US Army Coast. Eng. Res. Ctr. T. M. 27

CORROSION AND PROTECTION OF STEEL PILING IN SEAWATER

by

Laverne L. Watkins

TECHNICAL MEMORANDUM NO. 27

MAY 1969

U. S. ARMY, CORPS OF ENGINEERS

COASTAL ENGINEERING
RESEARCH CENTER

This document has been approved for public release and sale;
its distribution is unlimited.

Limited free distribution of this publication within the United States is made by the U. S. Army Coastal Engineering Research Center, 5201 Little Falls Road, N. W., Washington, D. C. 20016

T. M. 27

CORROSION AND PROTECTION OF STEEL PILING IN SEAWATER

by

Laverne L. Watkins

TECHNICAL MEMORANDUM NO. 27

MAY 1969

U. S. ARMY, CORPS OF ENGINEERS

COASTAL ENGINEERING
RESEARCH CENTER

ABSTRACT

The purpose of this report is to assemble in one paper much of the current knowledge involving corrosion of steel piling in seawater and methods of corrosion prevention. The study is based on a survey of literature. Causes of corrosion and the effects of environmental conditions such as galvanic couplings, marine fouling, abrasion, oxygen concentration and other factors are presented. Corrosion rates of bare steel piles and test results on protective coatings for steel are included. Factors involved in the use of cathodic protection and concrete jackets to protect steel piles are explained. The corrosion rates of plain carbon and low-alloy steels are compared.

References surveyed show that flame-sprayed zinc sealed with saran or vinyl is possibly the best coating system tested. Concrete jackets of proper design and construction are reported to be very effective. Cathodic protection also provides good corrosion protection. Combinations of cathodic protection with coatings or concrete jackets may be advantageous.

There is great need for more data from which to determine the most economical method of protecting steel piling in seawater.

FOREWORD

This report was prepared in response to a request from the Office, Chief of Engineers, U. S. Department of the Army, for more design data concerning the corrosion of steel piling in seawater. It is one phase of the project "Study of Corrosion of Steel Piling in Seawater" which is being carried out under the Corps of Engineers' Engineering Studies 311 sub-project, "Corrosion Mitigations", funded through the Rock Island District. Findings in this report relate directly or indirectly to the corrosion of steel piling in seawater.

The report was prepared by L. L. Watkins, a project engineer in the Design Branch, under the general supervision of G. M. Watts, Chief of the Engineering Development Division and R. A. Jachowski, Chief of the Design Branch.

At the time of publication, the Director of the Coastal Engineering Research Center was Lieutenant Colonel Myron Dow Snoke; the Technical Director was Joseph M. Caldwell.

NOTE: Comments on this publication are invited. Discussion will be published in the next issue of the CERC Bulletin

This report is published under authority of Public Law 166, 79th Congress, approved July 31, 1945, as supplemented by Public Law 172, 88th Congress, approved November 7, 1963.

CONTENTS

CONTENTS (Continued)

Page

Section VII (Continued)

Appendix A. TABLES I THROUGH XV

Appendix B. GLOSSARY OF CORROSION TERMS

ILLUSTRATIONS

Figure

ILLUSTRATIONS (Continued)

CORROSION AND PROTECTION OF STEEL PILING IN SEAWATER

Section I. INTRODUCTION

Steel piling is widely used in building marine structures. Steel sheet piling is often used in seawater to retain earth and prevent its erosion by water at such structures as bulkheads, quay walls, seawalls, and cellular construction for breakwaters and jetties. Steel H and cylindrical piles find wide use in seawater as supports for docks and offshore drilling platforms. They are also used in such structures as dolphins to resist lateral loads.

Although steel has many advantages as a material for marine construction, it has the disadvantage of corroding in seawater if not protected.

A number of factors may affect the rate at which steel corrodes in seawater. Some of the more important ones are the water temperature, the amount of dissolved oxygen, salinity, water velocity, abrasive materials in suspension, and the amount and type of marine organisms present. Effective methods of protecting steel from corrosion are to isolate the steel from the corrosive environment by a protective barrier or protect it by causing an electric current to flow to the steel from another source such as from another metal which is anodic to steel or from sources such as batteries or rectifiers. The latter method is known as cathodic protection. Barrier type protection consists of organic and inorganic coatings and concrete encasement.

Concrete jackets of good quality concrete and workmanship have a reputation for being effective in protecting steel from corrosion. However, the initial cost of this method is relatively high. No test data has been located from which to determine the protective life of concrete jackets on steel piling installed in seawater.

Tests conducted by the U. S. Naval Civil Engineering Laboratory indicate that some of the relatively new coatings are performing fairly well on pile specimens in seawater. Tests data on these coatings have been incorporated in this report. Indications are that the initial costs of most of these coatings are considerably higher than the short-lived asphaltic and coal-tar coatings commonly applied to steel piling in the past. Once the life spans of a number of the more durable coatings have been established, an analysis of the cost per year of protection will be very beneficial to designers and maintenance personnel.

Better techniques and materials are being continually developed for cathodic protection and if properly designed and installed, it can be very effective for protecting steel piling below the water level. Steel above the water line must be protected by one of the other methods since submersion in seawater is required to complete the electrical circuit for cathodic protection.

Section II. STEEL PILING

1. General

Steel sheet, H bearing, and cylindrical piles are made in a variety of sizes, and are used in marine structures such as piers, bulkheads, jetties, groins, dolphins, and offshore drilling platforms. Piles for these structures are rolled from several types of steel such as ordinary carbon steel, high strength steel, and steel with both high strength and improved corrosion resistance.

2. Ordinary Carbon Steels

Carbon steels with American Society for Testing Materials (ASTM) (1959) designations A-328, A-252-55, A-36 and A-7 are among those used to produce steel piling. The minimum yield points of these steels range from 30,000 to 38,500 pounds per square inch. These carbon steels give good service in unpolluted fresh water, but may deteriorate rapidly when exposed to splashing seawater or abrasive bottom materials in motion in seawater.

