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Marine Electrochemical Corrosion and Control Systems

T. J. LENNOX, JR.

Metals Performance Branch
Engineering Materials Division

October 1977

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Many aspects of marine corrosion and control systems are covered in this report. The major items discussed include: electrochemical theory, electrochemical reactions, types and causes of corrosion, reference electrodes, galvanic series, typical corrosion performance, corrosion characteristics, cathodic protection, and other methods of corrosion control. Antifouling systems are also discussed. Appendices include a glossary of corrosion terms and a metric guide with selected conversion factors.

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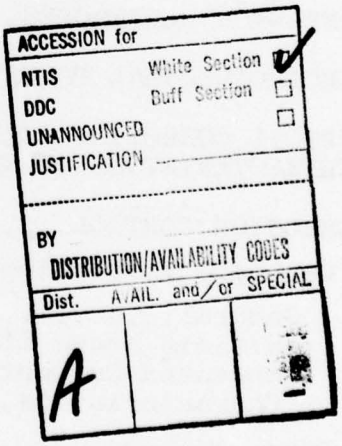
Metric guide
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PREFACE

The Naval Sea Systems Command (NAVSEA) is revising the NAVSEA Technical Manual (NSTM) which deals with Marine Corrosion and Cathodic Protection. As part of this project, the Marine Corrosion Section of the Naval Research Laboratory was requested and funded by NAVSEA to prepare the part of NSTM Chapter 9633 covering "Marine Electrochemical Corrosion and Control Systems."

The "Cathodic Protection Applications" section of Chapter 9633 is being prepared by the Naval Ship Engineering Center (NAVSEC). This latter section will include details on: 1)galvanic-anode design and maintenance 2)impressed-current system design, operation, and maintenance.

The attached Memorandum Report covers NRL's input to Chapter 9633. At some future date and if practical, the separate sections prepared by NRL and NAVSEC will be incorporated into one report.



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MARINE ELECTROCHEMICAL CORROSION AND CONTROL SYSTEMS

INTRODUCTION

This report is intended to provide a basic understanding of marine corrosion and corrosion control for those interested and responsible for maintenance, repair, and design of ships and systems of the Navy and to emphasize the ravages that corrosion can and will play on any metallic system used in or near the ocean. Many aspects of concern will be discussed in an attempt to illustrate corrosion and corrosion-control systems, but as with any document of this type, one cannot supply sufficient information in detail for a "cookbook type" approach to corrosion engineering.

SUPPLEMENTAL DOCUMENTS

NAVSHIPENGCEN Movies

1. Film No. MN-10146A, "Cathodic Protection"
2. Film No. MN-10146B, "Cathodic Protection Operation and Maintenance"
3. Film No. MN-11154, "Corrosion of Metals in Marine Environments"

Other Publications

1. "NACE Basic Corrosion," National Association of Corrosion Engineers, Houston, Texas (June 1975).
2. "Corrosion Handbook," H.H. Uhlig, Editor, John Wiley & Sons, New York (1948).
3. "Corrosion," edited by L.L. Shreir, Vol. 1 & 2, 2nd Edition 1976, Neunes-Butterworth, Boston, Mass.
4. ASTM Annual Standards, Part 10, 1976, American Society for Testing & Materials, Philadelphia, Pa.

Note: Manuscript submitted September 26, 1977.

5. "Marine Corrosion," F.L. LaQue, John Wiley & Sons, Inc., New York (1975).

6. "The Corrosion of Light Metals," H.P. Godard, W.B. Jepson, M.R. Bothwell, Robert L. Kane, John Wiley & Sons, Inc., New York (1967).

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9. Materials Performance - National Association of Corrosion Engineers, Houston, Texas.

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11. Offshore Technology Conference Proceedings, Houston, Texas, May, 1972.

SEAWATER - AN ELECTROLYTIC SOLUTION

Distilled water has a very low conductivity (high resistivity), because it does not contain conducting ions. Water, or other media such as soil, becomes a good conductor of electricity when a sufficient amount of the proper type of ions is present in the water. In corrosion usage, a solution or media in which a structure is immersed has come to be known as the electrolyte, although strictly speaking, an electrolyte is a substance that when added to water makes the solution conductive because of ion formation. One can also have a non-conducting solution; i.e., when a non-ionizable (non-electrolyte) substance, such as sugar, is dissolved in water.

Seawater is a highly conducting solution because it contains relatively large amounts of salts which are highly ionized. Salt (NaCl) is the major constituent in seawater. Table 1 shows the concentration of major constituents and some other constituents found in seawater.

The resistivity of seawater as a function of chlorinity, salinity and temperature is shown in Table 2. Open-ocean seawater is generally considered to have a nominal resistivity of 20-22 ohm-cm at 20°C (68°F). In harbors and estuaries, the resistivity can vary from that of seawater up to several hundred ohm-cm, depending on the amount of fresh water influx and other local conditions.

Because of the variety of ionic species in seawater, it is a buffered solution. The acidity or alkalinity of clean seawater, as described in terms of pH, is nominally 8.2. Again variations can be found depending on local conditions.

The oxygen content of seawater varies from place to place in the ocean. Locations can be found where the seawater is saturated with oxygen while other areas may have minimum-oxygen levels at certain depths. The solubility of oxygen in both seawater and distilled water varies with temperature, as shown in Table 3. Low-temperature seawater will generally contain higher-oxygen levels than high-temperature seawater, and the solubility of oxygen in seawater is less than in distilled water at a given temperature.

The temperature of seawater varies from one geographical area to another and from the surface to depth. The surface temperature ranges between approximately -2°C (28.4°F) and 35°C (95°F). The temperature of a shallow surface layer may be even higher. Seasonal variations are associated with the elevation of the sun and with changes of surface currents which depend on the prevailing winds. The annual variation is generally quite small in the tropics and greatest in the temperate zones. Water at great depths is generally not subject to temperature fluctuations and even in the tropics seldom exceeds 10°C (50°F).

Many of the microorganisms found in seawater are believed to be the early stages of marine fouling. Marine fouling grows on most structural materials when immersed in seawater, especially under quiescent conditions. Fouling may include hydroids, slime, grass, encrustaceous type, barnacles, and large softer types.

Marine fouling most readily attaches to structures when the structures are in stagnant seawater at locations near shore. Heavy marine fouling is generally associated with warmer seawater temperatures. In tropical seawater, fouling will usually occur at any time of the year. In temperate climates, fouling will occur only in certain seasons, i.e., when the seawater is warm. In the cold seawater that may be found in arctic areas, fouling is essentially non-existent.

Fouling in the open ocean occurs only near the surface where sunlight penetrates; principally hydroids and slime. Little or no fouling occurs below 200 meters (660 ft.).

Factors such as the oxygen content of seawater, pH, microorganism/fouling, and seawater temperature all play a part in either accelerating or lessening corrosion and the effectiveness of corrosion control systems.

ELECTROCHEMICAL THEORY

Corrosion is an electrochemical process, i.e., it is caused by interaction between differences on a metal surface

or interaction between different metals electrically connected to one another and immersed in a solution or media that can conduct electricity (electrolytic solution or media). Corrosion processes can best be visualized by reference to the common dry-cell battery as shown in Fig. 1.

When a dry-cell battery is stored on the shelf, the zinc will react with the conducting paste because the zinc surface is not homogeneous. Some areas will be more active (anode-corrosion) than other areas (cathode-no corrosion). Therefore, in long-term storage the zinc case will leak due to the corrosive action of the conductive paste on the zinc. If one bisected a dry cell and could separate corroded and non-corroded areas on the zinc surface, differences in potential could be noted. Figure 2 illustrates what one might find on the surface of zinc removed from a dry-cell battery after a period of shelf storage. The carbon rod does not react with the conducting paste.

However, when the zinc case and carbon rod are connected together by a load, such as a lamp bulb, the difference in activity between the zinc (anode) and carbon (cathode) becomes apparent. Because of the difference in potential between the zinc and the carbon (approximately 1.5 V), a current will flow between the zinc and the carbon. This current can be used to obtain electrical power and in the process the zinc case will corrode. The amount of zinc now consumed will be that due to the corrosion when it was not connected to the carbon rod plus that resulting from the current flow. Theoretically, each ampere-hour of current will consume or corrode 0.0008 kg (0.0018 lb) of zinc; 372 ampere-hours of current, i.e., 1 ampere of current flowing for 372 hours or 2 amperes flowing for 186 hours will consume 0.454 kg (one pound) of zinc.

In the dry-cell operation, the current which leaves the zinc anode flows to the carbon cathode. A piece of steel could replace the carbon rod and a current would flow between the zinc and the steel. The quantity of current flow, however, would be less because the potential difference between the zinc and steel is less. In seawater, the open-circuit potential difference between zinc and steel is nominally 0.5 volt. Based solely on voltage differences and assuming the same geometries for the zinc-steel and zinc-carbon cells, one could anticipate approximately one third the initial current from a zinc-steel cell compared to a zinc-carbon cell. However, these values should be used strictly as examples because other processes occur at both the anodes and cathodes which effect the potentials of the electrodes and the resulting current flow.

When two dissimilar electrodes, as the zinc and carbon in a dry-cell battery, are immersed in a conducting solution or paste and are not electrically connected, each electrode will assume its own characteristic open-circuit potential. The potential of the electrodes will remain essentially constant in the absence of a current flow. When the electrodes are electrically connected, a current will flow between them. This current flow causes electrochemical processes to occur on both the anode and the cathode.

The potential of the anode and the cathode may change as a result of the current flow. The potential of the anode which was originally more electronegative will tend to shift in the positive direction becoming less electronegative, while the potential of the cathode which was originally more electropositive will shift in the negative direction becoming less electropositive. A change in electrode potential as a result of current flow, as described above, is known as electrode polarization.

Cathodic polarization is the electrode process that makes it possible to cathodically protect ship hulls and other structures in seawater. In the case of the dry-cell battery, a depolarizer is added to the paste in order to minimize polarization and obtain maximum current flow. In the case of cathodic protection, polarization of the cathode is the goal so anodes are used which show little or no polarization.

Even though a depolarizer is added to a dry-cell battery, polarization occurs as shown by the fact that the available voltage from the cell is less when connected to a heavy electrical load (low resistance) than when connected to a light load. As a dry cell is used, the depolarizer is depleted resulting in diminished current flow. If it were possible to renew the depolarizer, one could have a dry-cell battery with an extended useful life. The polarization effect on the electrodes (zinc and carbon) in a dry-cell battery caused by the current flow is the reason that the current available from a cell is dependent upon the battery size even though all zinc-carbon dry cells have the same open-circuit potential.

If the concept of the dry-cell battery is understood, one can readily visualize the basic-corrosion process, the effects of connecting together dissimilar metals (galvanic corrosion), and the advantageous use of the corrosion process in providing cathodic protection to a structure which we do not want to corrode, i.e., using zinc anodes or an impressed-current anode system to polarize the hull and prevent, stop, or mitigate corrosion.

ELECTROCHEMICAL REACTIONS

As discussed earlier, essentially all corrosion that occurs in seawater is electrochemical in nature. This is true of corrosion on dissimilar metals when in electrical contact or on different areas on the same metal. This is usually discussed in terms of an anode where corrosion occurs and a cathode where generally corrosion does not occur. In seawater, corrosion occurs only if dissolved oxygen is present. Corrosion of iron in water containing dissolved oxygen can be expressed by the following reaction:

$$2Fe + 2H_2O + O_2 \rightarrow 2Fe(OH)_2 \qquad (1)$$

(iron) + (water) + (oxygen) → (ferrous hydroxide)

If excess oxygen is available, the following secondary reaction occurs:

$$4Fe(OH)_2 + 2H_2O + O_2 \rightarrow 4Fe(OH)_3 \qquad (2)$$

(ferrous hydroxide) + (water) + (oxygen) → (ferric hydroxide)

A similar reaction occurs when zinc is exposed to water containing dissolved oxygen:

$$2Zn + 2H_2O + O_2 \rightarrow 2Zn(OH)_2 \qquad (3)$$

(zinc) + (water) + (oxygen) → (zinc hydroxide)

The latter reaction can be divided into anodic and cathodic parts. The anodic part may be written:

$$2Zn \rightarrow 2Zn^{+2} + 4e \text{ (oxidation)} \qquad (4)$$

(zinc) → (zinc ions) + (electrons)

Simultaneously, a cathodic reaction must also occur in the corrosion process to use up the electrons generated in the anodic reaction:

$$O_2 + 2H_2O + 4e \rightarrow 4(OH)^- \text{ (reduction)} \qquad (5)$$

(oxygen) + (water) + (electrons) → (hydroxyl ions)

Reactions (4) and (5) may occur at separate areas on one piece of zinc or the anodic reaction may occur on the zinc while the cathodic reaction occurs on a dissimilar-metal cathode attached to the zinc. Adding Eqs. (4) and (5) yields the overall equation:

$$2Zn + 2H_2O + O_2 \rightarrow 2Zn^{+2} + 4(OH)^- \rightarrow 2Zn(OH)_2 \qquad (6)$$

(zinc) + (water) + (oxygen) → (zinc ions) + (hydroxyl ions) → (zinc hydroxide)

During the corrosion process, more than one oxidation or reduction reaction may occur. In the corrosion of an alloy, the component metal atoms may go into solution as their respective ions.

When the dissimilar-metals zinc and copper are electrically coupled in water, the reaction at the zinc can also be expressed as:

$$2Zn \rightarrow 2Zn^{+2} + 4e \text{ (oxidation)} \quad (4)$$

(zinc) → (zinc ions) + (electrons)

At the copper cathode, as with other cathodic metals, several reactions are possible. The most common one in seawater would be:

$$O_2 + 2H_2O + 4e \rightarrow 4(OH)^- \text{ (reduction)} \quad (5)$$

(oxygen) + (water) + (electrons) → (hydroxyl ions)

Another cathodic reaction that may occur is hydrogen-ion reduction. This reaction occurs during the corrosion of some metals and in the cathodic protection process but only after all of the available dissolved oxygen at the metal surface is consumed. The reaction can be expressed as:

$$2H^+ + 2e \rightarrow 2H \text{ (reduction)} \quad (7)$$

(hydrogen ions) + (electrons) → (atomic hydrogen)

The atomic hydrogen can either combine and discharge as hydrogen gas or it can enter the metal lattice.

Hydrogen-gas discharge is of concern mainly in confined spaces where the hydrogen can mix with the oxygen present in the air to produce explosive mixtures. Specific concentration of mixtures of hydrogen and air are readily ignited by electrical equipment or other sources of sparking. For example, such a mixture is readily ignited by striking a rusty-steel bulkhead with a steel hammer.

The atomic hydrogen entering the metal lattice is of great concern with high-strength steels (yield strength over 896 MPa; 130 ksi) because the dissolved hydrogen induces embrittlement and failure can occur much below the design loads. Some of the precipitation-hardened high-strength alloys, such as 17-4 PH stainless steels, are also quite susceptible to hydrogen cracking as are high-strength aircraft steels.

It is evident from reaction (5) that during the electrochemical corrosion and cathodic protection processes an alkaline condition develops at the cathode. As indicated previously, there are many constituents in natural seawater, such as calcium, magnesium, and strontium, that will precipitate under alkaline conditions. The precipitation of the calcium, magnesium, and strontium salts causes the white (or calcareous) deposit evident on a cathode such as a ship's hull at certain levels of cathodic protection and may also be evident on the cathode of a dissimilar-metal couple.

The formation and composition of these calcareous deposits are temperature dependent. They tend to form more readily in warmer seawater and in fact if the temperature is sufficiently high, they may form on metal surfaces in the absence of dissimilar-metal corrosion or intentional cathodic protection.

The formation of calcareous deposits on steel surfaces was used as a guide in the early stages of commercial-tanker cathodic protection to indicate the effectiveness of a cathodic protection system. This was based on the fact that if calcareous deposits formed on the tank surfaces the seawater layer next to the metal was alkaline and relatively non-corrosive. In addition, when calcareous deposits are formed, they act as a protective coating. This reduces the amount of electrical currents which must be supplied by the cathodic-protection system.

The high alkalinity buildup on metals such as aluminum, zinc, and lead, caused by excess levels of cathodic protection, may cause severe cathodic corrosion or corrosion by cathodic alkali. Corrosion of these metals under highly alkaline conditions is caused by a secondary reaction between the metal and the alkali generated at the cathode. Metals that corrode as cathodes are known as amphoteric metals because in the general sense they can be dissolved by either acid or alkali. An equation for the alkaline corrosion of aluminum is shown below:

$$3A\ell + 6\ (OH^-) \rightarrow 3A\ell O_2^{-2} + 3H_2$$

(aluminum) + (hydroxyl ions) → (aluminate ion) + (hydrogen)

Cathodic or alkaline corrosion of amphoteric metals, such as aluminum, is a real condition that can cause severe corrosion, especially under quiescent conditions in seawater. Special precautions must, therefore, be taken in attempting to cathodically protect these metals. This aspect will be covered in more detail in the "Cathodic

Protection Applications" Section of Chapter 9633 being prepared by the Naval Ship Engineering Center.

TYPES AND CAUSES OF CORROSION

General or Uniform Corrosion

The most common form of corrosion is general or uniform corrosion. In this situation, corrosion occurs over the entire surface, and the corroded surface is relatively flat. Little pitting is observed and any pits present are shallow. General corrosion does not present a premature failure problem because one can readily design in a corrosion allowance on a structure. Steel is an example of a metal that generally corrodes rather uniformly unless subjected to some specific conditions, such as stray currents on a coated hull.

