL (4)
6Al-4V <sup>d</sup>	W	402	2,370	0.0	NC	CEL (4)
6Al-4V <sup>e</sup>	W	402	2,370	0.0	NC	CEL (4)
6Al-4V	S	402	2,370	0.0	NC	CEL (4)
6Al-4V <sup>d</sup>	S	402	2,370	0.0	NC	CEL (4)
6Al-4V <sup>e</sup>	S	402	2,370	0.0	NC	CEL (4)
6Al-4V	W	181	5	0.0	NC; FS	CEL (4)
6Al-4V <sup>d</sup>	W	181	5	0.0	NC; FS	CEL (4)

Continued

Table 82. Continued.

Alloy	Environment <sup>d</sup>	Exposure (day)	Depth (ft)	Corrosion		Source <sup>c</sup>
				Rate (mpy)	Type <sup>b</sup>	
6Al-4V <sup>e</sup>	W	181	5	0.0	NC; FS	CEL (4)
6Al-4V	W	398	5	0.0	NC	CEL (4)
6Al-4V <sup>d</sup>	W	398	5	0.0	NC	CEL (4)
6Al-4V <sup>e</sup>	W	398	5	0.0	NC	CEL (4)
6Al-4V	W	540	5	0.0	NC	CEL (4)
6Al-4V <sup>d</sup>	W	540	5	0.0	NC	CEL (4)
6Al-4V <sup>e</sup>	W	540	5	0.0	NC	CEL (4)
6Al-4V <sup>d</sup>	W	588	5	0.0	NC	CEL (4)
6Al-4V <sup>e</sup>	W	588	5	0.0	NC	CEL (4)
6Al-2Cb-1Ta-1Mo	W	189	5,900	0.0	NC	CEL (4)
6Al-2Cb-1Ta-1Mo <sup>d</sup>	W	189	5,900	0.0	NC	CEL (4)
6Al-2Cb-1Ta-1Mo <sup>e</sup>	W	189	5,900	0.0	NC	CEL (4)
6Al-2Cb-1Ta-1Mo	S	189	5,900	0.0	NC; BD	CEL (4)
6Al-2Cb-1Ta-1Mo <sup>d</sup>	S	189	5,900	0.0	NC; BD	CEL (4)
6Al-2Cb-1Ta-1Mo <sup>e</sup>	S	189	5,900	0.0	NC; BD	CEL (4)
13V-11Cr-3Al	W	123	5,640	<0.1	NC	MEL (5)
13V-11Cr-3Al <sup>d</sup>	W	123	5,640	0.0	NC	CEL (4)
13V-11Cr-3Al <sup>e</sup>	W	123	5,640	0.0	NC	CEL (4)
13V-11Cr-3Al <sup>d</sup>	S	123	5,640	0.0	NC	CEL (4)
13V-11Cr-3Al <sup>e</sup>	S	123	5,640	0.0	NC	CEL (4)
13V-11Cr-3Al <sup>d</sup>	W	189	5,900	0.0	NC	CEL (4)
13V-11Cr-3Al <sup>e</sup>	W	189	5,900	0.0	NC	CEL (4)
13V-11Cr-3Al <sup>d</sup>	S	189	5,900	0.0	SCC <sup>b</sup>	CEL (4)
13V-11Cr-3Al <sup>e</sup>	S	189	5,900	0.0	NC; BD	CEL (4)
13V-11Cr-3Al <sup>d,i</sup>	W	360	4,200	0.0	SCC <sup>j</sup>	CEL (4)
13V-11Cr-3Al <sup>d,i</sup>	S	360	4,200	0.0	NC	CEL (4)
13V-11Cr-3Al <sup>d</sup>	W	403	6,780	0.0	NC	CEL (4)
13V-11Cr-3Al <sup>e</sup>	W	403	6,780	0.0	NC	CEL (4)
13V-11Cr-3Al <sup>d</sup>	S	403	6,780	0.0	SCC <sup>j</sup>	CEL (4)
13V-11Cr-3Al <sup>e</sup>	S	403	6,780	0.0	NC	CEL (4)
13V-11Cr-3Al	W	751	5,640	<0.1	NC	MEL (5)
13V-11Cr-3Al <sup>d</sup>	W	751	5,640	0.0	SCC <sup>j</sup>	CEL (4)
13V-11Cr-3Al <sup>e</sup>	W	751	5,640	0.0	NC	CEL (4)
13V-11Cr-3Al <sup>d</sup>	W	197	2,340	0.0	NC	CEL (4)
13V-11Cr-3Al <sup>e</sup>	W	197	2,340	0.0	NC	CEL (4)
13V-11Cr-3Al <sup>d</sup>	S	197	2,340	0.0	NC	CEL (4)
13V-11Cr-3Al <sup>e</sup>	S	197	2,340	0.0	NC	CEL (4)
13V-11Cr-3Al <sup>d</sup>	W	402	2,370	0.0	NC	CEL (4)
13V-11Cr-3Al <sup>e</sup>	W	402	2,370	0.0	NC	CEL (4)
13V-11Cr-3Al <sup>d</sup>	S	402	2,370	0.0	SCC <sup>j</sup>	CEL (4)

Continued

Table 82. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion		Source <sup>c</sup>
				Rate (mpy)	Type <sup>b</sup>	
13V-11Cr-3Al <sup>e</sup>	S	402	2,370	0.0	NC	CEL (4)
13V-11Cr-3Al <sup>d</sup>	W	181	5	0.0	SCC <sup>j</sup>	CEL (4)
13V-11Cr-3Al <sup>e</sup>	W	181	5	0.0	NC; FS	CEL (4)
13V-11Cr-3Al <sup>d</sup>	W	398	5	0.0	SCC (6) <sup>j</sup>	CEL (4)
13V-11Cr-3Al <sup>e</sup>	W	398	5	0.0	SCC (2) <sup>k</sup>	CEL (4)
13V-11Cr-3Al <sup>d</sup>	W	540	5	0.0	SCC (12) <sup>j</sup>	CEL (4)
13V-11Cr-3Al <sup>e</sup>	W	540	5	0.0	SCC (1) <sup>k</sup>	CEL (4)
13V-11Cr-3Al <sup>d</sup>	W	588	5	0.0	SCC (19) <sup>j</sup>	CEL (4)
13V-11Cr-3Al <sup>e</sup>	W	588	5	0.0	SCC (1) <sup>k</sup>	CEL (4)

<sup>a</sup>W = Totally exposed in seawater on sides of structure; S = Exposed in base of structure so that the lower portions of the specimens were embedded in the bottom sediments.

<sup>b</sup>Symbols for types of corrosion:

BD = Bluish discoloration on portion in bottom sediment.

CR = Cracked

FS = Fouling stains

HAZ = Heat-affected zone

NC = No visible corrosion

SCC = Stress corrosion cracking

Numbers in parentheses are number of stress corrosion cracks

<sup>c</sup>Numbers refer to references at end of report.

<sup>d</sup>Unrelieved 3-in.-diam weld bead in center of specimen, TIG process, nonconsumable tungsten electrode.

<sup>e</sup>Unrelieved butt weld across width of specimen, TIG process, nonconsumable tungsten electrode.

<sup>f</sup>TIG welded, commercially pure titanium filler metal used, unrelieved.

<sup>g</sup>Cracked in heat-affected zone of unrelieved transverse butt weld.

<sup>h</sup>Two cracks in each specimen perpendicular to and across circular weld beads; some branching; penetrated through 0.125-in.-thick plate. Bluish discoloration on portions of specimens in sediment.

<sup>i</sup>Exposed in Tongue-of-the-Ocean, Atlantic, 0.3-kt current, 4.5°C, 5.18-ml/l oxygen.

<sup>j</sup>Cracks radially across circular weld bead into base metal outside heat-affected zone.

<sup>k</sup>Cracks across weld bead normal to direction of welding.

Table 83. Stress Corrosion of Titanium Alloys

Alloy	Stress (ksi)	Percent Yield Strength	Exposure (day)	Depth (ft)	Number of Specimens Exposed	Number Failed	Source <sup>a</sup>
75A <sup>b</sup>	41	50	189	5,900	3	0	CEL (4)
75A <sup>b,c</sup>	41	50	189	5,900	3	0	CEL (4)
75A <sup>b</sup>	62	75	189	5,900	3	0	CEL (4)
75A <sup>b,c</sup>	62	75	189	5,900	3	0	CEL (4)
75A	25	35	403	6,780	2	0	CEL (4)
75A	35	50	403	6,780	2	0	CEL (4)
75A	53	75	403	6,780	2	0	CEL (4)
75A	25	35	197	2,340	3	0	CEL (4)
75A	35	50	197	2,340	3	0	CEL (4)
75A	53	75	197	2,340	3	0	CEL (4)
75A	35	50	402	2,370	3	0	CEL (4)
75A	53	75	402	2,370	3	0	CEL (4)
75A <sup>b</sup>	29	35	180	5	3	0	CEL (4)
75A <sup>b</sup>	41	50	180	5	3	0	CEL (4)
75A <sup>b</sup>	62	75	180	5	3	0	CEL (4)
75A <sup>d</sup>	<i>e</i>	—	181	5	4	0	CEL (4)
0.15 Pd <sup>b</sup>	25	50	189	5,900	3	0	CEL (4)
0.15 Pd <sup>b,c</sup>	25	50	189	5,900	3	0	CEL (4)
0.15 Pd <sup>b</sup>	37	75	189	5,900	3	0	CEL (4)
0.15 Pd <sup>b,c</sup>	37	75	189	5,900	3	0	CEL (4)
0.15 Pd <sup>b</sup>	24	35	180	5	3	0	CEL (4)
0.15 Pd <sup>b</sup>	34	50	180	5	3	0	CEL (4)
0.15 Pd <sup>b</sup>	51	75	180	5	3	0	CEL (4)
0.15 Pd <sup>d</sup>	<i>e</i>	—	181	5	4	0	CEL (4)
5Al-2.5Sn <sup>b</sup>	43	35	123	5,640	3	0	CEL (4)
5Al-2.5Sn <sup>b</sup>	61	50	123	5,640	3	0	CEL (4)
5Al-2.5Sn <sup>b</sup>	92	75	123	5,640	3	0	CEL (4)
5Al-2.5Sn <sup>d</sup>	<i>e</i>	—	123	5,640	3	0	CEL (4)
5Al-2.5Sn <sup>b</sup>	62	50	189	5,900	3	0	CEL (4)
5Al-2.5Sn <sup>b,c</sup>	62	50	189	5,900	3	0	CEL (4)
5Al-2.5Sn <sup>b</sup>	93	75	189	5,900	3	0	CEL (4)
5Al-2.5Sn <sup>b,c</sup>	93	75	189	5,900	3	0	CEL (4)
5Al-2.5Sn <sup>b</sup>	43	35	403	6,780	2	0	CEL (4)
5Al-2.5Sn <sup>b</sup>	61	50	403	6,780	2	0	CEL (4)
5Al-2.5Sn <sup>b</sup>	92	75	403	6,780	2	0	CEL (4)
5Al-2.5Sn <sup>d</sup>	<i>e</i>	—	403	6,780	2	0	CEL (4)
5Al-2.5Sn <sup>b</sup>	43	35	751	5,640	3	0	CEL (4)
5Al-2.5Sn <sup>b</sup>	61	50	751	5,640	3	0	CEL (4)
5Al-2.5Sn <sup>b</sup>	92	75	751	5,640	3	0	CEL (4)
5Al-2.5Sn <sup>d</sup>	<i>e</i>	—	751	5,640	3	0	CEL (4)

Continued

Table 83. Continued.

Alloy	Stress (ksi)	Percent Yield Strength	Exposure (day)	Depth (ft)	Number of Specimens Exposed	Number Failed	Source <sup>a</sup>
5Al-2.5Sn <sup>b</sup>	43	35	197	2,340	3	0	CEL (4)
5Al-2.5Sn <sup>b</sup>	61	50	197	2,340	3	0	CEL (4)
5Al-2.5Sn <sup>b</sup>	92	75	197	2,340	3	0	CEL (4)
5Al-2.5Sn <sup>d</sup>	<i>e</i>	—	197	2,340	2	0	CEL (4)
5Al-2.5Sn <sup>b</sup>	<i>e</i>	—	402	2,370	2	0	CEL (4)
5Al-2.5Sn <sup>b</sup>	43	35	180	5	3	0	CEL (4)
5Al-2.5Sn <sup>b</sup>	62	50	180	5	3	0	CEL (4)
5Al-2.5Sn <sup>b</sup>	93	75	180	5	3	0	CEL (4)
5Al-2.5Sn <sup>d</sup>	<i>e</i>	—	181	5	4	0	CEL (4)
7Al-2Cb-1Ta <sup>b</sup>	50	50	189	5,900	3	0	CEL (4)
7Al-2Cb-1Ta <sup>b,c</sup>	50	50	189	5,900	3	0	CEL (4)
7Al-2Cb-1Ta <sup>b</sup>	75	75	189	5,900	3	0	CEL (4)
7Al-2Cb-1Ta <sup>b,c</sup>	75	75	189	5,900	3	0	CEL (4)
7Al-2Cb-1Ta <sup>b</sup>	35	35	180	5	3	0	CEL (4)
7Al-2Cb-1Ta <sup>b</sup>	50	50	180	5	3	0	CEL (4)
7Al-2Cb-1Ta <sup>b</sup>	75	75	180	5	3	0	CEL (4)
7Al-2Cb-1Ta <sup>d</sup>	<i>e</i>	—	181	5	4	0	CEL (4)
6Al-2Cb-1Ta-1Mo <sup>b</sup>	60	50	189	5,900	3	0	CEL (4)
6Al-2Cb-1Ta-1Mo <sup>b,c</sup>	60	50	189	5,900	3	0	CEL (4)
6Al-2Cb-1Ta-1Mo <sup>b</sup>	89	75	189	5,900	3	0	CEL (4)
6Al-2Cb-1Ta-1Mo <sup>b,c</sup>	89	75	189	5,900	3	0	CEL (4)
6Al-4V	48	35	123	5,640	3	0	CEL (4)
6Al-4V <sup>b</sup>	49	35	123	5,640	3	0	CEL (4)
6Al-4V	68	50	123	5,640	3	0	CEL (4)
6Al-4V <sup>b</sup>	70	50	123	5,640	3	0	CEL (4)
6Al-4V	102	75	123	5,640	3	0	CEL (4)
6Al-4V <sup>b</sup>	105	75	123	5,640	3	0	CEL (4)
6Al-4V <sup>d</sup>	<i>e</i>	—	123	5,640	2	0	CEL (4)
6Al-4V <sup>b</sup>	66	50	189	5,900	3	0	CEL (4)
6Al-4V <sup>b,c</sup>	66	50	189	5,900	3	0	CEL (4)
6Al-4V <sup>b</sup>	99	75	189	5,900	3	0	CEL (4)
6Al-4V <sup>b,c</sup>	99	75	189	5,900	3	0	CEL (4)
6Al-4V	43	30	403	6,780	3	0	NADC (7)
6Al-4V	48	35	403	6,780	2	0	CEL (4)
6Al-4V <sup>b</sup>	49	35	403	6,780	2	0	CEL (4)
6Al-4V	71	50	403	6,780	3	0	NADC (7)
6Al-4V	68	50	403	6,780	2	0	CEL (4)
6Al-4V <sup>b</sup>	70	50	403	6,780	2	0	CEL (4)
6Al-4V	107	75	403	6,780	3	0	NADC (7)
6Al-4V	102	75	403	6,780	2	0	CEL (4)

Continued

Table 83. Continued.

Alloy	Stress (ksi)	Percent Yield Strength	Exposure (day)	Depth (ft)	Number of Specimens Exposed	Number Failed	Source <sup>a</sup>
6Al-4V <sup>b</sup>	105	75	403	6,780	2	0	CEL (4)
6Al-4V <sup>d</sup>	<sup>e</sup>	—	403	6,780	2	0	CEL (4)
6Al-4V	48	35	751	5,640	3	0	CEL (4)
6Al-4V <sup>b</sup>	49	35	751	5,640	3	0	CEL (4)
6Al-4V	68	50	751	5,640	3	0	CEL (4)
6Al-4V <sup>b</sup>	70	50	751	5,640	3	0	CEL (4)
6Al-4V	102	75	751	5,640	3	0	CEL (4)
6Al-4V <sup>b</sup>	105	75	751	5,640	3	0	CEL (4)
6Al-4V <sup>d</sup>	<sup>e</sup>	—	751	5,640	2	0	CEL (4)
6Al-4V	43	30	197	2,340	3	0	NADC (7)
6Al-4V	48	35	197	2,340	3	0	CEL (4)
6Al-4V <sup>b</sup>	49	35	197	2,340	3	0	CEL (4)
6Al-4V	68	50	197	2,340	3	0	CEL (4)
6Al-4V <sup>b</sup>	70	50	197	2,340	3	0	CEL (4)
6Al-4V	107	75	197	2,340	3	0	NADC (7)
6Al-4V	102	75	197	2,340	3	0	CEL (4)
6Al-4V <sup>b</sup>	105	75	197	2,340	3	0	CEL (4)
6Al-4V <sup>d</sup>	<sup>e</sup>	—	197	2,340	2	0	CEL (4)
6Al-4V	43	30	402	2,370	3	0	NADC (7)
6Al-4V	68	50	402	2,370	3	0	CEL (4)
6Al-4V	107	75	402	2,370	3	0	NADC (7)
6Al-4V	102	75	402	2,370	3	0	CEL (4)
6Al-4V <sup>d</sup>	<sup>e</sup>	—	402	2,370	2	0	CEL (4)
6Al-4V <sup>b</sup>	46	35	180	5	3	0	CEL (4)
6Al-4V <sup>b</sup>	66	50	180	5	3	0	CEL (4)
6Al-4V <sup>b</sup>	99	75	180	5	3	0	CEL (4)
6Al-4V <sup>d</sup>	<sup>e</sup>	—	181	5	4	0	CEL (4)
13V-11Cr-3Al <sup>b</sup>	49	35	123	5,640	3	0	CEL (4)
13V-11Cr-3Al <sup>b</sup>	70	50	123	5,640	3	0	CEL (4)
13V-11Cr-3Al <sup>b</sup>	105	75	123	5,640	3	0	CEL (4)
13V-11Cr-3Al <sup>d</sup>	<sup>e</sup>	—	123	5,640	2	0	CEL (4)
13V-11Cr-3Al <sup>b</sup>	63	50	189	5,900	3	0	CEL (4)
13V-11Cr-3Al <sup>b,c</sup>	63	50	189	5,900	3	0	CEL (4)
13V-11Cr-3Al <sup>b</sup>	95	75	189	5,900	3	0	CEL (4)
13V-11Cr-3Al <sup>b,c</sup>	95	75	189	5,900	3	0	CEL (4)
13V-11Cr-3Al <sup>d</sup>	<sup>e</sup>	—	189	5,900	2	1 <sup>f</sup>	CEL (4)
13V-11Cr-3Al <sup>b</sup>	49	35	403	6,780	2	0	CEL (4)
13V-11Cr-3Al <sup>b</sup>	70	50	403	6,780	2	0	CEL (4)
13V-11Cr-3Al <sup>b</sup>	105	75	403	6,780	2	0	CEL (4)
13V-11Cr-3Al <sup>d</sup>	<sup>e</sup>	—	403	6,780	2	1 <sup>f</sup>	CEL (4)
13V-11Cr-3Al <sup>b</sup>	49	35	751	5,640	3	0	CEL (4)

Continued

Table 83. Continued.

Alloy	Stress (ksi)	Percent Yield Strength	Exposure (day)	Depth (ft)	Number of Specimens Exposed	Number Failed	Source <sup>a</sup>
13V-11Cr-3Al <sup>b</sup>	70	50	751	5,640	3	0	CEL (4)
13V-11Cr-3Al <sup>b</sup>	105	75	751	5,640	3	0	CEL (4)
13V-11Cr-3Al <sup>d</sup>	<sup>e</sup>	—	751	5,640	2	1 <sup>g</sup>	CEL (4)
13V-11Cr-3Al <sup>b</sup>	49	35	197	2,340	3	0	CEL (4)
13V-11Cr-3Al <sup>b</sup>	70	50	197	2,340	3	0	CEL (4)
13V-11Cr-3Al <sup>b</sup>	105	75	197	2,340	3	0	CEL (4)
13V-11Cr-3Al <sup>d</sup>	<sup>e</sup>	—	197	2,340	3	0	CEL (4)
13V-11Cr-3Al <sup>d</sup>	<sup>e</sup>	—	402	2,370	2	1 <sup>f</sup>	CEL (4)
13V-11Cr-3Al <sup>b</sup>	44	35	180	5	3	0	CEL (4)
13V-11Cr-3Al <sup>b</sup>	63	50	180	5	3	0	CEL (4)
13V-11Cr-3Al <sup>b</sup>	95	75	180	5	3	3 <sup>b</sup>	CEL (4)
13V-11Cr-3Al <sup>d</sup>	<sup>e</sup>	—	181	5	4	1 <sup>g</sup>	CEL (4)
13V-11Cr-3Al <sup>b</sup>	<sup>e</sup>	—	398	5	2	2 <sup>i</sup>	CEL (4)
13V-11Cr-3Al <sup>d</sup>	<sup>e</sup>	—	398	5	2	2 <sup>j</sup>	CEL (4)
13V-11Cr-3Al <sup>b</sup>	<sup>e</sup>	—	540	5	2	1 <sup>i</sup>	CEL (4)
13V-11Cr-3Al <sup>d</sup>	<sup>e</sup>	—	540	5	2	2 <sup>k</sup>	CEL (4)
13V-11Cr-3Al <sup>b</sup>	<sup>e</sup>	—	588	5	2	1 <sup>i</sup>	CEL (4)
13V-11Cr-3Al <sup>d</sup>	<sup>e</sup>	—	588	5	2	2 <sup>l</sup>	CEL (4)

<sup>a</sup>Numbers refer to references at end of report.

<sup>b</sup>Unrelieved butt weld across width of specimen, TIG process, nonconsumable tungsten electrode, weld at apex of bow.

<sup>c</sup>Partially embedded in bottom sediment.

<sup>d</sup>Unrelieved 3-in.-diam weld bead in center of specimen, TIG process, nonconsumable tungsten electrode.

<sup>e</sup>Residual welding stresses.

<sup>f</sup>Specimen partially embedded in bottom sediment; cracked radially across the weld bead.

<sup>g</sup>Specimen in seawater; cracked radially across the weld bead.

<sup>h</sup>Specimens failed in heat-affected zones after 35, 77, and 105 days of exposure.

<sup>i</sup>Cracks across weld beads.

<sup>j</sup>Six cracks radially across weld beads.

<sup>k</sup>Twelve cracks radially across weld beads.

<sup>l</sup>Nineteen cracks radially across weld beads.



Table 84. Changes in Mechanical Properties of Titanium Alloys Due to Corrosion

Alloy	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>a</sup>
			Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
75A	123	5,640	87	+4	70	+5	30	-5	CEL (4)
75A	403	6,780	87	+4	70	+4	30	-16	CEL (4)
75A	751	5,640	87	+4	70	+11	30	-15	CEL (4)
75A	197	2,340	87	+5	70	+8	30	-11	CEL (4)
75A	402	2,370	87	+6	70	+7	30	-13	CEL (4)
75A	181	5	87	+8	70	+9	30	-18	CEL (4)
75A <sup>b</sup>	181	5	101	+2	84	-1	25	-24	CEL (4)
0.15 Pd <sup>b</sup>	181	5	66	+3	47	+4	28	-33	CEL (4)
5Al-2.5Sn <sup>b</sup>	403	6,780	130	+10	123	+10	14	-13	CEL (4)
5Al-2.5Sn <sup>b</sup>	751	5,640	130	+4	123	+5	14	-11	CEL (4)
5Al-2.5Sn <sup>b</sup>	402	2,370	130	+5	123	+4	14	-15	CEL (4)
5Al-2.5Sn <sup>b</sup>	181	5	138	+4	124	+1	17	-20	CEL (4)
8 Mn	402	2,370	132	+2	116	+3	12	+33	CEL (4)
4Al-3Mo-1V	123	5,640	155	0	115	-3	15	0	NADC (7)
4Al-3Mo-1V	403	6,780	155	+2	115	+2	15	0	NADC (7)
4Al-3Mo-1V	751	5,640	155	-17	115	-29	15	0	NADC (7)
4Al-3Mo-1V	1,064	5,300	155	-8	115	-13	15	+7	NADC (7)
4Al-3Mo-1V	402	2,370	201	+1	180	-2	4	+19	CEL (4)
7Al-12Zr	123	5,640	132	+1	126	+1	17	-24	NADC (7)
7Al-2Cb-1Ta <sup>b</sup>	181	5	111	+4	98	+1	18	-16	CEL (4)
6Al-4V	123	5,640	172	-3	143	+7	5	0	NADC (7)
6Al-4V	403	6,780	140	+16	136	+16	14	0	CEL (4)
6Al-4V <sup>b</sup>	403	6,780	148	+4	139	-1	13	-13	CEL (4)
6Al-4V	751	5,640	172	0	143	+8	5	+50	NADC (7)
6Al-4V	751	5,640	140	0	136	+4	14	0	CEL (4)
6Al-4V <sup>b</sup>	751	5,640	148	+3	139	+4	13	-13	CEL (4)
6Al-4V	197	2,340	172	-27	143	-22	5	-40	NADC (7)
6Al-4V	197	2,340	140	+2	136	+3	14	+2	CEL (4)
6Al-4V	402	2,370	140	+7	136	+6	14	-1	CEL (4)
6Al-4V <sup>b</sup>	402	2,370	148	+2	139	+1	13	-8	CEL (4)
6Al-4V	181	5	140	+3	136	+2	14	-9	CEL (4)
6Al-4V <sup>b</sup>	181	5	138	+3	132	-6	14	-29	CEL (4)
13V-11Cr-3Al <sup>b</sup>	403	6,780	144	+18	140	+18	9	-2	CEL (4)
13V-11Cr-3Al <sup>b</sup>	751	5,640	144	+18	140	+20	9	+6	CEL (4)
13V-11Cr-3Al <sup>b</sup>	402	2,370	144	+6	140	+5	9	-22	CEL (4)
13V-11Cr-3Al <sup>b</sup>	181	5	134	+5	126	+8	20	-36	CEL (4)

<sup>a</sup>Numbers refer to references at end of report.<sup>b</sup>Unrelieved butt weld across width of specimens, TIG process, nonconsumable tungsten electrode.

## MISCELLANEOUS ALLOYS

The miscellaneous alloys are those alloys or metals which are "one of a kind" or do not belong to any of the previous classes of alloys discussed. These alloys would not be considered constructional because of their price, mechanical properties, scarcity, and, in some cases, poor corrosion resistance. Many of them could be used advantageously in specialty or unique applications.

The chemical compositions of the miscellaneous alloys are given in Table 85, and their corrosion rates and types of corrosion in Table 86.

Alloys columbium, gold, platinum, 90% platinum-10% copper, 75% platinum- 25% copper, tantalum, and tantalum-tungsten (Ta60) were uncorroded during exposure both at depth and at the surface.

Alloy MP35N neither corroded nor was susceptible to stress corrosion during 189 days of exposure at the 6,000-foot depth. The MP35N bolts and nuts were in a block of 6Al-4V titanium and were torqued to 50 ft-lb. There was also no galvanic corrosion of either member of the couple.

The corrosion of the three magnesium alloys (M1A, AZ31B, and HK31A) and beryllium was so rapid that their use in seawater would be impractical.

Platinum alloys containing 50 and 75% copper were etched and pitted after 402 days of exposure at the 2,500-foot depth. Such alloys are usually used for contacts in electrical applications. These two alloys would not be satisfactory for use in seawater.

Silver was attacked by the uniform thinning type of corrosion in seawater. The thin tarnish-like film is an excellent insulator; hence, silver could not be used as electrical contacts in seawater.

### 8.1. DURATION OF EXPOSURE

The effects of duration of exposure on some of the miscellaneous alloys are shown in Figures 18, 19, and 20. The corrosion rates of arsenical, chemical, and tellurium lead, lead-tin solder, tin, and zinc decreased with duration of exposure (Figures 18 and

19), except for lead-tin solder and zinc at the 2,500-foot depth. The corrosion rates of these two alloys increased with increasing time of exposure. At the 6,000-foot depth the corrosion rate of tin increased initially, and, thereafter, decreased with increasing time of exposure. The extremely high corrosion rate for tin after 751 days of exposure (Table 86), obviously, is an error and must be disregarded.

Only surface seawater data were available for molybdenum and tungsten, and the effects of duration of exposure are shown in Figure 20. The corrosion rate of molybdenum decreased, becoming asymptotic with increasing time of exposure. The corrosion rate of tungsten increased linearly with time, at least during the first 760 days of exposure.

### 8.2. EFFECT OF DEPTH

The effects of depth on the corrosion of some of the miscellaneous alloys after 1 year of exposure are shown in Figure 21. The corrosion of lead, lead-tin solder, molybdenum, tungsten, and tin was greater at the surface than at depth in the Pacific Ocean. Only the corrosion of zinc was greater at depth than at the surface.

### 8.3. EFFECT OF CONCENTRATION OF OXYGEN

The effects of changes in the concentration of oxygen in seawater are shown in Figure 22. The corrosion rates of arsenical, chemical, and tellurium lead, lead-tin solder, molybdenum, tungsten, and tin were higher at the highest concentration of oxygen than at the lowest, but the increases were not necessarily proportional or linear. Only the corrosion of zinc was not uniformly influenced by changes in the concentration of oxygen in seawater between the limits of 0.4 to 5.75 ml/l.

#### 8.4. MECHANICAL PROPERTIES

The effects of exposure on the mechanical properties of columbium, molybdenum, and tantalum are given in Table 87. The mechanical properties of

these three alloys were not impaired by exposure in seawater.

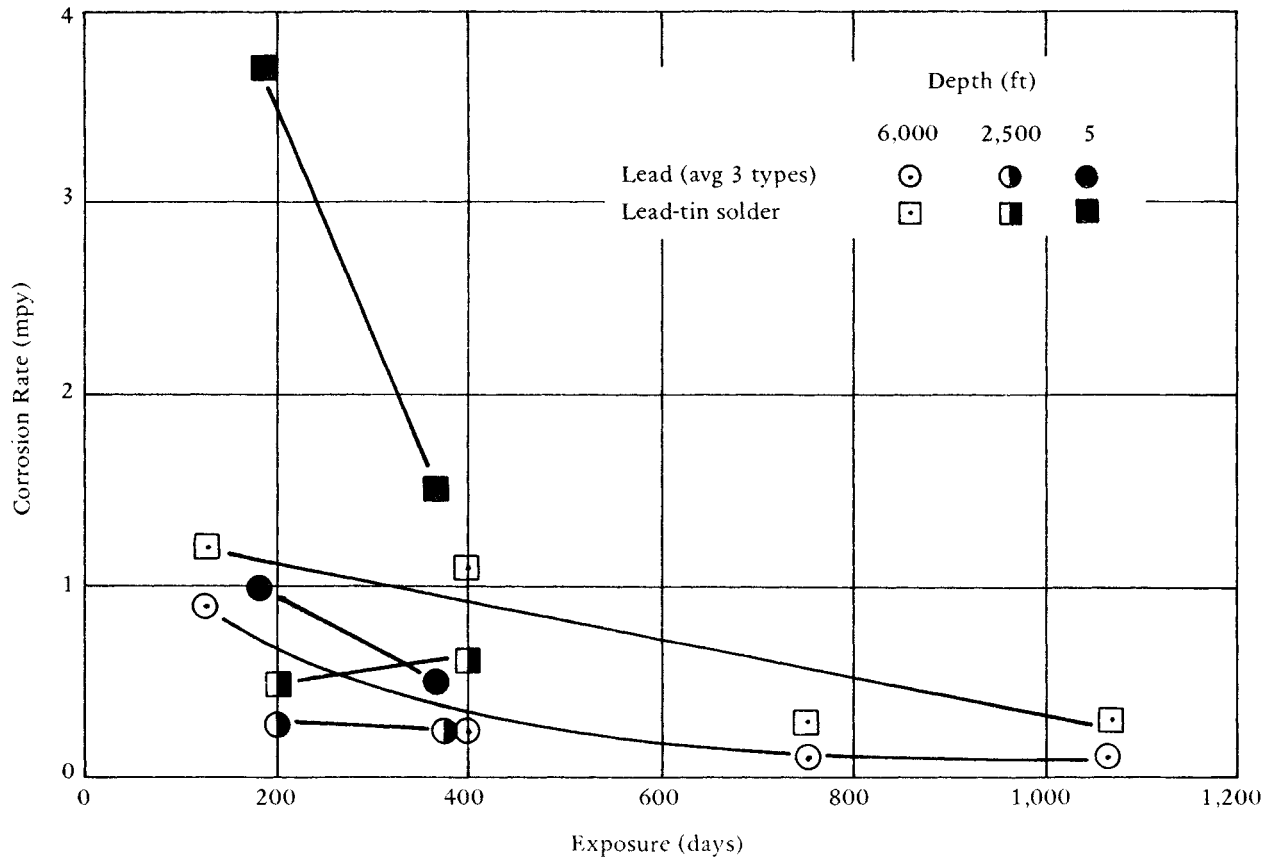


Figure 18. Effect of duration of exposure in seawater on the corrosion of lead and lead-tin solder at the surface and at depth.

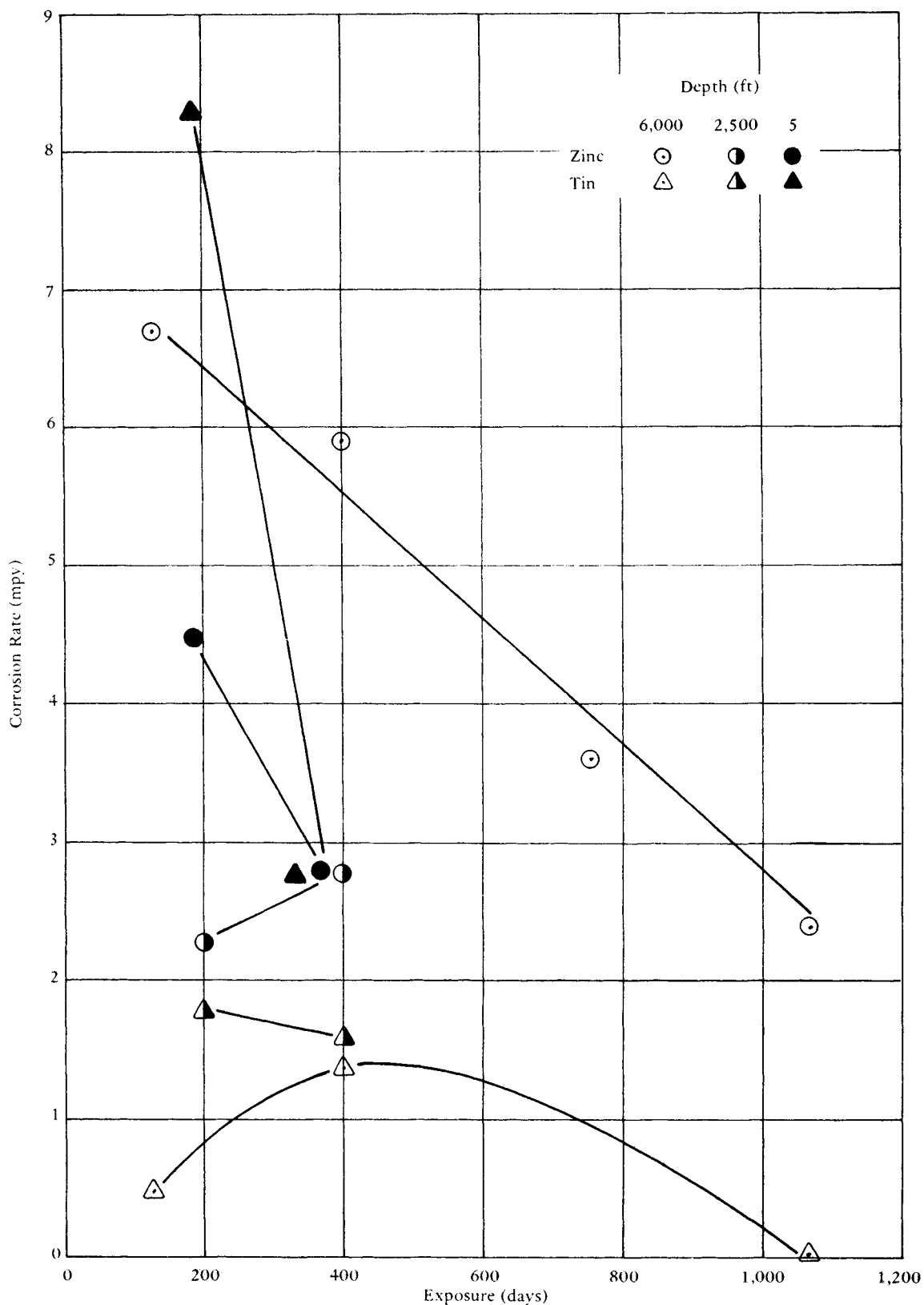


Figure 19. Effect of duration of exposure in seawater on the corrosion of tin and zinc at the surface and at depth.

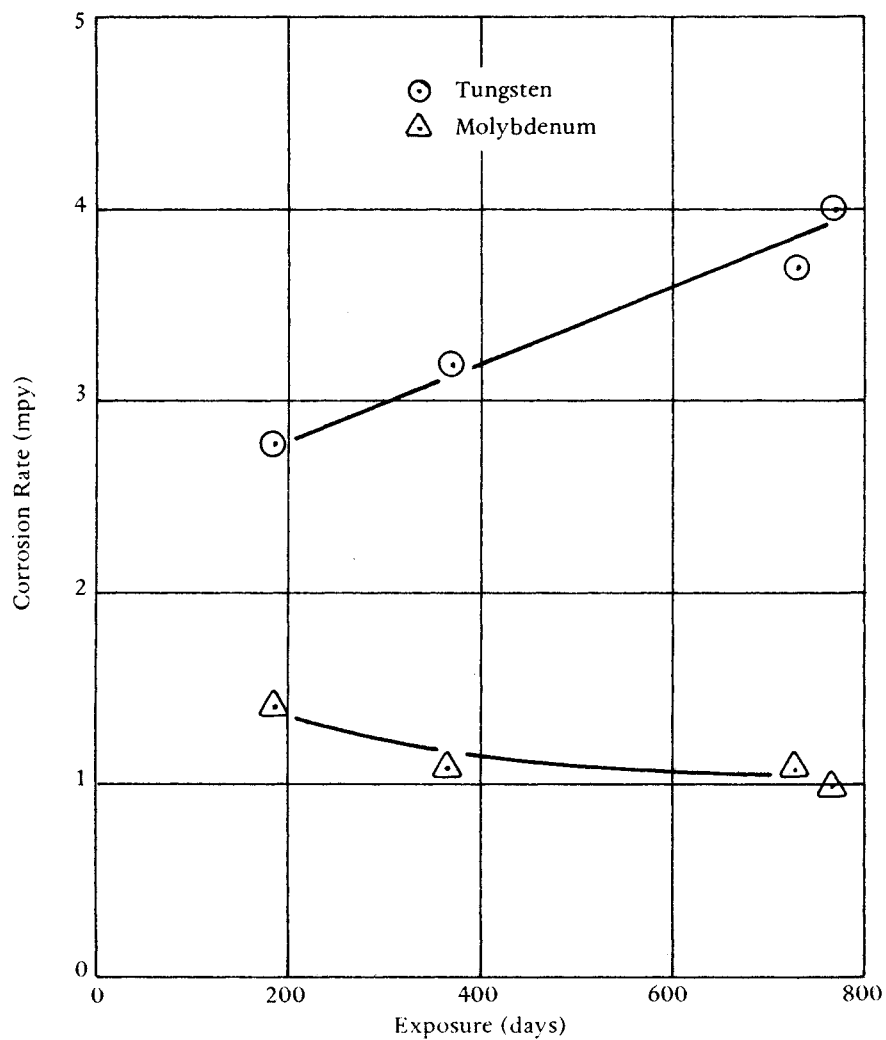


Figure 20. Effect of duration of exposure in surface seawater on the corrosion of molybdenum and tungsten.

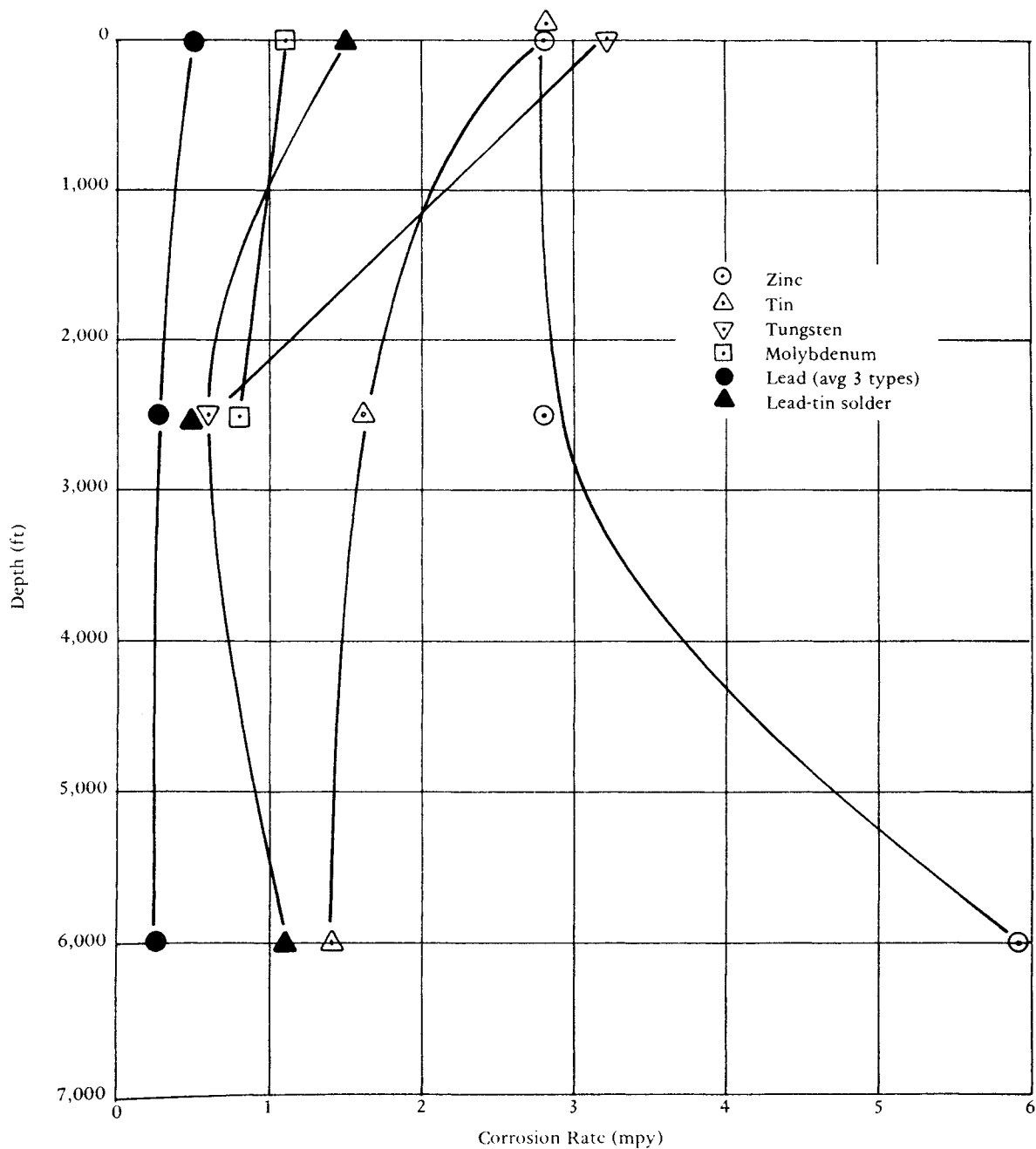


Figure 21. Effect of depth on the corrosion of miscellaneous alloys after 1 year of exposure.



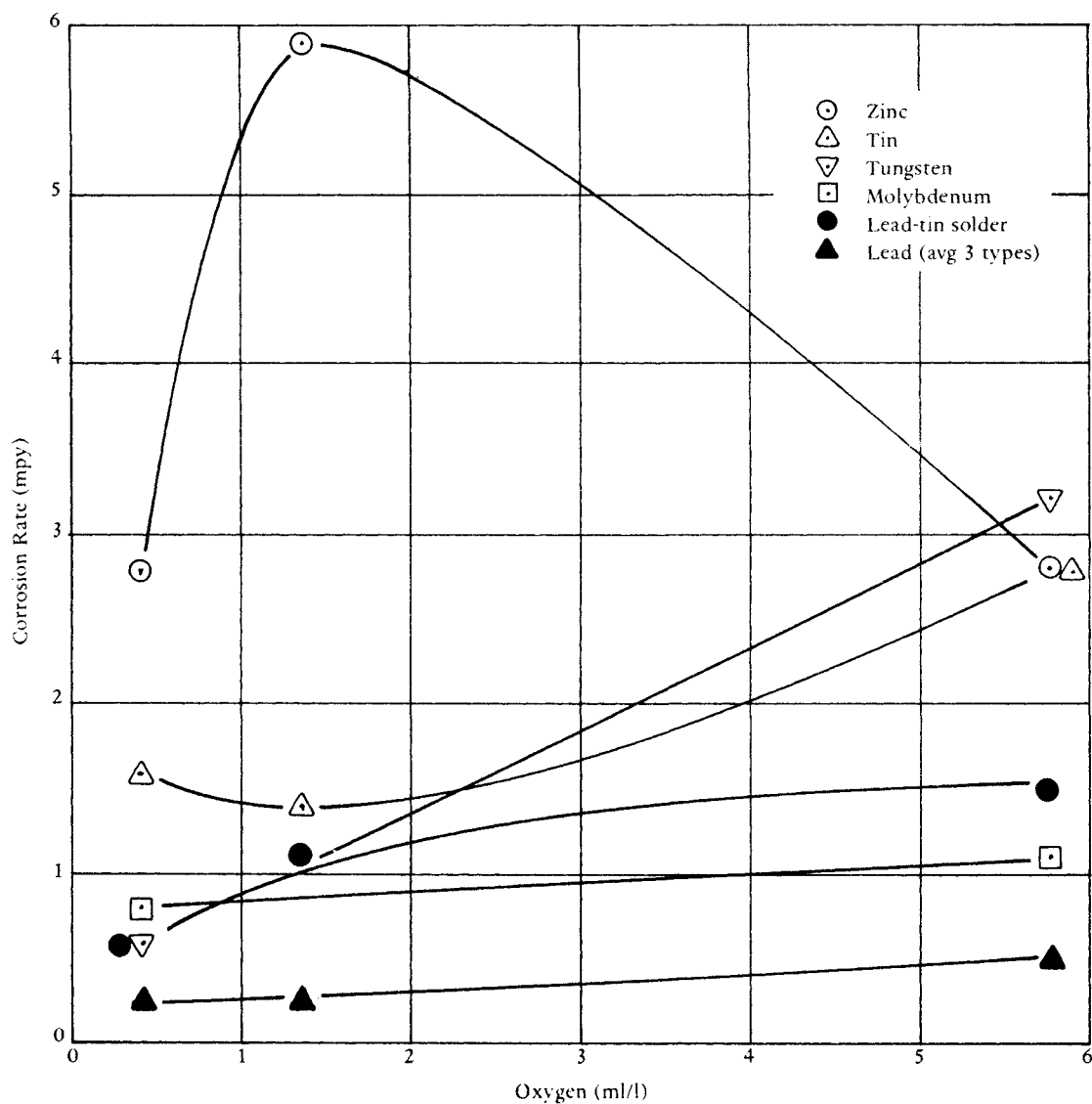


Figure 22. Effect of concentration of oxygen in seawater on the corrosion of miscellaneous alloys after 1 year of exposure.

Table 85. Chemical Composition of Miscellaneous Metals and Alloys, Percent by Weight

Alloy	Chemical Composition	Source <sup>a</sup>
Beryllium	99.0 Be	Boeing (6)
Columbium	99.75 Cb	CEL (4)
Columbium	99.8 Cb	CEL (4)
Gold	99.999 Au	CEL (4)
Lead, antimonial	99 Pb, 6 Sb	INCO (3)
Lead, chemical	99.9 Pb	INCO (3)
Lead, tellurium	99+ Pb, 0.04 Te	INCO (3)
Lead-tin solder	67 Pb, 33 Sn	INCO (3)
Magnesium, MIA	99 Mg, 1 Mn	INCO (3)
Magnesium, AZ31B	96 Mg, 2.6 Al, 1.1 Zn, 0.4 Mn	INCO (3)
Magnesium, AZ31B	95.3 Mg, 3.5 Al, 0.94 Zn, 0.25 Mn	NADC (7)
Magnesium, HK31A	96.2 Mg, 2.67 Th, 0.67 Zr, 0.45 Mn	NADC (7)
Molybdenum	99.9 Mo	CEL (4)
Platinum	99.99 Pt	CEL (4)
Platinum-copper, 90-10	90 Pt, 10 Cu	CEL (4)
Platinum-copper, 75-25	75 Pt, 25 Cu	CEL (4)
Platinum-copper, 50-50	50 Pt, 50 Cu	CEL (4)
Platinum-copper, 25-75	25 Pt, 75 Cu	CEL (4)
Silver	99.999 Ag	CEL (4)
Tantalum	99.9 Ta	CEL (4)
Tantalum	99.9 Ta, 0.010 C, 0.010 O, 0.005 N, 0.002 H	CEL (4)
Tantalum-tungsten, Ta 60	88.8-91.3 Ta, 8.5-11 W	CEL (4)
Tin	99.95 Sn	INCO (3)
Tungsten	99.95 W	CEL (4)
Zinc	99.9 Zn, 0.09 Pb, 0.01 Fe	INCO (3)
MP35N	35 Co, 35 Ni, 20 Cr, 10 Mo	CEL (4)

<sup>a</sup>Numbers refer to references at end of report.

Table 86. Corrosion Rates and Types of Corrosion of Miscellaneous Alloys

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion		Source <sup>c</sup>
				Rate (mpy)	Type <sup>b</sup>	
Beryllium	W	197	2,340	2.0	P (PR)(27)	Boeing (6)
Columbium	W	402	2,370	0.0	NC	CEL (4)
Columbium	S	402	2,370	0.0	NC	CEL (4)
Columbium	W	182	5	0.0	NC	CEL (4)
Columbium	W	364	5	0.0	NC	CEL (4)
Columbium	W	723	5	0.0	NC	CEL (4)
Columbium	W	763	5	0.0	NC	CEL (4)
Gold	W	402	2,370	0.0	NC	CEL (4)
Gold	S	402	2,370	0.0	NC	CEL (4)
Lead, antimonial	W	123	5,640	0.8	U	INCO (3)
Lead, antimonial	S	123	5,640	1.3	U	INCO (3)
Lead, antimonial	W	403	6,780	0.3	U	INCO (3)
Lead, antimonial	S	403	6,780	0.5	U	INCO (3)
Lead, antimonial	W	751	5,640	0.2	U	INCO (3)
Lead, antimonial	S	751	5,640	0.3	U	INCO (3)
Lead, antimonial	W	1,064	5,300	0.2	U	INCO (3)
Lead, antimonial	S	1,064	5,300	0.3	U	INCO (3)
Lead, antimonial	W	197	2,340	0.3	U	INCO (3)
Lead, antimonial	S	197	2,340	0.2	U	INCO (3)
Lead, antimonial	W	402	2,370	0.3	U	INCO (3)
Lead, antimonial	S	402	2,370	0.6	U	INCO (3)
Lead, antimonial	W	182	5	1.2	U	INCO (3)
Lead, antimonial	W	366	5	0.5	U	INCO (3)
Lead, chemical	W	123	5,640	0.8	U	INCO (3)
Lead, chemical	S	123	5,640	0.6	U	INCO (3)
Lead, chemical	W	403	6,780	0.2	U	INCO (3)
Lead, chemical	S	403	6,780	0.1	U	INCO (3)
Lead, chemical	W	751	5,640	0.1	U	INCO (3)
Lead, chemical	S	751	5,640	0.1	U	INCO (3)
Lead, chemical	W	1,064	5,300	0.1	U	INCO (3)
Lead, chemical	S	1,064	5,300	0.3	U	INCO (3)
Lead, chemical	W	197	2,340	0.3	U	INCO (3)
Lead, chemical	S	197	2,340	0.2	U	INCO (3)
Lead, chemical	W	402	2,370	0.2	U	INCO (3)
Lead, chemical	S	402	2,370	0.3	U	INCO (3)
Lead, chemical	W	182	5	0.8	U	INCO (3)
Lead, chemical	W	366	5	0.5	U	INCO (3)
Lead, tellurium	W	123	5,640	1.1	U	INCO (3)
Lead, tellurium	S	123	5,640	1.3	U	INCO (3)
Lead, tellurium	W	403	6,780	0.3	U	INCO (3)
Lead, tellurium	S	403	6,780	0.3	U	INCO (3)
Lead, tellurium	W	751	5,640	0.1	U	INCO (3)
Lead, tellurium	S	751	5,640	0.2	U	INCO (3)
Lead, tellurium	W	1,064	5,300	0.1	U	INCO (3)
Lead, tellurium	S	1,064	5,300	0.3	U	INCO (3)
Lead, tellurium	W	197	2,340	0.3	U	INCO (3)

Continued

Table 86. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion		Source <sup>c</sup>
				Rate (mpy)	Type <sup>b</sup>	
Lead, tellurium	S	197	2,340	0.3	U	INCO (3)
Lead, tellurium	W	402	2,370	0.2	U	INCO (3)
Lead, tellurium	S	402	2,370	0.3	U	INCO (3)
Lead, tellurium	W	182	5	1.0	U	INCO (3)
Lead, tellurium	W	366	5	0.5	U	INCO (3)
Lead-tin solder	W	123	5,640	1.2	U	INCO (3)
Lead-tin solder	S	123	5,640	0.7	U	INCO (3)
Lead-tin solder	W	403	6,780	1.1	U	INCO (3)
Lead-tin solder	S	403	6,780	0.6	U	INCO (3)
Lead-tin solder	W	751	5,640	0.3	U	INCO (3)
Lead-tin solder	S	751	5,640	0.4	U	INCO (3)
Lead-tin solder	W	1,064	5,300	0.3	U	INCO (3)
Lead-tin solder	S	1,064	5,300	0.5	G	INCO (3)
Lead-tin solder	W	197	2,340	0.5	U	INCO (3)
Lead-tin solder	S	197	2,340	0.3	U	INCO (3)
Lead-tin solder	W	402	2,370	0.6	U	INCO (3)
Lead-tin solder	S	402	2,370	0.7	U	INCO (3)
Lead-tin solder	W	182	5	3.7	U	INCO (3)
Lead-tin solder	W	366	5	1.5	G	INCO (3)
Magnesium, M1A	W	123	5,640	42.0	S	INCO (3)
Magnesium, M1A	S	123	5,640	43.0	S	INCO (3)
Magnesium, M1A	W	403	6,780	>20.0	100C	INCO (3)
Magnesium, M1A	S	403	6,780	7.3	S-G	INCO (3)
Magnesium, M1A	W	751	5,640	>10.0	100C	INCO (3)
Magnesium, M1A	S	751	5,640	>12.0	100C	INCO (3)
Magnesium, M1A	W	1,064	5,300	—	100C	INCO (3)
Magnesium, M1A	S	1,064	5,300	2.9	S	INCO (3)
Magnesium, M1A	W	197	2,340	—	100C	INCO (3)
Magnesium, M1A	S	197	2,340	9.0	S	INCO (3)
Magnesium, AZ31B	W	123	5,640	>59.0	100C	INCO (3)
Magnesium, AZ31B	W	123	5,640	—	P (PR)	NADC (7)
Magnesium, AZ31B	S	123	5,640	27.0	S	INCO (3)
Magnesium, AZ31B	W	403	6,780	>20.0	100C	INCO (3)
Magnesium, AZ31B	W	403	6,780	—	N-P (PR)	NADC (7)
Magnesium, AZ31B	S	403	6,780	6.6	S-G	INCO (3)
Magnesium, AZ31B	W	751	5,640	>10.0	100C	INCO (3)
Magnesium, AZ31B	S	751	5,640	>10.0	100C	INCO (3)
Magnesium, AZ31B	W	1,064	5,300	—	100C	INCO (3)
Magnesium, AZ31B	S	1,064	5,300	> 7.0	100C	INCO (3)
Magnesium, AZ31B	W	197	2,340	—	100C	INCO (3)
Magnesium, AZ31B	W	197	2,340	—	EX-G	NADC (7)
Magnesium, AZ31B	S	197	2,340	>15.0	50C	INCO (3)
Magnesium, AZ31B	W	402	2,370	—	100C	INCO (3)
Magnesium, AZ31B	S	402	2,370	11.0	S	INCO (3)
Magnesium, AZ31B	W	182	5	>40.0	95C	INCO (3)
Magnesium, AZ31B	W	366	5	>20.0	100C	INCO (3)

Continued

Table 86. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion		Source <sup>c</sup>
				Rate (mpy)	Type <sup>b</sup>	
Magnesium, HK31A	W	403	6,780	—	S-G <sup>d</sup>	NADC (7)
Magnesium, HK31A	W	197	2,340	—	EX-G <sup>d</sup>	NADC (7)
Molybdenum	W	402	2,370	0.8	C (9); U	CEL (4)
Molybdenum	S	402	2,370	0.8	C (6); U	CEL (4)
Molybdenum	W	182	5	1.4	U	CEL (4)
Molybdenum	W	364	5	1.1	U-ET	CEL (4)
Molybdenum	W	723	5	1.1	G	CEL (4)
Molybdenum	W	763	5	1.0	C (6); G	CEL (4)
Platinum	W	402	2,370	0.0	NC	CEL (4)
Platinum	S	402	2,370	0.0	NC	CEL (4)
90Pt-10Cu	W	402	2,370	0.0	NC	CEL (4)
90Pt-10Cu	S	402	2,370	0.0	NC	CEL (4)
75Pt-25Cu	W	402	2,370	0.0	NC	CEL (4)
75Pt-25Cu	S	402	2,370	0.0	NC	CEL (4)
50Pt-50Cu	W	402	2,370	—	ET	CEL (4)
50Pt-50Cu	S	402	2,370	—	ET; P	CEL (4)
25Pt-75Cu	W	402	2,370	—	ET; P	CEL (4)
25Pt-75Cu	S	402	2,370	—	ET; P	CEL (4)
Silver	W	402	2,370	0.6	U	CEL (4)
Silver	S	402	2,370	0.5	U	CEL (4)
Tantalum	W	402	2,370	0.0	NC	CEL (4)
Tantalum	S	402	2,370	0.0	NC	CEL (4)
Tantalum	W	182	5	0.0	NC	CEL (4)
Tantalum	W	364	5	0.0	NC	CEL (4)
Tantalum	W	723	5	0.0	NC	CEL (4)
Tantalum	W	763	5	0.0	NC	CEL (4)
Ta-60	W	182	5	0.0	NC	CEL (4)
Ta-60	W	364	5	0.0	NC	CEL (4)
Ta-60	W	723	5	0.0	NC	CEL (4)
Ta-60	W	763	5	0.0	NC	CEL (4)
Tin	W	123	5,640	0.5	G	INCO (3)
Tin	S	123	5,640	0.6	G	INCO (3)
Tin	W	403	6,780	1.4	P (17)	INCO (3)
Tin	S	403	6,780	1.7	SH-CR	INCO (3)
Tin	W	751	5,640	20.4	P (PR)(30)	INCO (3)
Tin	S	751	5,640	0.1	G	INCO (3)
Tin	W	1,064	5,300	< 0.1	SC-ET	INCO (3)
Tin	S	1,064	5,300	0.3	G	INCO (3)
Tin	W	197	2,340	1.8	C (2); CR (2)	INCO (3)
Tin	S	197	2,340	< 0.1	P (2)	INCO (3)
Tin	W	402	2,370	1.6	SC-P (9)	INCO (3)
Tin	S	402	2,370	0.1	C (1)	INCO (3)
Tin	W	182	5	8.3	P (PR)(30)	INCO (3)
Tin	W	366	5	2.8	C (PR)(30); P (PR)(30)	INCO (3)

Continued

Table 86. Continued.

Alloy	Environment <sup>a</sup>	Exposure (day)	Depth (ft)	Corrosion		Source <sup>c</sup>
				Rate (mpy)	Type <sup>b</sup>	
Tungsten	W	402	2,370	0.6	U	CEL (4)
Tungsten	S	402	2,370	0.5	U	CEL (4)
Tungsten	W	182	5	2.8	U	CEL (4)
Tungsten	W	364	5	3.2	U	CEL (4)
Tungsten	W	723	5	3.7	U	CEL (4)
Tungsten	W	763	5	4.0	U	CEL (4)
Zinc	W	123	5,640	6.7	P (13)	INCO (3)
Zinc	S	123	5,640	5.0	P (25)	INCO (3)
Zinc	W	403	6,780	5.9	C (PR)(30)	INCO (3)
Zinc	S	403	6,780	0.2	G	INCO (3)
Zinc	W	751	5,640	3.6	G	INCO (3)
Zinc	S	751	5,640	2.8	G	INCO (3)
Zinc	W	1,064	5,300	2.4	CR: E	INCO (3)
Zinc	S	1,064	5,300	0.7	G	INCO (3)
Zinc	W	197	2,340	2.3	P (2)	INCO (3)
Zinc	S	197	2,340	0.3	G	INCO (3)
Zinc	W	402	2,370	2.8	G	INCO (3)
Zinc	S	402	2,370	2.4	GASL	INCO (3)
Zinc	W	182	5	4.5	P (5)	INCO (3)
Zinc	W	366	5	2.8	P (10)	INCO (3)

<sup>a</sup>W = Totally exposed in seawater on sides of structure; S = Exposed in base of structure so that the lower portions of the specimens were embedded in the bottom sediments.

<sup>b</sup>Symbols for types of corrosion:

C = Crevice	PR = Perforated	GASL = General above sediment line.
CR = Cratering	S = Severe	
ET = Etched	SC = Scattered	
EX = Extensive	SH = Shallow	
G = General	U = Uniform	
N = Numerous	50C = 50% corroded	
NC = No visible corrosion	95C = 95% corroded	
P = Pitting	100C = 100% corroded	

Numbers in parentheses indicate maximum depth in mils.

<sup>c</sup>Numbers refer to references at end of report.

<sup>d</sup>Thick, black, brittle crust of corrosion products.

Table 87. Changes in Mechanical Properties of Miscellaneous Alloys Due to Corrosion

Alloy	Exposure (day)	Depth (ft)	Tensile Strength		Yield Strength		Elongation		Source <sup>a</sup>
			Original (ksi)	% Change	Original (ksi)	% Change	Original (%)	% Change	
Molybdenum	402	2,370	14	+3	12	+9	17	-20	CEL (4)
Molybdenum <sup>b</sup>	402	2,370	14	+3	12	+4	17	-29	CEL (4)
Molybdenum	181	5	14	-2	12	+1	17	-14	CEL (4)
Molybdenum	364	5	14	-5	12	+2	17	-29	CEL (4)
Tantalum	402	2,370	49	-3	37	-4	49	-6	CEL (4)
Tantalum <sup>b</sup>	402	2,370	49	-3	37	+1	49	-5	CEL (4)
Tantalum	181	5	49	-4	37	-11	49	-5	CEL (4)
Tantalum	364	5	49	-3	37	-18	49	+66	CEL (4)
Columbium	402	2,370	114	+6	102	-3	12	-17	CEL (4)
Columbium <sup>b</sup>	402	2,370	114	-3	102	0	12	0	CEL (4)
Columbium	181	5	114	-3	102	-2	12	+2	CEL (4)
Columbium	364	5	114	-5	102	-20	12	+33	CEL (4)

<sup>a</sup>Numbers refer to references at end of report.<sup>b</sup>Exposed in bottom sediments.



## WIRE ROPES

Wire ropes of many different chemical compositions, with different types of coatings, of different sizes, and of different types of construction were exposed in seawater at depth to determine their corrosion behavior. Some were stressed in tension to determine their susceptibility to stress corrosion or whether stress increased their rates of corrosion.

The chemical compositions of the ropes are given in Table 88, and their corrosion behavior in Table 89.

There was no visible corrosion on rope numbers 15, 18, 19, 20, 21, 22, 41 (751 days, 6,000 feet), 48, 49, 50, 51, 52, and 53. Rope number 15 was Type 316 stainless steel modified by adding silicon and nitrogen and was exposed for 189 days at the 6,000-foot depth. Wire rope number 41, conventional Type 316, was uncorroded after 751 days of exposure at the 6,000-foot depth, but was rusted with some internal wires broken and crevice corrosion after 1,064 days of exposure; its breaking strength was decreased by 41% after 1,064 days of exposure at the 6,000-foot depth. Because the conventional Type 316 stainless steel was not corroded until between 751 and 1,064 days of exposure, it cannot be stated that the addition of silicon and nitrogen to the Type 316 stainless steel improved its corrosion resistance.

Rope numbers 18, 19, 20, and 21 were nickel base alloys. Rope numbers 20 and 21 were also uncorroded when lying on or in the bottom sediment.

Rope number 22 was a cobalt base alloy which was also uncorroded when lying on or in the bottom sediment. It, also, was not susceptible to stress corrosion in either the seawater or the bottom sediment when stressed to 40% of its breaking strength.

Rope numbers 48, 49, 50, 51, 52, and 53 were 6Al-4V-Ti ropes and wires. The ropes and wires themselves were not corroded, but the Type 304 stainless steel fittings and steel tie wires were severely corroded galvanically.

All the other wire ropes, coated or uncoated, were corroded to varying degrees of severity, the most severe being the parting of the wires.