3. High Strength and Corrosion Resistant Steels

Several high-strength steels are now rolled into piling. Steels with ASTM designations A-440, A-441, and A-242 are in this category. In addition to these high-strength steels, another group of steels have been developed which contain columbium or vanadium. These steels have yield points ranging from approximately 45,000 to 55,000 pounds per square inch (Lindahl, 1964). Although these steels have higher strength, reports do not indicate any improvement in corrosion resistance. A high-strength low-alloy steel, which is often referred to as corrosion resistant steel, contains higher percentages of copper, nickel, silica and phosphorus than A-328 steel and is reported to be superior to the A-328 steel in resisting corrosion in the splash zone. It was concluded from tests at Harbor Island, North Carolina, that the corrosion resistance of this steel in the splash zone is three times that of A-328 steel where mild wave action exists and twice that of A-328 steel where considerable wave action exists (U. S. Steel, 1964).

Section III. SEAWATER

1. General

Seawater contains most of the known chemical elements, but it is basically a solution of salts dissolved in water. This salt water is the home of many types of plant and animal life. This section describes some of the more important characteristics of seawater which influence the corrosion of steel piling installed therein.

2. Salinity and Chlorinity

The salt content of seawater is usually expressed as salinity or chlorinity. Chlorinity is defined in Sverdrup, Johnson, and Fleming (1942) as the number giving the chlorinity in grams per kilogram of seawater sample and is equal to the number giving the mass in grams of "atomic weight silver" just necessary to precipitate the hologens in 0.3285233 kilograms of the seawater sample. The chlorinity of seawater ranges from about 18 to 20 parts per thousand, averaging about 19 parts per thousand. The term salinity is intended to denote the total amount of dissolved salt in seawater. For convenience, salinity is usually calculated from the chlorinity of seawater using the formula:

$$\text{Salinity} = 0.03 + 1.805 \times \text{chlorinity}$$

The salinity of seawater ranges from approximately 33 to 37 parts per thousand and the average in the open sea is of the order of 35 parts per thousand (Shreir, 1963).

3. Temperature

Seawater surface temperatures, in general, range from -2° to 35°C (approximately 28° to 95° F). Its freezing point is -2° C. Fluctuations in the temperature of seawater at a given location decreases with depth (Baxter, et al, 1960).

4. Electrolytic Qualities

Electrolytes are substances containing tiny charged particles called ions. Electrolytes conduct electric current by the flow of ions. Seawater contains ions as a result of the dissolved salts. The analysis of a sample of water from the North Pacific Ocean (Fink, 1960) revealed the presence of various cations (positively charged ions) and anions (negatively charged ions) as shown below:

Ions in North Pacific Seawater Samples

Cations	Percent	Anions	Percent
Na^+	1.056	Cl^-	1.898
Mg^{++}	0.127	$SO_4^=$	0.265
CA^{++}	0.040	HCO_3	0.014
K^+	0.038	Br^-	0.0065
Sr^{++}	0.001	F^-	0.0001
Sum:	1.262	Sum:	2.1836
		H_3BO_3 (undissociated)	0.003
		Grand Total 3.449 percent	

The ions contained in seawater are a necessity in carrying out the electrochemical process of corrosion. Further details on the part played by ions in the corrosion of steel piling are given in Section IV.

5. Electrical Resistance

The approximate electrical resistance range of seawater is 15 to 40 ohm-cm compared to 300 to 20,000 ohm-cm for fresh water. Ohm-cm refers to the resistance of matter 1 square centimeter in cross-section and 1 centimeter long (U. S. Army Corps of Engineers, 1962). This difference in electrical resistance between fresh water and seawater is one of the more significant factors which causes corrosion in seawater to proceed faster than in fresh water.

6. pH Value

Aqueous solutions will always contain positively charged hydrogen ions (H^+) and negatively charged hydroxyl ions (OH^-) as a result of the dissociation of water. It is the relative amounts of these ions that determine whether a solution is alkaline, neutral or acid. If hydrogen ions (H^+) are in excess, the solution acts as an acid; if hydroxyl ions (OH^-) are in excess, the solution acts as an alkali. The pH value of a solution is the means of denoting its degree of alkalinity, acidity or whether it is neutral. The pH value is calculated from the hydrogen ion concentration. The total amount of hydrogen and hydroxyl ions contained in a solution is nearly constant, therefore, it is known that, if the hydrogen ion concentration is increasing, the hydroxyl ion concentration is decreasing. The hydrogen and hydroxyl ion constant for pure water has been determined to be 10^{-14} or 10^{-7} hydrogen gram ions per liter and 10^{-7} hydroxyl gram ions per liter. The pH value of an electrolyte is determined by use of the formula:

$$pH = \text{Log}\ \frac{1}{H^+}$$

Using this formula, neutral solutions have a pH value of 7.0. Acidity increases from neutral as the pH value decreases from 7.0. Acidity approaches a maximum in a solution as pH approaches 0. The alkalinity of a solution increases from neutral as the pH value increases from 7.0 to a maximum of approximately 14.0. Seawater pH values normally range from 8.1 to 8.3 but may approach 7.0 in stagnant basins where hydrogen sulfide is present (Redfield, in Uhlig, 1948).

7. Fouling Organisms

Seawater is inhabited by many species of marine plants and animals. Some of these organisms are likely to become attached to marine structures and are known as fouling organisms.

Fouling organisms which are considered to have possibilities of affecting metals in seawater have been divided by Clapp (Uhlig, 1948) into three groups: Sessile organisms, semimotile fouling organisms and motile organisms.

Shell-building sessile organisms include annelids, barnacles, encrusting Bryozoa, mollusks and corals. Non-shell-building sessile organisms include marine algae, fillimentous Bryozoa, coelenterate, tunicates and calcareous and siliceous sponges. Semi-motile fouling organisms are those which possess the power to move if not restricted by outer forces, such as the growth of other organisms surrounding it. This group includes sea anemones, worms, certain crustacea and mollusks. Motile organisms such as worms, certain mollusks such as sea slugs and snails, may affect the corrosion of metal directly or indirectly due to the slimy film secreted by them (Clapp, in Uhlig, 1948). Ways in which fouling organisms affect the corrosion of steel piling are given in paragraph 7, "Marine Organisms" of Section V.

8. Bacteria

Seawater contains numerous types of bacteria. Anaerobic bacteria which thrive in oxygen-free environments where sulfate is present are of concern to corrosion engineers where stagnant water exists. Sulfate reducing bacteria can cause corrosion of material without the presence of oxygen.