Galvanic Corrosion

The corrosion that occurs when two or more dissimilar metals are electrically coupled and immersed in a conductive solution is called galvanic corrosion. Galvanic corrosion will occur when zinc is coupled to steel, aluminum is coupled to copper, or steel is coupled to copper. The most active metal will be the anode in the couple and will corrode while generally protecting the other metal, the cathode, from corrosion.

Pitting Corrosion

Pitting is the highly-localized corrosion that occurs on metals such as aluminum and stainless steels. Generally, a metal that depends on an oxide film for inherent corrosion resistance will pit when conditions are such that the protective oxide film breaks down at local areas either by mechanical rupture or chemical dissolution.

Crevice Corrosion

This type of corrosion can be very serious because of its highly localized nature. Crevice corrosion also occurs on metals that depend on an oxide film for protection. Generally, it results from areas on a metal being deprived of oxygen because of built-in crevices in the structure design or incidental crevices that can result from deposits, such as marine fouling or even trash attaching to the metal. Basically, the metal in the shielded or crevice area where the solution is void or low in oxygen becomes the anode, and the metal outside the crevice where the solution is richer in oxygen becomes the cathode. The metal area in

the crevice suffers extremely accelerated corrosion because of the differential aeration (or oxygen) cell which results. Aluminum alloys and stainless steels are susceptible to this type of corrosion in seawater.

Stray-Current Corrosion

Corrosion caused by stray-dc current is becoming a much more severe problem on ship hulls and other metallic structures in seawater. Stray-current corrosion can be caused by: improper grounding and isolation during welding operations, industrial plants using high-dc current, electrical railways, and other sources of dc current. Direct current will corrode almost any metal in a conductive solution. The severity of the corrosion will depend on the quantity of current discharged and the inherent corrosion characteristics of the metal in the particular solution in which the metal is exposed. Some metals, such as titanium, columbium, and tantalum which are used as the base metal for platinum clad or platinzed anodes in a cathodic protection system, require relatively high-minimum voltages to break down their protectives films in seawater. Actual data are subsequently shown in this report.

In seawater, stray current will cause severe corrosion on most structural alloys. With most metals, the corrosion will occur only where the current is discharged into the water. This is not the case, however, for aluminum, zinc, and other alloys which are amphoteric and can be corroded by excessive alkali formed at the location (the cathode) where stray currents are picked up from the water.

Stray-current corrosion will be more severe on well-coated structures than on bare structures because the discharged current will be concentrated and will flow from the structure principally at bared or pinhole areas. In many instances, it is extremely difficult if not impossible to determine the actual source of the stray currents.

Fretting Corrosion

At locations where two or more metals are joined mechanically, a type of corrosion known as fretting corrosion can occur. In situations where fretting corrosion occurs, the corrosion will generally be of the type which is characteristic of the metals in the environment. In the case of fretting corrosion, any protective film that might normally form on a metal is removed by the rubbing or sliding of the faying surfaces. Thus, one can observe any form of corrosion at a fretted surface.

Exfoliation Corrosion

A type of corrosion that can occur on aluminum alloys, including some 5000 and higher-strength 7000 series alloys in certain tempers or conditions, is known as exfoliation. This type of corrosion is characterized by the surface developing a delaminated appearance, which progresses approximately parallel to the outer surface of the metal.

Velocity Corrosion

Velocity corrosion is caused by the breakdown of protective films on metals by chemical or mechanical means. Once the film or certain portions of the film is lost, corrosion can proceed by galvanic corrosion or straight electrochemical dissolution of the bared surfaces. With some alloys such as stainless steel which depend on the development of a protective oxide film for their corrosion resistance, velocity, especially that associated with oxygen renewal, can be extremely beneficial to the corrosion resistance of the alloys. Under such velocity conditions, protective oxide films will form and protect the alloy from corrosion.

Perhaps an even more serious condition exists when differential velocity is encountered in a system. With some metals and alloys, differential velocity across the surface can result in severe galvanic effects, i.e., a significant potential difference may exist between one location on the surface and another caused by the difference in velocity at local areas across the surface. Differential velocity may be the cause of much of the accelerated corrosion observed when certain metals or alloys are exposed to velocity conditions.

Cavitation-Erosion

Other causes of corrosion associated with velocity are cavitation and erosion. Erosion is generally associated with mechanical deterioration of metals, i.e., similar to what one might see or experience when tides or seawater waves erode the land. Cavitation on the other hand can apparently be considered both a mechanical and an electrochemical phenomenon and is basically the result of excess velocity associated with turbulence on a metal. The erosion may cause a relatively uniform lose of metal from a "sanding action" whereas the lose of metal caused by cavitation will be highly localized removal of metal in the form of craters.

Pollution and Chemical Effects

Corrosion in seawater and harbor or brackish water can be altered drastically by pollution or chemical contamination. Metals and alloys normally depend on development of a protective film on their surface for inherent corrosion resistance, i.e., a barrier is developed between the metal and the corrosive solution. If an inadequate-protective film develops or if it is destroyed chemically, corrosion of the metal will occur.

A case in point is the severe corrosion of copper-nickel condenser tubes that occurred on ships at a fitting-out basin where the water was apparently contaminated with sulfide. Copper-nickel condenser tubes have provided many years of satisfactory service in Navy ships. This undoubtedly has been the result of the proper-protective films being formed on their surfaces. It has long been known that satisfactory-protective films develop in good, clean seawater. It has also been known that traces of iron present in the water either from iron-waster plates or steel headers have produced films on copper-nickel tubing that have been fully protective. Sulfide contaminated seawater or brackish water will result in a non-fully protective film on copper-nickel alloys with resultant severe localized corrosion.

A practical remedy to the situation of corrosion of copper-nickel condenser alloys by sulfide has been the injection of ferrous sulfate into the water or the electrolytic introduction of ferrous ion by the dissolving of iron as an anode in the water.

Stress Corrosion and Corrosion Fatigue

Two causes of premature failure of metal alloys used in seawater are the combined action of stress and corrosion (stress corrosion) and the combined action of fatigue and corrosion (corrosion fatigue). Neither of these causes of corrosion places high on the list of incidences for failure on surface ships, but they are recognized as serious because the failures which occur generally are of a catastrophic nature and therefore receive much attention.

Intergranular Corrosion

Another characteristic type of corrosion is based on the fact that metals are generally heterogeneous not only with respect to chemical composition but also with regard to microstructure. The heterogeneity with regard to

microstructure results in preferential corrosion at the grain boundary. This type of corrosion is called intergranular corrosion. It can be caused either by a chemically active grain boundary or a grain boundary that is galvanically active compared to the grain body.

REFERENCE ELECTRODES

There is no absolute means of determining the potential of various metals in specific solutions. One can only determine the relative potentials as measured to a reference electrode. Several types of reference electrodes are used in the laboratory and in field work. The characteristics of these reference electrodes are such that their potential at a given temperature is constant relative to a standard electrode (the saturated hydrogen-platinum electrode). The standard-hydrogen electrode is not used in field studies; it is used only for the most precise laboratory studies because of its size and complexity.

The more common electrodes for practical use in both the laboratory and the field are the saturated calomel electrode (SCE), the saturated copper-copper sulfate electrode (Sat. $Cu/CuSO_4$), and the silver-silver chloride-seawater electrode (Ag/AgCℓ/seawater). Each of these electrodes requires a bridge solution in conjunction with the metal and metal-salt component of the electrode. In the SCE, the solution is saturated KCℓ. In conjunction with the copper-copper sulfate electrode, the bridge solution is a saturated solution of copper sulfate. In the case of the Ag/AgCℓ/seawater reference electrode, the bridge solution is the seawater in which the electrode is immersed. Because no special-salt bridge is required, the Ag/AgCℓ electrode is the most practical and commonly used electrode in seawater.

High-purity zinc immersed directly in seawater is sometimes used as a reference electrode for special purposes because of its low cost and rugged mechanical properties. The potential of zinc in seawater is relatively constant, but measurements made with zinc electrodes are less accurate than with the more commonly used electrodes described above.

Reference electrodes used with the proper salt bridge have a constant voltage relationship. The potential of the Ag/AgCℓ/seawater electrode, which is used by the Navy to control cathodic-protection systems on ships, will vary somewhat with dilution of the seawater by fresh water. Studies have been made comparing these differences to the other commonly used electrodes, and a nomogram giving these comparisons is shown in Fig. 3.

ELECTROCHEMICAL POTENTIALS (Galvanic Series)

Many metals and alloys do not show a specific-stable potential in seawater, i.e., their potential will fluctuate with time of immersion. Metal and alloy potentials can be arranged in a "Galvanic Series", however, such a series is shown in Fig. 4. All potentials are relative to the Ag/AgCℓ/seawater reference electrode.

The mean potential and range of potentials for each metal and alloy are shown for quiescent seawater conditions. For some metals and alloys, potentials are also shown for velocity conditions up to 3.9 meters per second, m/s, (13 feet per second, fps). Very few metals or alloys exhibit single potential values; generally, a range of potentials are observed. Figure 4 also shows that the mean potential and range of potentials may differ considerably with exposure condition, i.e., quiescent seawater versus velocity conditions.

The galvanic-anode alloys of magnesium, zinc, and aluminum each show a relatively constant potential although the potential may vary over a narrow range. Constant potential when supplying current for a cathodic-protection system is a critical attribute required of galvanic anodes if they are to protect the hull of a ship or other structure from corrosion.

Potential data can be used as a guide to indicate whether corrosion might be expected when two metals are electrically coupled in seawater. The metals with the greatest potential difference will provide the most active couple, with the more negative (active) metal or alloy in the couple being the anode and susceptible to corrosion while the less negative (less active) component, the cathode, generally will be protected from corrosion. For example, the more negative aluminum alloys will show accelerated corrosion when coupled to the less negative copper alloys.

Although the potentials of metals, as shown in Fig. 4, will assist in qualitative predictions with regard to galvanic corrosion, other factors such as polarization of each metal in the couple will have a significant effect. This is indicated by the fact that more readily polarizable, less negative (cathodic) metals will cause less detrimental corrosion effects on the more negative (anodic) metals. Environmental factors, specific in many applications such as oxygen content, water velocity, and other local conditions, limit the predictive capability in corrosion engineering.

Generally, the best predictive capability is based on previous experience on the use of materials for specific applications.

If one electrically couples metals with a large-potential difference, such as aluminum and copper, accelerated corrosion will occur on the more active metal (aluminum). However, if the metals copper and lead are coupled in seawater, one would not expect a serious galvanic corrosion situation. One can also see from this galvanic series that zinc anodes will cathodically protect steel, most aluminum alloys, and other metals with less negative potentials.

Other more complex relationships, which cannot be explained on a quantitative basis, can also cause severe-corrosion problems. For example, although it is usually necessary for dissimilar metals to be electrically connected to cause galvanic corrosion, aluminum alloys may be severely corroded by adjacent-copper alloys even though there is no metallic contact.

In this case, the copper ions produced when the copper alloy corrodes are redeposited (plated out) on the aluminum surface. The aluminum alloy is then corroded by galvanic action between the aluminum and the copper deposited on the surface.

This effect is more common with copper or high-copper alloys, such as brass, but has also been observed on aluminum when in the proximity of nickel-copper alloys. This occurs because the amount of redeposited copper required to cause corrosion of the aluminum is very small.

The beneficial effect of ease of polarization of the cathodic metal becomes evident when one couples an aluminum alloy to a stainless-steel alloy. The galvanic series indicates a potential difference of several tenths of a volt. Based on this information, a serious-galvanic couple with accelerated corrosion of the aluminum would be anticipated. Stainless steels, however, are known to cathodically polarize quite readily in seawater. Therefore, when stainless steel is coupled to aluminum, the accelerated corrosion on the aluminum is not as severe as would be anticipated from the potential differences shown in the galvanic series.

Another factor affecting the extent of galvanic corrosion is the relative area ratio between the anodic metal and the cathodic metal in a galvanic couple. For

example, when an aluminum alloy is coupled to a copper alloy, it is preferable to have a relatively large area of aluminum coupled to a small area of the copper alloy. This will minimize the corrosion of the aluminum.

The area ratio of anode to cathode is significant in other types of corrosion, such as differential-aeration corrosion, because the severity of corrosion depends on the current density at the anodic areas. For a fixed value of current, the current density will be larger and the corrosion more severe when the anode area is small. If the same current is discharged from a larger-anode area, the current density will be lower and the corrosion less severe.

The extent of galvanic corrosion, crevice corrosion, dealloying, and some other types of corrosion will depend not only on potential differences and polarization but also on the relative area ratios between the susceptible material and the more cathodic metal or the cathodic area on the same metal.

A coating (paint) on a ship's hull or structure is also critical in the area relationship concept. As an example, consider a steel ship with one or more bronze propellers. If the hull is uncoated, a suitable relationship exists for general corrosion to occur on the steel hull. In contrast, when the steel hull is coated and imperfections exist in the coating, the corrosion on the steel hull will be concentrated at the coating imperfections. Under such conditions, although the overall-area ratio of hull-to-bronze propeller is favorable to uniform corrosion, the imperfect coating system will cause highly accelerated localized corrosion on the steel hull. Although such circumstances are of concern principally when no cathodic protection is provided to a hull or structure, the concept of altering conditions to unfavorable relative area ratios by applying coatings should be kept in mind.

Another special case is the accelerated corrosion of alloys susceptible to dealloying (e.g., the dezincification of brasses) when coupled to a less negative metal. The rate of dealloying may be greatly increased under this condition. For example, accelerated dealloying has been observed on yellow brass coupled to titanium in seawater. This type of accelerated corrosion can usually be prevented by cathodic protection.

Although metals and alloys that exhibit the more electronegative potentials are known as active, the

potential data in Fig. 4 do not indicate the relative inherent corrosion resistance of metal and alloys. Within a given class of metals, however, some limited conclusions can be drawn. Aluminum alloys with mean potentials more negative than -0.92 volts to the Ag/AgCℓ reference electrode appear to be less susceptible to localized corrosion than aluminum alloys with more positive mean potentials. In contrast, with stainless steels, there have been some preliminary indication of the reverse situation, i.e., alloys with the more positive-electrochemical potentials may be less likely to corrode in seawater.

Potential data are of value in providing information on the feasibility of cathodically protecting various metals in seawater. The data in Fig. 4 indicate that it is possible to cathodically protect mild steel and low alloy steels in seawater with galvanic anodes, and protection of these alloys is generally routine. The potential data also indicate that mild steel will cathodically protect most of the stainless steels from corrosion. It has been observed that stainless steels without some type of protection, i.e., either coupled to a mild-steel hull or provided with cathodic protection either from galvanic anodes or an impressed-current cathodic protection system, are very susceptible to crevice corrosion. Iron (mild steel) anodes are known to be effective in preventing crevice corrosion of stainless steel, but in some instances pitting is not always completely eliminated. Higher-potential galvanic anodes or impressed-current anodes will provide more complete protection.

Potential data are suitable in many instances in predicting that one metal may protect another but cannot be used to predict whether a metal will be detrimentally affected by hydrogen or other electrochemical-reaction products at the cathode.

In the case of hydrogen effects, it must be remembered that hydrogen may be produced during the normal corrosion of some metals in seawater. The degree of detrimental effects from hydrogen, produced in the normal-corrosion process of susceptible alloys, is not specifically known. It is known, however, that susceptible alloys such as certain high-strength steels and precipitation-hardened stainless steels are detrimentally affected by hydrogen produced in the cathodic-protection process even when the level of protection is no higher than the potential required to protect mild steel in seawater, i.e., a potential of approximately -0.80 volts to the Ag/AgCℓ/seawater reference electrode. Detrimental

effects on the load-bearing capacity of some precipitation-hardened stainless steels have been observed at the potential of a zinc anode, i.e., approximately -1.0 volt to the Ag/AgCℓ/seawater reference electrode.

Alkaline conditions which develop at the cathode may be detrimental to alloys of aluminum, zinc, and other amphoteric metals. In the case of aluminum alloys, the corrosion at the cathode may be as severe or more severe than the corrosion of the same aluminum alloy acting as an anode under similar conditions. Thus, great care must be excerised in attempting to cathodically protect ship hulls or other structures fabricated from amphoteric metals or alloys.

The 400-series stainless steel normally are not considered for use in seawater because of their poor-corrosion resistance. It has also been observed that cathodic protection can have detrimental effects on the 400-series stainless steels. These detrimental effects usually are observed as hydrogen blisters and in extreme cases cracking.

TYPICAL CORROSION PERFORMANCE AND CORROSION CHARACTERISTICS OF METALS AND ALLOYS

The development of a protective film on a metal surface is its primary defense against corrosion. Some metals develop protective films on their surfaces while others do not. If a metal does not develop a protective film on its surface in a particular environment, the metal will corrode at its initially-high rate for the total time of exposure to the environment. In most instances, the specific environment and conditions to which a metal is exposed will be key factors in determining whether a protective film will develop on the metal surfaces. In some instances a metal may have an inherent-protective film on its surfaces that will prevent it from corroding in that environment. However, when the environment or conditions, such as velocity, are changed, the protective film can breakdown either locally or in its entirety. Protective films can be inherent to a metal or can be artificially produced either in the environment to which the metal is to be exposed or in a controlled-chemical bath environment prior to exposure in the working environment.

Most metals will be protected by films in some environments. Generally, the metal films that are protective are those which are insoluble in the specific environment. Protective films of the oxide type are

responsible for the inherent corrosion resistance of titanium and some aluminum and chromium-steel alloys in specific environments. Lead sulfate builds up as a protective film on lead to make lead one of the most resistant materials in sulfuric acid. Zinc develops protective films on its surface in selected fresh waters that are generally hard and contain carbonate. Softened water which has lower carbonate content is generally more corrosive to zinc and its alloys.