Bare steel wires 1, 2, 3, 35, and 36, as expected, were completely covered with rust. There was no loss of strength after periods of exposure of as long as

1,064 days. These ropes had been lubricated during fabrication; the lubricant on the outer surfaces of the ropes had disappeared, but not on the internal surfaces during exposure. One rope, No. 2, was degreased prior to exposure; as a result, it was more severely corroded than the others on the outside surfaces, and there was light rust on many of the internal wires. One rope, No. 3, was degreased, then wrapped with 10-mil-thick polyethylene tape prior to exposure. There was heavy rust underneath the tape for a distance of about 3 feet from each end and there was light rust on about 75% of the internal wires. Wires 35 and 36 had been stressed in tension to 20% of their respective breaking strengths prior to exposure. These two ropes were covered with rust with no rust on the internal wires, did not fail by stress corrosion, and had no decrease in their breaking strengths.

The galvanized (zinc-coated) ropes were numbers 4, 5, 6, 23, 24, 25, 26, 27, 28, 37, and 38. The zinc coatings protected the steel wires, but there was no good correlation between the weight or thickness of coating and the duration of protection. In general, except for the electrogalvanized coating, the heavier the coating the longer the period of time before rust appeared on the ropes. The breaking strengths of the ropes were not impaired by exposures for as long as 1,064 days of exposure. Also, rope numbers 37 and 38 were not susceptible to stress corrosion when stressed to 20% of their respective breaking strengths.

Rope numbers 7, 8, 9, and 40, in addition to being galvanized, were also jacketed with plastic coatings. In all cases, seawater penetrated along the interfaces between the ropes and the jackets. There was some light rust on the strands of rope number 40 underneath the poly(vinyl chloride) jacket after 751 days of exposure. The polyurethane (rope number 7) and polyethylene (rope numbers 8 and 9) jackets protected the galvanized ropes to a considerable extent. The jackets were not punctured or broken, but seawater had penetrated to the metal ropes through the end terminations. That water had penetrated to the interface between the jackets and the ropes was proven by puncturing the jackets, at which time seawater spurled out under considerable

pressure. When a terminal was removed from one end of each specimen, the zinc coatings were gone from the portions of the ropes which had been inside the terminals and the wires of the strands were rusted. The polyethylene jacket on one rope (number 9) had been punctured in many places prior to exposure. After exposure these holes were filled with white corrosion products; there was pressure underneath the jacket; and there was no rust on the wires except inside the terminals.

Rope numbers 39, 43, 44, and 45 were aluminized (coated with a layer of aluminum). Aluminum coatings afforded considerable protection to steel ropes in the same manner as did zinc coatings. A 0.38-oz/sq ft of aluminum coating (1.4 mils thick) afforded protection to steel rope for about the same period of time as did an 0.83-oz/sq ft of zinc coating (1.4 mils thick). In deep-ocean environments, equal thicknesses of coatings of zinc and aluminum protected steel ropes for about the same periods of time, but on a weight basis zinc was about twice as heavy as aluminum. There was no decrease in breaking strength caused by corrosion. Also, rope number 39 was not susceptible to stress corrosion when stressed at 20% of its breaking strength.

Rope numbers 10, 11, 12, 13, 14, 15, 16, 17, 29, 30, 31, 32, 33, 34, 41, and 42 were stainless steels of different chemical compositions. The 0.1875-inch-diameter Type 304 stainless steel ropes (10, 11, 12, 13, 29, 30, and 31), stress relieved and not stress relieved, were corroded by crevice, pitting, and tunnel corrosion; and many of the wires had parted because of corrosion, particularly internal wires. There were only rust spots on the larger diameter, 0.250-through-0.375-inch, Type 304 ropes (32, 33, and 34) for equivalent periods of exposure. The addition of vanadium and nitrogen (rope number 16) to the Type 304 composition did not improve the corrosion resistance of the Type 304 stainless steel. The addition of copper (rope number 14) to the Type 316 stainless steel composition impaired its corrosion resistance, while the addition of silicon and nitrogen (rope number 15) did not appear to have any influence. The conventional Type 316 stainless steel (rope number 41) was uncorroded after 751 days of exposure, but after 1,064 days there were many internal wires broken as a result of attack by crevice corrosion. The breaking strengths of most of the

stainless steel ropes were impaired by exposure in seawater at depth. Rope numbers 41 and 42 were not susceptible to stress corrosion when stressed at 20% of their respective breaking strengths.

Two Type 304 stainless steel ropes (numbers 46 and 47) were clad with 90% copper-10% nickel alloy. Rope number 46, which had a clad layer 0.7 inch thick, had a green color after 402 days of exposure, indicating that the Cu-Ni clad layer had not been completely sacrificed. However, rope number 47, which had a clad layer 0.3 mil thick, was covered with a light film of rust, indicating that it had been completely sacrificed during the same period of time. In both cases the internal wires of the ropes were uncorroded.

Table 88. Chemical Composition of Wire Ropes

Rope	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Co	Fe <sup>a</sup>	Other
Fe-Cr-Ni-Mo-Cu	0.065	1.55	0.010	0.013	1.39	13.90	18.64	2.44	1.95	—	R	0.060 N, <0.01 Zr, <0.02 V
Fe-Cr-Ni-Mo-Si-N	0.072	1.60	0.013	0.015	2.28	13.80	18.70	2.47	< 0.02	—	R	0.17 N, <0.01 Zr, <0.02 V
Fe-Cr-Ni-V-N	0.070	1.35	0.012	0.014	0.98	13.70	19.56	< 0.01	< 0.02	—	R	0.15 N, <0.01 Zr, 3.50 V
Fe-Cr-Ni-Si	0.063	1.51	0.005	0.008	1.92	17.82	17.82	0.02	0.03	—	R	—
Ni-Mo-Cr-C	0.014	0.45	0.010	0.008	0.53	60.2	15.9	15.0	—	—	3.56	0.080 V, 3.14 W
Ni-Co-Cr-Mo	—	—	—	—	—	35.0	20.0	10.0	—	35.0	—	—
Ni-Cr-Mo 103	0.02	—	—	—	—	67.0	18.0	14.0	—	—	—	0.50 Cb
Ni-Cr-Mo 625	0.05	—	—	0.007	0.30	61.0	22.0	9.0	0.10	—	3.0	Cb + 4.0 Ta
Co-Cr-Ni-Fe-Mo	0.050	1.96	—	—	0.74	14.96	19.84	7.14	—	40.46	14.60	0.058 Al, 0.07 Be, 0.058 Zr, 0.011 Ca
Cr-Mn-N	0.07	14.3	0.021	0.003	0.67	0.27	18.4	—	—	—	R	0.48 N
AISI type 304 <sup>b</sup>	0.08	—	—	—	—	10.0	19.0	—	—	—	R	—
AISI type 316 <sup>b</sup>	0.08	—	—	—	—	12.0	17.0	2.5	—	—	R	—
90-10 Clad 304 <sup>b</sup>												
304 Core	0.08	—	—	—	—	10.0	19.0	—	—	—	R	—
90-10 Clad	—	—	—	—	—	10.0	—	—	90.0	—	—	—
Aircraft cable <sup>c</sup>												
Plow steel <sup>d</sup>												
Improved plow steel <sup>e</sup>												
Monitor steel <sup>f</sup>												
Monitor AA steel <sup>g</sup>												

<sup>a</sup>R = remainder.<sup>b</sup>Nominal chemical composition.<sup>c</sup>No chemical composition requirements; but strength requirements very high, especially for processed carbon steel wire.<sup>d</sup>No chemical composition requirements; only mechanical strength requirements.<sup>e</sup>No chemical composition requirements; mechanical strength requirements 15% higher than those for plow steel.<sup>f</sup>Same as plow steel.<sup>g</sup>Same as improved plow steel.

Table 89. Corrosion of Wire Ropes

Rope No.	Alloy <sup>a</sup>	Coating	Diameter (in.)	Construction	Stress on Rope (lb)	Exposure (day)	Depth (ft)	Breaking Load			Remarks
								Original (lb)	Final (lb)	% Change	
1	Flow steel	lubricated	0.875	7 x 19	0	123	6,000	48,200	48,200	0	Rust on crowns of outside wires; lubricant still in grooves; inside: wires bright; tensile fracture.
1	Flow steel	lubricated	0.875	7 x 19	0	751	6,000	48,200	45,800	-5	Outside: 100% rust; inside: wires bright; tensile fracture.
2	Flow steel	degreased	0.875	7 x 19	0	123	6,000	48,200	48,200	0	Outside: 100% rust; inside: wires light rust, few bright spots; tensile and torsion fractures.
2	Flow steel	degreased	0.875	7 x 19	0	751	6,000	48,200	49,300	+2	Outside: 100% rust; inside: wires light rust, few bright spots; tensile fracture.
3	Flow steel	degreased; covered with 10-mil polyethylene tape	0.875	7 x 19	0	123	6,000	48,200	48,900	+2	Rust underneath tape for about 3 feet from ends; inside: 50% light rust, 50% bright; tensile and torsion fractures.
3	Flow steel	degreased; covered with 10-mil polyethylene tape	0.875	7 x 19	0	751	6,000	48,200	48,200	0	Heavy rust at edges and underneath tape for about 3 feet from ends; inside: 75% light rust, 25% bright; tensile fracture.
4	Improved plow steel	Zn 0.50 oz/ft <sup>2</sup>	0.250	3 x 19	0	189	6,000	-	-	-	Outside: light, uniform rust, heavy in some grooves.
5	Improved plow steel	Zn 0.70 oz/ft <sup>2</sup>	0.500	3 x 19	0	189	6,000	-	-	-	Outside: yellow with few areas of heavy rust in grooves.
6	Improved plow steel	Zn 0.90 oz/ft <sup>2</sup>	0.500	3 x 7	0	189	6,000	-	-	-	Outside: grey-yellow, few areas of white corrosion products, few areas of heavy yellow corrosion products in grooves.
7	Improved plow steel	Zn 0.70 oz/ft <sup>2</sup> , polyurethane jacket	0.500	3 x 19	0	189	6,000	-	-	-	No breaks in coating; white corrosion products on ends of terminals; terminations not watertight.
8	Improved plow steel	Zn 0.70 oz/ft <sup>2</sup> , polyethylene jacket	0.500	3 x 19	0	189	6,000	-	-	-	No breaks in coating; white corrosion products on ends of terminals; terminations not watertight.
9	Improved plow steel	Zn 0.70 oz/ft <sup>2</sup> , punctured polyethylene jacket	0.500	3 x 19	0	189	6,000	-	-	-	No rust at punctures in jacket; no breaks in coating; white corrosion products at ends of terminals; terminations not watertight.
10	AISI Type 304	not stress relieved	0.1875	3 x 19	0	189	6,000	-	-	-	Dull grey with light rust stains; 12-in. length near center of wire covered with heavy red rust; some broken wires; when cleaned, many broken wires, tunnel, pitting, and crevice corrosion.
11	AISI Type 304	stress relieved	0.1875	3 x 19	0	189	6,000	-	-	-	Dull grey; some light rust stains; heavy rust at edges of silicone potting compound; broken wires at edge of silicone compound under heavy rust at one end (crevice corrosion); when cleaned, numerous broken wires, internal tunnel, pitting, and crevice corrosion.
12	AISI Type 304	not stress relieved	0.1875	3 x 7	0	189	6,000	-	-	-	Dull grey; light rust and some heavy rust in some areas; crevice corrosion; when cleaned, broken wires, tunnel, pitting, and crevice corrosion.

Continued

Table 89. Continued.

Rope No.	Alloy <sup>a</sup>	Coating	Diameter (in.)	Construction	Stress on Rope (lb)	Exposure (day)	Depth (ft)	Breaking Load			Remarks
								Original (lb)	Final (lb)	% Change	
13	AISI Type 304	stress relieved	0.1875	3 x 7	0	189	6,000	—	—	—	Dull grey; light rust stains; few pits on crowns of outside wires; when cleaned, crevice, pitting, and tunnel corrosion.
14	Fe-Cr-Ni-Mo-Cu	bare	0.125	3 x 7	0	189	6,000	—	—	—	Dull grey with mottled light yellow stains; when cleaned, incipient crevice corrosion.
15	Fe-Cr-Ni-Mo-Si-N	bare	0.125	1 x 7	0	189	6,000	—	—	—	No visible corrosion; metallic sheen still present.
16	Fe-Cr-Ni-V-N	bare	0.125	1 x 7	0	189	6,000	—	—	—	Failed by tunnel and crevice corrosion underneath silicone potting compound; only end loops recovered.
17	Fe-Cr-Ni-Si	bare	0.125	1 x 7	0	189	6,000	—	—	—	Grey, no visible corrosion; when cleaned, many areas of slight crevice corrosion and shallow pitting.
18	Ni-Co-Cr-Mo	bare	0.0625	1 x 7	0	189	6,000	—	—	—	No visible corrosion; original metallic sheen intact.
19	Ni-Mo-Cr C	bare	0.0625	1 x 7	0	189	6,000	—	—	—	No visible corrosion; original metallic sheen intact.
20	Ni-Cr-Mo 625	bare	0.250	7 x 19	0	189	6,000	7,400	—	—	No visible corrosion; original metallic sheen intact.
20	Ni-Cr-Mo 625 <sup>b</sup>	bare	0.250	7 x 19	0	189	6,000	7,400	—	—	No visible corrosion; original metallic sheen intact.
21	Ni-Cr-Mo 103	bare	0.250	7 x 19	0	189	6,000	7,000	—	—	No visible corrosion; original metallic sheen intact.
21	Ni-Cr-Mo 103 <sup>b</sup>	bare	0.250	7 x 19	0	189	6,000	7,000	—	—	No visible corrosion; original metallic sheen intact.
22	Co-Cr-Ni-Fe-Mo	bare	0.1875	3 x 19	0	189	6,000	4,000	—	—	Original blue film gone; no visible corrosion.
22	Co-Cr-Ni-Fe-Mo	bare	0.1875	3 x 19	1,600	189	6,000	4,000	—	—	No wire failures; original blue film gone; no visible corrosion.
22	Co-Cr-Ni-Fe-Mo <sup>b</sup>	bare	0.1875	3 x 19	0	189	6,000	4,000	—	—	Original blue film gone; no visible corrosion.
22	Co-Cr-Ni-Fe-Mo <sup>b</sup>	bare	0.1875	3 x 19	1,600	189	6,000	4,000	—	—	No wire failures; original blue film gone; no visible corrosion.
23	Aircraft cord	Zn 0.40 oz/ft <sup>2</sup>	0.0938	7 x 7	0	403	6,000	1,100	1,100	0	Dark grey to black; tensile fracture.
23	Aircraft cord	Zn 0.40 oz/ft <sup>2</sup>	0.0938	7 x 7	0	197	2,500	1,100	1,000	-9	Outside: 100% rust; inside: grey; tensile fracture.
24	Aircraft cable	Zn 0.40 oz/ft <sup>2</sup>	0.125	7 x 19	0	403	6,000	2,000	1,000	-50	Dark grey to black; inside: grey; tensile fracture.
24	Aircraft cable	Zn 0.40 oz/ft <sup>2</sup>	0.125	7 x 19	0	197	2,500	2,000	1,800	-10	Outside: 100% rust; inside: grey; tensile and torsion fractures.
25	Aircraft cable	Zn 0.50 oz/ft <sup>2</sup>	0.1875	7 x 19	0	403	6,000	3,500	4,000	+14	Outside: dark grey to black; inside: grey; tensile and torsion fractures.
25	Aircraft cable	Zn 0.50 oz/ft <sup>2</sup>	0.1875	7 x 19	0	197	2,500	3,500	3,700	+6	Outside: dark grey; inside: grey; tensile and torsion fractures.
26	Wire rope	Zn 0.50 oz/ft <sup>2</sup>	0.1875	1 x 7	0	403	6,000	2,600	2,600	0	Outside: 90% rust; inside: grey; tensile fracture.
26	Wire rope	Zn 0.50 oz/ft <sup>2</sup>	0.1875	1 x 7	0	197	2,500	2,600	2,500	-4	Outside: medium grey, few rust spots; inside: grey; tensile fracture.

Continued

Table 89. Continued.

Rope No.	Alloy <sup>a</sup>	Coating	Diameter (in.)	Construction	Stress on Rope (lb)	Exposure (day)	Depth (ft)	Breaking Load			Remarks
								Original (lb)	Final (lb)	% Change	
27	Wire rope	Zn 0.85 oz/ft <sup>2</sup>	0.250	1 x 7	0	403	6,000	5,900	4,600	-22	Outside: 100% yellow; inside: grey; tensile fracture.
27	Wire rope	Zn 0.85 oz/ft <sup>2</sup>	0.250	1 x 7	0	197	2,500	5,900	5,300	-10	Outside: medium grey, few rust spots; inside: grey; tensile fracture.
28	Aircraft cable	Zn 0.60 oz/ft <sup>2</sup>	0.250	7 x 19	0	403	6,000	6,100	5,900	-2	Outside: dark grey to black; inside: grey; tensile and torsion fractures.
28	Aircraft cable	Zn 0.60 oz/ft <sup>2</sup>	0.250	7 x 19	0	197	2,500	6,100	6,200	+2	Outside: dark grey to black; inside: grey; tensile fracture.
29	Aircraft cord	bare, Type 304	0.0938	7 x 7	0	403	6,000	800	100	-88	Internal strands corroded; tunnel, crevice, and pitting; many wires parted by corrosion.
29	Aircraft cord	bare, Type 304	0.0938	7 x 7	0	197	2,500	800	800	0	Outside: few rust spots; inside: bright; tensile fracture.
30	Aircraft cable	bare, Type 304	0.125	7 x 19	0	403	6,000	1,600	200	-88	Outside: few rust stains; inside: broken wires, crevice and pitting corrosion.
30	Aircraft cable	bare, Type 304	0.125	7 x 19	0	197	2,500	1,600	1,800	+13	Outside: original metallic lustre; inside: bright; tensile fracture.
31	Aircraft cable	bare, Type 304	0.1875	7 x 19	0	403	6,000	2,700	100	-96	Outside: many rust stains and broken wires, pitting, tunnel and crevice corrosion; inside: many broken wires, pitting, tunnel, and crevice corrosion.
31	Aircraft cable	bare, Type 304	0.1875	7 x 19	0	197	2,500	2,700	2,800	+4	Outside: few rust spots; inside: bright; tensile fracture.
32	Aircraft cable	bare, Type 304	0.250	7 x 19	0	403	6,000	5,100	5,000	-2	Outside: few yellow stains; inside: bright; tensile fracture.
32	Aircraft cable	bare, Type 304	0.250	7 x 19	0	197	2,500	5,100	5,100	0	Outside: original metallic sheen; inside: bright; tensile and torsion fractures.
33	Aircraft cable	bare, Type 304	0.3125	7 x 19	0	403	6,000	7,100	7,700	+8	Outside: few rust stains; inside: bright; tensile and torsion fractures.
33	Aircraft cable	bare, Type 304	0.3125	7 x 19	0	197	2,500	7,100	7,000	-1	Outside: original metallic lustre; inside: bright; tensile fracture.
34	Aircraft cable	bare, Type 304	0.375	7 x 19	0	403	6,000	11,900	11,700	-2	Outside: few rust stains; inside: bright; tensile and torsion fractures.
34	Aircraft cable	bare, Type 304	0.375	7 x 19	0	197	2,500	11,900	11,600	-3	Outside: few rust stains; inside: bright; tensile fracture.
35	Plow steel	lubricated	0.325	1 x 19	2,100	751	6,000	10,700	10,700	0	No stress failure; outside: 100% rust; inside: bright; tensile fracture.
35	Plow steel	lubricated	0.325	1 x 19	2,100	1,064	6,000	10,700	11,500	+7	No stress failure; outside: 100% rust; inside: bright; tensile fracture.
36	Improved plow steel	lubricated	0.326	1 x 19	2,900	751	6,000	14,300	14,900	+4	No stress failure; outside: 100% rust; inside: bright; tensile fracture.

Continued

Table 89. Continued.

Rope No.	Alloy <sup>a</sup>	Coating	Diameter (in.)	Construction	Stress on Rope (lb)	Exposure (day)	Depth (ft)	Breaking Load			Remarks
								Original (lb)	Final (lb)	% Change	
36	Improved plow steel	lubricated	0.326	1 x 19	2,900	1,064	6,000	14,300	15,300	+7	No stress failure; outside: 100% rust; inside: bright; tensile failure.
37	Plow steel	Zn 0.83 oz/ft <sup>2</sup>	0.340	1 x 19	2,100	751	6,000	10,400	10,900	+5	No stress failure; outside: grey with 5% scattered rust; inside: grey; tensile fracture.
37	Plow steel	Zn 0.83 oz/ft <sup>2</sup>	0.340	1 x 19	2,100	1,064	6,000	10,400	8,600	-17	No stress failure; outside: 20% rust, 80% yellow; inside: grey; tensile fracture.
38	Plow steel	Zn 1.50 oz/ft <sup>2</sup> , electrogalvanized	0.335	1 x 19	2,200	751	6,000	10,900	11,100	+2	No stress failure; outside: 50% rust, 50% grey; inside: grey; tensile fracture.
38	Plow steel	Zn 1.50 oz/ft <sup>2</sup> , electrogalvanized	0.335	1 x 19	2,200	1,064	6,000	10,900	11,600	+6	No stress failure; outside: 95% rust; inside: grey; tensile fracture.
39	Plow steel	Al 0.38 oz/ft <sup>2</sup>	0.335	1 x 7	1,400	751	6,000	6,900	7,000	+1	No stress failure; outside: white corrosion products with 10% rust stains; inside: grey; tensile fracture.
39	Plow steel	Al 0.38 oz/ft <sup>2</sup>	0.335	1 x 7	1,400	1,064	6,000	6,900	6,500	-6	No stress failure; outside: white corrosion products plus 50% rust; inside: grey and light rust; tensile fracture.
40	Plow steel	Zn 0.17 oz/ft <sup>2</sup> , polyvinyl chloride jacket	0.195	7 x 7	250	751	6,000	1,300	1,200	-8	No stress failure; PVC, dull; some light rust on strands underneath PVC; tensile fracture.
40	Plow steel	Zn 0.17 oz/ft <sup>2</sup> , polyvinyl chloride jacket	0.195	7 x 7	250	1,064	6,000	1,300	1,100	-15	No stress failure; PVC, dull; some light rust on strands underneath PVC; tensile and torsion fractures.
41	Aircraft cable	bare, Type 316, lubricated	0.135	7 x 7	350	751	6,000	1,700	1,400	-18	No stress failure; outside: original metallic lustre; inside: bright; tensile fracture.
41	Aircraft cable	bare, Type 316, lubricated	0.135	7 x 7	350	1,064	6,000	1,700	1,000	-41	No stress failure; outside: 50% rust, crevice corrosion; inside: rusted wires, some broken, crevice corrosion; tensile and brittle fractures.
42	Aircraft cable	bare, 18Cr-14Mn-0.5N	0.395	7 x 19	2,500	751	6,000	12,400	11,400	-8	No stress failures; outside: few rust spots; inside: bright; torsion fracture.
42	Aircraft cable	bare, 18Cr-14Mn-0.5N	0.395	7 x 19	2,500	1,064	6,000	12,400	12,500	+1	No stress failure; outside: considerable rust and broken wires; inside: some broken wires in all strands; torsion fracture.
43	Improved plow steel	Al 0.11 oz/ft <sup>2</sup>	0.1875	7 x 7	0	402	2,500	3,900	3,500	-10	Outside: white corrosion products with light rust stains.
44	Improved plow steel	Al 0.19 oz/ft <sup>2</sup>	0.250	1 x 19	0	402	2,500	8,800	7,800	-11	Outside: mottled white and grey
45	Improved plow steel	Al 0.19 oz/ft <sup>2</sup>	0.3125	1 x 19	0	402	2,500	14,000	13,000	-7	Outside: grey with some white corrosion products.
46	Type 304	90Cu-10Ni, 0.0007 in., 0.50 oz/ft <sup>2</sup>	0.1875	7 x 7	0	402	2,500	3,900			Outside: green.

Continued

Table 89. Continued.

Rope No.	Alloy <sup>a</sup>	Coating	Diameter (in.)	Construction	Stress on Rope (lb)	Exposure (day)	Depth (ft)	Breaking Load			Remarks
								Original (lb)	Final (lb)	% Change	
47	Type 304	90Cu-10Ni, 0.0003 in., 0.25 oz/ft <sup>2</sup>	0.280	37 x 7	0	402	2,500	—	—	—	Outside: light film rust; inside: bright, uncorroded.
48	6Al-4V-Ti	bare, Type 304 fittings	0.250	6 x 19	0	402	2,500	—	—	—	Fittings rusted, crevice and galvanic corrosion; cable, no corrosion
49	6Al-4V-Ti	bare	0.0625	1 x 19	0	402	2,500	—	—	—	No corrosion except one steel wire which had become introduced during fabrication.
50	6Al-4V-Ti	bare, steel fitting, steel tie wire	0.0625	6 x 19	0	402	2,500	—	—	—	Steel fitting and steel tie wire corroded galvanically; cable, no corrosion.
51	6Al-4V-Ti	bare	0.063	—	0	402	2,500	—	—	—	No corrosion.
52	6Al-4V-Ti	bare	0.045	—	0	402	2,500	—	—	—	No corrosion.
53	6Al-4V-Ti	bare	0.020	—	0	402	2,500	—	—	—	No corrosion.

<sup>a</sup>Immersed in seawater unless otherwise specified.<sup>b</sup>Immersed in bottom sediment.



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## **EFFECTS OF MARINE ORGANISMS**

Material for this chapter is taken from three reports. The first was prepared by S.M. Gerchakov and B. Sallman, of the Department of Microbiology, University of Miami School of Medicine, Miami, Florida (AD/A-045 815); the second, by E. Fischer and S. Finger, of the U.S. Naval Applied Science Laboratory, Brooklyn, New York (AD-814 148); and the third, by C.R. Southwell, J.D. Bultman, and C.W. Hummer, Jr., of the Naval Research Laboratory, Washington, D.C. (AD-777 719).

The following is from the report by S.M. Gerchakov and B. Sallman, which reviews some of the information available on biological corrosion and discusses possible mechanisms involved.

## BIOLOGICAL FACTORS IN METAL CORROSION

Microfouling and corrosion processes commence immediately upon exposure of a metallic substrate to a natural aquatic environment. In contrast to what is actually occurring in the environment, these two processes have been traditionally treated separately. Furthermore, in spite of the overwhelming evidence for biological involvement in metal corrosion processes, conventional corrosion studies have been conducted with a chronic absence of biological considerations. This apprehension was expressed by Compton (1), who pointed out the naiveté of some scientists who consider seawater a simple solution of sodium chloride contaminated with a few additional salts. He also called attention to the so-called "biological factors" which are so often mentioned with regard to the unique corrosive properties of seawater.

For the sake of discussion we may conveniently classify the elements involved in the microfouling-

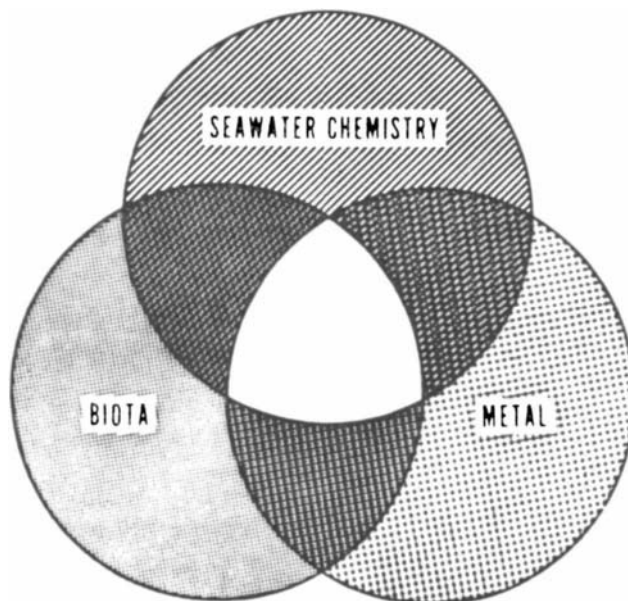
corrosion process into those which are living and those which are not. The nonliving ones can be separated into a solid phase and a liquid phase. These three elements (biota, metal, solution) interact with each other, and the product of the three-way interaction gives rise to the microfouling-corrosion phenomenon.

To illustrate this interaction we will refer to Figure 1, where the three elements, the active zones between any two elements, and the zone of interaction among all three elements, are easily identified.

Consider the biota/solution interaction, and ignore the metal element for the moment. This interaction is governed by the intrinsic properties of the individual elements and, in turn, may alter their own properties. Now consider the solution interacting with the metal, and ignore the biota element for the moment. This interaction is governed by the prevailing conditions at the solid/liquid interface. These conditions are affected by the nature of the interacting elements, and by the interactive process itself.

Introduction of the biota element into this network of interactions and feedbacks system does not simplify matters but brings us closer to the realization of what is happening in the natural environ-

**FIGURE 1: INTERACTION OF ELEMENTS CONTROLLING MICROFOULING-CORROSION PHENOMENON IN SEAWATER**



ment. If organisms become periphytic (this will be determined by the nature of the organisms and by the prevailing conditions at the solid/liquid interface), their metabolic activities may be enhanced (2), and they become an additional factor in the system.

## BIOFOULING

Biofouling of surfaces immersed in seawater has long been accepted as a natural phenomenon. The development of a fouling layer on a ship's hull, making it heavier and reducing its speed, has placed a heavy burden on the maritime economy since ancient times. It must be recognized, however, that the appearance of visible organisms such as barnacles, tubeworms, mussels, etc., is a relatively late occurrence in a chemical and biological sequence of events.

Solid substrates in contact with seawater will absorb organic matter on their surfaces (3)-(6). Whether the resulting organic film is glycoprotein (7) or "humic" (8) in nature, its presence affects the surface charge (9)(6) and surface wettability (10) of the substrate. These properties no doubt play an important role in the subsequent attachment of bacteria to the "conditioned" surfaces (11).

Bacteria are the first biofouling organisms to attach to surfaces exposed to seawater (12)(13). While the primary bacterial film on glass and stainless steel surfaces develops with time into a diverse periphytic community (which includes diatoms, filamentous algae, ciliated protozoa, etc.), bacteria continue to increase in numbers (14). In contrast, the surfaces of copper-based alloys, when exposed under the same conditions (15) develop less diverse periphytic communities, with bacteria being the dominating organisms.

The presence of a primary fouling layer composed of living microorganisms, detrital particles, and organic material may attract cyprids of some common barnacles (16) as well as larvae of other marine animals (17)(18).

Fouling is particularly troublesome in the more fertile coastal waters, and although it diminishes with distance from the shoreline, it does not disap-

pear in midoceanic regions and in the abyssal depths. The increasing utilization of coastal and estuarine waters for cooling purposes in power plants increases the magnitude of the fouling problems. The presence of a limited number of macrofouling agents such as barnacles, tubeworms, etc., on a ship's hull may be tolerated, but their presence on the inner surfaces of a piping system may impede water flow to an unacceptable degree. The existence of a microfouling layer on a ship's hull is of relatively little concern, while its existence as a 250-micron-thick layer may result in a 50% reduction in the heat transfer coefficient of a heat exchanger in an ocean thermal energy conversion (OTEC) power plant (19). In his report, Haderlie (20) reviewed the subject of microfouling in seawater and its significance for OTEC heat exchange surfaces, calling attention to an additional potential problem associated with microfouling/microbial corrosion.

## MICROBIOLOGICAL CORROSION

The implication of microorganisms in metal corrosion processes was suggested as early as 1891 when Garrett (21) postulated that the corrosive action of water on lead could be due to ammonia, nitrites and nitrates produced by bacterial action. Gaines (22) concluded that underground corrosion of iron and steel structures is partially due to bacterial activity. In fact, the iron bacterium *Gallionella ferruginea* was isolated from corrosion products on buried steel conduits, and high concentrations of sulfur and organic matter in the products indicated the presence of sulfur bacteria. Iron in deaerated water does not corrode appreciably, but the corrosion rate in some anaerobic natural environments is abnormally high. Von Wolzogen Kühr and van der Wlugt (23) postulated in their classical paper that certain organisms, primarily those of the bacterial genus *Desulfovibrio*, depolarize the cathode of the corrosion cell by removing hydrogen that accumulates on the surface of iron, and thus promote corrosion under anaerobic conditions. Thomas (24) noted the growth and accumulation of bacteria in steel water pipes. He proposed that bacteria might be the reason for the degree of corrosiveness of the water, unexplainable by its mineral composition. Drabelle (25), serving as a consulting engineer for the Iowa Electric Power and Light Company, posed in an article the question, "Do bacteria cause condenser tube corrosion?"

A number of reports have implicated a variety of different environments which apparently support microbial corrosion. For example, *Thiobacillus concretivorus* was isolated in large numbers from corroded concrete obtained from widely separate localities (26). It was found, however, that in an atmosphere similar to sewer conditions, rapid corrosion occurred only after the environment became favorable to *Th. concretivorus* growth and the proliferation of the organisms (27).

Kalinenko (28) found bacterial colonies on aluminum, brass and bronze plates immersed in natural seawater, and suggested that the bacterial colonies accelerate the electrochemical processes of metal corrosion. Rozenberg and Ulanovskii (29) stated that bacteria may enhance corrosion of stainless steel in seawater through decreasing the protective effects of cathode polarization, or bacteria may retard corrosion by sedimentation of  $\text{CaCO}_3$  and  $\text{Mg(OH)}_2$  from seawater on the steel surface.

Wacks, et al., (30) found *Desulfovibrio desulfuricans* to be responsible for the corrosiveness occurring in aviation gasoline stored in tanks containing small amounts of water. In fact, gasoline stored on culture media inoculated with this organism became corrosive after one week of incubation. Hendey (31), investigating *Cladosporium resinae* as fuel contaminant in kerosene fuel storage tanks and fuel tanks of aircraft, suggested that fungal metabolites are capable of attacking aluminum.

Comparisons were made in the relative corrosiveness of bacteria and fungi for metals in containers being used in space voyages. Tennyson and Brown (32) compared *Rhizopus* sp. and *Scopulariopsis* sp. with pure strains of unidentified species of bacteria isolated from human sources. Visual inspection was made of aluminum 1100 specimens which were subjected to cultures of these organisms. Fungi were noted to promote corrosion to a considerably greater extent than did bacteria, when Tang instant breakfast drink was used as a substrate. Brown and Pabst (33) confirmed this observation in their study which included 25 bacterial and fungal isolates acting on aluminum 1100, aluminum alloys 6061-T6 and 2014-T6, and stainless steel 321, in the presence of Tang or Armour Starr bouillon.

A variety of additional metal substrates have

been studied for biological corrosion. Copper was investigated by Thiam (34) who demonstrated an increased dissolution of this metal in the presence of *Aspergillus* sp. utilizing soil extract as a medium. Tawadsi and Kemchadse (35) reported that chrome-manganese steel corroded more rapidly in a variety of pure cultures of heterotrophic marine bacteria including *Bacillus tumescens* compared with sterile controls. Smith, et al., (36), however, failed to see any difference between the corrosion rate of 1016 carbon steel in raw and sterile aerated seawater.

Additional literature reports of the biological corrosion of metals may be found in reviews by Rogers (37), Costello (38) and Iverson (39).

### Mechanism of Corrosion

*General*—Zajic (40) briefly described corrosion as follows:

In its broadest concept, corrosion is an electrochemical reaction. It is caused by any kind of heterogeneity at different points on a metal surface. Once a surface makes contact with an electrolyte, however weak, different heterogeneous points show a variance in potential. They develop an electromotive force (emf) and form small local piles or corrosion cells. The more reactive metal acts as the anode, and its atoms pass into the ionic state; at the same time, hydrogen ions are driven back to the less reactive metal which acts as the cathode. When hydrogen forms at the cathode, the corrosion cell becomes polarized. The surface seeks an equipotential state and, as this state is reached, metallic dissolution on the anode follows and continues until the emf decreases and corrosion stops. Outside forces, of course, can intervene and it is these intervening forces which sustain or increase corrosion.

This description, although cursory in nature, directs attention to outside factors which contribute to corrosion processes. An in-depth discussion of corrosion and its mechanisms can be found elsewhere.



**Biological Involvement**—Although the mechanism of biological corrosion is not clear, and the literature on this subject—specifically as it concerns the seawater environment—is scant, it can be related to three different considerations:

- (a) Primary effect of microorganisms through the formation of differential concentration cells on the metal surfaces (for example, a respiring periphytic colony of organisms causing a difference in oxygen concentration between its microenvironment and the surrounding area). This will give rise to potential differences, with subsequent corrosion currents between the bacterial colony sites and the surrounding metal surface.
- (b) Direct removal of corrosion products (e.g., by a periphytic community removing the oxidized metal at anodic sites or utilizing the formed hydrogen at cathodic sites), which will cause the electrochemical corrosion reactions to be biased towards metal dissolution. These, respectively, may be considered as anodic or cathodic depolarization which will sustain corrosion currents.
- (c) Changes in the chemical environment at the metal/solution interface due to metabolic activity (e.g., changes in pH, or introduction of metabolites), which will affect corrosion processes.

Olsen and Szybalski (44) suggested that aerobic bacteria, such as *Gallionella ferruginea*, infecting metal surfaces will form microdifferential aeration cells due to a change in concentration of oxygen in the infected areas. As the bacterial colonies grow they form tubercles which further enhance the potential of the differential aeration cells due to poor mixing of water. In fact, Kutznetsov and Verzhbitskaya (45) observed tuberculation in which species of *Leptothrix*, *Crenothrix*, and *Spirophyllum ferrugineum* participated. Kalinenko (28) also observed tubercles of bacterial colonies growing on iron, aluminum, copper and bronze plates in seawater.

Anaerobic bacteria are probably the most studied microorganisms in biological corrosion investigations. The enhancing effect of sulfate reducers of the genus *Desulfovibrio* on corrosion processes was attributed to their ability to remove hydrogen from cathodic sites of corrosion cells. Iverson (46) presented direct evidence for this cathodic depolariza-

tion. Booth and Tiller (47) demonstrated that *Dv. desulfuricans*, which possessed hydrogenase activity, stimulated the cathodic reaction, while *Desulfotomaculum orientis* (hydrogenase-negative) did not. However, Willingham (48) found that hydrogenase activity of cell-free extracts did not correlate with its corrosiveness to mild steel in seawater.

Similar observations were made in the case of nitrate-reducing bacteria. Mara and Williams (49) reported that *Escherichia coli* (hydrogenase-positive) enhanced the corrosion of mild steel, while the effect of *Pseudomonas stutzeri* (hydrogenase-negative) was negligible. Ashton, et al., (50) investigating the hydrogenase-positive *E. coli* did not find any relation between nitrate utilization and corrosion of carbon-steel; they concluded that mechanisms other than cathodic depolarization may be operating.

Nelson (51) challenged the quantitative importance placed on cathodic depolarization as an accelerating factor in anaerobic microbial corrosion. Tiller and Booth (52), investigating the effect of sulfate-reducing bacteria on aluminum corrosion, concluded that although hydrogenase activity plays a role in the process, the presence of iron sulfide also accelerates corrosion. King and Miller (53) suggested that the presence of iron sulfide in sulfate-reducing situations is probably more important quantitatively than hydrogenase activity. King, et al., (54) stated that acceleration of corrosion of mild steel in the presence of sulfur-reducing bacteria is principally due to the formation of iron sulfide, and that hydrogenase activity plays an insignificant role.

Corrosion products such as  $H_2S$  from *Desulfovibrio desulfuricans*,  $CH_3COOH$  from *Clostridium aceticum*, and  $H_2SO_4$  from *Thiobacillus thiooxidans* metabolism are obvious contributors to corrosion processes. What may not be so obvious is that metabolic products such as mannitol produced in seawater by the action of bacteria on seaweeds appear to accelerate corrosion of brass (37) and that high molecular weight biomolecules, such as those isolated from cultures of *Pseudomonas aeruginosa* (55), are corrosive substances. Staffeldt and Calderon (56) found that the organic acids of the Krebs cycle promoted the corrosion of copper, while many enzymes were found to be considerably less active. Burns, et al., (57) reported that solutions of various organic acids (citric, fumaric, ketoglutaric, glutaric,

maleic, malic, itaconic, pyruvic, and succinic acid) formed metallic salts of copper, tin, and zinc in sterile solutions. These investigators found that the presence of oxygen was necessary for the formation of these salts. Thus, we may infer that the metals were oxidized electrochemically and that the acids removed the oxide film formed. Ashton, et al., (58) found acetic, ketoglutaric, succinic, and lactic acids in an anaerobic culture of *E. coli* where carbon-steel corrosion was enhanced. They suggested that the acid metabolites were responsible for accelerating the corrosion by dissolution of the iron oxide formed on the metal surface. Webb (59) demonstrated that amino acids accelerate the corrosion rate of copper. Kramer (60) confirmed this effect of amino acids and found that dicarboxylic acids also enhanced the corrosion of copper.

It is apparent that, although the precise mechanism of microbiological corrosion is ill-understood, microorganisms and their extracellular metabolites exert a significant influence on the otherwise strict electrochemical process of metal oxidation in the environment.

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The report by E. Fischer and S. Finger is the source of the following data on corrosion of various metals in the deep ocean.

The Navy is increasingly involved with the corrosion and deterioration of materials to be used in the exploration of and operation in the deep ocean. A significant part of the corrosion and deterioration can be attributed to the action of microorganisms in the environment. The Naval Applied Science Laboratory has conducted exposures of a variety of metals (and organic materials) in the Tongue-of-the-Ocean, Bahamas, at 4500-foot depth. These exposures served a threefold purpose: to provide needed general corrosion data for a variety of metals in the deep ocean; to facilitate acquiring corrosive microorganisms from corrosion products, sediment and water; and to provide corrosion data to be used in judging the reliability of corrosion rates obtained under deep-ocean simulated conditions in the Laboratory.

The U.S. Naval Applied Science Laboratory has investigated the possibility of microbial corrosive and deteriorative mechanisms being operative un-

der deep-ocean conditions which include high hydrostatic pressure, osmotic pressure and low temperatures. All of these physical factors are generally depressive to cellular activities, with the possible exception of certain adapted organisms, and as such, may have significant effects on biological corrosive mechanisms. Research concerning these effects is required in view of the anticipated utilization of the ocean bottom in numerous applications including antisubmarine warfare. In situ testing of materials in the deep ocean has been undertaken in order to establish corrosion data under actual ocean conditions. These data serve as criteria for judging experimental data in the laboratory under accelerated test conditions and add to the store of information on the corrosion characteristics of a variety of metals for deep ocean use.

## EXPERIMENTAL WORK

Specimens were removed from a bottom corrosion rack after 3- and 6-month exposures. Immediately after removal, microbiological isolations were made from corrosion products. Specimens were washed with fresh water to remove sediment and seawater. After two such washes, they were rinsed with acetone and dried. Specimens were then sealed in polyethylene bags for shipment to the Laboratory.

Determination of corrosion rates and gross appearance of corrosion products on samples was performed in the laboratory. Corrosion products were removed by treatment of the samples in inhibited acid baths after degreasing with toluene and acetone. Uncorroded appropriate controls were simultaneously prepared to correct for the small amount of loss caused by the acid treatment. Specific acid treatments are listed in Table 1 in relation to metal types.

After the corrosion product removal, specimens were washed free of acid, dried with acetone, heated at 240°C for 10 minutes to remove all absorbed water, and then weighed. Surface areas were determined. Data on corrosion weight loss and size for each sample were prepared for computer analysis, and corrosion rates (inches per year) were calculated by the following general formula:

$$\text{Corrosion Rate (ipy)} = \frac{1}{\text{exposure (yr)}} \times \frac{\text{final volume}}{\text{final area}} \times \frac{\text{weight loss}}{\text{final weight}}$$



**TABLE 1: REMOVAL OF CORROSION PRODUCTS**

Metal Type	Treatment
Aluminum	Concentrated nitric acid in an ultrasonic bath at 25°C.
Mild Steel	10% hydrochloric acid by volume with 0.5% (by weight) 1,3-diethyl-2-thiourea in an ultrasonic bath at 25°C.
Monel (Alloy 400)	10% sulfuric acid by volume in an ultrasonic bath at 25°C.
Stainless steel	30% nitric acid by volume in an ultrasonic bath at 25°C.
Lead, chemical	Saturated ammonium acetate in an ultrasonic bath at 25°C.
Zirconium	Saturated ammonium acetate in an ultrasonic bath at 25°C.
Zinc	Saturated ammonium acetate in an ultrasonic bath at 25°C.
Titanium, commercial RC-55	50% hydrochloric acid by volume in an ultrasonic bath at 25°C.
Copper	5% sulfuric acid by volume in an ultrasonic bath at 25°C.
Copper-Nickel alloy (30% Ni)	10% sulfuric acid by volume in an ultrasonic bath at 25°C.
Nickel (200 "A")	10% sulfuric acid by volume in an ultrasonic bath at 25°C.

Corrosion rate for each sample and general ob-

servations of the type of corrosion are presented in Table 2.

## CONCLUSION

Comparison of the corrosion rates for each metallic specimen gives essential information concerning the durability of metals in a specific ocean bottom location. Metals can readily be arranged in order of durability by use of Table 2. By comparison of the corrosion rates for 3-month and 6-month samples, the decrease in the corrosion rate after the 6-month exposure shows the tendency of various metals to passivate partially. This was also true of aluminum in galvanic couples with mild steel in which the progressive passivation of the aluminum reduced its corrosion rate and its galvanic protection of the steel. Only structural alloys of aluminum were used in the aluminum steel couples. It is possible that pure aluminum may not have become passivated. The effect of oxygen concentration cells is seen in the increased corrosion of aluminum and the decreased corrosion of mild steel (total specimen) resulting from the artificially created, partially anaerobic environment. Thus, the aerobicity of the local ocean bottom environment is an important parameter in metal durability, and the "zone of bottom influence" is significant. Aluminum 6061 was found to be the least corrosion-resistant aluminum alloy.

**TABLE 2: CORROSION RESULTS**

Metal and Condition	Exposure (months)	Corrosion Rate (ipy)	General Observation After Removal from the Ocean Bottom
Aluminum 5086			
Plate	3	$2.74 \times 10^{-4}$	No significant pitting
Plate	6	$1.98 \times 10^{-4}$	No significant pitting
Aluminum 6061			
Plate	3	$4.81 \times 10^{-4}$	Heavy pitting in localized areas.
Plate	6	$5.49 \times 10^{-4}$	Very heavy and more frequent pitting in localized areas.
Aluminum 5052			
Plate	3	$2.16 \times 10^{-4}$	No significant pitting
Plate	6	$2.10 \times 10^{-4}$	No significant pitting
Aluminum 5456			
Plate	3	$2.69 \times 10^{-4}$	No significant pitting
Plate	6	$2.75 \times 10^{-4}$	Skin effect causing lamellar corrosion on edges.
Mild steel			
Plate	3	$6.00 \times 10^{-3}$	Generalized surface corrosion (iron oxide)
Plate	6	$5.75 \times 10^{-3}$	Crevice corrosion beneath Teflon spacer

(continued)

TABLE 2: (continued)

Metal and Condition	Exposure (months)	Corrosion Rate (ipy)	General Observation After Removal from the Ocean Bottom
Stainless steel 304			
Disc	3	$5.34 \times 10^{-5}$	No significant corrosion
Disc	6	$1.15 \times 10^{-5}$	No significant corrosion
Copper			
Disc	3	$1.26 \times 10^{-3}$	Red corrosion product (cuprous oxide)
Disc	6	$1.01 \times 10^{-3}$	Dark red corrosion product (cuprous oxide and cupric oxide)
Zirconium			
Disc	3	$5.42 \times 10^{-5}$	No significant corrosion
Disc	6	$2.05 \times 10^{-5}$	No significant corrosion
Titanium			
Disc	3	$7.88 \times 10^{-5}$	No significant corrosion
Disc	6	$2.14 \times 10^{-5}$	No significant corrosion
Magnesium			
Disc	3	40% weight loss	Extensive corrosion
Disc	6	80% weight loss	Extensive corrosion
Zinc			
Disc	3	$2.72 \times 10^{-3}$	Extensive pitting concentrated beneath Teflon spacer
Disc	6	$3.15 \times 10^{-3}$	Extensive pitting concentrated beneath Teflon spacer
Nickel			
Disc	3	$5.23 \times 10^{-5}$	No significant corrosion
Disc	6	$1.92 \times 10^{-5}$	No significant corrosion
Monel			
Disc	3	$2.99 \times 10^{-4}$	Crevice corrosion beneath Teflon spacer
Disc	6	$2.83 \times 10^{-4}$	Crevice corrosion beneath Teflon spacer
Tin			
Disc	3	—	Extensive pitting, crevice corrosion
Disc	6	—	Extensive pitting, crevice corrosion
Mild steel			
Disc	3	$4.49 \times 10^{-3}$	Generalized surface corrosion
Disc	6	$7.89 \times 10^{-3}$	Crevice corrosion and surface corrosion
Lead			
Disc	3	$3.52 \times 10^{-4}$	No sulfide coating
Disc	6	$2.50 \times 10^{-4}$	No sulfide coating
Copper-Nickel			
Disc	3	$3.18 \times 10^{-4}$	No significant corrosion
Disc	6	$2.62 \times 10^{-4}$	Very slight local anodic corrosion
<b>Oxygen Concentration Cell Corrosion</b>			
Mild steel	3	$4.78 \times 10^{-3}$	General corrosion on inner face
Aluminum 5456	3	$3.08 \times 10^{-4}$	Very slight corrosion on inner face
Aluminum 5086	3	$2.66 \times 10^{-4}$	Fitting beneath nylon washers
Aluminum 6061	3	$4.91 \times 10^{-4}$	Extensive pitting beneath nylon washers
Aluminum 5052	3	$3.71 \times 10^{-4}$	Slight crevice corrosion beneath nylon washers
<b>Galvanic Couples</b>			
Aluminum 5052 }		$2.62 \times 10^{-4}$	No significant corrosion
Aluminum 5456 }	6	$4.05 \times 10^{-4}$	Slight pitting on inside face
Aluminum 5052 }		$7.00 \times 10^{-4}$	Slight localized pitting on inside face
Aluminum 6061 }	6	$6.51 \times 10^{-4}$	General corrosion on inside face
Aluminum 5052 }		$1.33 \times 10^{-4}$	No significant corrosion
Aluminum 5086 }	6	$1.43 \times 10^{-4}$	No significant corrosion
Aluminum 5456 }		$1.20 \times 10^{-3}$	Heavy pitting on inside face
Aluminum 6061 }	6	$5.34 \times 10^{-4}$	Heavy pitting on inside face

(continued)

TABLE 2: (continued)

Metal and Condition	Exposure (months)	Corrosion Rate (ipy)	General Observation After Removal from the Ocean Bottom
Aluminum 5086 } Aluminum 5456 }	6	$1.32 \times 10^{-4}$ $1.46 \times 10^{-4}$	No significant corrosion No significant corrosion
Aluminum 6061 } Aluminum 5086 }	6	$6.74 \times 10^{-4}$ $5.93 \times 10^{-4}$	Slight pitting on inside face Slight pitting on inside face
Aluminum 5052 } Mild steel }	3	$2.41 \times 10^{-3}$ $2.86 \times 10^{-3}$	Deep pitting beneath bolt heads; pitting Slight corrosion
Aluminum 5086 } Mild steel }	3	$3.15 \times 10^{-3}$ $2.19 \times 10^{-3}$	Very heavy pitting beneath bolt heads; along edges due to skin effect Slight corrosion
Aluminum 5456 } Mild steel }	3	$3.52 \times 10^{-3}$ $1.73 \times 10^{-3}$	Heavy pitting beneath bolt heads; severe edge corrosion due to skin effect Slight corrosion
Aluminum 6061 } Mild steel }	3	$3.25 \times 10^{-3}$ $1.98 \times 10^{-3}$	Deep pitting; severe edge corrosion due to skin effect Slight corrosion
Aluminum 5052 } Mild steel }	6	$1.26 \times 10^{-3}$ $3.29 \times 10^{-3}$	Extensive pitting beneath bolt heads Slight corrosion
Aluminum 5086 } Mild steel }	6	$2.22 \times 10^{-3}$ $2.69 \times 10^{-3}$	Extensive deep corrosion beneath bolts and along edges. Pitting on both surfaces. Slight corrosion
Aluminum 5456 } Mild steel }	6	$2.13 \times 10^{-3}$ $2.46 \times 10^{-3}$	Deep pitting beneath bolt heads; along edges. Slight corrosion
Aluminum 6061 } Mild steel }	6	$1.99 \times 10^{-3}$ $3.50 \times 10^{-3}$	Skin effect along edges; deep pitting Slight corrosion

## RECOMMENDATIONS

Corrosion data obtained from specimens exposed in the deep ocean must be used as criteria for judgment of reliability of laboratory experiments. This is true not only for experiments dealing with electrochemical corrosion, but also for biological corrosion. On-site deep ocean environmental parameters (high hydrostatic pressure, gas content, low temperature, dissolved materials, sediment type, and biological content) should be reproduced in laboratory deep-ocean corrosion research. Concerning biological corrosion, the two prime influences are hydrostatic pressure and low temperature.

The following data on long-term exposures of carbon steel specimens to the ocean environment are from the report by C.R. Southwell, J.D. Bultman, and C.W. Hummer, Jr.

## ESTIMATING SERVICE LIFE OF STEEL IN SEAWATER

Structural carbon steel is one of the most useful

and widely used construction materials. Its combination of high strength, formability, weldability, and relative economy of use is unmatched by other materials. As a result, the tonnage of steel produced far overbalances the total tonnage for all other construction metals. It is used widely in the marine environment for ship hulls, buoys, containers, retaining walls, piles, and underwater construction members of all types. Its biggest drawback for marine use is its susceptibility to corrosion in the saline environment.

The cost of protecting steel from marine corrosion is staggering. Part of this expenditure may be unnecessary. Two of the reasons for this overprotection are that steel corrosion is voluminous and ugly, giving the appearance of great damage, and that actual corrosion rates of this material over extended periods are relatively unknown. Corrosion rates reported in the literature are usually obtained from short-term tests averaged over the entire period of exposure, starting from zero time; however, marine corrosion of carbon steel normally proceeds very rapidly initially and then levels off to a linear relationship. This steady-state rate for the linear portion of the corrosion-vs-time curve is the most im-

portant value for estimating the service life of a steel structure in seawater. Another factor in overprotection is the little-understood effect of biological activity on the corrosion rates. Ferrous metals are probably more affected by marine organisms than any other class of metal, yet these biological influences have been practically ignored by corrosion scientists. Classical treatises on corrosion usually disregard the biological impact or mention it only as a minor or isolated effect.

Because of the extensive use of steels in marine structures, the corrosion rates of these metals in different seawaters and the effects of different marine organisms on their corrosion rates are of great interest to the Navy. This report analyzes the roles certain marine organisms play in controlling steel corrosion, establishes the steady-state rates of carbon steel in different seawater environments between 9°N and 51°N latitude, and develops methods for using these rates for estimating losses over extended exposure periods.

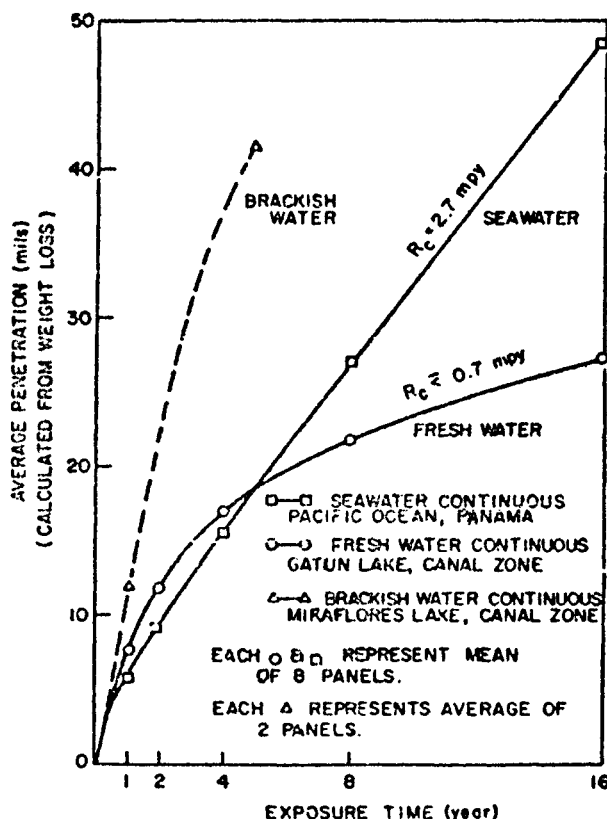
## ANALYSIS OF DATA FROM LONG-TERM EXPOSURES

A 16-year study of the corrosion rates of a large number of metals exposed in the Pacific Ocean at Naos Island, Panama Canal Zone, and in other tropical aqueous and atmospheric environments has been completed by the Naval Research Laboratory (61)-(64). The metal most intensively investigated in this study was structural carbon steel (AISI 1020). Long-term corrosion-vs-time relations for this metal in tropical seawater were established at the Naos Island site. These relationships were determined by exposing 30 steel replicates and removing six of these at 1, 2, 4, 8, and 16 years. Weight loss, pit depths, and tensile strength changes were measured for each panel, and observations were made on the amount and types of fouling and corrosion products. Similarly, 30-set arrays were exposed at mean-tide elevation at Naos Island and in the fresh water of Gatun Lake, Canal Zone. A few panels were also immersed in the (<1%) brackish water of Miraflores Lake, Canal Zone. The corrosion rates obtained and the biological activity observed for the four different environments provide interesting insights into the true corrosion rates of steel in aqueous environments and the important influence of marine organisms on corrosion in seawater.

## Comparison of Four Aqueous Environments

In the four environments described above (three continuous immersions and one mean tide) the corrosion differences for carbon steel are considerable. Corrosion-vs-time curves are shown for the three underwater exposures in Figure 2. In continuous seawater immersion at Naos Island all panels were completely covered within a year by hard fouling organisms, predominantly encrusting bryozoa. At subsequent removals it was observed that the buildup on the metal consisted of three distinct layers: the top layer was an essentially continuous fouling cover; the second layer was comprised of hard corrosion scale, and finally, next to the metal surface, there was a continuous layer of a soft black corrosion product, rich in sulfides.

**FIGURE 2: CORROSION-VS-TIME CURVES FOR CARBON STEEL IN THREE DIFFERENT AQUEOUS ENVIRONMENTS**



On the specimens exposed at mean tide, fouling did not develop as rapidly; however, at between 1 and 2 years a complete calcareous cover of barnacles

had become attached, and subsequently the sulfide-containing layer was formed next to the metal. In the fresh and mildly brackish water no hard fouling collected, and heavy sulfide deposits were not observed.

### Oxygen Diffusion Control in Fresh Water

From the curve in Figure 2 and the visual observations of the panels it was determined that in fresh water, with no marine biological activity, the steel sustained high initial weight losses followed by an ever-decreasing corrosion rate. A linear corrosion-vs-time relation was approached only after 8 years, at which time the rate had dropped to less than 1 mpy. Since the corrosion rate is normally controlled by the amount of oxygen available for depolarization of cathodic areas, such a relation indicates that the constantly increasing film of corrosion products caused a continuing reduction in oxygen diffusion to the metal surface, and a parabolic time-vs-corrosion relation resulted.

### Biological Control in Marine Environments

In the much more corrosive medium, the corrosion rate seemed to be modified and regulated by the action and interaction of marine fouling macro-organisms and marine bacteria. The steel panels continuously immersed in seawater corroded very rapidly at first, but they quickly developed a fouling cover which then provided appreciable protection to the metal. Without fouling, the seawater would undoubtedly have produced the highest corrosion losses of any of the four environments; this is indicated by comparing the brackish water and seawater curves in Figure 2, as well as the two curves from the Caribbean Sea to be discussed later. The slightly brackish water could not sustain marine fouling, and the absence of fouling was conducive to increased corrosion, overbalancing the opposing corrosion-reducing effect of low salinity. The result was a much higher 4 year corrosion loss for the brackish water specimens than for the seawater panels protected by fouling.

The seawater curve in Figure 2 is practically linear after the first year of exposure. Such a linear relation would be improbable if the corrosion were being controlled by the diffusion of oxygen through a continually thickening corrosion scale and fouling

cover; another explanation was therefore sought. With the long-term data available for study it was postulated that some time before the first measurement, at one year, the combined corrosion scale and fouling cover reached sufficient thickness to form an effective barrier against oxygen diffusion to the corroding surface. The exclusion of oxygen from the metal surface is probably not entirely dependent on the impermeability of the fouling cover, since as a consequence of their respiration, aerobic saprophytic bacteria present in the outer fouling layers may also contribute by intercepting some or all of the inward-moving oxygen. This possible protective role of these organisms has been discussed in the literature (65)(66).

When conditions become such that little or no oxygen reaches the metal surface, the corrosion rate should drop to a very low value. No such drop was detected in the Naos Island immersion exposures; however, the fouling developed very rapidly at this site, and it is possible that a dip in the rate occurred sometime before the first measurement at one year.

The low rate did not continue, however, because of the activity of anaerobic sulfate-reducing bacteria on the metal surfaces. These bacteria of the genus *Desulfovibrio* were first recognized as important in soil corrosion by the Dutch researchers van der Vlugt and von Wolzogen Kuhr (23). Their theory on microbial corrosion by *Desulfovibrio* provided for the removal by these organisms of hydrogen adsorbed on cathodic surface areas, thereby causing cathodic depolarization and continuing solution of metal ions in anodic areas. Aerobic depolarization results from an inward diffusion of oxygen to the corroding surface where it combines with the hydrogen to form water. In anaerobic environments, according to the Dutch hypothesis, this reaction is transferred to the sulfate-reducing bacteria which utilize the hydrogen to reduce sulfate to sulfide. This material then reacts with ferrous ions to form FeS. This theory has been strengthened by later studies (67)(68). On the other hand, subsequent investigations (69)(70) have indicated that sulfide by-products of bacterial metabolism acting either directly or galvanically are more important. Although the true bacterial corrosion process still remains to be fully understood, there is general agreement that for appreciable corrosion to occur from sulfate-reducing



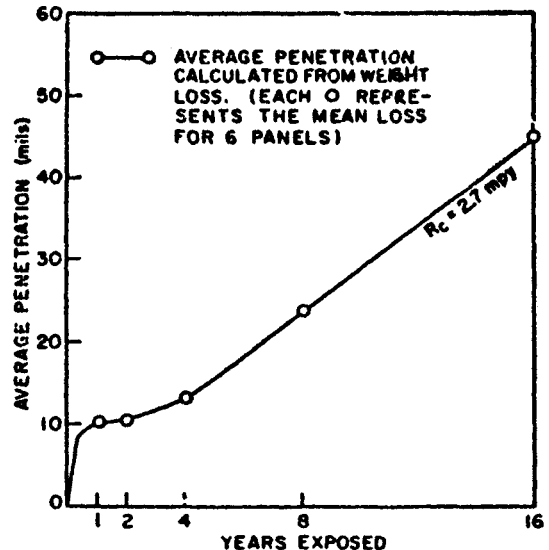
bacteria, the following conditions must exist: (a) an absence of oxygen, (b) a source of sulfates, (c) a source of organic nutrients, and (d) the presence of ferrous ions (71).

After buildup of the oxygen-excluding cover of fouling, corrosion scale, and possibly marine slime, an anaerobic environment develops at the metal surface. This provides the final necessary condition requisite for the growth of sulfate-reducing bacteria. The other requirements are satisfied in normal seawater by the presence of ferrous ions from the metal, sulfate from the water, and a nutrient supply from the decomposing fouling organisms. Once these environmental conditions are established, the corrosion, which has been slowed by the natural protective fouling and corrosion scale cover, increases and approaches a constant rate which remains independent of further thickening of the cover. The seawater curve in Figure 2 shows that at Naos Island the steady-state rate for average penetration of carbon steel was 2.7 mpy. This value was approached after the first year and continued virtually unchanged through the 16 years of exposure.

When the corrosion losses were plotted against time for the mean-tide panels, some interesting results were revealed which seemed to contribute significantly to a biological control theory of marine corrosion. Figure 3 presents the curve for these mean-tide data. It can be seen that corrosion loss was very high during the first year (10 mpy)—almost double that found for continuous immersion. Fouling, mostly barnacles, collected on these panels, but at a much slower rate than for the continuously immersed specimens nearby. Only after a year of exposure did the mean-tide fouling become sufficiently dense to provide a high degree of protection to the metal. Because of this protection the corrosion rate during the exposure interval between 1 and 2 years dropped to a very low value of less than 0.5 mpy. Conditions of a slower fouling buildup and a higher oxygen availability at mean-tide elevation probably delayed the development of completely anaerobic conditions of the metal surface; this evidently resulted in an extension of the period of protection by fouling. If bacterial growth could be inhibited at this point, the corrosion rate should remain very low, and as in the case of weathering steel in the atmosphere, in which many years of service are obtained with little or no maintenance, long-term marine du-

rability of uncoated structural steels should be attainable.

**FIGURE 3: CORROSION-VS-TIME CURVE FOR CARBON STEEL EXPOSED AT A MEAN-TIDE ELEVATION**



Eventually anaerobic bacterial activity did develop on the specimens at mean tide, and after 4 years reached a degree equal to that of continuous immersion. The final corrosion rate between 4 and 16 years' exposure was constant and exactly the same as the steady-state rate of 2.7 mpy for the continuously immersed panels.