A factor of significance in corrosion protection is that many materials are suited to the metabolism of some types of marine bacteria (Muroaka, 1963). For this reason, many of the protective coatings for steel may be damaged or destroyed by marine bacteria. Muroaka gives four ways in which bacteria takes part in the fouling of marine structures as follows:

a. Being a source of food for barnacles.

b. Affording footholds for other animals.

c. Aiding sessile organisms in depositing their calcareous cements.

d. Discoloring glazed or bright surfaces (fouling proceeds faster on dull dark surfaces).

Section IV. CORROSION OF STEEL PILING IN SEAWATER

1. General

The corrosion of steel piling in seawater is caused by electrochemical action. This corrosion process primarily involves the steel, an electrolyte, in this case seawater, and oxygen. As a result of the corrosion process, iron, the principal constituent of steel, is restored to the state in which it is mined as ore (iron oxide). Iron oxides that form on the surface of steel as a result of the corrosion process may greatly retard further reaction. Black iron oxide (Fe_3O_4) offers good protection from further corrosion whereas the iron oxides (Fe_2O_3 and $Fe_2O_3 .\ x\ H_2{}^{O}$) do not appreciably protect the underlying metals (Baxter and Steiner, 1960).

2. The Corrosion Process

Steel in contact with an electrolyte inherently has areas of differing electrical potential. The difference in potential causes electric currents to flow in the steel and through the electrolyte. The current flow in the electrolyte is in the form of ion transfers. Positive Fe^{++} ions are released into the solution (electrolyte) from the anodic surfaces of the steel. The positive ions in the electrolyte are attracted to the cathode since there is a reduction process present which produces OH^- ions. These ions combine to form $Fe(OH)_2$(ferrous hydroxide). The OH^- ions are formed by the dissociation of water (H_2O) producing hydrogen atoms (H^+) and the OH^- (Hydroxide ion). When an Fe^{++} ion is released into an electrolyte, it gives up two electrons ($2e^-$). These electrons are given up at the anode and flow through the metal to a cathodic area. Two hydrogen atoms ($2H^+$) from dissociated water may combine with two electrons ($2e^-$) at the cathode to form hydrogen molecules (H_2) which will either cling to the cathodic surfaces, bubble off as gas or combine with oxygen to form water. In addition to the reaction described above in the steel corrosion process, there can be other reactions such as the conversion of ferrous iron to ferric iron.

Section V. FACTORS AFFECTING THE CORROSION OF STEEL PILING IN SEAWATER

1. General

A number of factors may influence the rate at which the corrosion process of steel piling proceeds in seawater. Some are:

a. Water temperature
b. Concentration of oxygen in electrolyte (seawater)
c. pH value of the seawater
d. Marine fouling on piling
e. Salinity of the seawater
f. Velocity of the water relative to the structure
g. Galvanic effect of unlike metals

Details concerning the effects of these factors are given in the paragraphs to follow.

2. Temperature

Temperature affects the corrosion of steel in seawater in several ways. One is that chemical reactions of the corrosion process are accelerated in warmer water. Another is that the marine fouling organisms which may affect the corrosion rate are more numerous in warmer waters. Temperature also affects the capacity of the water to dissolve oxygen.

Data compiled by LaQue (Uhlig, 1948) indicates that the tendency for the chemical process of corrosion to proceed faster in warmer water is often counteracted by the metal surface having a heavier protective covering of marine fouling. This is considered to be the reason some investigators have found that, contrary to expectations, corrosion in warmer waters has proceeded at practically the same rate as in cooler waters.

3. Oxygen Concentration

Oxygen can affect the corrosion of steel in seawater in several ways. It may cause variations in the electrical potential of metal areas in a solution when its concentration varies along the metal surface; it acts as a cathode depolarizer; it reacts with the ferrous atoms to form oxides of the metal. Areas of low oxygen concentrations on a metal surface are anodic to those of higher oxygen concentration (U. S. Army Corps of Engineers, 1962).

Temperature and oxygen are interrelated in seawater corrosion. Figure 1 shows variations in the corrosion rate of steel in air-saturated and partially de-aerated sodium chloride solutions at various temperatures. Seawater near the surface is nearly saturated with oxygen in areas where considerable wave action and spray exists (Fink, 1960).

4. pH Value

There is little change in the corrosion rates of steel surfaces between pH values of 4 and 9.5 at a given temperature. The surface is in contact with a layer of hydrous ferrous oxide and corrosion can only progress as fast as oxygen can diffuse the protective layer (U. S. Army Corps of Engineers, 1962). As alkalinity increases from 9.5, the iron tends to become passive as the permeability of the surface layer by oxygen is decreased. As the pH value drops below 4, the protective corrosion product layer is dissolved and the acid reacts directly with the metal. An example of the effect of pH value on corrosion rate is shown in Figure 2. These curves were obtained by exposing mild steel specimens to water having an oxygen concentration of 5 milliliters per liter. Hydrochloric acid and sodium hydroxide were added as required to produce the desired acidity and alkalinity for the investigation.

5. Salinity

Although the total salinity of seawater may vary in different locations, the proportions of various salts relative to each other remain virtually the same (Fink, 1960). Of the various ions in seawater resulting from the dissolved salts, the chloride ion is the most significant. This is attributed to its being present in larger quantities and to its ability to penetrate corrosion product films to continue its activity in the corrosion process. Figure 3 shows the effect of sodium chloride concentration on the corrosion rate of iron and the solubility of oxygen as a function of salinity. Note that the concentration of sodium chloride does not affect the oxygen solubility until a concentration of 5 to 10 grams per liter is reached.