Very few metals or alloys develop fully protective films on their surfaces in seawater. The most resistant metals for seawater applications are: titanium alloys, some aluminum alloys, some copper alloys, and some nickel alloys. With most alloys, one has to know the intended conditions of service application before a judgment can be made as to satisfactory use because there are conditions under which most metals or alloys will corrode in seawater.

One of the basic mistakes made by designers of equipment for use in the ocean is to accept literally that stainless steels are corrosion resistant in seawater. If one will study the technical literature rather than some of the older sales type literature on the corrosion performance of materials, it will be obvious that stainless steels should not be used in seawater without supplementary protection, especially under quiescent conditions or intermittent quiescent conditions. Under some conditions, e.g., in a continuous service pump where continually aerated seawater is passed over the surface, stainless steels may give satisfactory service. However, both satisfactory and unsatisfactory performance have been observed in nominally identical usage.

There are many applications in seawater where it is evident to the novice that indeed stainless steel is truly corrosion resistant because it has held up very well as a thru-hull penetration gland or fitting. The true reason that a stainless-steel part will give the appearance of being corrosion resistant in quiescent seawater is that the stainless steel was in fact bonded electrically to the steel hull which provided sufficient cathodic protection to make it essentially corrosion free. If this same stainless-steel part was not bonded to the steel hull or some other source of cathodic protection, it would undoubtedly be corroded severely at crevices and possibly other local areas where crevices had built up as a result of some incidental attachment or marine growth. Another word of caution to the designer of equipment for

seawater use is the fact that it is generally impossible to prevent crevices from being formed under debris or marine fouling, i.e., it is generally impractical to eliminate crevice corrosion even though crevices have been designed out of the system.

Tables 4-8 give data on the corrosion rates, maximum depths of corrosion, principal types of corrosion and maximum-depth rates per year for aluminum and its alloys, copper and its alloys, nickel and its alloys, steels and stainless steels, and miscellaneous alloys.

The data in Tables 4-8 have been derived from several sources.* In most instances the data can be regarded as "typical corrosion engineering type data" because they have been obtained in natural seawater on relatively large-size specimens exposed for extended periods.

It has long been the judgment of practicing corrosion engineers that short-term data obtained on small laboratory-size specimens in synthetic environments cannot be relied upon to provide "engineering type data" suitable for seawater applications. Thus, the data shown in Tables 4-8 are considered the best available, short of obtaining data from an actual structure fabricated from the alloys of concern. As with any "corrosion engineering type data," the data presented in Tables 4-8 are still incomplete with regard to final-engineering design. Whenever possible, the choice of an alloy for seawater service should be based on experience with identical or similar designs.

These data also emphasize that corrosion data are variable; a range of corrosion rates and maximum depth of corrosion will be observed for any one metal or alloy. These variations are undoubtedly due in part to differences in the homogeneity of the alloy and subtle differences in local environment and exposure conditions. For many of the alloys, even slight differences in seawater velocity can cause significant differences in corrosion and corrosion characteristics. This is illustrated by the data for Aluminum and Its Alloys in Table 4.

For critical structures, it would behoove the designer to fabricate an item for use in the sea of the most corrosion-resistant materials where this can be justified. If this is not feasible, then the second best approach would be the use of less corrosion-resistant material supplemented with an adequate coating and cathodic-protection system. As indicated previously, most

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*see references included with each table

structural alloys can be effectively cathodically protected by a suitably designed cathodic protection system.

Details on cathodic-protection applications and design in the Navy using galvanic and impressed-current systems and maintenance for these systems will be covered in the "Cathodic Protection Application" Section of Chapter 9633 being prepared by the Naval Ship Engineering Center.

CORROSION CONTROL

There are several basic methods that can be used to stop or prevent corrosion. The primary-corrosion control method is the selection of the correct metal or alloy for the service conditions anticipated. The many items discussed earlier as factors affecting corrosion must be considered. Even with all this information available, however, it is not a menial task to always properly and economically select the proper alloy.

During the selection of metals or alloys for an anticipated-service condition, the use of a less corrosion-resistant material protected by a coating and/or cathodic protection must also be considered for economic reasons.

A widely used method of providing corrosion resistance to susceptible alloys is the application of galvanic or sacrificial coatings such as zinc or aluminum. In most cases, these coatings can be applied by more than one method. The relatively-thin coatings are applied by either hot dipping or electrolytic deposition. Heavier coatings are generally applied by metal spraying. Depending upon the intended use, the sacrificial coatings can be sealed and top-coated with organic coatings or left bare.

Cathodic Protection

General

Cathodic protection is an electrochemical method used to prevent or stop corrosion. There are two types of cathodic-protection systems. In the most basic system, anodes of a metal alloy, such as magnesium, zinc, or aluminum, provide the current galvanically because of the relatively electronegative potentials of these metals compared to the metal being protected. This type of cathodic protection is known as the galvanic-anode system. The second type of cathodic-protection system is known as the impressed-current system. In this system, the anode used is relatively inert and a voltage is impressed on the

anode. The direct-current (dc) voltage and current are supplied either from a dc motor generator or by rectifying alternating current.

In the general scheme of protecting against corrosion of submerged portions of ship hulls (or other structures), the primary defense is an organic coating (paint) system. Such a coating is usually supplemented with a cathodic-protection system to protect areas that are uncoated, such as drydock block areas or pinholes in the coating. Pinholes generally exist in most organic coating systems because it is essentially impossible to obtain a pinhole free coating. A properly designed cathodic-protection system will also provide protection to areas on a hull that become bared in service due to the deterioration of the coating for whatever cause.

Cathodic protection functions by supplying sufficient current to ship hulls so that all areas on the hull assume relatively uniform potentials and thus effectively eliminate local anodes on the hull. On a corroding hull, some areas are active (anodic) and corrode while other areas are inactive (cathodic) and do not corrode. By supplying dc current, the hull polarizes until the potentials of the local cathodes become as negative as the local anodes. Under these conditions, the discrete anodes and cathodes are eliminated, and corrosion does not occur on the structure.

The most often used galvanically active metals for cathodic protection systems are alloys of magnesium, zinc, and aluminum. These anode metals are used to cathodically protect steel and other less active metals in seawater. In certain special instances, other metals more active than the metal to be protected have been used. Iron (steel) anodes are known to provide cathodic protection to stainless steel and thus eliminate crevice corrosion in seawater. Iron has also been shown to be beneficial for the protection of copper-nickel piping in seawater. However, this protection is not a true cathodic protection effect but rather the presence of dissolved iron from the waster plates improves the protective film on copper-nickel in condenser tube applications.

Galvanic Anode Electrochemical Characteristics

Table 9 summarizes the electrochemical characteristics and properties of the commonly used galvanic anode alloys of magnesium, zinc, and aluminum. As mentioned previously, iron (steel) anodes can cathodically protect other metals, notably stainless steels, in seawater. However, no

systematic study has been made on the electrochemical characteristics of steel or iron anodes for use as galvanic anodes. Therefore, data for iron are not included in Table 9.

One of the primary requirements for galvanic anodes is an ability to continually provide useful current. All of the anodes listed in Table 9 have the ability to continuously provide current. The amount of current provided will depend on the type, size, and shape of anodes used. The design aspects of using galvanic anodes for cathodic protection will be covered more completely in the "Cathodic Protection Application" Section of Chapter 9633. However, it is imperative that galvanic anodes used in seawater be procured to meet the Military Specifications, shown in Table 9.

Impressed-Current Anode Electrochemical Characteristics

There are several types of impressed-current anodes used for the cathodic protection of ship hulls and other structures in seawater. These anodes include platinum clad or platinized titanium, columbium, and tantalum. The characteristics and properties of the base metal used for these anodes and for platinum are shown in Table 10. For active Navy ship hull protection, platinized or platinum clad anodes are used exclusively.

Other impressed-current anodes available for use in seawater include: silicon iron, graphite, lead-silver, lead-antimony-silver, and lead with platinum buttons. Some of these anodes have been used for protection of both active and inactive ship hulls. Each of these materials has specific drawbacks such as: brittleness (silicon-iron and graphite), mechanically soft materials (lead-silver, lead-antimony-silver, and lead with platinum buttons). These drawbacks plus the fact they must operate at limited and low-current densities to obtain satisfactory useful life makes the platinum-clad or platinized anodes more desirable for Navy and other uses. Table 11 shows the consumption rate of impressed-current anodes.

Impressed-current anodes mounted directly on a hull (or structure) require a dielectric shield beneath and adjacent to all anodes in order to prevent the wastage of current to the hull. Magnesium galvanic anodes also require a shield to prevent current wastage when attached directly to the hull or structure being protected. The size and type of dielectric shields required will be covered in detail in the "Cathodic Protection Application" Section of Chapter 9633.

Other Methods

Deoxygenation

Deoxygenation is the removal of oxygen from a solution. This can be accomplished by bubbling an inert gas through the solution, by raising the temperature of the solution sufficiently to dispell the oxygen, or by adding chemicals to the solution which remove the oxygen by reacting with it. Deoxygenation is used for feedwater for high-pressure boilers and for some sonar domes.

Inhibitors

Inhibitors used to reduce the corrosion of metals (or alloys) include: soluble oils, chromates, and organic inhibitors. A major difficulty in the application of corrosion inhibitors is the variation of the oxygen content of the water from point to point in the system. In a thin layer of water between a flake of scale and the metal on which it is lying, the oxygen can be depleted. The difference in oxygen content between the body of water and the stagnant water will set up a corrosion current which is difficult to suppress.

Inhibitors are commonly used in small amounts and added continuously or intermittently to prevent corrosion of metals. Generally, the concentration of the inhibitor required can only be determined on the basis of experimental laboratory studies, service trials, and overall practical experience.

Successful use of inhibitors requires considerable knowledge of their action and a thorough understanding of the system under consideration. Inhibitors are rarely used in the form of single compounds. It is more usual for formulations to be made from two, three, or more inhibitors because individual inhibitors are effective with only a limited number of metals. Substances that may successfully reduce or eliminate corrosion on a metal in one environment may stimulate corrosion on the same metal in other environments. In still other environments, although decreasing the overall corrosion rate, the inhibitors may bring about an increase in the intensity of corrosion at restricted anodic areas, leading to pitting and rapid perforation.

Before deciding on the use of inhibitors, one must consider the economics, i.e., does the loss due to corrosion exceed the cost of the inhibitors, maintenance, and

operation of the inhibitor system. Selection of the concentration and type inhibitor must also be based on consideration of the disposal problem. It is also important to ensure that an inhibitor is chemically compatible with the liquid to which it is added.

Generally, a certain minimum concentration of an inhibitor is required although the initial concentration is usually higher than the maintenance concentration. Inhibitors are widely used to control corrosion but usually are related to specific circumstances. An inhibitor concentration must be established for a specific application for a specific system and generally the same inhibitors and concentrations may not be applicable to other systems.

The presence of certain ions, such as chlorides and sulfates, tend to oppose the beneficial action of inhibitors. Generally, the concentration of inhibitors required for protection depends on the concentration of the aggressive ions, i.e., chloride, etc. Clean, smooth metal surfaces usually require lower concentrations than rough or dirty surfaces. Contaminated metal surfaces also effect the concentration of inhibitors required. Inhibitors usually have a specific limited pH range over which they are most effective.

Some inhibitors are considered safe and others dangerous. When present in an insufficient concentration, a safe inhibitor will allow only uniform corrosion. Dangerous inhibitors will lead to enhanced localized corrosion, e.g., pitting, and make the situation worse. Chloride ions have a depassivating effect and, therefore, it is important to maintain inhibitor concentration at a safe level in waters containing chlorides. Higher concentration of inhibitors is usually required with higher temperatures.

Waters containing appreciable quantities of organic matter may not be inhibited with oxidizing inhibitors, such as chromate and nitrates, because the organic matter consumes the inhibitor. Generally, organic inhibitors at low concentrations (10-20 ppm) offer the best protection in organic contaminated brines. Inhibitors may also lose their effectiveness due to microorganism breakdown and depletion of the inhibitor by bacterial attack. Inhibitors may also serve as a nutrient source for some microbial organisms. Inhibitors are not always effective against stress corrosion, fatigue, fretting, or cavitation effects. In crevice corrosion, inhibitor access can be a problem.

Vapor-phase inhibitors (VPI) are compounds which are transported in a closed system by volatilization. The

potential user of VPI may have to test several of those commercially available prior to establishing the most suitable one for a particular application.

Toxicity, disposal, and effluent problems with inhibitors are receiving greater attention. These place severe restrictions on the choice of an inhibitor with a move toward low chromate-phosphate. For some applications, even this approach is not acceptable. Inhibitor formulations from biodegradable chemicals are being introduced.

Anodizing

Although anodic films can be formed on many metals, only aluminum and its alloys and to a lesser extent magnesium are anodized on a commercial scale, mainly for atmospheric-corrosion protection. Anodizing, an electrolytic process, will produce a thick nonporous oxide coating on the metal surfaces in a suitable solution.

Anodizing provides aluminum with some degree of improved-corrosion resistance in atmospheric-service exposure, but the additional protection obtained is not spectacular. Anodized coatings provide a good base for paints on aluminum, which is otherwise difficult to paint without special surface preparation. Anodic coatings give increased adhesion and life to paint coatings because they provide an inert surface between the metal and paint. Decorative anodized films with varied colors can be produced with particular alloys, film thickness, and dying.

Hard anodic films 50-100 μm (2-4 mils) thick can be produced for resistance to abrasion and wear under conditions of slow-speed sliding. These films are generally dark in color and often show a fine network of cracks. Hard films are generally left unsealed but may be impregnated with silicone oils to improve frictional properties. The normal hardness of the anodic film is between quartz and topaz, i.e., MOH's scale 7-8. A maximum hardness of 200-500 VPN (Vickers Pyramid Number) can be obtained for special applications. Such a film would be from 50-75 μm (2-3 mils) thick.

Anodized films are effectively sealed for improved protection and still better results may be obtained by incorporating inhibitors in the sealing solutions. Sealing is not very effective on the relatively dense films produced in the chromic acid process but enhances the protection afforded by the more porous films produced by the sulfuric acid process.

Concrete and Portland Cement

Cement coatings are protective to steel because the cement maintains an alkaline pH at the steel surface which effectively prevents corrosion. However, cement and especially fresh cement can cause corrosion of aluminum and its alloys and other amphoteric metals because of the free alkali in fresh cement. If cement is to be used in conjunction with amphoteric metals, an impermeable barrier such as asphalt must be provided between the cement and the amphoteric metal to prevent corrosion.

Cement can be applied to metals by casting, troweling, or spraying and for corrosion protection is usually applied in thicknesses that range from 6-25 mm (1/4 to 1 inch). Thick coatings are usually reinforced with wire mesh.

Generally, Portland cements and concrete are sensitive to damage by mechanical or thermal shock.

Concrete can be used to protect steel against corrosion in seawater, but the Navy's main shipboard use of concrete has been as ballast in some peak tanks of ships.

Explosion Bonded Metals

To prevent galvanic corrosion of aluminum in an aluminum-steel couple, it is generally necessary to electrically insulate the aluminum from the steel. To maintain this insulation in ship construction, where aluminum superstructures and pad-eyes are used on steel hulls, is not very practical and corrosion will be rampant.

An approach to the solution of the corrosion problem caused when the aluminum is joined to the steel hull is the use of aluminum-steel sections in which the aluminum and steel are explosively bonded. This allows the steel portion of the section to be welded to the steel deck and the aluminum portion to be joined to the aluminum superstructure.

The thin, smooth joint is relatively easy to protect because the joint is not overlapped and salt-laden moisture or sea-spray salts cannot accumulate to cause accelerated corrosion of the aluminum.

Electrical Bonding

Two instances where bonding of structures are important include: the prevention or mitigation of stray current corrosion and the bonding of all structures or parts of structures to be cathodically protected into one harmonious electrical unit.

With regard to stray currents, corrosion is of concern and will be accelerated at the location where current leaves the structure and enters the water to seek a return path to its origin. In some instances, the accelerated corrosion caused by the stray currents can be mitigated by tying into a known return with an electrical bond.

With regard to cathodic protection, the only parts of a hull (or structure) that will be protected from corrosion by a cathodic protection system used to protect the hull will be those structures and appendages that are electrically bonded to the hull. For example, on a ship's hull the rudder will not be protected if it is electrically isolated from the hull. In such an instance, the rudder should be bonded to the hull with a bonding strap.

ANTIFOULING SYSTEMS

Protection against marine fouling is required wherever seawater comes in contact with ship hulls or piping systems, especially when the seawater velocity is low at least part of the time. In a piping and condenser system, a supply of chlorine in the proper amount for the existing fouling and velocity conditions will generally keep marine-fouling growth from thriving. Chlorine can be obtained: by electrolytic decomposition of the seawater, in gaseous form, or from the chemical sodium hypochlorite. The electrolytic decomposition of seawater eliminates the need to carry gas equipment on board ship and does not require space for bulk storage as would be the case if sodium hypochlorite were used. Electrolytic chlorinators are presently available that are rated by the manufacturers for extended service in seawater. Platinized titanium anodes coated with 200 micro-inches (0.2 mil) of platinum are rated for five years. Apparently longer-life anodes can be supplied for special conditions.

These systems are currently not used on Navy ships. Studies on the compatibility of materials and systems with this antifouling technique need to be developed to be certain that existing piping would not be excessively corroded and to study quantities of chlorine required to be economical and effective.