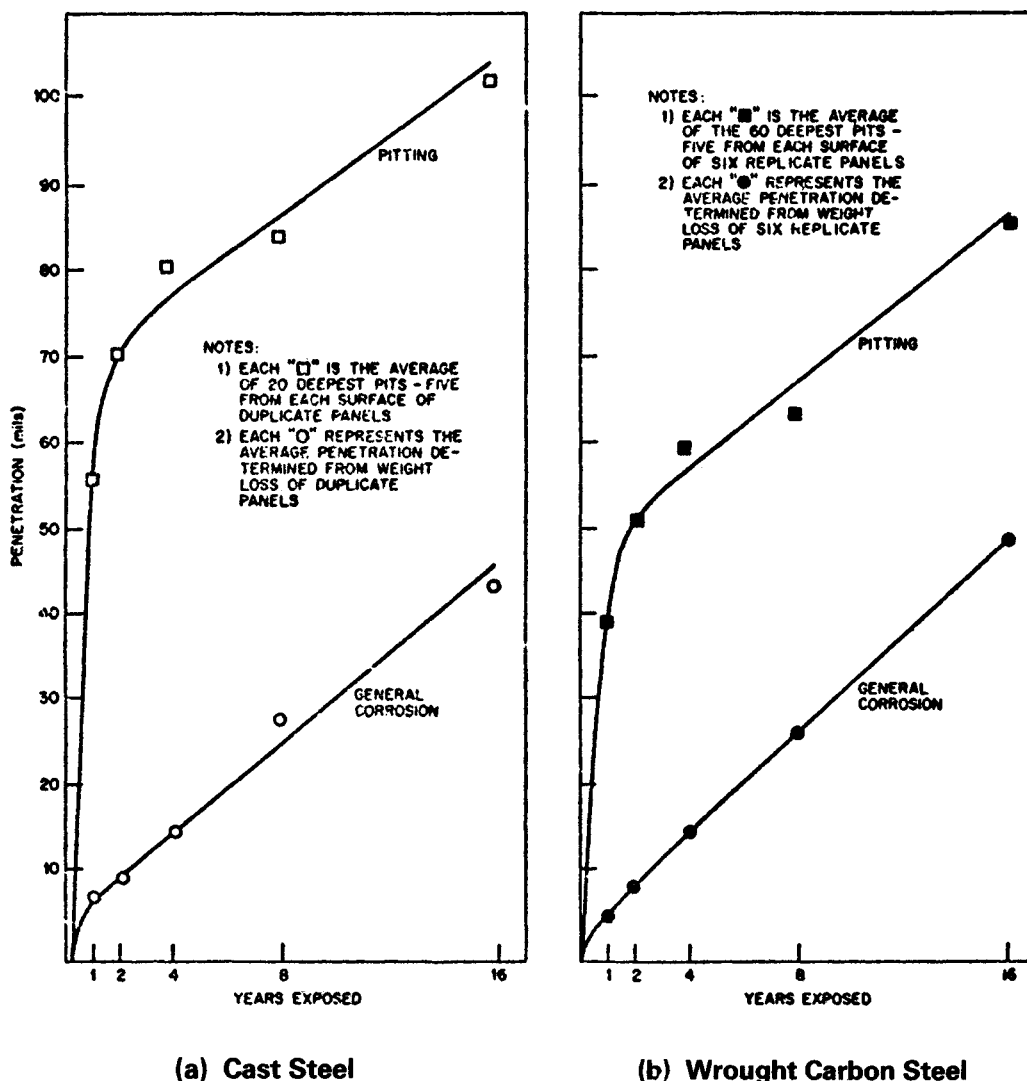
In addition to carbon steel, other structural ferrous metals were included in the Naos Island exposures; these included eight low-alloy steels, a machined cast steel, and an Aston process wrought iron. With the exception of the low-alloy steels containing chromium—chromium steels showed lower initial but higher final rates (61)—all fell within the range of 2.4 to 2.7 mpy for the final steady-state corrosion rate.

Most of the discussion so far has been limited to general surface corrosion (average penetration) determined by specimen weight loss. In carbon steel this is directly related to tensile strength reduction and is thus a good indicator of structural strength loss. Where perforation of a structure or container is the major concern, however, pitting penetration be-

comes an important consideration. The effect of biological activity on pitting rates is therefore of considerable interest. Some of the data from the long-term studies provide insight into biopitting. Curves for cast and wrought carbon steel for pitting and weight loss are shown in Figure 4. It can be seen that the average pitting penetration starts at a much higher rate than the weight loss; by the end of two years the average of the deepest pits is 5 to 7 times the depth of the average penetration based on

weight loss. After the second year of exposure, however, pitting also appears to be controlled by marine organisms; between 2 and 16 years the average pitting curve is linear and approximately parallels the general corrosion curve at 2.5 to 2.7 mpy. This seems to indicate that once closed-system, anaerobic corrosion conditions are established, the normal pitting potential patterns are eliminated and corrosion by bacterial activity proceeds uniformly over the entire surface.

**FIGURE 4: WEIGHT-LOSS AND PITTING CURVES FOR STEELS CONTINUOUSLY IMMERSSED IN SEAWATER**



## CORROSION STUDIES AT FIVE OCEAN SITES

By the end of these long-term studies it was known that at the Naos Island site fouling was acting as an oxygen-shielding, self-healing protective covering, and that sulfate-reducing bacteria were active over the entire panel surfaces. However, it had not been determined when this shielding became effective, when the anaerobic bacteria took control of the corrosion process, or how these events related to the final linearity of the curves. Furthermore, all the long-term seawater data were based on exposures at one site only, where encrusting bryozoa were the principal fouling organisms. Completely unknown were the effects of different ocean locations and whether the anaerobic bacteria could become established and dominate the corrosion process under other types of fouling and in waters of different temperature and salinity. Neither was it known how other types of fouling would affect the corrosion rates.

When NRL personnel initiated a biological deterioration survey at several ocean exposure sites in 1969-1970, it was decided to establish the corrosion rate of structural steel at each of these sites and to investigate further the bio-control theory of marine corrosion. Racks containing 12 to 14 carbon steel disks, all cut from the same sheet of metal, were immersed at five different marine sites. All racks were suspended 6 feet above the bottom in seawater averaging 12 to 18 feet deep at mean low tide. The first biological evaluation staff containing a steel specimen rack was installed at Naos Island at the same Pacific-side location used for the original long-term corrosion studies. This array was followed by one on the Caribbean coast of the Isthmus of Panama, at the Coco Solo Naval Station on Manzanillo Bay, an arm of the Caribbean.

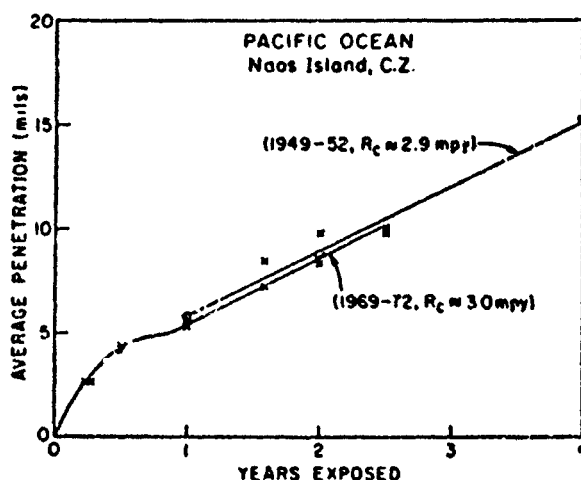
Subsequently, arrays were exposed at the Patuxent River Naval Air Station on Chesapeake Bay; at NRL's Marine Corrosion Laboratory at Fleming Key, Key West, Florida; and in St. Andrew Bay, Gulf of Mexico, at the Naval Coastal Systems Laboratory at Panama City, Florida. Two specimens from each rack were removed at six or seven different time intervals, beginning with some early removals at less than one month. From these duplicate specimens the average corrosion penetration was determined by weight loss, and the weight and type of marine

fouling were established. Finally, the onset and extent of sulfate-reducing bacterial activity were evaluated by inoculating Sulfate API Broth (specific for sulfate-reducing bacteria) with material from the soft, black corrosion layer found next to the metal and by testing for the presence of sulfide in this layer by hydrogen sulfide generation, using lead acetate paper as an indicator.

So that exposure results could be correlated with the earlier 16-year data, the same carbon steel (AISI 1020) was used, and although panels were shaped differently for the two exposures, the same edge-to-area ratio (0.056) was maintained; also, the same procedures were used for preexposure pickling to remove mill scale and for postexposure cleaning to remove fouling and corrosion products (61).

The longest-term data, for 2.5 years, was obtained at Naos Island, where by the first 3 to 6 months the samples were covered with a complete coating of encrusting bryozoans. The first point of interest from these repeat exposures at this site is a comparison of the two sets of data collected 20 years apart. Figure 5 shows the corrosion-vs-time relation for the exposure series at Naos Island compared with the first portion of the curve for the original long-term data collected at the same site. The agreement is quite good, and the best-fit lines indicate that the steady-state rate for the more recent exposures is also about 3 mpy, as it was 20 years earlier.

**FIGURE 5: CORROSION CURVES FOR CARBON STEEL IMMERSSED IN THE PACIFIC OCEAN AT NAOS ISLAND, IN 1949 AND 1969**





In the newer study at Naos Island, specimens removed in less than 1 year reveal very high initial corrosion rates, up to 16 mpy or 80 mdd (milligrams per square decimeter per day) at 21 days. The curve, however, dips appreciably between 6 and 12 months, and the corrosion rate is slowed to less than 1.5 mpy. As with the more pronounced corrosion drop in the original mean-tide exposures, this dip may represent a period of fouling protection prior to the full-scale development of a sulfate-reducing bacterial population. However, this transient attenuation in corrosion rate was not as pronounced at the other four underwater test sites in the later exposures.

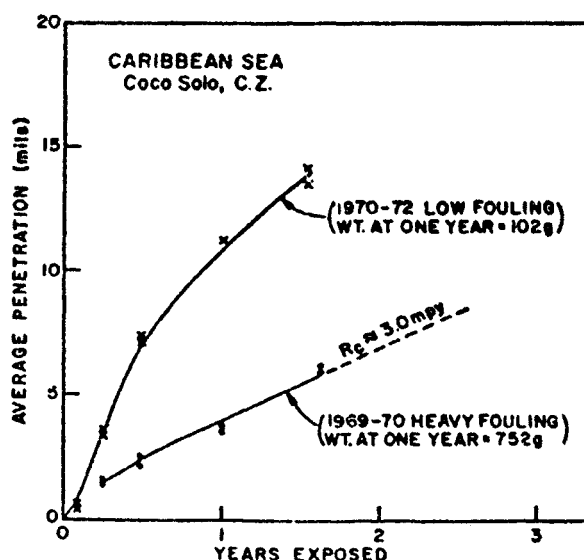
### Protective Effects of Marine Fouling

Although extensive marine borer and fouling studies have been made on the Caribbean side of Panama in Manzanillo Bay at Coco Solo, the corrosiveness of the water at this site had not been previously determined. The water temperature averages about 1°C higher than at Naos Island and the oxygen content is also slightly higher, so the corrosion rate should be as great or a little greater. However, the fouling which consists primarily of barnacles is normally extremely heavy, accumulating a mass of approximately 62 g/dm<sup>2</sup> in three months. Probably because of this rapid and heavy accumulation of barnacles, the first-year corrosion loss was only about ⅓ of the first-year loss at Naos Island.

Corrosion curves for heavy and light fouling attachment at a single site (Caribbean, Coco Solo) are presented in Figure 6, which demonstrates the protective effect of a heavy fouling cover. The lower curve represents normal fouling conditions at Coco Solo. The protective fouling developed very rapidly, and at 3 months it appeared that the corrosion had already changed to a bacterial process. A steady-state rate of about 3 mpy had been established. The upper curve is the result of an unusual and fortunate set of circumstances. Coco Solo harbor had been in use as a test site for over 10 years and the water had always produced an extremely heavy barnacle attachment, but during this recent test period something drastically inhibited the barnacle population. The reason for the sudden decrease in barnacles has not been established, although it is possible that weed killers used in clearing drainage channels emptying into the harbor may have been the cause.

When this decrease in fouling was noted, a second rack of steel specimens was immersed at the Coco Solo site. The upper curve is for this second, lightly fouled set of specimens. A comparison of the two curves gives us the best insight yet obtained into the protective effects of marine fouling. They show the difference in seawater corrosion at a specific location when the amount of fouling cover was reduced about 85%. At 1 year the corrosion loss was over 3 times as great for the rack with low fouling.

**FIGURE 6: CORROSION-TIME CURVES FOR CARBON STEEL IN CARIBBEAN SEAWATER AT COCO SOLO**



With the data presented from the more recent studies combined with those from the earlier long-term exposures, it becomes evident that complete covers of marine fouling can be useful in reducing steel corrosion. The fact that anaerobic conditions developed at all metal surfaces indicated the effectiveness of the different types of fouling in preventing oxygen from reaching the metal surface and scavenging hydrogen. Development of methods for assuring a heavy fouling cover on stationary marine structures is a desirable research goal. Crisp and Meadows (72) have shown that barnacles can be attracted to surfaces treated with barnacle extracts. In one instance an order of magnitude increase in settlement was obtained. Such methods may have practical applications in the treatment of steel surfaces and should be investigated for this purpose.

Comparative corrosion and biological data for all of the five test locations during the first year of exposure are shown in Table 3. At the two temperate-climate sites, Chesapeake Bay near the Patuxent River and St. Andrew Bay on the Gulf of Mexico, the panels were not completely covered with macro-fouling during most of the first year of exposure. At both of these sites a variety of organisms was present, with the predominant forms being algae and barnacles in Chesapeake Bay and algae, oysters, and tunicates in St. Andrew Bay. Although seasonal temperature changes and growing cycles at these two temperate-water sites exert a masking influence on the short-term data available, the fouling at these two locations also seems to provide considerable early corrosion protection to the steel surfaces.

At Key West, Florida different fouling prevailed; there the specimens rapidly collected a thick coating of plants, principally algae of the genus *Enteromorpha*. Very little calcareous fouling was observed at this site. Probably because of its more rapid development, this vegetable fouling provided the most effective early protection to the steel. The high initial corrosion loss normal for most seawater sites was not in evidence at Key West; for example, the average rate through the first 90 days was only 22 mdd, compared with 55 mdd at Naos Island. The final steady-state corrosion rate at Key West, however, also seems to be controlled by sulfate-reducing bacteria and falls into the same 2 to 3 mpy range normal for the four other sites.

### Distribution and Influence of Sulfate-Reducing Bacteria

Most previous studies of corrosion by sulfate-reducing bacteria have been directed toward soil-burial corrosion or effects in laboratory cultures; little attention has been focused on the importance of these organisms in the marine environment. The natural exposure data from both NRL studies indicate a dominant role for these anaerobic bacteria in the corrosion of structural ferrous metals in the ocean. At all locations, including the half-salinity of Chesapeake Bay, marine sulfate-reducing bacteria were active on the metal. By the end of the first year's exposure, iron sulfide by-products were found generally over most of the specimen surfaces. Pitting on all panels was moderate, and isolated barnacles and spots of heavy fouling attachment did not seem to induce deeper pitting underneath. Where the anaerobic bacteria were active a soft, nonadherent layer, which seemed to be mostly iron sulfide, formed over all of the metal surfaces beneath the accumulated corrosion and fouling products. With this layer present, the covering material of fouling and corrosion scale can be easily removed in large unbroken pieces. It appears from these exposures that, at all sites, after a sufficient amount of fouling cover develops, anaerobic conditions are established at the metal surface and the corrosion process becomes bacterially controlled.

The fact that all the different forms of fouling,

**TABLE 3: BIOLOGICAL ACTIVITY AND CORROSION AT DIFFERENT MARINE EXPOSURE SITES**

Location	Average Salinity (ppt)	Year Exposed	Fouling	Weight of Fouling Attachment at 1 yr (g/dm <sup>2</sup> )	Metal Weight Loss 1 yr (g/dm <sup>2</sup> )	Sulfate-Reducing Bacteria at 1 yr
Panama Pacific Naos Is., C.Z.	30	1969	Encrusting <i>Bryozoa</i>	16	10.6	Very heavy
Panama Caribbean Coco Solo, C.Z.	31	1969	Very heavy barnacles	90	7.3	Very heavy
Chesapeake Bay Patuxent NATC	16	1969	Algae and barnacles	19	7.2	Moderate
St. Andrew Bay Panama City, Fla.	26	1971	Scattered oysters and tunicates	53	11.0	Moderate
Fleming Key Key West, Fla.	37	1970	Very heavy algae ( <i>Enteromorpha</i> )	15	7.4	Heavy

from algae to a very heavy barnacle cover, barred the passage of oxygen sufficiently to permit the development of sulfate-reducing bacteria at the metal surface, indicates that corrosion rates can be drastically lowered in most seawater environments if the sulfate-reducing bacteria can be selectively inhibited.

### BIOLOGICALLY CONTROLLED CORROSION RATES AT DIFFERENT GEOGRAPHICAL LOCATIONS

After the biological processes of marine fouling and marine bacteria have exerted their influences, the corrosion rates are stabilized to a final steady state. Although some of the data from the five NRL sites are very short-term, it appears that all final rates will fall within a range of 2 to 3 mpy. This is considerably lower than the marine corrosion rates for carbon steel usually reported in the literature ( $\geq 5$  mpy); however, such literature reports almost invariably include the initial high first-year loss. This initial corrosion is of no great significance in itself, but if used with short-term results to establish a corrosion rate can be very misleading. If 3 mpy can be accepted as a reasonably consistent upper limit for most low-velocity seawater environments, design engineers will have considerably more latitude in the use of structural steels in seawater.

To investigate additional geographical locations and to establish steady-state corrosion rates from

longer exposures, data have been examined from all known seawater corrosion studies where adequate information was obtained for carbon steel (73)-(76). Curves from these studies show much the same pattern as those for the NRL sites; after initial high losses, the corrosion rate levels off to a steady state. It can be assumed that these linear relations result from the combined activity of fouling and sulfate-reducing bacteria. The first-year losses and final constant rates for seven different ocean sites are presented in Table 4. The best-fit lines for the linear portion of the time-vs-corrosion curves were used to determine these steady-state corrosion rates. Even though temperatures, biofouling, and seasonal growing cycles are quite varied for the seven sites, which range in latitude from 9°N to 51°N, once the corrosion rate has stabilized the final steady-state rates are all within the narrow limits of 2 to 3 mpy.

Whereas the large differences in water temperature between these extremes of latitude would have considerable effect on normal aqueous corrosion, with bacterial corrosion the temperature effect is less significant; the *Desulfovibrio* bacteria that corrode steel are known to thrive between 10°C and 40°C and to be active over most of this range (77).

All of the exposure results reported in Table 4 are for relatively clean, low-velocity, inshore seawater, suitable for the growth of both macrofouling and

**TABLE 4: CORROSION RATES OF CARBON STEEL IN SEAWATER AT VARIOUS LOCATIONS**

Exposure Location	North Latitude (dy)	Duration of Exposure (yr)	First-Year Loss (Av Penetration, mpy)	Steady-State Corrosion Rates* (Av Penetration, mpy)
Panama Pacific Naos Is., C.Z.	8.55	16	5.8	2.7
Panama Caribbean Coco Solo, C.Z.	9.21	1.5	3.6	$\leq 3.0$
Key West, Fla	24.35	2.0	3.7	$\leq 2.9$
Kure Beach, N.C.	33.85	8	5.7	2.2
Point Mugu, Calif.	34.06	2.1	5.8	$\leq 2.4$
Harbor Is., N.C.	34.20	2.5	4.5	$\leq 2.1$
Emsworth, Eng.	50.80	4	4.0	$\leq 2.1$

\*Slope of the linear portion of the time-corrosion curve (after the first year).

marine microorganisms. Polluted or diluted seawater, arctic seawater, high-velocity water, and other waters in which oxygen is present but in which marine fouling cannot thrive could produce higher corrosion rates. Furthermore, these results were obtained with descaled samples that had edge-to-area ratios of 0.056 and no dissimilar metal contacts. Higher edge-to-area ratios could increase the average metal loss. Galvanic effects caused by large areas of mill scale, dissimilar metal contact, or variations in electrolyte seem to override bacterial control and accelerate pitting. Other variations from normal conditions could be expected to dominate or influence corrosion rate control.

### ESTIMATION OF METAL LOSS FOR EXTENDED PERIODS OF EXPOSURE

From the data in Table 4, 2.0 to 2.5 mpy seem to be a reasonable range for average penetration in normal temperate-climate seawater, while 2.5 to 3.0 mpy seem to best represent the range in tropical seawater. With these values in hand, equations for estimating the life of structural steel in normal in-shore seawaters can be simply derived as follows:

The general equation for average penetration of steel in seawater is

$$\bar{P}_t = \bar{P}_1 + R_c(t-1) \quad (1)$$

where  $\bar{P}_t$  = average penetration in mils at time  $t$  in years

$\bar{P}_1$  = average penetration in mils for the first year of exposure

$R_c$  = constant corrosion rate in mpy (slope of the linear portion of the time-vs-corrosion curve).

For temperate seawater (where  $R_c \leq 2.5$  mpy),

$$\bar{P}_t \leq \bar{P}_1 + 2.5(t-1) \quad (2)$$

For tropical seawater (where  $R_c \leq 3.0$  mpy),

$$\bar{P}_t \leq \bar{P}_1 + 3.0(t-1) \quad (3)$$

Thus for any time  $t$  the average corrosion penetration can be estimated if the first-year loss is known or can be approximated. Since in extended projections  $P_1$  is only a minor consideration, an approximate value of 5 mils (based on the results in

Table 4) can be used for both tropical and temperate exposures without introducing appreciable error. Equations (2) and (3) can then be reduced to

$$\bar{P}_t \leq 2.5t + 2.5 \quad \text{for temperate seawater, and} \quad (4)$$

$$\bar{P}_t \leq 3.0t + 2.0 \quad \text{for tropical seawater.} \quad (5)$$

These formulas indicate that the estimated average penetration of a carbon steel surface after 10 years of service would be no more than 28 mils for temperate and 32 mils for tropical seawater.

Very little useful corrosion loss information from actual unprotected structures has been reported; such data could be applied to check the validity of these formulas. One report, by Larrabee (78), gives the average penetration of steel H piles exposed in unpolluted seawater near Santa Barbara, California as 40 mils over a 20-year period. This is in fairly good agreement with the <53 mils predicted by equation (4).

### SUMMARY

The data obtained from long- and short-term exposures of structural carbon steel in natural aqueous environments have shown the important influence of marine organisms on the corrosion rates of ferrous metals in seawater. Very high corrosion rates, up to 16 mpy, were measured during initial periods of exposure prior to development of a macrofouling cover. The length of the prefouling period, the types and quantities of fouling, and the corrosion losses during the first year of exposure varied considerably for the different ocean locations. By the end of 1 to 1.5 years of exposure, most of the test specimens had become covered with a mat of fouling organisms. These natural covers, although different in composition at the different sites, all seemed to offer considerable protection to the steel panels.

The beneficial effect of the natural protective fouling coating diminishes appreciably when it becomes sufficiently thick (and bio-active) so as to exclude oxygen from the metal surface. Then sulfate-reducing bacteria take control of the corrosion process, and in the anaerobic environment maintained at the metal surface by the self-healing fouling

cover, a final steady-state corrosion rate is established. These final rates are surprisingly consistent for the different ocean locations.

In normal temperate and tropical seas, where both fouling organisms and sulfate-reducing bacteria are active, structural steel, after the first year of exposure, generally corrodes at a steady-state rate between 2 and 3 mpy. The rate of 3.0 mpy appears to be the upper limit for corrosion in tropical seawater, while the upper limit found for temperate climate seawater is about 2.5 mpy.

With these low rates established, the design of steel structures to allow for expected loss, in lieu of more costly protective maintenance procedures, becomes a practical consideration.

To utilize fully the natural self-healing protective coatings provided by marine fouling, methods of attracting fouling to a metal surface and of maintaining a healthy coating on the metal would have to be studied.

In conjunction with the fouling investigation, studies of procedures for controlling the anaerobic sulfate-reducing bacteria population should be undertaken; if these bacteria can be selectively controlled while maintaining an adequate fouling cover, then very low corrosion rates for bare steel immersed in seawater should be attainable.

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- (76) Reinhart, F.M. and Jenkins, J.F., "Corrosion of Materials in Surface Seawater After 12 and 18 Months of Exposure," *Naval Civil Engineering Laboratory Technical Note N-1213* (January 1972).
- (77) Miller, J.D.A. and Tiller, A.K., "Microbial Corrosion of Buried and Immersed Metal," *Microbiol. Aspects of Metallurgy* (J.D.A. Miller, editor), 61-105, New York, Elsevier (1970).
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# **AN ANNOTATED BIBLIOGRAPHY FOR CORROSION OF METALS**

Material in the following chapter, a comprehensive bibliography as of July 1972, is from a paper by L.A. Beaubien included in a report by Beaubien, I. Wolock, and C.L. Buchanan, of Ocean Technology Division, Naval Research Laboratory, and C.L. Whitman, Naval Ordnance Station, Indian Head, Maryland (AD-747 245).

## INTRODUCTION

Many publications are available on corrosion of metals in seawater. Presented here is an annotated bibliography representing, within the limitations in scope to be described in the next subsection, the major work in this field. Special attention should be called to two of the entries. One is a book on marine corrosion by Fink and Boyd (entry 70) which [—until their updated MCIC Report 78-37 of March 1978—see first chapter of this book] contained the most comprehensive collection published of facts and data on various types of seawater corrosion, arranged according to both material and environment. The other is an earlier profusely indexed and cross-referenced bibliography compiled by Keehn (entry 117) which covers practically all topics related to marine corrosion, including foreign entries, but is not comprehensive on most topics, including the areas covered in this report.

## SCOPE AND ARRANGEMENT

This bibliography deals primarily with the corrosion of unstressed, unprotected metals immersed in quiescent seawater at ambient temperature. Such topics as biological fouling, stress corrosion cracking, cathodic protection, and corrosion at high temperatures, characteristic of desalination equipment

or at high velocities characteristic of turbine operation, are not generally represented. Exceptions are citations for individuals or groups working on a wide range of marine corrosion problems, documentation of their work being more or less complete. Also, when no abstract was available and selection was based on title alone, some latitude was taken on title evaluation.

The resulting entries date primarily from 1950, with some few entries going back to the middle 1940s. No attempt was made to uncover items which predate presently available abstracting and indexing services. Entries are primarily limited to publications in English except for a few title translations. Further foreign-language entries can be found in the aforementioned work of Keehn. The abstracts presented are either those of the original author or are from some outside bibliographic source. Some editing, however, was done on the longer abstracts from the Prevention of Deterioration Center.

References are listed alphabetically and numbered according to the first author named and chronologically under each author. Coauthors' names are given in the original entry but are not considered in the order of arrangement. All authors and coauthors are listed in the author index. An index by material is also given.

1

Ailor, W. H. and Reinhart, F. M.  
CORROSION OF ALUMINUM ALLOYS IN SEA WATER.  
J. Am. Soc. Nav. Engrs., 76: No. 3:  
443-449, 1964.

In French.

Results of tests, carried out for periods from 6 months to 3 years, on corrosion by sea water of panels of following alloys: 1050-H18, 8099-18, 3003-H18, Alclad 2011, and 5050 are given. Same type of corrosion has been studied on galvanized steel sheet.

2

Ailor, W. H. ALUMINUM IN SEAWATER.  
Geo-Marine Technology, 1: No. 4: 38-42, 1965.

3

Ailor, W. H. EVALUATION OF ALUMINUM PANELS EXPOSED IN THE PACIFIC OCEAN AT 2,340 FEET FOR SIX MONTHS. Metallurgia, p.3-12, March 1967.

Results obtained from the exposure for six months of thirteen alloys at a depth of over 2,300 ft. in the Pacific Ocean substantiate the excellent seawater characteristics of aluminium and its alloys. These results confirm the desirability of using aluminium-magnesium alloys for marine applications and show the effectiveness of cladding in protecting aluminium-zinc-magnesium-copper core alloys. The attack on aluminium alloys in deep-sea exposure generally takes the form of pitting, as in marine surface and atmospheric exposures. This pitting is of a magnitude which is of little consequence for those alloys designed for seawater applications and is comparable to depth of pitting found in surface exposures. No fouling was evident for panels exposed at test depth. A shiny iridescence was observed on some panels. Results indicate that such high-strength alloys as 7079 and X7002 can be used for seawater applications when properly protected by a higher potential cladding alloy such as 7077.

4

Ailor, W. H. EVALUATION OF ALUMINUM AFTER ONE-YEAR DEEP SEA EXPOSURE.  
J. Hydronautics, 2: No. 1: 26-33, 1968.

5

Ailor, W. H., Jr. ALUMINUM ALLOYS AFTER FIVE YEARS IN SEAWATER. In: Materials Performance and the Deep-Sea Symposium Papers American Society for Testing and Materials. Seventy-first Annual Meeting, (Held in San Francisco, Calif., June 23-29, 1968) ASTM Special Technical Publication 445. p.115-130, Feb. 1969.

Eight aluminum alloys and panels of high-purity aluminum were exposed for five years in seawater at Harbor Island, N. C. Replicate 4 by 12-in. panels of each material were exposed in half-tide immersion and full immersion. Removals in triplicate were made at the end of one-, two-, and five-year exposures. Other than the 1199 aluminum (99.99 percent purity), seven aluminum-magnesium alloys (5000 series) and one aluminum-zinc-magnesium-copper alloy 7079 were tested. Panels were degreased prior to exposure and were cleaned ultrasonically in a chromic-phosphoric acid solution after exposure. After depth of pitting was measured, tension specimens were cut from each panel, and the ultimate tensile and yield strengths and elongations were determined. All panels were heavily fouled with barnacles and other marine growth for all exposure periods. The fouling apparently had some effect on the pitting depth of the aluminum in tidal immersion. Little change in tensile properties after five-years' exposure was noted for the 1199, 5083-0, 5086-0 or 5454-H32. Tensile losses were recorded for several alloys as follows: 5086-H112 (4.8%), 5154-H38 (6.2%), and 5457-H34 (4.3%). The high-purity 1199 and alloys 5154-H38, 5086-H112, and 5456-H321 showed losses of 6 to 10 percent in elongation while the change in elongation for the 5457-H34 was a decrease of about 16 percent. The 7079-T6, which can only be used in seawater when protected, had severe exfoliation corrosion. Confirming other work, we found the corrosion rates to be greater for the full-seawater immersion than for the tidal immersion. The lowest five-year corrosion rate in the half-tide location was 0.07 mdd (milligrams per square decimeter per day) for the 5083-0, and the highest rate for the aluminum-magnesium 5000 series was 0.11 mdd for the 5454-H32 alloy. In full-immersion tests the lowest rate was 0.12. For comparison, the rates for the 7079-T6 alloy were 0.79 mdd in tidal and 3.4 mdd in full immersion. Corrosion weight losses and depth of pitting had reduced rates of growth over the interval between two years and five years. Maximum depth of pitting for an alloy was generally at least four times the magnitude of the average of the twenty deepest pits. The deepest pit found for any alloy after five years was 33.0 mils for 5456-H321 in half-tide immersion and 38.0 mils for the same alloy in full immersion. Least pitting depth occurred in 5457-H34 (less than 4.5 mils for both exposures).

6

Alexander, A. L., Forgeson, B. W., Mundt, H. W., Southwell, C. R. and Thompson, L. J.  
CORROSION OF METALS IN TROPICAL ENVIRONMENTS, PART 1 - FIVE NON-FERROUS METALS. Corrosion, 14: No. 2: 33-41, February 1958.

7

Ambler, H. R. PRELIMINARY REPORT ON CORROSION OF SOME COMMON METALS IN SEA AND CREEK WATER. Gt. Brit. Tropical Testing Establishment, Port Harcourt, Nigeria, Report No. 335: 4 p., March 1954.

Preliminary results are given on the corrosion of sheet samples of sandblasted mild steel, brass, and aluminum immersed in tropical waters at Lagos Harbor (0.22-3.00% salinity, pH 7.2-8.0, temperature 25.5-29 C) and at Port Harcourt Creek (1.3-2.08% salinity, pH 7.2-8.0, temperature 27-29.5 C). In addition, laboratory exposures were made in static and aerated creek water, static and aerated distilled water, and static boiled distilled water.

Corrosion of mild steel was high, up to 70 mil per yr. It corroded most on tidal immersion and less than half as much under total immersion. Brass, however, corroded much more on total than on tidal immersion. Aluminum showed no regular effect. Corrosion in the laboratory with creek water, aerated or static, was much less, particularly for brass, than in the actual creek exposure, suggesting the influence of biological factors. A mild steel panel totally immersed at Port Harcourt for 2 1/2 mo and subsequently placed in dilute acid, produced a strong smell of hydrogen sulfide, suggesting activity by sulfate-reducing bacteria. A similar panel, examined after 2-wk exposure, produced no detectable hydrogen sulfide. Aerated distilled water was as corrosive under laboratory conditions as was creek water for steel, but not for brass.

8

Anderson, D. B. and Vines, R. F. ANODIC CORROSION OF PLATINUM-GROUP METALS IN SEA-WATER. In: Proceedings 2nd Internat. Congress on Metallic Corrosion, New York, 1963, p. 763-766: 1966.

Tests were conducted on Pt, Pt alloys and Pt-group metal alloys, and showed Pt anodes were uniformly consumed at an average rate of 6-7 mg/amp. year in sea-water over a wide range of c.d. Pd, Ag, Pd-40 percent Ag, Pd-10 percent Ru, and Pd-10 percent Rh alloys were consumed at excessive rates; Pt-(5 and 10 percent) Ru, Pt-(5 and 10 percent) Ir, and Pt-(5 and 10 percent) Rh behaved slightly worse than unalloyed Pt, while Pt-12 percent Pd and Pt metal were hardly affected. Test results and apparatus are detailed.

9

Anderson, E. A. ZINC IN MARINE ENVIRONMENTS. Corrosion, 15: No. 8: 409t-412t, 1958.

10

Anonymous. MARINE EXPOSURE TESTS ON Ti-Al AND Zr-Al COUPLES. Light Metals, 16: p. 223, July 1953.

Results of preliminary corrosion tests indicate that full precautions in marine exposure are probably necessary when either titanium or zirconium is used in conjunction with aluminum alloys in any composite assembly involving a joining system.

In these tests three specimens were prepared. (1) Titanium sheet was riveted to A4D aluminum alloy sheet with zinc chromate paste between faying surfaces, (2) zirconium replaced titanium in a similar combination, and (3) Titanium was riveted to A4D sheet without jointing compound. The specimens were tied to stakes in the Menai Straits in such a way that sea water and atmospheric exposure times were about equal. Visual examination after 2 mo showed the titanium and zirconium to be unaffected. The aluminum alloy in both specimens using jointing compound was severely attacked, pitting was particularly severe in areas of distortion produced by stamp marks. The attack on the aluminum alloy was not quite as severe in the specimen joined without chromate.

11

Anonymous. SEA WATER TESTING FACILITY EXPOSES METALS AND ALLOYS TO VARIOUS CORROSIVE ENVIRONMENTS. Materials Protection, 7: No. 10: 58-59, Oct. 1968.

12

Anonymous. THE BEHAVIOUR OF STAINLESS STEEL IN SEA-WATER. Anti-Corrosion Methods and Materials, 14: No. 7: p. 9-11, July 1967.

Presents a critical examination of the behavior of stainless steel in seawater. The behavior varies but alloys containing nickel (austenitic) have the highest corrosion resistance and are the ones most likely to be used. Both pitting and stress-corrosion cracking are discussed. The behavior of stainless steel in chloride solutions, at areas of oxygen shielding and when pitting in the presence of stress, suggest caution and careful use. Many design authorities do not permit the use of stainless steels in any marine environment where the chances of oxygen screening and stress may occur.

13

Anonymous. RESISTANCE OF ALUMINUM ALLOYS TO SEA WATER AND AIR. Rev Aluminium, No. 330: p. 473-478, Apr. 1965.

Corrosion tests on A-G3, A-G4, A-G4MC, A-G5 and A-Sg Al alloys under conditions

simulating those in superstructures of ocean-going vessels. A-G4 grade, currently used in naval construction, withstood all types of tests best. Both bare and painted specimens stood up well in immersion or alternating immersion-emersion tests of several years' duration, while high-corrosion rates were found in semi-immersion tests and in specimens near water-air separation surface. Riveted steel-Al alloy assemblies exposed to sea air behaved well when joint was made with strip of insulating material between metals, or at least with coat of zinc chromate paint. In total immersion tests in sea water on same types of joints, heavy corrosion of Al alloy in contact with insulation strip occurred when Al alloy was not painted or when belts or rivets were not tightened sufficiently or spaced closely enough to provide perfectly tight joint. Even best assembly procedures were not sufficient to guarantee electrical insulation between Al alloy and steel when joints were wet, as in presence of stagnant water, although use of toxic organic-base paints was helpful in these cases.

14

Babakov, A. A., Ulanovskii, I. B., Tufanov, D. G., Korovin, Ye. M. SEA-WATER CORROSION OF STAINLESS STEELS. Akademiya nauk SSSR. Institut fizicheskoy khimii. Trudy, No. 8: Moskva, 345-353, 1960.

In Russian.

An extensive study has been conducted on the corrosion behavior of various stainless steels in Black Sea waters. Five steel groups were tested: 1) steels of the 2X13 (AISI 420) type, plain and with additions of Mo, Cu or B; 2) steels of the X17H2 (AISI 431) type, plain and with additions of Mo, B, or Al; 3) steels 1X18H9T (AISI 321) and 1X18H11B (AISI 347); 4) a series of experimental steels containing 18% Cr and 6-11% Ni with addition of Cu, Nb, Ti, N or B; and 5) a series of experimental Cr-Mn steels containing 13-14% Cr, 13-14 or 18% Mn with additions of Ni, Cu, Ti or N. The most promising results were shown by X17H2 steel additionally alloyed with 2% Mo, by 1X18H11B steel, and by an experimental steel with 18% Cr, 6% Ni, 1.18% Cu, 0.82% Nb and 0.30% N. The respective weight losses after a 2-year test (3 months for X17H2 steel with Mo) were 0.1, 0.36, and 0.39 g/dm<sup>2</sup>. Steel of the 2X13 type were severely damaged during the first three months of the tests. Corrosion was mostly of the localized (in areas of contact with nonmetallic holding devices and barnacles) and pitting type. The weight losses varied between 1.5 g/dm<sup>2</sup> for steel with an addition of 0.96% Cu to 2.8 g/dm<sup>2</sup> for plain 2X13 steel. The X17H2

steel corroded in the same manner, but to a much lesser degree. The weight losses varied from 0.1 g/dm<sup>2</sup> for steel with 2% Mo to 0.9 g/dm<sup>2</sup> for steel with 0.003% boron. Mo in amounts below 2% had no beneficial effect. Of the austenitic Cr-Ni steel the highest weight loss, 1.20 g/dm<sup>2</sup>, was shown by 1X18H9T steel. Also in this case the corrosion was of a localized type. The weight losses of austenitic Cr-Mn steels were high and varied (in the 2-year test) from 5.4 to 6.3 g/dm<sup>2</sup>.

15

Bailey, G.L. COPPER-NICKEL-IRON ALLOYS RESISTANT TO SEAWATER CORROSION. J. Inst. Metals, 79: 243-292, July 1951.

This report describes the development of copper alloys containing 5-10% nickel and 1-2% iron. These materials are easily worked and are resistant to corrosion by moving sea-water.

The corrosion resistance of 70:30 cupronickel to moving aerated sea-water is greatly increased by the presence of 0.30% iron. Iron contents of 1% or more increase the tendency of this alloy to local pitting at areas shielded from oxygen. Alloys of low nickel content (5-10%) are greatly inferior to the 70:30 alloy if the iron content is below 1%; the addition of 1.3-2% iron confers on these low-nickel alloys corrosion resistance of the same order as that of the 70:30 alloy containing 0.3-0.5% iron.

Alloys containing 5-10% nickel and 1-2% iron offer optimum resistance to sea-water corrosion when quenched from temperatures of the order of 850-950 C. The resistance is reduced, particularly in contaminated waters, by annealing at, or slowly cooling to temperatures of the order of 600 C. The reduction in corrosion-resistance accompanying these heat treatments is due to the separation of a second solid solution richer in nickel and iron.

Optimum corrosion-resistance is not compatible with hot workability. Heating to 600-700 C during hot working causes breakdown of the corrosion-resistant structure and increases liability to cracking. The corrosion-resistance of the alloys, as normally manufactured in tube form, is ordinarily not sufficiently below the optimum to justify the troublesome steps necessary to ensure the best possible results. Whatever the heat-treatment or structure, alloys containing 5-10% nickel and 1-2% iron can be readily cold-worked and hot worked if suitable precautions are taken in manufacture.

16

Baker, H. R., Bolster, R. N., Leach, P. B.,



Singleterry, C. R. EXAMINATION OF THE CORROSION AND SALT CONTAMINATION OF STRUCTURAL METAL FROM THE USS TECUMSEH. Naval Research Laboratory. Report No. NRL-MR-1987. AD-687 394. 18 p., Mar. 1969.

The USS Tecumseh, sunk during the Civil War battle of Mobile Bay, is to be raised by the National Armed Forces Museum. Structural specimens were studied to determine the effectiveness of various methods of removing seawater salts from the corroded metal. The nature of the scale deposits and the extent of corrosion were also studied. With the exception of the rivets, the wrought iron of the hull was found to be in surprisingly good condition. The peened ends of the rivets had been deeply attacked, and cast iron deck plates had been perforated in places. Hull joints had been penetrated by corrosion and seawater. Ultrasonic cleaning was found to be ineffective in removing salts due to their encapsulation by the scale. Sandblasting to remove the scale, followed by flushing with water, appears to be the best cleaning technique. Analysis and examinations of the scale showed that there were typically 3 distinct layers, 2 of iron oxides and an exterior calcareous accretion. The formation of the scale layers can be explained by accepted corrosion mechanisms.

17

Basil, J. L. REPORT ON THE RESISTANCE TO CORROSION OF CAST AND WROUGHT ALUMINUM ALLOYS IN SEA WATER; ALUMINUM COMPANY OF AMERICA, ...Washington, D.C., EXHIBITOR. Naval Engineering Experiment Station, Report C-3371-C: February 1950.

Samples of nine wrought and six cast aluminum alloys were exposed from December to June in sea water at 50-75 F flowing at the rate of 3 fps. The corrosion resistance of the wrought alloy 52S-1/2H (2.5Mg-0.25Cr) was excellent, and that of the wrought alloy 63S-T5 (0.4Si-0.7Mg) was fair. The other alloys had poor resistance and would be severely damaged by prolonged exposure to flowing sea water.

The wrought alloys 75S-T6 (1.6Cu-2.5Mg-5.6 Zn-0.3Cr), 61S-T6 (0.25Cu-0.6Si-1.0Mg-0.25Cr), 4S-1/2H (1.0Mg-1.2Mn), and 3S-1/2H (1.2Mn) pitted to a depth readily measurable by depth gage or pointed micrometer. An alclad sample was penetrated to the 3S core, indicating that the coating alloy (72S) had comparatively low corrosion resistance. Two samples of 72S-0 (1.0Zn) showed no pitting on the surface but corrosion started at the edges and penetrated from one edge to the other. Evidence of intergranular corrosion was observed in the wrought alloys 61S-T6, 75S-T6, and 24S-T (4.5Cu-1.5Mg-0.6Mn).

Of the cast alloys, 220-T4 (10.0Mg) and 356-T6 (7.0Si-0.3Mg) were the most resistant to corrosion. Alloys B-214 (1.8Si-3.8Mg) and 214 (3.8Mg) were most susceptible to pitting attack. Alloys B-214, 220-T4, 356-T6, 43(5.0Si), and 195-T5 (4.5Cu-0.8Si) showed evidence of intergranular corrosion.

Test specimens were bolted at each end to a rectangular micarta rack. The racks were laid in a trough so that they were 2 in. above the bottom and 3 in. below the water surface. The direction of flow was normal to the longitudinal edges. The test site was Kure Beach, N. C.

18

Basil, J. L. THE RESISTANCE TO CORROSION OF CAST AND WROUGHT ALUMINUM ALLOYS IN SEA WATER. U.S. Naval Engineering Experiment Station, Report 4H(4)066918: October 1952.

A number of wrought- and cast-aluminum alloys were tested for corrosion resistance in natural sea water at Wrightsville Beach, N.C., and in brackish estuary water at Annapolis, Md.; results were compared with those of a similar test series carried out at Kure Beach, N.C. The effect of high water velocity was tested by rotating immersed specimens at high speeds. Resistance to impingement attack was determined by means of jet tests. Specimens were also exposed to quiet sea water, to sea water flowing at 10 fps, and to river water.

The aluminum alloys generally suffered considerably less corrosion damage at Wrightsville Beach than at Kure Beach, owing perhaps to the presence of corrosive decomposition products of marine organisms. At Wrightsville Beach, the wrought alloys 3S-1/2H (1.2% manganese) and 52S-1/2H (2.5% magnesium, 0.25% chromium) and the cast alloys 214 (3.8% magnesium) and 220 T4 (10% magnesium) were rated very good to excellent. Although they sustained considerable corrosion damage in the Kure Beach tests, they were superior to other aluminum alloys tested in the same location. The test results also emphasized the importance of insulating aluminum alloy assemblies from other metal systems.

19

Basil, J. L. RESISTANCE TO CORROSION OF SEVERAL WROUGHT ALUMINUM ALLOYS IN NATURAL SEA WATER. Navy Marine Engineering Lab. Report No. 040037A 4: AD- 43 667. March, 1954.

20

Basil, J. L. and Rausch, M. W. SEA WATER CORROSION TEST OF ALUMINUM ALLOY PIPE. U.S. Naval Engineering Experiment Station, Evaluation Report 040037A 5: AD 56666. February 1955.



Results of sea-water corrosion tests on insulated pipe sections of 3S Alclad, 3S, and 52S aluminum alloys indicate that all three alloys have good resistance to general corrosion and corrosion-erosion but that the first two alloys are more resistant to pitting than is 52S. Pitting rates indicate a life expectancy of at least 10 yr for 3S and Alclad 3S pipe with a wall thickness of 0.133 in. exposed to water at a velocity of 10 ft per sec.

After 30 to 42 mo, the 3S aluminum pipe contained many small pits and a number of deeper pits with a maximum depth of 0.04 in. Alclad 3S pipe, after 12 to 24 mo, showed large shallow pits (0.16 to 0.019 in.) in the cladding material; there was no evidence of core pitting. 52S alloy pipes in test for 12 to 24 mo showed a number of scattered pits (maximum depth 0.041 in.) but no general roughening of the surfaces. All pipe showed corrosion-erosion beveling on the edges where the water entered. No intergranular corrosion was observed in any location.

The most serious disadvantage of aluminum alloys is that they are anodic to other metals and would corrode rapidly from galvanic attack if coupled to other metals in seawater piping. Their successful use would require either exclusion of other metals or complete insulation from them which probably would be impractical in piping systems on major naval vessels. Other problems are choice of fittings, especially valves, and a suitable method of joining.

21

Basil, J. L. SEA WATER CORROSION TEST OF ZINC, ALUMINUM, AND MAGNESIUM ANODES. U.S. Naval Engineering Experiment Station. Research and Development Report 910039A; AD 214703: 15 p. February 1959.

Anodes of high purity zinc, 95-5 Al-Zn alloy, and 91-6-3 Mg-Al-Zn alloy with 0.033 to 0.06% copper were tested as 5 in. diameter, 1/2 in. thick rotating discs at 1225 rpm, or a peripheral velocity of 27 fps, in sea water for 7 to 31 days. The severe corrosion-erosion conditions greatly accelerated anode consumption. Current outputs, however, were increased proportionately so that galvanic efficiencies were not reduced significantly over those in static tests. The aluminum alloy was the most corrosion-erosion resistant, zinc was next, and the magnesium alloy last. The metal loss for the aluminum alloy was about 50% greater than in the static test, while that of zinc was about 200% greater. In the magnesium alloys, neither copper content nor casting location (surface or interior) appeared to exert any significant effect.

The lack of effect of copper may be due to the modifying influence of the 0.20% manganese in the alloy, or to the rapid wastage of magnesium which masks the effect of minor constituents.

22

Basil, J. L. THE CORROSION OF METALS AS A FUNCTION OF SEAWATER VELOCITY. Marine Engineering Lab. Report MEL A 72 64, AD 442 345L: 11 p., 1964.

23

Basil, J. L. CORROSION OF MECHANICAL SEAL MATERIALS INDUCED BY COUPLING TO CARBON. Marine Engineering Lab., Report No. 117 64, AD 445 822L: 8 p., Aug. 1964.

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Beck, W. THE INTERNATIONAL CONGRESS OF FOULING AND MARINE CORROSION, JUNE 8-13, 1964. Office of Naval Research, London. TR C14 64, AD 450 804: 11 p., Sept. 1964.

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Beckner, C. F. MARINE FOULING AND CORROSION OF INSTRUMENTATION AT ARGUS ISLAND. Naval Oceanographic Office, Washington, D.C., Oceanographic Prediction Div. Report Informal Manuscript-0-55-65, AD 479 369L: 9 p., January 1966.

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Berry, W. E. REVIEW OF RECENT DEVELOPMENTS. CORROSION AND COMPATIBILITY. Battelle Memorial Inst., Defense Metals Information Center. Report AD-848 603: 4 p., Feb. 1969.

27

Boeing Co. RESULTS OF 197 DAY EXPOSURE TO DEEP OCEAN ENVIRONMENT ON STRUCTURAL MATERIALS AND COATINGS. Report No. D2-125376-1, AD-826 888L: 48 p., April 1967.

Specimens of coated and uncoated metals, stressed metals, and plastics which were exposed for 6 months at a depth of 2500 feet in the Ocean off the California Coast. The subsequent evaluation of these specimens is the subject of this report.

28

Bomberger, H. B., Cambourelis, P. J., and Hutchinson, G. E. CORROSION PROPERTIES OF TITANIUM IN MARINE ENVIRONMENTS. J. Electrochem. Soc., 101: 442-447, September 1954.

Data are presented on the behavior of commercially pure titanium and several common structural metals exposed to sea, industrial, and rural atmospheres for approximately 5 yr and to sea water at Kure Beach, N.C., up to 4.5 yr. Long-time tests designed to show susceptibility to

- sea-water erosion, crevice corrosion, galvanic corrosion, pitting, stress corrosion, and corrosion fatigue had no noticeable effect on titanium metal. Titanium coupled to Inconel, silver, and Types 302 and 316 stainless steels had a negligible effect on the corrosion rates of these materials, but the corrosion rates of Monel, copper, low-carbon steel, and aluminum alloys were in some cases more than doubled by contact with titanium.
- 29  
Booth, F. F. and Budd, M. K. CORROSION BEHAVIOUR OF TIG WELDS IN ALUMINUM SHIP-BUILDING ALLOYS. *Welding & Metal Fabrication*, 30: 483-486, December 1962.
- Inert-gas tungsten arc (TIG) welded sheet specimens of the aluminum alloys N5, N4, H19 and H20 were subjected to 1- and 5-yr intermittent immersion in Brixham harbor, Eng., and to 4-mo immersion in a laboratory solution of 3% sodium chloride and 0.5% hydrogen peroxide. Alloy designations are those in B.S. 1470-1477.
- Only welds in H20W were significantly corroded after 1 yr in sea water. After 5 yr, corrosion was negligible on N5-0, N51/4H and N41/2H. H19 in the W condition had a few broad pits; in the WP condition, attack was negligible. H20 in the W condition had deep pits in the heat-affected zone; in the WP condition, there were a few broad shallow pits.
- In the laboratory, there was severe corrosion near the weld on H19W and H20W specimens but only slight pitting remote from the weld on H19WP and H20WP. N41/2H was almost unaffected, but N5-0 showed deep attack at the weld-to-parent-metal interface.
- It is concluded that aluminum-magnesium alloys are the best for welded marine applications and that aluminum-magnesium-silicon alloys are good if fully heat-treated. Painting the latter alloys is advisable for severe applications but is not always necessary. Marine fouling has negligible effect on corrosion. The laboratory test is more aggressive than 5-yr exposure in sea water and predicts service behavior well.
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Booth, F. F., Latimer, K. G., CORROSION BEHAVIOR OF ALUMINUM-TO-STEEL JOINTS WITH SPECIAL REFERENCE TO ALUMINUM SUPER-STRUCTURES ON SHIPS. In: *Proceedings 2nd International Congress on Metallic Corrosion*, New York, N.Y., March 11-15, 1963, p. 780-788
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Boyd, W. K. CORROSION IN DEEP-OCEAN AND RELATED ENVIRONMENTS. U.S. Government Research and Development Reports, 40: No. 11: p. 28, June 5, 1965. PB-167 126.
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Brooks, R. E. CORROSION DESIGN IN THE MARINE APPLICATION OF ALUMINUM ALLOY FLOODLIGHTS. *Corrosion*, 16: No. 2: 41T-42T, Feb. 1960.
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Brouillette, C. V. CORROSION RATES IN SEA WATER AT PORT HUENEME, CALIFORNIA, FOR SIXTEEN METALS, JULY 1951-JANUARY 1954. *Naval Civil Engineering Lab. Rept. No. NCEL-TN-194*, AD- 81 212: 26 p., Oct. 1954.
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Brouillette, C. V. CORROSION RATES IN PORT HUENEME HARBOR. *Corrosion*, 14: 16-20, August 1958.
- The corrosion rates of 16 metals and alloys were determined over a period of 30 mo total immersion in the sea water at Port Hueneme, California. Lead evidenced the least attack and magnesium alloys the most. Corrosion rates in the harbor at Port Hueneme where maximum flow rate is only about 0.2 ft per sec appear to be typical of the sea water along the California Coast, but were aggravated to some extent by marine growth. Pitting was a major factor in the corrosion of aluminum, stainless steel, and Monel. Clad aluminum (2024) showed less corrosion than any of the other aluminum group specimens. Deep pitting was prevented by cathodic protection provided by the cladding to the aluminum alloy substrate. Aluminum bronze and phosphor bronze corroded very slightly (about 0.5 mil per yr) and without pitting. Manganese bronze and Naval brass showed a similar corrosion pattern, but corrosion rate was about 1.1 mils per yr. Pitting on Monel was heavy particularly under areas of marine growth. Copper corrosion was confined almost entirely to panel edges with little attack on the flat surfaces. This was attributed to differences in temper at the edges caused by cutting from sheet stock. Low carbon steel corroded rapidly (6.8 mils per yr average with initial rates as high as 7.5 mils per yr).
- 35  
Brouillette, C. V. CORROSION RATES OF URANIUM ALLOYED STEEL IN MARINE HYDROSPACE. *Naval Civil Engineering Lab. Rept. No. NCEL-TN-950*, AD-829 844: 23 p., Feb. 1968
- Corrosion rates in the 3 hydrospace environments were primarily controlled by the dissolved oxygen concentrations and to a lesser extent by temperature. Segrega-

tion of uranium in the steels, which possibly could have occurred during production, could not be detected. Profuse micro-pitting over the surface of the uranium-alloyed stainless steel was attributed to the uranium. Corrosion rates of steel in deep ocean were low.

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Brown, B. F., Waldron, L. J., Peterson, M.H. CORROSION AND CATHODIC PROTECTION OF UNDERWATER SURVEILLANCE SYSTEMS - A GENERAL REVIEW OF THE PROBLEM. Naval Research Lab. Report No. NRL-MR-1436, AD-635 765: 10 p., June 1963.

A general review of the problem of corrosion of metallic assemblies for underwater surveillance is given, based on two years observing deep sea corrosion and on extensive technical discussions with personnel in contractors' plants and in Naval Activities having cognizance over surveillance systems. Recommendations to minimize corrosion failures in such systems are given.

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Brown, B. F., Lennox, T. J., Peterson, M. H. Smith, J. A., Waldron, L. J. INTERIM REPORT OF PROGRESS ON MARINE CORROSION STUDIES. Naval Research Lab. Report MR 1549, July 1964.

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Brown, B. F., Lennox, T. J., Newbegin, R. L. Peterson, M. H., Smith, J. A., Waldron, L.J. MARINE CORROSION STUDIES, DEEP OCEAN TECHNOLOGY, STRESS-CORROSION CRACKING, CATHODIC PROTECTION, SECOND INTERIM REPORT OF PROGRESS. Naval Research Lab., NRL Memo Report 1574, Nov. 1964.

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Brown, B. F., Forgeson, B. W., Lennox, T. J., Lupton, T. C., Newbegin, R. L., Peterson, M. H., Smith, J. A., Waldron, L. J. MARINE CORROSION STUDIES. STRESS-CORROSION CRACKING, DEEP OCEAN TECHNOLOGY, CATHODIC PROTECTION, CORROSION FATIGUE. Naval Research Lab., Third Interim Report of Progress, NRL Memo Report 1634, July 1965.

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Brown, B. F. HANDBOOK OF OCEAN AND UNDERWATER ENGINEERING. San Francisco., McGraw-Hill Book Company, p. 7-2 - 7-11, 7-26,- 7-30. 1969.

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Brown, B. F. A PERSPECTIVE VIEW OF DATA ON LOCALIZED CORROSION FOR THE MARINE DESIGNER. Marine Technology Society Journal, 3: No. 6: 67-69; Nov/Dec 1969.

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Brown, B. F., CORROSION IN THE MARINE ENVIRONMENT. In: Marine Technology 1970. Vol. 2: 1225-1231, 1970.

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Bulow, C. L. CORROSION AND BIOFOULING OF COPPER-BASE ALLOYS IN SEA WATER. Trans. Electrochem. Soc. 87: 319-352, 1945.

Slight modifications of the composition of copper alloys will in many cases greatly affect their corrosion resistance in unpolluted flowing sea water and their resistance to biofouling by macroorganisms.

ASTM tension specimens were carefully annealed, cleaned, analyzed, weighed, measured, and arranged in corrosion test racks. The two main groups studied were (1) copper-zinc and modified copper-zinc alloys and (2) copper-base alloys.

The specimens were exposed to flowing sea water (60 - 90 cm per sec) at Kure Beach, N.C. for periods of 6 and 12 mo at a temperature ranging from 2 to 30 C. After a few months exposure, all specimens were covered with slime. Some showed excessive biofouling by relatively large marine flora and fauna. The addition of small percentages of aluminum, arsenic, and iron to certain compositions resulted in marked increase of fouling.

Addition of small amounts of aluminum to some copper alloys increased the resistance to impingement corrosion, while arsenic or tin had the opposite effect on muntz metal. Of copper-zinc alloys those with 66% copper or 80 - 85% copper were most resistant to corrosion.

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Bulow, C. L., USE OF COPPER BASE ALLOYS IN MARINE SERVICES. Naval Engineers Journal, 77: No. 3: 470-482, June 1965.

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Butler, G. CORROSION AND ITS PREVENTION IN WATERS. London, Leonard Hill, 254-258, 1966.

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Central Dockyard Lab. Portsmouth, England. ALUMINUM SILICON BRONZE, EVALUATION FOR MARINE SERVICE. Report No. C.D.L. ACC/N247/69, AD-865 186: 10 p., 1969.

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Clarkin, P. A., and Bever, M. B. CORROSION RESISTANCE OF CARBO-NITRIDED STEEL. Metal Progress, 66 :No. 6: 108-109, December 1954.

The corrosion resistance of carbo-nitrided

steel was determined by total immersion in aqueous 3% sodium chloride solution and in fresh flowing sea water. Comparison tests were run on carburized specimens. The specimens were of normalized A.I.S.I. 1018 steel, surface ground and case hardened at 1400-1700 F in atmospheres containing 3-5% methane and 0-15% ammonia. Carbo-nitriding at low temperatures and with high ammonia concentrations resulted in the formation of a layer of carbon-nitrogen-iron compounds at the surface of the steel. Four specimens, each with a surface of 0.12 sq dm, were immersed simultaneously for 2-4 days in 8 liters of salt solution at  $30.0 \pm 0.5$  C aerated with 400 ml air per min per liter. Three series of specimens each with a surface area of 0.3 sq dm were exposed for 21-133 days in sea water moving at 1-2 ft per sec.

Plain carbon steel carbo-nitrided under conditions which did not lead to compound formation, corroded in aqueous sodium chloride solution at the same rate as carburized steel. Wide variations in the carbonitriding conditions and tempering had no appreciable effect on the corrosion behavior in the salt solution, but the presence of a compound layer cut the corrosion rate by about one half.

The sea-water tests, which were carried to the point of complete penetration in some specimens, suggested that under such extreme conditions the compound layer may be undesirable. In the sea water a heavy calcareous deposit formed on carbonitrided specimens having a compound layer on the surface, and no deposit or only traces formed on cases without the compound layer. This deposit was attributed to the fact that the surface is cathodic to the underlying metal; once such a case is penetrated, corrosion is accelerated by galvanic action between the core and the remaining case. However, for applications which require a case having both moderate hardness and moderate resistance to corrosion, e.g., in sodium chloride solution, carbo-nitriding under conditions which produce a compound layer at the surface should be considered.

- 48 Cleary, H. J. ON THE MECHANISM OF CORROSION OF STEEL IMMersed IN SALINE WATER. First Annual Offshore Technology Conference. Vol. 1. Preprints, Held in Houston, Tex., May 18-21, 1969 : 375-388, 1969.

- 49 Cordova, H., I., Kubose, D. A. EROSION-CORROSION OF HAYNES-25 ALLOY: RADIOACTIVE TRACER TECHNIQUES. Naval Radiological Defense Lab. Report No. USNRDL-TR-67-142, AD-663 566: 25 p., Aug. 1967.

The erosion-corrosion caused by the washing of a mixture of seawater and ocean-bottom material across a specimen of haynes-25 at ambient room temperature was studied with radioactive tracer techniques. The results obtained under the conditions of this study showed that the corrosion rate in such an environment increased 4 orders of magnitude over that observed in seawater alone.

- 50 Cotton, J. B., and Downing, B. P. CORROSION RESISTANCE OF TITANIUM TO SEAWATER. Inst. Marine Engineers Trans., 69: No. 8: 311-319, 1957.
- 51 Cox, F. G. THE CORROSION RESISTANT PROPERTIES OF ZIRCONIUM. PART 1 AND 2. Corrosion Prevention and Control 5: 39-42 April 1958, 46-48 June 1958.
- A review is presented of the corrosion-resistant properties of zirconium with reference to various mineral acids, organic acids, alkalis, sea water, salt spray, inorganic salt solutions, miscellaneous reagents, and high temperature water and steam. General corrosion data are presented in tabular form.
- 52 Crisci, J. R., Foster, M. L. DETERMINATION OF MECHANICAL PROPERTIES AND CAUSES OF FAILURE OF AUTEC - TOTO II DEEP SEA MOOR WIRE ROPE. Naval Applied Science Lab. Report No. NASL-930-44-PR-3, AD-840 610L. 26 p., Sept. 1968.

- 53 Cuthbertson, J. W. THE RESISTANCE TO CORROSION BY SEA-WATER OF SOME  $\alpha$ -TIN AND  $\alpha$ -TIN-ALUMINUM BRONZES. J. Inst. Metals, 72: 317-342: 1946.
- A study was made of the resistance to impingement corrosion, deposit attack, and simple immersion corrosion of tin and tin-aluminum  $\alpha$ -bronzes in the presence of sea water. It was shown that resistance to impingement corrosion demands primarily a high tin content, not less than 10%. An additional 1% of aluminum does not significantly affect resistance to impingement corrosion but improves resistance to other types of corrosion. Ternary bronzes containing 8% tin, the minimum amount for safety, require aluminum in order to resist impingement attack.

Aeration of the sea water is found to increase the rate of deposit and general attack of all the bronzes but does not significantly alter the order of corrod-ibility. The average rate for bronzes, under these conditions, is 20 - 40 mg per



sq dm per day. However, the more resistant bronzes are superior to cupro-nickel (rate 35 - 45) and aluminum brass (rate 25) under the same conditions.

A simple prefilming process has been developed which can improve the resistance of the bronzes to impingement and general corrosion. Its usefulness is limited under deposit attack.

Comparative tests on alloys prepared by normal methods of casting and from de-gassed melts and on materials having variable and controlled grain-size have established the importance of homogeneous structure and fine grain size in combatting impingement attack.

The annotated bibliography was compiled to provide information and guidance to the marine scientist or engineer who must contend with those animals and plants which attach themselves to man-made underwater objects, i.e., fouling organisms. The references selected for this bibliography are those which help answer one or more of the following questions: What kind of fouling can one expect to find in various parts of the world; what are the factors which tend to promote or discourage the settlement and growth of fouling organisms; and What are the effects of this settlement and growth on the performance of coatings, sensors, and hardware.

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Eastwood, L. W., Fink, F. W., Davis, J. A. THE RELATIVE CORROSION RESISTANCE OF MAGNESIUM ALLOYS IN SALT WATER. Light Metal Age, 4: No. 4: 16-19, 1946.

Magnesium alloys of high purity, having 0.001% iron or less, have markedly improved resistance to salt-water corrosion regardless of their zinc content. With iron contents near 0.015%, representative of commercial purity, none of the alloys regardless of zinc content can be regarded as resistant to salt water corrosion. Therefore the use of high zinc alloys for their supposed resistivity to this type of corrosion is questionable.

Four types of alloys were tested. Two were German alloys of commercial purity with zinc contents of approximately 0.4% and iron contents ranging from 0.005 to 0.015%. The other two were American commercial types containing 2 and 3% zinc and 0.005 - 0.022% iron. High purity samples of these last two alloys, specially prepared for these tests, were also studied along with a third type containing approximately 1% zinc. Iron content of these high purity samples ran as low as 0.001%. The alloys were subjected to various heat treatments, aging, and quenching conditions.

In the heat treated and aged condition all four alloys of commercial purity appeared to have similar resistance to salt water, but before aging the alloys containing 0.4% zinc had slightly higher corrosion rates than those containing 2 or 3% zinc. All of the samples regardless of zinc content or purity had, in general, high resistance to atmospheric corrosion.

Previous work has indicated that although there is some decrease in the salt water corrosion rate of magnesium alloys containing up to 3% zinc, the major benefit of zinc addition is obtained at a level of 0.5% without sacrificing amenability of the

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Danek, G. J., Basil, J. L. SEA-WATER CORROSION BEHAVIOR OF ACI-CD-4M CU ALLOY. Navy Marine Engineering Lab. Report No. 113 64; AD-446 415L: 14 p., Aug. 1964.

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DeLuccia, J. J. and Taylor, Edward. EVALUATION OF METALLIC MATERIALS EXPOSED TO THE DEEP OCEAN ENVIRONMENT AT 5,640 FEET FOR 123 DAYS. Naval Air Engineering Center, Report No. NAEC-AML-2132: 72 p., June 1965.

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DeLuccia, J. J. . EVALUATION OF METALS IN DEEP OCEAN ENVIRONMENTS. Metals Protection. No. 5: p. 49-51, Aug. 1966.