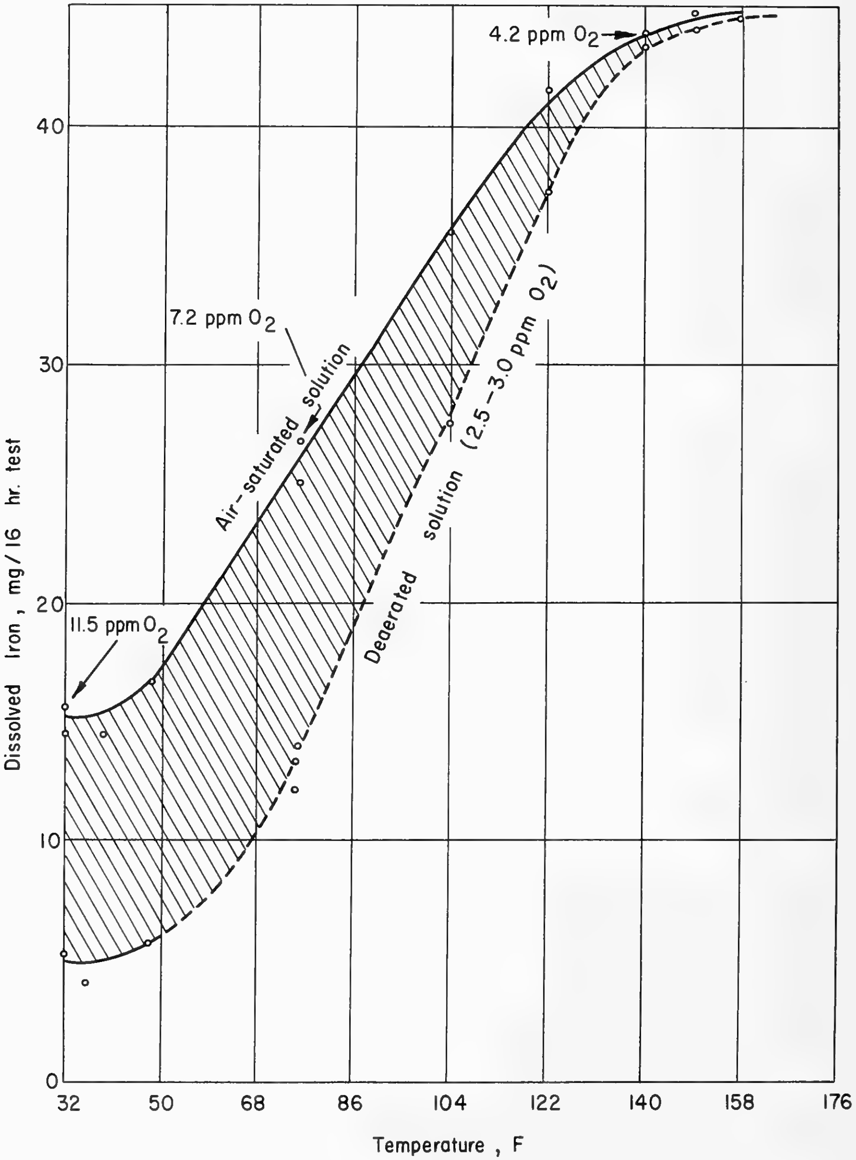


Figure 1. Corrosion of iron in 3% sodium chloride solution showing the effect of temperature and aeration. (From Fink, 1960)

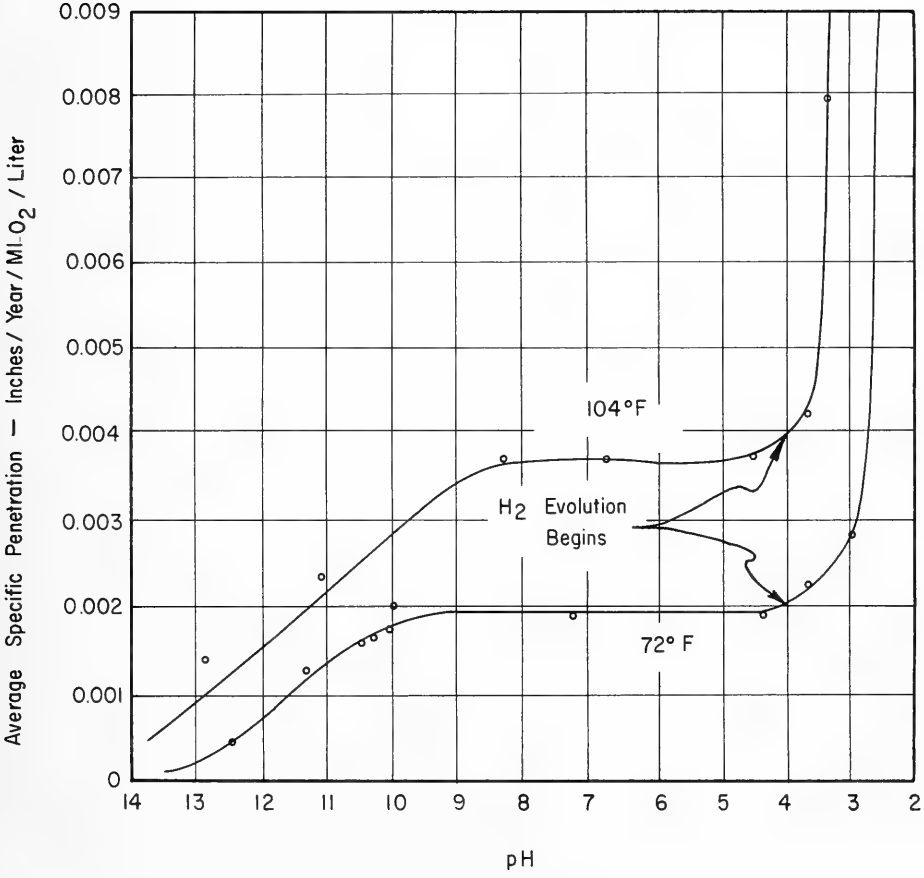


Figure 2. Effect of pH on corrosion of mild steel
(From U.S. Army, Corps of Engrs, 1962)