For the external hulls of ships, fouling control in the Navy has been accomplished by the use of organic (paint) coatings using a toxin incorporated in the coating. In most instances and for structural alloys other than aluminum, the cuprous oxide containing antifouling paint systems are used. These antifouling coatings are covered under appropriate military specification. For aluminum alloys, cuprous oxide

antifouling paints are not satisfactory because they cause accelerated corrosion of the aluminum even in the presence of a 125 μm (5 mil) anticorrosion barrier coating. Tributyltin oxide antifouling coatings are more suitable for use on aluminum alloys than are the cuprous oxide containing paints. To be effective, antifouling toxins must be sufficiently soluble so that adequate toxin is present to retard the fouling organisms. The toxins are normally formulated with a binder from which they are slowly leached into solution. Antifouling paints have a limited service life (generally 2 years) because the reservoir of toxic materials eventually is exhausted from the coating.

In the past there has been some commercial interest, mainly foreign, in the use of toxins added to a solution to prevent fouling in piping and the external hulls of ships. This system provides fouling protection by injecting an organotin toxin into the inlet water boxes of the ships seawater system. For the external hull, the toxin is dispersed (streamed) around the exterior hull while at rest through an appropriate pipe distribution system.

With any toxin for fouling control, consideration is required on the corrosion effects of the toxin on the structure or piping system and the environmental problems in handling the toxin.

SUMMARY

As part of the updating and revision of Chapter 9633 on Marine Corrosion and Cathodic Protection of the Naval Sea Systems Command Technical Manual (NSTM), the Marine Corrosion Section of the Naval Research Laboratory was requested to prepare the section on "Marine Electrochemical Corrosion and Control Systems."

This report is NRL's input to the revision of Chapter 9633 and includes detailed discussion on: seawater; electrochemical theory and reactions; types of corrosion; causes of corrosion; reference electrodes; electrochemical potentials; typical corrosion performance; corrosion characteristics of metals and alloys; cathodic protection; galvanic anode and impressed current anode electrochemical characteristics; other methods of corrosion control; and antifouling systems. Also included in this report are two appendices; one a glossy of corrosion terms and the other a metric guide with selected conversion factors.

The present state-of-the-art technology in electrochemical corrosion theory and corrosion control systems is the basis for this comprehensive guide on "Marine

Electrochemical Corrosion and Control Systems." Although much discussion and detail is included in this report, it is impractical to provide sufficient information to permit a "cookbook" type approach to corrosion engineering. In many instances, the only valid approach would be based on in-service performance. Use should be made of past experience with materials for a particular service. Even with this approach, however, metals and alloys may not always perform similarly under conditions that appear to be similar. Suttle differences in alloy composition, heat treatment, the environment, and etc. may cause drastic differences in service performance.

A second part of this updating of Chapter 9633 is being prepared by the Naval Ship Engineering Center and will cover "Cathodic Protection Applications" detailing galvanic anode design and maintenance, and impressed current design, operation, and maintenance.

ACKNOWLEDGMENT

The author acknowledges the helpful discussions, suggestions and review of the manuscript by M.H. Peterson. The Naval Sea Systems Command is also acknowledged for financial support of this project. Thanks are also due the Office of Naval Research and the Naval Research Laboratory for their continued support which provided for development of much of the information presented herein.

TABLE 1. CONCENTRATION OF MAJOR AND SOME OTHER CONSTITUENTS OF SEAWATER
Chlorinity = 19.00 0/00*

Constituent	Parts per Million	Constituent	Parts per Million
chloride (Cl^-)	18,980	potassium (K^+)	380
sodium (Na^+)	10,556	bicarbonate (HCO_3^-)	140
sulfate (SO_4^{-2})	2,649	bromine (Br^-)	65
magnesium (Mg^{+2})	1,272	strontium (Sr^{+2})	13
calcium (Ca^{+2})	400		

*0/00 denotes g/kg

TABLE 2. RESISTIVITY OF SEAWATER AS A FUNCTION OF CHLORINITY (AND SALINITY) AND TEMPERATURE

0/00*		Resistivity (ohm-cm) Temperature °C		
Chlorinity	Salinity	15	20	25
16	28.91	27.7	24.8	22.4
17	30.72	26.2	23.5	21.2
18	32.52	24.9	22.3	20.1
19	34.33	23.7	21.2	19.2
20	36.13	22.7	20.3	18.3
21	37.94	21.7	19.5	17.6
22	39.74	20.9	18.7	16.9

*denotes g/kg

TABLE 3. SOLUBILITY OF OXYGEN IN WATER AS A FUNCTION OF TEMPERATURE

Temperature		Oxygen Solubility milliliters per liter (mℓ/ℓ)	
°C	°F	Distilled Water	Seawater (Normal Salinity)
-2	28.4	-	8.52
0	32	9.90	8.08
5	41	8.65	7.16
10	50	7.64	6.44
15	59	6.83	5.86
20	68	6.18	5.38
25	77	5.67	-
30	86	-	5.42

Table 4. Aluminum and Its Alloys

Alloy			Seawater Total Immersion		Corrosion								
					Rate		Maximum Depth		Principal Type			Maximum Depth Rate (per year)	
Designation	UNS	Source of Data	Condition	Time	mpy*	μm/y*	mils**	μm**	Pitting	Crevice	Other	mils**	μm**
AA1100F	A91100	(1)Key West, Fla.	Quiescent	368 days	-	-	13	330	-	√	-	12.9	328
AA1100	A91100	(2)Harbor Island, N.C.	?	1 yr.	-	-	0	0	-	-	-	0	0
AA1100	A91100	(2)Harbor Island, N.C.	?	2 yr.	-	-	0	0	-	-	-	0	0
AA1100	A91100	(2)Harbor Island, N.C.	?	5 yr.	-	-	40	1016	√	-	-	8	203
AA1100	A91100	(2)Harbor Island, N.C.	?	10 yr.	-	-	0	0	-	-	-	0	0
AA1100	A91100	(2)Halifax, N.S.	?	1 yr.	-	-	17	432	√	-	-	17	432
AA1100	A91100	(2)Halifax, N.S.	?	2 yr.	-	-	32	813	√	-	-	16	406
AA1100	A91100	(2)Halifax, N.S.	?	5 yr.	-	-	0	0	-	-	-	0	0
AA1100	A91100	(2)Halifax, N.S.	?	10 yr.	-	-	29	737	√	-	-	2.9	74
AA1100	A91100	(2)Esquimalt, B.C.	?	1 yr.	-	-	30	762	√	-	-	30	762
AA1100	A91100	(2)Esquimalt, B.C.	?	2 yr.	-	-	26	660	√	-	-	13	330
AA1100	A91100	(2)Esquimalt, B.C.	?	5 yr.	-	-	15	381	√	-	-	3	76
AA1100	A91100	(2)Esquimalt, B.C.	?	10 yr.	-	-	0	0	-	-	-	0	0
AA1100	A91100	(2)Brixham, England	?	10 yr.	-	-	11	279	√	-	-	1.1	281
AA1100	A91100	(4)Panama, C.Z.	Quiescent	16 yr.	0.03	0.76	33	838	√	-	-	2	52
AA1100-H14	A91100	(1)Key West, Fla.	Quiescent	368 days	-	-	4	102	-	√	-	4	102
AA2014-T6	A92014	(1)Key West, Fla.	Quiescent	368 days	-	-	13	330	-	√	-	12.9	328
AA2014-T6	A92014 Alclad	(2)Brixham, England	?	10 yr.	-	-	14	356	√	-	-	1.4	36
AA2024-T351	A92024	(1)Key West, Fla.	Quiescent	368 days	-	-	49	1245	-	-	Outside Crevices	49	1245
AA2219-T87	A92219	(1)Key West, Fla.	Quiescent	368 days	-	-	48	1219	-	√	-	48	1210
AA3003-H14	A93003	(1)Key West, Fla.	Quiescent	368 days	-	-	31	787	-	-	Outside Crevices	30.8	781
AA3003	A93003	(2)Harbor Island, N.C.	?	1 yr.	-	-	0	0	-	-	-	0	0
AA3003	A93003	(2)Harbor Island, N.C.	?	2 yr.	-	-	0	0	-	-	-	0	0
AA3003	A93003	(2)Harbor Island, N.C.	?	5 yr.	-	-	13	330	√	-	-	2.6	66
AA3003	A93003	(2)Harbor Island, N.C.	?	10 yr.	-	-	21	533	√	-	-	2.1	53
AA3003	A93003	(2)Halifax, N.S.	?	1 yr.	-	-	13	330	√	-	-	13	330
AA3003	A93003	(2)Halifax, N.S.	?	2 yr.	-	-	15	381	√	-	-	7.5	191
AA3003	A93003	(2)Halifax, N.S.	?	5 yr.	-	-	21	533	√	-	-	4.2	107
AA3003	A93003	(2)Halifax, N.S.	?	10 yr.	-	-	22	559	√	-	-	2.2	56
AA3003	A93003	(2)Esquimalt, B.C.	?	1 yr.	-	-	5	127	√	-	-	5	127
AA3003	A93003	(2)Esquimalt, B.C.	?	2 yr.	-	-	20	508	√	-	-	10	254
AA3003	A93003	(2)Esquimalt, B.C.	?	5 yr.	-	-	0	0	-	-	-	0	0
AA3003	A93003	(2)Esquimalt, B.C.	?	10 yr.	-	-	10	254	√	-	-	1	25
AA3003	A93003	(2)Brixham, England	?	10 yr.	-	-	46	1168	√	-	-	4.6	117

(Continues)

Table 4 (Continued) Aluminum and Its Alloys

Alloy			Seawater Total Immersion		Corrosion								
					Rate		Maximum Depth		Principal Type			Maximum Depth Rate (per year)	
Designation	UNS	Source of Data	Condition	Time	mpy*	μm/y*	mils**	μm**	Pitting	Crevice	Other	mils**	μm**
AA5050-H34	A95050	(1)Key West, Fla.	Quiescent	368 days	-	-	6	152	-	√	-	6.0	152
AA5052-H32	A95052	(1)Key West, Fla.	Quiescent	368 days	-	-	3	76	-	√	-	3	76
AA5052-H34	A95052	(1)Key West, Fla.	Quiescent	368 days	-	-	5	127	-	√	-	5	127
AA5052	A95052	(2)Harbor Island, N.C.	?	1 yr.	-	-	0	0	-	-	-	0	0
AA5052	A95052	(2)Harbor Island, N.C.	?	2 yr.	-	-	0	0	-	-	-	0	0
AA5052	A95052	(2)Harbor Island, N.C.	?	5 yr.	-	-	0	0	-	-	-	0	0
AA5052	A95052	(2)Harbor Island, N.C.	?	10 yr.	-	-	0	0	-	-	-	0	0
AA5052	A95052	(2)Halifax, N.S.	?	1 yr.	-	-	5	127	√	-	-	5	127
AA5052	A95052	(2)Halifax, N.S.	?	2 yr.	-	-	20	508	√	-	-	10	254
AA5052	A95052	(2)Halifax, N.S.	?	5 yr.	-	-	6	152	√	-	-	1.2	30
AA5052	A95052	(2)Halifax, N.S.	?	10 yr.	-	-	12	305	√	-	-	1.2	30
AA5052	A95052	(2)Esquimalt, B.C.	?	1 yr.	-	-	16	406	√	-	-	16	406
AA5052	A95052	(2)Esquimalt, B.C.	?	2 yr.	-	-	6	152	√	-	-	3	76
AA5052	A95052	(2)Esquimalt, B.C.	?	5 yr.	-	-	0	0	-	-	-	0	0
AA5052	A95052	(2)Esquimalt, B.C.	?	10 yr.	-	-	5	127	√	-	-	0.5	13
AA5052	A95052	(2)Brixham, England	?	10 yr.	-	-	7	178	√	-	-	0.7	18
AA5083-0	A95083	(1)Key West, Fla.	Quiescent	368 days	-	-	1	25	-	√	-	1	25
AA5083	A95083	(2)Harbor Island, N.C.	?	1 yr.	-	-	16	406	√	-	-	16	406
AA5083	A95083	(2)Harbor Island, N.C.	?	2 yr.	-	-	13	330	√	-	-	6.5	165
AA5083	A95083	(2)Harbor Island, N.C.	?	5 yr.	-	-	6	152	√	-	-	1.2	30
AA5083	A95083	(2)Harbor Island, N.C.	?	10 yr.	-	-	10	254	√	-	-	1	25
AA5083	A95083	(2)Halifax, N.S.	?	1 yr.	-	-	4	102	√	-	-	4	102
AA5083	A95083	(2)Halifax, N.S.	?	2 yr.	-	-	23	584	√	-	-	11.5	292
AA5083	A95083	(2)Halifax, N.S.	?	5 yr.	-	-	16	406	√	-	-	3.2	81
AA5083	A95083	(2)Halifax, N.S.	?	10 yr.	-	-	22	559	√	-	-	2.2	56
AA5083	A95083	(2)Esquimalt, B.C.	?	1 yr.	-	-	29	737	√	-	-	29	737
AA5083	A95083	(2)Esquimalt, B.C.	?	2 yr.	-	-	38	965	√	-	-	19	483
AA5083	A95083	(2)Esquimalt, B.C.	?	5 yr.	-	-	47	1194	√	-	-	9.4	239
AA5083	A95083	(2)Esquimalt, B.C.	?	10 yr.	-	-	55	1397	√	-	-	5.5	140
AA5083	A95083	(2)Brixham, England	?	10 yr.	-	-	34	864	√	-	-	3.4	86
AA5086-H32	A95086	(1)Key West, Fla.	Quiescent	368 days	-	-	<1	<25	-	-	-	<1	<25
AA5086-H34	A95086	(1)Key West, Fla.	Quiescent	368 days	-	-	<1	<25	-	-	-	<1	<25
AA5086-H112	A95086	(1)Key West, Fla.	Quiescent	368 days	-	-	<1	<25	-	-	-	<1	<25
AA5154-H38	A95154	(1)Key West, Fla.	Quiescent	368 days	-	-	2	51	-	√	-	2	51
AA5154	A95154	(2)Harbor Island, N.C.	?	1 yr.	-	-	12	305	√	-	-	12	305
AA5154	A95154	(2)Harbor Island, N.C.	?	2 yr.	-	-	9	229	√	-	-	4.5	114
AA5154	A95154	(2)Harbor Island, N.C.	?	5 yr.	-	-	5	127	√	-	-	1	25
AA5154	A95154	(2)Halifax, N.S.	?	1 yr.	-	-	0	0	-	-	-	0	0
AA5154	A95154	(2)Halifax, N.S.	?	2 yr.	-	-	12	305	√	-	-	6	152
AA5154	A95154	(2)Halifax, N.S.	?	5 yr.	-	-	15	381	√	-	-	3	76
AA5154	A95154	(2)Esquimalt, B.C.	?	1 yr.	-	-	0	0	-	-	-	0	0
AA5154	A95154	(2)Esquimalt, B.C.	?	2 yr.	-	-	0	0	-	-	-	0	0
AA5154	A95154	(2)Esquimalt, B.C.	?	5 yr.	-	-	3	76	√	-	-	0.6	15
AA5257-H25	-	(1)Key West, Fla.	Quiescent	368 days	-	-	<1	<25	-	-	-	<1	<25

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Table 4. (Continued) Aluminum and Its Alloys

Alloy			Seawater Total Immersion		Corrosion								
					Rate		Maximum Depth		Principal Type			Maximum Depth Rate (per year)	
Designation	UNS	Source of Data	Condition	Time	mpy*	μm/y*	mils**	μm**	Pitting	Crevice	Other	mils**	μm**
AA6061-T6	A96061	(1)Key West, Fla.	Quiescent	368 days	-	-	11	279	-	√	-	11	279
AA6061-T6	A96061	(5)Key West, Fla.	Quiescent	729 days	-	-	18	457	-	-	Outside Crevice	9	229
AA6061-T6	A96061	(5)Key West, Fla.	Quiescent	696 days	-	-	54	1372	-	√	-	28	711
AA6061-T6	A96061	(6)Key West, Fla.	Quiescent Alt. Imm.	696 days	-	-	27	686	-	-	Outside Crevice	14.2	361
AA6061-T6	A96061	(5)Key West, Fla.	0.75 fps (0.23 m/s)	728 days	-	-	62.5P	1588	-	√	Outside Crevice	31.3	795
AA6061-T6	A96061	(2)Harbor Island, N.C.	?	1 yr.	-	-	67	1702	√	-	-	67	1702
AA6061-T6	A96061	(2)Harbor Island, N.C.	?	2 yr.	-	-	100	2540	√	-	-	50	1270
AA6061-T6	A96061	(2)Harbor Island, N.C.	?	5 yr.	-	-	144	3658	√	-	-	28.8	731
AA6061-T6	A96061	(2)Harbor Island, N.C.	?	10 yr.	-	-	130	3302	√	-	-	13	330
AA6061-T6	A96061	(2)Halifax, N.S.	?	1 yr.	-	-	50	1270	√	-	-	50	1270
AA6061-T6	A96061	(2)Halifax, N.S.	?	2 yr.	-	-	67	1702	√	-	-	33.5	851
AA6061-T6	A96061	(2)Halifax, N.S.	?	5 yr.	-	-	90	2286	√	-	-	18	457
AA6061-T6	A96061	(2)Halifax, N.S.	?	10 yr.	-	-	122	3099	√	-	-	12.2	310
AA6061-T6	A96061	(2)Esquimalt, B.C.	?	1 yr.	-	-	60	1524	√	-	-	60	1524
AA6061-T6	A96061	(2)Esquimalt, B.C.	?	2 yr.	-	-	100	2540	√	-	-	50	1270
AA6061-T6	A96061	(2)Esquimalt, B.C.	?	5 yr.	-	-	125	3175	√	-	-	25	635
AA6061-T6	A96061	(2)Esquimalt, B.C.	?	10 yr.	-	-	125	3175	√	-	-	12.5	318
AA6061-T6	A96061	(2)Brixham, England	?	10 yr.	-	-	51	1295	√	-	-	5.1	130
AA6061-T6	A96061	(4)Panama, C.Z.	Quiescent	16 yr.	0.03	0.76	79	2007	√	-	-	4.9	124
AA6061-T651	A96061	(1)Key West, Fla.	Quiescent	368 days	-	-	<1	<25	-	-	-	<1	<25
X7002-T6	-	(1)Key West, Fla.	Quiescent	368 days	-	-	9	229	-	√	Edges Cracked	8.9	226
Alclad X7002-T6	-	(1)Key West, Fla.	Quiescent	368 days	-	-	2	51	-	√	-	2	51
X7005-T63	A97005	(1)Key West, Fla.	Quiescent	368 days	-	-	<1	<25	-	-	-	<1	<25
AA7075-T7351	A97075	(1)Key West, Fla.	Quiescent	368 days	-	-	16	406	-	√	Outside Crevice	15.9	404
AA7075	A97075	(2)Harbor Island, N.C.	?	10 yr.	-	-	66	1676	√	-	-	6.6	168
AA7079-T6	A97079	(1)Key West, Fla.	Quiescent	368 days	-	-	18	457	-	√	-	17.9	455
7106-T63	-	(1)Key West, Fla.	Quiescent	368 days	-	-	<1	<25	-	-	-	<1	<25
AA7178-T6	A97178	(1)Key West, Fla.	Quiescent	368 days	-	-	38	965	-	√	Edges Severely Cracked	37.7	958
Alclad 7178-T6	-	(1)Key West, Fla.	Quiescent	368 days	-	-	3	76	-	-	Edges Cracked & Corr. Outside Crevice	3	76

NOTES:

*mpy = mils penetration per year
μm/y = micrometers penetration per year

**1 mil ≈ 0.001 inch ≈ 25.4 μm
P = penetrated

SOURCE OF DATA:

(1) R.E. Groover, T.J. Lennox, Jr., and M.H. Peterson, NRL Memorandum Report 1961, January 1969.