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DeLuccia, J. J. Piland, J.A., CORROSION OF LIGHT ALLOYS IN DEEP OCEAN ENVIRONMENTS. Naval Air Development Center, Aero Materials Dept. Report No. NADC-MA-6946; AD-865 586L: 59 p., Feb. 1970.

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DeLuccia, J. J. METALLIC CORROSION IN THE DEEP-OCEAN ENVIRONMENT, SIX MONTHS AT 2,340 FEET. Naval Air Development Center, Aero Materials Dept. Report No. NADC-MA-6868; AD-848 907L: 73 p., Jan. 1969.

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DePalma, J. R. MARINE FOULING AND BORING ORGANISMS IN THE TONGUE OF THE OCEAN, BAHAMAS-EXPOSURE II. Naval Oceanographic Office, Report No. IMRO 64 62; AD-447 263: 8 p., Oct. 1962.

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DePalma, J. R. AN ANNOTATED BIBLIOGRAPHY OF MARINE FOULING FOR MARINE SCIENTISTS AND ENGINEERS. Journal of Ocean Technology, Vol. 2: No. 4: 33-44, July 1968.

low-zinc alloys to heat treatment, or accentuating their susceptibility to micro-porosity.

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Eichhorn, K. THE RESISTANCE TO CORROSION OF SEA WATER PIPING MADE OF COPPER AND COPPER ALLOYS. *Werkstoffe u. Korrosion*, Vol. 8: 453-456, August/September, 1957.

In German with English summary.

The choice between unalloyed copper and copper alloys for sea water piping on ships is determined mainly by the rate of flow. At low velocities, unalloyed copper has good resistance to corrosion due to its positive potential and the ability to form a protective layer ranging from a monomolecular thickness to 100 Å. Where construction and operating conditions permit its use, 99.25 and 99.5% copper, free of oxygen with 0.3 to 0.5% arsenic should be used. Under normal conditions, flow rates of 1.8 m per sec for pure copper and 2.1 m per sec for copper containing arsenic are considered safe. Sea water impurities, deposits, or increased turbulence at pipe connections can cause local breakdowns of the protective layer at nominal velocities as low as 1.4 m per sec, leading to erosion of the pipe wall and eventually to anodic disintegration of the bare metal spots.

Lines made of copper-nickel alloys containing 5% nickel, approximately 1% iron and 0.5% manganese, or of 2% aluminum brass are considerably more durable than those of unalloyed copper, especially at the higher velocities. The latter forms an erosion resistant layer in sea water and its permissible flow rate is 4.6 m per sec, twice as high as that of unalloyed copper. Forming properties (hot and cold) of the alloys are similar to those of pure copper. Pipes of large diameters may be made; connections are welded or brazed as usual without difficulties. For brazing aluminum brass, silver solder is preferred.

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Evans, U. R. METALLIC CORROSION, PASSIVITY, AND PROTECTION. New York, Longmans, Green & Company, 1948.

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Ferrara, R. J. CORROSION OF BALL VALVES IN SEAWATER SERVICE. Naval Ship Research and Development Center. Rept. MATLAB-173/68, AD-841 332L: 33p., Sept. 1968.

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Fifer, D. E. SOME ASPECTS OF MARINE CORROSION AND ITS PREVENTION.

Australasian Corrosion Engineering, 6: No. 7: 15-20, July 1962.

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Fink, F. W. METALS FOR SEA WATER SERVICE. *Ind. Eng. Chem.*, 52: No. 9: 70-A-71A, 73A, Sept. 1960.

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Fink, F. W. METAL CORROSION IN SALINE WATERS. *Battelle Technical Review*, 12: No. 9: p. 5-8, Sept. 1963.

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Fink, F. W., Fuller, R. G., Nowacki, L. J. NAVIGATIONAL BUOY CORROSION AND DETERIORATION. In: *Congres International de la Corrosion Marine et des Salissures*, Cannes, France, June 8-12, 1964, *Proceedings*. p. 77-82, 1965.

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Fink, F. W. ALLOYS FOR SEAWATER CORROSION. *Materials Protection*, 6: No. 5; p. 40-43, 1967.

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Fink, F.W., Boyd, W. K. THE CORROSION OF METALS IN MARINE ENVIRONMENTS. Columbus, Ohio, Bayer & Co., 1970.

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Fischer, E. MICROBIOLOGICAL CORROSION: DEEP SEA. Naval Applied Science Lab. Rept. No. NASL-TM-2: AD-814 136L. 18p., Aug. 1965.

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Fleetwood, M. J. NONFERROUS METALS FOR OCEAN ENGINEERING. *Werkstoffe u. Korrosion*, Vol. 21: 267-273, 1970.

Following a comparative survey of the corrosion behavior of various nonferrous metals in sea water the author deals with the individual variables (flow rate, water depth, aeration) and the mechanical requirements such metals have to meet. Possible applications of Cu and Ni alloys are listed in this context, reference is made to recently developed alloys: weldable CuNi casting alloys, high strength CuNi alloys for use in sea water at high flow rates, high strength NiCrMo alloy for ropes which even during extended exposure to sea water must not lose their strength nor be susceptible to crevice corrosion.

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Forgeson, B. W., Southwell, C. R., and Alexander, A. L. CORROSION OF METALS IN TROPICAL ENVIRONMENTS. PART 3. UNDER-WATER CORROSION OF TEN STRUCTURAL STEELS. Naval Research Laboratory, Report 5153: 24p., August 1958.

Structural steels (9 by 9 by 1/4 in. panels) of ten different compositions were exposed in the Panama Canal Zone for 8 yr. Comparisons are made between the severity of corrosion in the natural tropical environments of sea water mean tide, and sea water and fresh water continuous immersion. Results are correlated with similar corrosion tests made on the east and west coasts of the United States.

The corrosion of unalloyed low-carbon steel (Fed. Spec. QQ-S-741) in tropical sea water was of the same magnitude as temperate sea water corrosion at Kure Beach, N.C., and less than at Port Hueneme, Calif. After 8 yr at the three Panama environments, the maximum difference in the corrosion rates between continuous immersion in sea water, in fresh water, and at the mean tide exposure was 15%. Corrosion curves indicate that sea water corrosion proceeded at a linear rate, fresh water corrosion decreased with time, and sea water mean tide corrosion accelerated with time. Accelerated pitting attack on unalloyed low carbon steel with a millscale surface was evidenced only in the sea water immersion. In both the fresh water and mean tide exposures, pitting attack and weight loss on millscale, pickled, and machined surfaces were essentially equal at the end of 8 yr.

No significant difference was found in type or magnitude of corrosion between unalloyed and copper bearing low-carbon steels.

Additions of 3 and 5% chromium were beneficial in fresh water; pitting attack was slightly less and weight losses decreased more than 50% in comparison to unalloyed low-carbon steel. In sea water, however, the frequency of pitting on chromium steels was much greater. Weight loss of proprietary (3%) and AISI type 501 D (5%) chromium containing samples exceeded that of unalloyed steel by 63% and 30%, respectively.

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Forgeson, B. W., Southwell, C. R., and Alexander, A. L. CORROSION OF METALS IN TROPICAL ENVIRONMENTS. PART 3. UNDERWATER CORROSION OF TEN STRUCTURAL STEELS. Corrosion, 16: 87-96, March 1970.

Corrosion of ten structural steels exposed to tropical sea and fresh waters was evaluated following an 8 yr exposure period.

The corrosion of unalloyed low carbon steel in Panama tropical sea water is the same magnitude as temperate Sea water corrosion at Kure Beach, North Carolina and less than at Port Hueneme, California. The profuse

marine growth in Panama may have afforded some protection.

After 8 yr, there was a maximum of 15% difference in the corrosion rates of unalloyed low carbon steels at the three environments in Panama - sea water immersion, fresh water immersion, and sea water mean tide. However, the shapes of the curves for these exposures indicate that sea water corrosion is proceeding at a linear rate, fresh water corrosion is steadily decreasing with time, and mean tide corrosion is accelerating. It is emphasized that short term tests would have given erroneous results. Unalloyed low-carbon steel with a mill scale surface showed accelerated pitting attack only in sea water immersion. Pitting attack and weight loss on millscale, pickled, and machine surfaces were essentially equal after 8 yr in both the fresh water and mean tide exposures.

No significant difference in type or magnitude of corrosion was found between copper-bearing steel and unalloyed low carbon steel in any of the three Panama locations.

The inclusion of 2 and 5% nickel in structural steel did not increase corrosion resistance in fresh water or at mean tide. In sea water, the nickel addition accelerated both weight loss and pitting-type corrosion attack.

Addition of 3 or 5% chromium improved corrosion resistance of panels immersed in fresh water. Pitting attack was slightly less and weight loss more than 50% less than for unalloyed low carbon steel. However, in sea water, although the severity of pitting was about the same in all three steels, the pitting frequency was much greater on chromium steels. Weight losses of 3 and 5% chromium steel exceeded that of the low carbon steel by 63 and 30%, respectively. In mean tide exposure, weight losses of the three steels were the same but pitting attack on the chromium steel was double that of mild steel and immeasurably higher in frequency.

Proprietary low-alloys steels in general were not more resistant to underwater corrosion than mild unalloyed steel and for certain conditions they were appreciably less resistant.

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Forgeson, B. W., Southwell, C. R. and Alexander, A. L. CORROSION OF METALS IN TROPICAL ENVIRONMENTS. PART 5. STAINLESS STEELS. Naval Research Laboratory, Report 5517: 20 p., Sept. 1960.



- Over a period of 8 yr, six stainless steels (AISI No. 410, 430, 301, 302, 321) were exposed to underwater and atmospheric environments in the Panama Canal Zone. In sea water, stainless steels were inferior to phosphor bronze and to structural steels. They were severely pitted during sea water immersion; mean tide produced one fourth to one tenth the pitting of continuous immersion. The greater pitting attack in tropical than in temperate areas may result from heavy marine fouling. These steels are not recommended for sea water service where perforation of structure is a consideration. When submerged in fresh water, stainless steels were practically unattacked. They were superior to ordinary steels and equal to phosphor bronze. Tropical atmospheres appear to be no more corrosive to stainless steel than temperate climates; the marine were slightly greater than the inland effects. However, precautions should be taken to eliminate cracks where passivity-destroying agents could accelerate pitting attack.
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Forgeson, B. W., Southwell, C. R. and Alexander, A. L. CORROSION OF METALS IN TROPICAL ENVIRONMENTS, PART 5 - STAINLESS STEELS. Corrosion, 17: No. 7: 97-104, July 1961.
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Forgeson, B. W., Waldron, L. J. ABYSSAL CORROSION AND ITS MITIGATION. PART II. RESULTS OF A PILOT TEST EXPOSURE. Naval Research Laboratory, Rept. No. NRL-MR-1383: AD-296 545: 25p., Dec. 1962.
- Abyssal corrosion and its mitigation. Results of exposure of various materials (metals and non-metallic materials) at several depths up to 500 ft in Tongue of the Ocean for 3-1/2 mos.
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Geld, I. DEEP SEA CORROSION OF MACHINED ALUMINUM PLATE. Naval Applied Science Laboratory, Rept. No. NASL-940-33-TM-24: AD-840 677L: 6p., Oct. 1968.
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Geld, Isidore, Acampora, Mario. CORROSION OF MACHINED ALUMINUM PLATES AT DEEP SUBMERGENCE. Naval Applied Science Lab. Rept. No. NASL-940-33-PR-6: AD-860 048L; 30p., Sept. 1969.
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Godard, H. P., Booth, F. F. CORROSION BEHAVIOUR OF ALUMINIUM ALLOYS IN SEAWATER. In: Congres International de la Corrosion Marine et des Salissures, Cannes, France, June 8-12, 1964, Proceedings. p.37-52, 1965.
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Godard, H. P., Jepson, W. B., Bothwell, M. R., Kane, R. L. CORROSION OF LIGHT METALS. New York, Wiley, 1967.
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Gordon, H. B. HOW METALS RESIST SEA WATER. Materials Engineering, 65: No. 5; p.82, May 1967.
- Presents a brief discussion and a table showing relative sea water corrosion rates of over 50 common metals and alloys. The main purpose of the table is to give materials engineers and designers a tool for comparing the relative sea water corrosion resistance of materials. The table lists depth of corrosion in inches per year times  $10^4$ . These values were computed from measured weight loss.
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Goya, H. A., Lai, M. G., Kubose, D. A., Cordova, H. I. SNAP FUELS AND CAPSULE MATERIALS: A COMPENDIUM OF USNRDL LABORATORY PROCEDURES FOR THEIR STUDY. Naval Radiological Defense Lab., Rept. No. USNRDL-TR-68-55: AD-835 167L: 47p, Feb. 1968.
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Gray, K. O. PROPERTIES OF MATERIALS IN DEEP-OCEAN ENVIRONMENT. Naval Civil Engineering Lab., Rept. No. NCEL-TN-380: AD-489 585: 9 p., March 1960.
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Gray, K. O. EFFECTS OF THE DEEP OCEAN ENVIRONMENT ON MATERIALS - A PROGRESS REPORT. Naval Civil Engineering Lab. Tech. Note N-446, July 30, 1962.
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Gray, K. O. ENVIRONMENT OF DEEP OCEAN TEST SITES (NOMINAL DEPTH, 2000 FEET) LATITUDE 33 DEGREES 46 MIN N, LONGITUDE 120 DEGREES 37 MIN W. Naval Civil Engineering Lab. Rept. No. NCEL-TN-657: AD-461 145: 28p., Feb. 1965
- NCEL has exposed specimens of a large number of construction materials on submersible test units (STU) in 5300 and 5800 feet of water. The purpose is to determine that materials are most suitable to withstand the effects of this environment. The environmental factors considered significant are presented. The sea water at these sites is uncontaminated and normal for this part of the Pacific Ocean. The particular depth at which the STUs are located places them in an environment with a relatively low dissolved oxygen concentration. In this area, the oxygen minimum zone is located at a depth between 1800 and 2800 feet with dissolved oxygen values

as low as 0.20 milliliters per liter. Measurements averaging from 1.26 to 1.50 milliliters of dissolved oxygen per liter of sea water, 2.53 to 2.40 °C for temperature, and 34.56 to 34.59 parts per thousand for salinity were obtained from the near bottom waters at these two depths (5300 and 5800 feet).

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Greenblatt, J. H. CORROSION OF MAGNESIUM ALLOYS CONTAINING IRON AND NICKEL. J. Applied Chem., 9: 401-405, August 1959.

Magnesium alloys containing either 200 ppm or 2% nickel were immersed in sea water and corrosion rates determined either alone or coupled to steel cathodes of various sizes inserted in plastic or steel blocks. Ratio of cathode to anode areas were varied from 1:1 to 50:1. Rates were determined by weight loss, rate of hydrogen evolution, and rate of recession of the metal surface of the imbedded magnesium plug.

For uncoupled alloys the corrosion rate was higher for the 2% nickel alloys than the iron alloys. The initial state was important. For both alloys, a hydrochloric etch gave a higher rate. Nitric acid gave low initial rates presumably because of tight oxide film formed.

Both alloys, coupled to steel cathodes, showed a decreased rate of corrosion, the decrease increasing with cathode size. This is attributed to formation of an oxide film over the alloy. Some but not all of the decrease could be accounted for by accumulation of hydroxyl ions which, even at small concentrations, favor film formation and maintenance. Initial pretreatment is important since a smaller current density is required to maintain a protective film than to form it. For cathode to anode areas of 10:1, the critical current density is at least 50 ma per sq cm.

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Groover, R. E. ANALYSIS OF THE FAILURE OF THE AUTEC TOTO II DEEP SEA MOOR AND PERFORMANCE OF ITS CATHODIC PROTECTION SYSTEM. Naval Research Laboratory, Memorandum Report No. 1950: 40 p., Nov. 1968.

The report contains background information on the design and installation of a wire rope three-point deep sea moor which was originally coated with a bituminous substance and the critical areas protected with a magnesium galvanic anode cathodic protection system designed by the Naval Research Laboratory. The report also describes the failure of the moor after 4 1/2 years service and its subsequent

salvage, and presents the results of a study of the corrosion pattern, proposes the cause of failure, and evaluates the performance of the cathodic protection system. Recommendations are presented for the protection of future moors and for possible research directed towards the understanding and prevention of failure of wire rope structures in sea water under conditions of static stress and of fatigue.

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Groover, R. E., Lennox, T. J., Jr., Peterson, M. H. MARINE CORROSION STUDIES: CHARACTERIZATION OF THE CORROSION BEHAVIOR AND RESPONSE TO CATHODIC PROTECTION OF NINETEEN ALUMINUM ALLOYS IN SEA WATER. Naval Research Laboratory, Memorandum Report No. 1961: 24 p., Jan. 1969.

The corrosion characteristics of nineteen structural aluminum alloys were studied in quiescent sea water. Some alloys were exposed with and without cladding, and others at more than one strength level for a total of twenty-six material conditions. The response to cathodic protection of all the alloys studied was also determined. The electrochemical potentials of the alloys were monitored during the experiment and a relationship was developed between the electrode potential and the corrosion characteristics of the alloys. These mean potential values were found to differ significantly in many instances from the electrochemical potential values determined by other investigators from laboratory measurements in sodium chloride-hydrogen peroxide solution. Cathodic protection from galvanic anodes was effective in reducing the corrosion damage to acceptable limits except edge attack was not eliminated on one of the high strength 7XXX series aluminum alloys.

90

Groover, R. E., Lennox, T. J., Jr., Peterson, M. H. CATHODIC PROTECTION OF 19 ALUMINUM ALLOYS EXPOSED TO SEA WATER - CORROSION BEHAVIOR. Materials Protection, 8: No. 11: 25-30, Nov. 1969.

Data are reported on the corrosion behavior and electrochemical potentials of 19 structural aluminum alloys in quiescent sea water. A relationship was developed between the electrode potential and corrosion severity. Cathodic protection from galvanic anodes was effective in reducing the corrosion damage to acceptable limits for most of the alloys studied.

91

Groover, R. E., Lennox, T. J., Jr., Peterson, M. H. MARINE CORROSION STUDIES:

THE CORROSION CHARACTERISTICS AND RESPONSE TO CATHODIC PROTECTION OF COPPER ALLOYS IN QUIESCENT SEAWATER. Naval Research Laboratory, Memorandum Report 2183: AD-718 310: 54 p., Oct. 1970.

The corrosion characteristics dealloying susceptibility, marine fouling characteristics, and the response to cathodic protection of seventeen copper alloys and unalloyed copper, which served as a control, were studied in quiescent seawater. Detailed examination after 735 days showed that several alloys in the unprotected condition had severely corroded either by deep localized attack or by dealloying. The corrosion rates were determined; on the unprotected specimens a maximum rate of 0.74 mils per year was observed. Cathodic protection from zinc anodes reduced the corrosion rate to essentially zero and prevented localized corrosion except in Naval brass and Muntz metal where metallurgical studies indicated that dealloying was not completely prevented. Histograms have been presented for the electrochemical potentials of each specimen, and a galvanic series for the copper alloys has been included. There was no correlation between the electrochemical potentials and the type or severity of corrosion. The resistance of the copper alloys to marine fouling varied widely. All unprotected specimens fouled to some extent, whereas the cathodically protected specimens were heavily fouled.

92

Groves, Don. OCEAN MATERIALS. Naval Engineers Journal, 80: No. 2: 185-203, April 1968.

93

Guilhaudis, André. THE RESISTANCE OF LIGHT ALLOYS TO MARINE CORROSION. Rev. aluminium, 29: 85-91, 127-133, 175-179, March-May 1952.

In French

To obtain accurate estimates of the corrosion resistance of metals exposed to sea water and marine atmosphere, laboratory tests must be supplemented by field tests. This was done at the St.-Jean-de-Luz Mediterranean coast and at Salin-de-Giraud Atlantic coast marine corrosion test stations. The following results were obtained from a 2-yr exposure of protected and unprotected pure aluminum and various aluminum alloys.

Corrosion of pure aluminum was most severe when exposed to sea-water spray, less severe when alternately immersed,

and least severe when continuously immersed in sea water. In general, corrosion resistance increased as the purity of the aluminum increased from 99.7 to 99.99%. However, alternately immersed 99.7 and 99.8% pure specimens showed pitting, whereas specimens exposed to spray were heavily tarnished but showed no pits.

An aluminum alloy containing 0.70% manganese, 0.32% iron, 0.27% silicon, and 0.055% copper showed no pits whether immersed continuously or alternately; when subjected to spray, it tarnished after 3 mo.

Aluminum alloys containing 3-5% magnesium were among the most resistant unprotected alloys. An A-G5 alloy containing 0.44% manganese, 5.15% magnesium, 0.16% iron, 0.13% silicon and 0.035% copper, heat-treated at 400 C, increased in tensile strength during the first 3 mo, but decreased thereafter, particularly during the first year. Its percentage elongation decreased only slightly during the first 6 mo, but more rapidly thereafter when exposed to seawater spray. When immersed continuously in the sea, however, elongation decreased rapidly during the first 6 mo, and increased again during the next 6 mo before decreasing gradually during the second year.

Aluminum-magnesium-silicon alloys of the A-SG type (1.26% silicon, 0.98% magnesium, 0.16% iron, and 0.01% copper) which frequently also contain manganese, were superior to A-G5 aluminum-magnesium alloys in salt-spray resistance and equivalent under continuous immersion, provided they were tempered at 530 C for 45 min and water-quenched. Additional annealing at 175 C for 3 hr made the A-SG alloys more susceptible to corrosion.

Aluminum-copper-magnesium alloys, particularly A-V4G, were among the less resistant alloys. They showed serious pitting, and, in thin gauges, they showed perforations in as short a time as 3 mo, especially when partially annealed.

Because rain washes off salt deposits, surfaces exposed both to spray and rain were less corroded than those exposed only to spray. In contrast to most alloys tested, A-V4G corroded more severely when immersed constantly than when alternately immersed. In general this alloy should be protected when in contact with sea water. Provided it is thick enough, A-V4G can be used unprotected when exposed to spray.

Aluminum-zinc-magnesium-copper alloys of

the A-Z8GU type (8.49% zinc, 2.65% magnesium, 1.66% copper 0.34% iron, 0.25% chromium, 0.13% silicon, and 0.10% manganese) behaved essentially like A-V4G aluminum-copper-magnesium alloy. They showed local pittings and perforations when immersed, especially in the annealed condition, and almost greater losses in elongation than A-V4G under salt spray.

Plating with 99.5% pure aluminum or aluminum-zinc alloys A-Z3 provided good protection for both A-U4G and A-Z8GU alloys. The plated alloys showed increased resistance to both spray and permanent immersion. After the 2-yr immersion, the tensile strength of A-Z8GU plated with A-Z3 only dropped from 56.9 to 51 kg per sq mm, while its elongation dropped from 10.4 to 7.6%. After 2-yr seawater spray, plated A-V4G (Vedal) retained a strength of 39.5 kg and an elongation of 21%, compared with 34 kg and 10% respectively, for nonplated A-V4G. Comparative data on the seawater resistance of copper, nickel, tin, zinc, ordinary and stainless steels, and brass confirmed the merits of aluminum, aluminum-manganese, aluminum-magnesium, and aluminum-magnesium-silicon alloys, and of plated A-U4G and A-Z8GU alloys.

94

Guilhaudis, A. LIGHT METAL ALLOYS EXPOSED TO MARINE ATMOSPHERE. Corrosion et Anti-corrosion, 10: 80-85, March 1962.

In French

Corrosion tests on aluminum alloys at Salin-de-Giraud, Biarritz and Saint-Jean-de-Luz experiment stations are described. At Salin-de-Giraud, samples were exposed on a raft mounted on cylindrical floats, and large enough to accommodate vertical frames containing 400, 150 x 200 mm plates. The frames were partially immersed in water, so that half of the samples were exposed to marine atmosphere, half were immersed in sea water. The alloys for raft construction included A-G-3 (3% magnesium, 0.5% manganese) and A-G-5 (5% magnesium, 0.5% manganese): for the floats, A-5 ( $\leq$  0.5% iron and silicon) was used. Surfaces were protected by anodizing, primer and an antifouling top coat. No anodic oxidation was applied to the floats. The raft was constructed in 1946 and repainted in 1949 at which time it showed no corrosion, with the exception of rivets, around which the paint was completely deteriorated. Between 1949 and 1956, maintenance consisted in repairs of mechanical damages suffered during storms and in cleaning. The condition of the metals remained

generally good, despite partial deterioration of the paint. Corrosion spots appeared on some of the rivets and on floats. The latter were reconditioned by metallization or welding, and are still in service after 15 yr. At Biarritz, the test installation was constructed in 1952, and consists of a samples-supporting frame and a base, both made of A-G-3, resting on the sand. The construction becomes immersed in water during high tide and emerges at low tide. Base and frame are protected by a phosphatizing primer and a glycerophthalic top coat. After nearly 10 yr, there are only isolated corrosion spots on the metal surfaces. Samples of A-G-5 exposed for 5 yr show only a few small corrosion spots.

95

Hache, A. and Deschamps, P. STUDY OF SEA WATER CORROSIVITY. Corrosion et Anti-corrosion, 2: 134-140, July-August 1954.

In French

Using a new accelerated test for determining the corrosivity of salt solutions and natural sea water, the weight loss of an immersed steel specimen was shown to depend essentially on the volume and on the oxygen content of the solution.

Steel samples were immersed for short (1-24 hr) and medium (1-15 days) periods of time in various volumes of a 3% sodium chloride solution and of a filtered, stabilized natural sea water. The progress of corrosion was followed by determining colorimetrically with 1,10-phenanthroline the amount of iron dissolved.

For samples having a surface area of 1 sq dm and immersed for periods up to 24 hr, a constant corrosion rate during the entire test was obtained only if the volume of salt solution or sea water equaled or exceeded 4 liters. Otherwise, the depletion of oxygen in solution stifled the corrosion. To maintain a constant corrosion rate for several days, impractically large solution volumes would be required. It is hoped that the method of short-time immersions in adequate volumes of water can be adapted to the study of seasonal changes in the aggressiveness of natural sea water toward steel.

96

Hache, A., Barriety, L. and Debyser, J. THE EFFECT OF PHOTOSYNTHESIS ON THE CORROSION OF STEEL IN SEA WATER. Werkstoffe u. Korrosion, 10: 145-148: March 1959.

In German with English summary.



A linear relationship was found between the corrosion of steel and the oxygen content of sea water or sodium chloride solutions in which the metal was immersed. Seasonable variations in the properties of sea water were noted, especially the content of dissolved oxygen due to photosynthesis by algae.

97

Hache, A., Barriety, L., and Debyser, J.  
INFLUENCE OF PHOTOSYNTHESIS ON THE  
CORROSION OF STEEL IN SEA WATER.  
Corrosion et anti-corrosion, 7: 56-61,  
February 1959.

In French

Corrosion of steel in sea water tanks containing an abundant growth of algae was more extensive than in pure sea water. Laboratory and field tests were conducted to determine the possible role in corrosion of oxygen liberated in the process of photosynthesis. In laboratory experiments, pairs of 50 x 50 mm steel plates were immersed in a 3% solution of sodium chloride at 24 C; 5 to 30 mg oxygen/liter was introduced by bubbling the pure gas through the solution.

The rate of corrosion of the steel samples, determined gravimetrically, was directly proportional to the concentration of oxygen in the solution and, within the 6.5 to 8 range, did not depend on the pH. In field experiments, in which steel samples similar to the above were immersed in sea water tanks containing algae and in tanks containing pure sea water through which oxygen was bubbled, a direct relation was obtained between the oxygen content of the water and the rate of steel corrosion. At equal concentrations, photosynthetic and artificially introduced oxygen had the same effect on corrosion. Due to unfavorable weather conditions during the experimental period, the maximum concentration of the photosynthetic oxygen was only 20 mg/liter. The maximum concentration of the artificially introduced oxygen was 30 mg/liter. Corrosion rate values obtained in field experiments were corrected for a temperature of 24 C (5% for each degree difference), to make them comparable with the values obtained in laboratory experiments. At the same oxygen content, the corrosion rate in sea water was somewhat lower than in 3% sodium chloride.

98

Hache, A. STUDY OF THE CORROSION BEHAVIOR  
OF SOME STEELS EXPOSED AT DIFFERENT TEST  
STATIONS. Rev. Met., 59: 519-529,  
June 1962.

In French

Structural steels (of the type used in ship hulls), including 4 Thomas steels, 2 Martin steels, and 2 steels stabilized with 0.12% vanadium and 0.44% chromium, respectively, were subjected to corrosion tests involving immersion in sea water and/or exposure to the atmosphere at various locations.

Despite differences in the degree of infestation with marine organisms, immersion tests showed relatively small differences in the corrosion rates from one station to another, with average weight losses at the end of 4 yr ranging from 519 gm at Abidjan to 178 gm at Biarritz. In these tests, the behavior of all steels was practically identical. The relatively high rate at Abidjan can be related to the high water temperature, while the relatively low rate in Biarritz is apparently due to rust accumulation on the metal, made possible by the absence of underwater currents.

99

Hazard, P. M. HOW ENVIRONMENT AFFECTS  
OCEAN CABLES. Bell Labs. Record, 39:  
No. 3: 92-96, March 1961.

100

Hibert, C. L. ALUMINUM ALLOYS FOR MARINE  
USE. General Dynamics/Convair.  
Rept. No. ZM 658: AD-259 725: lv.:  
June 1961.

101

Holsberg, P. W., CORROSION STUDIES OF  
10Ni-2Cr-1Mo-8Co STEEL. Naval Ship  
Research and Development Lab.  
Rept. No. NSDRL/A-8-438: AD-867 332:  
27 p., March 1970.

102

Horne, R. A. PHYSICAL CHEMISTRY OF THE  
DEEP OCEAN ENVIRONMENT.  
Inc. Rept. No. TR-11: AD-462 328: Contract  
Nonr 4424 00: 23 p., May 1965.

This paper reviews the results of some simple experiments which we have performed in our Laboratory over recent years in a simulated deep ocean environment.

103

Hsieh, Wu-Yu, and Turkovskaya, A. V.  
CORROSION OF COPPER-NICKEL ALLOYS IN  
SEA WATER. Izvest. Vysshikh Ucheb.  
Zavenenii, Tsvetnaya Met. 4: No. 4:  
145-148, 1961.

In Russian

The corrosion rates and electrode potentials in artificial sea water were determined for electrolytic copper, electrolytic nickel and for twelve copper-nickel alloys containing 4.75 to 59.1% nickel. Measurements were made in stationary and circulating water, with circulation speeds  $\leq 17.3$  m/sec.

Under all experimental conditions the corrosion rate of copper-nickel alloys decreased with increasing content of nickel, reached a minimum at approximately 20% and remained constant at higher contents. The corrosion rate was higher in circulating than in stationary water, and was related directly to the speed of circulation. The rate increased sharply above 8 m/sec. Correspondingly, the electrode potentials of the alloys became more positive with increasing nickel content, and were shifted toward more negative values by circulation of the electrolyte, the magnitude of the shift increasing in proportion to circulation speed. Under conditions of anodic polarization, the electrode potentials rose sharply at a nickel content of 20%, and changed little at higher contents. When the electrode potentials were measured under conditions of continuous removal of corrosion products from the surface (by means of a rotating carborundum disc), the potentials became more negative with increasing nickel content up to about 20%, and remained approximately constant at higher contents.

These results show that in copper-nickel alloys, a limit resistance to corrosion is reached at a nickel content of about 20%, and that the resistance to corrosion is due to increased passivation tendency at this nickel content.

104

Hutchinson, G. E., and Permar, P. H.  
CORROSION RESISTANCE OF COMMERCIAL PURE  
TITANIUM. Corrosion, 5: 319-325, Oct. 1949.

Titanium possesses outstanding resistance to corrosion in sea water, marine atmospheres, water-saturated chlorine, chloride salts, and strong oxidizing agents. Fouling organisms can grow on titanium surfaces but their presence does not encourage pitting or other types of corrosion.

Sample strips of metal were unaffected by a 120-day exposure either in the sea-spray test rack, 80 ft from the ocean, or in the marine atmospheric test lot, 800 ft from the ocean. Specimens totally submerged in sea water subject only to tidal fluctuation showed no pitting or crevice corrosion and negligible over-all attack; increasing the velocity of the water to 3 fps in a sea water trough had no effect.

Exposure for 30 days to impingement attack in an aspirator-type sea water jet of 12 fps velocity and 23.5 C average temperature caused no appreciable weight loss and no surface erosion or corrosion.

Data obtained with a high-speed galvanic tester indicate that titanium is near the bottom of a galvanic series of metals and alloys in sea water.

105

Hudson, J. C., and Stanners, J. F.  
THE CORROSION RESISTANCE OF LOW-ALLOY  
STEELS. J. Iron & Steel Inst., 180:  
271-284, July 1955.

A systematic investigation was made of the effect of small amounts of alloying elements on the corrosion resistance of sixty mild steels in industrial atmospheres and in seawater over a 5-yr period. Laboratory spray tests also were conducted to compare reproducibility of results.

In general, low-alloy additions gave considerable reduction in atmospheric corrosion. The most resistant steels rusted at one third the rate of unalloyed mild steel during the first 1 or 2 yr of exposure. With longer exposure this inhibiting effect was even more apparent. The most useful of the alloying elements were chromium, copper, and nickel with aluminum and beryllium showing some advantage. On immersion in seawater, there was less improvement in resistance; under the stagnant conditions of flow used in these tests, the addition of 3% chromium to mild steel roughly halved its wastage by corrosion over a 5 yr period.

Carbon content within the range of 0.04-0.51% is not a major factor in the resistance of plain carbon steels to atmospheric corrosion. High carbon steels were less corrodible in an industrial atmosphere than low carbon steels but this position was reversed in seawater. The differences, however, were only about 20% in each case.

Heat treatment is not a major factor in determining the severity of corrosion of low alloy steel over long periods of exposure to air and sea water but it may have a pronounced influence in laboratory tests extending over a few weeks only.

There was little difference in the general corrosion of cast irons and plain carbon steels when immersed in sea water, although the former may be seriously weakened by local attack and graphitization. Laboratory tests of the intermittent spray

type yielded only fair correlation with the results of outdoor exposure, probably because the rusting of steels in the laboratory does not proceed sufficiently far for the difference in the properties of the rusts on the various steels to become fully operative.

106

Hunt, J. R., Bellware, M. D. OCEAN ENGINEERING HARDWARE REQUIRES COPPER-NICKEL ALLOYS. Navy Marine Engineering Laboratory, p. 243-275: 1967.

The copper-nickel alloys were developed early in this century to fill the need for marine materials more resistant to both quiet and moving sea water (velocity effects) than other copper alloys. They retain a high degree of the anti-fouling characteristics of copper. Nickel improves durability in sea water, and at the same time, imparts a high degree of fabricability found in few alloy systems. Over the years, these alloys have become available in the many forms required, with specifications having been established for plate, sheet, strip, rod, wire, pipe, tubes, castings, and welding electrodes. Copper-nickel offers the designer and user of the increasing array of ocean engineering hardware the opportunity to standardize and simplify many of his materials requirements with an alloy system of proven marine durability. The versatility of these alloys and their availability and fabricability in so many forms permits the use of a single alloy for various components and thus avoids problems of galvanic origin. Mechanical and corrosion properties, as well as welding and other fabricating procedures are listed and described. The why, when, where and how approach is directed towards both design and fabrication.

107

International Nickel Co., Inc. REPORT ON SPECIMENS REMOVED FROM SEA WATER TESTS AT KURE BEACH, N.C., MAY 1948. 23 p., July 1948.

This study was designed to indicate commercially significant differences in the corrosion of various metals in sea water.

Mild steel, 2% nickel steels, and various other low alloy steels, all with pickled surfaces, were immersed in 3 - 4 ft of sea water for 9.7 yr under conditions devoid of galvanic effects. Insignificant differences both in weight losses and pitting were found among the steels; but these steels, as a class, have some advantage over carbon steel with respect to pitting.

Panels of mild and high tensile steels welded with various electrodes were immersed for 1209 days, and a second identical series for 870 days. All welds satisfactorily resisted corrosion except Murex #80 and Fleetweld #5 welds on high tensile steel and Unionmelt welds on mild steel. There was no evidence of localized accelerated corrosion along the margins of the austenitic welds.

A mild steel plate was made up with four rows of countersunk rivets including those of SAE 2115 nickel steel, 2% nickel - 1% copper steel, carbon steel, and wrought iron. The plate was immersed in sea water for 10 yr and losses were measured by micrometer calipers. Behavior of nickel or nickel-copper steel rivets in carbon steel plates was much better than those of carbon steel or wrought iron. There was practically no attack on either button head or countersunk head; corrosion of the carbon steel around the alloy rivets was no greater than elsewhere.

Specimens of a killed carbon steel, two American steels containing 3% and 5% chromium, and two French steels, one containing 2% chromium - 1% aluminum and the other 3.7% chromium - 1.3% aluminum, were sandblasted; half were either tested in the unpainted condition or were painted with a coal-tar enamel and then immersed. The other half was given a passivating treatment and part of these exposed without paint and the remainder coated with the coal-tar enamel before immersion. One series was removed after 165-days exposure, the other after 351 days. The passivating treatment apparently did not improve corrosion resistance of any sample, but one coat of enamel was beneficial. All low alloy steels corroded similarly, and were superior to the killed carbon steel.

In a test to determine the effect of structure on corrosion, panels of killed carbon steel were exposed to sea water for 198 days. Panels which had been heat treated to produce a spheroidized carbide structure corroded almost twice as fast as those with a lamellar pearlite structure. Pitting occurred to the same extent on both.

Samples of several types of nitrided and unnitrided stainless steels were immersed for 178 days. The nitrided steel showed a relatively high over-all corrosion rate comparable with that of carbon steel. The unnitrided metal was bright but apparently more susceptible to pitting.

Nickel-antimony-lead bearing bronze was almost as resistant as the standard lead-tin alloy when exposed to sea water for 307 days. The nickel-antimony-tin-lead



type was inferior to both, corroding more rapidly and being more susceptible to pitting.

Pure hot-rolled zinc samples immersed for periods ranging from 186 to 1460 days corroded at a slightly greater rate than impure specimens.

108

International Nickel Co., Inc. TOUGH MATERIALS FOR TOUGH SERVICE. ALLOY DEVELOPED FOR CONDENSER TUBE AND OTHER CORROSION RESISTANT USES SHOWS NEGLIGIBLE ATTACK ON WELDED AND UNWELDED SAMPLES AFTER 11 YEARS IN SALT WATER. INCO 22 no. 2: 8 p., Summer, 1948.

Two samples of a 70/30 cupro-nickel alloy, one welded and one unwelded, were immersed in sea water for 11 yr. The welded sample was partly immersed for almost 5 yr in polluted harbor water at Newport News, Va., then exposed at Kure Beach, N.C. for an additional 6 yr in sea water flowing at the rate of 120 ft per min. The unwelded sample was immersed for 11 yr at Kure Beach. Results were identical for both; the corrosion rate was 0.0002-in. penetration per year. The 70/30 compound also resisted fouling by marine organisms, stress-corrosion cracking, pitting, and erosion, and was not susceptible to dezincification.

109

International Nickel Co., Inc. REPORT ON SPECIMENS REMOVED FROM SEA WATER TESTS AT KURE BEACH, N.C., MAY 1949. 30 p., October 1950.

Effects of minor constituents on sea water corrosion of 70:30 copper-nickel alloy. Alloys containing various percentages of zinc, iron, manganese, tin, chromium, and arsenic were exposed for approximately 10 yr at a depth of 3-4 ft in sea water flowing at a velocity of 1-2 fps. Corrosion rates, measured by weight loss and pitting, decreased considerably with prolonged exposure, regardless of minor constituents present. Zinc had little effect on weight loss but tended to aggravate pitting of iron-modified alloys; the zinc content should be kept at or below 0.5%. For service in low-velocity flow, the iron content need not be as high as for high velocity use, e.g., in condenser tubes. Some quantity of iron, however, is desirable, since a very low iron content led to relatively severe over-all attack. Under the given experimental conditions, as much as 0.9% iron can be used without increasing susceptibility to pitting. Manganese was slightly beneficial, especially in reducing pitting, in alloys in which the zinc

content did not greatly exceed the iron content. The main action of tin was to suppress a detrimental effect of 1% zinc. Chromium and arsenic by themselves did not show any important effects.

Zinc-coated steel. The life of a hot-dipped zinc coating was approximately 1 yr per ounce of coating weight when immersed in sea water flowing at a rate of 1-2 fps.

Behavior of Hastelloy C. In similar sea water exposures up to 10 yr, Hastelloy C, like Hastelloy A and B, corroded less in the rolled and sandblasted conditions than in the cast and ground conditions. Neither type specimen showed any pitting or crevice corrosion under bakelite washers used to insulate samples from the exposure rack.

Sea water tests on Stellite. Specimens immersed under similar flow conditions for approximately 7 yr showed crevice corrosion. Stellite was much less susceptible to pitting than to corrosion, but corroded slightly faster in the ground state than in the as-rolled condition with scale present.

Sea water tests on Illium. In 5-yr sea water exposure, Illium G corroded faster than Illium R, but did not pit. Illium R exposed without removing the hot rolling scale pitted on the surface at breaks in the oxide scale. This was probably caused by local galvanic action at the breaks with the scale being cathodic to the base alloy. Both this sample and a pickled Illium R sample corroded under the bakelite washers.

Behavior of Zincilate in sea water. Steel panels with four different Zincilate coatings were exposed approximately 1 yr at a depth of 3-4 ft and a flow rate of 0-4 fps. The Zincilate treatments did not prevent fouling but did reduce the corrosion rate considerably.

Behavior of low-alloy chromium and chromium-aluminum steels with various surface treatments. Painted and unpainted steels were passivated by immersing them in concentrated nitric acid for 5-6 min at room temperature, rinsing, immersing 10-15 min in boiling 3% potassium chromate-0.5% disodium phosphate solution, and drying. The treatment did not improve the corrosion resistance of the steels when exposed 2 yr to quiet sea water. One coat of Bitumastic B50 paint applied cold was beneficial. The four low-alloy steels tested, viz., two French steels, one containing 2% chromium and 1% aluminum, the other containing 3.7% chromium and 1.3% aluminum; and two American steels containing 3 and 5% chromium, respectively, corroded in

about the same way, all being superior to a killed carbon steel control.

Behavior of titanium-nickel-cobalt-silicon alloys in sea water. Ti-Ni-Co-Si #10 and #54 corroded to about the same extent during a 1.5-yr exposure in quiet sea water. One specimen of the #54 alloy started to corrode around the edges and the other suffered severe attack on the surface, probably because of poor insulation at the fastening.

110

International Nickel Co., Inc. REPORT ON SPECIMENS REMOVED FROM SEA WATER TESTS AT KURE BEACH, N.C., MAY 1950. 36 p., February 1951.

A study was made of the corrosion of steel specimens in sea water. Unless otherwise stated the specimens were immersed at a depth of 3-4 ft in an intake basin at Kure Beach, N.C., where the tide rose and fell but had no definite flow.

Welded steel panels. One series of mild and high-tensile steel panels welded with various electrodes was immersed in flowing sea water for 1877 days; a second series was immersed in an intake basin for 1538 days. All the welds resisted corrosion satisfactorily except Murex #80 and Fleetweld #5 on high-tensile steel, and Unionmelt on mild steel, which seemed to be pitted. There was no evidence of localized accelerated corrosion along the margins of austenitic stainless steel welds.

Cast Iron and Type 2 Ni Resist welded with Ni Rod and R-29. Visual inspection of the welds after 671 days of exposure showed the welds to be resisting corrosion satisfactorily.

Rimmed steel. There was not much difference in corrosion resistance or susceptibility to pitting in samples from the butt core, middle skin, or top skin of ingots taken from the same heat. Specimens from the middle skin, however, corroded more and showed larger differences in thickness range than did the other specimens.

Copper steel and Types 316 and 304 stainless steel. Immersion tests lasting approximately 2 yr in both the intake basin and in sea water flowing at 0.4 fps showed that there was little difference in the performance of these alloys under the slightly different test conditions.

Rivets. Copper plates joined with steel rivets and steel plates joined with copper rivets were immersed for 14 mo. The steel rivets were completely corroded away from

the copper panel but the copper rivets in the steel plate were unaffected. Because of the favorable area relationships in the assembly of steel plates with copper rivets, the galvanic acceleration of the corrosion of the steel was negligible; where the reverse area relationship existed, the galvanic action of the copper on the steel was great.

Fine silver. Fine silver specimens, 4 by 12 in., were insulated by bakelite from Monel racks and immersed for 597 days in an intake basin, then for 317 days in sea water flowing at 0-4 fps, and finally reimmersed for 127 days in the flowing water. The corrosion rate varied during the three periods but the over-all corrosion was the same in both panels tested; the rate was uniform with time and was more severe in summer than in winter.

Special washers and zinc oxide to prevent crevice corrosion. Washers that had been vacuum-impregnated with Superla #8 wax and knurled to a depth of 0.010 in. on one side did not prevent crevice corrosion of austenitic steel in a 419-day immersion test. Washers were placed both with the knurled and smooth side next to the steel. Hi-Seal Plastic Jointing Compound, Hi-Seal Plastic Threading Compound, and Hi-Seal Plastic Sealing compound were applied under bakelite washers used to insulate specimens from Monel racks and fastenings. None of these materials satisfactorily prevented crevice corrosion in Type 430 stainless steel with #4 finish or Type 304 stainless steel. Hi-Seal Plastic Jointing Compound may be slightly superior. Zinc oxide smeared under the washer provided excellent protection from crevice corrosion for Type 304 stainless steel immersed for 92 days.

Glass-coated steel. Steel specimens were coated with glass, leaving a bare spot 0.25 in. square in the center of each side. After 470 days immersion, attack at the bare spots was less than on completely bare specimens. Crowding both the anodic and cathodic portions of the corrosion reaction into a relatively small surface tended to diminish rather than increase the rate of corrosion.

Synthetic rubber coatings. Panels coated with neoprene, Buna D hard rubber, and Thiokol were immersed for 2 yr in 3-4 ft of sea water flowing at 1-2 fps. None of the coatings prevented fouling. After 11 mo the Thiokol coating was crazed and at the end of 18 mo barnacles were cutting into it. After 2 yr the panels were removed from the flowing water and immersed to the same depth in the intake basin. At the end of 75-mo total exposure, the

neoprene and Buna S coatings were not damaged, although barnacle bases were on the surfaces. There were more barnacle bases on the Thikol-coated specimen; the coating was gone from one corner and had been lifted along one edge. None of the specimens, however, were in much worse condition than when removed from the flowing water.

Effect of structure on the corrosion of killed carbon steel. Specimens of carbon steel having a spheroidized carbide structure corroded almost twice as fast during the first 6 mo as did specimens of the same steel having a lamellar pearlite structure. During the next year the spheroidized carbide structure corroded at a slightly faster rate than formerly but the lamellar pearlite structure corroded about 5 times the rate noted for the first 6 mo and about twice as fast as the spheroidized carbide specimen. During the third exposure period (322 days) the corrosion rate was appreciably reduced for specimens of both structures and although the spheroidized structure corroded at a faster rate, the lamellar structure still showed a higher total corrosion rate. Specimens of both materials were severely perforated at the end of the three periods totalling 891 days. During the first period of exposure, corrosion occurred in the decarburized zone of the lamellar pearlite specimen and during the next two periods progressed into regions not decarburized. Corrosion of the spheroidized structure proceeded into the decarburized zone during the entire test and hence showed no rapid acceleration of corrosion rate.

Bolts and nuts. Cast iron bars were bolted together with bolts and nuts made of cast iron, Ni Resist, Carson Cadillac, or steel and immersed for 517 days. Ni Resist showed superior corrosion resistance.

111

International Nickel Co., Inc., SUMMARY OF DATA COVERING EXPOSURE OF MANGANESE MODIFIED CHROMIUM NICKEL AUSTENITIC STAINLESS STEELS TO CORROSION BY SEA WATER AND SALT AIR. 10 p., June 1956.

Chromium-nickel and chromium-manganese stainless steels were immersed in flowing sea water (3 to 4 ft deep, 1 to 2 fps flow velocity) at Kure Beach, N.C. for 191 and 324 days. These alloys were also exposed for 1 to 9 yr to marine atmospheres 80 and 800 ft from the beach. The manganese additions varied from 4 to 20%.

All specimens showed severe localized corrosion by the salt water. Stainless steels

containing high manganese were less resistant than 18-8 stainless (types 302 and 304) although neither of the 18-8 alloys is considered satisfactorily resistant to salt water under complete and continuous immersion for prolonged periods. Copper powder-vaseline paste applied under the bakelite washers was not completely effective in preventing corrosion.

The marine atmospheric resistance of a chromium 18, nickel 4, manganese 4 was superior to that of an 18-8 stainless (Type 302) after 1 yr, but not after 9 yr in the 800 ft lot. After 5 yr exposure in the 800 ft lot, manganese-chromium alloys similar in composition to AISI Type 201 (chromium 18, nickel 4, manganese 6) were approximately equivalent to 18-8 (Type 304) stainless steel in corrosion resistance. Alloys of higher manganese content (9 to 10%), with and without nickel, were less resistant to this environment than stainless Type 304.

Exposure conditions were more severe at the Kure Beach 80 ft lot. With the exception of AISI Type 201, all of the manganese-chromium grades exposed at this location were less resistant than 18-8 (Type 304). The highest manganese content compatible with corrosion resistance in this environment was 9%. When nickel was added to the 9% manganese-chromium stainless steel, corrosion resistance was further reduced.

112

Janecka, Hans. BIO-DETERIORATION OF CENTER MATERIALS AND STRUCTURES IN THE MARINE ENVIRONMENT. A BIBLIOGRAPHY. National Academy of Science, National Research Council, Prevention of Deterioration Center. Report PDC 60 zDC 60 013, Rev. 1, AD-440 946: 82 p., Dec. 1963.

113

Jenkins, J. F., Reinhart, F. M. SEAL SYSTEMS IN HYDROSPACE, PHASE I - MECHANICAL INTEGRITY OF FLANGE SEAL SYSTEMS. Naval Civil Engineering Lab. Report NCEL-TN 999, AD-843 582L: Nov. 1968. Long-term effects of hydrospace on seals and gaskets are under investigation at NCEL. Phase I includes investigation of the mechanical integrity of fifteen seal systems by means of tests in pressure vessels. There was no seal extrusion or leakage of any of the configurations investigated. Long-term ocean exposures and cyclic loading of seal systems in pressure vessels are planned.

114

Jenkins, J. F., Reinhart, F. M. SEAL SYSTEMS IN HYDROSPACE, PHASE II. CYCLIC LOADING OF FLANGE AND HATCH SEAL SYSTEMS. Naval

Civil Engineering Lab. Report NCEL TN-1022, AD-684 080: March 1969.

Long-term effects of hydrospace on seals and gaskets are under investigation at NCEL. Phase II includes investigation of the effects of cyclic loading on fifteen seal systems by means of tests in pressure vessels. Fourteen of fifteen test systems withstood 20 pressure cycles to 5,000 PSI without leakage or visible seal damage. Long term ocean exposures of seal systems are planned.

115

Jenkins, J. P., Reinhart, F. M. SEAL SYSTEMS IN HYDROSPACE, PHASE III: EFFECTS OF LONG TERM HYDROSPACE EXPOSURE ON SEAL SYSTEM INTEGRITY. 189 DAYS AT 5,900 FEET. Naval Civil Engineering Lab. Report No. NCEL-TN-1072, AD-865 361: 48 p., Jan. 1970.

Long-term effects of hydrospace on seals and gaskets are under investigation at NCEL (Naval Civil Engineering Laboratory). Phase III includes the evaluation of fifteen seal systems and five metallic seal flange materials after exposure to the marine environment for 189 days at a depth of 5,900 feet in the Pacific Ocean.

116

Jones, R. E. DESIGN, PLACEMENT, AND RETRIEVAL OF SUBMERSIBLE TEST UNITS AT DEEP-OCEAN TEST SITES. Naval Civil Engineering Lab., Report No. NCEL-TR-369, AD-615 769: 92 p., May 1965.

Four submersible test units (STU'S) were emplaced, exposing specimens of various materials to the sea floor sediment and to the surrounding water for various time periods and at various depths. Emplacement of the four and the retrieval of one (after 4 months) are reported in detail, and the rigging and instrumentation systems are described. The heaviest STU emplaced so far weighed almost 7,500 pounds and supported about 2,400 specimens of 600 different materials. Emplacements were made at depths of 2,400, 5,600, and 6,700 feet. Operations and system performance are discussed and conclusions and recommendations are presented.

117

Keehn, P. A. BIBLIOGRAPHY ON MARINE CORROSION. Meteorological and Geostrophical Abstracts. Report No. Contrib-4: AD-821 559: 160 p., June 1967.

118

Khan, D. K. Mukherjee, D. P., and Bannerjee, T. SEA WATER CORROSION OF NICKEL AND OTHER METALS. N.M.L. Technical Journal, 8: p. 17-21, Nov. 1966.

The authors report some results obtained in initial studies at Digha, of corrosion of following materials by sea water under natural and laboratory conditions: mild steel, galvanized steel, copper, brass, nickel, Monel alloy 400, zinc and aluminum alloys. In the field tests, corrosion rates were determined for specimens subjected to alternate immersion and exposure at high tide and low tide or buried in the sea bed, for one month in each case. In the laboratory tests specimens were totally immersed in natural sea water for one month and experiments were conducted to study the influence of temperature and pH on corrosion by sea water. Mild steel samples were used to determine effect of inhibitors (potassium chromate, sodium nitrite, sodium arsenate) and of sea water velocity on corrosion rate and were also totally immersed for 24 hours in artificial sea water and in 0.1N NaCl solution. Under intermittent exposure, copper and brass had lowest corrosion rates and nickel and Monel alloy 400 suffered least corrosion when buried in sea bed. It was found in general, corrosion rate of specimens buried at half-tide level was greater than of those buried in sea bed. Rates of corrosion in laboratory tests were greater than under natural conditions and velocity, temperature and pH of test solutions are shown to have had a considerable influence on results.

119

Kirk, W. W., Covert, R. A., and May, T. P. CORROSION BEHAVIOR OF HIGH-STRENGTH STEELS IN MARINE ENVIRONMENTS. Metals. Eng. Quart., 8 :no. 4: 31-38: Nov. 1968.

The performance of 18Ni and 12Ni-5Cr-3Mo maraging steels and HY 80 and 4340 low-alloy steels in long-term corrosion tests (up to three years) is described. Cathodic protection is shown to be an effective method of minimizing corrosion and improving corrosion fatigue strength. The danger of H<sub>2</sub> embrittlement from excessive cathodic polarization of the 12Ni-5Cr-3Mo steel is discussed. The atmospheric corrosion resistance of the maraging steels was found to be greater than that of the other grades. In sea water, all specimens corroded uniformly, with the exception of 12-5-3 material, which suffered severe pitting. This pitting was eliminated by cathodic protection with mild steel anodes. Specimens of 18Ni material with yield strengths on the low side were more resistant to stress corrosion cracking than specimens of higher strength. The effect of thermal history on the cracking behavior of the maraging steels was observed. In addition to providing cathodic protection,



mild steel was particularly beneficial as a barrier coating on the maraging grades.

120

Koshelev, G. G., Rozenfel'd, I. L.  
CORROSION RESISTANCE OF LOW-CARBON AND LOW-ALLOY STEELS IN SEA WATER. Sudostroenie, 25: 12-17, November 1959.

In Russian

Steel sheet specimens (260 x 180 x 3 mm), rolled and normalized without removal of the oxide, or normalized with subsequent removal of the oxide, were mounted in steel frames, the frames placed between porcelain insulating plates to protect them from mechanical damage, and immersed in the sea at depths of 30 and 85 cm for periods up to 6 yr. Corrosion of the samples was evaluated visually and by weight loss after removal of corrosion products by cathodic polarization in 20% sodium hydroxide at a current density of 3-5 amp/sq dm.

Visual examination showed that the low-alloyed steels MS-1 and SKhL-1 corroded in a nonuniform manner, and showed more localized damage than the carbon steel ST-3 and the low-alloyed steel MK. The average corrosion rate was about the same for all steels from which the oxide layer was not removed. During 6 yr, the average weight loss was 2.5 to 3 kg/sq m, or 0.5 kg/sq m per yr. The depth of corrosion averaged 0.2 mm/yr for SKhL-1 and MS-1 steels, 0.12 mm/yr for MK steel, and 0.008 mm/yr for the carbon steel ST-3. Removal of the oxide layer after heat treatment reduced the corrosion rate of all steels by approximately 10%, and decreased the tendency of the low-alloyed steels toward localized corrosion. After 5 yr immersion in sea water the tensile and yield strengths of the steels decreased 20 to 37%, the reduction being greatest for steel SKhL-1, which also had the highest tendency toward nonuniform corrosion. The rate of mechanical strength loss was high during the first 2 yr, then levelled off. Removal of the oxide layer somewhat reduced the overall loss of mechanical strength, and resulted in a more uniform rate of loss during the 5 yr. period.

121

Koshelev, G. G., Rozenfel'd, I. L.  
CORROSION STABILITY OF LOW-CARBON AND LOW-ALLOY STEELS IN SEA WATER. Foreign Tech. Div., Air Force Systems Command. Report No. FTD. TT, MT63 125, 64 71405. AD 605 881: 8 p., Dec. 1963.  
Transl. of Akademiia Nauk SSSR. Institut Fizicheskoi Khimii, Trudy, 8: p. 333-344, 1960.

122

Krafack, Karla, Franke, Erich. CORROSION BEHAVIOR OF 90/10 COPPER-NICKEL ALLOYS CONTAINING IRON. Werkstoffe u. Korrosion 4: 310-315: Aug./Sept. 1953.

In German

Sea-water-exposure tests showed that small amounts of iron improve the corrosion resistance of 70/30 copper-nickel alloys and that 90/10 copper-nickel alloys with up to 2% iron develop satisfactory corrosion resistance without quenching and annealing. Contrary to pure copper-nickel alloys, such as monel metal, those containing iron are resistant to marine growth in both quiet and flowing sea water.

After 998 days' immersion in quiet sea water, coldrolled 88/12 copper-nickel alloy sheet containing 1.81% iron showed weight loss and pitting depth only one third that of 70/30 copper-nickel alloy sheet containing no iron. Under the same conditions but over a longer period, 90/10 copper-nickel alloys were attacked only one sixth as severely as arsenic-containing admiralty brass. When exposed for 300 days to flowing sea water (0.122 m per sec), annealed 90/10 copper-nickel alloys with 0-3.5% iron content all showed good corrosion resistance. Quenched samples containing 0.8-2.2% iron were more strongly attacked than were the corresponding non-quenched compositions. The 90/10 copper-nickel alloys containing 0.7-2% iron also showed good corrosion resistance for over 41 days in sea water at velocities up to 3.658 m per sec. They were superior to admiralty brass and to low-iron 70/30 copper-nickel alloys, and equivalent or superior to aluminum brass and high-iron 70/30 copper-nickel. Similar tests on 70/30 copper-nickel alloys showed that pitting decreases as the iron content increases. Quench annealing has no effect on 1.5% iron alloy, but is beneficial for the 2.0% iron alloy and mandatory for the 3.5% iron alloy.

Corrosion-erosion tests on disks rotated in sea water at various velocities for 55 days at 0.6 C showed that corrosion resistance is 1% lower in samples heat-treated to precipitate the iron-rich phase and that 90/10 alloys are better than 70/30 copper-nickel alloys.

Exposures of condenser pipes, internally protected by a 2.1 lead-tin coating, to water flowing at 3 m and even at 4.57 m per sec at 9-16 C for up to 10 mo again demonstrated the remarkable corrosion resistance of 70/30 copper-nickel alloys

containing 0.52% iron and particularly of 90/10 alloy pipes containing 1.5-2% iron. Welds in 70/30 copper-nickel alloys with or without 0.5% iron performed well in service over a period of 2 yr.

Galvanic corrosion tests showed that the 90/10 alloy is more easily polarized in turbulent sea water than is pure copper, but that copper can be replaced by 90/10 copper-nickel in contact with a less noble metal such as cast iron without disadvantage. The 70/30 copper-nickel alloy is much more susceptible to galvanic corrosion than is the 90/10 alloy.

The 90/10 copper-nickel alloys retain their corrosion resistance at elevated temperatures, say 163 C, for 54 days. Spray tests at 49 C revealed that an iron content of 1% produces the most favorable results. Pipes of 90/10 copper-nickel with 0.7% iron lasted more than 4 yr in sea water, whereas admiralty brass pipes showed considerable corrosion after 1-2 yr. Copper-nickel alloys 90/10 with up to 1.5% iron also showed satisfactory results.

Chlorination of salt water produced no substantial change in the corrosion behavior of 90/10 copper-nickel alloy. Corrosion resistance decreased, however, with rising iron content. Best results in the 70/30 series were obtained with 0.4% iron content.

The 70/30 alloy is more resistant to attack by hydrogen sulfide, ammonium hydroxide, and hydrochloric acid than the 90/10 alloy. Welded and soldered 90/10 copper-nickel pipe showed satisfactory resistance to sea-water corrosion.

123

Kubose, D. A., Cordova, H. I. ELECTRO-CHEMICAL CORROSION STUDIES OF SNAP CONTAINER MATERIALS. Naval Radiological Defense Laboratory. Report No. USNRDL-TR-1036, AD-635 682; Contract AT(49-S)-2084; 28 p., June 1966.

Corrosion rates of Haynes 25, Hastelloy C and Hastelloy N in natural seawater were determined by galvanostatic polarization techniques. Values of approximately 0.01 mils per year were obtained for each of the alloys. No significant effect of aeration and solution stirring on the corrosion rates was observed.

124

Kubose, D. A., Lai, M. G., Goya, H. A., Cordova, H. I. MEASUREMENT OF SEAWATER CORROSION OF SNAP CONTAINER ALLOYS USING RADIOACTIVE TRACER TECHNIQUES. Naval Radiological Defense Laboratory. Report

No. USNRDL-TR-1092, AD-645 553; 45 p., January 1967.

Corrosion rates of Haynes 25, Hastelloy C and Hastelloy N in seawater were measured using two radioactive tracer techniques. These techniques involved (1) measurement of the radioactivity leached into seawater from radioactive alloy specimens and (2) performing neutron activation analysis of corrosion products in seawater in which inactive alloy specimens had been placed. The second technique was used to determine whether the gamma recoil from the thermal neutron activation of the alloys in the first technique had affected their corrosion properties. It was found that the gamma recoil from neutron activation had only a small effect on the corrosion rate of the alloys. The average corrosion rates obtained for hastelloy C and Hastelloy N were 0.00005 mil per year and 0.0001 mil per year, respectively. No appreciable differential leaching of the cobalt, nickel and chromium components of these alloys was observed. The results obtained for Haynes 25 indicated differential leaching had occurred. The corrosion rate calculated from the amount of cobalt released was 0.000001 mil per year while that calculated from the amount of chromium released was 0.00001 mil per year.

125

Kubose, D. A., Cordova, H. I. CORROSION STUDIES OF HAYNES 25 ALLOY IN SEAWATER USING ELECTROCHEMICAL TECHNIQUES. Naval Radiological Defense Laboratory. Report No. USNRDL-TR-67-64, AD-656 897; Contract AT (49-5)-2084; 31 p., Aug. 1967.

Electrochemical corrosion rate measurements were made on uncoated, emissively coated and thermally shocked and uncoated specimens of Haynes 25 alloy in seawater at room temperature and 90C. The corrosion rates of the emissively coated specimens were about an order of magnitude higher than those of the uncoated specimens. No significant difference between the corrosion rates measured at room temperature and at 90C was observed for either the uncoated or the emissively coated specimens. Thermal shocking of uncoated specimens (by quenching from 500C to room temperature) did not increase their corrosion rates. The corrosion rates observed were on the order of 0.003 mils per year (MPY) for the uncoated and the thermally shocked uncoated specimens and 0.04 MPY for the emissively coated specimens.

126

Kubose, D. A., Goya, H. A., Lai, M. G.,

Cordova, H. I. SEAWATER CORROSION STUDIES OF EMISSIVELY-COATED HAYNES 25: RADIO-ACTIVE TRACER TECHNIQUES. Naval Radiological Defense Laboratory. Report No. USNRDL-TR-67-109, AD-659 978: Contract No. AT(49-5)-2084: 28 p., October 1967.

Corrosion rates of uncoated, half- and completely-emissively-coated Haynes 25 have been measured in seawater by use of radioactive tracer techniques. The corrosion rates observed for the (1) uncoated and (2) half- and completely-coated specimens were nominally 0.000003 and 0.0001 mil per year (MPY), respectively. It was established that the observed corrosion rates of the half- and completely-coated specimens were due entirely to corrosion of Haynes 25 and not to the corrosion of the emissive coating. The higher corrosion rates were attributed primarily to the fact that the actual surface area of the Haynes 25 was much larger than the geometric surface area because of surface preparation prior to application of the emissive coating. A re-examination of the corrosion rate based upon the amounts of cobalt and chromium released to the seawater indicated that the previously reported differential leaching of these components of Haynes 25 was an experimental artifact due to errors in counting extremely low amounts of chromium-51. Present observations show that the cobalt-and-chromium-based corrosion rates are the same and agree with the previous cobalt-based corrosion rate.

127

Kubose, D. A., Cordova, H. I. ELECTROCHEMICAL CORROSION STUDIES OF GALVANICALLY COUPLED SNAP-21 MATERIALS. Naval Radiological Defense Laboratory. Report No. USNRDL-TR-68-26, AD-668 161: 36 p., January 1968.

Electrochemical corrosion rate measurements on materials used in the Snap-21 radioisotopically-fueled power system have been made in seawater at room temperature. The materials examined included aluminum, copper, Hastelloy C, Hastelloy X, nickel, 3-4 stainless steel, tantalum, titanium-621 alloy and uranium-8% molybdenum alloy. The normal corrosion rate of each material was measured by means of galvanostatic polarization techniques. A galvanic series of the materials in seawater was determined and the galvanic currents between galvanically coupled materials were measured with a zero-resistance ammeter circuit. The effect of galvanic coupling of construction materials of the SNAP-21 system does not materially change the containment time of the Sr-90 fuel in the corrosive seawater environment.