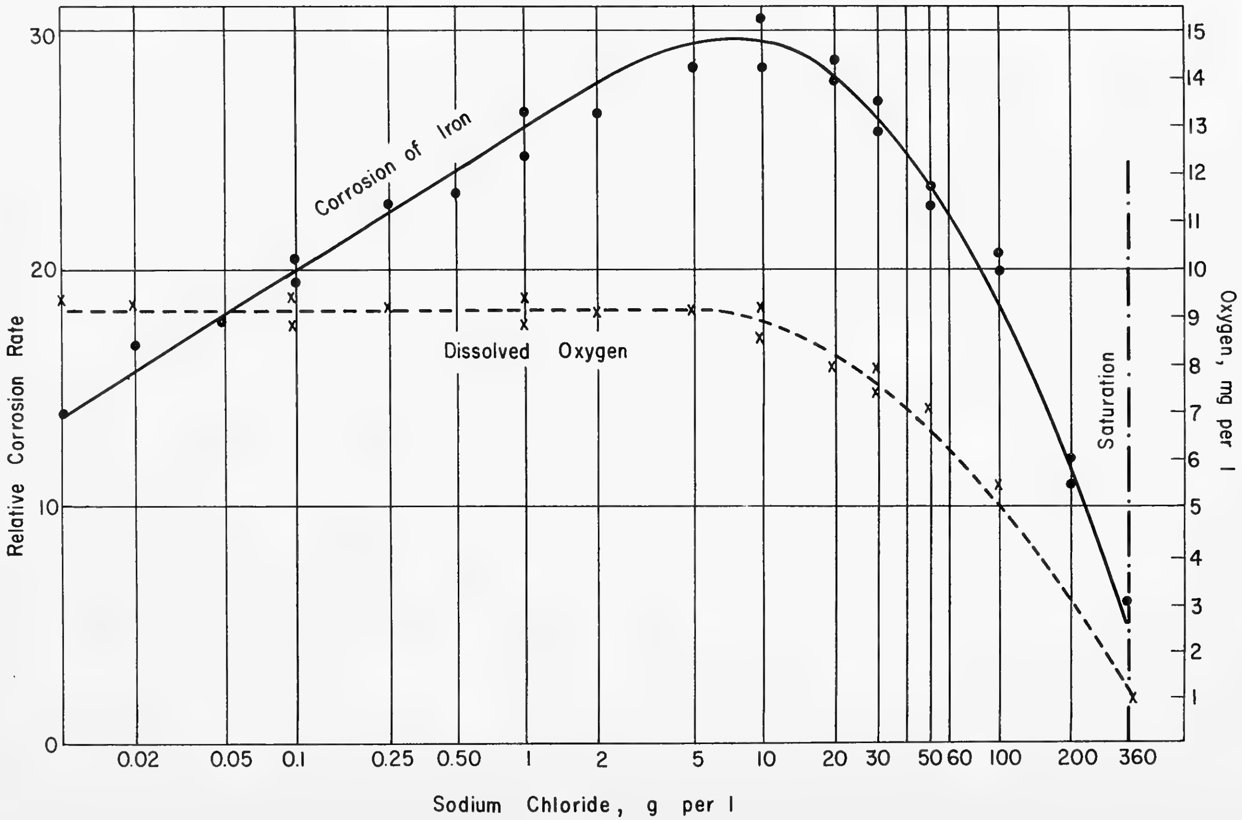


Figure 3. Variation of corrosion of iron as a function of the salinity, T = 75 F. (From Fink, 1960)

6. Water Velocity

The highest water velocities at pile structures which may significantly affect their corrosion are probably those caused by wave action. These velocities depend upon wave conditions possible at the site and should seldom exceed 25 feet per second. The effect of water velocity on corrosion rates in seawater is quite different from the effect in fresh water. It is more difficult to attain passivity of metals in seawater.

Tests in neutral waters have shown that the corrosion rate increases with an increase in water velocity up to a certain point. Further velocity increase may then cause the corrosion rate to decrease (Copson, 1952). The increase in corrosion rate with increased velocity is attributed to the force of the water eroding the existing protective oxide films thereby exposing new metal to the corrosive environment. The decrease in the corrosion rate when the water velocity exceeds a certain high has been shown to be due to the increased oxygen supply permitting a film of ferric hydroxide to form (Copson, 1952). This film apparently adheres to the metal at relatively high velocities. Other tests (Copson, 1952) are reported to have shown that it is quite difficult to reach a state of corrosion passivity in seawater. Figure No. 4 shows the effects of water velocity on the corrosion of steel in seawater. The difficulty in producing corrosion passivity in seawater can probably be attributed to the chloride ions. Water with zero velocity (stagnant) can usually be expected to have a lower corrosion rate but a higher rate of localized pitting (Copson, 1952).

7. Marine Organisms

Marine organisms may affect the corrosion rate of steel piling in several ways, such as:

a. Penetrating soft protective coatings and exposing base metal to seawater.

b. Forming protective films on metal surfaces.

c. Burrowing into protective concrete encasements.

d. Organisms smothered by larger ones may form acids which attack the metal surface.

e. By producing metabolic byproducts, including hydrogen sulfide, acids, carbon dioxide and ammonia which may take part in the corrosion of metal (Snyder and Hull, 1965).

f. The formations of fouling organism may cause localized stagnant water conditions which in turn create differential oxygen cells.

8. Galvanic Effect of Unlike Metals

Caution should be taken in connecting unlike metals or creating unlike conditions in the same metal or alloy for structures in seawater

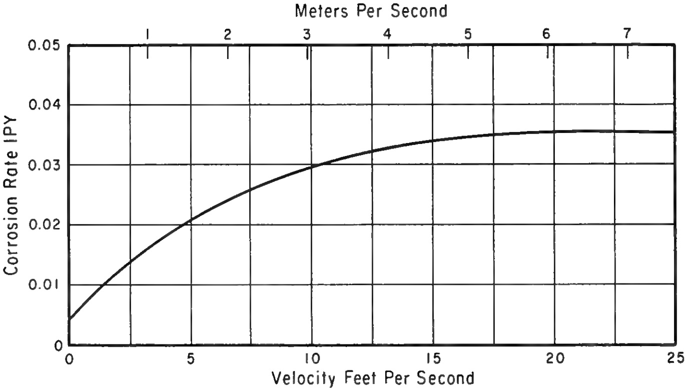


Figure 4. Effect of velocity on corrosion of steel by seawater at atmospheric temperature (From LaQue in Uhlig, 1948)

since galvanic corrosion will result. When two unlike metals are connected in an electrolyte, such as seawater, an electric current flows in the metals and through the electrolyte. The least noble metal or alloy (the one highest in the galvanic series) will corrode. The metal which corrodes is also the one from which the current flows into the electrolyte.

The order of some metals and alloys in the galvanic series as derived from tests in seawater are shown in Table XV, Appendix A; the information in this table is from a report by LaQue and Cox (1940). Revisions were made to show the current aluminum designation. The order of the metals in the various groups may change depending on incidental conditions of exposure. Galvanic action due to combining metals shown within a group in Table XV should be relatively low (LaQue and Cox, 1940). In the event it is desirable to use materials from different groups in combination, the galvanic effect will ordinarily be less if materials are selected from groups closest together in the table.