(2) H.P. Godard, W.J. Jepson, M.R. Bothwell, and Robert L. Kane, "The Corrosion of Light Metals," John Wiley & Sons, Inc., New York, 1967.

(3) F.L. LaQue, "Marine Corrosion," John Wiley & Sons, New York, 1975.

(4) C.R. Southwell and J.D. Bultman, NRL Report 7834, Jan. 2, 1975.

(5) M.H. Peterson and T.J. Lennox, Jr., Materials Performance 16, 4, 16-18 (1977).

(6) T.J. Lennox, Jr., R.E. Groover, and M.H. Peterson, NRL Report 7648, Nov. 16, 1973.

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Table 5. Copper and Its Alloys

Name	Alloy UNS	Source of Data	Seawater Total Immersion Condition	Time	Corrosion: Rate mpy*	Rate μm/y*	Maximum Depth mils**	Maximum Depth μm**	Principal Type: General	Dealloying	Pitting	Crevice	Outside Crevice	Maximum Depth Rate (per year) mils**	Maximum Depth Rate (per year) μm**
Copper	C12000	(1)Key West, Fla.	Quiescent	735 days	0.37	9	4	102	-	-	√	√	-	2	51
Copper	C12000	(2)Panama, C.Z.	Quiescent	16 yr.	0.09	2	37	1448	-	-	√	-	-	3.5	89
Copper	C12000	(3)Harbor Island, N.C.	Quiescent	?	1.2-7	3-178	-	-	-	-	√	-	-	7	178
Beryllium, Copper	C17200	(1)Key West, Fla.	Quiescent	735 days	0.46	12	9	229	-	√	-	√	-	4.5	114
Beryllium, Copper	C17500	(1)Key West, Fla.	Quiescent	735 days	0.10	3	3	76	-	√	-	√	-	1.5	38
Commercial Bronze, 90%	*C22000*	(1)Key West, Fla.	Quiescent	735 days	0.09	2	6	152	-	√	-	√	√	3	76
Commercial Bronze, 90%	C22000	(2)Panama, C.Z.	Quiescent	16 yr.	-	-	51	1295	-	-	√	-	-	3.2	81
Red Brass, 85%	C23000	(1)Key West, Fla.	Quiescent	735 days	0.07	2	2	51	-	√	-	√	-	0.5	13
Low Brass, 80%	C24000	(2)Panama, C.Z.	Quiescent	16 yr.	0.1	3	53	1346	-	-	√	-	-	3.3	84
Cartridge Brass, 70%	C26000	(1)Key West, Fla.	Quiescent	735 days	0.31	8	13	330	-	√	-	√	√	6.4	163
Cartridge Brass, 70%	C26000	(2)Panama, C.Z.	Quiescent	16 yr.	-	-	-	-	-	√	-	-	-	-	-
Yellow Brass, 66%	C26800	(1)Key West, Fla.	Quiescent	735 days	0.31	8	22	559	-	√	-	√	√	10.9	277
Yellow Brass, 66%	C26800	(3)Harbor Island, N.C.	Quiescent	?	50 to <100	1270 to >2540	-	-	-	√	√	-	-	>100	>2540
Muntz Metal, 60%	C28000	(1)Key West, Fla.	Quiescent	735 days	0.63	16	-	-	-	√	-	√	√	-	-
Muntz Metal, 60%	C28000	(2)Panama, C.Z.	Quiescent	16 yr.	-	-	-	-	-	√	-	-	-	-	-
Admiralty, Arsenical	C44300	(1)Key West, Fla.	Quiescent	735 days	0.34	9	4	102	-	√	-	√	√	2	51
Admiralty, Arsenical	C44300	(3)Harbor Island, N.C.	Quiescent	?	1-3	25-76	-	-	-	-	√	-	-	3	76
Naval Brass, Uninhibited (Grade A)	C46400	(1)Key West, Fla.	Quiescent	735 days	0.26	7	-	-	-	√	-	√	√	-	-
Naval Brass, Uninhibited (Grade A)	C46400	(2)Panama, C.Z.	Quiescent	16 yr.	-	-	-	-	-	√	√	-	-	-	-
Phosphor Bronze, 10% D	C52400	(1)Key West, Fla.	Quiescent	735 days	0.24	6	7	179	-	√	-	√	√	3.5	89
Aluminum Bronze, 5% Al	C60800	(1)Key West, Fla.	Quiescent	735 days	0.13	3	0	0	-	-	-	-	-	0	0
Aluminum Bronze, 5% Al	C60800	(2)Panama, C.Z.	Quiescent	16 yr.	0.1	3	21	533	-	-	√	-	-	1.3	33
Aluminum Bronze D, 7% Al, 2% Fe	C61400	(1)Key West, Fla.	Quiescent	735 days	0.05	1	<1	<25	-	√	-	√	√	<0.5	<13
Aluminum Bronze D, 7% Al, 2% Fe	C61400	(3)Harbor Island, N.C.	Quiescent	?	35	889	-	-	-	√	-	-	-	-	-
High Silicon, Bronze A	C65500	(1)Key West, Fla.	Quiescent	735 days	0.74	19	12	305	-	√	-	√	-	5.6	142
High Silicon, Bronze A	C65500	(2)Panama, C.Z.	Quiescent	16 yr.	0.2	5	80	2032	-	-	√	-	-	5	127
Copper Nickel, 10%	C70600	(1)Key West, Fla.	Quiescent	735 days	0.07	2	0	0	√	-	-	-	-	0	0
Copper Nickel, 10%	C70600	(3)Harbor Island, N.C.	Quiescent	?	0.1-0.6	3-15	-	-	-	-	√	-	-	0.6	15
Copper Nickel, 10%	C70600	(3)Harbor Island, N.C.	Quiescent	?	1-3	25-76	-	-	√	-	-	-	-	-	-
Copper Nickel, 30%	C71500	(1)Key West, Fla.	Quiescent	735 days	0.07	2	0	0	√	-	-	-	-	0	0
Copper Nickel, 30%	C71500	(2)Panama, C.Z.	Quiescent	16 yr.	0.1	3	37	940	√	-	-	-	-	2.3	58
Copper Nickel, 30%	C71500	(3)Harbor Island, N.C.	Quiescent	?	0.1-0.5	3-13	-	-	-	-	√	-	-	0.5	13
Copper Nickel, 30%	C71500	(3)Harbor Island, N.C.	Quiescent	?	1-8	25-203	-	-	√	-	-	-	-	-	-
Copper Nickel, 30% Ni, 5% Fe	-	(1)Key West, Fla.	Quiescent	735 days	0.14	6	43	1092	-	√	-	-	-	21.4	544
Manganese Bronze	C86500	(3)Harbor Island, N.C.	Quiescent	?	<40	<1016	-	-	-	√	√	-	-	>40	>1016
G Bronze	C90700	(3)Harbor Island, N.C.	Quiescent	?	1-3	25-76	-	-	-	-	√	-	-	3	76
G Bronze	C90700	(3)Harbor Island, N.C.	Quiescent	?	1-2	25-51	-	-	√	-	-	-	-	-	-
M Bronze	C92200	(3)Harbor Island, N.C.	Quiescent	?	1-3	25-76	-	-	-	-	√	-	-	3	76
Manganese Bronze	C95700	(3)Harbor Island, N.C.	Quiescent	?	1-3	25-76	-	-	√	√	-	-	-	3	76
Nickel Aluminum Bronze	C95800	(3)Harbor Island, N.C.	Quiescent	?	1-3	25-76	-	-	-	-	√	-	-	3	76
Nickel Aluminum Bronze	C95800	(3)Harbor Island, N.C.	Quiescent	?	1-2	25-51	-	-	√	-	-	-	-	-	-
Velocity Conditions:			***												
Copper	C12000	(3)Harbor Island, N.C.	<2 fps (<0.6 m/s)	?	<3	<76	-	-	√	-	-	-	-	-	-
Copper	C12000	(3)Harbor Island, N.C.	>4 fps (>1.2 m/s)	?	>5	>127	-	-	√	-	-	-	-	-	-
Aluminum Brass	C68700	(3)Harbor Island, N.C.	<7 fps (<2.1 m/s)	?	<2	<51	-	-	√	-	-	-	-	-	-
Aluminum Brass	C68700	(3)Harbor Island, N.C.	>8 fps (>2.4 m/s)	?	>5	>127	-	-	√	-	-	-	-	-	-
Copper Nickel, 10%	C70600	(3)Harbor Island, N.C.	<9 fps (<2.7 m/s)	?	<1	<25	-	-	√	-	-	-	-	-	-
Copper Nickel, 10%	C70600	(3)Harbor Island, N.C.	12-15 fps (3.7-4.6 m/s)	?	>5	>127	-	-	√	-	-	-	-	-	-
Copper Nickel, 30%	C71500	(3)Harbor Island, N.C.	<15 fps (<4.6 m/s)	?	<1	<25	-	-	√	-	-	-	-	-	-
Copper Nickel, 30%	C71500	(3)Harbor Island, N.C.	15-50 fps (4.6-15.3 m/s)	?	<10	<254	-	-	√	-	-	-	-	-	-
Copper Nickel, 30%	C71500	(3)Harbor Island, N.C.	50-120 fps (15.3-36.6 m/s)	?	>50	>1270	-	-	√	-	-	-	-	-	-
Manganese Bronze	C86500	(3)Harbor Island, N.C.	20-120 fps (6.1-36.6 m/s)	?	-	-	-	-	-	√	-	-	-	-	-
G Bronze	C90700	(3)Harbor Island, N.C.	<50 fps (<15.3 m/s)	?	<10	<254	-	-	√	-	-	-	-	-	-
G Bronze	C90700	(3)Harbor Island, N.C.	50-120 fps (15.3-36.6 m/s)	?	>40	>1016	-	-	√	-	-	-	-	-	-
Nickel-Aluminum-Bronze	C95800	(3)Harbor Island, N.C.	<80 fps (<24.4 m/s)	?	<10	<254	-	-	√	-	-	-	-	-	-
Nickel-Aluminum-Bronze	C95800	(3)Harbor Island, N.C.	90-120 fps (27.5-36.6 m/s)	?	>30	>762	-	-	√	-	-	-	-	-	-

NOTES:

*mpy = mils penetration per year
μm/y = micrometers penetration per year

**1 mil = 0.001 inch = 25.4 μm

***fps = feet per second
m/s = meters per second
1 ft = 0.305 meters

SOURCE OF DATA:

(1) R.E. Groover, T.J. Lennox, Jr., and M.H. Peterson, NRL Memorandum Report 2183, October 1970.
(2) C.R. Southwell and J.D. Bultman, NRL Report 7834, Jan. 2, 1975.
(3) F.L. LaQue, "Marine Corrosion," John Wiley & Sons, New York (1975).

Table 6. Nickel and Its Alloys

Alloy			Seawater Total Immersion		Corrosion									
					Rate		Maximum Depth		Principal Type					Maximum Depth Rate (per year)
Name	UNS	Source of Data	Condition	Time	mpy*	μm/y*	mils**	μm**	General	Pitting	Crevice	Outside Crevice	Edges	mils**	μm**
Nickel 200	N02200	(1)Key West, Fla.	Quiescent	575 days	0.05	17	81	2057	-	-	√	√	Severe	51.4	1306
Nickel 200	N02200	(2)Panama, C.Z.	Quiescent	16 yr.	1.4	35.6	192P	4879	-	√	-	-	-	12	305
Nickel 200	N02200	(3)Harbor Island, N.C.	Quiescent	?	13-60	330-1524	-	-	-	√	-	-	-	60	1524
Nickel 200	N02200	(3)Harbor Island, N.C.	Quiescent	?	0-0.8	20.3	-	-	√	-	-	-	-	-	-
Monel 400	N04400	(1)Key West, Fla.	Quiescent	575 days	0.07	2	17	432	-	-	√	√	-	10.8	274
Monel 400	N04400	(2)Panama, C.Z.	Quiescent	16 yr.	0.3	7.6	82	2083	-	√	-	-	-	5.1	130
Monel 400	N04400	(3)Harbor Island, N.C.	Quiescent	?	0-18	0-457	-	-	-	√	-	-	-	18	457
Monel 400	N04400	(3)Harbor Island, N.C.	Quiescent	?	0-1	0-25.4	-	-	√	-	-	-	-	-	-
Monel K 500	N05500	(1)Key West, Fla.	Quiescent	575 days	0.02	0.6	4	102	-	-	√	√	-	2.5	64
Inconel 600	N06600	(1)Key West, Fla.	Quiescent	575 days	0.25	6.4	18	452	-	-	√ Severe	√	-	11.4	290
Inconel 617	-	(1)Key West, Fla.	Quiescent	575 days	0	0	0	0	-	-	-	-	-	0	0
Inconel 625	N06625	(1)Key West, Fla.	Quiescent	576 days	0.004	0.1	0	0	-	-	-	-	-	0	0
Inconel 706	N09706	(1)Key West, Fla.	Quiescent	575 days	0.63	16	50	1270	-	-	√	-	√	31.7	805
Inconel 718	N07718	(1)Key West, Fla.	Quiescent	575 days	0.15	3.7	32	813	-	-	√	-	Slight	20.3	516
Alloy 20 Cb-3	N08020	(1)Key West, Fla.	Quiescent	575 days	0.04	1.1	12	305	-	-	√	-	√	7.6	193
Alloy 20 Cb-3	N08020	(3)Harbor Island, N.C.	?	?	0-10	0-254	-	-	-	√	-	-	-	10	254
Incoloy 800	N08800	(1)Key West, Fla.	Quiescent	575 days	0.24	6.2	95P	2413P	-	-	√	-	-	60.3	1532
Incoloy 825	N08825	(1)Key West, Fla.	Quiescent	575 days	0	0	9	229	-	-	√	-	-	5.7	145
Incoloy 825	N08825	(3)Harbor Island, N.C.	Quiescent	?	0-10	0-254	-	-	-	√	-	-	-	10	254
Hastelloy C276	N10276	(1)Key West, Fla.	Quiescent	576 days	0.004	0.1	0	0	-	-	-	-	-	0	0
Velocity Conditions:			***												
Nickel 200	N02200	(1)Key West, Fla.	0.75 fps (0.23 m/s)	574 days	2.7	67.8	108P	2743P	-	-	√	√	Very Severe	68.7	1745
Nickel 200	N02200	(3)Harbor Island, N.C.	20-120 fps (6.1-36.6 m/s)	?	0 to <1	0 to <25.4	-	-	√	-	-	-	-	-	-
Monel 400	N04400	(1)Key West, Fla.	0.75 fps (0.23 m/s)	574 days	0.30	7.5	61P	1550P	-	-	√	-	√	38.8	986
Monel 400	N04400	(3)Harbor Island, N.C.	<3 fps (<0.93 m/s)	?	-	-	-	-	-	√ maybe	-	-	-	-	-
Monel 400	N04400	(3)Harbor Island, N.C.	6-15 fps (1.?-4.7 m/s)	?	<1	<25	-	-	√	-	-	-	-	-	-
Monel 400	N04400	(3)Harbor Island, N.C.	20-120 fps (6.1-36.6 m/s)	?	0 to <1	0 to <25	-	-	√	-	-	-	-	-	-
Monel K500	N05500	(1)Key West, Fla.	0.75 fps (0.23 m/s)	574 days	0.09	2.4	12	305	-	-	√	√	√	7.6	193
Inconel 600	N06600	(1)Key West, Fla.	0.75 fps (0.23 m/s)	574 days	0.9	22.8	64P	1626P	-	-	√	-	√	40.7	1034
Inconel 617	-	(1)Key West, Fla.	0.75 fps (0.23 m/s)	574 days	0.008	0.2	7	178	-	-	√	-	-	4.4	112
Inconel 625	N06625	(1)Key West, Fla.	0.75 fps (0.23 m/s)	574 days	0	0	2	51	-	-	-	√	-	1.3	33
Inconel 706	N09706	(1)Key West, Fla.	0.75 fps (0.23 m/s)	574 days	1	25.4	62P	1575P	-	-	√	√	√ & Tunneling	39.4	1001
Alloy 20 Cb-3	N08020	(1)Key West, Fla.	0.75 fps (0.23 m/s)	574 days	0.12	3.1	66	1676	-	-	√	-	-	42	1067
Incoloy 800	N08800	(1)Key West, Fla.	0.75 fps (0.23 m/s)	574 days	0.68	17.2	95P	2413P	-	-	√	-	-	60.4	1534
Incoloy 825	N08825	(1)Key West, Fla.	0.75 fps (0.23 m/s)	574 days	0.1	2.5	63	1600	-	-	√	-	-	40	1016
Hastelloy C276	N10276	(1)Key West, Fla.	0.75 fps (0.23 m/s)	575 days	0.008	0.2	<1	<25	-	-	-	√	-	<1	<25

NOTES:

*mpy = mils penetration per year
μm/y = micrometers penetration per year

**1 mil = 0.001 inch = 25.4 μm

***fps = feet per second
m/s = meters per second
1 ft ≈ 0.305 meters

SOURCE OF DATA:

(1) T.J. Lennox, Jr., and M.H. Peterson, NRL, unpublished data.