128

Kubose, D. A., Lai, M. G., Goya, H. A., Cordova, H. I. SEAWATER CORROSION STUDIES OF SNAP-21 MATERIALS. Naval Radiological Defense Laboratory. Report No. USNRDL-TR-68-109, AD-678 455: Contract AT(49-5)-3002: 43 p., Dec. 1968.

The corrosion rates of several SNAP-21 materials measured in seawater at ambient room temperature and pressure (Hastelloy C, Hastelloy X, titanium-621, beryllco-165) have been compared to those measured in 200C seawater vapor (Hastelloy C, Hastelloy X), in seawater under a hydrostatic pressure of 7000 PSI (Hastelloy C, titanium-621, beryllco-165) (23C) and in seawater in an ionizing radiation field of 200,000 R/HR (Hastelloy C, Hastelloy X) (30C). Significant increases in corrosion rate were observed only for Hastelloy C and Hastelloy X in hot seawater vapor (approximately two orders of magnitude) and for Hastelloy C in seawater under high hydrostatic pressure (approximately an order of magnitude).

129

Kubose, D. A., Cordova, H. I. ELECTRO-CHEMICAL CORROSION-RATE MEASUREMENT OF GALVANICALLY COUPLED SNAP-23 MATERIALS IN SEAWATER. Naval Radiological Defense Laboratory. Report No. USNRDL-TR-69-14, AD-852 974L: 36 p., January 1969.

130

Kubota, Hiroyuki, SEA-WATER CORROSION AND STEELS RESISTANT TO IT. Nippon Kokan Tech. Rep. (Overseas), No. 10: 27-40, March 1970.

The factors affecting the corrosivity of sea water are discussed and the mechanism of marine corrosion on steel is described. Factors mentioned include salinity, flow rate, and temp. Methods of preventing corrosion by using sea-water-resistant steels are described and the development of corrosion resistant steels, e.g. 'NK Marine', 'Mariner', NEP-TEN 50 and 60, and APS 20A grades, is mentioned. The chemical compositions and mechanical properties of these steels are given and trials carried out during the development of corrosion resistant steels are reported.

131

Lagutina, A. G., Danil'chenko, K. P., Shevehenko, O. F., Barannik, V. P. THE CORROSION OF SHIPBUILDING MATERIALS IN SEA WATER. Zashchita Metallov, 6; No. 1: 48-51, 1970.

In Russian

A comparative study was made in natural



and in laboratory conditions of the corrosion in sea water of the most commonly used shipbuilding materials, i.e. (i) steel 3S [C 0.12-0.20%], (ii) bronze AMTs-9-2 [9:2 Al-Ni], (iii) monel NMZhMTs [28: 2.5: 1.6 Cu-Fe-Mn, Ni remainder], (iv) AMG-6T [Al-6% Mg contg. Ti], stainless steels (v) 1Kh18N10T [18: 10 Cr-Ni, Ti-stabilized] and (vi) OKh17N7Yu [17:7:1 Cr-Ni-Al], and (vii) brass L62 (Muntz metal, 62% Cu). Specimens were immersed 40 m from the shore at various depths and in the laboratory in flowing and stagnant sea water. Corrosion rates were higher in natural conditions than in laboratory tests (artificial or natural sea water), e.g. after 1 year the corrosion rates of (ii), (vii) and (iv) were 5-6 times higher in the sea. With (iii), (v), and (vi) there was also a difference in the type of corrosion severe pitting in the sea but very little attack in the laboratory. With (i) rates were similar in the sea and laboratory flowing sea water tests but lower in stagnant tests. The principal factors responsible for the increased attack in natural conditions were biological (affecting the physicochemical properties of the sea water) and mechanical (natural movement affecting the cathodic process).

132

Langer, N. A., Ryabov, V. P., Zotova, L. M. NATURAL CORROSION STUDIES OF ALUMINUM-STEEL WELDED JOINTS. *Avtom. Svarka*, 21: No. 4; 23-28, April 1968.

In Russian

The corrosion resistance of joints of AMTs and AMG6 to St.3 and Kh18N10T in sea-water and in air near the sea was studied. Specimens were exposed to sea atmospheres 10d-12 months. After 8 months, AMG6/kh18N10T joints had the highest corrosion resistance. Mechanical properties of joints are tabulated.

133

LaQue, F. L. SEA WATER CORROSION TESTS. In: *Corrosion Handbook*, Herbert Uhlig, ed. New York, Wiley, p. 1060-1071, 1948.

134

LaQue, F. L. BEHAVIOR OF METALS AND ALLOYS IN SEA WATER. In: *Corrosion Handbook*, Herbert Uhlig, ed. New York, Wiley, p. 383-430, 1948.

135

LaQue, F. L. A CRITICAL LOOK AT SALT SPRAY TESTS. *Materials & Methods*, 35: No. 2: 77-81, February 1952.

The author appraises the value of salt-spray tests and concludes that they are inadequate. They should not be used as a guide in research and should not be substituted for special tests designed to study, individually or in combination, those factors which determine the overall quality of products to be improved. A salt-spray test can be useful for inspecting different modifications of the same kind of metal. It can also be used for different lots of the same product once some standard level of performance has been established; however, success or failure in the test does not guarantee similar behavior in actual service.

Specific criticisms directed at the test are as follows: There is rarely a parallel between conditions in the salt-spray box and those prevailing in nature. Consequently the assumption that exposure to salt spray for several hours is equivalent to natural exposure for months or years is not warranted. Moreover, the mode or pattern of deterioration produced does not match that observed in service. Accurate measurements of the protective value of either metal or nonmetal coatings are not possible.

With nonmetal coatings, the test is not reliable because the environment of the salt-spray test is designed to be destructive to the base metal rather than to the coating, and assessment of coating behavior is based on corrosion of the metal base rather than the coating. The effects of light and moisture on lacquers and enamel coatings or the effects of wind-driven rain or intense sunlight on protective oil and grease coatings cannot be duplicated. Accurate determination of discontinuities in a protective coating is hampered by formation of new discontinuities if the test is run too long or by differences in the amount of fog condensing on surface portions that are exposed at different angles. The effect of slope and angle of exposure also prevents the test from being valuable as a measure of coating thickness.

Galvanic effects cannot be accurately observed because conditions within the salt-spray box cannot be made to duplicate those existing in other corrosive media. The accumulation of soluble corrosion products exaggerates their secondary corrosive effects. Galvanic action is also influenced by the relatively high electrical conductivity of films of condensed brine as compared with films of condensate that form on metal surfaces in natural environments. This tends to increase the areas

involved in galvanic couples with an increase in galvanic action.

The test is also unreliable for the detection of free iron which contaminates the surface of stainless steel.

136

LaQue, F. L. THEORETICAL STUDIES AND LABORATORY TECHNIQUES IN SEA WATER CORROSION TESTING EVALUATION. Corrosion, 13: 303t-314t, 1957.

137

LaQue, F. L., Tuthill, A. H. ECONOMIC CONSIDERATIONS IN THE SELECTION OF MATERIAL FOR MARINE APPLICATIONS. Society of Naval Architects and Marine Engineers. Transactions 69: 1-21, 1962.

138

LaQue, F. L., and Copson, H. R. eds. CORROSION RESISTANCE OF METALS AND ALLOYS, 2nd. Edition. New York, Reinhold, p. 332., 1963.

139

LaQue, F. L. PRECAUTIONS IN INTERPRETATION OF CORROSION TESTS IN MARINE ENVIRONMENTS. Industrie Chimique Belge, Brussels, 29: No. 11: 1177-1185, Nov. 1964.

140

LaQue, F. L. MATERIALS SELECTION FOR OCEAN ENGINEERING. In: Ocean Engineering, Wiley and Sons, Inc., New York. p. 588-632, July 1968.

This review of the requirements of materials for use in ocean engineering applications will concentrate on resistance to deterioration in ocean environments. This is justified by the fact that such requirements represent the principal distinction between ocean-engineering and other engineering applications. The usual properties related to the strength of structures and devices and how they may be fabricated are not peculiar to ocean-engineering applications and can be dealt with by reference to voluminous pertinent literature, much of it recently related to projected designs for pressure vessels, etc., proposed for undersea use.

141

LaQue, F. L. DETERIORATION OF METALS IN AN OCEAN ENVIRONMENT. In: Proceedings, International Symposium, Held in New York City, Sept. 12-14, 1967. Ocean Engineering, 1: No. 2: 121-199, Dec. 1968 and 1: No. 3: 299-314, Feb. 1969.

Discussion is concentrated on the types of deterioration and the circumstances under which it occurs for the several classes of material employed in ocean

engineering applications. Suggestions as to how difficulties may be avoided are given equal attention. Aluminium alloys are dealt with in terms of alloy selection, effects of deep submergence, stress corrosion, effects of high temperatures and galvanic action. The copper base alloys are discussed in terms of tolerance for velocity effects, sulphide pollution, stress-corrosion, and such selective attack as dezincification, etc. The stainless steels and nickel base alloys are considered with respect to susceptibility to pitting, crevice corrosion, and stress-corrosion. Titanium and the superstrength steels are discussed principally with respect to resistance to stress-corrosion cracking (SCC). Galvanic action and cavitation erosion phenomena are dealt with generally in terms of all classes of material.

142

LaQue, F. L. ANALYSIS OF MARINE CORROSION FAILURES. In: Failure Analysis, 1969, 299-320, 322-326. Met. A., 6907-72 0113.

Analysis of marine corrosion failures is described in terms of the many factors that must be considered, in three broad categories. These categories cover factors related to the metal, to the environment and to design. This approach is illustrated by case histories devoted to instances in which certain factors were of dominant importance. These included an inadequate content of a critical element, dezincification, stress effects, graphitization, too high a velocity, uneven velocity, crevice corrosion, vibration, cavitation, cyclic stresses, micro- and macro-organisms, stray currents, galvanic effects and metal salts. Examples of accelerated corrosion include the effect of Cu corrosion products on Al in a heat exchanger assembly and the attack of Al or Ni-Cu tubing by Hg leached from antifouling paints. Cavitation erosion of Mn bronze marine propeller blades is discussed.

143

Larrabee, C. P. CORROSION OF STEELS IN MARINE ATMOSPHERES AND IN SEA WATER. Carnegie-Illinois Steel Corp., Corrosion Research Laboratory. Trans. Electrochem. Soc. 87: 123-140, 1945.

In sea water, plain and low-alloy steels are shown to have an average corrosion rate of about 22 mg/dm<sup>2</sup>/day (0.004 in./yr average penetration). Pitting attack characterizes the corrosion of stainless steels, although the presence of 2 - 3% molybdenum in 18/8 stainless or very high alloy content diminishes this tendency.

144

Larrabee, C. P. CORROSION RESISTANCE OF HIGH-STRENGTH, LOW-ALLOY STEELS AS INFLUENCED BY COMPOSITION AND ENVIRONMENT. *Corrosion*, 9: No. 8: 259-271, Aug. 1953.

145

Larrabee, C. P. CORROSION-RESISTANT EXPERIMENTAL STEELS FOR MARINE APPLICATIONS. *Corrosion*, 14: No. 11: 501t-504t, 1958.

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Larrabee, C. P. STEEL HAS LOW CORROSION RATE DURING LONG SEA WATER EXPOSURE. *Materials Protection*, 1: p. 95-96, December 1962.

Twenty H-sections of carbon steel piles immersed 23.6 yr in unpolluted sea water at Santa Barbara, Calif., cleaned in the field and measured (at 3 in. from each of the four edges), showed an average annual flange loss of  $1.53 \pm 0.23$  mils. End sections of nine piles cleaned and measured in the laboratory had average annual losses of: flanges, 1.34 mils; webs, 1.72 mils; weighed average,  $1.46 \pm 0.25$  mils. Annual weight losses of the nine end sections averaged  $1.73 \pm 0.21$  mils. After 20 yr, an annual loss of 1 mil is predicted.

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Lee, R. W. H. BIBLIOGRAPHY ON MICROBIAL CORROSION OF METALS. Prevention of Deterioration Center, National Academy of Science, National Research Council. Report No. S63 025, PDL48074, AD-601 247: 74 p., July 1963.

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Lennox, T. J., Jr., Peterson, M. H., Brown, B. F., Groover, R. E., Newbegin, R.L., Smith, J. A., Waldron, L. J. MARINE CORROSION STUDIES, STRESS CORROSION CRACKING, DEEP OCEAN TECHNOLOGY, CATHODIC PROTECTION, CORROSION FATIGUE; FOURTH INTERIM REPORT OF PROGRESS. Naval Research Laboratory, Memorandum Report No. 1711, 127 pgs., May 1966.

This is the Fourth Interim Report of Progress made in Marine Corrosion Studies conducted by the METALLURGY DIVISION OF NRL. It provides information on studies which are underway. Conclusions reached are preliminary in nature. These deal with four experimental areas: stress-corrosion studies, cathodic protection studies, metallic corrosion studies, and corrosion fatigue studies. Marine corrosion research is characterized at the present time by the necessity to conduct experiments that often may extend over a period of many months or even years. In some instances the intermediate evaluations may provide the only available guidance at the time in a given problem area.

149

Lennox, T. J., Jr., Peterson, M. H., Groover, R. E. MARINE CORROSION STUDIES: THE ELECTROCHEMICAL CHARACTERISTICS OF SEVERAL PROPRIETARY ALUMINUM GALVANIC ANODE MATERIALS IN SEA WATER (FIFTH INTERIM REPORT OF PROGRESS). Naval Research Laboratory. Memorandum Report No. 1792, 40 p., May 1967.

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Lennox, T. J., Jr., Peterson, M. H., Groover, R. E. MARINE CORROSION STUDIES: THE CORROSION CHARACTERISTICS AND RESPONSE TO CATHODIC PROTECTION OF SEVERAL STAINLESS STEEL ALLOYS IN QUIESCENT SEA WATER; WITH A PARTIALLY ANNOTATED BIBLIOGRAPHY. Naval Research Laboratory, Memorandum Report No. 1948, AD-684 073: 52 p., Nov. 1968.

Crevice corrosion was the most serious type of attack found on unprotected stainless steel, but random pitting not associated with any observed crevice was also found. Stainless steel alloys 21CR-6NI-9MN, 17-4 PH H1025, 205, 304, 316, 410, and 430 were seriously attacked by crevice corrosion. Stainless No. 20CB-3 was much more resistant to this type of attack but was not completely immune. Cathodic protection from either carbon steel or aluminum anodes effectively reduced the crevice corrosion on the stainless steels studied, but in some cases the steel anodes were not effective in reducing the depth or incidence of random pitting. Aluminum anodes are judged unsuitable for use on 17-4 PH H1025 stainless steel as this level of cathodic protection caused accelerated cracking of this alloy. Additional studies on cathodically polarized 17-4 PH stainless steel (aged at 925F for 4 hours) indicated a considerable reduction in the load-bearing capacity of a precracked specimen when it was polarized to the potential of a zinc or aluminum anode.

151

Lennox, T. J. Jr., CORROSION ANALYSIS OF 304 STAINLESS STEEL WIRE ROPE AND FITTINGS FROM A NOMAD BUOY MOORING SYSTEM AFTER 34-MONTHS CONTINUOUS SERVICE IN THE GULF OF MEXICO. Naval Research Laboratory. Memorandum Report No. 2045, 20 pgs., Sept. 1969.

Samples for a 1250-ft length of 304 stainless steel wire rope and associated stainless steel tube thimbles and stainless steel cable clamps were studied to determine the extent of corrosion after 34-months continuous immersion in the Gulf of Mexico. This 3/4-in.-diam wire rope (6 x 19 Warrington - IWRC 7 x 7) was used in the upper portion of a Nomad buoy mooring system. The performance of this particular buoy

design is important because of its possible influence on the national buoy program.

152

Lennox, T. J., Groover, R. E., Peterson, M.H. CORROSION AND CATHODIC PROTECTION OF WIRE ROPES IN SEAWATER. In: Sixth Marine Technology Society Conference, Corrosion Symposium, Wash. D. C., 29 June - 1 July, 1970. Marine Technology Society, Vol. 2: p. 1281-1294, 1970.

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Lindberg, R. I., ALUMINUM IN MARINE ENVIRONMENTS. Am. Soc. Naval Engrs. J., 73: 133-138, February, 1961.

154

Little, Arthur D. Inc. MARINE CORROSION AND FOULING. Report, Proj. Trident, AD-415 256: 32 p., n.d.

The nature, causes, and prevention of marine corrosion and fouling are reviewed. Emphasis is given to those anticipated Trident problems which lie outside the more familiar corrosion and fouling experience. In particular, an effort is made to determine to what extent coastal waters test data, and service data from from ships, buoys, and cables may be applied to other environments and devices. The electrochemical mechanism of corrosion is discussed as a framework for understanding the effects of the various factors which influence corrosion rate: for example, temperature, oxygen concentration acidity, bimetallic coupling, organic excretions, and protective coatings. Mention is made of such special problems as pitting, stress corrosion cracking, and interaction of fouling with corrosion. Marine fouling, together with the destructive effects of marine borers on woods and plastics, varies widely and often unpredictably with geographical location, temperature, water velocity, depth and a host of other factors, current knowledge of corrosion and fouling effects are summarized.

155

Loginow, A. W. CORROSION OF EXPERIMENTAL SUBMARINE HULL STEELS IN MARINE ENVIRONMENTS. United States Steel Corp. Applied Research Lab. Report No. S-13305, and S-23309-1, AD-482 784L: Contract Nobs-88540. 21 p., September 1965.

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Loginow, A. W. CORROSION OF 12NI-5CR-3MO MARAGING STEEL WELDMENTS. United States Steel Corp., Applied Research Lab. Tech. Report No. ARL-B-63502, AD-817 367L: Contract, Nobs-94535, 27 p., July 1967.

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Loginow, A. W. FOUR-YEAR CORROSION TESTS OF HY-130 AND HY-80 STEELS IN MARINE ENVIRONMENTS. United States Steel Corp., Applied Research Lab. Tech. Report, AD-855 821L: Contract Nobs 94535. 25 p., July 1969.

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Loginow, A. W. FOUR-YEAR CORROSION TESTS OF 12NI-5CR-3MO MARAGING STEEL IN MARINE ENVIRONMENTS. Tech. Report, AD-855 822L: 22 p., July 1969.

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Lowe, T. A. INVESTIGATION OF THE CORROSION RESISTANCE OF ALUMINUM-STEEL ASSEMBLIES EXPOSED TO SEA WATER. PART I: ASSEMBLY FABRICATION AND INSTALLATION. Kaiser Aluminum and Chemical Corp. Report No. MS PR61 67, AD-440 865L: Contract Nobs 72433. 14 p., September 1961.

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Lowe, T. A. INVESTIGATION OF THE CORROSION RESISTANCE OF ALUMINUM-STEEL ASSEMBLIES EXPOSED TO SEA WATER. PART II. FIRST VISUAL INSPECTION. Kaiser Aluminum and Chemical Corp., Report No. MSPR62 64, Interim Progress Rept. No. 20, AD-441 658L: Contract Nobs 72433. 4 p., Nov. 1962.

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Lowe, T. A. INVESTIGATION OF THE CORROSION RESISTANCE OF ALUMINUM-STEEL ASSEMBLIES EXPOSED TO SEA WATER. PART III: EVALUATION OF ONE-YEAR SAMPLES. Kaiser Aluminum and Chemical Corp. Report No. MS PR63 10, Progress Report No. 21, AD-431 266: Contract Nobs 72433. 35 p., March 1963.

The first set of riveted, aluminum-steel assemblies was removed after exposure in tide-range immersion for one year. An evaluation of these assemblies was made on the basis of exterior appearance, the condition of faying surfaces, and a comparison of their breaking strength with unexposed, control samples. The results of this evaluation show that (1) there has been a small loss in the breaking strength of exposed assemblies, (2) the attack of faying surfaces is more a function of the protective paint and joint insulation system than of the rivet material or the aluminum alloy used in the assembly, and (3) significant attack of aluminum exterior surfaces by copper, deposited from the anti-fouling paint used, may cause significant damage of the samples still in test before completion of the program.

162

Lowe, T. A. INVESTIGATION OF THE CORROSION RESISTANCE OF ALUMINUM-STEEL ASSEMBLIES



- EXPOSED TO SEAWATER. PART IX: EVALUATION OF FIVE-YEAR SAMPLES. Kaiser Aluminum and Chemical Corp. Report No. MS-PR-66-43, Progress Rept. No. 27, AD-484 896L: Contract No. NObs-72433. 54 p., May 1966.
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Macander, Aleksander, Francy, C. D. INSTALLATION OF NASL DEEP SEA MATERIALS EXPOSURE ARRAYS IN THE TONGUE OF THE OCEAN. Naval Applied Science Lab. Report No. NASL-930-6, Progress Rept. No. 1, AD-818 426L: 25 p., July 1967.
- 164  
Maersch, R. E. THE EFFECT OF MINOR ALLOYING ADDITIONS ON THE SEA-WATER CORROSION BEHAVIOR OF ALUMINUM-BRONZE ALLOYS. U.S. Navy Marine Engineering Laboratory, Report No. MEL 196/66, AD-635 288: 18 p., June 1966.
- Some compositions of aluminum-bronze alloys suffer an insidious type of selective-phase attack in seawater. One proposed method to improve the corrosion behavior of these materials was the addition of minor alloying elements to promote the formation of microstructural constituents that are electrochemically compatible. Three experimental alloys, containing small amounts of tin, nickel and arsenic, respectively, were analyzed after sea-water exposure. None of the minor alloying additions imparted significant improvement in corrosion behavior of the base alloy.
- 165  
Mafflard, J. AN EXAMPLE (AMONG OTHERS) OF THE EXCELLENT CORROSION RESISTANCE OF ALUMINIUM ALLOYS IN SEA-WATER: 20 YEARS IMMERSION WITHOUT A TRACE OF CORROSION. Revue Aluminium, No. 386: 638, June 1970.
- In French
- A mooring buoy which has been in service since 1950 is illustrated. Fabricated in 3-mm Duralinox A-G5, the buoy shows no sign of corrosion. It has been taken from the water only three times in 20 years for attention to the chain and securing rings. This is one of numerous examples of the good resistance of Al alloys to marine conditions.
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May, T. P., Weldon, B. A. COPPER-NICKEL ALLOYS FOR SERVICE IN SEA WATER. In: Proceedings, Congres International de la Corrosion Marine et des Salissures. Cannes, France, June 8-12, 1964. p. 141-156, 1965.
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McGoff, V. M. J., Glaser, C. J. CORROSION OF INCONEL BY SEA WATER. MSA Research Corp. Progress Report MSA Memo. 138, Contract No. NObs 77023: 15 p., Jan. 20, 1959.
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Mears, R. B. and Brown, R. H. RESISTANCE OF ALUMINUM-BASE ALLOYS TO MARINE EXPOSURES. Trans. Soc. Naval Architects Marine Engrs. 52: 91-113, 1944.
- In order to study corrosion in various alloys, the Aluminum Research Laboratories have tested over 100,000 specimens. The compositions and properties of the aluminum alloys examined are given. In most tests, the comparative resistance to corrosion was evaluated by the change in mechanical properties after various periods of exposure. In addition, the exposed samples were often sectioned and the depth and type of attack determined by microscopic examination.
- Alloy specimens were exposed in a variety of sea and harbor waters. Generally, 1 set of specimens was exposed continuously submerged in the water and another was placed at tide level where it was alternately immersed in water and exposed to air. Periods of exposure were 1 and 2 yr. for each sample, depending upon the test site. Results indicate that all the aluminum alloys tabulated have a high resistance to sea water. Alclad 3S and Alclad 24S-T are the most resistant alloys; neither showed significant changes in tensile strength at any location. Alloy 52S-1/2H is the next most resistant, followed by 52S. Alloys 53S-T and 61S-T are similar and somewhat inferior to 52S. Aluminum-copper alloys, such as 17S-T and 24S-T, are definitely attacked in sea water and should not be used in such locations unless protected.
- Galvanic effects caused by contact between dissimilar metals are likely to be more pronounced in marine exposures than in many other locations because of the high conductivity of the sea water. Aluminum alloys are anodic to most of the other common structural alloys. A potential series for the common aluminum alloys and other materials is included in the report. Metals high in this series tend to corrode selectively and protect metals lower in the series.
- Contact of either magnesium or zinc with aluminum alloys in sea water will result in an increased attack of the magnesium or the zinc. In the case of the magnesium-

aluminum alloy couple, sufficient current may flow to the aluminum alloy to cause special cathodic corrosion. Magnesium-base alloys are the only structural base alloys which have been found to cause this special cathodic corrosion. Aluminum-base alloys containing substantial amounts of magnesium are resistant to cathodic corrosion of this type.

Contact between aluminum alloys and unalloyed and stainless steels normally results in some selective attack of the aluminum alloy.

Contact between aluminum alloys and copper generally leads to very pronounced selective attack of the aluminum alloy. Copper alloys such as brass or bronze or nickel alloys such as cupro-nickel or monel behave like copper itself when in contact with aluminum alloys.

If aluminum alloys must be employed with copper or copper alloys in structures immersed in sea water, the use of zinc attachments for cathodic protection is one of the most satisfactory measures. The zinc will be selectively attacked, and the electric current generated will protect both aluminum and copper.

169

Mendizza, A. THE STANDARD SALT-SPRAY TEST: IS IT A VALID ACCEPTANCE TEST? Am. Soc. Testing Materials. Spec. Tech. Publ. 197: p. 107-126, 1957.

Comparative salt spray tests were run on nickel plated NAX or 1010 steel. Plate thicknesses were 0.00075 to 0.0015 in., 0.0015 in. over copper flashing, and 0.006 in. over 0.009 in. copper. All specimens received a final 0.00002 in. thick coating of chromium. Sets of sixteen replicate panels were distributed among four laboratories and tested in four separate runs in accordance with ASTM Method B-117 (20% salt solution). Rust spot counts were made after every 24 hr period. Total test time varied from 48 to 96 hr depending on plate thickness.

A statistical analysis of results from three of the coating systems showed that the test boxes were not consistent nor were the platers. Although data are given as both large and small rust spots, these measures were not statistically independent and the test laboratories showed a strong negative correlation between small spots and large spots. The platers, on the other hand, show a strong positive correlation between size of spots. In all three cases, the residual variation, i.e., the factor which statistically is over and

above variations attributed to plater and tester, was quite large, and would require sample sizes of about 10 sq ft in order to determine specification requirements of not more than six rust spots per sq ft of area. It was concluded that the salt spray test procedure as currently practiced fails to perform as a standard test.

170

Metals and Controls Inc. EVALUATE, TEST AND MANUFACTURE AN IMPROVED WIRE ROPE AND CABLE. Quarterly Progress Rept. No. 6, AD-807 266: Contract No. N0bs-92232. 23 p., September 2, 1966.

The data resulting from post-exposure testing after six-months in seawater are presented showing general and specific corrosion of the various materials tested. Post-exposure and pre-exposure tensile test data are presented for comparison and the only material that exhibited a significant strength loss was solid stainless steel in the 5,000 pound and 10,000 pound mooring tests.

171

Milligan, S. SAMPLE TEST EXPOSURES TO EXAMINE CORROSION AND FOULING EFFECTS ON MATERIALS IN THE DEEP OCEAN. Naval Underwater Ordnance Station. Report No. TM-359, AD-477 273: 44 p., January 1966.

172

Moeller, Richard. SEA WATER CORROSION OF ENGINEERING MATERIALS. Undersea Technology, 4: p. 20-23, April 1963.

173

Munitz, A. J. ANALYZING FAILURES OF OCEAN COMMUNICATIONS CABLE. Undersea Technology, 7: No. 5: 45, 47-49, May 1966.

174

Muraoka, J. S. THE EFFECTS OF MARINE ORGANISMS ON ENGINEERING MATERIALS FOR DEEP-OCEAN USE. Naval Civil Engineering Lab., Report No. R-182, AD-287 952: March 1962.

A literature survey was made of the effects of Marine organisms on various types of engineering materials particularly in deep-ocean environments. Numerous materials such as manila ropes, cotton fishing nets, petroleum hydrocarbons, rubber products, steel, submarine cables (telegraph and telephone), concrete, and cork (floats) have been attacked and destroyed by various marine organisms in various depths, from shallow protected waters to ocean depths exceeding 7,200 feet. Marine organisms which have been observed to be responsible for the destruc-

tion of these materials include species of wood- and rock-burrowing animals, purple sea urchins, sharks, fish and microorganisms.

A proposed field and laboratory study to accumulate further biological and engineering data about the relative behaviors of various materials to marine biological deterioration is presented.

175

Muraoka, J. S. DEEP-OCEAN BIODETERIORATION OF MATERIALS. PART I. FOUR MONTHS AT 5,640 FEET. Naval Civil Engineering Lab. Report No. NCEL-TR-329, AD-608 939. 39 p., November 1964.

This is part I of a series of reports on the biodegradation of materials in the deep ocean. It covers the data obtained by sampling mud, sea water, and rocks, and data obtained by exposing 1,324 specimens of 492 materials for 4 months on the Pacific Ocean floor at a depth of 5,640 feet. The materials were attached to a submersible test unit (STU). The STU was retrieved in February 1964, and returned to the Laboratory for tests and analyses. There were no marine fouling organisms attached to the metal test specimens. Some of the plastic materials were covered with a bacterial slime growth. Cotton rope, manilla hemp rope, and burlap wrappings were deteriorated by microbial activity. Pine test panels and manilla hemp rope were attacked by marine boring organisms (*Xylophaga Washingtona Bartsch*). Various species of fouling organisms were found on rock samples collected from the ocean floor in the vicinity of the STU test site. Also presented are equipment and methods for obtaining samples and data on oceanographic cruises as well as those used with the STU.

176

Muraoka, J. S. DEEP-OCEAN BIODETERIORATION OF MATERIALS, PART II. SIX MONTHS AT 2,340 FEET. Naval Civil Engineering Lab. Report No. NCEL-TR-393, AD-619 014: 48 p., August 1965.

This is part II. of a series of reports on the biological deterioration of materials in the deep ocean. It covers the data obtained after exposing 2,385 specimens of 603 different materials for 6 months (197 days) on the Pacific Ocean floor at a depth of 2,340 feet (Test site II.). The materials were attached to a submersible test unit (STU). The STU was retrieved in December 1964 and returned to the Laboratory for test and analysis. There were marine fouling organisms attached to the plastic ropes, aluminum buoys, polyethylene-jacketed wire rope,

nickel-plated shackles, and on some metal test specimens. Most of the plastic and all of the rope materials were covered with bacterial slime growth. Wood panels, plastics, and manilla rope were attacked by marine borers. Cotton and manilla rope specimens and jute-fiber burlap wrappings were severely deteriorated by bacterial action. Metal, glass, natural and butyl rubber, and some plastics with a smooth and extra hard surface were not affected. The biological effects on materials recovered from test site II are briefly compared with materials recovered from test site I.

177

Muraoka, J. S. DEEP-OCEAN BIODETERIORATION OF MATERIALS. PART III. THREE YEARS AT 5,300 FEET. Naval Civil Engineering Lab. Report No. NCEL-TR-428, AD-631 078: 53 p., February 1966.

The report covers data obtained after exposing 1,318 test specimens of 316 different materials for 35 months on the Pacific Ocean floor at a depth of 5,300 feet. The materials were attached to a submersible test unit (STU). The STU was retrieved in February 1965 and returned to the Laboratory for tests and analyses. Hydroid growths were found on all the test specimens placed on the STU. A few species of tube worms were found attached to metals, plastics, and coated test specimens. Most of the plastics and all the rope materials were covered with bacterial slime growth. Cotton and manilla rope specimens were severely deteriorated by bacterial action. Wood panels, plastics, and manilla ropes were attacked by marine borers, metals, natural and butyl rubber, and certain plastic materials were not affected.

178

Muraoka, J. S. DEEP-OCEAN BIODETERIORATION OF MATERIALS, PART IV. ONE YEAR AT 6,800 FEET. Naval Civil Engineering Lab. Report No. R-456, AD-636 412: June 1966.

As Part IV of a series of reports on the biological deterioration of materials in the deep ocean, this report covers the data obtained after exposing metallic and nonmetallic specimens for 13 months on the floor of the Pacific Ocean at a depth of 6,800 feet (test site I). The specimens were attached to a submersible test unit that was retrieved in February 1965. Preliminary examination of the specimens was made aboard ship, and the final examination, tests, and analyses were performed at the Naval Civil Engineering Laboratory.

On recovery, most of the plastic materials



and all of the rope specimens were covered with bacterial slime. Cotton and manila rope specimens were severely deteriorated by marine microorganisms. Wooden test panels, plastics, and manila ropes were attacked by molluscan borers. Glass, metals, natural and butyl rubber, and certain plastic materials were not adversely affected.

The results of breaking-strength tests on ropes, weight loss measurements of wood panels, moisture absorption tests on plastics, and insulation resistance and voltage breakdown tests on electrical insulating materials are presented.

179

Muraoka, J. S. DEEP-OCEAN BIODETERIORATION OF MATERIALS, PART V. TWO YEARS AT 5,640 FEET. Naval Civil Engineering Lab. Report No. R-495, AD-642 838: November 1966.

As part V of a series of reports on the biological deterioration of materials in the deep ocean, this report covers the data obtained after exposing metallic and nonmetallic specimens for 24 months on the floor of the Pacific Ocean at a depth of 5,640 feet. The test specimens were attached to a submersible test unit that was placed on the sea floor on 2 October 1963 and was recovered on 22 October 1965. Preliminary visual examination of the recovered test specimens was made aboard ship, and the final examination, tests, and analyses of these materials were performed at the Naval Civil Engineering Laboratory.

Most plastic specimens and all rope specimens were covered with bacterial slime. The cotton and manila ropes were severely deteriorated by marine microorganisms. Wood panels and manila ropes were riddled by marine borers. The surface of all the plastic materials in direct contact with wood were deteriorated by these borers. Glass, rubber, and certain plastic materials were not adversely affected.

The results of breaking-strength tests on ropes, hardness and moisture absorption tests on plastics, and insulation resistance and voltage breakdown tests on electrical insulating materials are presented in this report.

180

Muraoka, J. S. DEEP-OCEAN BIODETERIORATION OF MATERIALS. PART VI. ONE YEAR AT 2,370 FEET. Naval Civil Engineering Lab. Report No. NCEL-TR-525, AD-651 124: 65 p., May 1967.

As Part VI of a series of reports on the

biological deterioration of materials in the deep ocean, this report covers the data obtained after exposing metallic and nonmetallic specimens for 13.4 months on the floor of the Pacific Ocean at a depth of 2,370 feet. (test site II). The specimens were attached to a submersible test unit that was emplaced in April 1965 and retrieved in May 1966. Preliminary examination of the specimens was made aboard ship, and the final examination, tests, and analyses were performed at the Naval Civil Engineering Laboratory. On recovery, most of the plastic materials and all of the rope specimens were covered with bacterial slime. Cotton and manila ropes were severely deteriorated by marine microorganisms. Wood panels, certain plastics, and manila ropes were attacked by Molluscan borers. Some of the plastics were attacked by borers directly from seawater environment without the aid of wood bait pieces. Hydroids and tubeworms were found on metal panels. Sea anemone, snails, and crabs were also found attached to various test panels. The surface of a silicone rubber electrical cable insulation was deteriorated by some marine organisms. Typical fouling organisms such as barnacles and bryozoa were not found. Glass, elastomers, and certain plastics were not adversely affected. Data from evaluation of these specimens are presented.

181

Muraoka, J. S. EFFECT OF DEEP OCEAN ORGANISMS ON CONSTRUCTIONAL MATERIALS. In: Proceedings, First Joint Aerospace and Marine Corrosion Technology Seminar, held in Los Angeles, Calif., July 10-12, 1968. p. 115-116, 1968.

182

Muraoka, J. S. DEEP-OCEAN BIODETERIORATION OF MATERIALS - SIX MONTHS AT 6,000 FEET. Naval Civil Engineering Lab. Report No. NCEL-TN-1081, AD-869 397: 45 p., April 1970.

The note reports the data obtained after exposing metallic and nonmetallic specimens for 6.3 months on the floor of the Pacific Ocean at a depth of 6,000 feet (Test site I). The test specimens were attached to a submersible test unit (STU) that was emplaced August 7, 1968 and retrieved on February 12, 1969. Preliminary examination of the specimens was made aboard ship, and the final examination, tests, and analyses were performed at the Naval Civil Engineering Laboratory. Typical fouling organisms such as barnacles, bryozoa, and mussels were not found on test panels exposed at 6,000 feet, but the surfaces of plastics, metals and ropes were coated with a thin film of microbial slime. Untreated wood and ropes made of natural fibers (cotton

and manila) were severely damaged by microorganisms and molluscan borers. Plastic panels which were in direct contact with wood were also affected by the wood borers. Strangely, extensive borer damage to wood panels was restricted to a narrow area extending from the mud-line to a distance of one or two feet above it. Certain chemically treated wood, certain plastics, rubber, and glass were resistant to biodeterioration. Ropes made of polyethylene and polypropylene increased in tensile strength after exposure at 6,000 feet. A limited study on the corrosion of carbon steel and aluminum alloy helped to confirm a long held suspicion that microorganisms might play a role in the corrosion of metals in the ocean.

183

Muraoka, J. S. RELATIONSHIP BETWEEN MARINE FOULING AND CORROSION RATE OF CARBON STEEL AND ALUMINUM ALLOY AT THE SURFACE AND AT 6,000-FOOT DEPTH. Naval Civil Engineering Lab. Report No. NCEL-TR-681, AD-708 012: 57 p., May 1970.

Carbon steel (1010) and aluminum alloy (7178-T6) panels were exposed at the surface (23 to 286 days) and at 6,000-foot depth (189 days) in the Pacific Ocean; (1) to determine the effects of fouling organisms on the corrosion rate and (2) to compare the biological corrosion rate of identical test panels submerged at the two depths. Seawater samples obtained at the surface and at depth were analyzed for dissolved oxygen concentration, PH, salinity and temperature. Bacteriological tests were also conducted on seawater samples. The test panels were submerged in the sea as follows to obtain data on corrosion rates: (1) enclosed inside an initially sterile plastic cylindrical chamber with both ends sealed with membrane filters (control panels), (2) placed inside a cylinder covered with 210-mesh nylon screen cloth, (3) placed inside a cylinder with both ends uncovered, and (4) attached to a phenolic plastic strip (exposed panels). The control specimens became contaminated; however, from corrosion data obtained on test panels exposed on the seafloor in 6,000 feet of water. It is concluded that slime films played a significant role in accelerating corrosion of test specimens. Test panels exposed at the surface corroded at faster rates than replicate test panels which were exposed on the seafloor in 6,000 feet of water. The corrosion rates of both steel and aluminum alloy panels approach constancy after extended exposure in the sea. The various environmental factors and their effects on the corrosion rates

at the surface of the sea and at great depth on the seafloor are discussed.

184

National Bureau of Standards Notes. LONG-TIME EXPOSURE TESTS OF METALS. Journal of the Franklin Institute, 238: No. 3: 212-213, September 1944.

185

NAVAL Applied Science Laboratory, BIBLIOGRAPHY ON MICROBIOLOGICAL CORROSION (DEEP SEA). Report No. TM-1, AD-640 402: 25 p., June, 1965.

The bibliography covers the significant literature on marine microorganisms known to be effective in promoting corrosion and deterioration of materials, with particular reference to microorganisms found in the ocean depths. Brief comments are included for each reference cited except for those significant articles which were not readily obtainable. Papers concerning the effects on high hydrostatic pressures and low ambient temperatures of the ocean depths on the enzymatic mechanisms of certain microbial species are listed for reference in future work along these lines in conjunction with deterioration and corrosion.

186

Naval Civil Engineering Laboratory. EXAMPLES OF CORROSION OF MATERIALS EXPOSED ON STU II-1 IN THE DEEP OCEAN (2340 FEET OF DEPTH FOR 197 DAYS.). Technical Note No. N-695, February 26, 1965.

187

Navy Marine Engineering Laboratory. SEA WATER EXPOSURE TEST OF PURE ALUMINUM COATED STEEL PANELS. Report No. 0400198, AD- 80 430L: July 1955.

188

Niederberger, R. B. CORROSION TESTS OF TYPES 201 AND 202 CR-NI-MN STAINLESS STEELS IN SEA WATER AND MARINE ATMOSPHERE. Naval Engineering Experiment Station. Report No. 91015A, AD-217 455: 13 p., November 1958.

The marine corrosion behavior of Types 201 and 202 chromium-nickel-manganese stainless steels in most respects was similar to that of the corresponding chromium-nickel steels (Types 301 and 302). The chromium-nickel-manganese steels developed light rust and dark brown stains during a 13-mo exposure in a marine atmosphere. No pitting was evident. During sea water immersion, however, the steels sustained severe pitting and worm-holing. For both 201 and 202 alloys, panels in half-hard condition suffered greater weight losses than those in the annealed condition. In addition, unlike

the chromium-nickel steels, they developed stress corrosion cracks along sheared edges and at drilled holes where residual stresses were present. Sensitization at 1200 F for 24 hr lowered resistance to stress corrosion cracking.

189

Niederberger, R. B., Basil, J. L. Bedford, G. T. CORROSION AND STRESS CORROSION OF 5000-SERIES AL ALLOYS IN MARINE ENVIRONMENTS. Corrosion, 22: No. 3: p. 68-73, March 1966.

190

Niederberger, R. B., Ferrara, R. J., Plummer, F. A. CORROSION OF NICKEL ALLOYS IN QUIET AND LOW VELOCITY SEA WATER. Materials Protection and Performance, Vol. 9: No. 8: 1970.

Twenty-two commercially available nickel alloys were subjected to a 2-year investigation. Objectives were to evaluate the relative corrosion behavior of a wide sampling of nickel alloys, and to determine relationships between corrosion resistance and the type and quantity of alloying elements. Data from the investigation were used to arrange the alloys in an order of merit.

191

Nikitina, N. S., Ulanovskii, T. B. SOME DATA ON THE MICROBIOLOGICAL FACTORS OF THE CORROSION OF STEEL IN SEA WATER. Akademiia Nauk SSSR. Murmanskaiia Biologicheskaiia Stantsiia, Dal'niye Zelentsy, Trudy No. 3: 190-200, 1957.

In Russian

Steel samples were immersed in the North Sea for 5, 10, 20 and 150 days during the period of slowest bacterial development from September to January. Bacterial count was 150,000 after 5 days and 310 million per sq cm after 150 days. At 150 days, there were 6,250 aerobic, 250 denitrifying, and 250 x 10<sup>6</sup> anaerobic sulfur bacteria per sq cm. Nitrifying bacteria were not observed. The intensive development of anaerobic bacteria was attributed to the absorption of a relatively immobile layer of water on the steel surface and the exhaustion of oxygen from this layer by the corrosive process.

The effect of aerobic putrefactive bacteria on the corrosion of steel was studied with steel samples exposed to two cultures, one isolated from the corrosion product, the other from sea water. Corrosion rates of samples submerged for 6 mo in sterile sea water were 0.0294, 0.0379, and 0.0366 g per sq m per hr for a bacteria-free control. Samples exposed to the two cultures showed a 20 to 25% in-

crease in corrosion rate. This increase was attributed to increased acidity of the liquid medium and changed electric potential of the metal due to metabolic activity of aerobic bacteria.

192

Nowlan, N. V. INFLUENCE OF WATER MOVEMENT ON CORROSION - NONFERROUS METALS. Corrosion Technology, London. 7: 397-399, December 1960.

193

Oppenheimer, C. H. THE MICROBIAL CORROSION OF IRON. Miami Univ., Inst. of Marine Science. Final Report, Nov. '58 - Dec. '64, AD-653 368: Contract No. Nonr-840(21). 18 p., March 1967.

The investigation showed the potential and magnitude for microbial corrosive effects on iron in marine environments. Aerobic and anaerobic corrosion cells can be developed by a wide variety of microorganisms. Aerobic corrosion is developed through metabolic oxygen consumption by bacteria on localized iron surfaces where organic food is present. Alternating bands of aerobic-anaerobic zones are formed in sediments by layering effects of deposition involving different amounts of organic materials. The layering does produce oxygen differential cells that are very corrosive. Anaerobic corrosion cells are produced by depolarization of the iron due to proton or hydrogen uptake. The activity is proportional to hydrogenase activity or to the presence of hydrogen acceptors in the area. Suitable tests involving weight loss of iron test coupons can be employed to show the corrosive nature of microorganisms in the environment.

194

Orman, M. CORROSION OF ALUMINIUM ALLOYS IN SEA ATMOSPHERES. Prace Inst. Hutniczych, 13: 225-227, 1961.

In Polish with English summary

Two aluminum-manganese and seven aluminum-magnesium alloys were exposed 2 m below the sea surface and on a pier of a Baltic harbor for 8 yr. Samples were 2 mm thick sheet, either cold-rolled or annealed. The manganese alloys (samples A and B) contained 1.35 and 1.22% manganese and were stabilized with 0.13 and 0.30%, respectively, of titanium. Five of the magnesium alloys contained about 3% magnesium, and either chromium, chromium + manganese, or chromium + vanadium as stabilizers (samples C, D, E, F, and K). The remaining two alloys contained 5% magnesium with manganese + chromium as

stabilizers (samples G and H). The extent of corrosion was evaluated from loss of tensile strength and elongation, expressed as percentage loss per year.

The results of 8-yr tests are tabulated. Based on tensile strength losses, all alloys, with the exception of alloy K (5% magnesium, 0.07% manganese, and 0.25% chromium), have good resistance to sea water. Aluminum-manganese alloys are less resistant than aluminum-magnesium alloys. Alloy H (5% magnesium, 0.25% manganese, and 0.30% chromium) has high resistance to corrosion and is recommended for construction of sea-going vessels. Elongation decreased more rapidly than tensile strength. Alloys C and H had the lowest rate of elongation loss (not > 4%/yr); alloys A and B had the highest ( $\leq 11$  and 7%, respectively). Alloy F (3% magnesium, 0.34% chromium, and 0.34% vanadium) had the lowest rate of tensile strength loss (a maximum of 0.44%/yr for cold-rolled samples and 0% for annealed samples). The corrosion rate of alloys exposed to marine atmosphere was generally higher than in immersion tests; like the latter, elongation losses exceeded losses of tensile strength. Alloy H was highly resistant. Manganese, chromium, and vanadium additives appear effective in increasing the corrosion resistance of aluminum-magnesium alloys when their total content is at least 0.5%. Thus, alloy H, containing 0.55% of chromium + manganese, is more resistant than alloy G, containing only 0.42% of the same components. Among the magnesium alloys with 3% magnesium, alloy F, containing 0.68% of chromium + vanadium, is the most resistant. Considering the relatively high rate of mechanical strength loss of alloys A and B, aluminum-manganese alloys are unsuitable for use in a marine atmosphere.

195

Pavlov, S. E. CORROSION OF ALUMINUM ALLOYS UNDER SEA CONDITIONS. Akademia Nauk SSSR. Komissia PO Bor'be S Korrozii Metallov, Trudy, No. 1: 58-75, 1951.

In Russian

196

Pelzel, E. CORROSION BEHAVIOR OF SPECIAL CAST BRASS ALLOYS. Metal, 7: 767-771: October 1953.

In German

Aluminum brasses containing 0.31-1.54% iron, 0.31-1.26% manganese, and 0.30-1.50% nickel, silicon brasses with small additions of lead, arsenic, manganese, and nickel; and copper-zinc alloys of 50-60%

copper content with additions of nickel and tin were tested for corrosion resistance in a solution of 3% sodium chloride plus 0.1% hydrogen peroxide. In addition the aluminum brasses were also tested in 10% hydrochloric acid and artificial sea water.

In the artificial sea water tests, addition of 0.4-0.6% iron and manganese to brass containing 1.16-1.74% aluminum had the same corrosion-inhibiting effect as had 1% nickel. A combination of nickel and manganese was not noticeably better than nickel alone. Tin bronze again showed inferior resistance to unalloyed and special alloy brasses. Tinned brass, which offered no resistance to attack by hydrochloric acid, showed remarkable resistance to artificial sea water.

197

Peterson, M. H., Waldron, L. F. INVESTIGATION OF MILD STEEL CORROSION RATE IN SAN DIEGO HARBOR. Corrosion, 17: No. 4: 112, April 1961.

198

Peterson, M. H., Lennox, T. THE CORROSION BEHAVIOR OF STAINLESS STEELS IN SEA WATER. Naval Research Lab. Report No. NRL-MR-1795, AD-657 938: 33 p., June 1967.

The corrosion behavior of several series of stainless steels is discussed. Photographs of typical attack in both experimental panels and operational equipment are shown. Because of the susceptibility of stainless steel to pitting, its use in sea water should be avoided in new designs. The 300 series, however, may be used if provided with cathodic protection. The 400 series stainless steels are unsuitable for use in sea water even if provided with cathodic protection.

199

Peterson, M. H., Lennox, T. J., Groover, R. E. A STUDY OF CREVICE CORROSION IN TYPE 304 STAINLESS STEEL. In: Proceedings of National Association of Corrosion Engineers, Twenty-Fifth Conference, Held in Houston Tex., March 10-14, 1969. p. 314-317, 1970.

The study described in this paper was initiated to determine the reliability of cathodically protected Type 304 stainless steel O-ring seals in sea water. The corrosion of cathodically protected and unprotected flange type O-ring seals was studied both in quiescent sea water and in sea water with a flow rate of 1:2 foot per second. At the conclusion of the immersion phase of the experiment some preliminary measurements were made to gain insight into the solution chemistry of the corrodent in



differential aeration cells on stainless steel.

200

Peterson, V. C., Tamor, David. TESTS SHOW HOW SEA WATER AFFECTS WIRE-STRAND AND ROPE. Materials Protection, 7: No. 5: 32-34, May 1968.

Tests were conducted to determine the relative corrosion resistance of aluminized strand and wire rope, austenitic stainless steel, galvanized wire, and copper-nickel clad Type 304 stainless in sea water. The tests were conducted at Woods Hole, Mass. and in the warmer waters of Wrightsville Beach, N. C. and Boca Raton, Fla. Visual examinations were made periodically and strengths reported after exposures of up to 596 days. Specimens were exposed to the atmosphere, partial immersion, total immersion, and to mud zone environments.

201

Plummer, F. A. SEA-WATER CORROSION CHARACTERISTICS OF NICKEL-BASE ALLOYS. Naval Ship Research and Development Lab. Report No. MATLAB-297, AD-854 698L: 38 p., May 1969.

202

Porte, H. A. THE EFFECT OF ENVIRONMENT ON THE CORROSION OF METALS IN SEA WATER - A LITERATURE SURVEY. Naval Civil Engineering Lab. Report No. NCEL-TN-907, AD-820 155L: 27 p., July 1967.

203

Prochko, R. J., Myers, J. R., and Saxer, R.K. CORROSION OF BERYLLIUM BY SALT WATER. Mat. Prot., Vol. 5: No. 12: December 1966.

Chloride in aqueous environments has a deleterious corrosive effect on beryllium. Tests with pickled and anodized specimens of sheet beryllium reveal its use is limited by pitting attack and stress-corrosion failure. This paper describes experiments in five environments: distilled water, synthetic sea water, natural sea water, 3 percent NaCl solution and 3.5 percent NaCl solution.

204

Rausch, M. W. SALT WATER CORROSION TESTS OF ALUMINUM CASTING ALLOYS, TERNALLOY 5 TERNALLOY 7. Navy Marine Engineering Lab. Report No. 040037A 7, AD-102 079L: v.p., April 1956.

205

Rausch, M. W. SEA WATER CORROSION RESISTANCE AND TENSILE PROPERTIES OF ALUMINUM ALLOY 6066-T6 EXHIBITED BY HARVEY ALUMINUM CORPORATION LOS ANGELES, CALIFORNIA.

Navy Marine Engineering Lab.  
Report No. 910037A, AD-213 737L: v.p.,  
February 1958.

206

Redfield, A. C., Weiss, C. M. THE RESISTANCE OF METALLIC SILVER TO MARINE FOULING. Biol. Bull., 94: No. 1: 25-28, February 1948.

A specimen of coin silver, which contains about 10% copper, remained entirely free of fouling throughout an exposure of 1 yr in the sea at Miami Beach, Fla. Two panels of pure silver began to foul within 1 - 2 mo, and both were completely covered at the end of 4 mo of exposure. One of the pure silver specimens had been pre-soaked in sea water 2 mo prior to test; the corrosive coating thus formed resisted fouling during the early months of exposure better than a clean surface of bright silver. Coin silver is believed to be more resistant than pure silver to fouling because of its higher rate of solution when exposed in the sea.

There was no indication that the surface of silver from which solution was prevented by coupling with zinc or iron had any anti-fouling effect; pure silver specimens thus treated fouled heavily during the first month of the 12-mo test period. Silver coupled to nickel showed slight resistance to fouling only during the first 2 mo; contact with copper had scarcely any effect. The results were proportional to the differences in potential of the coupled metals.

207

Reed, S. A. CORROSION OF CARBON AND ALLOY STEELS IN WATER AND SEAWATER. Oak Ridge National Lab. Report TM-1612: Contract W-7405-eng-26: 20 p., October 1966.

Current knowledge of factors that govern corrosion and service life of steel in sea water evaporation environments is summarized. Some data from OSW research and development reports are included. It is concluded information currently available is inadequate to provide any reliable estimate of life expectancy of carbon steel in sea water evaporator environments. Additional testing is necessary at lower dissolved oxygen levels to determine more precisely role of oxygen in corrosion of steel in hot sea water and brine.

208

Reinhart, F. M. PRELIMINARY EXAMINATION OF MATERIALS EXPOSED ON STU 1-3 IN THE DEEP OCEAN, (5640 FEET OF DEPTH FOR 123 DAYS). Naval Civil Engineering Lab. Report No. NCEL-TN-605, AD-601 892: 34 p., June, 1964.

Preliminary results of corrosion of materials, based solely upon visual examinations, exposed in 5640 feet of water in the Pacific Ocean for 123 days showed only a few cases of deterioration different from those usually found in moving surface sea water. The clad layers on two aluminum alloys corroded at a much faster rate than normal for surface sea water. The lace-work and undersurface types of attack on certain stainless steels appear to be similar to types of attack by stagnant surface sea water; this could be attributed to low oxygen content as well as lack of a significant movement of deep sea water. Other materials, both metallic and non-metallic were not seriously deteriorated and some showed absolutely no evidence of deterioration.

209

Reinhart, F. M. EXAMPLES OF CORROSION OF MATERIALS EXPOSED ON STU II-1 IN THE DEEP OCEAN (2340 FEET OF DEPTH FOR 197 DAYS). Naval Civil Engineering Lab. Report No. NCEL-TN-695, AD-614 903: 52 p., February 1965.

Preliminary results of corrosion of materials, based solely upon visual examinations, exposed in 2340 feet of water in the Pacific Ocean for 197 days showed only a few cases of deterioration different from those usually found in moving surface sea water. The clad layers on two aluminum alloys corroded at a much faster rate than normal for surface sea water. The lace-work and undersurface types of attack on certain stainless steels appear to be similar to types of attack by stagnant surface sea water; this could be attributed to low oxygen content as well as lack of a significant movement of deep sea water. Other materials, both metallic and nonmetallic, were not seriously deteriorated and some showed absolutely no evidence of deterioration. In order to obtain meaningful results, considerable critical examination of the various specimens will be required.

210

Reinhart, F. M. DEEP OCEAN CORROSION. Geo-Marine Technology, 1; No. 9: 15-26, September 1965.

211

Reinhart, F. M. EFFECT OF DEEP OCEAN ENVIRONMENTS ON THE CORROSION OF SELECTED ALLOYS. Naval Civil Engineering Lab. Report No. NCEL-TN-781, AD-626 586: 32 p., October 1965.

This is a partial report covering eight materials selected as representative of

the different classes of alloys exposed in the Pacific Ocean at depths ranging from 2340 to 5640 feet for periods of time ranging from 123 to 1064 days. Aluminum alloy, 5086-H34, was attacked by intergranular corrosion which was manifested by pitting and edge penetration. It was also attacked by crevice corrosion. Its corrosion rates and pit depths increased with time of exposure. Copper alloy No. 715, alloy steel AISI 4130 and the extra high strength low alloy steels corroded uniformly; their corrosion rates decreasing with increasing time of exposure regardless of depth. The nickel base alloy, Hastelloy C, was uncorroded. The austenitic stainless steel, 20-CB, also was uncorroded except for crevice corrosion after 197 days of exposure at a depth of 2340 feet. No significant effect of pressure on the corrosion behavior of these alloys is evident from the data presented.

212

Reinhart, F. M. VISUAL OBSERVATIONS OF CORROSION OF MATERIALS ON STU I-1 AFTER 1064 DAYS OF EXPOSURE AT A DEPTH OF 5300 FEET IN THE PACIFIC OCEAN. Naval Civil Engineering Lab. Report No. NCEL-TN-793, AD-643 490: 50 p., November 1965.

Visual observations of materials exposed on the bottom of the Pacific Ocean at a depth of 5300 feet for 1064 days showed that the corrosion of most of the alloys in the mud was different from the corrosion in the water 6 feet to 10 feet above the bottom. The stainless steels exhibited a honey-comb type of attack very similar to the type of attack by stagnant surface sea water. The 5000 series aluminum alloys showed deep pitting; this could be explained on the basis of the low oxygen content combined with the nearly stagnant condition of the sea water. The 70% Ni-30% Cu alloy which was partially embedded in the sediment showed pitting that undoubtedly was caused by the composition of the peculiar environment in the water-sediment interfacial zone. The plastic materials were unaffected except those portions encased in wood which were attacked by wood boring animals. Hydroids attached themselves to and grew on both metallic and non-metallic materials with no apparent deteriorative effects.

213

Reinhart, F. M. CORROSION OF MATERIALS IN HYDROSPACE. Naval Civil Engineering Lab. Report No. NCEL-TR-504, AD-644 473: 117 p., December 1966.

A total of 1,590 specimens of 107 different alloys were exposed at depths of 2,340, 5,300, and 5,640 feet at two sites in the Pacific Ocean for 197, 1,064, and 123 days to determine the effects of deep ocean environments on the corrosion of materials. The corrosion rates, pit depths, types of corrosion, changes in mechanical properties, and analyses of corrosion products of the alloys are presented. Titanium alloys and two nickel base alloys (Ni-Fe-Cr-825 and Ni-Mo-Cr-'C') were immune to corrosion. The corrosion rates of copper alloys and steels decreased with a decrease in the oxygen concentration of the seawater and with increasing time of exposure at a nominal depth of 5,500 feet. The corrosion rates of most of the aluminum alloys increased with increasing time of exposure and with decreasing oxygen concentration of seawater. Muntz metal, and nickel-manganese bronze were attacked by dezincification and aluminum bronze by dealuminification. All the stainless steels except types 316 and 316L, 20-Cb and 17 Cr - 7 Ni - 0.7 Ti - 0.2 Al were attacked by pitting corrosion. Only two precipitation hardened stainless steels were susceptible to stress corrosion cracking. The oceanographic parameters varied with depth. Changes in temperature and oxygen concentration exerted the most influence on the corrosion of the alloys.

214

Reinhart, F. M. CORROSION OF MATERIALS IN HYDROSPACE. In: Proceedings 4th. U.S. Navy Symposium on Military Oceanography. (Held at the Naval Research Laboratory, Wash. D.C. May 1967.) 1: p. 265-288, 1967.

Presents results of the evaluation of the irons, steels, low alloy steels, alloy cast irons, metallic coated steel, uncoated and metallic coated steel wire ropes and anchor chains for six exposure periods and two nominal depths: NCEL's STU program to establish the best materials to be used in deep ocean construction considers simple corrosion as well as stress corrosion. The corrosion rates of all the alloys decreased asymptotically with time, and became constant at rates varying between 0.5 and 1.0 MPY after three years of exposure at 5500 feet. These rates are about 1/3 those of wrought steels at the surface, and at 2350 feet were lower than those at 5500 feet and decreased with time. Additional detailed results are delineated.

215

Reinhart, F. M. CORROSION OF MATERIALS IN HYDROSPACE - PART I. IRONS, STEELS, CAST

IRONS, AND STEEL PRODUCTS. Naval Civil Engineering Lab. Technical Note No. TN-900: 75 p., July 1967.

A total of 1300 specimens of 47 iron base alloys were exposed at depths of 2,340, 2,370, 5,300, 5,640 and 6,780 feet at two sites in the Pacific Ocean for 197, 402, 1064, 123, 751 and 403 days respectively to determine the effects of deep ocean environments on their corrosion behavior. Corrosion rates, pit depths, types of corrosion, changes in mechanical properties, effects of stress, and analyses of corrosion products are presented. The Corrosion rates of all the alloys, both cast and wrought, decreased asymptotically with duration of exposure and became constant at rates varying between 0.5 and 1.0 mils per year after three years of exposure in sea water and partially embedded in the bottom sediments at a nominal depth of 5,500 feet. These corrosion rates are about one-third those at the surface in the Atlantic Ocean. At the 2,350 foot depth, the corrosion rates in sea water also decreased with duration of exposure but tended to increase slightly with duration of exposure in the bottom sediments. The corrosion rates at the 2,350 foot depth were less than those at the 5,500 foot depth. The mechanical properties were unimpaired. Silicon and silicon-molybdenum cast irons were uncorroded. A sprayed 6 mil thick coating of aluminum protected steel for a minimum of three years and a hot dipped 4 mil thick coating of aluminum protected steel for a minimum of 13 months while a hot dipped 1.7 mil thick coating of zinc protected steel for about 4 months.

216

Reinhart, F. M. CORROSION OF MATERIALS IN HYDROSPACE. PART II - NICKEL AND NICKEL ALLOYS. Naval Civil Engineering Lab. Report No. NCEL-TN-915, AD-821 256: 65 p., August 1967.

A total of 635 specimens of 75 different nickel alloys were exposed at two different depths in the Pacific Ocean for periods of time varying from 123 to 1064 days to determine the effects of deep ocean environments on their corrosion resistance. Corrosion rates, types of corrosion, pit depths, effects of welding, stress corrosion cracking resistance, changes in mechanical properties and analyses of corrosion products of the alloys are presented. Of those alloys tested, the following were practically immune to corrosion: nickel-chromium-iron alloy 718; nickel-iron-chromium alloys, except 902; nickel-chromium-molybdenum alloys; nickel-cobalt-chromium alloy; nickel-chromium-



iron-molybdenum alloys; nickel-chromium-cobalt alloy; and nickel-molybdenum-chromium alloy. Alloys attacked by uniform or general corrosion were the cast nickel-copper alloys; nickel-molybdenum-iron alloy and nickel-molybdenum alloy. Alloys attacked by crevice or pitting corrosion were the nickels; wrought nickel-copper alloys; nickel-chromium-iron alloys except 718; nickel-iron-chromium alloys 902; nickel-tin-zinc alloy; nickel-beryllium alloy; nickel-chromium alloys; and nickel-silicon alloy.

217

Reinhart, F. M. CORROSION OF MATERIALS IN HYDROSPACE. PART III - TITANIUM AND TITANIUM ALLOYS. Naval Civil Engineering Lab. Technical Note N-921, AD-821 257L: 31 p., September 1967.

A total of 475 specimens of 10 titanium alloys were exposed at two different depths in the Pacific Ocean for six different periods of time varying from 123 to 1064 days to determine the effects of deep ocean environments on their corrosion resistance. Specimens of the alloys were also exposed in surface seawater for 181 days for comparison purposes. Corrosion rates, types of corrosion, pit depths, effects of welding, stress corrosion cracking resistance and changes in mechanical properties are presented. The alloys were immune to corrosion and stress corrosion cracking except alloy 13V-11Cr-3Al with unrelieved circular welds. This alloy with unrelieved circular welds failed by stress corrosion cracking after 181 days of exposure at the surface, 403 days at 6,780 feet and 402 days at 2,370 feet. The 13V-11Cr-3Al alloy with unrelieved butt welds failed by stress corrosion cracking when stressed at 75 percent of its yield strength after 35, 77 and 105 days of exposure at the surface. The mechanical properties of the alloys were not affected. Some information from TOTO in the Atlantic Ocean is included for comparative purposes.

218

Reinhart, F. M. CORROSION OF MATERIALS IN HYDROSPACE - PART IV. COPPER AND COPPER ALLOYS. Naval Civil Engineering Lab. Technical Note No. N-961, AD-835 104: 58 p., April 1968.

A total of 1050 specimens of 46 different copper alloys were exposed at two depths, 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 analyses of corrosion products of the alloys are presented. Copper, beryllium-copper, arsenical admiralty brass, aluminum brass, nickel brass, G bronze, modified G bronze, M bronze, leaded tin bronze, phosphorous bronze A, phosphorous bronze D, nickel-aluminum bronzes, Ni-Vee bronze A, Ni-Vee bronze B, Ni-Vee bronze C, copper-nickel alloys 95-5, 80-20, 70-30 containing 0.5 percent iron, 70-30 containing 5 percent iron, 55-45, nickel-silver containing 18 percent nickel, and Cu-Ni-Zn-Pb corroded uniformly and were low, 1 MPY or less after 1 year at a depth of 2,500 feet and after 2 years at a depth of 6,000 feet. The remainder of the alloys were attacked by selective corrosion; commercial bronze, red brass, yellow brass, Muntz metal, Naval brass, manganese bronze, nickel-manganese bronze, wrought 5 and 7 percent aluminum bronzes, cast 10, 11 and 13 percent aluminum bronzes, 3 percent silicon bronze and silicon bronze A. The copper alloys were not susceptible to stress corrosion cracking. Only the mechanical properties of the alloys attacked by selective corrosion were adversely affected. The corrosion products consisted of cupric chloride, copper hydroxide-chloride, metallic copper, copper oxy-chloride and nickel hydroxide.

219

Reinhart, F. M. CORROSION OF DSRV MATERIALS IN SEA WATER - 3 MONTHS EXPOSURE. Naval Civil Engineering Lab. Report No. NCEL-TN-1007, AD-682 954: 23 p., January 1969.

A sea water exposure program was initiated to determine the effects of galvanic and crevice corrosion on selected combinations of alloys; and the efficacy of sealing compounds, paint coatings and galvanic anodes for preventing corrosion, crevice corrosion and galvanic corrosion.