Another practice which should ordinarily be followed when coupled unlike metals will be in contact with seawater is to keep the area of the anodic metal or alloy large in comparison to the cathodic material. This practice spreads the corrosion due to the galvanic electric current over a larger area.

Section VI. CORROSION RATE OF UNPROTECTED STEEL PILING IN SEAWATER

1. General

The corrosion rate of unprotected steel piling in marine structures can vary considerably depending on environmental conditions. Some of the more influential environmental factors were discussed in the preceding paragraphs.

Due to the vertical extent of steel piling in marine structures, there are variations in environmental exposure, and therefore, differences in rates of corrosion at various levels. Corrosion rates for steel piling should, therefore, be stated for particular exposure zones in order to be of value.

2. Ordinary Carbon Steel

There appears to be general agreement among corrosion specialists that bare steel structures of ordinary steel continuously submerged in relatively uncontaminated seawater will corrode at a rate of approximately 5 mils per year. As previously stated, corrosion rates can vary considerably between the various corrosion zones, and at the same zone of structures at different locations, depending on conditions at the site. Figures 5 through 7 show rates of loss of metal thickness at various elevations along unprotected piles installed at the locations indicated.

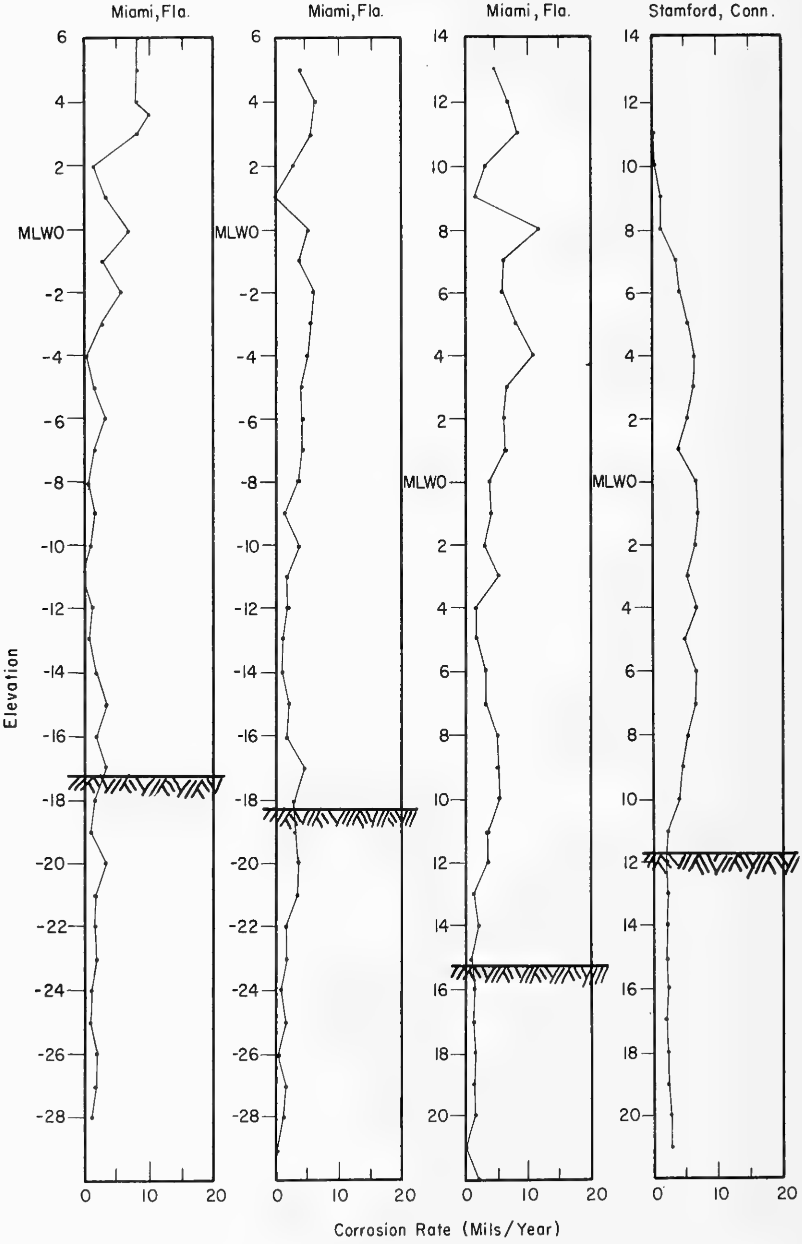


Figure 5. Corrosion rates of unprotected steel piling in seawater. (After U. S. Army, Corps of Engrs, 1952)