(2) C.R. Southwell and J.D. Bultman, NRL Report 7834, Jan. 2, 1975.

(3) F.L. LaQue, "Marine Corrosion," John Wiley & Sons, New York (1975).

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Table 7. Steels and Stainless Steels

Alloy			Seawater Total Immersion		Corrosion								
					Rate		Maximum Depth		Principal Type			Maximum Depth Rate (per year)	
Name	UNS	Source of Data	Condition	Time	mpy*	μm/y*	mils**	μm**	General	Pitting	Crevice	mils**	μm**
Mild Steel	G10200	(4)NRL	Quiescent	28 days	3-8	76-203	-	-	√	-	-	-	-
Mild Steel	G10200	(6)Panama, C.Z.	Quiescent	16 yr.	2.7	69	155	3937	√	√	-	9.7	246
Mild Steel	G10200	(7)Harbor Island, N.C.	Quiescent	?	7-15	178-381	-	-	-	√	-	15	381
Mild Steel	G10200	(7)Harbor Island, N.C.	Quiescent	?	4-14	102-356	-	-	√	-	-	-	-
Low Alloy Steel	-												
Cu-Ni	-	(6)Panama, C.Z.	Quiescent	16 yr.	2.7	69	130P	3302P	√	√	-	8.1	206
Cu-Cr-Si	-	(6)Panama, C.Z.	Quiescent	16 yr.	4.8	122	99P	2515P	√	√	-	6.2	157
Cu-Ni-Mn-Mo	-	(6)Panama, C.Z.	Quiescent	16 yr.	2.5	64	139	3531	√	√	-	8.7	221
Cr-Ni-Mn	-	(6)Panama, C.Z.	Quiescent	16 yr.	5.0	127	237P	6020P	√	√	-	14.8	376
17-4 PH H1025 SS	S17400	(1)Key West, Fla.	Quiescent	649 days	-	-	50	1270	-	√	√	28.1	714
Cr-Ni-Mn SS	S20500	(1)5600 ft. Tongue of the Ocean	Quiescent	111 days	1.2	30	63P	1600P	-	√	√	207	5258
Cr-Ni-Mn SS	S20500	(1)5600 ft. Tongue of the Ocean	Quiescent	1050 days	0.84	21	63P	1600P	-	√	√	21.9	556
22Cr-13Ni-5Mn	S20910	(5)Key West, Fla.	Quiescent	176 days	-	-	62P	1575P	-	-	√	128.6	3266
216 SS	S21600	(5)Key West, Fla.	Quiescent	546 days	-	-	60	1524	-	-	√	40.1	1019
21Cr-6Ni-9Mn	S21900	(1)Key West, Fla.	Quiescent	649 days	-	-	60	1524	-	-	√	33.7	856
302 SS	S30200	(6)Panama, C.Z.	Quiescent	16 yr.	-	-	151P	3835P	-	√	-	9.4	239
304 SS	S30400	(1)Key West, Fla.	Quiescent	490 days	-	-	48P	1219P	-	-	√	35.8	909
304 SS	S30400	(1)5600 ft. Tongue of the Ocean	Quiescent	111 days	0	0	27	686	-	-	√	88.8	2256
304 SS	S30400	(1)5600 ft. Tongue of the Ocean	Quiescent	1050 days	0.24	6	63P	1600P	-	-	√	21.9	556
304 SS	S30400	(7)Harbor Island, N.C.	Quiescent	?	10 to >100	254 to >2540	-	-	-	√	-	>100	>2540
304 SS	S30400	(7)Harbor Island, N.C.	Quiescent	?	0-5	0-127	-	-	√	√	-	5	127
304 SS	S30400	NRL-Key West, Fla.	Quiescent	576 days	-	-	58P	1473P	-	-	√	36.8	935
316 SS	S31600	(1)Key West, Fla.	Quiescent	649 days	-	-	45	1143	-	-	√	25.3	643
316 SS	S31600	(1)5600 ft. Tongue of the Ocean	Quiescent	111 days	0	0	19	483	-	-	√	62.5	1586
316 SS	S31600	(1)5600 ft. Tongue of the Ocean	Quiescent	1050 days	0	0	0	0	-	-	-	0	0
316 SS	S31600	(6)Panama, C.Z.	Quiescent	16 yr.	-	-	95P	2413P	-	√	-	5.9	150
316 SS	S31600	(7)Harbor Island, N.C.	Quiescent	?	2 to >100	51 to >2540	-	-	-	√	-	>100	>2540
316 SS	S31600	(7)Harbor Island, N.C.	Quiescent	?	0-5	0-127	-	-	√	√	-	5	127
321 SS	S32100	(6)Panama, C.Z.	Quiescent	16 yr.	-	-	237P	6020P	-	√	-	14.8	376
26Cr-1Mo	-	(5)Key West, Fla.	Quiescent	552 days	-	-	62P	1575P	-	-	√	41	1041
6X	-	NRL-Key West, Fla.	Quiescent	218 days	-	-	65P	1651P	-	-	√	108.8	2764
405 SS	S40500	(3)Key West, Fla.	Quiescent	384 days	-	-	62P	1575P	-	-	√	58.9	1496
409 SS	S40900	(3)Key West, Fla.	Quiescent	384 days	-	-	107P	2718	-	-	√	101.7	2583
430 SS	S43000	(3)Key West, Fla.	Quiescent	384 days	-	-	74P	1880P	-	-	√	70.3	1786
434 SS	S43400	(3)Key West, Fla.	Quiescent	384 days	-	-	67	1702	-	-	√	63.7	1618
446	S44600	(3)Key West, Fla.	Quiescent	384 days	-	-	80P	2032P	-	-	√	76.0	1930
400 Series	-	(7)Harbor Island, N.C.	Quiescent	?	>60	>1524	-	-	-	√	-	>60	>1524
Velocity Conditions:			***										
Mild Steel	G10200	(7)Harbor Island, N.C.	5-15 fps (1.5-4.6 m/s)	?	5-30	127-762	-	-	√	-	-	-	-
Mild Steel	G10200	(7)Harbor Island, N.C.	20-120 fps (6.1-36.6 m/s)	?	30-300	762-7620	-	-	√	-	-	-	-
304 SS	S30400	(7)Harbor Island, N.C.	0-3 fps (0-0.92 m/s)	?	3	76	-	-	-	Deep √	-	3	76

316 SS	**S31600**	**(7)Harbor Island, N.C.**	**Quiescent**	**?**	**0-5**	**0-127**	**-**	**-**	**√**	**√**	**-**	**5**	**127**
321 SS	S32100	(6)Panama, C.Z.	Quiescent	16 yr.	-	-	237P	6020P	-	√	-	14.8	376
26Cr-1Mo	-	(5)Key West, Fla.	Quiescent	552 days	-	-	62P	1575P	-	-	√	41	1041
6X	-	NRL-Key West, Fla.	Quiescent	218 days	-	-	65P	1651P	-	-	√	108.8	2764
405 SS	S40500	(3)Key West, Fla.	Quiescent	384 days	-	-	62P	1575P	-	-	√	58.9	1496
409 SS	S40900	(3)Key West, Fla.	Quiescent	384 days	-	-	107P	2718	-	-	√	101.7	2583
430 SS	S43000	(3)Key West, Fla.	Quiescent	384 days	-	-	74P	1880P	-	-	√	70.3	1786
434 SS	S43400	(3)Key West, Fla.	Quiescent	384 days	-	-	67	1702	-	-	√	63.7	1618
446	S44600	(3)Key West, Fla.	Quiescent	384 days	-	-	80P	2032P	-	-	√	76.0	1930
400 Series	-	(7)Harbor Island, N.C.	Quiescent	?	>60	>1524	-	-	-	√	-	>60	>1524
Velocity Conditions:			***										
Mild Steel	G10200	(7)Harbor Island, N.C.	5-15 fps (1.5-4.6 m/s)	?	5-30	127-762	-	-	√	-	-	-	-
Mild Steel	G10200	(7)Harbor Island, N.C.	20-120 fps (6.1-36.6 m/s)	?	30-300	762-7620	-	-	√	-	-	-	-
304 SS	S30400	(7)Harbor Island, N.C.	0-3 fps (0-0.92 m/s)	?	3	76	-	-	-	Deep √	-	3	76
304 SS	S30400	(7)Harbor Island, N.C.	6-15 fps (1.8-4.6 m/s)	?	<1	<25	-	-	√	-	-	-	-
304 SS	S30400	(7)Harbor Island, N.C.	20-120 fps (6.1-36.6 m/s)	?	nil	nil	-	-	-	-	-	-	-
316 SS	S31600	(7)Harbor Island, N.C.	0-3 fps (0-0.92 m/s)	?	3	76	-	-	-	Deep √	-	3	76
316 SS	S31600	(7)Harbor Island, N.C.	6-15 fps (1.8-4.6 m/s)	?	<1	<25	-	-	√	-	-	-	-
316 SS	S31600	(7)Harbor Island, N.C.	20-120 fps (6.1-36.6 m/s)	?	nil	nil	-	-	-	-	-	-	-

NOTES:

*mpy = mils penetration per year
μm/y = micrometers penetration per year

**1 mil = 0.001 inch = 25.4 μm

***fps = feet per second
m/s = meters per second
1 ft ≈ 0.305 meters

SOURCE OF DATA:

(1) T.J. Lennox, Jr., M.H. Peterson, and R.E. Groover, NRL Memorandum Report 1948, November 1968.

(2) T.J. Lennox, Jr., M.H. Peterson, and R.E. Groover, NRL Memorandum Report 2348, April 1971.

(3) R.E. Groover, T.J. Lennox, Jr., and M.H. Peterson, Paper Number OTC 1580, Offshore Technology Conference Proceedings, Vol. I, p. 659, Houston, Texas, May 1-3, 1972.

(4) T.J. Lennox, Jr., and M.H. Peterson, NRL Report 7721, Apr. 4, 1974.

(5) T.J. Lennox, Jr., and M.H. Peterson, NRL Report 8016, Aug. 4, 1976.

(6) C.R. Southwell and J.D. Bultman, NRL Report 7834, Jan. 2, 1975.

(7) F.L. LaQue, "Marine Corrosion," John Wiley & Sons, New York (1975).

Table 8. Miscellaneous Alloys

Alloy			Seawater Total Immersion		Corrosion Rate		Corrosion Maximum Depth		Corrosion Principal Type			
Name	UNS	Source of Data	Condition	Time	mpy*	μm/y*	mils**	μm**	Light Etch	Crevice	Isolated Pits	Pits Hot Seawater
MP-35N	R30035	(1) Key West, Fla.	Quiescent	576 days	0.004	0.1	0	0	√	-	-	-
Elgiloy	-	(1) Key West, Fla.	Quiescent	576 days	0.008	0.2	Curved Spec. No Quant. Meas.		√	√	-	-
Ti-6Al-4V	-	(1) Key West, Fla.	Quiescent	575 days	0	0	1	25	-	-	√	-
Titanium	-	(2) Harbor Island N.C.	Quiescent	?	0	0	0	0	-	-	-	√
Velocity Conditions:			***									
MP-35N	R30035	(1) Key West, Fla.	0.75 fps (0.23 m/s)	576 days	0.004	0.1	0	0	√	-	-	-
Elgiloy	-	(1) Key West, Fla.	0.75 fps (0.23 m/s)	575 days	0.0016	0.4	Est.10	Est.250	-	√	-	-
Ti-6Al-4V	-	(1) Key West, Fla.	0.75 fps (0.23 m/s)	575 days	0	0	1	25	-	√	-	-
Titanium	-	(2) Harbor Island N.C.	0-120 fps (0-36.6 m/s)	?	0	0	0	0	-	-	-	-

NOTES:
*mpy = mils penetration per year
μm/y = micrometers penetration per year
**1 mil = 0.001 inch = 25.4 μm
***fps = feet per second
m/s = meters per second
1 ft ≈ 0.305 meters

SOURCE OF DATA:
1. T.J. Lennox, Jr. and M.H. Peterson, NRL, unpublished data.
2. F.L. LaQue "Marine Corrosion," John Wiley and Sons (New York) 1975.

Table 9. Galvanic-Anode Characteristics and Properties

Anode Characteristic or Property	Anode Material: Magnesium MIL-A-21412A	Zinc MIL-A-18001H	Aluminum (0.5% Zn-0.05% Hg Alloy)
Typical Potential (volts vs. Ag/AgCl reference electrode)	1.55	1.04	1.06
Current Capacity (ampere hours/kg)	1104	812	2759
(ampere hours/lb)	500 (@ 50% Efficiency)(1)	368 (@ 99% Efficiency)(1)	1250 (@ 93% Efficiency)(1)
Nominal Anode Consumption (kg/ampere year)	7.7	10.9	3.2
(lb/ampere year)	17	24	7
Density (kilogram per cubic meter)	1744	7141	2740
(lb/cubic inch)	0.063	0.258	.099

(1) When comparing anode alloys, it is preferable to consider the current capacity in ampere hours/kg or ampere hours/lb rather than to discuss efficiency because ampere hours/kg is a directly measurable quantity and the electrochemical equivalents of alloys do not have to be considered.

TABLE 10. IMPRESSED CURRENT ANODE CHARACTERISTICS AND PROPERTIES

Property or Characteristic	Material			
	Ti	Cb	Ta	Pt
Breakdown Voltage (V)	8-14	35-50	180-220	-
Electrical Resistivity (microohm-cm at 20°C)	42	14.8	12.4	10.6
Density (grams/cc @ 20°C)	4.54	8.4	16.6	21.4
Linear Coefficient of Thermal Expansion ($x10^{-6}$ per °C, at 25°C)	8.5	7.1	6.5	9

TABLE 11. CONSUMPTION RATE OF IMPRESSED-CURRENT ANODES

Material	Consumption Rate (Nominal) (kg/Ayr)	(lb/Ayr)
Mild Steel	9.1 at 10.8 A/m^2	20 at 1 A/ft^2
Silicon-iron	0.68 at 54-108 A/m^2	1.5 at 5-10 A/ft^2
Lead-antimony-silver alloy	0.09 at 54-108 A/m^2	0.2 at 5-10 A/ft^2
Graphite	0.54 at 54-108 A/m^2	1.2 at 5-10 A/ft^2
Platinum alloy and platinum plated titanium	Negligible	Negligible