220

Reinhart, F. M. CORROSION OF MATERIALS IN HYDROSPACE - PART V. ALUMINUM ALLOYS. Naval Civil Engineering Lab. Technical note No. N-1008, AD-683 334: 87 p., January 1969.

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 the 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.

221

Reinhart, F. M. CORROSION OF MATERIALS IN SURFACE SEA WATER AFTER 6 MONTHS OF EXPOSURE. Naval Civil Engineering Lab. Technical Note No. N-1023, AD-684 081: 39 p., March 1969.

A total of 880 specimens of 215 different alloys were completely immersed in surface sea water for six months to obtain data for comparison with deep ocean corrosion data. Corrosion rates, types of corrosion, pit depths, and changes in mechanical properties were determined. The highly alloyed nickel alloys, titanium alloys, silicon cast irons, specialty stainless steels, columbium, tantalum and tungsten alloy were uncorroded both at the surface and at depth. The corrosion rates of the copper base alloys, nickel base alloys, steels, and cast irons decreased as the concentration of oxygen in sea water decreased. The copper base alloys, steels, cast irons, molybdenum, tungsten, leads and lead-tin solder corroded uniformly. All the aluminum alloys were attacked by pitting and crevice corrosion and sea water was more aggressive at depth than at the surface. The effect of the oxygen concentration of sea water on the corrosion of aluminum alloys was inconsistent. The stainless steels were attacked by crevice, pitting, edge and tunnel corrosion except types 310, 317 and 329, 20Cb, 20Cb-3 and AM350 on which there was only incipient crevice corrosion. Crevice corrosion was more severe in surface waters than at depth.

222

Reinhart, F. M. CORROSION OF DSRV MATERIALS IN SEA WATER - SIX MONTHS EXPOSURE. Naval Civil Engineering Lab. Report No. NCEL-TN-1037, AD-857 325: 31 p., July 1969.

In order to provide information needed about specific corrosion problems involved with the design of the DSRV, a sea water exposure program was initiated to determine: the galvanic and crevice corrosion on selected combinations of alloys and the efficacy of sealing compounds, paint systems and sacrificial anodes as protective measures.

223

Reinhart, F. M. CORROSION OF DSRV MATERIALS IN SEA WATER - 12 MONTHS NATURAL EXPOSURE AND 98 CYCLES IN PRESSURE VESSELS. Naval Civil Engineering Lab. Report No. NCEL-TN-1096, AD-871 192L: 44 p., May 1970.

In order to evaluate specific corrosion problems involved in the design of the DSRV (Deep Submergence Rescue Vessel), a corrosion test program was initiated to determine: (1) the effects of galvanic and crevice corrosion on selected combinations of metals, and (2) the efficacy of selected paint coatings, sealing compounds and galvanic anodes for mitigating corrosion, crevice corrosion and galvanic corrosion. Composite specimens representative of proposed DSRV construction materials and methods were exposed for 370 days at mean tide level in sea water and to cyclic exposure to pressurized sea water. This report presents an evaluation of these composite specimens after exposure.

224

Reinhart, F. M. CORROSION OF MATERIALS IN SURFACE SEA WATER AFTER 6 MONTHS OF EXPOSURE. Naval Civil Engineering Lab. Report NCEL-TN-1023, AD-684 081: 77 p., March 1969.

A total of 880 specimens of 215 different alloys were completely immersed in surface sea water for six months to obtain data for comparison with deep ocean corrosion data. Corrosion rates, types of corrosion, pit depths, and changes in mechanical properties were determined.

225

Rice, E. F. T. A METHOD OF CONSIDERING COSTS WHILE SELECTING MATERIALS FOR CORROSION SERVICE. Corrosion, 10: p. 252, August 1954.

A suggested corrosion-rating guide for three price classes of metals and alloys lists three permissible and one prohibitory corrosion-rate levels in order of increasing penetration (in inches per year). This arrangement of resistance merit v. cost permits the selection of materials for anticorrosive service within justified cost

limits. Absolute performance, however, must be determined by actual field tests.

Class I metals, which comprise relatively expensive materials such as silver, tin, Hastelloys, Chlorimets, Ilium, and titanium, are entirely satisfactory for corrosion losses of 0-0.003 ipy. They should be used with caution at 0.003-0.006 ipy penetrations, only under special conditions for short exposures where penetration attains 0.006-0.010 ipy, and not at all where corrosion rates exceed 0.010 ipy. Class II materials, comprising metals and alloys of intermediate cost such as stainless steels, Monels, nickel, Inconel, Durimets, Everdur, Duriron, Durichlor, Stellite, copper, magnesium, bronzes and aluminum, are suitable for use where corrosion losses are 0-0.005 ipy; they are applicable with caution between 0.005-0.012 ipy and for short exposure between 0.012-0.020 ipy, but not for corrosion losses above 0.020 ipy. Use of Class III materials, which include the few relatively cheap metals such as steel, cast iron, lead, brass, and zinc, is justified for corrosion losses up to 0.009 ipy. They can be used with caution between 0.009-0.030 ipy, and for short terms at 0.030-0.055 ipy, but not at all where penetration exceeds 0.055 ipy. In all three cost classes, the incidence of pitting invalidates these limits and justifies application only under special conditions for short exposures. For platinum, gold, tantalum, and zirconium, Class I limits should be divided by 5.

All given limits are conservative figures developed from a study of the corrosion literature and from analyses of hundreds of laboratory and plant tests over a period of 12 yr.

226

Richards, John T. THE CORROSION OF BERYLLIUM COPPER STRIP IN SEA WATER AND MARINE ATMOSPHERES. *Am. Soc. Testing Materials, Proc.* 53: p. 911-929, 1953.

The corrosion resistance of beryllium copper was found to compare favorably with that of copper under many conditions of sea water or marine atmosphere exposure and can be considered for marine applications requiring high strength and the corrosion resistance of copper.

Beryllium copper and beryllium-cobalt-copper in various tempers and conditions were exposed to sea water and marine atmospheres at Harbor Island and Kure Beach, N.C. For comparative purposes, samples (in the annealed condition) of

phosphorus deoxidized copper, arsenical admiralty, iron-modified 70-30 cupro-nickel, and phosphor bronze (Grade A) were included in many of the tests. Weight losses and decreases in strength and elongation for test periods up to 2 yr were determined.

In quiet sea water, the corrosion resistance of beryllium copper was less than that of cupro-nickel but equal to that of copper or admiralty. With increasing water velocities, the resistance offered by beryllium copper was still less than cupro-nickel but superior to copper or admiralty. In flowing sea water, partial immersion or waterline effects caused no appreciable change in corrosion rate.

High-velocity tests, such as rotating-spindle, Engineering Experiment Station (EES), and jet impingement, yielded slightly anomalous results. For example, beryllium copper was more resistant to corrosion in the rotating spindle and EES tests than in the sea water jet test. Under open-circuit and polarizing conditions, galvanic potential and corrosion were similar to the values obtained with other copper-base materials.

Beryllium copper offered better resistance to corrosion by marine atmospheres than either copper or phosphor bronze. The corrosion rate at 80 ft from the sea was substantially greater than at 800 ft. It also provided slightly better resistance to sea water or marine atmosphere than did beryllium-cobalt-copper. Although cold rolling or precipitation hardening caused a marked improvement in the strength of these alloys, material condition exerted no observable influence upon corrosion resistance. For all materials, the corrosion rate decreased with increasing exposure time but increased, often rapidly, with a rise in velocity. Test results are in fair agreement with those of other investigators. In several instances data do not agree with service experience.

227

Rigo, J. H. SEA WATER TESTS DETERMINE CORROSION RESISTANCE OF STRANDED STEEL WIRE. *Materials Protection*, 1: p. 28-33, 36-37, July 1962.

Stressed and unstressed specimens of single and stranded steel wire were exposed 13 mo in the ocean at Wrightsville Beach, N.C. Wires were fully immersed; the 15-ft stranded samples were anchored in the mud at one end and exposed to the atmosphere at the other.

Represented were Bright Mild Flow and Bright Monitor steels, with and without various coatings, and two stainless steels. Some specimens were cathodically protected at two levels by magnesium anodes.

Susceptibility to pitting renders AISI Type 316 and USS Tenelon stainless steel strands unsuitable for long-term continuous service without cathodic protection. Zinc coated steel wires corrode only superficially; cathodic protection or an extruded poly(vinyl chloride) covering extends the life of single wire or strands. Aluminized steel may outperform zinc coated items of comparable coating thickness. Cathodic protection, however, removes aluminum faster than the zinc and advantages of aluminizing remain doubtful. Single wires corrode faster and differently than stranded specimens. Stainless steel single wires show no pitting but strands and cable do.

228

Rigo, J. H. CORROSION RESISTANCE OF STRANDED STEEL WIRE IN SEA WATER. Materials Protection, 5: No. 4: 54-58, April 1966.

229

Rogers, T. H. A METHOD FOR ASSESSING THE RELATIVE CORROSION BEHAVIOUR OF DIFFERENT SEA-WATERS. J. Inst. Metals, 76: p. 597-611, February 1950.

The Copper Corrosion Index (C.C.I.) test was developed to evaluate the relative corrosiveness of sea waters toward copper-base alloys. The C.C.I. is the average amount of copper, in milligrams, corroded from three specimens of 16-gauge copper 0.25 dm sq during 22 hr in 350 ml sea water at 20 C, aerated by a constant jet of filtered air. The C.C.I. values range from 3 to 30; high values are usually associated with high corrosiveness. Comparisons between alloys should be made in the same sea water, preferably in a C.C.I. range of 12-18.

Corrosive behavior of sea water varies widely with the time of year, the locality at which the water sample is taken, and the length of time the sample is stored before use. Corrosiveness is not readily shown by ordinary chemical tests. Small amounts of contaminants produced by biological activity are important factors that are not readily analyzed and that may retard as well as accelerate corrosion. Salinity and pH are fairly constant and are not important. Corrosive activity does not correlate with polarographic measurements, electrode potentials or

polarization curves.

Sea-water corrosion of copper-base alloys is associated with the formation and breakdown of metal surface films, which can be detected by low-power microscopic examination. Sea waters having high C.C.I. values tend to form films on the alloy that may inhibit attack, cause highly localized corrosion, or blister and cause accelerated attack. In such exposure, low-power microscopic examination should supplement the C.C.I. determinations. Sea waters having a low C.C.I. give less visible evidence of film formation and cause widespread attack on alloys inclined to undergo impingement attack in service, but little or no attack on alloys known to be resistant in service. Certain copper-base alloys are more resistant than others to changes in C.C.I., and these usually behave well in service. Aluminum brass and cupro-nickel (70Cu-30Ni-0.5Fe) show little corrosion in waters having a C.C.I. below 20. Admiralty metal and cupro-nickel (70Cu-30Ni-0.04Fe) are very sensitive to change in C.C.I.

All-around resistance of an alloy can be assessed only by testing in different sea waters. The addition of iron salts to sea water decreases the C.C.I. and tends to make it more constant, although this effect may not be permanent.

230

Rogers, T. H. THE CORROSION BEHAVIOUR OF NON-FERROUS METALS IN SEA WATER. Trans. Inst. Marine Engrs. (Canadian Div. Supplement). No. 2: p. 31-37, December 1960.

Survey of the sea water corrosion resistance of aluminum alloys, brasses, bronzes, cupro-nickel alloys, Cu-Ni-Fe alloys, gun metals, Cu, Monels and Sn and Pb alloys.

231

Rogers, T. H. MARINE CORROSION HANDBOOK. New York, McGraw-Hill, 1960.

232

Rogers, T. H. MARINE CORROSION. London, George Newnes, 1968.

233

Rowlands, J. C. STAINLESS STEELS AND RELATED ALLOYS VERSUS MARINE ENVIRONMENTS. Corrosion Technol., 6: p. 359-363, December 1959.

Sheet specimens of seven martensitic, one ferritic, and nine austenitic stainless steels plus four high-nickel alloys in seven different surface conditions were



fully immersed in sea water for 3 to 20 mo. Similar panels, in the bright surface condition, were subjected up to 9 yr to half-tide immersion and marine atmospheres. In addition, crevice corrosion rigs (using a flat piece of Perspex to simulate crevices) were immersed in sea water for 30 mo, and galvanic corrosion trials were conducted with stainless steels coupled to graphite, copper, and mild steel.

All alloys tested, except in crevices, showed good intrinsic corrosion resistance to sea water. The austenitic steels, especially an 18/8 chromium-nickel steel containing 2.5% molybdenum, were the least susceptible to crevice corrosion but no alloy was immune. The slightly higher corrosion rates exhibited by rough surface finishes may have been caused by greater attraction of barnacles for such surfaces, with a resulting greater tendency toward crevice formation. Crevice gaps had to be extremely small for maximum corrosion to occur. The passive surface oxide film, upon which stainless alloys rely for their corrosion resistance, probably did not fail mechanically but was damaged by an electrochemical process, whereupon crevice corrosion proceeded because of differential aeration.

Under half-tide conditions, crevice corrosion again was the major form of damage. It was less severe, however, than under full immersion, probably because the surface oxide film had time to heal (re-anneal) while the specimens were dry. Samples exposed to atmospheric conditions showed no significant corrosion, but all surfaces were tarnished, and all steels showed a tendency to rust. In general, the most corrosion resistant were the austenitic alloys, followed by the martensitic alloys; the high-nickel alloys were slightly better than the ferritic alloy. In resistance to crevice corrosion, austenitic steels again headed the list, followed by high-nickel alloys, the martensitic steels being less resistant than the ferritic steel.

234

Rowlands, J. C. PREFERENTIAL PHASE CORROSION OF NAVAL BRASS IN SEA WATER. In: Proceedings, 2nd. International Congress on Metallic Corrosion, New York, N.Y., March 11-15, 1963. p. 795-800, 1963.

235

Rozenberg, L. A. ROLE OF SULFATE-REDUCING BACTERIA ON THE CORROSION OF LOW-ALLOY AND STAINLESS STEEL IN SEA WATER.

Akad. Nauk SSSR. Inst. Okeanol., Trudy 49: p. 258-265, 1961.

In Russian

Weighed samples of a stainless steel and a low-alloy steel unprotected and coated with a red lead anticorrosive paint were suspended in flasks containing sterile artificial sea water with sodium formate added (as a source of carbon) and in flasks containing the same medium inoculated with a pure culture of Vibrio desulfuricans. The flasks were incubated for 6 mo under anaerobic conditions at 25 to 27 C.

On the unprotected low-alloy steel, the numbers of microorganisms at 6 mo reached 1.4 to 2.3 million/cm<sup>2</sup>, and the concentration of hydrogen sulfide 80 to 160 mg/liter. On the coated low-alloy steel 0.5 to 0.6 million/cm<sup>2</sup> cells were present; the hydrogen sulfide concentration was 45 to 60 mg/liter. These lower values are attributed to the toxic effect of the paint. Low-alloy steel in both sterile and inoculated flasks began to corrode after ~ 10 days incubation. In sterile flasks, the initial rate was 0.02 to 0.03 gm/cm<sup>2</sup>/hr; after 6 mo, it was 0.008 to 0.014 gm/cm<sup>2</sup>/hr. In inoculated flasks, the rate of corrosion of unprotected samples was 60 to 80% higher, and that of coated samples slightly lower than in the sterile medium. On stainless steel, V. desulfuricans developed well, reaching about 1.5 million cells/cm<sup>2</sup>, after 6 mo. The rate of corrosion was low (0.0007 to 0.001 gm/cm<sup>2</sup>/hr in sterile sea water), but was about 60% higher in the presence of bacteria.

236

Rozenberg, L. A., Korovin, Yu. M., Ulanovskii, I. B. EFFECT OF BACTERIA ON THE CORROSION OF STAINLESS STEELS. In: Marine Fouling and Borers, p. 252-261, 1968.

In Russian - Translated by National Science Foundation.

237

Rush, P. J. PRELIMINARY STUDIES CONCERNING STRUCTURES IN THE DEEP OCEAN. Naval Civil Engineering Lab. Technical Note No. N-447, AD-278 457: 14 p., June 27, 1962.

The bottom areas of deep oceans offer an entirely new environment for the use of structural materials. Except for signal cables, no man-made structures have been subject to long-term exposure to these conditions. Information about reactions of various materials under combinations

of high pressure, constant cold temperature, and immersion in salt water is scant. Available literature on corrosion in ocean waters has mostly to do with shallow depths where the problems of pressure, temperature, oxygen concentration and chemical elements are different from those to be expected in the very deep waters.

238

Satake, Jiro, Moroishi, Taishi, Nakajima, Takashi. THE EFFECT OF ALLOYING ELEMENTS ON SEA WATER CORROSION OF STEEL. I.- LABORATORY CORROSION TESTS. Corros. Eng. (Boshoku Gijutsu)., 18; No. 8: p. 19-24, August 1969.

In Japanese.

Four types of laboratory corrosion tests involving total or intermittent immersion in artificial sea water or tap water were carried out in order to study the effect of alloying elements on sea-water corrosion of Cu-bearing steel. The alloy compositions of 32 test steels varied with respect to C, Si, Mn, P, Cu, Ni, Cr, Ti and Al contents. Regression analysis was applied to the test results. Manganese, Ni, Ti and Al were found to have no effect on the corrosion. Carbon was harmful, while Cr and P, in some cases Cu and Si, were beneficial. Martensitic structure of 2% Cr steel was preferable to ferrite-pearlite structure as far as corrosion resistance to intermittent immersion in artificial sea water was concerned. Chromium content in the matrix appears to control the corrosion rate.

239

Schenk, Max. ALUMINUM AND WATER. Metalloberfläche, 4: p. B33-B36, March, 1952.

In German

Corrosion of aluminum in natural waters occurs only in places on the metal surface where the natural oxide film has been damaged or where its growth is being prevented. Provided the contact with water is not too prolonged, a continuous, undamaged oxide film will protect aluminum against all types of natural water. Uninterrupted contact of aluminum with water or moisture leads to severe corrosion. Stagnant water is more dangerous than flowing water, and anodic oxidation gives little protection.

The aggressivity of fresh waters, including rain, snow, river water, and ground water, varies with their hard-

ness, oxygen content, and similar factors. Hard waters are less corrosive than soft waters.

Sea water is much more dangerous than fresh water. Aluminum exposed to sea water will corrode even after the metal is removed. The hygroscopic magnesium salts present in sea water prevent complete drying of the aluminum in air, so that the corrosive action continues after the metal is supposedly dry. Some aluminum alloys are more resistant to sea water than others. Anodizing can prolong the life of aluminum in sea water provided the water contains no heavy metal ions.

Among industrial waters, distilled water is the least harmful, but even this water can become dangerous for aluminum if it contains traces of metals such as copper and iron, which originate from tanks, armatures, pipes and pumps. Such water attacks aluminum even in the purest state, and anodic oxidation is ineffective. Tap water in continuous contact with copper pipes must be included in this category, even if it wets the aluminum only temporarily. Proper treatment of industrial waters is therefore mandatory.

240

Schlain, David, Kenahan, C. B. CORROSION RESISTANCE OF TITANIUM ALLOYS COMPARED WITH COMMERCIAL PURE TITANIUM. Corrosion, 14: p. 25-28, September 1958.

Titanium as well as its alloys with 8% manganese, 5% aluminum - 2-1/2% tin, 2% aluminum, 6% aluminum, 1% copper, and 5% copper are similar in chemical and galvanic properties. They are completely resistant to corrosion in synthetic ocean water, tap water, 1% sodium hydroxide, and 5% ferric chloride solutions. Contact with aluminum in synthetic ocean water or with magnesium in tap water does not affect this resistance.

241

Schreir, L. L., ed. CORROSION (2 VOL.). New York, John Wiley & Sons, 1963.

242

Schreitz, W. G. CORROSION-EROSION PROPERTIES OF 90/10 COPPER-NICKEL ALLOYS IN SEA WATER. Naval Engineering Experiment Station. Report 4B(6)17X1603: 35 p., November 1951.

Results of sea water corrosion-erosion studies indicate that 90/10 copper-nickel alloy containing 1.0-1.75% iron, 0.75% manganese, and other constituents in accordance with ASTM B 111-49 is a suitable alternate as a sea water piping material

for the 70/30 copper-nickel alloy of Navy Spec. 44 T40a.

Laboratory type specimens 3/4 by 4 by 1/16 in. were tested by rotating them in sea water at 15 and 30 ft per sec. 90/10 Alloys with iron contents from 0.01 to 1.96% were compared with 70/30 alloys with both low and high iron contents. The corrosion rates of 90/10 alloys containing 1-2% iron were less than half the rate for low iron (0.05%) 70/30 copper-nickel, and it is concluded that for optimum corrosion-erosion resistance the 90/10 alloys should contain at least 1% iron. Heat treatment to put all the iron in solid form appears to enhance the behavior of the alloy. If the iron is not completely held in solution, however, no appreciable benefit is obtained from increasing the iron content above 1 or 1.25%.

Of three 90/10 copper-nickel piping branches assembled with bronze fitting of the silver brazing type, one with 1.5% iron which was operated for 9 mo at a sea water velocity of 9 ft per sec, behaved better than a similar system made up with 70/30 copper-nickel containing 0.05% iron and approached that of a high iron 70/30 alloy. Two branches of 90/10 piping operated for 6 mo at a water velocity of 15 ft per sec were in good condition when inspected.

Silver brazing did not appreciably change the magnetic permeability of the commercial 90/10 piping nor did it affect its corrosion resistance. There was no appreciable galvanic action between the pipe and the bronze fittings.

243

Schwartzlose, R. A., Sessions, M. H. EFFECT OF CORROSION, FISHBITES AND FOULING ON DEEP OCEAN MOORING MATERIALS. Proceedings, First Joint Aerospace and Marine Corrosion Technology Seminar. Held in Los Angeles, Calif., July 10-12, 1968.

244

Shal'nev, K. K. RESISTANCE OF METALS TO CAVITATION CORROSION IN FRESH WATER AND SEA WATER. Canada Defense Research Board, Defense Scientific Information Service. Translation T-153-R, AD 63515: 6 p., November 1954.

In Russian - Translation by E.R. Hope, from Doklady Akad. Nauk 95, 229-232, March 1954.

The resistance of brass, bronze, and gray cast iron to cavitation corrosion in fresh water and sea water was determined by the vibrator method using a magnetostriction apparatus. A sample of the test metal was fastened to the tip of the vibrator tube

which was driven at 8000 cycles per sec with an amplitude of 0.09 mm. The test pieces were immersed in boiled tap water or synthetic sea water at 25 C to a depth of 6 mm; the weight loss was determined after 90 min.

The hardness of the brasses and bronzes was a considerable factor in their resistance to cavitation corrosion; the composition of the water had little effect on the degree of attack. In contrast, the weight loss of gray cast iron in sea water was nearly twice as great as the weight lost in fresh water. The individual corrosion pits also were deeper in sea water than in fresh water.

A stagewise mechanism is postulated to explain the difference in cavitation corrosion observed in the gray cast iron in sea water and fresh water. The mechanism differs from mechanical and thermodynamic theories which state that the chemical composition of the water has no significance in the development of high pressures and temperatures produced in the collapse of cavitation hollows and which are considered the chief causes of cavitation corrosion.

245

Shcherbakov, P. S., Zobachev, Yu. Ye., Shuprun, I. A. CORROSION IN FLOWING SEA WATER. Sudostroyeniye, No. 6: p. 55-59, 1962.

In Russian

The Corrosion Laboratory of the Central Scientific Research Institute of the Maritime Fleet has conducted research on the corrosion of a number of steels and Cu, Al, and Mg alloys in flowing synthetic sea water. Temperature varied from 17 to 20 C and water speed from 2 to 16 m/sec, while exposure time was 250 hr. All materials showed higher corrosion rate as water speed increased. The corrosion rates were found to be 0.3 to 2.5 mm/yr. for carbon and low-alloy steels, 0.006 to 0.014 mm/yr. for stainless steels, 0.03 to 0.1 mm/yr. for Al-bronze, 0.03 to 0.26 mm/yr. for brass, and 0.03 to 0.59 mm/yr for M3 Cu (ASTM B72-55T). The dissolution rate of Mg and Al-base alloy protectors was found to be 1.0 to 30.0 mm/hr and was greatly accelerated by the presence of impurities (Fe, Cu, Ni).

246

Shcherbakov, P. S. EFFECT OF SODIUM NITRATE ON THE RATE OF CORROSION OF LOW-CARBON STEEL AT VARYING RATES OF MOTION OF THE LATTER IN SEA WATER. Zhur. Fiz. Khim., 36: p. 1360-1363, June 1962.



In Russian

The corrosion rates in flowing sea water of low-carbon steel, four low-alloy steels and gray iron were measured in a rotating disk apparatus. The disk carrying the samples was immersed in artificial sea water at 18 to 20 C and rotated at speeds from 2 to 16 m/sec for 250 hr. The water was changed every 50 hr. The samples were tested in water without additives and in the presence of varying concentrations of sodium nitrite.

At a nitrite concentration of 4, 2, and 1%, the rate of corrosion of low-carbon steel was less than 0.1 mm/yr and was practically independent of flow rate. At 0.35 and 0.1% concentrations, the rate was considerably higher and increased with flow rate, although more slowly than in water containing no nitrite. At higher inhibitor concentrations the rate in stationary sea water was 30 to 35% higher than in flowing water. No significant differences were observed between low-carbon steel and low-alloyed steels. Gray iron showed a higher rate, but the effects of sodium nitrite were essentially similar to its effects on steels.

To study the effects of sodium nitrite on the electrode processes, anodic and cathodic polarization curves of low-carbon steel were obtained at various sodium nitrite concentrations in stationary water and in water flowing at a rate of 2, 4, 12 and 16 m/sec. At 0.25% sodium nitrite, anodic polarization was weak and the potentials were more positive at lower flow rates. At 1 and 4% nitrite, an opposite phenomenon was observed: the potentials were shifted toward more positive values with increasing flow rate. Bubbling of oxygen through the sea water during anodic polarization shifted the potentials toward more positive values at all concentrations of the inhibitor. Cathodic polarization curves showed a rapid increase of potentials with increasing current density, but the limit diffusion current was practically the same at all concentrations of sodium nitrite and in its absence.

The reduction of the corrosion rate in flowing sea water, as compared with stationary water, in the presence of 1 to 4% sodium nitrite can be explained by assuming the participation of oxygen in the formation of the protective film on the metal surface. This assumption can also explain why in sea water the minimum protective concentration of sodium nitrite is many times greater than in fresh water. In sea water, the chloride ions are adsorbed on the metal surface, displacing oxygen, and thus interfering with protective film formation. Consequently,

complete passivation of the metal surface requires relatively large concentrations of sodium nitrite, and is facilitated by the presence of oxygen. The role of oxygen becomes particularly important at higher flow rates, when the protective film is exposed to mechanical damage. Under these conditions, restoration of the continuity of the film or its 'repair' is promoted in the presence of oxygen.

247

Southwell, C. R., Alexander, A. L., Forgeson, B. W., Mundt, H. W., Thompson, L. J. CORROSION OF METALS IN TROPICAL ENVIRONMENTS, PART 1. TEST METHODS USED AND RESULTS OBTAINED FOR PURE METALS AND A STRUCTURAL STEEL. Naval Research Lab., NRL Report 4929, June 1957.

248

Southwell, C. R., Forgeson, B. W., Alexander, A. L. CORROSION OF METALS IN TROPICAL ENVIRONMENTS, PART 2. ATMOSPHERIC CORROSION OF TEN STRUCTURAL STEELS. Naval Research Lab., NRL Report 5002, December 1957.

249

Southwell, C. R., Forgeson, B. W., Alexander, A. L. CORROSION OF METALS IN TROPICAL ENVIRONMENTS, PART 3. UNDERWATER CORROSION OF TEN STRUCTURAL STEELS. Naval Research Lab., NRL Report 5113, August 1958.

Eight year immersion studies of a modern controlled process (Aston) wrought iron were made in the tropical waters of Panama. The iron was most heavily corroded when continuously immersed in sea water. Weight losses in continuous fresh water immersion and at sea water mean tide were approximately equal. Pitting penetration was lowest at mean tide. At least 4 yr exposure was required to reach a condition of linear relationship between corrosion and time. The slopes of the curves at 8 yr suggest that for longer periods of exposure greater divergences can be expected, with sea water causing increasingly heavy corrosion, mean tide an intermediate amount, and fresh water relatively less.

Accelerated pitting penetration from exposure of samples with millscale surfaces is apparent only for continuous immersion in sea water. In this medium, millscale on wrought iron seems less harmful than steel millscale.

There is practically no difference between wrought iron and mild structural steel for the first 4 yr in both continuous sea and fresh water immersion. After 8 yr the wrought iron weight loss is significantly less than that for steel. At mean tide the wrought iron shows less corrosion damage at all periods of exposure.

When coupled together, wrought iron is anodic to steel in both sea and fresh water. However, a quantitatively signifi-

cant galvanic corrosion of wrought iron occurs only in continuous sea water immersion. Protection of steel by wrought iron requires a large area of wrought iron in relation to steel; under these conditions, the corrosion of steel is reduced by approximately one half.

In tropical atmospheric environments, wrought iron was much more heavily damaged by corrosion than any of the four proprietary low alloy steels tested.

250

Southwell, C. R., Forgeson, B. W., Alexander, A. L. CORROSION OF METALS IN TROPICAL ENVIRONMENTS, PART 2 - ATMOSPHERIC CORROSION OF STRUCTURAL STEELS. Corrosion, 14: No. 9: p. 55-59, September 1958.

251

Southwell, C. R., Forgeson, B. W., Alexander, A. L. CORROSION OF METALS IN TROPICAL ENVIRONMENTS. PART 4. WROUGHT IRON. Naval Research Lab. NRL Report 5370, AD-228 448: 15 p., October 1959.

252

Southwell, C. R., Forgeson, B. W., Alexander, A. L. CORROSION OF METALS IN TROPICAL ENVIRONMENTS, PART 5. STAINLESS STEELS. Naval Research Lab., NRL Report 5517, September 1960.

253

Southwell, C. R., Forgeson, B. W., Alexander, A. L. CORROSION OF METALS IN TROPICAL ENVIRONMENTS. PART 4. WROUGHT IRON. Corrosion, 16: p. 120-126, October 1960.

The corrosion of Aston process wrought iron alone and galvanically coupled with mild structural steel was studied over an 8 yr period in five Panama Canal environments: continuous sea water immersion, mean tide immersion, continuous fresh water immersion, marine atmosphere and inland atmosphere. Comparison data on several structural steels exposed under the same conditions are given.

Continuous sea water immersion corroded wrought iron most heavily; weight losses in continuous fresh water and mean tide were approximately equal. Mean tide produced lowest pitting penetration. Slopes of curves at 8 yr exposure suggest greater divergence with increasing exposure time. Comparison of wrought iron and mild structural steel after 4 yr in continuous sea and fresh water showed practically no difference in the metals. After 8 yr, however, the wrought iron loss was significantly less than that of steel. At mean tide the wrought iron showed less corrosion damage at all periods of exposure. Even greater differences, in favor of the wrought iron, are probable for longer exposure periods.

Coupling tests showed that wrought iron is anodic to the steel in both sea and fresh waters. However, a quantitatively

significant galvanic corrosion of wrought iron occurred only for the continuous sea water immersion. Protection of steel by wrought iron requires a large area of the iron in relation to the steel, and under these conditions the corrosion of steel is reduced by approximately one half.

Millscale accelerates pitting only in continuous sea water. It was less harmful on wrought iron than on steel. After 8 yr in the marine atmosphere weight loss of wrought iron was 1.6 times greater than in the inland atmosphere. In both marine and inland atmosphere 8 yr weight losses of wrought iron were more than double that of any of four low alloy structural steels.

254

Southwell, C. R., Hummer, C. W., Alexander, A. L. CORROSION OF METALS IN TROPICAL ENVIRONMENTS. PART 6. ALUMINUM AND MAGNESIUM. Naval Research Lab., Report No. NRL-6105, AD-609 618: 20 p., December 1964.

The corrosion resistance of three alloys of aluminum and two alloys of magnesium has been studied following exposure up to 16 years in five natural tropical environments. These include sea-water immersion, freshwater immersion, and exposure to tidal sea water, a tropical marine atmosphere, and a tropical inland atmosphere. Aluminum 1100, aluminum alloy 6061-T, and magnesium alloy AZ31X were exposed to each of the environments listed. In addition, clad aluminum 2024-T and magnesium alloy AZ61X were exposed to the two tropical atmospheres. Weight loss, pitting, and change in tensile properties were measured to show the extent of corrosion for each of these materials. Aluminum alloys demonstrate extremely high resistance to each environment, with the exception of tropical fresh water, in which case serious pitting occurred. Alloy 6061-T demonstrated some superiority in all environments to aluminum 1100.

255

Southwell, C. R., Alexander, A. L., Hummer, C. W. CORROSION OF METALS IN TROPICAL ENVIRONMENTS - ALUMINUM AND MAGNESIUM. Materials Protection. 4: No. 12: 30-35, December 1965.

256

Southwell, C. R., Hummer, C. W., Alexander, A. L. CORROSION OF METALS IN TROPICAL ENVIRONMENTS. PART 7. COPPER AND COPPER ALLOYS. SIXTEEN YEARS EXPOSURE. Naval Research Lab. Report No. NRL-6452, AD-644 930: 34 p., October 1966.

The corrosion of copper and nine wrought copper alloys is reported for exposures in five tropical environments for one, two, four, eight, and sixteen years. Weight loss, pitting, and change in tensile

strength were measured to evaluate corrosion resistance. Higher corrosion rates are shown for tropical sea water immersion and tropical marine atmosphere than similar exposures in temperate climates. Of the various alloys studied, 5% Al bronze showed the highest general corrosion resistance: its 16-year losses in sea water were only 1/5 that of copper. Copper and the high-copper alloys were resistant to all environments and generally had decreasing corrosion rates with time of exposure. Tensile tests revealed heavy dezincification in the lower-copper brasses when exposed in marine environments, and for two of the brasses in fresh water immersion. As a result of the decreasing corrosion rates or dezincification, anti-fouling properties of copper alloys decreased with time of exposure. All were moderately to heavily fouled after 16 years in sea water. Galvanic effects were pronounced in tropical sea water. The corrosion of copper alloys was accelerated appreciably by contact with stainless steel (316) of 1/7 their area, while similar carbon steel strips gave effective cathodic protection of plates of brass and bronze over the long term.

257

Southwell, C. R., Alexander, A. L.  
CORROSION OF METALS IN TROPICAL ENVIRONMENTS. PART 8. NICKEL AND NICKEL-COPPER ALLOYS - SIXTEEN YEARS' EXPOSURE. Naval Research Lab., Report No. NRL 6592, AD-661 835: 24 p., October 4, 1967.

Corrosion of nickel and nickel-copper alloys in five natural tropical environments is reported for exposure periods of 1, 2, 4, 8, and 16 years. Data collected include weight loss, pitting, change in tensile strength of simple plates, and weight loss of galvanic couples. Corrosion in the tropics is compared with available exposure results from temperate latitudes in the United States, and generally the tropical corrosion was appreciably higher. The weight-loss-vs-time curves are normally curvilinear relations but considerable variation in the direction and magnitude of the curvature was observed for the different metals and environments. With respect to pitting, the high nickel alloys developed severe early pitting under sea water. However, the initial high penetration rates leveled off to very low rates after the first 1 to 2 years' exposure. Comparison under tropical sea water of monel and copper-nickel with various other nonferrous metals shows copper-nickel with comparatively high corrosion resistance, but monel with the lowest sea-water resistance of the group. Galvanic corrosion results show the long-term efficiency of carbon steel anodes in cathodically protecting nickel-copper alloys in sea water. Ad-

ditional galvanic data reveal that considerable anodic corrosion can be induced in a normally sea-resistant metal if coupled with certain nickel alloys. The nickel metals were highly resistant to corrosion in the tropical atmospheres. There was no measurable pitting in these terrestrial exposures and only small weight losses. The losses that were measured though showed increasing resistance of the metals with increasing nickel content. Since tropical corrosion is near the upper limit of corrosiveness of natural environments, these long-term results should afford safe, practical information for design and protection of structures in all latitudes.

258

Southwell, C. R., Alexander, A. L.  
CORROSION OF METALS IN TROPICAL ENVIRONMENTS - COPPER AND WROUGHT COPPER ALLOYS. Materials Protection, 7: No. 1: 41-47, January 1968.

259

Southwell, C. R., Alexander, A. L.  
CORROSION OF METALS IN THE TROPICS: STRUCTURAL FERROUS METALS. In: National Association of Corrosion Engineers Twenty-fourth annual conference, 1968. Held in Cleveland, Ohio, March 18-22, 1968.

Reported is a study including history and summary of major metals revealing paucity of reliable long-term data in natural underwater environments. This study is one in a series describing results of long-term comprehensive corrosion investigation conducted in five local natural environments in the Canal Zone. Corrosion losses occurring in sea water, brackish water, fresh water, and mean tide are measured by weight loss, depth of pitting, and change in mechanical (tensile) properties. Data are included for a representative group of cast and wrought structural metals. Data from tropical environments are compared with that available from more temperate latitudes. Comparisons are made of different structural alloys over long periods of underwater exposure.

260

Southwell, C. R., Alexander, A. L.  
CORROSION OF STRUCTURAL FERROUS METALS IN TROPICAL ENVIRONMENTS - RESULTS OF 16 YEARS' EXPOSURE TO SEA WATER AND FRESH WATER. In: Proceedings, 24th. Conference, NACE, Sea Water Section. p. 685-695, 1969.

261

Southwell, C. R., Alexander, A. L. THE CORROSION OF METALS IN AQUEOUS ENVIRONMENTS OVER EXTENDED PERIODS. In: Third Inter-Naval Corrosion Conference, London, England. 1969.

262

Southwell, C. R., Alexander, A. L.  
CORROSION OF METALS IN TROPICAL ENVIRONMENTS - NICKEL AND NICKEL-COPPER ALLOYS. Materials Protection, 8: No. 3: 39-44, March 1969.

Corrosion data are reported for nickel and nickel-copper alloys exposed for 16 years to fresh water, sea water, sea water mean tide, and marine and inland atmospheres in the Panama Canal Zone. Major emphasis is on the sea water environments. Results reported include weight loss, pitting, and change in tensile strength for simple plates and weight loss for galvanic couples. Marine corrosion in the tropics is compared with available nickel alloy results from temperate latitudes in the United States. Time vs. weight loss and time vs. pitting curves are presented. A few other nonferrous metals are included for comparison.

263

Southwell, C. R. THE CORROSION RATES OF STRUCTURAL METALS IN SEA WATER, FRESH WATER, AND TROPICAL ATMOSPHERES. Corrosion Science, Great Britain, 9: p. 179-183, March 1969.

264

Southwell, C. R., Alexander, A. L.  
CORROSION OF METALS IN TROPICAL ENVIRONMENTS. PART 9. STRUCTURAL FERROUS METALS - SIXTEEN YEARS' EXPOSURE TO SEA AND FRESH WATER. Naval Research Lab. Report No. NRL-6862, AD-687 705: 32 p., April 1969.

Effects of corrosion on 20 structural ferrous metals immersed in seawater and fresh water and exposed at mean-tide elevation have been measured at various intervals during 16 years. Corrosion rates and time-corrosion curves derived from both weight loss and pitting have been established. The final constant rates provide significant data for comparing the corrosion resistance of the different metals in the various environments and for estimating service life over more extended periods.

265

Southwell, C. R., Alexander, A. L. MARINE CORROSION OF CAST AND WROUGHT NON-FERROUS METALS RESULTS OF SIXTEEN YEARS EXPOSURE IN THE TROPICS. In: Proceedings, Twenty-fifth Conference National Association of Corrosion Engineers. Held in Houston, Tex., March 10-14, 1969. p. 288-298, 1970.

A large mass of corrosion data from the waters and atmosphere of Panama has been collected as the result of a series of

studies initiated in 1947. Tropical exposures have the advantage of producing slightly higher corrosion rates than normally accrue from temperature latitudes, and therefore usually represent upper limit rates for corrosion in uncontaminated natural environments. These results, then, will contribute substantially in filling existing gaps in practical corrosion-rate knowledge. The major portion of the effort was directed toward evaluation of corrosion in marine environments. Fifty-two metals and alloys were selected for the 16-year study. Bimetallic couples as well as single plates were included. Over 13,000 individual specimens were exposed and a total of 168,000 data measurements made. This report will present the 16-year results for all wrought and cast non-ferrous metals exposed in three marine environments. Data from fresh water immersion are included for purposes of comparison.

266

Southwell, C. R., Alexander, A. L.  
CORROSION OF METALS IN TROPICAL WATERS: STRUCTURAL FERROUS METALS. Materials Protection, 9: No. 1: 14-22, January 1970.

Corrosion data are reported for 20 structural ferrous metals exposed up to 16 years in natural tropical waters, including sea water, fresh water and mean tide elevation. Time-corrosion curves derived from both weight loss and pitting are presented for many of the ferrous alloys and tabulated data for all metal environment combinations are included. These comprehensive long term results comprise the most extensive collection of accurate sea water and fresh water corrosion data presently available. After initial periods of changing slopes, corrosion rates for most of the ferrous metals stabilize to constant values. These steady state rates are presented for each exposure and provide a significant means for comparing the corrosion resistance of the different metals in the various environments and for estimating useful life over extended periods. Corrosion curves for eight low alloy steels, Aston process wrought iron, and various cast irons and steels are evaluated against C steel. Marine corrosion in the tropics is compared with available ferrous metal results from temperate latitudes.

267

Stewart, W. C., LaQue, F. L. CORROSION RESISTING CHARACTERISTICS OF IRON MODIFIED 90:10 CUPRO NICKEL ALLOY. Corrosion, 8: p. 259-277, August 1952.



Laboratory corrosion-erosion tests and service tests have demonstrated that, in installations where high resistance to corrosion and erosion by salt water is required, 90/10 cupronickel alloys with 1.5% or higher iron contents are equivalent to or superior to 70/30 cupronickel and similar alloys, such as Admiralty brass. They are reliable and economic substitutes for high-nickel alloys in condenser tubes and seawater piping systems, and are definitely superior where freedom from marine fouling organisms is also desired.

Cold-rolled strips of 88/12 cupronickel containing 1.8% iron, corroded at a rate of 0.0002 in. per yr, i.e., only one-third as fast as did a low-iron 70/30 cupronickel, when both were exposed for nearly 3 yr in slow-flowing seawater conducive to pitting and fouling. Similar, but shorter exposure of a 90/10 cupronickel containing 0.8% iron indicated that the iron content need not be as high as 1.8% to achieve good resistance to sea water, at least not under relatively quiet conditions. This alloy corroded without significant pitting at a rate of 0.0006 in. per yr, i.e., only one-sixth as fast as did similarly exposed arsenical Admiralty brass. Irrespective of their iron contents or heat treatments, a series of 90/10 alloys immersed in relatively quiet seawater remained substantially free from marine fouling, whereas the monel racks and fastenings showed heavy fouling attachments. Under these conditions, the freedom from fouling of the iron-modified 90/10 alloys is attributable to, and in agreement with their corrosion rates. These rates are sufficiently high to release copper in corrosion products at an average rate above 5 mg per sq dm per day - a value previously established as being required for a copper-containing surface to keep itself free from marine fouling organisms.

In high-velocity jet-impingement tests, 90/10 cupronickel containing 0.7 or 2% iron showed better resistance than Admiralty brass or low-iron 70/30 cupronickel. Its resistance was about equal or better than that of aluminum brass, and about equal to that of 70/30 cupronickel with high (0.5%) iron content. 90/10 Cupronickel containing 2 and 3.5% iron and quench annealed to hold the iron in solution performed better under jet impingement than did 90/10 alloys containing 0.8 and 1.5% iron.

Essentially identical conclusions were reached from erosion-corrosion tests on cupronickel samples mounted on a rotating

disc, and on disc specimens mounted on a rotating spindle. Resistance increased with increasing iron content. The higher the speed of rotation, the higher the iron content required to confer protection against attack. Even when heat-treated to precipitate a maximum amount of iron, the 90/10 alloys were still superior to 70/30 cupronickels and to Admiralty brass. With 3.5% iron content, quench-annealing to hold the iron in solution was necessary for best erosion-corrosion resistance.

268

Stover, H. E. PREMATURE FAILURE OF COPPER-NICKEL ALLOYS IN SEA WATER. Corrosion, 17: p. 83-84, October 1961.

Monel and 90/10 copper-nickel bands used to tie plastics film around creosoted wooden pilings for protection against marine borer attack failed from extreme corrosion after 1 yr in salt water (Port of Los Angeles) despite the far greater expected service life of the alloys in this environment. Corrosion seemed to be greatest near the mudline. The black corrosion product on both metals was a mixture of sulfides and alloyed metals; both metals became somewhat magnetic. Several possible theories to explain these premature failures are advanced.

269

Summerson, T. J., Pryor, M. J., Keir, D. S., Hogan, R. J. PIT DEPTH MEASUREMENTS AS A MEANS OF EVALUATING THE CORROSION RESISTANCE OF ALUMINUM IN SEA WATER. Am. Soc. Testing Materials, Spec. Tech. Publ. No. 196: p. 157-175, November 1957.

This method is based on a statistical treatment of penetrometer measurements of every pit present on test specimens of aluminum immersed in sea water for periods up to 24 mo. The best approximation to normal frequency distribution curves is obtained by plotting the square root of the pit depth against the frequency of pitting. Calculations of the mean square root pit depth, the standard deviation, and standard error of the mean square root pit depth are shown. The importance of the mean square root pit depth, the standard deviation, and the frequency of pitting in determining the manner by which pitting corrosion proceeds is discussed.

A sampling procedure is suggested whereby quantitative data on the resistance of aluminum to pitting corrosion in sea water can be determined at arbitrarily chosen confidence limits by measuring only a fraction of the total number of pits present.

270

Sutton, Frank. EVALUATION OF TITANIUM AS A SALT WATER PIPING MATERIAL. Naval Engineering Experiment Station. Evaluation Report 910037D, AD-212 792: 8 p., September 1958.

An experimental piping system was constructed of 75A titanium tubing of 1-1/4 in. outside diameter by 1/16 in. wall thickness. Valves and fittings were of cast titanium; joints were welded in a helium atmosphere.

After handling sea water for 39 mo at an average velocity of 20 fps, the system showed no signs of erosion or corrosion. Bronze valves which were included for 11 mo of the run showed moderate body corrosion and erosion; their Monel seats and discs were roughened slightly. The run was too short to evaluate galvanic corrosion of the bronze.

Because of its high cost and difficult working, titanium piping is recommended for use only at velocities too high for copper-nickel systems.

271

Tavadze, F. N., Mandzhgaladze, S. N. CORROSION RESISTANCE OF TITANIUM ALLOYS. Naval Intelligence Command, Translation Div. AD-715,254: 6 p., November 19, 1970.

Translation from Korrozionnava Stoikost Titanovykh Splavov, Moscow, 1969, p.177-182.

Titanium has good resistance to corrosion in sea water, has high strength, and a low specific weight, so has wide-ranging future prospects for use in shipbuilding. Titanium is very widely used as a shipbuilding material.

272

Taylor, Edward. EVALUATION OF METALLIC MATERIALS EXPOSED TO THE DEEP OCEAN ENVIRONMENT AT 5640 FEET FOR 123 DAYS. Naval Air Engineering Center. Report No. NAEC-AML-2132, AD-466 955: June 1965.

Over 200 metallic specimens of 30 different compositions attached to submersible test unit 1-3 exposed to the deep ocean environment at 5640 ft. approximately 31 nautical miles west of Port Hueneme, California, for a period of days have been evaluated for deteriorative effects. Specimens were exposed in the following conditions: (A) heat treated; (B) welded; (C) painted; (D) stressed; and (E) coupled. Corrosion rates were calculated for those metals exhibiting uniform general attack such as the alloy steels, stainless steels and copper base alloys. Those metals under-

going selective corrosion such as pitting of certain aluminum alloys were evaluated for the frequency and severity of attack. Certain high strength steels and stainless steels exposed at stress levels below their yield strengths were metallographically examined for evidences of microstructural attack and/or stress corrosion cracking. No evidence of either phenomenon were found in the specimens in question. Severe macroscopic crater type pitting was disclosed in 5456-H34 aluminum alloy. An increase, over shallow depth exposures, in the severity of intergranular attack and exfoliation attack is noted in the appropriately susceptible tempers of the 2000 and 7000 series aluminum alloys, in both the welded and non-welded conditions.

273

Taylor, E. CORROSION RESISTANCE OF MULTIPHASE ALLOYS. Materials Protection, 9: No. 3: p. 29-31, March 1970.

According to the author, Multiphase Alloy MP35N is virtually immune to seawater attack, is highly resistant to corrosion in a wide range of chemical environments, is not susceptible to stress corrosion cracking by hot or cold chlorides, and is not embrittled by hydrogen. Its ultra high strength and excellent fatigue properties make it applicable in the hydrospace and aerospace industries.

274

Terai, Shiro, Baba, Yoshio. EFFECT OF SURFACE TREATMENTS ON THE CORROSION OF ALUMINUM AND ITS ALLOYS IN CONTACT WITH OTHER METALS IN ARTIFICIAL SEA WATER. Sumitomo Light Metal Tech. Rept., 3: p. 9-17, January 1962.

In Japanese with English summary

The effects of painting and of chemical conversion and electrochemical treatments on the corrosion of aluminum and its alloys in contact with other metals were studied in artificial sea water (6% NaCl + 0.3% H<sub>2</sub>O<sub>2</sub>) for periods  $\leq$  15 days.

Carbon steel, copper and silver in contact with aluminum or its alloys caused similar rapid and severe corrosion; stainless steel and titanium caused pronounced corrosion. Zinc or tin-plated steel did not greatly increase corrosion.

With 99.99% aluminum, pitting was severe and concentrated at the junctions; with 99.2% (Commercial purity) aluminum, corrosion was more distributed, with remarkably greater weight losses. With or without surface treatment, pit depth in 5052 alloy (2.29 Mg, 0.27 Cr, 0.28 Fe)

was less than in 99.2% aluminum or 3003 alloy (1.16 Mn, 0.45 Fe). There was no detectable weight loss of 2117 (2.65% Cu, 0.32% Fe) in contact with other metals.

Contact corrosion of aluminum and its alloys protected by Boehmite, ammonia, MBV or Alodine treatment was about half that after chemical polishing or non-treatment. With sulfuric or oxalic acid anodizing, contact corrosion was less than after chemical conversion treatments, but some pits about 0.2 mm deep occurred at the junctions with other metals. Zinc chromate primer or vinyl coating gave the best protection to aluminum in contact with other metals.

275

Thompson, J. C., Logan, R. K., Nehrich, R. B.  
A SURVEY OF MATERIALS RESEARCH IN OCEAN ENVIRONMENTS. Navy Electronics Lab.  
NEL Report 1110: 44 p., July 31, 1962.

276

Thompson, J.C. Logan, R. K. EFFECTS OF DEEP- AND SHALLOW-OCEAN ENVIRONMENTS ON CONSTRUCTION MATERIALS. Naval Electronics Lab. Center. Report No. NELC-1593,  
AD-848 079: 20 p., November 1968.

277

Tomashov, N. D. CORROSION AND PROTECTION OF METALS IN SEA WATER. Akademiia Nauk SSSR, Institut Fizicheskoi Khimii, Trudy, No. 8, Issledovaniia PO Korrozii Metallov, No. 6: p. 313-332, 1960.

278

Tomashov, N. D. THEORY OF CORROSION AND PROTECTION OF METALS. p. 454-481,  
New York, The MacMillan Company, 1966.

Trans. and Edited by B. H. Tytell, I. Geld,  
and H. S. Preiser.

279

Tracy, A. W., Hungerford, R. L. THE EFFECT OF THE IRON CONTENT OF CUPRO-NICKEL ON ITS CORROSION RESISTANCE IN "SEA WATER".  
Proc. Am. Soc. Testing Materials. 45:  
p. 591-617, 1945.

The beneficial effect of iron additions on the corrosion resistance of cupro-nickel alloys exposed to a 3% solution of sea salt in motion was investigated. Sheet metal specimens were attached to fiber disks rotated in the test solution; tube specimens were placed in an experimental condenser.

For sheet metal specimens, the extent of corrosion was determined by measuring losses in thickness with sharp-pointed micrometers. Corrosion of the tube specimens was judged by visual examinations.

The greatest improvement in resistance was imparted to cupro-nickels which had between 10 and 20% nickel. The addition of iron improved the alloy with 5% nickel to a fair degree and the alloy with 2% nickel somewhat. Approximately 1% iron had no effect in increasing the resistance of copper to "sea water" impingement corrosion. As the nickel content of cupro-nickels decreased from 30 to 5%, more iron was required for optimum corrosion resistance. For example 0.5% iron was required for the 30% cupro-nickel, 0.6% for the 20%, 0.75% for the 10% and 1% for the 5% alloy.

There was no indication in these tests that a critical relationship between the iron and manganese content of cupro-nickels affected corrosion resistance.

The data tend to confirm statements in the literature that 30% cupro-nickel builds a more protective film in sea water that is thoroughly aerated than in sea water deficient in air. This may be the basis of the better service understood to be obtained from 30% cupro-nickel in ships, where the velocity and turbulence of the sea water is greater than in central power stations, where the oxygen content may be low due to pollution of harbor waters.

280

Tuthill, A. H., Schillmoller, C. M.  
GUIDELINES FOR SELECTION OF MARINE MATERIALS. Paper presented at the Ocean Science and Ocean Engineering Conference, Washington, D. C., Marine Technology Society, June 1965.

281

Tuthill, A. H. MARINE CORROSION.  
Mach Design, 40: No. 30: 117-122,  
December 19, 1968.

Design and material selection for combating galvanic and crevice corrosion and stress-corrosion cracking in structures exposed to sea water are discussed. Reviews the effects of water turbulence and depth, and water or equipment velocity on corrosion and failure. Data are presented for a variety of ferrous and nonferrous materials on corrosion potentials in flowing (8-13 fps) sea water at 50 to 80 F., galvanic relationships for fastener, pump and valve materials and the fouling resistance of materials in sea water.

282

Tuthill, A. H., Schillmoller, C. M.  
GUIDELINES FOR SELECTION OF MARINE MATERIALS. Nav. Eng. J., 81: No. 2:  
66-89, April 1969.



Users and designers of marine equipment have available a large backlog of published data and experience for the selection of economical materials that will give reliable and durable service. Charts and summaries of these data are presented that permit the designer to screen his initial materials selection in terms of general wasting away, pitting, crevice effects, fouling, velocity effects and cavitation, galvanic effects, selective attack, stress corrosion cracking, deep immersion, and cost. These principles are applied in the selection of materials for sea water heat exchange systems, propellers, stern tube bearings, marine hardware, fasteners, marine wire rope, buoys, and floating platforms. Materials considered are Ni-Cr-Mo alloys, Ti, 304, 316, and 400 steels, Ni-Cr alloys, Ni-Cu alloys, Ni, 70/30 Cu-Ni, 90/10 Cu-Ni, Cu, admiralty, Al brass, bronzes, Zn, Al, C steel, cast iron, austenitic Ni cast iron, etc.

283

Uhlig, H. H. BEHAVIOR OF NICKEL-COPPER ALLOYS IN SEA WATER. Record Chem. Progress. 7: p. 56-57, 1946.

Nickel-copper alloys below 40% nickel are apparently in the active state and release sufficient copper ions in sea water to discourage fouling. Above 40% nickel, the alloys are passive; in this state corrosion of the general surface (not the pits) is insufficient to release a toxic minimum of copper. The appearance of corrosion pits is due to the action of passive-active cells. At this percentage composition it seems that the alloys should transform from the active to the passive state or the reverse.

Nickel is characteristically subject to biological fouling in sea water and corrodes in localized areas called pits. This form of corrosion depends on the electrolytic action of so-called passive-active cells and occurs in many passive metals, including chromium and the stainless steels. Passivity is that state in which a metal, normally active according to the EMF series, exhibits the electrochemical behavior of a more noble metal.

Copper, unlike nickel, does not foul in sea water and corrodes uniformly. The corrosion rate as measured by weight loss of metal is somewhat higher for copper than for nickel.

284

Uhlig, H. H., ed. CORROSION HANDBOOK. New York, John Wiley & Sons, 1948.

285

Uhlig, H. H. CORROSION AND CORROSION CONTROL, New York, John Wiley & Sons, 1963.

286

Ulanovskii, I. B., Nikitina, N. S. THE INFLUENCE OF PUTRIFYING AEROBIC BACTERIA ON THE CORROSION OF STEEL IN SEA WATER. Mikrobiologiya, 25: p. 66-71, January-February 1956.

In Russian with English Summary

Intensification of corrosion of steel in sea water containing putrifying bacteria is due to differential aeration and a decrease in pH values of sea water close to the steel surface where bacteria concentrate.

Tests were carried out using bacteria isolated from sea water and from corrosion products on steel in sea water. Sheet steel panels (100 x 50 x 1 mm) were cleaned, immersed for 15 min in 2 day old cultures of the bacteria, then suspended in sterile sea water at 15 to 18 C. Water was changed weekly. The bacteria isolated from corrosion products were more aggressive than those isolated from sea water. Thus, after 6 mo exposure the corrosion rate for steel exposed to bacteria isolated from corrosion products was 0.0379 g per sq m per hr, while for steel exposed to bacteria from sea water the rate was 0.0366. For a sterile, noninoculated surface similarly exposed, the rate was 0.0296 g per sq m per hr, or roughly 20 to 25% less than when bacteria were present.

The corrosion rate after only 2 wk of test was 0.0637 g per sq m per hr for bacteria-inoculated panels and 0.0469 g for sterile sheets. In the following 2 mo the rate of corrosion decreased rapidly. The number of bacteria at the start of the test was 3500 per sq cm of steel surface; after 30 days it was 1,660,000.

287

Ulanovskii, I. B., Korovin, Yu. M. CORROSION OF STAINLESS STEEL AT CONTACTS WITH NON-METALLIC MATERIALS. Zhur. Priklad. Khim. 31: p. 1366-1370, September 1958.

In Russian

Three types of stainless steels were placed in contact with rubber, plexiglas, or textolite and exposed to sea water at 15 to 16 C. Corrosion at the contact was attributed not only to galvanic effects, but to a stagnant zone between the

electrodes and to chlorine ions.

Data were plotted showing that current intensity, and hence corrosion, increased with cathode size. With anode areas of 0.8 sq cm, weight losses after 24 hr were 2.2, 1.0, 0.8, 0.6, and 0.4 mg at cathode areas of 540, 270, 145, 80 and 45 sq cm, respectively.

The influence of pH on the electric potential of steel in sea water was studied by adding hydrochloric acid. At low pH, the electrode potential shifted to the negative; at pH 4 this shift was especially marked. The pH decreased from 8.4 to 2 as anode current density increased from 0 to 0.2 ma per sq cm over a 24 hr period. The pH decreased from 8.4 to 3.9 with continued anode polarization for 25 hr at a current density of 0.012 ma per sq cm. The electrical potential of steel changed from -0.25 to -0.75 v at pH 5.5 and from 1.75 to -0.5 v at pH 4.3. The potential was stable at pH 2.3 and 3.0.

Peripheral corrosion of samples was observed at the contact gap after 120 hr in Black Sea water in 6- and 20-liter vessels. After 240 hr, corrosion covered 50% of the contact surface; after 360 hr, complete corrosion was observed. The onset of corrosion led to the formation of metal chloride solutions and to increases in pH as a result of the lowered electrode potential of the entire contact surface. Corrosion at the contact gap increased as the metal potential shifted to more negative values and the pH decreased below 5.5. In extended tests, the water in the vessels was changed every 48 hrs to assimilate natural conditions.

288

Ulanovsky, I. B. CORROSION OF ALUMINUM AND ITS ALLOYS IN SEA-WATER. *Zashchita Metallurg*, 2: No. 4: 462-466, 1966.

In Russian

The corrosion of Al and several typical commercial Al alloys in sea-water was studied. On increasing pH of sea-water, stationary potentials of Al and its alloys begin moving in negative direction, even a change from pH 8 to 8.5 producing a shift of several hundred mV. This has a substantial effect on corrosion processes. Owing to reduction of O on Al, medium becomes more alkaline in cathodic regions, and potentials of these regions gradually becomes more negative; corrosion-pair current thus falls.

289

Ulanovskii, I. B., Turpaeva, E. P., Simkina, R. G., Korovin, Yu. M. EFFECT OF THE MUSSEL MYTILUS GALLO-PROVINCIALIS L. ON STEEL CORROSION. *Marine Fouling and Borers*, p. 246-251, 1968.

Translated by Mercado, A National Science Foundation, Special Foreign Currency, Science Information Program.

290

Upton, B. CORROSION RESISTANCE IN SEA WATER OF MEDIUM STRENGTH ALUMINUM BRONZES. *Corrosion*, 19: p. 204t-209t, June 1963.

Corrosion behavior of medium strength 90-10 aluminum bronzes of the BS 2032 type in sea water is markedly affected by the microstructural constituents present and their form. Resistance is good in the absence of  $\gamma_2$  in a continuous form. Factors influencing  $\gamma_2$  formation are cooling rate from the  $\alpha + \beta$  region and chemical composition. Beta phase retention, hence good corrosion resistance, is favored by a rapid cooling rate and high manganese content; nickel also favors beta retention, but it is much less potent than manganese. The effect of iron is variable and depends on the aluminum content. In the absence of alloying elements, beta breakdown is sensitive to aluminum content; it is faster at a high aluminum content. Silicon addition gives rise to a close-packed hexagonal  $\kappa$  phase not easily decomposed to  $\alpha + \gamma_2$ . This insensitivity to cooling rate, coupled with satisfactory mechanical properties and corrosion resistance, could provide a basis for design of an alternative alloy to B.S. 2032. A tentative specification is 6.0 to 6.4% aluminum, 2.0 to 2.4% silicon, 0.8 to 1.0% iron with the balance copper.

291

Upton, B. BRAZING ALLOYS FOR MARINE SERVICE. *British Corrosion Journal*, 1: No. 4: 134-137, 1966.

Microstructure of brazing alloys to B.S. 1845 and to certain proprietary specifications is reviewed and related to corrosion performance in sea water on joints with copper, 70/30 cupro-nickel and 7% aluminium bronze. Factors influencing corrosion are illustrated and discussed and recommendations are made as to suitability of various braze metal-parent metal combinations. Of seven brazing alloys tested with three parent materials, only two were completely satisfactory, two could be used within certain limitations and three were unsatisfactory.

292

Uusitalo, Eino, Makimattila, Iikka.  
THE SEA WATER CORROSION OF SHIPBUILDING  
PLATES. Teknillisen Kemian Aikakauslehti,  
18: p. 513-517, 1961.

In Finnish with English summary

Study of the effects of temperature, salt level, rate of flow and attack duration on the corrosion rate of ship plates shows differences  $\leq 10\%$  between 10 different types of plate. Corrosion rates follow a parabolic law in relation to the duration of attack and the flow rate. Corrosion increases between 0 and 50 C; the effect of salt content ( $\sim 2\%$ ) is greatest at 25 C. There is no fundamental difference between the corrosion rates of killed and rimmed plates. Corrosion resistance increases with increase in copper, nickel, chromium, and arsenic contents. Increase in carbon content seems to improve the resistance of killed plates and to lower that of rimmed plates. Differences in corrosion rates of different types of plate are much greater when the plates are connected under various conditions.

293

Uusitalo, E. GALVANIC CORROSION OF STEEL  
PLATES AND WELD METALS OF HULLS IN SEA  
WATER. In: Proceedings, 2nd. Inter-  
national Congress on Metallic Corrosion,  
New York, N.Y., March 11-15, 1963.  
p. 812-814, 1963.

294

Uusitalo, Eino. EFFECT OF FLOW RATE ON THE  
GALVANIC CORROSION OF LOW-CARBON STEELS  
IN SEA WATER. Corrosion, 17: p. 89-92,  
February 1961.

The effect of flow rates ranging from 0 to 5 m/sec on the galvanic corrosion of eight low carbon steels in sea water at 0 C was studied by recording current-potential curves of the steel and by measuring the potentials, current strengths and weight losses of galvanic cells formed by coupled steels.

The corrosion of coupled steels was up to 15 times greater at high rates of flow than in still water, but variation of flow rate did not alter the order of nobility of the steels. The higher the silicon content of the specimens (which included weld metals and ship plates), the lower the nobility - composition being otherwise similar.

295

Vaders, E. CORROSION, PARTICULARLY OF  
COPPER-ZINC-ALLOYS, FROM SEAWATER AND  
CHEMICAL SOLUTIONS, PART II. Metall,

16: p. 1210-1224, December 1962.

In German

A large number of experimental copper alloys, especially copper-zinc alloys in sheet form, were evaluated for their resistance to artificial sea water, 10% sulfuric and acetic acids, 10% potassium and ammonium hydroxides and a sulfite solution. Alternate immersion tests in sea water were continued for 180 days. Weight losses in  $\text{gm/m}^2/\text{day}$  were determined.

Generally good agreement was observed between laboratory results and service performance. In synthetic sea water, zinc-free copper alloys as a group behaved worse than zinc-containing alloys. Aluminum, nickel and iron improved the resistance of zinc-free copper alloys; silicon and lead impaired their resistance against all corrosive media, except sulfurous acid (sulfite cooking liquor). DIN alloy 1714 showed the lowest weight loss among zinc-free compositions; this is in agreement with the known service performance of this alloy. Among zinc-containing copper alloys, as among all alloys examined, the aluminum-containing composition was by far the best. Manganese and lead improved or impaired the resistance of copper-zinc alloys, depending on alloy composition. High amounts of manganese or silicon reduced resistance of both zinc-containing and zinc-free alloys. Additions of nickel appeared to be beneficial up to  $\sim 10\%$ ; higher proportions often impaired resistance. This agrees with the observation that high-nickel alloys often do not perform according to expectations in sea water. In alternate immersion tests, copper-zinc alloys containing additions of aluminum with or without manganese gave the best performance; aluminum-free alloys were inferior. In flowing sea water, which was more corrosive than stagnant sea water, zinc-containing alloys were expectedly superior to zinc-free alloys; additions of manganese showed a detrimental effect, especially in higher proportions. High amounts of nickel improved resistance to flowing sea water, whereas additions of aluminum were less effective than in the static immersion test. In general, no significant differences were observed between annealed and unannealed specimens, although some unannealed (rolled or cast) specimens were more resistant to corrosion than the corresponding annealed alloys.