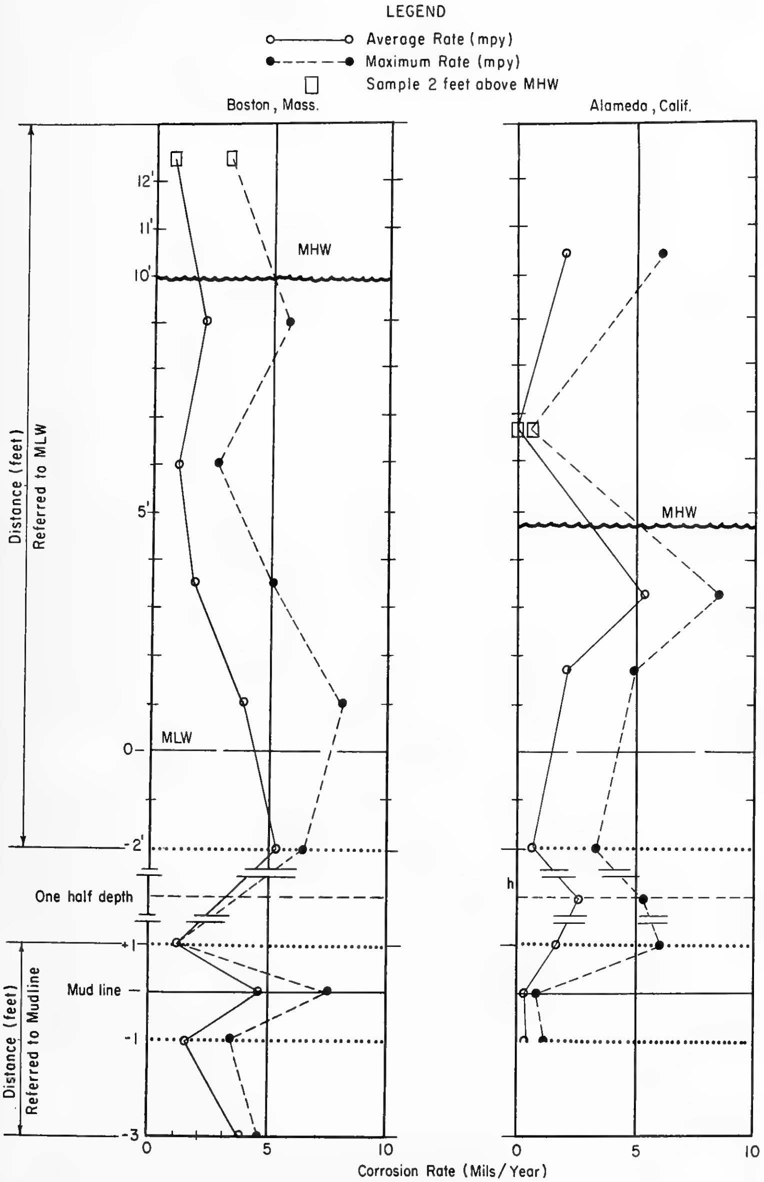


Figure 6. Corrosion rates of unprotected steel piling at Boston and Alameda. (After Brouillette and Hanna, 1960)

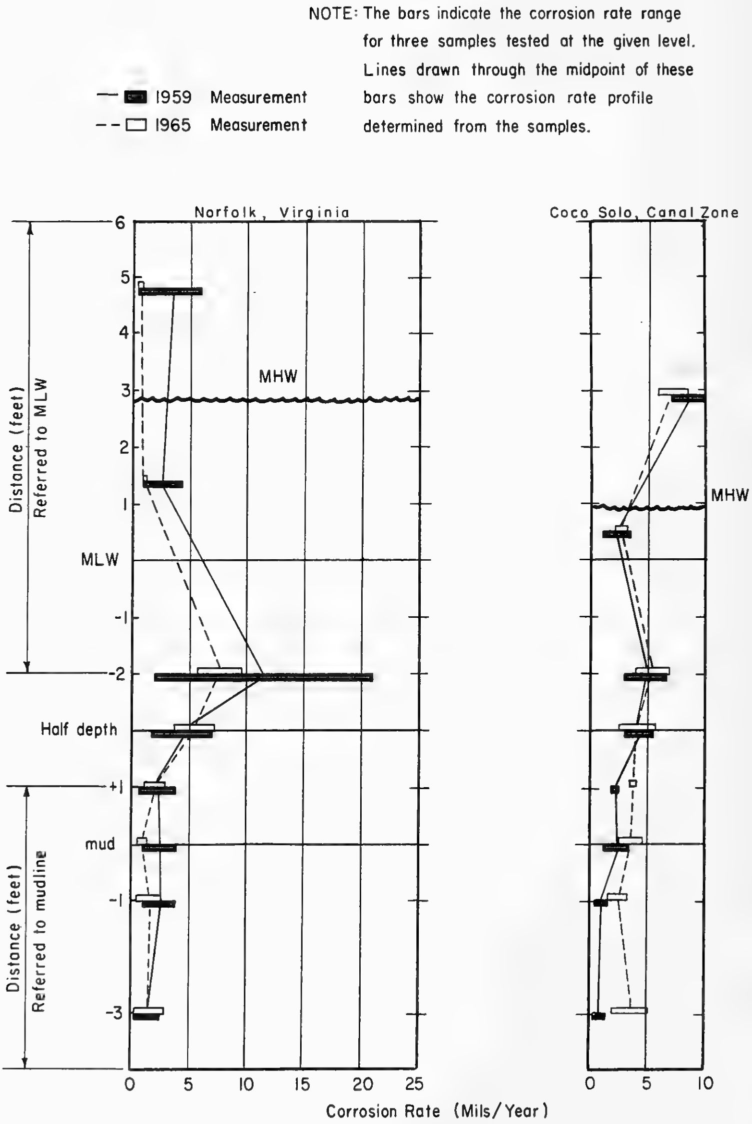


Figure 7. Corrosion rates of unprotected steel piling at Norfolk and Coco Solo. (After Brouillette and Hanna, 1960)

Profiles showing the pitting rates of the piles concerned in Figure 7 are given in Figure 8.

Tests indicate that when piling is installed where there is considerable movement of abrasive bottom materials, the portion of the piling subjected to the abrasion will deteriorate at the fastest rate (Ross, 1948, Alumbaugh, 1962).

Observation of steel sheet pile groins installed at Palm Beach, Florida, indicated that the localized corrosion rate in the sand abrasion zone could be as high as 373 mils per year (Ross, 1948). Due to the severity of corrosion in this zone and the distinctive difference in the environment, it is felt that it should be treated as a separate zone when it exists.

The most severe corrosion zone on steel piling after the abrasion zone is the splash zone when a structure is located where splashing water exists a large percentage of the time. Localized corrosion rates as high as 63 mils per year have been reported for this zone (Rayner, 1952).

3. Low Alloy Steels

Various metals have been added to steel with the objective of producing steel which is more corrosion resistant in a marine environment. Steel bars containing percentages of copper were tested by immersing in seawater and found to be somewhat more resistant to corrosion than ordinary steel (U. K. Department of Scientific and Industrial Research, 1928). However, in alternately wet and dry conditions, steel with higher copper content lost more weight than that with lower percentages of copper. The improved corrosion resistance of copper-bearing steel is attributed to the copper causing a more durable corrosion film to form which retards further corrosion. Ross (1948) reports that steel sheet pile groins containing copper showed no superiority over ordinary steel in tests at Palm Beach, Florida. Mariner steel piling, containing more copper, silica and phosphorus than A-328 steel, is expected to give 2 to 3 times the corrosion resistance of A-328 steel in the splash zone, depending on the degree of exposure to wave action (U. S. Steel, 1964). Figure 9 shows comparative corrosion rates for these two steels.