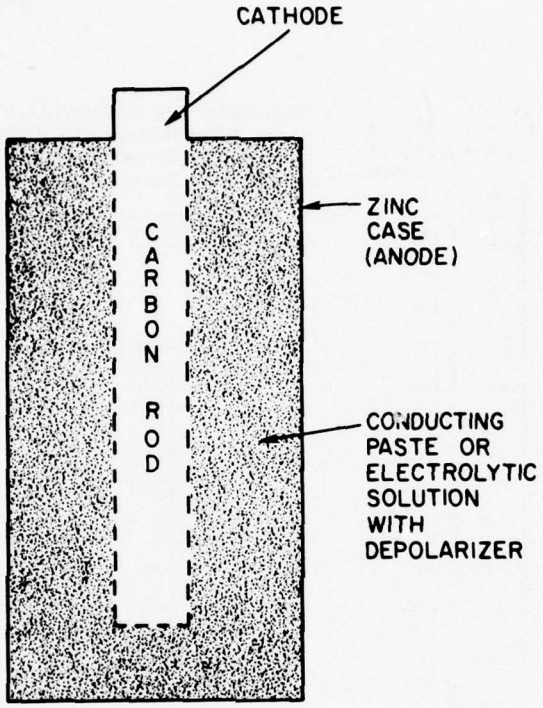


Fig. 1 - Common dry-cell battery

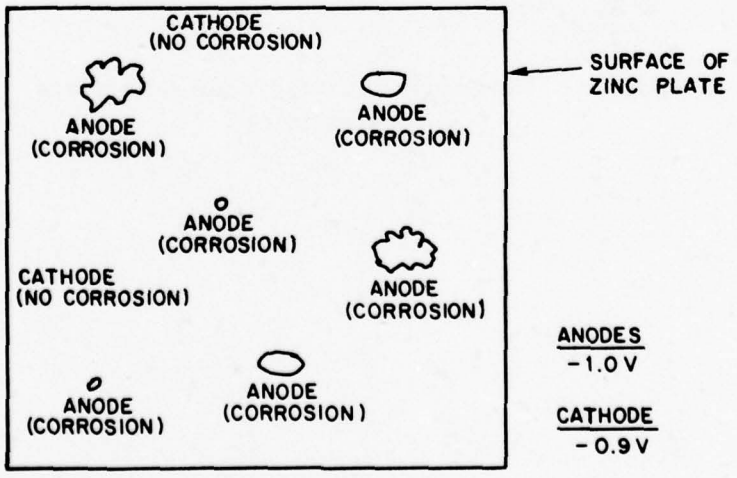


Fig. 2 - Zinc surface of dry-cell battery after shelf storage

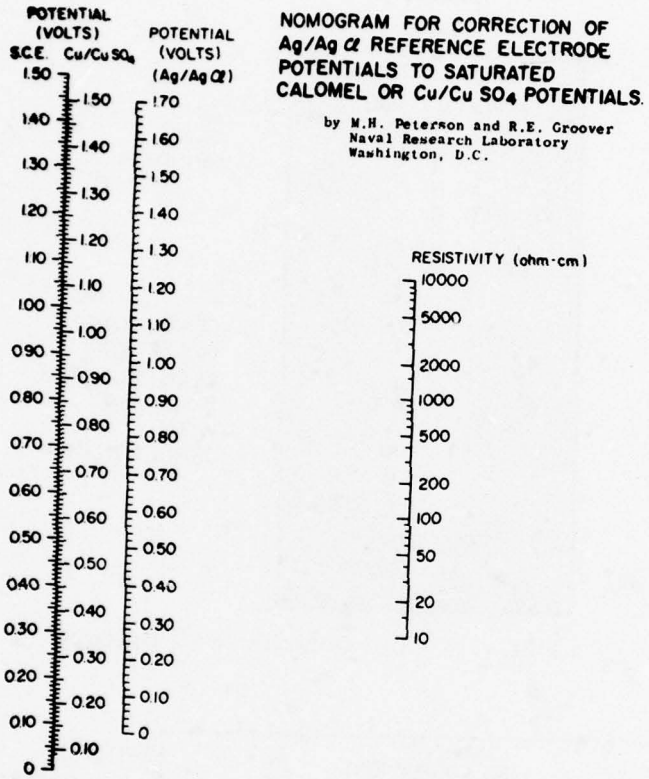
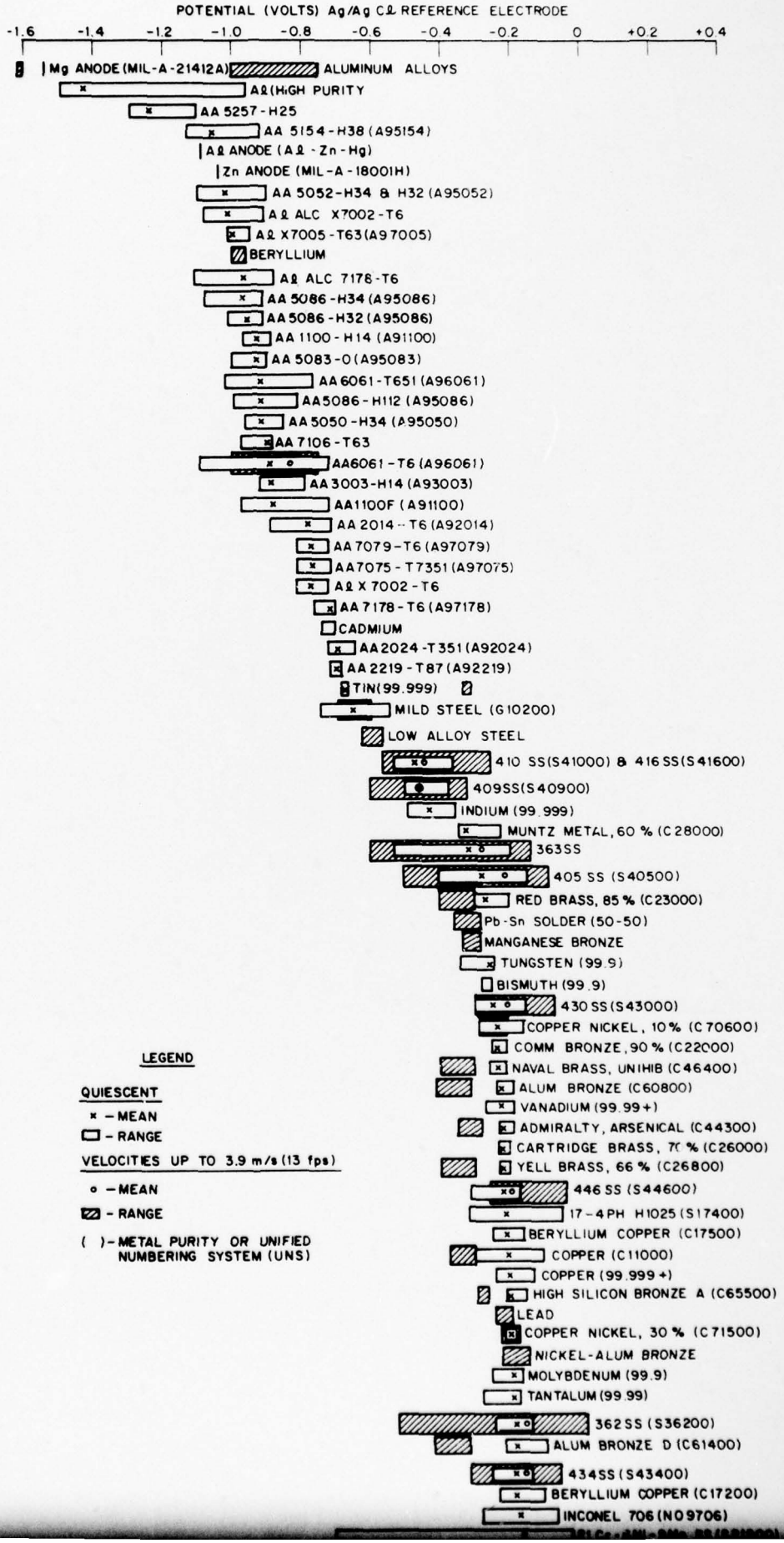


Fig. 3 - Nomogram of electrode potentials vs. resistivity


POTENTIAL (VOLTS) Ag/Ag Cℓ REFERENCE ELECTRODE
-1.6
-1.4
-1.2
-1.0
-0.8
-0.6
-0.4
-0.2
0
+0.2
+0.4
Mg ANODE (MIL-A-21412A)
ALUMINUM ALLOYS
Aℓ (HIGH PURITY
AA 5257 - H25
AA 5154 - H38 (A95154)
Aℓ ANODE (Aℓ - Zn - Hg)
Zn ANODE (MIL-A-18001H)
AA 5052 - H34 & H32 (A95052)
Aℓ ALC X7002 - T6
Aℓ X7005 - T63 (A97005)
BERYLLIUM
Aℓ ALC 7178 - T6
AA 5086 - H34 (A95086)
AA 5086 - H32 (A95086)
AA 1100 - H14 (A91100)
AA 5083 - O (A95083)
AA 6061 - T651 (A96061)
AA 5086 - H112 (A95086)
AA 5050 - H34 (A95050)
AA 7106 - T63
AA 6061 - T6 (A96061)
AA 3003 - H14 (A93003)
AA 1100F (A91100)
AA 2014 - T6 (A92014)
AA 7079 - T6 (A97079)
AA 7075 - T7351 (A97075)
Aℓ X 7002 - T6
AA 7178 - T6 (A97178)
CADMIUM
AA 2024 - T351 (A92024)
AA 2219 - T87 (A92219)
TIN (99.999)
MILD STEEL (G10200)
LOW ALLOY STEEL
410 SS (S41000) & 416 SS (S41600)
409 SS (S40900)
INDIUM (99.999)
MUNTZ METAL, 60 % (C28000)
363 SS
405 SS (S40500)
RED BRASS, 85 % (C23000)
Pb - Sn SOLDER (50 - 50)
MANGANESE BRONZE
TUNGSTEN (99.9)
BISMUTH (99.9)
430 SS (S43000)
COPPER NICKEL, 10 % (C70600)
COMM BRONZE, 90 % (C22000)
NAVAL BRASS, UNIHIB (C46400)
ALUM BRONZE (C60800)
VANADIUM (99.99+)
ADMIRALTY, ARSENICAL (C44300)
CARTRIDGE BRASS, 70 % (C26000)
YELL BRASS, 66 % (C26800)
446 SS (S44600)
17 - 4 PH H1025 (S17400)
BERYLLIUM COPPER (C17500)
COPPER (C11000)
COPPER (99.999+)
HIGH SILICON BRONZE A (C65500)
LEAD
COPPER NICKEL, 30 % (C71500)
NICKEL - ALUM BRONZE
MOLYBDENUM (99.9)
TANTALUM (99.99)
362 SS (S36200)
ALUM BRONZE D (C61400)
434 SS (S43400)
BERYLLIUM COPPER (C17200)
INCONEL 706 (NO9706)
LEGEND
QUIESCENT
× - MEAN
□ - RANGE
VELOCITIES UP TO 3.9 m/s (13 fps)
o - MEAN
▨ - RANGE
( ) - METAL PURITY OR UNIFIED NUMBERING SYSTEM (UNS)

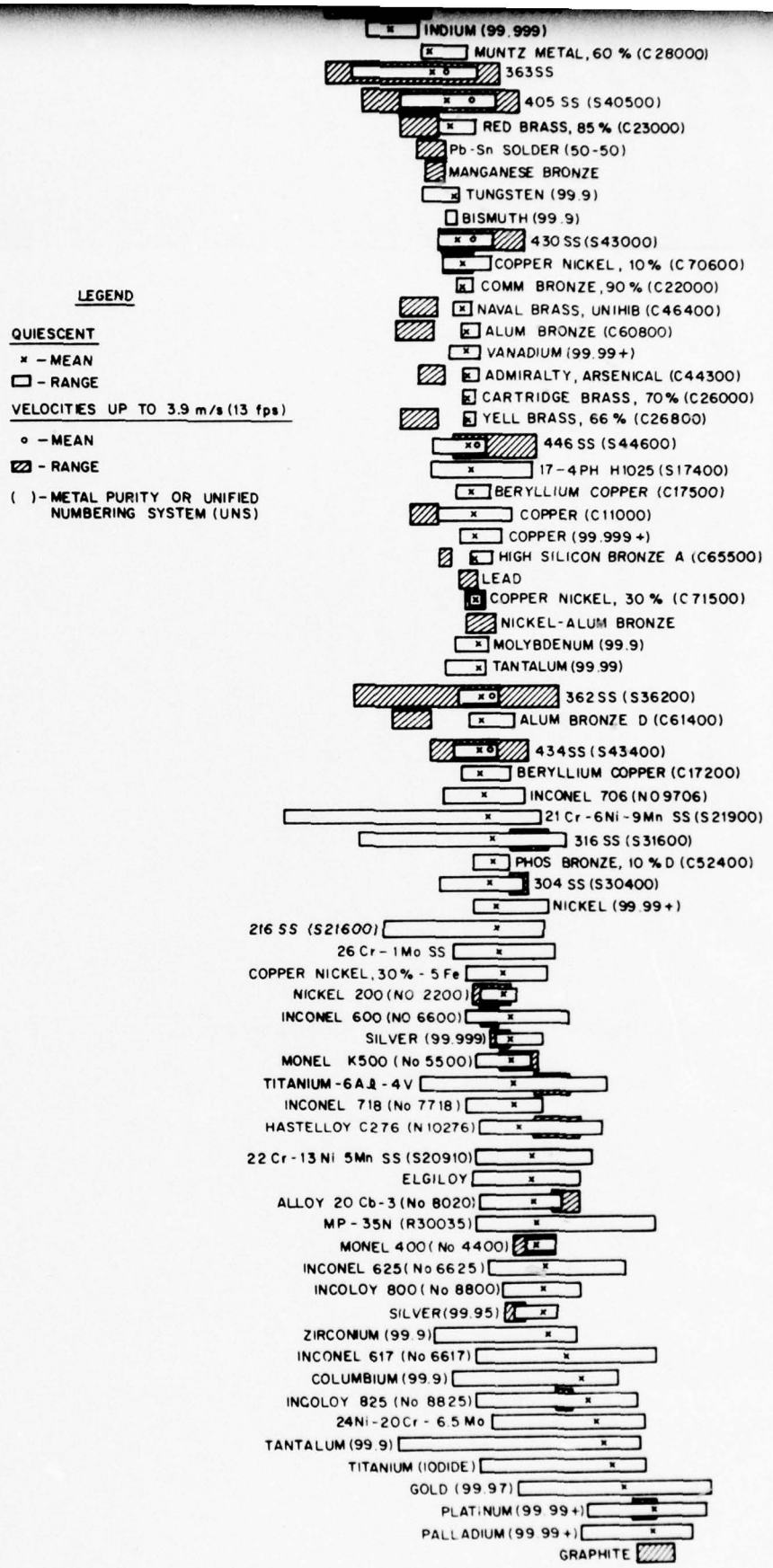


Fig. 4 - Electrochemical potential (galvanic series) of metals and alloys in seawater

APPENDIX I

GLOSSARY OF CORROSION TERMS

Acid - a solution that contains an excess of hydrogen ions and exhibits a pH below the neutral value of 7.

Active - a state in which a metal tends to corrode (opposite to passive); freely corroding; the negative direction of electrode potential in the absence of cathodic protection.

Adhesion - the attractive force that exists between a metal or paint coating and the substrate.

Alclad - an alloy system in which a thin layer of aluminum, or an aluminum alloy, is bonded metallurgically to a high strength aluminum alloy of lower corrosion resistance to provide a combination of improved corrosion resistance and high strength.

Aluminizing (hot dip) - coating of iron and steel with aluminum or an aluminum alloy using a molten metal bath into which the item to be coated is immersed and withdrawn after a period of time.

Amphoteric metal - a metal that is dissolved by both acids and bases. Aluminum, zinc and lead are examples of amphoteric metals.

Anaerobic - an absence of air or uncombined (free) oxygen.

Anion - an ion or radical which is attracted to the anode in an electrochemical cell because of the negative charge on the ion or radical ($C\ell^-$, OH^-).

Anode - the electrode of an electrochemical cell at which oxidation is the principle reaction. The electrode where corrosion occurs and metal ions enter the solution.

Anodic polarization - the change of the electrode potential in the noble (positive) direction due to current flow.

Anodizing - the formation of oxide films on metals by the anodic oxidation of the metal in an electrolytic solution.

Anti-fouling - the prevention of marine organism attachment or growth on a submerged metal surface through chemical toxicity. Achieved through: the chemical composition of the metal, including toxins in the coating, or by some other means distributing the toxin at the areas to be kept free of fouling.

Aqueous - pertaining to water; an aqueous solution is a water solution.

Base - a solution that contains an excess of hydroxyl ions and exhibits a pH above the neutral value of 7.

Base metal - a metal on which another metal is deposited or clad. The metals that are joined by welding. The metals at the negative end of the Emf series.

Buffer - a substance, or mixture of substances, which when present in an electrolytic solution tends to diminish fluctuations in pH.

Cathode - the electrode of an electrochemical cell at which reduction is the principle reaction. The electrode where corrosion does not occur unless the electrode metal is amphoteric.

Cathodic corrosion - corrosion of a metal when it is a cathode. Occurs on amphoteric metals such as Aℓ, Zn, Pb, when the pH at the cathode is strongly alkaline as a result of the normal cathodic reactions. It is a secondary reaction between the alkali generated and the amphoteric metal.

Cathodic polarization - the change of the electrode potential in the negative direction due to current flow.

Cathodic protection - a technique or system used to reduce or eliminate the corrosion of a metal by making it the cathode of an electrochemical cell; by means of an impressed dc current or attachment of sacrificial anodes such as zinc, magnesium or aluminum.

Cation - an ion or radical which is attracted to the cathode in an electrochemical cell because of the positive charge on the ion or radical (as H^+, Zn^{++} or NH_4^+).

Cavitation - the formation and sudden collapse of vapor bubbles in a liquid; usually resulting from local low pressures - as on the trailing edge of a propeller; this develops momentary high local pressure which can mechanically destroy a portion of a surface on which the bubbles collapse.

Cavitation damage - the degradation of a solid body resulting from its exposure to cavitation. This may include loss of material, surface deformation, or changes in properties or appearance.

Cell - a circuit or system consisting of an anode and a cathode in electrical contact in a solid or liquid conducting environment.

Chemical conversion coating - an adherent protective or decorative nonmetallic coating intentionally produced as a reaction product layer on a metal surface by chemical reaction of a metal with a suitable chemical; such as an iron phosphate film on iron developed by phosphoric acid (H_3PO_4). Used most often to prepare a surface prior to the application of a paint coating.

Concentration cell - an electrochemical cell, the potential of which is caused by a difference in concentration of some component in the solution.

Corrosion - the chemical or electrochemical reaction between a metal and its environment that results in the deterioration of the metal or its properties; the transformation of a metal, used as a material of construction, from the elementary to the combined state.

Corrosion fatigue - the process by which a metal fails under conditions of simultaneous corrosion and repeated cyclic loading. Premature failure will occur at lower stress levels and fewer cycles than in the absence of the corrosive environment.