296

Vind, H. P., Noonan, M. J. BIOLOGICAL  
CORROSION AT NAVAL SHORE FACILITIES  
(WITH APPENDED BIBLIOGRAPHY ON BIOLOGICAL  
CORROSION). Naval Civil Engineering Lab.

Report No. NCEL-TN-831, AD-684 423:  
93 p., July 1966.

Bacteria and other organisms frequently initiate or accelerate corrosion of metals. Experiments were undertaken to ascertain if the presence of microorganisms is necessary for corrosion to occur. In aerated sea water, iron corrodes fairly rapidly whether or not microorganisms are present; but in sea water, from which oxygen is excluded, iron rusts very slowly unless sulfate-reducing bacteria or their metabolic by-product, hydrogen sulfide, is present. To induce rapid anaerobic corrosion, the bacteria must be supplied with carbohydrates or other nutrients. Anaerobic conditions and bacterial nutrients might both be found in the layer of slime that accumulates on the surfaces of structures placed in the ocean.

297

Von Fraunhofer, J. A. LEAD CORROSION IN SEA-WATER. Anti-corros. Methods Mater., 16: p. 21-24, 26-27, May 1969.

Study of the corrosion of lead in sea water and saline solution and of the anodic behavior of lead in chloride solutions was carried to give information applicable to the use of submerged telecommunications cables and the growing use of lead anodes for cathodic protection of marine structures. Review of previous work (39 references) on corrosion of lead in chloride solutions, effect of oxygen on rate of lead corrosion, corrosion rate of lead in sea water, and mechanism and rate of corrosion of lead alloys (lead with silver, cobalt, thallium, platinum, and tin), is presented. Although the corrosion resistance of lead and lead alloys in sea-water favors its wide use, there is still insufficient knowledge available on the nature of the corrosion product that is formed upon the metal and the role played by the metals used in the alloys.

298

Vreeland, D. C. ANODIC SEA-WATER CORROSION OF COMPOSITE METALLIC MATERIALS FOR MECHANICAL SHAFT SEALS. Naval Ship Research and Development Center. Report NSRDC 2479, AD-828 192L: 37 p., February 1968.

299

Vreeland, D. C. GALVANIC CORROSION BEHAVIOR OF WEAR-RESISTANT MATERIALS FOR MECHANICAL SHAFT SEALS. Navy Marine Engineering Lab. Report No. MEL-242/66, AD-635 592: 15 p., July 1966.

Shaft seals currently used on submarines employ mating wear surfaces which are supported by monel carrier rings. Galvanic corrosion effects between various candidate mating materials and monel have been investigated by the exposure of couples in seawater. The 14 materials exposed included seven cobalt-chromium alloys, six sintered carbide materials, and one copper-lead-tin alloy. The results indicate that galvanic coupling to monel had no adverse effect on the corrosion behavior of five of the cobalt-chromium alloys, and one of the sintered carbide materials.

300

Vul'fson, V. I. CORROSION EXPERIMENTS ON METALS IN SEA WATER. Akademiia Nauk SSSR. Komissia PO Bor'be S Korroziei Metallov, Trudy, No. 1; p. 44-57, 1951.

301

Wacker, G. A. STRESS-CORROSION STUDIES OF ALUMINUM ALLOY 7079-T6 IN SEAWATER. Navy Marine Engineering Lab. Report No. MEL-444/65, AD-626 374: 22 p., January 1966.

The stress-corrosion susceptibility of aluminum alloy 7079 in the T6 temper was investigated as a function of longitudinal, long-transverse, and short-transverse plate orientations. The alloy was found to be susceptible to stress-corrosion and pitting attack. Specimens oriented in the short transverse direction had the lowest resistance to damage in seawater. Variations in orientation-dependent stress-corrosion cracking susceptibility were related to microstructural characteristics. The alloy is considered unsuitable for Naval applications under conditions conducive to stress corrosion.

302

Wacker, G. A. STRESS-CORROSION STUDIES OF ALUMINUM ALLOY 5456-H321 IN SEAWATER. Naval Ship Research and Development Center. Report No. NSRDC 2436, AD-656 573: 27 p., July 1967.

The stress-corrosion susceptibility of aluminum alloy 5456 in the H321 temper was investigated as a function of longitudinal, long transverse, and short transverse plate orientations. The alloy was found to be subject to pitting attack but immune to stress-corrosion cracking in flowing seawater at ambient temperature.

303

Wacker, G. A. EFFECTS OF MARINE ENVIRONMENT ON HIGH-STRENGTH STEELS.



In: Materials Performance and the Deep Sea, p. 68-87, 1969.

Summarizes the general and stress-corrosion cracking behavior of several classes of high-strength steels in the marine environment. Eleven experimental heats of maraging steel were evaluated for resistance to stress-corrosion cracking in sea water. Those alloys containing 10 and 12% Ni were found to be susceptible to pitting attack and stress-corrosion cracking, while 18% Ni maraging steels were found to be highly resistant to pitting attack. The corrosion characteristics of 5Ni-Cr-Mo-V HY-130 steel were also investigated in natural sea water. The stress corrosion threshold stress for HY-130 was determined utilizing the criteria of no failure for six months of exposure in natural sea water under sustained stress in the precracked cantilever test. A major portion of the investigative work was concentrated on answering the question of whether long-term continuous cathodic protection of HY-130 in natural sea water will lead to eventual problems associated with H<sub>2</sub> embrittlement. The effect of cathodic protection on the low-cycle corrosion fatigue behavior of HY-130 was also determined.

304

Waldron, L. J., Peterson, M. H., Forgeson, R. W. ABYSSAL CORROSION AND ITS MITIGATION. PT. I, DETAILS OF PILOT TEST EXPOSURE. Naval Research Lab. NRL Memorandum Report 1282: March 1962.

305

Waldron, L. J., Forgeson, B. W., Peterson, M. H., Brown, B. F. ABYSSAL CORROSION AND ITS MITIGATION. PT. II. RESULTS OF A PILOT TEST EXPOSURE. Naval Research Lab. NRL Memorandum Report 1383. December 1962.

306

Waldron, L. J., Forgeson, B. W., Peterson, M. H., Brown, B. F. ABYSSAL CORROSION AND ITS MITIGATION. PT. III. RESULTS OF EXPOSURES ON DEEP SEA BUOYS OF THE WOODS HOLE OCEANOGRAPHIC INSTITUTE (EXPERIMENTS T-IV AND T-V.) Naval Research Lab., NRL Memorandum Report 1377: January 1963.

307

Waldron, L. J., Forgeson, B. W., Peterson, M. H., Brown, B. F. PERFORMANCE OF STAINLESS STEEL GALVANICALLY COUPLED TO OTHER METALS. Naval Research Lab., NRL Memorandum Report 1388: AD-679 659: 12 p., January 1963.

The report presents the results of exposing specimens of AISI type 316 stainless

steel, provided with standard crevices, and galvanically coupled with various other metals, in sea water. The exposure lasted 115 days. Complete protection against all forms of corrosion (including crevice corrosion) was afforded the 316 steel by coupling with most of the metals, including the standard aluminum-base and zinc-base galvanic anodes. No evaluation of the effectiveness of magnesium alloys could be made because the anode was completely expended before termination of the experiment. AISI type 316 L was observed to crevice-corrode when coupled to the regular 316, and in that instance the 316 did not crevice-corrode.

308

Waldron, L. J., Peterson, M. H., Brown, B. F. PRELIMINARY EXPERIMENTS ON DEEP SEA CORROSION AND CORROSION PREVENTION. Naval Research Lab., NRL Memorandum Report 1242: AD-693 119: 12 p., 1969.

Panels of mild steel were exposed in constant immersion near the surface of the ocean at Chincoteague, Virginia, and at 3100 feet in the sea near the Bahama Islands. Similar panels coupled to aluminum-zinc galvanic anodes of commercial composition and panels of AISI type 304 stainless steel were similarly exposed. The results of these short-term tests (two months) indicated that (1) mild steel corroded much faster at the deeply submerged location than at the surface, (2) galvanic anodes were fully effective in preventing corrosion at the deep location, but the current demands appeared to be more severe than near the surface, and (3) the stainless steel panel at Chincoteague suffered severe crevice corrosion, but the one in the deep site was totally unattacked.

309

Watkins, L. L. CORROSION AND PROTECTION OF STEEL PILING IN SEAWATER. Army Coastal Engineering Research Center. Report No. TM-27, AD-690 803: 108 p., May 1969.

The report, based on a survey of literature, assembles much of the current knowledge concerning corrosion and protection of steel piling in seawater. Causes of corrosion and effects of environmental conditions are presented. Results of tests on protective coatings for steel are included. Corrosion rates of bare steel piles and the factors involved in the use of cathodic protection and concrete jackets are explained. References surveyed show that flame-sprayed zinc sealed with vinyl is possibly the

best coating system tested. More data is needed from which to determine the most economical method of protecting steel piling in seawater.

310

Wesley, W. A. TOTAL IMMERSION TESTS. In: Corrosion Handbook, Uhlig, H. H., Ed., p. 959-965, New York, Wiley, 1948.

311

Wheatfall, W. L. METAL CORROSION IN DEEP-OCEAN ENVIRONMENTS. Navy Marine Engineering Lab. Report No. MEL-429/66, AD-645 481: 31 p., January 1967.

Experiments were conducted in deep-ocean environments to determine whether unusual corrosion phenomena exist at great depths that are not present in water near the surface. A total of five exposures were made at various locations in the Pacific Ocean. Two exposures were at 5640 feet, and one each at 2340, 5300, and 6780 feet. In some cases, similar tests were conducted in shallow water. Results from general corrosion tests of metals representing six typical alloy classes, and also from crevice-corrosion tests on a stainless steel and nickel alloy, revealed that, in general, there were no major differences between corrosion phenomena in deep-ocean and shallow-water environments. Variations in behavioral patterns that were observed could largely be explained on the basis of differences in oxygen content.

312

Wheatfall, W. L. METAL CORROSION IN DEEP-OCEAN ENVIRONMENTS. Naval Engineers Journal, 79: No. 4: 611-618, August 1967.

313

Williams, W. L. ALUMINUM BRONZES FOR MARINE APPLICATIONS. J. Am. Soc. Naval Engrs., 69: p. 453-461, August 1957.

Commercial aluminum bronzes usually contain 4 to 11% aluminum and may contain iron, nickel, manganese, and silicon. The corrosion rates of these in sea water vary almost linearly with water velocity which is the most important variable affecting general corrosion. Local accelerated attacks may occur in the form of pittings, crevice corrosion, impingement attack, dealuminization, and galvanic action. Dealuminization, which is recognized by a distinct copper color, appears most commonly at the waterline of partially immersed alloys. Crevice corrosion occurs in all specimens around and under their nonmetallic mountings and, occasionally, at sites where barnacles

are attached. Impingement attacks, which are associated with turbulent water flows, are commonly found at the inlet ends of condenser tubes and in pipe lines downstream from the fittings.

The potentials of aluminum bronzes and comparison alloys in sea water flowing at 13 ft. per sec were measured with a saturated calomel half-cell and a potentiometer. The potentials of aluminum bronzes (0.13 to 0.34) were comparable to those of other resistant materials used in sea water environments.

Heliarc and carbon arc welding produced no significant changes in the corrosion properties of alloys exposed in several environments. Also no serious galvanic corrosion occurred between the base alloys and weld deposits. Aluminum bronzes are not susceptible to stress-corrosion cracking in marine environments.

The bronzes are subject to varying degrees of fouling in quiet sea and brackish estuary waters. The amount of copper released by corrosion appears to be unrelated to the toxicity to fouling organisms. Fouling is not a problem at water velocities of 1.5 ft per sec or higher.

Corrosion fatigue properties of aluminum bronzes compare favorably with those of other copper-base alloys. Resistance patterns in sea and brackish river water are similar.

Aluminum bronzes are used for salt water piping, condenser components, valve stems, propellers, and numerous other components in military and merchant vessels.

314

Williams, W. L. EFFECT OF CARBON CONTENT ON MARINE CORROSION RESISTANCE OF CAST 19-9 CR-Ni STEEL. Navy Marine Engineering Lab. Report No. 040039A, AD- 23 781: September 1953.

315

Williams, W. L. METALS FOR HYDROSPACE. Journal of Materials, American Society for Testing and Materials. 2: No. 4: 769-800, December 1967.

Effective use of the under-sea frontier presents major challenges to metallurgists and materials engineers. These challenges are related to a need for high-performance alloys in pressure hulls, machinery, and auxiliary equipment operating under severe environmental conditions. Special problems and approaches to their solution are discussed in areas of design against brittle fracture, high- and low-cycle

fatigue, and various types of marine corrosion and their relation to ocean depth. Examples are given of steels, titanium alloys, and copper alloys developed primarily for deep-ocean technology. Attention is given throughout to the relation between material-property data and performance of actual equipment. Finally, brief mention is made of metallurgical problems in construction of large tanks in which structures and machinery can be tested under simulated deep-ocean conditions.

316

Zanis, C. A., Crisci, J. R. EFFECTS OF WELDING AND POST-WELD HEAT TREATMENT ON THE SEA WATER CORROSION RESISTANCE OF MANGANESE-NICKEL-ALUMINUM BRONZE. Naval Applied Science Lab., Report No. NASL-930-76-PR-4, AD-861 871L: 28 p., November 1969.

317

Zeiger, H. CORROSION RESISTANCE OF ALUMINUM IN CONTACT WITH OTHER METALS. Aluminium, Paris, 37: No. 5: 284-288, May 1961.



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## BEHAVIOR OF NONMETALLIC MATERIALS

Material in the following chapter is from the report by L.A. Beaubien, I. Wolock, and C.L. Buchanan, of Ocean Technology Division, Naval Research Laboratory, and C.L. Whitman, of Naval Ordnance Station, Indian Head, Maryland (AD-747 245).

Immediately after a general introduction is a paper by Wolock, "Polymeric Materials and Composites," followed by Beaubien's report, "Ceramics, Paper, Fabrics, Photographic Materials, and Magnetic Tape," and then Buchanan's, "Electronic Components." Each of these three papers concludes with its own set of references. A fourth paper, "Propellants and Explosives," by C.L. Whitman, completes the chapter.

## BACKGROUND AND GENERAL INTRODUCTION

As tasks become more varied at greater depths in the oceans, a larger spectrum of materials and components with differing areas of utility is required. Unfortunately many materials deteriorate to some extent when immersed for extended times in seawater. Although such deterioration has long been recognized for many presently used or candidate materials, in many cases relatively little work has been done to determine its actual nature and extent. Even for materials reasonably well studied, it is often difficult for a designer to locate the available information or to put differing, or even contradictory, opinions into perspective. Two extensive symposia have been held on the performance of materials in a marine environment, and the resulting papers published.\* However, these papers were not intended to serve as comprehensive reviews on deterioration, and they were limited primarily to structural materials.

The present project was undertaken to determine the actual state of knowledge of the effect of seawater on a large class of materials and components, by uncovering and assembling all available information. The choice of materials to be covered was dictated by interest in structures or systems intended either to be placed on the ocean floor or to be moored fully submerged and by interest in marine rescue and salvage operations. Hence materials which are primarily associated with shoreline facilities, such as wood and concrete, are not included. Likewise, the topic of marine fouling itself, as distinct from the possible damage to materials by the fouling organisms, is not covered.†

The principal sources of information were the Defense Documentation Center, Oceanic Library and Information Exchange, and the abstracts compiled between 1945 and 1964 by the now defunct Prevention of Deterioration Center. These were augmented by searches through the Atomic Energy Commission Abstracts, the Department of Commerce Index to Federal Research and Development Reports, and pertinent technical journals. In some cases authorities were contacted for additional information.

\*Ocean Engineering, Vol. 1, Nos. 2, 3, and 4 (1968-1968); "Materials Performance and the Deep Sea," ASTM Special Technical Publication 445, Phila., Pa., American Society for Testing and Materials, 1969.

† For information on the related subjects of marine deterioration of wood and biological fouling, the following references are suggested: "Marine Borers, an Annotated Bibliography," W.F. Clapp and D.R. Kenk, ONR Report ACR-74, 1963; "Marine Borers, Fungi, and Fouling Organisms," E.K.G. Jorns and S.K. Eltringham, editors, Organization for Economic Cooperation and Development, Paris, 1971; "Marine Fouling and Its Prevention," Woods Hole Oceanographic Institute, U.S. Naval Institute, 1952.

## POLYMERIC MATERIALS AND COMPOSITES

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## POLYMERIC MATERIALS

There has been great interest in polymeric materials for applications in the ocean such as submarine telephone cable coverings, mooring lines, seals and gaskets, and various structural components. These materials combine good electrical properties with good resistance to general deterioration and corrosion in water. Furthermore the materials resist marine biological attack. To evaluate this behavior characteristic and to obtain general information on the behavior of polymeric materials in the ocean environment, a number of ocean exposures have been conducted for extended times.

Workers at the Bell Laboratories have reported the results of exposures of up to 15 years at Wrightsville Beach, North Carolina, and Daytona Beach, Florida, at respective depths of 3 feet and 5 feet. The sites were selected because of the relatively high level and diversified types of marine borer activity. Seven large-scale exposure tests have been conducted for up to 3 years by the Naval Civil Engineering Laboratory at two locations off the coast of California at respective depths of approximately 2300 feet and 5600 feet deep. The Naval Civil Engineering Laboratory also conducted exposures for the Naval Air Development Center at the two locations for up to 2 years, in addition to one exposure in 35 feet of water in the Port Hueneme, California, area for 1 year. The Naval Applied Science Laboratory conducted an exposure at a depth of 4200 feet in the Tongue of the Ocean, Bahamas, for 1 year.

## Plastics

Connolly [1],\* Connolly et al. [2], and Muraoka [3-10], and others [11-16] have reported on extensive exposure tests of a large number of plastic materials. The materials included in these exposures are listed in Table 1.

As was pointed out, these exposures were conducted in different locations, at different depths, and at different times. Every material exposed by Muraoka and almost every material exposed by Connolly gave some indication of borer attack in at least one exposure. In most cases, however, the attack was limited to surface indentations up to 1/8 inch in diameter and 1/16 inch deep. In some cases Connolly observed borer damage early in the exposure period, with no additional damage during several years of additional exposure. In some cases Muraoka observed borer damage on a plastic specimen at the area of contact with the sediment on the ocean bottom, but there was no damage 1 or 2 feet above the bottom. In other cases damage was observed only under or in the vicinity of the wood bait in contact with the specimen, and in still other cases damage was observed only under a piece of jute-tape wrapping which enabled the borer to get a start in penetrating the specimen. In some cases, borers attacked a given material during one exposure but not during other exposures at different times at the same approximate location. Thus, like many other natural processes, borer attack was unpredictable.

Although borer attack on plastics was usually restricted to rather shallow surface damage, Connolly et al. [2] reported instances of substantive borer penetration, as deep as 3/4 inch. Two plasticized poly(vinyl chloride) plastics, one with trioctyl phosphate and the other with a nitrile rubber-polyester, "were heavily penetrated by borers and lost their mechanical integrity." Two specimens of nylon pipe were penetrated by borers during the first year of

\*These references are listed at the end of this section on polymeric materials and composites.

Table 1  
Reported Exposure Tests of Plastics

Material	References
Acrylonitrile-butadiene-styrene	1, 2
Cellulose acetate	3-9
Cellulose acetate butyrate	7, 11
Chlorinated polyether	1, 2
Epoxy	1, 2
Ethyl cellulose	5, 9
Fluorinated ethylene-propylene	3-8
Nylon	1-9
Polyacetal	1-9
Polycarbonate	1-9, 12
Polyester	1, 2
Polyethylene	1-9
Poly(ethylene-ethyl acrylate) copolymer	2
Polyethylene terephthalate	1
Poly(methyl methacrylate) (acrylic)	3-9, 13-16
Poly(monochlorotrifluoroethylene)	1, 2
Polypropylene	1-4, 6-9
Polystyrene	1, 3-9
Polytetrafluoroethylene	1-10
Poly(vinyl chloride)	1-9, 11
Poly(vinylidene chloride)	3, 10

exposure, but there was no additional damage during the next 9 years. A silica-filled styrene polyester casting suffered borer penetration after 6 years of exposure but none additional for the next 7 years, and an epoxy resin cast rod suffered a sufficient number of borer attacks so as to reduce its mechanical strength.

A number of factors would appear to influence the extent of borer damage of plastic materials. Penetration of plastics by borers may be aided by their starting in materials such as wood or jute wrapping or becoming established in heavy irregular calcareous fouling and then penetrating into the adjacent plastic material. Connolly [1] stated that borer attack appears to be directly related to the character of the surface. Generally, waxy or smooth materials such as polyethylene and polypropylene did not show penetration, although there were exceptions.

Muraoka [4] attributed failure of borers to penetrate into plastic materials to four causes: a hard surface; a waxlike surface; a soft, flexible smooth surface; and thick bacterial slime growth, which interfered with the borer getting a start. Connolly reported a pholad entry into a silica-filled polyester casting, which was surprising in view of the extremely hard nature of the formula and the fact that it contains silica. He stated that one theory suggests that pholads may be able to burrow into materials harder than their shells of aragonite because the materials are often friable and the harder grains that are broken off serve as an abrasive at the point of the burrowing.

Bultman and Southwell [11] investigated the effect of material hardness on the susceptibility of poly(vinyl chloride) to borer attack. Several PVC plastics were formulated in which the hardness was varied systematically by the amount of plasticizer in the formulations or by addition of inert fillers. The harder PVC plastics were just as heavily attacked by both teredos and pholads as the softer ones. In addition, cellulose acetate butyrate which had a surface hardness comparable to the PVC formulation with no plasticizer was attacked more severely than the softer experimental formulations. The authors postulated that the less-yielding nature of the harder materials facilitated removal of shavings from the surface by the boring organisms and that these shavings were less likely to clog the denticulated ridges of the shell so that the rasping action could proceed more efficiently.



Pomerat and Weiss [17] studied the collection of sedentary populations on the surfaces of submerged samples of 40 different construction materials. The five plastics exposed were low in the relative amount of fouling accumulated. The results obtained suggested that smooth, nonporous, nonfibrous surfaces, especially if also hard, are poor accumulators of sedentary organisms.

The more severe damage reported by Connolly [1] as compared with the superficial damage reported by Muraoka [3-9] may be due to the exposure locations. Connolly et al. [2] pointed out that "since the environment is biologically more aggressive in shallow water than in deep water, the findings from this program represent the worst situation that could be encountered." The average water temperatures at Wrightsville Beach and Daytona Beach were 17.3°C and 21.9°C respectively, whereas they were 2.5°C and 5.0°C at the two Pacific locations used by Muraoka. This alone could have resulted in greater borer activity at the sites used by Connolly.

The influence on the extent of borer activity of location and the time at which the exposure is taking place would appear to be evident from Muraoka's work. He reported similar behavior for a large group of plastics exposed at the same time, but this behavior varied from one exposure to another at the same location.

In most cases the plastics were not attacked by marine microorganisms. However, some poly(vinyl chloride) plastics containing lead stabilizers have become blackened by sulfate-reducing anaerobic bacteria. These microorganisms as a result of their utilization of the organic material, produce hydrogen sulfide which reacts with the lead compounds, turning the plastic black. However, there is no indication that this discoloration affects the properties of the plastic.

Bultman and Southwell [11] exposed various experimental polymeric materials, otherwise suitable for marine electric cable insulation, for 6 months to 14 months in the Pacific Ocean at Naos Island, Canal Zone, and in the Caribbean at Coco Solo, Canal Zone. Twenty-five candidate formulations containing poly(vinyl chloride) resin were prepared, incorporating in various combinations three plasticizers, three toxicants, and a wide variety of inert fillers. Commercial cellulose acetate butyrate was also included. The presence of inert fillers or toxicants or a change in plastic hardness in the PVC formulations had little effect on the amount of pholad damage. However, the PVC formulations containing the inert, inorganic fillers and those containing the toxicants were relatively free of damage by the teredos. Plastic hardness had little effect in this case also.

Connolly et al. [2] observed that two high-density polyethylene materials cracked at the points where they were fastened to the racks after 6 years. This phenomenon is exhibited by some polyethylenes and is not attributed to biological causes. In addition, by infrared analysis, Connolly et al. [2] detected carbonyl groups in unprotected polyethylene rods exposed 13 to 14 years, indicating that this material can oxidize slowly in shallow water where oxygen content is higher than at great depths. Thus some types of deterioration may be encountered during extended underwater exposure which are not biological in origin.

Yoshida et al. [18] also found that polyethylene degrades in water due to oxidation, caused by oxygen dissolved in the water. Once oxidation begins and chain scission occurs in the polyethylene materials, cracks grow in the polyethylene due to environmental stress cracking caused by the water. In addition, if polyethylene insulation is in direct contact with copper wire, oxidation of the polyethylene is accelerated due to catalytic action of the copper. It is therefore desirable in underwater applications to use a tin-plated conductor in contact with polyethylene and to use crosslinked polyethylene, if possible, containing an antioxidant and with minimum internal stresses.

Lawton [19] reported on the recovery in 1958 of a nonarmored deep-sea submarine telegraph cable that had been laid in 1951 in 7500 feet of water near Nova Scotia. The polyethylene insulation, which deliberately had been left exposed, showed no evidence of attack except for light scorings 1/32 inch deep or less. These were observed only in areas where hemp spun-yarn had been applied. Apart from this damage the cable after 7 years submersion could not be distinguished from its condition when manufactured. Munitz [20] reported on the recovery

of 299 samples of failed submarine telegraph cables in which none of the polyethylene insulation examined showed any signs of degradation.

Muraoka [7,8] reported hardness and water absorption measurements for a large number of plastics that had been exposed up to 2 years. Cellulose acetate, nylon, and poly(methyl methacrylate) showed decreases in durometer readings after exposure. The first two materials also had over 1% water absorption, which would be predicted from laboratory tests.

Lee [13-16] reported the results of mechanical tests on 1/8-inch cast and 1/4-inch biaxially stretched poly(methyl methacrylate) sheet after four ocean exposures in the Pacific at 2300 and 5600 feet for up to 2 years. There was no evidence of biological attack on any of the specimens. The mechanical test results were somewhat erratic. There did not appear to be any appreciable change in tensile strength, flexural strength, or modulus, but there was an indication of decrease in compressive strength.

Wallace and Colletti [12] conducted mechanical and optical tests on six types of polycarbonate sheet after 1 year of exposure at 4200 feet in the Tongue of the Ocean, Bahamas. They found no appreciable change in tensile, impact, or optical properties and no evidence of biological attack.

#### Plastic Tapes and Films

Connolly [1] reported that three types of plastic tape (polyethylene terephthalate, oriented polystyrene, and polytetrafluoroethylene) had suffered severe mechanical damage in 7 years. This was caused by fouling organisms growing under overlaps and tearing the tape. Polymono-chlorotrifluoroethylene tape failed after 10 years in the same manner [2]. Muraoka [3-9] reported that a black pressure-sensitive electrical plastic tape 0.010 inch thick was attacked by borers in two out of seven exposures, but the damage consisted only of shallow holes without complete penetration. A gray rubber tape exhibited slight surface cracking but did not fail.

Muraoka [10] exposed poly(vinylidene chloride) (PVDC) and polytetrafluoroethylene (PTFE) plastic films which had been applied to the surface of painted and unpainted carbon steel panels and unpainted stainless steel and K Monel panels using a pressure sensitive adhesive. These panels were submerged in 20 feet of water near Port Hueneme, California, to determine if the plastic film coverings could be used to protect metal surfaces from fouling and corrosion, to permit removal of marine growth by stripping off the plastic covering, and to prolong fouling-free and corrosion-free intervals. The PVDC- and PTFE-covered panels were exposed for 5 and 8-1/2 months respectively. When retrieved, the panels were completely covered with marine growth. However, the plastic films were in good condition. The PTFE film could be stripped off with little difficulty, removing the marine growth and leaving a clean surface. In the case of the PVDC film, there was heavy crevice corrosion along the edges of the stainless steel panels due to seawater coming in contact with the metal through small rupture holes in the film.

Muraoka also exposed specimens of polyethylene film [5] and poly(vinylidene chloride) film [5,9] for up to 3 years with no evidence of biological attack.

#### Plastic Fibers and Ropes

Connolly [1] reported that after 7 years of exposure noncellulosic synthetic fibers gave no indication of either borer or microbiological attack. These included polyacrylonitrile, poly-(acrylonitrile-vinyl chloride) copolymer, polyethylene terephthalate(polyester), nylon, and poly(vinyl-chloride-acetate) copolymer. On the other hand, cellulose acetate and cellulose triacetate fibers were destroyed by borers and microorganisms in 1 to 4 years.

Muraoka [3-9] reported that in seven exposures of up to 3 years, 1/4-inch nylon and 5/16-inch polypropylene ropes were not attacked by borers or by microorganisms. On the other hand, 1/2-inch cotton and manila ropes exposed at the same time were severely damaged by microorganisms and by borers and microorganisms respectively. Strength tests were

conducted on the rope specimens after five of the exposures [4,6-9]. Although the results varied somewhat, in general the nylon and polypropylene ropes retained approximately 80% and 100% of their respective initial strength after exposures of up to 2 years. The cotton and manila ropes, on the other hand, retained 0 to 50% of their initial strength under the same conditions. In one 6-month exposure [9] polyethylene rope retained its full initial strength.

One type of "deterioration" encountered by plastic ropes and insulation is what has been reported as fishbite, occurring at certain depths in some locations and resulting in complete parting of a line in many cases. Stimson [21] reported on the failures of 18 buoy stations in deep water off the coast of Bermuda, in which the 9/16-inch polypropylene mooring cables broke. There was a high mortality rate in the first few days. After the fifth day, the rate dropped and remained remarkably constant through 200 days. Failure was attributed to fishbite, resulting in parting of the line. Stimson reasoned that if the attacks were provoked by the attachment of fouling organisms to the cable, the incidence could be expected to increase with time, but this did not seem to be the case. Turner and Prindle [22] reported on the distribution of fishbites in the lines of two deep moorings that were set in 2000 meters of water off of Bermuda. In one mooring exposed for 1 week in the spring using 9/16-inch polypropylene with a poly(vinyl chloride) sheath, fishbites were found from 400 to 800 meters. The second mooring was exposed for 6 weeks in the fall using 0.145-inch steel cable with a 0.0875-inch-thick polyethylene coating, and in this case fishbites were found from 150 to 1500 meters with diminished frequency deeper than 1000 meters. Turner and Prindle [23] reported further figures on the incidence of fishbite in the polyethylene-coated steel line after exposure of up to 82 days. Most bites occurred between 600 and 1200 meters, with the peak of activity between 900 and 1000 meters. The deepest bite detected was at 1550 meters. From the tooth fragments found and the geometry of the bites, the damage was attributed to a fish *Sudis hyalina*. It is suspected that the fish are attracted by luminescent organisms entangled on the lines.

Muraoka [24] also reported that certain varieties of marine fish are attracted to white polyethylene-covered cables and lines. He recommends the use of black polyethylene-covered cables, since they do not attract fish. Macander [25] reported on the recovery of a deep sea array that had been submerged for 1 year at 4200 feet at the Tongue of the Ocean, Bahamas. There was no damage of any type to a black polypropylene-coated steel wire rope which rested on the ocean bottom or to a black polypropylene rope catenary whose maximum and minimum operational depths were 4200 feet and 2600 feet respectively.

## Rubber and Elastomers

Many rubber materials have been exposed because of great interest in their use as electrical insulation as well as gaskets and seals. These include the materials listed in Table 2.

Table 2  
Reported Exposure Tests of Rubber Materials

Material	References
Butyl rubber	1-9, 14
Chlorinated polyethylene	11
Chlorobutyl rubber	14
Ethylene-propylene rubber	2, 11, 26, 27
Chlorosulfonated polyethylene	11
Fluoroelastomer	26, 27
Natural rubber	1-9
Neoprene	1-9, 12, 27
Nitrile-butadiene rubber	1, 2
Silicone rubber	1-9, 12
Styrene-butadiene rubber	1-9
Polyurethane	2
Vinyl-Buna N rubber	27

The results have indicated, in general, little deterioration in physical properties and good resistance to borers and microorganisms, although there are exceptions. Muraoka [3-9] reported no attack by marine organisms for exposures of up to 3 years for butyl, natural, and neoprene rubbers. Styrene-butadiene rubber exhibited slight damage in two out of seven exposures, but silicone rubber underwent serious surface deterioration in every exposure apparently due to the nibbling of marine animals. Connolly [1] and Connolly et al. [2] reported severe surface cracking of silicone rubber in addition to borer damage. They also reported surface cracking of natural rubber after 6 years, significant borer attack on two formulations of neoprene but not on a third, borer attack on one formulation of styrene-butadiene rubber and surface cracking on another after 7 years, and severe borer attack as well as chemical deterioration in 2 years for an ester-based polyurethane, but they reported no deterioration or attack for an ether-based polyurethane in 5 years. Three formulations of ethylene-propylene rubber showed no deterioration in 5 years, but a fourth exhibited surface blistering in 7 years in areas where fouling organisms were attached. A nitrile-butadiene rubber exhibited no deterioration in 15 years.

Bultman and Southwell [11] exposed chlorosulfonated polyethylene, ethylene-propylene rubber, and chlorinated polyethylene for 8 months to 14 months in the Pacific Ocean at Naos Island, Canal Zone. These materials were attacked by borers on faces in contact with wood but not directly from the water. The intensity of attack was less than that for a series of poly(vinyl chloride) plastics previously referred to and having approximately the same hardness range. It was postulated that this may have been due to a physical peculiarity involving a combination of toughness and elasticity.

Measurement of tensile properties by Connolly after exposure gave the approximate results listed in Table 3.

Table 3  
Approximate Changes in Tensile Properties  
of Rubber Materials After Exposure [1,2]

Rubber	Loss in Strength* (%)	Loss in Elongation* (%)
14 Years of Exposure		
Neoprene	15	35
Natural rubber	20	15
Nitrile-butadiene rubber	40	35
Styrene-butadiene rubber	30	35
Silicone rubber	70	70
4 Years of Exposure		
Polyurethane (ester)	40	25
Polyurethane (ether)	0	50
Ethylene-propylene rubber	0 to 30	25

\*Approximate values.

Colacicco [26] exposed ethylene-propylene terpolymer and fluoroelastomer O-rings for 6 months at 2300 feet. In a second exposure Colacicco [27] exposed ethylene-propylene rubber, fluoroelastomers, vinyl-modified Buna N rubber, and neoprene O-rings for 2 years at 5600 feet. In both cases some of the specimens were exposed while under compression and some while elongated. Numerous properties were determined after the exposures were concluded, including hardness, compression set, permanent set, tensile strength, and elongation. In most cases there was little difference between the exposed specimens and laboratory-aged specimens. In general the tensile strength was not appreciably affected, whereas the elongation decreased 20% to 40% for the materials studied.

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Wallace and Colletti [12] conducted various mechanical tests, including tensile, tear, and hardness tests, on various compositions of chlorobutyl and butyl rubbers which had been submerged for 1 year at 4200 feet in the Tongue of the Ocean, Bahamas. In general there was no appreciable change in properties of these materials and no evidence of biological attack. In addition neoprene O-ring seals performed satisfactorily after the 1-year exposure; the mechanical properties of several silicone elastomer products did not change appreciably, but two silicones did degrade.

Muraoka [3-8] exposed 15-inch lengths of electric wire consisting of various types of polymeric electrical insulation, 0.015 inch thick, over No. 16 tin-coated copper wire. Insulation resistance and voltage breakdown at 1000 volts for 10 seconds were measured before and after exposure. In most cases specimens were exposed 0.5 foot above the sediment or 3 feet above the sediment. Some of the specimens of each material were exposed as straight wire (unstressed) and some coiled (stressed). The insulating materials used were polyethylene, poly(vinyl chloride), silicone rubber, styrene-butadiene rubber, and neoprene.

The results were quite erratic. There was no consistent difference in behavior between the specimens exposed 0.5 foot and 3 feet above the sediment or between the straight and coiled specimens. All of the materials in most cases exhibited significant decreases, usually 50% or more, in insulation resistance. However, in spite of these major decreases in insulation resistance, the silicone rubber specimens were the only ones that failed the voltage breakdown test for several of the exposures. These failures were probably due to the surface deterioration of silicone rubber referred to earlier.

## COMPOSITES

Organic-matrix fiber-reinforced composites are of great interest for use in the marine environment because of their high strength, relatively low density, good electrical properties, and corrosion resistance. In evaluating these materials for subsurface ocean use, there are two main areas of concern: biological attack and degradation in properties due to water. A number of ocean exposures have been conducted to determine these effects. The materials exposed included those listed in Table 4.

Table 4  
Reported Exposure Tests of Composites

Material	References
Epoxy/glass laminates	1-4, 6, 8, 13-16, 28
Melamine/glass laminates	3, 4, 6-8
Phenolic/cotton laminates	3-9
Phenolic/glass laminates	13-15
Phenolic/nylon laminates	3, 4, 6, 8
Phenolic/paper laminates	3, 4, 6-8
Polyester/glass laminates	1, 2, 13-16, 28, 29

With only two exceptions none of the materials exposed were damaged by borers. One exception was a phenolic laminate with unidentified reinforcement exposed by Muraoka [7,8]. Marine borers made holes in this material during two exposures in an area where wood was in contact with the plastic. The borers had attacked the wood first and then continued into the plastic. Borers also attacked 3/4-inch-diameter phenolic/cotton laminate rod under the wood bait during two exposures [5,7] and directly from the seawater environment without the aid of any wood bait piece during a third exposure [8] making holes about 1/16 inch in diameter by 1/16 inch deep.

Connolly et al. [2] reported that two epoxy/glass-cloth laminates showed no significant visible change after 9 years of exposure. A polyester/glass-mat laminate exhibited minute pitting after 3 years of exposure, possibly due to microbial damage. There was also noticeable erosion of the resin around the surface fibers. After 8 years of exposure the epoxy

laminates showed an 18% decrease in flexural strength and the polyester laminate showed a 25% decrease, and a roughly linear downward trend in strength appeared to be continuing. The insulation resistance of both types of materials decreased an order of magnitude after 1 year of exposure.

Fried [28] reported on the exposure of glass-reinforced plastic laminates at depths of 5700 feet in the Tongue-of-the-Ocean for 3 years. One was a polyester/Style-1000-Volan-glass-cloth laminate; the other was an epoxy/parallel-filament composite, otherwise unidentified. The polyester laminate was essentially unaffected by the exposure. However the epoxy laminate decreased approximately 15% in compressive strength in 100 days and 50% in 3 years. The interlaminar shear strength decreased approximately 30% in 100 days and 70% in 3 years. Fried pointed out that this behavior was not typical of epoxy/fiberglass laminates and may have been due to the lack of a suitable finish on the glass.

Goldfarb [29] reported the results of exposure tests conducted on polyester/fiberglass laminates immersed in the ocean at Kure Beach, North Carolina, 3 feet below the surface. Groups of specimens were removed each year for 5 years, the fouling scrapped off, and the materials kept under water until tested. No mention was made of biological attack having taken place. There were five types of glass reinforcement, consisting of Garan-finished 181 glass cloth, Volan-finished 1000 glass cloth, 1-1/2-ounce Garan-finished glass mat, Garan-finished woven roving, and a combination of 1000-114 glass cloth with 1-1/2-ounce glass mat.

The best material was the laminate made with Garan-finished 181 glass cloth. This material exhibited a slight increase in flexural properties and hardness and approximately a 20% decrease in compressive strength and Izod impact strength, compared with the original values. The other materials exposed decreased in physical properties by up to approximately 40%, and the largest decreases were usually in compressive properties.

These tests demonstrated what has also been shown in laboratory, namely that the surface finish on the glass reinforcement and the construction and type of reinforcement can have an appreciable effect on the strength retention of laminates. It is also significant that these polyester/glass laminates made in 1954 could be exposed in the ocean for 5 years with a minimal loss in strength. Considerable improvements in resins and in finishes since that time should result in greatly improved performance for current laminates.

Fried and Graner [30] reported on the strength of a polyester/fiberglass composite used for a submarine fairwater. This component was subjected to subsurface and above-surface ocean environment. The laminate was fabricated in 1953 with Style-181 Volan-finished glass cloth and a polyester resin. The fairwater was removed after 11 years of service, and the properties of the material were determined. The flexural strength, measured with the material wet, had decreased approximately 15%, and the flexural modulus had decreased approximately 5%. The Barcol hardness had decreased by only 3 units. The mechanical properties still exceeded the original requirements in the specification.

Lee [13-16] conducted tests on polyester/glass, epoxy/glass, and phenolic/glass laminates that had been exposed for 6 months and 1 year at 2300 feet, 2 years at 5640 feet, and 1 year at 35 feet. The exact composition of these materials was not presented. The results obtained were somewhat variable. The reductions in flexural strength, flexural modulus, and tensile strength varied up to 20%, and the reductions in compressive strength varied up to 40%.

## SUMMARY AND CONCLUSIONS

In evaluating materials for extended use in the ocean, it is necessary to consider the susceptibility to biological attack and to chemical deterioration in water. To assess these factors, many polymeric materials and organic composites have been exposed in the ocean for up to 15 years. Many plastic materials were included, in the form of sheets, rods, films, and ropes. With the general exception of cellulose, these materials were not attacked by marine microorganisms. However, every material can be attacked by borers. When attack does occur, it usually consists of relatively shallow surface scoring. Attack can be precipitated by the proximity of other materials which are highly susceptible to borer attack, such as wood. There is

a greater probability of attack in areas of high marine biological activity — in warm shallow water rather than in colder deep water, and at the ocean bottom rather than away from the bottom. There is some indication that materials with hard surfaces or with smooth, waxy surfaces are not as susceptible to borer attack, but exceptions to this general rule have been observed.

Plastic tapes, which were wrapped around rods for exposure tests, were damaged by fouling organisms attaching themselves and growing under overlaps and tearing the tapes.

Cellulosic fibers and ropes were attacked by borers and microorganisms and were severely damaged, whereas synthetic materials were generally not affected. Nylon and polypropylene ropes retained 80% and 100% of their respective original strength during two years of exposure, whereas cotton and manila ropes retained only 0 to 50%.

Another type of deterioration encountered was that of failure of polyethylene ropes due to fishbite. This has occurred near Bermuda in depths up to 1500 meters and was attributed to the *Sudis hyalina*. It has also been reported that the same effect was not observed for black polyethylene ropes.

Many types of rubber have been exposed, with generally good resistance to borers and to microorganisms and moderate loss in physical properties. Most rubber materials were either not attacked or suffered slight surface damage. The main exceptions were silicone rubber and polyurethane. Silicone rubber suffered severe surface deterioration, probably from marine animals, as well as borer attack. Ester-based polyurethanes are generally not stable in water over extended periods, but the ether-based polyurethanes are. Most of the rubbers exhibited significant decreases in elongation as a result of extended exposure in the ocean.

Several types of polymeric insulation over copper wire exhibited significant decreases in insulation resistance as a result of long-term immersion in water, but only the silicone rubber failed due to voltage breakdown.

The organic-matrix fiber-reinforced composites subjected to extended ocean exposures were not usually attacked by borers or other marine life, but did undergo some degradation in strength properties. The extent of deterioration depends on a number of variables that have been evaluated in numerous laboratory investigations. They include the resin, reinforcement, curing agent, reinforcement surface finish, reinforcement construction, curing conditions, resin content, and void content. The results published indicate that well-fabricated composites will decrease 20% and less in physical properties as a result of several years of exposure in the ocean. Static loading or fatigue loading of the composite during this period will increase the extent of degradation.

As a brief summarization, most polymeric materials will not degrade seriously as a result of extended immersion in the ocean. These materials, with some exceptions, are not attacked by marine microorganisms. Any polymer can be attacked by borers, usually with only slight surface damage. On the other hand the material can be submerged for years with no attack. Now that these general principles of biological behavior have been established, additional extended underwater tests must be viewed as having limited value for polymeric materials. The effect of water on these materials can be determined more exactly and much less expensively in laboratory tests.

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## CERAMICS, PAPER, FABRICS, PHOTOGRAPHIC MATERIALS, AND MAGNETIC TAPE

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### INTRODUCTION

This section deals with the effect of the subsurface ocean environment on some miscellaneous materials and components having varying degrees of utility for ocean technology applications. The materials included are ceramics, paper, and textiles, and the components covered are photographic materials and magnetic tape. The environmental aspects considered for most of these items are the material deterioration due to the chemical effect of the seawater and biological attack by marine organisms.

Since little or no information was found on these materials from the literature searches, the bulk of this report is based on the experience or opinion of recognized authorities. Not only have there been essentially no organized investigations of the effect of the sea environment on these items, but there is no indication of any such studies being planned for the immediate future.

### CERAMICS

For purposes of this study a ceramic is considered to be any inorganic nonmetal which is formed by either a temperature or a temperature-and-pressure process. This definition includes glass, graphite, alumina (such as substrates for microelectronics), and the commonly recognized ceramics such as the porcelains used for electrical insulation but excludes concretes and cements.

It is the consensus of all ceramists contacted that ceramic materials likely to be used for undersea applications will not be adversely affected by seawater over any reasonable time frame.

With the exception of some data on microscope slide glass drawn from evaluation tests of deep ocean materials conducted by the Naval Civil Engineering Laboratory, no evidence was found of any scientific studies of the effect of seawater on ceramics. However, there are numerous examples from underwater archaeological sites in the Mediterranean, and off the coast of Florida, of ceramics ranging from porcelain to ordinary earthenware which have been unaffected by centuries of immersion. Likewise, although some deterioration of glass has been noted in samples which have been immersed for as long as 200 or 300 years, immersion times of 50 years or less appear to have no deleterious effect. This conclusion is in agreement with results of the aforementioned NCEL exposures conducted in the Pacific Ocean at depths of 2300 and 5600 feet, which produced no noticeable deterioration for exposures up to 2 years [1-5]. The general opinion of ceramists is that most modern ceramics and glasses will likewise not deteriorate over the relatively short times (up to several years) they would be expected to perform in submerged systems.

It should be recognized, however, that some modern ceramics developed specifically for their electrical or optical properties, such as the new chalcogenide glasses used for their excellent infrared transmission, may degrade to some extent in seawater. Specific studies of these materials will be required to determine their sensitivity to seawater.

## PAPER AND PRINTED DOCUMENTS

Since no examples of actual long-term exposure tests were uncovered, the following information on the deterioration of paper and printed documents in seawater is based primarily on discussions with sources experienced in paper chemistry, in particular personnel of the National Bureau of Standards, Bureau of Engraving and Printing, and Institute of Paper Chemistry.

The following general conclusions hold for grades of paper normally used for writing and printing but may not apply to extreme examples such as newsprint and paper specially treated for wet strength:

- The effect of seawater on paper, whether based on cotton or wood fiber, will be no different than that of ordinary fresh water.
- Paper will not disintegrate in water without accompanying mechanical action or biological attack (borers, etc.).
- The tear strength of the paper when wet will usually be considerably less than when dry, but most of the strength will return upon drying.
- The inks used for printed documents will normally last indefinitely in water.

### Paper in General

Paper, whether based on wood pulp or cotton fiber (rag bond, etc.), is a cellulosic material which relies for its strength on fiber-to-fiber hydrogen bonding. When immersed in water these hydrogen bonds are weakened, so that the tear strength of unmodified paper usually diminishes in minutes or hours to a small fraction of the dry strength, with no further change in strength with time after this initial weakening. However, most of the initial strength can be recovered by drying without excessive mechanical action. The addition of sea salts to the water would be expected to have little effect, since seawater is usually slightly basic and paper (cellulose) is generally attacked by acids but not by bases.

Further deterioration, to the point of annihilation or disintegration, would require either biological or mechanical action. The amount of mechanical action required to cause disintegration would depend on the wet tear-strength of the paper, which will vary with the type of fiber and binder. Biological deterioration of paper (actually the cellulose), whether by borers or by microorganisms, is primarily a function of location. Ordinarily paper would not be expected to survive in offshore areas less than 600 feet deep or at any depth within a few feet of the bottom, since these are prime zones of biological activity. However, paper and other cellulosic materials have remained free from attacks when silted over on the ocean bottom for more than 200 years. (see below)

A possible complication in the recovery and preservation of submerged paper is that for tightly packed sheets under pressure the return of hydrogen bonding during drying might also result in the sticking together of adjacent sheets, so that in some cases it might be best to separate the sheets when still wet or at some stage prior to complete drying.

The deterioration characteristics of paper can be modified by wet-strength additives, which are not normally found in writing and printing paper but may be encountered in photographic paper, maps, etc. As an example, a good rag stock combined with a resin modifier can maintain a wet tear strength very close to the dry strength for an extended time. Within this time frame the paper can withstand significant amounts of mechanical action without disintegration. At the other extreme, there are weak papers, such as newsprint, which may deteriorate quickly in water with little or no attendant mechanical action. As with wet-strength paper, these weak paper stocks are not ordinarily used for writing or (except for newsprint) for printing.

## Inks

Printing inks, with the possible exception of newspaper inks, usually consist of a carbon-black pigment combined with a natural oil vehicle. As a result, print using this type of ink has some inherent film integrity and is generally not soluble in water. The likeliest means of disintegration of print is by deterioration of the paper substrate. An ink not labeled washable or water-soluble will ordinarily not be affected by water.

## Structural Paper Products

The behavior of paper products such as packing and shipping containers, although similar to that of paper alone, is complicated by the presence of water-soluble adhesives. Containers intended specifically for marine applications use layers of wet-strength paper (combined with waterproofing treatments of the outside surface) bonded together with relatively water resistant adhesive. Containers of this type can be expected to maintain their integrity in water for extended periods of time, but they will eventually weaken, since even the best adhesives presently used are water soluble to some extent. Containers, such as ordinary corrugated boxes, which are not specially designed for marine use would most likely lose their integrity and structural utility in less than an hour, primarily due to dissolution of the adhesive and resulting delamination.

## Example of Silted-Over Paper

In June 1964 an archaeological team working the site of a Spanish galleon wrecked between 1650 and 1700 4 miles off the coast of Florida in 40 to 45 feet of water recovered several pieces of paper which had been silted over on the bottom. When dried, these linen fiber sheets, which were covered with clearly legible gothic print consisting of lampblack and vegetable oil, displayed a strength close to that of the estimated original strength. Although the animal sizing used in making this paper and type of ink used would probably produce a permanence above that of present-day papers and documents, still its survival for such a long time when protected from biological and mechanical action by only a layer of silt would indicate that paper in general can survive in seawater for extended periods of time when properly protected, even in biologically active areas.

## FABRICS (TEXTILES) AND FIBERS

Fabrics can be separated into two categories, depending on whether the fibers used are natural or man-made. The man-made category can in turn be separated into natural-polymer and synthetic-polymer fibers. The behavior of man-made fibers (and therefore of the resulting fabrics) and also the behavior of some natural fibers used for such applications as mooring and towing lines, were covered in the first section, on polymeric materials. Specific discussion in this present subsection is limited primarily to aspects of deterioration of natural fibers which are not covered in the first section.

Natural and man-made fibers are chemically inert in seawater. However, both natural and natural-polymer fibers are usually destroyed by biological activity in 1 to 6 months, although some natural polymers may not be destroyed for as long as 4 years under ideal conditions. Synthetic polymers appear to be generally free from biological deterioration. Since fiber deterioration is strictly biological, it depends strongly on geographical location, depth, and periodic variations in local biological environment.

Natural fibers are either cellulosic (such as cotton, linen, hemp, jute, sisal, kapok, ramie and manila) or proteinic (such as wool and silk) and are chemically inert in pure water but are susceptible to damage by a wide spectrum of biological life. Because of this susceptibility to biological attack, coupled with the relative indestructibility of synthetic polymer fibers and the limited marine utility of fibers and fabrics in general, little information has been published on the deterioration of natural fibers in seawater.



Two sources are a 1921 paper by Dorée [6], and a series of early (1920's) publications by the Bureau of Fisheries [7]. The paper by Dorée is based on controlled laboratory immersion tests on cotton coupled with data from uncontrolled immersion tests at Brighton, England, on a variety of cellulosic and proteinic fibers. The basic results of this study were that untreated natural fibers were completely destroyed by microbiological life in a month or less (except for wool, which lasted a little longer), and that, at least in the case of cellulosic materials, deterioration was solely due to the microorganisms (in the presence of oxygen), with no effect of oxygen or sea salts by themselves. The data from the Bureau of Fisheries, obtained from several geographic sites with differing environmental conditions, supported these findings, with the addition of the conclusions that deterioration might be expected to be greater in summer than in winter, due to a stirring of the bottom during winter, and that there are locations, such as near lime deposits, where biological deterioration can be greatly slowed if not eliminated. The results of both sources on the effect of preservative treatments are too old to be of specific importance; they do indicate that such treatments can prolong the useful life of natural fibers for several months but not indefinitely.

An additional characteristic of natural fibers is that cellulosic fibers increase in strength when wet. For example the wet strength of cotton increases up to 25% [8].

The Textile Technology, Charlottesville, Virginia, provides a comprehensive abstracting service covering all journals, both foreign and domestic, concerned with the production and performance of fabrics and fibers. It is unlikely that descriptions of any recent or future work by the textile community on the deterioration of either natural or man-made fibers would not be found in this digest.

## PHOTOGRAPHIC MATERIALS

Inquiries were made to various manufacturers and processors of film, as well as to government and private organizations which would be likely to encounter the problem of recovery or processing of seawater-contaminated film. The meager information that was uncovered is based on limited, and often undocumented, tests by the sources mentioned, as well as on the opinion of personnel with considerable experience in photographic chemistry. Since the information uncovered dealt almost exclusively with exposed but undeveloped film, this case will be assumed in the following discussion unless otherwise stated. Likewise, only black-and-white film is considered, since no information could be found on color film.

There seemed to be some difference of opinion among the sources, but some generally accepted conclusions are the following. Exposed but undeveloped film at room temperature will lose some image density over the first day or two of immersion in seawater which may or may not be 100% recoverable depending on the type of film used. This deterioration of the image is less at a lower temperature, so that images on some films may be essentially unaffected after exposures of as long as a month at 0°C. Generalized interpolation between these extremes of time and temperature on the basis of existing information is not possible. Also since image degradation is a chemical process, the environment can be important, such as whether the film is close to metal surfaces. In all cases experimentation is required with part of the film to determine the developing procedure for the remainder.

## Chemical Effects

Experience at E. I. duPont de Nemours and Co. with photorecording tape, described as similar to camera film, coupled with some tests, indicated that undeveloped film will undergo rapid loss of image (80% loss) after 3 to 4 hours' exposure in water due to chlorine fogging. However, a fresh-water washing can eliminate most of this fogging and allow recovery of almost all of the image. Limited tests at NRL [9] on Plus X film submerged in synthetic seawater at room temperature indicated a serious degradation of the image after 1 day and complete destruction of the image after 4 days. However, the same test procedure at 0°C showed essentially no loss of image after 4 days of immersion and a gradual loss thereafter through

the 35-day duration of the test, at which time usable images were still recoverable. These NRL tests involved a standard development procedure which was not experimentally varied as a function of immersion time.

According to the same duPont source, an immersion of weeks or longer is accompanied by a more permanent type of fogging, due to the action of organic sulfur and similar compounds, which produces an overall blackening of the image. It was then predicted that some information could still be salvaged by experimenting with restrainers during processing. It was also expected that this fogging would increase with depth, although this increase with depth would tend to be offset by the protective influence of lower temperatures. These opinions would appear to conflict somewhat with the results of the limited NRL tests, again using standard rather than experimental development techniques, which indicate a complete loss of image after 4 days of immersion except at very low temperatures.

The single example uncovered of retrieval and processing of saltwater-contaminated film is that of a rocket spectroscopy package recovered from 6000 feet of water after 14 days of immersion. Usable images were obtained from one camera having Teflon-coated internal surfaces, but none were obtained from the other uncoated cameras. The exotic nature of this particular nongelatinous film precludes immediate application of these results to more conventional films. However, it does point out the possible sensitivity of photodeterioration in seawater to chemical reaction with the surrounding media.

### Nonchemical Effects

The effects mentioned have been purely chemical and applicable only to undeveloped film. No information appears available on either processed negatives or prints, but the opinion of most sources is that deterioration of these items would be primarily nonchemical. Most film and prints have a gelatinous emulsion which is soluble in water. In the case of developed and undeveloped film, the backing is relatively indestructible in seawater, so that any deterioration would have to consist of either a loosening of the bonds in the gelatin to such an extent that it could float away from the backing (an untested possibility which is a point of apparent disagreement among the sources) or of some attendant mechanical action which would scrape the softened gelatin from its backing. In the case of rolled film the expanding gelatin might either ooze out the sides of the roll or mechanically damage the plastic backing, causing distortion or destruction of the image. A further problem for rolled film, and also for closely packet sheet film, would be sticking of the expanded gelatin to the uncoated face of the neighboring film, with attendant problems of separation. Hence films and prints should be kept immersed in water after recovery while awaiting processing.

In the case of prints the softening of the gelatin is accompanied by a weakening of the hydrogen bonds in the paper, producing a sensitivity to lesser mechanical actions that might not scrape off the gelatin but which could cause disintegration of the backing and therefore of the print. Limited tests at NRL in completely quiescent water indicate that photographic paper is not likely to disintegrate when immersed in water for considerable times (weeks or longer) without mechanical agitation. However, these same tests did produce one example of complete disintegration and separation of the gelatin coating from its paper backing after 4 to 6 weeks of immersion, without any noticeable effect on the paper backing. Unfortunately this example infers nothing about the possible disintegration of gelatin on a film backing because of the different nature of bonding.

### Handling Procedure

The following procedure, essentially that proposed by Eastman for handling film that has been immersed in seawater, appears to be the consensus, based on the assumption of the most extreme case: a tightly rolled undeveloped film.

If there is any sticking of the layers due to the softened gelatin, either at the edges or throughout the roll, then the best separation technique must be determined by experimentation. The following steps, which must be carried out in the dark for undeveloped film, are suggested:

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Attempt to separate the film immediately after removal from water, without allowing any drying; in severe cases separate the film under water, possibly with the use of a neutral wetting agent and/or a 5% sodium sulfate solution to suppress swelling of the gelatin; immerse in a rehardening bath such as a stop bath of acetic acid and sodium sulfate, or in extreme cases a formulation hardener; if the undeveloped film is exposed, experimentally process it; wash in alkaline wetting agent solution and carefully wipe both base and emulsion surfaces.

For the step of experimentally processing exposed undeveloped film the following is recommended. A sample of the film should be tested first in the recommended developer. This sample preferably should be taken a considerable relative distance into the roll. If fog is apparent, then it is necessary to modify the developer to produce the maximum differentiation between fog and information (image). It is suggested that the entire roll be bathed in a 1.0-gram-per-liter KBr solution prior to development. Then a series of small strips should be tested to determine how much bromide (a restrainer) should be added to the developer and how much development time is required to produce the best result. This concentration may range from 20 to 40 grams per liter of developer, and the time of development may range from seconds to minutes.

## MAGNETIC TAPE

Inquiries were made of tape manufacturers as well as of government organizations which would be likely to encounter the problem of seawater-contaminated magnetic tape. These inquiries uncovered no examples of either accidentally immersed tapes or tests of the effect of seawater on such tapes. However, the consensus was that the effect of seawater on a finished-product tape would differ little from the effect on the individual components: plastic backing and metal-oxide-plus-polymer-binder coating. The type of magnetic tape likely to be used or encountered in marine applications (polyester-backed tape) will ordinarily not deteriorate in seawater. However during extended submersion in biologically active areas marine organisms may grow between the layers and cause mechanical damage.

### Backing

The backing of magnetic tape is a plastic material, usually polyester but sometimes cellulose acetate, and is generally considered to be free from chemical attack by seawater. The only documented type of damage to polyester tapes similar to the backing used for recording tape appears to be a mechanical rupturing reported by Connolly [10] of an insulation tape immersed in seawater for 7 years. This rupturing was caused by the growth of marine organisms which had worked their way in between the tape and the rods on which they were wrapped. Although no information was found on cellulose acetate tapes as such, Connolly reported examples of complete destruction of cellulose acetate fibers within 1 to 5 years by marine organisms. Connolly's studies were in a shallow region of high biological activity.

### Coating

The coating usually consists of a proprietary mixture of many constituents (possibly 20 or more) but for purposes of behavior in seawater can probably be considered as a mixture of magnetic oxide particles in a polymer binder. This mixture in its solidified form should be chemically inert in water. The oxide particles, which may be iron, chromium, etc., should also be free from deterioration, since they are already oxidized and as such are not susceptible to further oxidation.

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## ELECTRONIC COMPONENTS

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### INTRODUCTION

Many experiments have been conducted to determine the effect of hydrostatic pressure on electronic components. The results of these tests indicate that most requirements for electronic circuit components can be met by proper selection of off-the-shelf components. The only type of circuit element which could not be operated under pressure was the general family of mechanical resonators such as tuning forks and crystals. A literature search revealed, however, that few experiments were conducted (and even fewer reported) in which circuits or circuit elements were subjected to seawater under pressure.

The literature search, on the degradation of electronic equipment caused by its protracted immersion in seawater at some appreciable depth, was conducted via the Defense Documentation Center and via individuals known to have worked in this field. The type of equipment considered of interest was equipment designed for use in conventional environments, not those especially designed for deep submergence. The DDC search yielded almost no useful information. The majority of the applicable literature came from journals, internal reports, and symposium proceedings, not included in the DDC files. The end of this section is a bibliography of work of sufficient interest to warrant inclusion. No experiments were performed expressly for this study, although the investigation of damage to electronic equipments from the submersible Alvin, which were exposed to seawater at a depth of 5100 feet for 9 months, was underway during this study and will be reported here.

### TYPES AND EXTENT OF DAMAGE

An operating electronic device immersed in seawater may incur three serious types of damage: short circuiting due to the seawater, electrolytic action, and collapse of components due to hydrostatic pressure.

#### Short Circuiting

Short circuiting (assuming the existence of normal operating potentials) may overload some of the components and destroy them by excessive currents. If internal batteries are used, these currents may persist for a fairly long time, and the batteries themselves may be overloaded causing heating or even rupture. A rupture may release chemicals which have additional corrosive effects.

The literature contains almost no information on short-circuit damage to operating circuits which were accidentally flooded. In numerous cases in the author's experience, extensive damage was unusual. Usually only one or a few connecting wires or terminals would burn out and the remainder of the circuit would be intact. The damage was normally localized at the point to which the power was supplied to the circuit. With printed circuits the connecting wires are usually much larger than the circuit-board conductors so the circuit-board conducting material is destroyed, although the previous location of this material is normally visible.

### Electrolytic Action

When an operating circuit is immersed in seawater, two types of electrolytic action can be expected. If internal power is supplied to the equipment during immersion, the circuits carrying current will be subjected to severe electrolytic action, and some of the conductors will be removed and deposited in other areas. After the internal power is dissipated, the long-term electrolytic corrosion continues, driven by the dissimilar metallic components in the common seawater electrolyte.

Much information has been developed on electrolytic corrosion in experiments in which metal samples are electrically isolated from each other. The literature is silent however on damage to actual equipment containing combinations of different metals and other materials under these conditions.

The equipment removed from the submersible *Alvin* is one of the best sources of information. In this case the equipment was not powered at the time of immersion, so no damage due to short circuiting occurred. The damage caused by electrolytic corrosion was obvious. Even the most cursory inspection of the circuit boards permitted easy location of every piece of ferrous metal in the assembly. A surprising number and variety of electronic components use ferrous connecting leads. Several types of capacitors and numerous transistors contained ferrous leads, and these were frequently corroded to the point of being physically detached. The area of the circuit board surrounding these connectors was clearly visible due to the characteristic rust coloring. For similar components in redundant circuits, there was a high degree of uniformity in the corrosion in spite of differences in physical location.

Electrolytic action was most damaging in electromechanical devices where small sizes of copper wire are close to ferrous metals. Motors, meters, and relays were generally damaged beyond further use.

### Hydrostatic Pressure

If an electronic circuit is exposed to appreciable hydrostatic pressure, certain components will deform or collapse. The results may be of no consequence in some cases and may be catastrophic in others.

The literature deals mainly with the hydrostatic effects on the electronic-circuit components. While this literature is mostly concerned with the determination of the characteristics of the components while under pressure, the data usually also consider the characteristics after the pressure has been removed.

The most severe and catastrophic damage occurs in glass envelopes such as oscilloscope tubes and other vacuum tubes. Implosion of cathode-ray tubes in several of the *Alvin* electronic equipments did essentially no secondary damage. The shields surrounding these tubes were not distorted or scarred as might have been anticipated. This observation holds for other vacuum tubes which were not enclosed in shields, although there were few such tubes in the equipment.

Much of the literature is concerned with semiconductor devices. The conclusion reached is that the semiconducting material itself is not seriously altered by the application of triaxial stress. The actual component however may react very differently due to the particular mechanical design of the protective enclosure.

A standard TO5 transistor case is a good example. The electronic equipment from the *Alvin* contained hundreds of TO5-style transistors, which were all severely deformed by the 2200 pounds of hydrostatic pressure. The deformation was uniform and consisted of inward collapse of the top of the transistor cover. These caps are usually constructed of steel. In most cases the metal deformed into a new shape strong enough to withstand the pressure. Such units operated as well as before as far as could be determined. In the few instances of failure the metal either deformed far enough to make contact with the semiconductor chip itself or cracked and allowed the unit to flood.

Semiconductors in glass envelopes are usually able to function after being subjected to high pressure. However, in the Alvin electronics, in which hundreds of glass diodes were used, the diodes showed a high failure rate after being put back in service. In some cases the glass envelopes were partly flooded, and when the temperature rose during equipment operation the envelope would burst open. In other cases the glass envelope was broken either at the time the pressure was applied or during its removal. The vibration or thermal stresses caused by operating the equipment would then cause the diode to malfunction.

Resistors appear quite immune to permanent damage by hydrostatic pressure. While the pressure is applied, carbon composition resistors have been observed to decrease in resistance substantially. There has been no indication that a permanent change occurs. Film-type resistors and wire-wound units show little change even while under pressure. The only type of resistor which has been observed to be unreliable after being under pressure was a glass-encapsulated precision unit. These components behaved similar to the glass diodes.

Numerous types of capacitors are employed in electronic circuits. Many of these types were tested during and after application of hydrostatic pressure. In the most general case it is concluded that if the unit does not contain void space, or bubbles of air or gas, the unit will show little change due to the application of pressure. One exception is polarized high-dielectric-constant barium titanate capacitors. Such units may show a change during and after pressurization.

The permanent damage to capacitors is usually associated with deformation of the case of the capacitor. Often the aluminum case of wet-electrolyte capacitors has been severely distorted by application of pressure. Such components may not show a change in capacitance but will usually no longer withstand the full rated voltage. The many types of capacitors molded in plastic usually operate satisfactorily both during and after the application of pressure.

The literature contains numerous examples of operation of inductors under and after pressure. Those which contain iron powders in a plastic matrix will usually show an inductance proportional to pressure. This is not a permanent change however. The only case covered in the literature of a large permanent change was a special grain-oriented core constructed for square-loop operations. No case is treated in which computer-type core materials were tested. Such components would probably be rendered inoperable by a single application of pressure, since they use materials similar to the grain-oriented square-loop core.

The mechanical components such as switches, plugs, sockets, panels, and enclosures are not treated in the literature cited. Experience with the equipment removed from the Alvin indicates that such components show little damage due to long exposure to the sea.

## POSTSUBMERSION TREATMENT OF EQUIPMENT

Reference has been made to the condition and behavior of the electronic equipment removed from the Alvin after her 9-month submersion at 5100 feet. It is important that the conditions under which this uncontrolled experiment was conducted are understood. The absence of power at the time of submersion, the intact hull, and the careful handling and cleaning after retrieval minimized the damage. The electronic equipment would have been severely damaged after it was removed from the water if it had been allowed to remain in the air without being cleaned.

During the 9 months exposure at 5100 feet the equipment was surrounded by the intact hull. The only access through which water circulation was possible was the open hatch. Undoubtedly this prevented any extensive intrusion of benthic fauna or sediment.

When the Alvin was recovered, special precautions were taken to avoid damage to the equipment due to exposure to the atmosphere. Most of the water was pumped out before the Alvin was lifted from the water onto a floating barge. Immediately thereafter a viewport was removed, allowing most of the remaining water to drain out. The electronic equipment was immediately removed from the submersible and placed in containers filled with fresh water.



The total time during which the equipment was exposed to the atmosphere was only 1 hour or so. At a later time when adequate equipment and trained personnel were assembled, the equipment was treated by standard techniques [1] to remove the salt water.

## SUMMARY AND CONCLUSIONS

The literature review indicates a scarcity of information directly related to deterioration of electronic equipment when exposed to the ocean environment at an appreciable depth. The three main causes of deterioration are considered to be short circuiting of power circuits, electrolytic corrosion, and hydrostatic-induced deformation.

Short circuiting has no literature cited. The experience of the author indicates that damage from short circuiting is highly localized and renders the circuit completely inoperable but does not destroy components more critical than batteries and cables.

Electrolytic corrosion likewise has not been specifically treated in the literature. There is a wealth of information on electrolytic corrosion of individual metallic materials in seawater but not of several metals in intimate contact as commonly occurs in electronic equipment. The author's experience is that the corrosion is highly selective, mostly against ferrous material, and does not destroy the equipment in the sense that it cannot be refurbished or rebuilt. In fact the Alvin equipment did not look like it had been submerged after a thorough cleaning.

Hydrostatically caused deformation has been rather extensively discussed in the literature. Hydrostatic pressure will completely destroy void-containing objects such as vacuum tubes or capacitors. Still the damage to the permanent parts of the equipment has been insignificant. Most of the passive circuit components will survive high pressures, and many of the active components likewise will show little change.

In general, although the damage to electronic equipment caused by exposure to the sea will be extensive, it will not preclude refurbishing of the equipment if such is required.

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## PROPELLANTS AND EXPLOSIVES

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## INTRODUCTION

Ocean technology tasks, particularly salvage or rescue operations, may involve direct handling of submerged ordnance and similar items which present a considerable safety hazard. All submerged items must be presumed to be in the original and hazardous state unless proven otherwise. It is therefore important to know what kind of behavior to expect from potentially dangerous submerged ordnance components, such as propellants and explosives.

Consideration of the effect of seawater on ordnance is complicated by the wide and seasonal variations in pressure, temperature, salinity, biological agents, oxygen, and solar radiation that may be encountered. Resistance of ordnance items to pressure and to corrosion varies; although the cases are usually sealed, they will leak at rates differing with conditions. In addition the item submerged will affect the immediate environment, with the greatest effect occurring in interior areas. Leaching of salts, oxidizers, and antibacterials; corrosion of metals; electrolytic couples; precipitation; and other interreactions will modify and change the rate of degradation. The net effect of submersion on ordnance, therefore, is difficult to predict except in a general statement unless the specific prevailing conditions are accurately known.

Tests of the action of seawater on propellants and explosives have not been extensive. In addition pertinent information is well buried in files, and retrieval is difficult or impossible.

## GENERAL NATURE AND INGREDIENTS OF PROPELLANTS

Even though direct correlation between the effects on single ingredients and materials in situ may not always be possible, still it is convenient to start this study with consideration of the effect of seawater immersion on these isolated elements. Such a simplified approach immediately suggests the importance of solubility, state (liquid or solid), biological action, and hydrolysis in the degradation and deactivation processes.

Table 5 gives a comprehensive list of ingredients under common names and commonly used designations or abbreviations. Various grades of some materials may be used, such as nitrocellulose with different nitrations and degrees of polymerization or aluminum with a range of particle sizes. In these cases Table 5 considers the average grade only. Materials are further altered in curing of composite propellants, as when polyols are reacted to form urethanes or when liquid polybutadiene is crosslinked to form elastomers. In these cases the table considers the resulting material rather than the parent compound. The last three columns of the table assume that the ingredient is wet with a large but finite volume of seawater at elevated pressure with the temperature at or near 25°C.

Propellants are compounded from the ingredients shown in Table 5 and may contain from two to 20 ingredients. These propellants are fuel/oxidizer systems with ingredients added as stabilizers, plasticizers, catalysts, and modifiers and for other purposes as indicated in the table. Usually, however, any single ingredient acts in a multifunctional role, with nitroglycerine being an oxidizer, fuel, and plasticizer, diphenylamine being a stabilizer and fuel, dibutyl phthalate being a fuel and plasticizer, etc. Therefore the loss of one or more of the ingredients by solution or degradation or the addition of salt water may seriously impair the functioning of the unit. As a general rule, solid propellants, except those containing large amounts of water-soluble material, will fire when wet, but performance when wet or after drying will be

Table 5  
Effect of Seawater on Propellant and Explosive Ingredients

Compound	Designation	Principal Use	Normal State	Soluble in Water	Effect of Seawater*	Estimated Life in Seawater*	Ignitable Under Water
Diphenylamine	DPA	Stabilizer	Solid	Slightly	Ox	5 years	No
Dipropyl adipate	DNPA	Fuel, plasticizer	Liquid	Slightly	Ox, Bi, Hy	5 years	No
Ethyl cellulose	—	Fuel, binder, inhibitor	Solid	Insoluble	Sw, Bi, Ox	5 years	No
Ethylene glycol dinitrate	EGDN	Oxidizer	Liquid	Slightly	Rd, Bi, Hy	5 years	Yes
Ferric acetylacetonate	FeAA	Catalyst	Solid	Slightly	Ox, Bi	1 year	No
Ferric octoate	—	Catalyst	Solid	Slightly	Ox, Bi	1 year	No
Ferric oxide	Fe <sub>2</sub> O <sub>3</sub>	Catalyst	Solid	Insoluble	—	—	No
Ferrocene	—	Catalyst	Solid	Insoluble	Bi, Ox	2 years	No
Graphite	—	Antistatic	Solid	Insoluble	—	—	No
Guanidine nitrate	—	Oxidizer	Solid	Soluble	Rd, Bi, Hy	1 year	No
Guanidine perchlorate	—	Oxidizer	Solid	Soluble	Rd, Bi, Hy	1 year	No
Hydroxylammonium nitrate	HAN	Oxidizer	Solid	Soluble	Rd, Bi, Hy	1 month	No
Hydroxylammonium perchlorate	HAP	Oxidizer	Solid	Soluble	Rd, Bi, Hy	1 month	No
Hydrazine nitrate	HN	Oxidizer	Solid	Soluble	Rd, Bi, Hy	1 month	No
Hydrazine perchlorate	—	Oxidizer	Solid	Soluble	Rd, Bi, Hy	1 month	No
Isoprene	—	Fuel, binder	Solid	Insoluble	Bi, Ox	5 years	No
Lead azide	—	Explosive	Solid	Insoluble	Ox	5 years	Yes
Lead carbonate, basic	—	Catalyst	Solid	Insoluble	—	—	No
Lead 2-ethylhexoate	—	Catalyst	Viscous	Insoluble	Hy, Ox	1 year	No
Lead maleate	Tri-Mal	Catalyst	Solid	Insoluble	Ox, Hy	5 years	No
Lead dioxide	PbO <sub>2</sub>	Oxidizer	Solid	Insoluble	Rd	5 years	No
Lead $\beta$ resorcyate	—	Catalyst	Solid	Insoluble	Ox, Hy	1 year	No
Lead salicylate	—	Catalyst	Solid	Insoluble	Ox, Hy	1 year	No
Lead stearate	—	Catalyst	Solid	Insoluble	Ox, Hy	5 years	No
Lead styphnate	—	Explosive	Solid	Insoluble	Rd	5 years	Yes
Lead styphnate, basic	—	Explosive	Solid	Insoluble	Rd	5 years	Yes
Lead thiocyanate	Pb(SCN) <sub>2</sub>	Explosive	Solid	Insoluble	—	—	Yes
Lithium hydride	LiH	Fuel	Solid	Reacts	Rea	1 day	No
Lithium perchlorate	LiClO <sub>4</sub>	Oxidizer	Solid	Soluble	Rd	1 month	No
Magnesium	Mg	Fuel	Solid	Reacts	Rea, Ox	2 years	No
Magnesium carbonate	MgCO <sub>3</sub>	Buffer	Solid	Insoluble	—	—	No
Magnesium oxide	MgO	Catalyst	Solid	Insoluble	—	—	No
Mercury fulminate	—	Explosive	Solid	Insoluble	Ox	5 years	Yes
Milori blue	—	Catalyst	Solid	Insoluble	Ox	5 years	No
Nitric acid	RFNA, HNO <sub>3</sub>	Oxidizer	Liquid	Soluble	Rd, Bi	1 week	No
Nitrocellulose	NC	Oxidizer, fuel, binder	Solid	Insoluble	Rd, De, Bi, Hy, Sw	4 years	Yes
2-Nitrodiphenylamine	2NDPA	Stabilizer	Solid	Slightly	Ox	5 years	No
Nitroglycerin	NG	Oxidizer	Liquid	Slightly	Rd, Bi, Hy	3 years	Yes
Nitroguanidine	NQ	Oxidizer	Solid	Soluble	Bi, Hy, Rd	1 year	No
Nitrostarch	NS	Oxidizer, binder	Solid	Insoluble	Bi, Rd, Hy, Sw	3 years	Yes
Nylon	—	Binder	Solid	Insoluble	Bi, Ox	5 years	No
Oxamide	—	Fuel	Solid	Insoluble	Bi, Ox	2 years	No
Pentaerythritol tetranitrate	PETN	Explosive	Solid	Slightly	Bi, Rd, Hy	4 years	Yes
Phenyl $\beta$ -naphthylamine	PBNA	Stabilizer	Solid	Insoluble	Ox	2 years	No
Polybutadiene, crosslinked	—	Binder	Solid	Insoluble	Bi, Ox, Hy	5 years	No
Polybutadiene, liquid	—	Plasticizer	Liquid	Insoluble	Bi, Ox, Hy	2 years	No
Polybutadiene, crosslinked copolymers	—	Binder	Solid	Insoluble	Bi, Ox, Hy	5 years	No
Polyester, crosslinked	—	Binder	Solid	Insoluble	Bi, Ox, Hy	5 years	No
Polyester, crosslinked copolymer	—	Binder	Solid	Insoluble	Bi, Ox, Hy	8 years	No
Polyfluoro vinylidene	Viton A	Binder, thermite	Solid	Insoluble	—	—	No
Polymethyl vinyl tetrazole	PMVT	Binder	Solid	Soluble (linear)	Bi, Ox, Sw	1 year	No
Polysulfide, crosslinked	—	Binder	Solid	Insoluble	Bi, Ox	5 years	No

Table 5 (Continued)

Compound	Designation	Principal Use	Normal State	Soluble in Water	Effect of Seawater*	Estimated Life in Seawater*	Ignitable Under Water
Acetyl triethyl citrate	ATC	Plasticizer	Liquid	Slightly	Bi, Hy, Ox	1 year	No
Aluminum	Al	Fuel	Solid	Insoluble	Bi, Ox	1 year	No
Aluminum hydride	AlH <sub>3</sub>	Fuel	Solid	Reacts	Rea, Ox	1 week	No
Ammonium dichromate	(NH <sub>4</sub> ) <sub>2</sub> Cr <sub>2</sub> O <sub>7</sub>	Oxidizer, catalyst	Solid	Soluble	Rd, Bi	1 week	No
Ammonium nitrate	AN	Oxidizer	Solid	Soluble	Bi, Rd	1 week	No
Ammonium oxalate	—	Fuel	Solid	Soluble	Bi, Ox	1 week	No
Ammonium perchlorate	AP	Oxidizer	Solid	Soluble	Rd, Bi	1 week	No
Ammonium picrate	D	Explosive	Solid	Soluble	Rd, Bi	1 year	No
Ammonium sulfate	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	Fuel, oxidizer	Solid	Soluble	Bi, Rd	1 week	No
Aniline	C <sub>6</sub> H <sub>7</sub> N	Fuel	Liquid	Slightly	Ox	1 year	No
Barium nitrate	Ba(NO <sub>3</sub> ) <sub>2</sub>	Oxidizer, catalyst	Solid	Soluble	Rd	1 week	No
Barium peroxide	BaO <sub>2</sub>	Oxidizer	Solid	Slightly	Rd	1 year	No
Beryllium	Be	Fuel	Solid	Insoluble	Ox	2 years	No
Beryllium hydride	BeH <sub>2</sub>	Fuel	Solid	Reacts	Rea, Ox	1 day	No
Boron	B	Fuel	Solid	Insoluble	Ox	2 years	No
Butyl stearate	—	Plasticizer	Liquid	Slightly	Ox, Bi	1 year	No
Carbon black	CB	Fuel, catalyst	Solid	Insoluble	Ox	5 years	No
Cellulose acetate	CA	Fuel, binder	Solid	Insoluble	Hy, De, Sw, Bi	5 years	No
Charcoal	—	Fuel	Solid	Insoluble	Ox	5 years	No
Chlorine pentafluoride	ClF <sub>5</sub>	Oxidizer	Liquid	Reacts	Rea	1 week	No
Chlorine trifluoride	ClF <sub>3</sub>	Oxidizer	Liquid	Reacts	Rea	1 week	No
Copper chromite	—	Catalyst	Solid	Insoluble	—	10 years	No
Cupric salicylate, basic	MBCS	Catalyst	Solid	Insoluble	Hy	5 years	No
Cyclotetramethylene tetranitramine	HMX	Oxidizer, explosive	Solid	Insoluble	Hy, Bi, Rd	5 years	Yes
Cyclotrimethylene trinitramine	RDX	Oxidizer, explosive	Solid	Insoluble	Hy, Bi, Rd	5 years	Yes
Isodecyl pelargonate	IDP	Plasticizer, fuel	Liquid	Insoluble	Ox, Bi, Hy	5 years	No
Dibutyl phthalate	DBP	Plasticizer, fuel	Liquid	Insoluble	Ox, Bi, Hy	5 years	No
Dibutyl sebacate	DBS	Plasticizer, fuel	Liquid	Insoluble	Ox, Bi, Hy	5 years	No
Diethyl diphenylurea	Centralite I	Stabilizer	Solid	Insoluble	Ox	5 years	No
Diethylene glycol dinitrate	DEGDN	Oxidizer, explosive	Liquid	Slightly	Rd, Bi, Hy	5 years	Yes
Diethyl phthalate	DEP	Plasticizer, fuel	Liquid	Insoluble	Ox, Bi, Hy	5 years	No
Dimethyl diphenylurea	Centralite II	Plasticizer, fuel	Liquid	Insoluble	Ox, Bi, Hy	5 years	No
Dimethyl hydrazine	UDMH	Liquid, fuel	Liquid	Soluble	Ox, Bi	1 year	No
Bis-dinitrophenoxy ethane	—	Fuel, oxidizer	Solid	Insoluble	Rd, Bi	5 years	Yes
Dinitrophenyloxy ethanol	—	Fuel, oxidizer, plasticizer	Solid	Slightly	Rd, Bi	2 years	Yes
Bis-dinitropropyl acetal	BDNPA	Fuel, oxidizer, plasticizer	Liquid	Slightly	Rd, Bi	5 years	Yes
Bis-dinitropropyl formal	BDNPF	Fuel, oxidizer, plasticizer	Liquid	Slightly	Rd, Bi	5 years	Yes
Dinitrotoluene	DNT	Fuel, oxidizer, plasticizer	Solid	Slightly	Rd	5 years	Yes
Diethyl adipate	DOA	Fuel, plasticizer	Liquid	Insoluble	Ox, Bi, Hy	5 years	No
Diethyl phthalate	DOP	Fuel, plasticizer	Liquid	Insoluble	Ox, Bi, Hy	5 years	No

Table 5 (Continued)

Compound	Designation	Principal Use	Normal State	Soluble in Water	Effect of Seawater*	Estimated Life in Seawater*	Ignitable Under Water
Polytetrafluoroethylene	Teflon	Binder, thermite	Solid	Insoluble	—	—	No
Polyurethane, crosslinked	—	Binder	Solid	Insoluble	Bi, Ox, Hy	5 years	No
Polyvinyl chloride	PVC	Binder	Solid	Insoluble	Bi, Ox, Hy	10 years	No
Potassium nitrate	KNO <sub>3</sub>	Oxidizer	Solid	Soluble	Bi, Rd	1 year	No
Potassium perchlorate	KClO <sub>4</sub>	Oxidizer	Solid	Slightly	Bi, Rd	5 years	Yes
Potassium sulfate	K <sub>2</sub> SO <sub>4</sub>	Flash	Solid	Soluble	Bi, Rd	1 year	No
Propylene glycol dinitrate	PGDN	suppressor	Liquid	Slightly	Bi, Hy, Rd	3 years	Yes
Red lead	Pb <sub>3</sub> O <sub>4</sub>	Oxidizer	Solid	Insoluble	—	—	No
Resorcinol	—	Stabilizer	Solid	Soluble	Ox	2 years	No
Silicon	Si	Fuel	Solid	Insoluble	Ox	3 years	No
Silicon	—	Catalyst	Solid	Insoluble	—	—	No
Silver iodate	AgIO <sub>3</sub>	Oxidizer	Solid	Slightly	Bi, Hy, Rd	1 year	Yes
Sodium barbiturate	—	Catalyst	Solid	Soluble	Bi, Ox, Hy	1 year	No
Sodium nitrate	NaNO <sub>3</sub>	Oxidizer	Solid	Soluble	Rd, Bi	1 year	No
Sorbitol pentanitrate	SPN	Oxidizer	Viscous	Insoluble	Bi, Hy, Rd	4 years	Yes
Sulfur	S	Fuel, catalyst	Solid	Insoluble	Bi, Ox	5 years	No
Sucrose octacetate	SOA	Plasticizer	Solid	Slightly	Ox, Bi, Hy	3 years	No
Tetracene	—	Explosive	Solid	Slightly	Bi, Hy	5 years	Yes
Tetryl	—	Explosive	Solid	Insoluble	Hy, Rd	3 years	Yes
Tin	Sn	Fuel	Solid	Insoluble	Ox	—	No
Triaminoguanidine nitrate	TAGN	Oxidizer	Solid	Soluble	Hy, Rd, Bi	1 year	No
Triethyl citrate	—	Plasticizer	Liquid	Slightly	Bi, Ox, Hy	2 years	No
Triethylene glycol dinitrate	TEGDN	Oxidizer	Liquid	Slightly	Bi, Hy, Rd	3 years	Yes
Trimethylolethane trinitrate	MTN, TMETN	Oxidizer	Liquid	Insoluble	Hy, Bi, Rd	5 years	Yes
Trinitrotoluene	TNT	Explosive	Solid	Slightly	Rd	5 years	Yes
Tungsten	W	Fuel	Solid	Insoluble	Ox	5 years	No
Zirconium	Zr	Fuel	Solid	Insoluble	Ox	—	No

\*Bi = biodegrades; De = decomposes; Hy = hydrolyzes; Ox = oxidizes; Rea = reacts; Rd = reduces; Sw = swells.

unsatisfactory. Some solid propellants may be successfully reworked and most may be identified with some precision even after long immersion. A classification of propellants (and explosives) into classes and types is given in Table 6.

Table 6  
Classification of Propellants

Class	Type
Nitrocellulose base	Single base, double base, triple base, composite modified double base*
Composite	Linear binders,* crosslinked binders,* fuel-rich composites
Liquid	Monopropellants, binary systems
Hybrid	Liquid-solid systems

\*May also be used as explosives.



## Nitrocellulose Propellants

Four propellant compositions are nitrocellulose based. In addition to their own specific properties, all the formulations contain stabilizers to inhibit autocatalytic decomposition by removing free  $\text{NO}_2$  from the system. These stabilizers also act as free-radical scavengers, antioxidants, and antibiological agents.

**Single Base** — Single-base propellants, which are used exclusively as gun propellants, are hard strong colloids that age relatively slowly in seawater. These propellants have been recovered from sunken ships, reworked, and used. In addition propellants for the 20-, 30-, and 50-mm weapons have a deterrent coating of DNT, ethyl centralite, dibutyl phthalate, or combinations thereof. These coatings, especially DNT and EC, would tend to inhibit biological degradation but would complicate reclamation. The information on single-base gun propellants is included in Table 7.

**Double Base** — Double-base propellants are softer, have shorter shelf lives, and are more subject to leaching by seawater than are single-base compositions. Flake or ball double-base propellants with high surface-to-volume ratios are used in ammunition for pistols, shotguns, and rifles. These are more liable to degrading attack than are the denser lower-surface-to-volume grains used in larger caliber weapons. A double-base composition is also used in mortar propellants and in many rocket motors. The mortar propellants are sheets or small extruded grains which are designed with relatively high surface-to-volume ratios and high burning rates; the composition and properties of these (Table 8) are similar to those of the double-base formulations shown in Table 7.

Small rocket grains are formed by extrusion, and large ones are formed by casting. Grain diameters for gas generators and cartridge actuating devices may range from a few inches up to 4 feet for large booster/sustainer units. Lengths vary from inches to 12 feet. These grains are mechanically strong colloids or plastics that are permeated only slowly by water. In equilibrium with liquid water at ambient temperatures and pressures the propellant contains 2 to 3% water, depending on the specific composition. The initial and immediate effect of water is a decrease of the mechanical strength, and this effect is reversible. The long-term effect is hydrolysis of the polymer and plasticizers, nitration and oxidation of the stabilizer, and hydrolysis and oxidation of the ballistic modifiers in nonreversible reactions. In the presence of biologically active agents the hydrocarbons and nitrates are consumed. The rate of leaching of soluble salts is low. If aluminum has been added in small concentrations for suppression of resonant burning and to increase delivered energy levels, the aluminum would not be rapidly attacked by salt water due to the passivation of the metal by nitrates and low transport of salt through the colloid.

**Triple Base** — Triple-base propellants (Table 7) have been used exclusively for guns larger than 3 inches but have been essentially phased out. They contain up to 60% nitroguanidine, which is subject to serious leaching by water, and the basic products resulting from decomposition of the nitroguanidine greatly increases the degradation of the remaining propellant. Rework of these propellants after short immersions would not be practical.

**Composite Modified Double Base** — The properties of composite modified double-base propellants and their reactions to seawater (Table 9) are quite different from those of orthodox materials. The composite modified double-base propellants contain nitrocellulose, nitroglycerin, ammonium perchlorate, HMX, aluminum, stabilizers, and plasticizers in various combinations. Water dissolves the relatively high percentages of soluble salts in the structure. The concentrated solutions of ammonia together with the salt present in seawater corrode the aluminum with generation of hydrogen. The resorcinol used as one stabilizer and other water-soluble materials are lost by leaching. The remaining porous network softens and then collapses; subsequent hydrolysis and disintegration of everything except the HMX follows.

Table 7  
Effect of Seawater on Gun Propellants

Type	Principal Ingredients	Type of Coating	Form	Life in Seawater (years)	Identifiable After Immersion	Ignitable When Wet	Usable When Wet	Usable After Drying	Reworkable
Small Arms									
Double base	NC, NG, stabilizer, plasticizer, water	Graphite	Flake or ball	5	Yes	Yes	No	No	Yes
Small-Caliber Guns									
Single base	NC, stabilizer, solvent, water	DNT, EC, or DBP plus graphite	Cylinder, single perforation	10	Yes	Yes	No	No	Yes
Single base	NC, DNT, DBP, stabilizer, solvent, water	DNT, EC, or DBP plus graphite	Cylinder, single perforation	10	Yes	Yes	No	No	Yes
Large-Caliber Guns									
Single base	NC, stabilizer, solvent, water	None	Cylinder, seven perforations	10	Yes	Yes	No	No	Yes
Single base	NC, DNT, DBP, stabilizer, solvent, water	None	Cylinder, seven perforations	10	Yes	Yes	No	No	Yes
Triple base	NC, NG, NQ, stabilizer, plasticizer, solvent, water	None	Cylinder, seven perforations	2	Yes	Doubtful	No	No	Doubtful



Table 8  
Effect of Seawater on Double-Base Rocket Propellants

Application	Composition	Shelf Life (years)	Life in Seawater (years)	Ignitable In Water	Usable When Wet	Usable After Drying*	Reworkable
Motors and cartridge actuating devices in sheets or small grains	NC, NG, stabilizer, plasticizer, $\text{KNO}_3$ or $\text{Ba}(\text{NO}_3)_2$	10	5	Yes	No	Yes	Yes
Rockets and gas generators in small to large grains	NC, NG, stabilizer, plasticizer, modifiers	5 to 8	5	Yes	No	No <sup>†</sup>	No <sup>†</sup>
Rockets and gas generators in small to large grains	NC, NG, stabilizer, plasticizer, modifiers, Al	5 to 8	3 to 5	Yes	No	No <sup>†</sup>	No <sup>†</sup>

\*Assuming a short immersion time.

<sup>†</sup> Possible but not practical.

Table 9  
Effect of Seawater on Composite Modified Double-Base Propellant

Composition	Shelf Life (years)	Life in Seawater (years)	Ignitable in Water	Usable When Wet	Usable After Drying*	Reworkable
NC, NG, stabilizers, $\text{NH}_4\text{ClO}_4$ , Al, plasticizers	5	1	Yes	No	No	Doubtful <sup>†</sup>
NC, NG, stabilizers, $\text{NH}_4\text{ClO}_4$ , Al, plasticizers, HMX	5	1	Yes	No	No	Doubtful <sup>†</sup>

\*Assuming a short immersion time.

<sup>†</sup> The procedures are complicated and possibly impractical.

### Composite Propellants

Modern composite propellants (Table 10) comprise a large and varied family. Grains range from small units used in gas generators to large masses used in ICBM boosters. Small grains may be formed by pressure molding, extrusion, or casting, and large assemblies are cast. Grains may be cartridge loaded or case bonded (cast in place). In general, composites may be described as solid oxidizers and fuels loaded in polymeric binders with the solids comprising as high as 88% of the propellant weight. Binders may be linear polymers such as polyvinyl chloride and cellulose acetate or may be crosslinked rubbers such as urethanes and polybutadienes cured in situ. Many other ingredients may be added for alteration of ballistic properties, mechanical properties, or flame temperature or to achieve other specific effects. All formulations contain stabilizers and antioxidants or other substances that will inhibit biological attack. Like double-base propellants, composites will absorb water until equilibrium is

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Table 10  
Effect of Seawater on Composite Propellants

Composition	Type of Binder	Initial Effect of Water	Long-Term Effect of Water	Life in Seawater (years)	Identifiable After Immersion	Ignitable When Wet	Usable When Wet	Usable After Drying	Reworkable
With Ammonium Nitrate									
Isoprene, $\text{NH}_4\text{NO}_3$ , catalysts, curatives	Crosslinked	Strong swelling, leaching	—	1	—	No	No	No	No
Cellulose acetate, $\text{NH}_4\text{NO}_3$ , plasticizers, catalysts	Linear	Strong swelling, leaching	—	1	—	No	No	No	No
Polybutadiene-methylvinylpyridine, $\text{NH}_4\text{NO}_3$ , plasticizers, catalysts	Crosslinked	Strong swelling, leaching	—	1	—	No	No	No	No
Stable Compositions									
Polyvinyl chloride, $\text{NH}_4\text{ClO}_4$ , plasticizer, stabilizer	—	Slight swelling, some leaching	Leaching, split-off HCl, complete degradation	10	—	Yes	No	No	No
Polyester, $\text{KClO}_4$	—	Very slight swelling	Slow leaching, chain scission, complete degradation	10	—	Yes	No	No	No
Teflon, Viton A, $\text{NH}_4\text{ClO}_4$ , Al	—	Almost none	Leaching, corrosion of Al	10	—	Yes	No	No	No
General Compositions									
Urethane, $\text{NH}_4\text{ClO}_4$ , plasticizer, stabilizer	—	Swelling, leaching	—	3 to 5	Yes	Yes	No	No	No
Urethane, $\text{NH}_4\text{ClO}_4$ , Al, plasticizers, stabilizers	—	Swelling, leaching, corroding	—	3	Yes	Yes	No	No	No
Polybutadiene, $\text{NH}_4\text{ClO}_4$ , Al, plasticizers, stabilizers	—	Swelling, leaching, corroding	—	3	Yes	Yes	No	No	No
Polysulfide, $\text{NH}_4\text{ClO}_4$ , plasticizers	—	Swelling, leaching	—	3 to 5	Yes	Yes	No	No	No
Polyurethane, $\text{NH}_4\text{ClO}_4$ , BDNPA or BDNPF, Al	—	Strong swelling	—	2 to 4	Yes	Yes	No	No	No
Polybutadiene, $\text{KClO}_4$ , $\text{Pb}(\text{NO}_3)_2$ , Al	—	Swelling	—	5 to 8	Yes	Yes	No	No	No
Polyester, HMX	—	Slight swelling	—	5 to 8	Yes	Yes	No	No	No

established. The initial and reversible effect of absorbed water lowers mechanical properties; the leaching and later hydrolytic, corrosive, degradative, and oxidative reactions are irreversible.

Fuel-rich composite propellants are used in air-augmented motors. The two current service versions contain polybutadiene/Al/ $\text{NH}_4\text{ClO}_4$  or polybutadiene/B/ $\text{NH}_4\text{ClO}_4$ . These burn rapidly and completely in air but incompletely without a supply of extra oxygen. These are less hazardous under water than are balanced composites. Otherwise their properties will be similar to those given in Table 10 for the polybutadiene-based propellants containing aluminum.

## Liquid Propellants

Some rocket motors are powered by liquid propellants. A common arrangement for these systems is separate tankage for oxidizers and fuels. An example of this is found in the red-fuming-nitric-acid/unsymmetric-dimethyl-hydrazine system. When the two components are mixed, they are hypergolic (self-igniting). The fuels will also burn in air; they may present a corrosion or toxicity problem. The oxidizers are mostly soluble in or react with water. Under certain conditions they may decompose rapidly in air with explosive force, and they are corrosive and toxic. Considered separately these fuels and oxidizers have the properties indicated in Table 5.

Liquid monopropellants are storable mixtures of fuel and oxidizer with other ingredients added to impart specific properties. The only one in service use is Otto Fuel II, a mixture of propylene glycol dinitrate, dibutyl sebacate, and 2-nitrodiphenylamine, used in the Mark 46 and 48 torpedoes. This material is slightly volatile, slightly soluble in water, and in general will show reactions in seawater similar to those of double-base propellants. The probable life in seawater should be 2 to 4 years. The practicality of rework after significant exposure to seawater is doubtful. Advanced liquid monopropellants are being studied or are in development. The most promising of those, hydroxylammonium perchlorate/organic solvent/water and perchloric acid/piperidine/water are quite water soluble and will disperse rapidly in the sea without leaving dangerous residues.

## Hybrid Propellants

Hybrid propellants are those using liquid oxidizers and solid fuel grains. Simple fuels such as polyethylene are inert but will burn in air; in relatively massive form they may survive in water for long periods without appreciable change. Those containing free metal such as aluminum, magnesium, or boron are only slightly more hazardous in air and will not burn in water; in seawater the metals corrode, and their probable lives are not greater than 5 years. Fuel grains containing metal hydrides such as  $\text{LiH}$ ,  $\text{AlH}_3$ , or  $\text{BeH}_2$  will burn rapidly in air and will react rapidly with water to form hydrogen. Their life expectancy in water, even when they are massive, is quite short, possibly less than 1 week. Liquid oxidizers such as those used in binary liquid systems are used in these hybrid systems. Properties of the oxidizers are as given in Table 5.

## EXPLOSIVES AND IGNITION-ELEMENT, TIME-DELAY, AND TRACER COMPOSITIONS

Compositions used in squibs, igniters, and fuses are usually, but not always, easily ignited mixtures (Table 11). They are designed to produce hot gases, hot particles, or both. These formulations must ignite on demand and burn to produce the required heat or pressure in a specified short time. Traces of water therefore can adversely affect proper functioning, and large quantities of water can completely inhibit action. Many of these compositions, such as black powder, contain essential but highly soluble ingredients. These compositions are used in small quantities, and usually the surface-to-volume ratio is high. Seawater therefore will have a more immediate and drastic effect on these compositions than on the massive and well-consolidated propellants. They may be deactivated in a few minutes in excess water and completely leached in a few hours. In these cases direct identification is impossible, but a reasonably probable conclusion can be obtained by careful examination of residues. Thus a residue of graphite, charcoal, and sulfur can identify black powder by inference.

Time-delay compositions (Table 12) are frequently used in conjunction with propellants and explosives. These powders with high surface-to-volume ratios are used to delay action from the initial trigger to the final ignition. The burning rate must be finely controlled, and minor amounts of water affect performance drastically. The initial effect of water slows the burning rate, since heat is removed by vaporization of the liquid. As a permanent effect, water alters the surface properties of the fuel (metal) and slows the advance of the flame front.

Table 11  
Effect of Seawater on Ignition – Element Compositions

Type and Composition	Life in Water	Identifiable After Immersion	Ignitable When Wet	Ignitable After Drying	Usable When Wet	Usable After Drying	Reworkable
Squib, Igniter, and Fuse Compositions							
Percussion igniter – mercury fulminate, $\text{KClO}_3$ , $\text{Sb}_2\text{S}_3$	1 year	Yes*	Yes	Yes	–	–	No
Black powder – $\text{KNO}_3$ , charcoal, S, graphite	1 hour	Yes*	No	No	–	–	No
B, $\text{KNO}_3$	1 hour	Yes*	No	No	–	–	No
Hot spot – Mg, Teflon	10 years	Yes	Yes	Yes	–	–	No
Hot spot/pressure – Al, $\text{NH}_4\text{ClO}_4$ , oil	1 day	Yes*	No	No	–	–	No
ALA – Zr, $\text{Fe}_2\text{O}_3$ , $\text{SiO}_2$	5 years	Yes	Yes	Yes	–	–	No
Percussion Primer Compositions							
$\text{KClO}_3$ , $\text{Ba}(\text{NO}_3)_2$ , $\text{Pb}(\text{CNS})_2$ , glass, TNT	1 week	Yes*	Yes	–	No	No	No <sup>†</sup>
Basic lead styphnate, tetracene, $\text{Ba}(\text{NO}_3)_2$ , $\text{Sb}_2\text{S}_3$ , Al	1 to 2 years	Yes*	Yes	–	No	No	No <sup>†</sup>
$\text{KClO}_3$ , $\text{Sb}_2\text{S}_3$ , $\text{Pb}(\text{CNS})_2$ , TNT	1 to 2 months	Yes*	Yes	–	No	No	No <sup>†</sup>
Lead styphnate, tetracene, $\text{Ba}(\text{NO}_3)_2$ , $\text{Sb}_2\text{S}_3$ , Zr, $\text{PbO}_2$ , TNT	1 to 2 years	Yes*	Yes	–	No	No	No <sup>†</sup>
Electric Primer Compositions							
$\text{KClO}_3$ , lead nitroresorcinat, NC	1 year	Yes*	Yes <sup>‡</sup>	–	No	No	No <sup>†</sup>
$\text{KClO}_3$ , $\text{Pb}(\text{CNS})_2$	1 year	Yes*	Yes <sup>‡</sup>	–	No	No	No <sup>†</sup>
$\text{KClO}_3$ , diazo dinitrophenol (DDNP)	1 year	Yes*	Yes <sup>‡</sup>	–	No	No	No <sup>†</sup>
$\text{KClO}_3$ , DDNP, charcoal, nitrostarch	1 year	Yes*	Yes <sup>‡</sup>	–	No	No	No <sup>†</sup>

\*By inference from related residue.

<sup>†</sup>Not feasible.

<sup>‡</sup>With heat.

Table 12  
Effect of Seawater on Time-Delay Compositions

Composition	Life in Water (years)	Identifiable After Immersion	Ignitable When Wet	Usable When Wet	Usable After Drying	Reworkable
Si, Pb <sub>3</sub> O <sub>4</sub> , NC, camphor	1	Yes	Yes	No	No	No*
B, BaCrO <sub>4</sub>	1	Yes	Yes	No	No	No*
Zr/Ni alloy, BaCrO <sub>4</sub> , KClO <sub>4</sub>	1	Yes	Yes	No	No	No*
Mg, BaCrO <sub>4</sub> , PbCrO <sub>4</sub>	1	Yes	Yes	No	No	No*
W, BaCrO <sub>4</sub> , KClO <sub>4</sub> , SiO <sub>2</sub>	1	Yes	Yes	No	No	No*
Cr, BaCrO <sub>4</sub> , ClO <sub>4</sub>	1	Yes	Yes	No	No	No*

\*Possible but not practical.

Tracer compositions (Table 13), which are placed in small amounts in a cavity at the fore end of a projectile, are similar in many respects to ignition and time-delay materials. Since tracer compositions are exposed to weather and spray at times, they must be reasonably waterproof and durable. Tracers are used with ammunition for small-caliber guns to provide a line of sight for directing fire; performance, especially in bright sunlight, is not critical for proper functioning of the round.

Table 13  
Effect of Seawater on Tracer Compositions

Composition	Life in Water (years)	Identifiable After Immersion	Ignitable When Wet	Reworkable
Mg, BaO <sub>2</sub> , asphalt	1	Yes*	Yes	No†
Mg, SrO <sub>2</sub> , zinc stearate	1	Yes*	Yes	No†
Mg, Sr(NO <sub>3</sub> ) <sub>2</sub> , KClO <sub>4</sub> , strontium oxalate, calcium resinate	1	Yes*	Yes	No†
Mg, Ba(NO <sub>3</sub> ) <sub>2</sub> , barium oxalate, binder	1	Yes*	Yes	No†
Mg, Sr(NO <sub>3</sub> ) <sub>2</sub> , sodium oxalate, binder	1	Yes*	Yes	No†
Mg, Ba(NO <sub>3</sub> ) <sub>2</sub> , binder	1	Yes*	Yes	No†

\*By inference.

†Possible but not practical.

Warheads with their attendant explosive charges, time-delay fuses, detonators, electronic components, and hardware constitute the payload delivered by most gun and rocket systems. Detonators are either lead azide formulations, mercury fulminate mixtures as shown in Table 11, or similar in composition and properties to the percussion igniters of Table 11.

Booster explosives, usually PETN, tetryl, or RDX/wax may be used in relatively small amounts to amplify the action of the detonator; properties of these will be as shown in Table 5. Main bursting charges may be small or very large projectiles, underwater mines, and large aerial bombs. Usually the cavities are well sealed within the hardware, and the probability that the charges will get wet when immersed in seawater is small. Units under water may be

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expected to last a long time. In some cases mines designed for underwater use have functioned after 25 years of submersion. If the hardware is breached and the explosive is wetted by the seawater, some charges such as TNT in massive form will persist for long times, whereas others such as ammonium picrate are appreciably soluble in water and will be dissipated shortly. The effects of seawater on some high explosives are shown in Table 14.

## ASSEMBLED ORDNANCE

Ordnance ready for use acts or reacts quite differently in seawater than do ingredients or compounded mixtures. These devices and their packaging are designed to withstand rough field and combat usage. The contents are afforded reasonable protection against liquid and vaporized water, and many articles will survive submersion at moderate depths. The number of failures will increase with increasing depth, with only those items in extremely heavy cases such as bombs, projectiles, and warheads able to resist the crushing pressures at greater depths. In general, large articles and rocket motors (with tender weather seals) will be wetted more often at any given depth than small objects such as ammunition for small guns. Cases may also be breached by mechanical damage such as that resulting from collapsing bulkheads and impact from hitting bottom. Corrosion during long-term submersion may result in failure of metal cases, and some plastic fittings may be less durable than metal when subjected to the byproducts of propellant/water reactions. The net result is that one cannot predict whether any article of ordnance has been breached and wetted if submerged at moderate depth. All submerged items must be presumed to be in the original and hazardous state unless proven otherwise.

### Ammunition for Small Arms

Ammunition for small arms is furnished in assembled charges. A shotgun round consists of a plastic case, a brass end-cap with a percussion igniter, plastic wads, chilled shot or lead slug, and rapid-burning double-base propellant. Rounds for pistols and rifles have brass cases with percussion igniters, brass projectiles over steel cores, paper or plastic wads, and double-base propellant. Cartridges are packed in cardboard boxes, and these boxes are further packed in waterproof ammunition cases of galvanized steel. These rounds are small and fairly waterproof. Many will remain hazardous even when submerged at moderately high pressures for long periods. Rounds not wetted can be salvaged and used in emergency situations. They can be recovered, identified, and characterized. Since each individual cartridge is small and rework entails large handling costs, salvage is probably not economically feasible.

### Ammunition for Small-Caliber Guns

Ammunition for small-caliber weapons is similar in construction to rifle cartridges. The warheads of these larger rounds may have bursting charges and some may be tracer rounds. Methods of handling and stowage are similar to those used for small-arms ammunition. In general, cartridges recovered from shallow water after short-term immersion can be identified and characterized. Items from dry cases can be used in emergency situations. The feasibility of general use of dry rounds or of reworking large numbers of salvaged items is questionable.

### Ammunition for Large Caliber Guns

Ammunition for large guns, up to and including some 5-inch, 54-caliber rounds, are assembled like the smaller cartridge cases. Projectiles are of steel, and all projectiles carry bursting charges. They may have proximity fuses, time delays, and other associated devices. Ignition is by an electrical squib, which ignites a secondary larger black-powder charge which, in turn, fires the propellant. These rounds may be quite large and therefore more subject to crushing by hydrostatic pressure or leakage at the seal between projectile and case. Some of these rounds may remain dry in shallow to moderately deep water for long times. They can be recovered, identified, and evaluated. Since failure of a charge can be catastrophic, it is



Table 14  
Effect of Seawater on Explosives

Name	Composition	Initial Effect of Seawater	Life in Seawater (years)	Detonable When Wet	Detonable After Drying	Usable When Wet	Usable After Drying	Reworkable
Amatol	NH <sub>4</sub> NO <sub>3</sub> , TNT	NH <sub>4</sub> NO <sub>3</sub> dissolves	1	No	No	No	—	Yes
Tritonal	TNT, Al	Al corrodes NO <sub>2</sub> groups reduce	1 to 2	Yes	Yes	Doubtful*	—	Yes
Pentolite	TNT, PETN	Little, if any	Over 5	Yes	Yes	Doubtful*	—	Yes
Tetrytol	Tetryl, TNT	Little, if any	Over 5	Yes	Yes	Doubtful*	—	Yes
Picrotol	TNT, D	D dissolves	1 to 3	Yes	Yes	No	—	Yes
PBXN-5	RDX, Viton A	—	Over 5	Yes	Yes	No	—	Yes
Ednatol	TNT, EDNA	—	2 to 4	Yes	Yes	Doubtful*	Yes	Yes
Composition B	RDX, TNT, wax	—	5 to 8	Yes	Yes	Doubtful*	Yes	Yes
Torpex	TNT, RDX, Al	—	2	Yes	Yes	Doubtful*	Doubtful	Doubtful
Composition A3	RDX, wax	—	5 to 8	Yes	Yes	Doubtful*	Yes	Yes
Composition C3	RDX, polyisobutylene, nitrotoluene, DNT, TNT, NC	—	5	Yes	Yes	Doubtful*	Yes	Yes
HBX	TNT, RDX, Al, wax	—	2 to 4	Yes	Yes	Doubtful*	Doubtful	Doubtful
PBXN-103	NC, NH <sub>4</sub> ClO <sub>4</sub> , 2NDPA, MTN, TEGDM	—	2 to 3	Yes	Yes	No	No	No
PBXW-106	RDX, urethane, BDNPA, BDNPF	—	2 to 3	Yes	Yes	Doubtful*	Yes	Doubtful
Octol	TNT, HMX	—	5 to 10	Yes	Yes	Doubtful*	Yes	Yes

\*Detonation may be incomplete.



probably inadvisable to attempt use of salvaged rounds except in cases of great emergency. These shells do represent a considerable investment in hardware, recoverable propellant, and explosive. Rework of such salvaged ammunition, especially that for the 5-inch weapons, may be feasible.

Partially assembled rounds are used for some 5-inch, 54-caliber guns and some 8-inch guns. With these rounds the projectile constitutes one package; the cartridge case containing the electrical igniter, main ignition charge, propulsion charge, wads, and plugs forms the complimentary package. The projectile with its explosive well sealed in steel may be expected to remain in good condition at great depths for long periods. It can be reused if not corroded and if the detonator assembly remains dry. The cartridge case, however, is more susceptible to wetting than is an assembled round. The end plugs (cork on old rounds, plastic on newer units) will yield at relatively low pressures, allowing water to enter the case. The immediate utility of the unit will be destroyed by the action of the water on the secondary igniter (black powder), and the propellant charge will deteriorate rapidly.

Unassembled rounds are used in some 8-inch weapons and in 12-inch and 16-inch guns. Projectiles are a separate package, as with partially assembled charges. The principal ignition system, which is loaded separately, is watertight but at moderate pressures may rupture, take on water, and be deactivated rapidly. Propellant is contained in cloth bags and is also loaded separately. The bags contain igniter charges and flashless pellets ( $\text{KNO}_3$  and  $\text{K}_2\text{SO}_4$ ) if required. The bagged propellant is stored in watertight containers but has no other protection. Once wet, igniters and flashless pellets leach rapidly and the propellant deteriorates over some 5 to 8 years. The propellant can be and has been salvaged and reworked. Rework is practical because usage is large, with about 740 pounds of propellant required for one firing of a 16-inch, 54-caliber gun.

#### Rocket Motors

Solid propellant for rocket motors is either cartridge loaded or case bonded (cast in place). Mechanical property requirements for the two systems are quite different; case-bonded propellant is low-modulus material, whereas propellant for cartridge loads is high-strength, high-modulus material. It is relatively easy to remove a cartridge-loaded grain from the motor; it is only necessary to remove one end of the motor, release the pressure plate, and slide the propellant-and-inhibitor assembly out. Recovery of the propellant and hardware is therefore quite simple. Case-bonded propellant must be cut out with high-pressure water jets. It is practical to salvage hardware by this procedure, but the propellant and liner are irretrievably damaged.

Seals on rocket motors with solid propellants are adequate for protection against weather and normal hazards such as reduced pressure (air-launched missiles) or slightly elevated pressure as in a submarine. Most seals would fail, however, under hydrostatic pressure existing at moderate sea depths. Most propellants and igniters will be wetted and decomposition proceed as indicated in the various tables. When wet, igniters may fire but would probably fail to ignite the propulsion unit, since most of the heat would be dissipated by the seawater. The charge, however, could be ignited from an external source such as a cutting torch. Most units would not operate when wet, and performance would not be satisfactory after drying. Salvaged units, even those in advanced stages of corrosion and decomposition, can be identified by analysis with some accuracy. It is even possible to obtain significant information from burnt-out cases recovered from the sea.

Rockets fueled with binary liquids with each liquid stored in a separate tank are probably not more durable than solid propellant rockets. Failure would first be rupture of the tanks by pressure at moderate depths, with rapid dissipation of the fuel and oxidizer. Hypergolic or spark-ignited motors will not fire when significant amounts of water are present in the combustion chamber. In cases where tankage is sound and fuel delivery systems (pressurizing apparatus or pumps) intact, motors may be used after drying. These considerations also apply to liquid monopropellant and hybrid systems.

## CONCLUSIONS

The resistance of any specific article of ordnance to attack by seawater depends on the type of packaging and packing, structural strength of the assembly, materials of construction, rate of corrosion, tightness of seals, and susceptibility of the propellant, explosive, and associated devices to water damage.

Certain items such as mines, depth charges, and torpedoes are designed for undersea use and will remain intact and operative in seawater for long periods. They have been studied, and life expectancy under various conditions is known. Other items are intended for use in the atmosphere and are not fabricated to withstand ocean conditions. Of the items considered in this report, bombs are the most resistant to crushing or wetting, followed in order by projectiles, small-arms ammunition, small-caliber ammunition, small rockets, large rockets, and partially assembled ammunition.

When the contents of ordnance items remain dry, the salvaged piece may be identified and analyzed with great accuracy. It may be used after inspection in emergency conditions or used without inspection if failure to operate is an acceptable risk. It may be economically feasible to return such items to a central location, inspect them, and return serviceable units to current stockpiles.

It is quite probable, however, that essential parts will be wet by the seawater from leaking seals or crushing by hydrostatic pressure. If contents are wetted, the unit will become non-operative in a short time, but it may remain in a hazardous condition for long periods. Some materials, such as black powder, will be degraded in a matter of hours, but others will persist for years. The rate of degradation will depend on the chemical nature of the materials, water temperature, pressure, salinity, biological activity, and other factors. In most cases salvaged articles and contents can be identified, analyzed, and characterized to a large extent even after prolonged exposure to seawater.

Salvage for reclamation or rework poses other problems. In most instances such processes are not feasible or practical. Labor and hazards associated with recovery, shipping, unloading, and rework of small articles, even in large numbers, precludes such considerations. Large pieces usually contain advanced and complicated propellant and explosive formulations that would be difficult or impossible to rework to obtain reliable, high-performance products. In some cases recovery of large articles to obtain hardware or metals for reuse may be attempted, provided submersion time has been relatively short. In past efforts simple compositions in assembly containers such as single-base propellant in bags or canisters have been recovered, reworked, and used, but these operations cannot be considered as a model for future activities.

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# CORROSION RESISTANT MATERIALS HANDBOOK 1976

## Third Edition

by Ibert Mellan

This famous book, first published in 1966 and now already in its third, greatly enlarged and completely revised edition, will help you cut losses due to corrosion by enabling you to choose the proper *commercially available* corrosion resistant materials for your particular purpose.

The great value of this outstanding reference work lies in the extensive cross-indexing of thousands of substances. The 151 tables are arranged by types of **corrosion resistant materials**. The **Corrosive Materials Index** is organized by *corrosive chemicals* and other *corrosive substances*: it refers you

to specific recommendations in the tables. New in this edition are a separate **Trade Names Index** and a listing of **Company Names and Addresses**.

For the first time there appears also a group of 13 tables comparing the respective anticorrosive merits of commercial engineering and construction materials essential to industry.

The tables in this book represent selections from manufacturers' literature made by the author at no cost to, nor influence from, the makers or distributors of these materials.

### Contents:

1. **SYNTHETIC RESINS AND POLYMERS**  
(87 Tables)
2. **RUBBERS AND ELASTOMERS** (8 Tables)
3. **CEMENTS AND MORTARS** (13 Tables)
4. **METALS AND ALLOYS** (27 Tables)
5. **GLASS AND CERAMICS** (2 Tables)
6. **WOOD** (1 Table)
7. **COMPARATIVE CORROSION RESISTANCES  
OF MATERIALS OF CONSTRUCTION** (13 Tables)
8. **CORROSIVE MATERIALS INDEX**
9. **TRADE NAMES INDEX**
10. **COMPANY NAMES AND ADDRESSES**

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665 pages

# CORROSION INHIBITORS 1976 Manufacture and Technology

by Maurice William Ranney

*Chemical Technology Review No. 60*

Modern corrosion inhibitors with anti-degradant properties not only inhibit the corrosion of metals and other materials, but also stabilize and readjust the medium or environment in which they are applied.

A customary corrosion inhibitor, for instance, will prevent acid attack in an automotive crank case by building up a protective barrier on the surface of the metal substrate by physical adsorption, chemisorption or other reaction with the substrate, but a modern antidegradant corrosion inhibitor will try to forestall the formation of acids in the crank case oil in the first place, while forming a protective coating on the metal as a second step.

Naturally, such corrosion inhibitors must be designed individually for given applications: Aluminum is attacked by alkalis, salts, and certain acids. Concrete is attacked by acids. Iron and its various alloys are very sensitive toward oxygen-containing compounds.

How to design, manufacture and apply such antidegradant corrosion inhibitors is taught in this book which describes over 260 processes relating to the protection of materials susceptible to corrosive chemical action.

A partial and very condensed table of contents follows here. Numbers in parentheses indicate the number of processes per topic or chapter. Chapter headings and some of the more important subtitles are given here.

- 1. COOLING WATER, BOILERS, AND WATER SUPPLY PLANTS (41)**  
Glycine, Chelating Agent, Phosphoric Ester + Divalent Metal Salt  
Silicon-Containing  
Aminomethyl Phosphonates  
Substituted Succinimides  
Benzotriazoles + Tolyltriazoles  
Fatty Amines + Diquaternary Diamine  
Gluconate and Silicates  
Metal Phosphates, Borates and Mercaptobenzothiale + Hydrazine

- 2. AQUEOUS ACIDS—PICKLING BATHS (18)**  
Alkylbenzylalkylsulfonium Salts  
Dicyclohexylthiourea  
Dialkyl Sulfides & Sulfoxides  
Nitriles, Aldoximes, Ketoximes  
Rosin Amine, Ethyloctynol and Propargyl Alcohol

**3. OIL WELL & REFINERY OPERATIONS (46)**

Imidazoline and Hydrazine  
Phenanthridine Phosphonic Compounds  
Phosphoramidates  
1,2-Dithiolium Compounds  
Cuprous Iodide  
Added to Treating Acid  
Weighted Microcapsular Materials  
Antimony & Vanadium Compounds with Alkanolamines

**4. FUEL AND LUBRICANT ADDITIVES (24)**

Cresyl Phosphate Imidazoline Salts  
Fatty Amine Carboxylates  
Ditalow Amine + Stearates  
Succinimide + Polyisocyanates  
Glycerol +  $\alpha$ -Olefin Epoxides  
Terephthalic Acid Dispersions  
Mannich Bases with Boron

**5. FUNCTIONAL FLUID ADDITIVES (21)**

Alkali Metal Organophosphates  
Nitrogen-Containing Antioxidants  
Triphenylborine  
Perfluoroalkylene Ethers for Cavitation Control  
Machine Tool Lubricants

**6. GREASE COMPOSITIONS (17)**

Sulfonate & Naphthenate Salts  
Overbased Sulfonates  
Polymer-Containing Greases  
Microcrystalline Wax + Metal Salts  
Organic Nitrites & Amines  
Fluorinated Polyether + Triazines  
Di-n-Alkylbenzene Oils for Low Temperature Grease

**7. METAL SURFACE TREATMENTS AND COATINGS (34)**

Cobalt-Chromate Treatment  
Vanadium-Contg. Phosphate Coating  
Zinc Phosphatizing Compositions  
N-Oleoylsarcosine

**8. ADDITIONAL APPLICATIONS (30)**

Embrittlement Prevention  
Urea-Formamide Fluids  
Diazo Coating Solutions

- 9. GENERAL PROCESSES FOR CORROSION INHIBITORS (25)**  
Imidazoline + Fatty Amine Emulsions  
Aminoalkyl Phosphonates + Na-Nitrite  
Oil-Soluble Compositions  
Alkenyl Succinimides  
Polyphosphonates

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338 pages

# **TOXIC METALS 1976**

## **Pollution Control and Worker Protection**

by Marshall Sittig

*Pollution Technology Review No. 30*

This is a practical book about those metals and their compounds that are most likely to cause poisoning—in industry while being processed, and in the general environment while the disposal of their process-effluents is being implemented.

Each toxic metal survey gives leads to available information on

- Toxicity**
- Extent of Exposure**
- Detection & Determination**
- Environmental Standards**
- Handling Procedures & Precautions**
- Removal from Air**
- Removal from Water**
- Solid Waste Disposal**
- Economic Impact of Controls**

Specific data are given on permissible intake, acute and chronic toxicities, also on sensitization and the resulting hypersensitivities. In addition some mention is made of possible carcinogenicity and other immunologic pathogenesis as seen in beryllium poisoning.

What is most important and effective in the prevention of toxic metals poisoning is thorough removal of the toxic agents in a manner that positively precludes ingestion or contact by all potential victims, and therein lies the emphasis and main endeavor of this book.

Where it is necessary to remove toxic metals from the air, it is frequently a question of particulate removal. General techniques for their removal from water include

- 1. Chemical Precipitation**
  - a. Lime
  - b. Alum
  - c. Iron Salts
- 2. Chemical Treatment**
  - a. Oxidation
  - b. Reduction
- 3. Ion Exchange**
- 4. Filtration & Ultrafiltration**
- 5. Electrochemical Treatment**
- 6. Evaporative Recovery**

Detailed monographs are furnished for the following metals:

- ANTIMONY**
- ARSENIC**
- BARIUM**
- BERYLLIUM**
- BORON**
- CADMIUM**
- CHROMIUM**
- COPPER**
- INDIUM**
- LEAD**
- MANGANESE**
- MERCURY**
- MOLYBDENUM**
- NICKEL**
- SELENIUM**
- TIN**
- VANADIUM**
- ZINC**

Each survey monograph, including the rather comprehensive introduction, is followed by a detailed list of pertinent references. In the case of government publications complete bibliographical data and report numbers are given in order to facilitate acquisition.

Not discussed in this book are the harmful effects—acute, delayed, or chronic—that may be produced in body tissues by exposure to ionizing radiations from radioactive isotopes of metals. Specialized uses in the atomic energy field require specialized antipollution measures and worker protection far beyond the scope of this book.

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349 pages

# SPECIALTY STEELS 1977 Recent Developments

by G. B. Rothenberg

*Chemical Technology Review No. 83*

This book describes the preparation, properties and uses of special purpose steels. It presents formulation and evaluation data for all types of carbon steels, high strength-low alloy steels, tool steels, stainless steels, heat resisting steels, low carbon structural steels and magneto-electric steels.

The durability and versatility of the various steels is expressed by their wide range of mechanical and physical properties. By the proper choice of carbon content and addition of alloying elements, and with suitable heat treatment, steel can be made so relatively soft and ductile that it can be cold drawn into complex shapes like automobile bodies, or deep drawn into one-piece tubs for domestic washing machines or industrial reactors. Conversely, steel can be made extremely hard to resist wear, or tough enough to withstand enormous loads and shock without deforming or breaking. In addition many steels can easily be formulated to resist rusting and other corrosion by the atmosphere or by chemicals and to withstand extreme heat.

Steel, because of its abundance, durability, versatility and low cost, is probably the most useful metal known to man.

203 processes in all, emphasizing the latest advances in steel production. A partial and condensed table of contents follows here. Chapter headings and important subtitles are given. Numbers in parentheses are numbers of topics.

## 1. CARBON STEELS (20)

- High Strength Steels
- Nitrided Steel
- Cold-Workable Steel
- Steel Wire for Concrete
- Hypoeutectoid Steel
- Silicon-Bearing Steel
- Improving Drawing Properties

## 2. HIGH STRENGTH-LOW ALLOY STEELS (16)

- Cold Rolled Variables
- Corrosion Resistance Factors
- High Impact Cast Steels
- Bainitic Steel for H<sub>2</sub> Embrittlement
- Fragmentation Shells
- Imparting Toughness
- Special Purpose Steel Sheets

## 3. TOOL STEELS (37)

- Ni-Cr-Mo Cast Steels
- Sintered Steels

- Bonded Carbide Hard Alloy
- High Speed Drill Steel
- Press Forging Die Steel
- Columbium Carbide for Wear Resistance
- Vanadium Steels
- Antifriction Bearing Steel
- P contg. Steel Powders
- Machinable Steels

## 4. STAINLESS STEELS (53)

- Oxidation Resistance
- Sulfidation Resistance
- Chloride Pitting
- Steel for Cryogenic Service
- Galling Resistance
- Castable Ni-Cr Steel
- Weldable Stainless Steel
- Low Alloy Valve Steel
- Ferritic Steels
- Martensitic Steels
- Austenitic Steels

## 5. HEAT RESISTANT STEELS (20)

- Creep Rupture Strength
- Deep Drawing
- Nb-Zr-Ti Steel
- Nickel-Chromium-Titanium for Heat Resistance
- Weldable Ferrite Steels

## 6. CONSTRUCTIONAL STEELS (16)

- Low Temperature Steels
- For Arctic Service
- Cold Rolled Steel
- Continuous Annealing
- Notch-Tough Steel
- Hot Rolled Steel
- Use of Niobium
- Good Weldability

## 7. MAGNETO-ELECTRIC STEELS (19)

- Silicon Steels
- Si-Al Oriented Steel
- Single-Oriented Sheets
- High Magnetic Induction
- Silicon-Copper Steels
- Cobalt-Iron Magnetic Alloy
- High Cobalt Magnets

## 8. VARIOUS STEELMAKING PROCESSES (22)

- Imparting Drawability
- Liquid Sintering
- Adding Alloys
- Powder Alloy Steels
- Leaded Steel

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270 pages



# EXTRACTIVE METALLURGY 1977

## Recent Advances

by Edward J. Stevenson

*Chemical Technology Review No. 93*

The efficient extraction and recovery of metals found in the earth's crust or on the bottom of her oceans has become increasingly important as modern industrial societies consume vast quantities of these materials.

With the increased awareness on the part of both the public and the metals-winning industry of the ecological dangers that can arise from continued customary mining procedures and the increased problems of pollution caused by obsolete refining methods, the search for clean low-energy processes has become paramount.

This book describes over 230 processes from the recent U.S. patent literature. The world-wide search for new and efficient metal recovery methods is nowhere more evident than is shown here by the scope of these processes.

Many of these processes encompass the extraction and isolation of several metals. However, for continuity and clarity, the organization of this book is focused on the major metallic component most commonly sought in a given process. Improved uses of raw materials and of human and energy resources are emphasized as is any step that might lead to a cleaner, less energy-consuming process.

A partial and condensed table of contents follows here. Chapter headings and important subtitles are given. Numbers in parentheses indicate the number of topics covered.

### 1. COPPER SMELTING & ROASTING (23)

- Continuous Processes
- Exhaust Gases
  - to Pretreat Pyrite
- Suspension Smelting
- NO<sub>2</sub> Roast Medium
- Vertical Combustion Passage
  - and Cyclone Chamber
- Direct Reduction of Me Oxides
- Oscillating Elongated Furnace

### 2. Cu ACID LEACHING (21)

- Aids to Leaching
- Acetonitrile and SO<sub>2</sub>
- Other Organic Nitriles
- Nitric Acid Leaching
- Solution Mining
- Removal of Selenium

### 3. AMMONIA LEACH (10)

- Chelated Fe Oxidation Catalyst

- Removal of Metal from Solution
- Other Leaching Processes

### 4. CUPROUS CHLORIDE & FERRIC CHLORIDE (10)

- CuCl Electrolytic Recovery
- Sulfur Vapor Reactor
- Chlorine Gas for FeCl<sub>3</sub> Winning
- Other Chloride Processes

### 5. COPPER FROM SOLUTIONS (22)

- Cementation
- Suspended Minipellet Precipitants
- Pig Iron Granules
- Use of Thiosulfates
- Solvent Extraction
- Use of Phenolic Oximes
- Electrolytic Processes
- Very Pure Cu for Electronics

### 6. NICKEL AND COBALT (38)

- General Reduction Processes
- Moving Bed Reactor
- Flotation & Magnetic Separation
- Carbon Monoxide Reduction
- Chlorine Leach:
  - Fluid Bed Construction
- Ammoniacal Leach
- Roast NH<sub>4</sub>-Carbonate Leach
- Co Stripping with Oximes
- Mg(OH)<sub>2</sub> and CaO as Precipitants

### 7. OCEAN FLOOR NODULES (16)

- Halidation
- Low Temperature Process
- Waste Product Streams
  - as Reducing Agents

### 8. Pb, Zn, Mo and Mn (33)

- Lead Recovery from Sulfides
- Reactor Design for Zn
- Automatic Leaching Systems
- Cadmium-Zinc Separation
- Molybdenum by Thermal
  - Dissociation of MoS<sub>2</sub>
- Mn via Transport Compounds

### 9. PRECIOUS METALS (20)

- Alloying Processes
- Aqua Regia Processes for Au
- Ammine Complexes
  - plus Dimethylglyoxime

### 10. U, Ti, Ta, Re, Ga, OTHER METALS (40)

- Static Leaching Under Pressure
- Fluidizing Tower Equipment
- Sodium Aluminate Liquors
  - for Recovery of Gallium
- Slag Fluidizing Agents
- Submerged Smelting
- Solar Evaporators

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255 pages