Corrosion potential - the potential that a corroding metal exhibits under specific conditions of concentration, time, temperature, aeration, velocity and etc., in an electrolytic solution and measured relative to a reference electrode under open-circuit conditions.

Corrosion product - metal reaction product resulting from corrosion. The term applies to solid compounds, gases or ions resulting from a corrosion reaction.

Corrosion rate - the speed with which corrosion progresses. Usually an average expressed as though it was linear. Common units used are: mpy (mils penetration per year), mm/y (millimeter penetration per year), μm/y (micrometers penetration per year). 1 mil = 0.001 inch, 1 mm $\approx$ 0.001 meter, 1 μm $\approx$ 0.000001 meter.

Couple - a cell developed in an electrolytic solution resulting from electrical contact between two dissimilar metals; two dissimilar metals in electrical contact.

Cracking - fracture of a metal in a brittle manner along a single or branched path.

Crazing - a network of cracks on a surface.

Crevice corrosion - localized corrosion resulting from the formation of a concentration cell caused by a crevice formed between two surfaces - one at least of which is a metal.

Current capacity - the hours of current that can be obtained from a unit weight of a galvanic anode metal. Usually expressed in ampere hours per pound (Ah/lb) or ampere hours per kilogram (Ah/kg).

Current density - the current per unit area of surface of an electrode. Common units used are:

mA/ft^2 (milliampere per square foot)
mA/m^2 (milliampere per square meter)
A/ft^2 (amperes per square foot)
A/m^2 (amperes per square meter)
$10mA/m^2 \approx 1\ mA/ft^2$

Current efficiency - the ratio of the actual total current measured from a galvanic anode in a given time period and the total current calculated from the weight loss of the anode and the electrochemical equivalent of the anode metal, expressed as a percentage.

Dealloying - selective removal by corrosion of a constituent of an alloy (such as the selective leaching or corrosion of Aℓ, Ni, Mo, Zn from an alloy).

Depolarization - the elimination or reduction of polarization by physical or chemical means.

Dezincification - preferential corrosion of zinc from brass resulting in mechanically weak copper - rich areas in the form of plugs or layers; sometimes both zinc and copper corrode, but copper is redeposited.

Differential aeration (oxygen concentration) - an electrochemical cell, the potential of which is due to a difference in air (oxygen) concentration in the solution at one area of the metal - solution interface compared with that at another area of the same metal; the area in contact with the solution of lower concentration is the anode and will corrode.

Electrochemical cell - a system consisting of an anode and a cathode in metallic contact and immersed in an electrolytic solution. The anode and cathode may be different metals or dissimilar areas on the same metal surface; a cell in which chemical energy is converted into electrical energy.

Electrode - a metal or nonmetallic conductor in contact with an electrolytic solution which serves as a site where an electric current enters the metal or nonmetallic conductor or leaves the metal or nonmetallic conductor to enter the solution.

Electrode potential - the difference in electrical potential between an electrode and the electrolytic solution with which it is in contact; measured relative to a reference electrode.

Electrogalvanizing - galvanizing by electroplating.

Electrolysis - the production of chemical changes in an electrolytic solution caused by the passage of electrical current through an electrochemical cell. (Should not be used to mean corrosion by stray currents).

Electrolyte - a substance which in solution gives rise to ions; an ionic conductor usually in aqueous solution; a chemical substance which on dissolving in water renders the water conductive.

Electrolytic cell - a system in which an anode and cathode are immersed in an electrolytic solution and electrical energy is used to bring about electrode reactions. The electrical energy is thus converted into chemical energy. (Note: the term "electrochemical cell" is frequently used to describe both the "electrochemical cell" and the "electrolytic cell".

Electrolytic cleaning - a process of removing soil, scale, corrosion products & etc., from a metal surface by subjecting it as an electrode to an electrical current in an electrolytic solution.

Electrolytic solution - a solution which conducts electric current by the movement of ions; a solution containing an electrolyte.

Electromotive Force Series - (Emf) - a list of elements arranged according to their standard electrode potentials, (hydrogen electrode is a reference point and given the value zero) with "noble" metals such as gold being positive and "active" metals such as zinc being negative.

Electronegative potential - a potential representing the active or anodic end of the Emf or Galvanic Series.

Electroplating - electrodeposition of an adherent layer of a metal or alloy on a substrate of desirable chemical, physical and mechanical properties.

Electropositive potential - a potential representing the noble or cathodic end of the Emf or Galvanic Series.

Embrittlement - severe loss of ductility of a metal or alloy.

Endurance limit - the maximum cyclic stress level a metal can withstand without an eventual fatigue failure.

Erosion - the deterioration of a surface due to mechanical interaction between that surface and a moving fluid. The deterioration is accelerated by the presence of solid particles or gas bubbles in suspension.

Erosion - corrosion - the combined action of erosion and corrosion leading to the deterioration of a surface.

Exfoliation corrosion - corrosion that proceeds laterally from the sites of initiation along planes parallel to the surface, generally at grain boundaries, forming corrosion products that force metal away from the body of the metal, giving rise to a layered appearance.

External circuit - the wires, connectors, measuring devices, current sources and etc., that are used to bring about or measure the desired electrical conditions within the test cell. Also known in corrosion parlance as that part of an electrochemical cell external to the solution.

Fatigue - a process leading to failure under conditions of repeated stress cycles which are well below the normal tensile strength.

Filiform corrosion - corrosion that occurs in the form of randomly distributed threadlike or hairlike filaments that progresses across a metal surface; usually associated with corrosion under lacquers or other organic films (coatings or paints).

Film - a thin surface layer that may or may not be visible.

Fouling - the covering of surfaces submerged in natural waters, such as seawater, with marine growth such as flora and fauna and barnacles & etc.

Fretting corrosion - fretting refers to metal deterioration caused by repetitive slip at the interface between two surfaces. When metal loss is increased by corrosion one has fretting corrosion.

Galvanic cell - an electrochemical cell having two electronic conductors (commonly dissimilar metals) as electrodes or two similar metals in contact with each other and immersed in dissimilar electrolytic solutions.

Galvanic corrosion - corrosion of a metal because of electrical contact with a more noble metal or nonmetallic conductor in a corrosive environment. Often used to refer specifically to "Bimetallic Corrosion"; sometimes called "couple action".

Galvanic couple - two or more dissimilar conductors, commonly metals, in electrical contact in the same electrolytic solution.

Galvanic Series - a list of metals and alloys arranged according to their relative corrosion potentials in a given environment. Note that this may not be the same order as in the Electromotive Force Series.

Galvanizing (hot dip) - coating of iron and steel with zinc using a molten metal bath into which the item to be coated is immersed and withdrawn after a period of time.

General corrosion (Uniform corrosion) - corrosion in which no distinguishable area of the metal surface is solely anodic or cathodic, i.e., anodes and cathodes are inseparable and are usually thought to change location on the surface; an area on the surface at times will be anodic and at other times cathodic.

Half-cell - one of the electrodes and its immediate environment in an electrochemical cell; an electrode and environment arranged for the passage of current to another electrode for the measurement of its electrode potential; when coupled with another half-cell, an overall cell potential develops which is the sum of both half cell potentials.

Heat affected zone (HAZ) - area adjacent to a weld where the thermal cycle has caused microstructural changes which generally affect corrosion behavior.

Holiday - a discontinuity (hole or gap) in a protective coating (paint).

Hydrogen blistering - the formation of blister-like bulges on or below the surface of a ductile metal caused by excessive internal hydrogen pressure. Hydrogen may be formed during cleaning, plating, corrosion, cathodic protection and etc.

Hydrogen cracking - cracking induced by the presence of hydrogen in the metal as for example through pickling, cleaning, cathodic protection and etc.

Hydrogen embrittlement - severe loss of ductility caused by the presence of hydrogen in the metal as for example through pickling, cleaning, cathodic protection and etc.

Immunity - a state of resistance to corrosion of a metal caused by thermodynamic stability of the metal.

Impingement corrosion - a form of erosion corrosion generally associated with the local impingement of a high velocity, flowing fluid against a solid surface.

Inhibitor - a chemical substance or combination of substances that, when present in the proper concentration and form in the environment, prevents or reduces corrosion.

Intergranular corrosion - corrosion that occurs preferentially at the grain boundaries of a metal or alloy.

Ion - an electrically charged atom (as Na^{+}, $A\ell^{+3}$, $C\ell^{-}$, S^{-2}) or group of atoms known as "radicals" (as NH_4^{+}, SO_4^{-2}, PO_4^{-3}).

Local action - corrosion due to action of local cells, i.e., galvanic cells caused by nonuniformities between adjacent areas on a metal surface exposed to an electrolytic

solution; galvanic anode effeciency is reduced by local action.

Local cell- a galvanic cell caused by small differences in composition in the metal or the solution.

Localized corrosion - corrosion in which one area (or areas) of the metal surface is corroded (anodic) and another area (or areas) is uncorroded (cathodic) i.e., anodes and cathodes are physically separable.

Metal ion concentration cell - a galvanic cell caused by a difference in metal ion concentration in the solution at two locations on the surface of the same metal.

Metal spraying - application of a metal coating to a metallic or nonmetallic surface by means of a spray of metal particles. The metal particles may be produced by atomizing a metal wire in a flame-gun or by introducing metal powder into a similar gun.

Metallizing - a process of coating a surface with a layer of metal; spraying, vacuum deposition, dipping, plasma jet, cementation and etc., are used.

Mill scale - the oxide layer: formed during heat treatment or hot working of metals; produced during fabrication by hot rolling; often refers to steel forming magnetic oxide, Fe_3O_4 (magnetite).

Noble - a state in which a metal tends not to be active; the positive direction of electrode potential.

Noble metal - a metal which is not very reactive, as silver, gold, platinum and which may be found naturally in metallic form on earth.

Noble potential - a potential toward the positive end of a scale of electrode potentials.

Open-circuit potential - the potential of an electrode measured with respect to a reference electrode when essentially no current flows to or from the electrode.

Oxidation - loss of electrons by a species during a chemical or electrochemical reaction; as when a metal goes from the metallic state to the corroded state when acting as an anode; when a metal reacts with oxygen, sulfur and etc. to form a compound as oxide or sulfide.

Passivator - an inhibitor which changes the potential of a metal appreciably to a more noble (positive) value.

Passive - the state of a metal when its corrosion behavior is much more noble (resists corrosion) than its position in the Emf series would predict.

Patina - a green coating of corrosion products of copper (basic sulfate, carbonate or chloride) which develops on copper and some copper alloys after prolonged atmospheric exposure.

pH - a measure of the acidity or alkalinity of a solution. A value of seven is neutral; low numbers are acid, large numbers are alkaline; a measure of the hydrogen ion activity defined by: $pH = \log_{10} \frac{1}{a_{H^+}}$ where a_{H^+} = hydrogen ion activity.

Pickle - a solution (usually acid) or a process used to remove mill scale or other corrosion products from a metal.

Pitting corrosion - localized corrosion in which appreciable penetration into the metal occurs resulting in the formation of cavities.

Pitting factor - the ratio of the depth of the deepest pit resulting from corrosion divided by the average corrosion as calculated from weight loss.

Polarization - the shift in electrode potential from the open-circuit value resulting from the effects of current flow.

Potential - a numerical value (measured in volts) for an electrode in a solution and defined with reference to another specified electrode.

Prime coat - a first coat of paint applied to inhibit corrosion or improve adherence of the next coat.

Protective potential - a term used in cathodic protection to define the minimum potential required to mitigate or suppress corrosion. For steel in quiescent seawater a value of - 0.80 volt to a Ag/AgCℓ is generally used.

Reduction - gain of electrons by a species during a chemical or electrochemical reaction; as when a metal ion in solution goes to the metallic state at a cathode in an electrochemical cell.

Reference electrode - a half-cell of reproducible potential by means of which an unknown electrode potential can be determined on some arbitrary scale (i.e., Ag/AgCℓ, SCE, $Cu/CuSO_4$ & etc.); a standard to which the potentials of other metal and nonmetallic conductor electrodes is measured and compared.

Rusting - corrosion of iron or iron base alloy to form a reddish-brown product known as rust which is primarily hydrated iron oxide. A term properly applied only to ferrous alloys.

Season cracking - cracking resulting from the combined effect of corrosion and stress; usually associated with stress-corrosion cracking of brass in ammoniacal environments.

Shield - a non-conducting coating, paint or sheet which is used to beneficially change the current on a cathode or anode; normally used with impressed current or other high potential cathodic protection systems to prevent current wastage close to the anodes.

Slushing compound - a non-drying oil or grease applied to metals generally for temporary corrosion protection.

Stray-current corrosion - corrosion caused by current flow from a source (usually dc) through paths other than the intended circuit or by extraneous currents in the electrolytic solution.

Stress corrosion - corrosion of an alloy caused by the simultaneous application of stress and exposure to a corrosive environment.

Stress-corrosion cracking - cracking of an alloy produced by the simultaneous action of a corrosive environment and sustained or static tensile stress (internal or applied).

Sulfate-reducing bacteria - a species of anaerobic bacteria that is capable of causing rapid corrosion of iron and steel in near-neutral solutions in the absence of dissolved oxygen.

Sulfide stress cracking - stress corrosion cracking of a metal in an environment containing hydrogen sulfide.

Tarnish - dulling, staining or discoloration of metals due to the formation of thin films of corrosion products.

Thermal spraying - a group of processes wherein finely divided metallic or nonmetallic materials are deposited in a molten or semimolten condition to form a coating. The coating material may be in the form of powder, ceramic rod, wire, or molten materials.

Thermogalvanic corrosion - the corrosion resulting from the galvanic cell caused by a thermal gradient (temperature difference) across the metal surface.

Tuberculation - localized corrosion that results in corrosion products that appear over the corroded areas as knoblike mounds (tubercules).

Weld decay - a term applied to areas adjacent to welds of certain alloys which have been subjected to corrosion because of metallurgical changes in the alloy; commonly applied to certain grades of stainless steel in which case it results from precipitation of chromium carbides at the grain boundaries.

Appendix II

Metric Guide and Selected Conversion Factors

Item	U.S. Customary Units	International System (SI) Units
length	inch (in) foot (ft)	meter (m)
area	square inch (in^2) square foot (ft^2)	square meter (m^2)
volume	cubic inch (in^3) cubic foot (ft^3) gallon (U.S. liquid)	cubic meter (m^3) liter (ℓ)
mass	ounce (oz) avoirdupois pound (lb)	kilogram (kg)
velocity	feet per minute (fpm)	meters per second (m/s)
time	minute (min) hour (h) day (d) week (wk) month (mo)	second (s) preferred, but all used. Abbreviations for week and month are not used.
temperature	degrees Fahrenheit (°F) or degrees Celsius (°C)	kelvin (K) Celsius (°C)
electrical current	ampere (A) milliampere (mA)	ampere (A) milliampere (mA)
potential	volt (V)	volt (V)
electrical resistance	ohm (R or Ω)	ohm (R or Ω)
current density	milliamperes per square foot (mA/ft^2)	milliamperes per square meter (mA/m^2)
	amperes per square foot (A/ft^2)	amperes per square meter (A/m^2)
current capacity	ampere hours per pound (Ah/lb)	ampere hours per kilogram (Ah/kg)

Item	U.S. Customary Units	International System (SI) Units
pit depth	mils (m) or 0.001 inch (in)	micrometers (μm) or millimeters (mm)
corrosion rate	mils penetration per year (mpy)	micrometers penetration per year (μm/y)
	inches penetration per year (ipy)	millimeters penetration per year (mm/y)

Recommended Prefixes and Symbols

Unit	Prefix	Symbol
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

Selected Conversion Factors

To Convert From	To	Multiply by
mil (m)	micrometer (μm)	2.54×10^{1}
	millimeters (mm)	2.54×10^{-2}
inch (in)	meter (m)	2.54×10^{-2}
foot (ft)	meter (m)	3.05×10^{-1}

To Convert From	To	Multiply by
square inches (in^2)	square meters (m^2)	6.45×10^{-4}
square feet (ft^2)	square meters (m^2)	9.29×10^{-2}
cubic inches (in^3)	cubic meters (m^3)	1.64×10^{-5}
cubic feet (ft^3)	cubic meters (m^3)	2.83×10^{-2}
gallons (U.S. liquid)	liters (ℓ)	3.76
gallons (U.S. liquid)	cubic meters (m^3)	3.79×10^{-3}
ounce (avoirdupois) oz.	kilogram (kg)	2.83×10^{-2}
pound (avoirdupois) lb	kilogram (kg)	4.54×10^{-1}
pounds per cubic inch (lb/in^3)	kilograms per cubic meter (kg/m^3)	2.77×10^{4}
pounds per cubic foot (lb/ft^3)	kilograms per cubic meter (kg/m^3)	1.60×10^{1}
kip per square inch (kip/in^2 or ksi)	pascal (Pa)	6.89×10^{6}
minutes (min)	seconds (s)	60
feet per minute (fpm)	meters per second (m/s)	5.08×10^{-3}
milliamperes per square foot (mA/ft^2)	milliamperes per square meter (mA/m^2)	1.08×10^{1}
amperes per square foot (A/ft^2)	amperes per square meter (A/m^2)	1.08×10^{1}
ampere hours per pound (Ah/lb)	ampere hours per kilogram (Ah/kg)	2.20
degrees Fahrenheit (°F)	degrees Celsius (°C)	0.556(°F-32)
degrees Fahrenheit (°F)	kelvin (K)	0.556(°F-32) + 273
degrees Celsius (°C)	kelvin (K)	°C + 273