Section VII. CORROSION PROTECTION FOR STEEL PILING

1. General

Methods now used to combat the corrosion of steel structures in seawater include the encasement of steel in concrete, the application of various protective coatings, cathodic protection, and various combinations of these methods. The paragraphs to follow will describe these methods of protection and present information of value when considering their use.

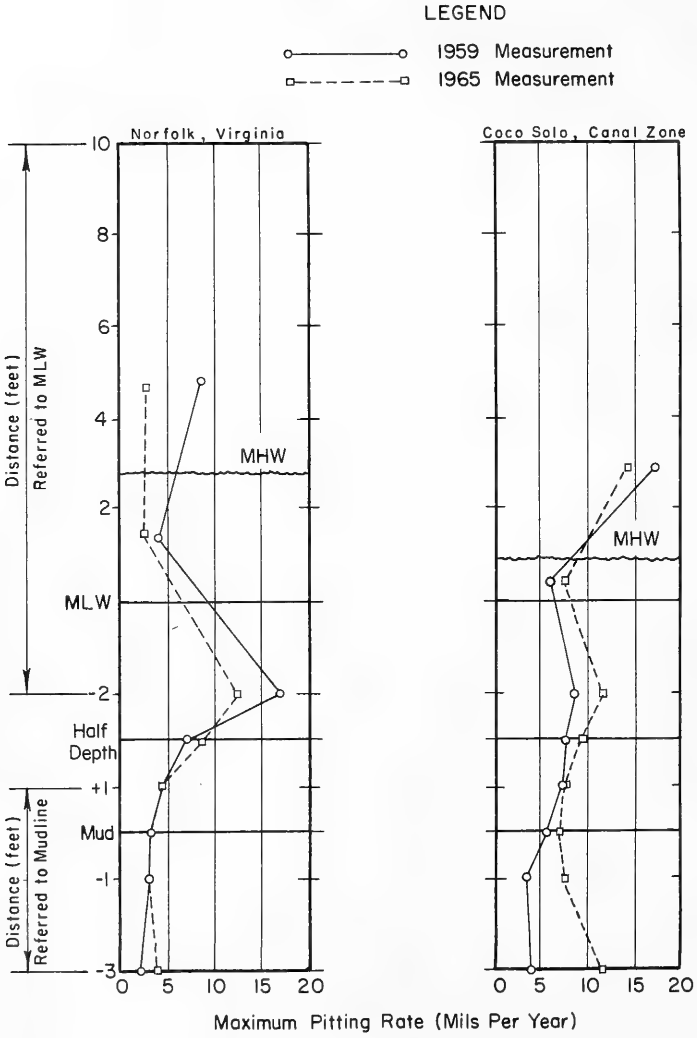


Figure 8. Pitting profile. (From Brouillette and Hanna, 1966)

NOTE: Mariner steel composition contains higher percentages of copper, nickel, silica, phosphorus than A-328.

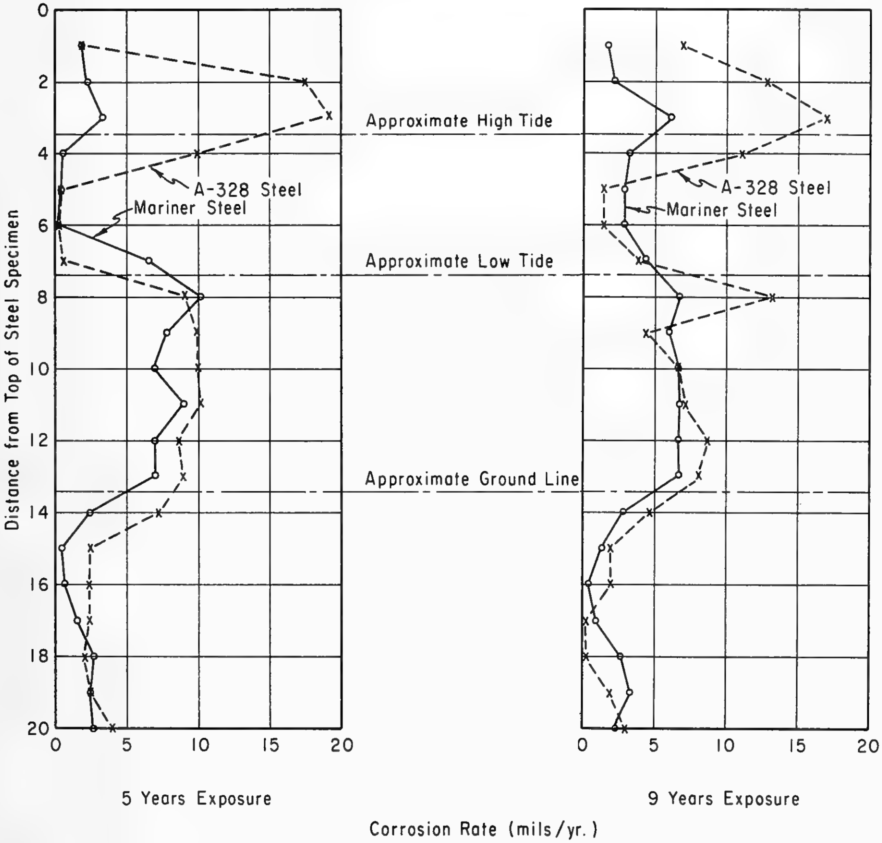


Figure 9. Seawater corrosion comparison for A-328 steel and mariner steel. (After U. S. Steel Corp., 1964)

2. Protective Coatings for Steel Piling

Protective coatings on steel piling are intended to act as a barrier to separate the steel surface from its corrosive environment. The development of suitable coatings for long-term protection of steel in seawater has been quite slow. Coating systems which appear to be worthwhile for protecting steel piling are, in general, rather new, and long-range test data are not available for many of them. However, test results located are presented.

There are numerous types of coatings now in existence, many of which are used in combination with other types as well as alone. References to combination coating systems in this report will be made in terms of the basic type of topcoat material.

Most of the test results on coatings contained in this report were obtained from tests carried out by the U. S. Naval Civil Engineering Laboratory. They have apparently done most of the testing of coatings suitable for steel piling.

Some of the coating data presented resulted from testing coatings on mooring buoys and panels. Although the performance of coatings on mooring buoys may be similar to their performance on steel piling, this is not necessarily so. It is felt, however, that the performance of coatings on buoys relative to each other will be applicable for steel piling. Test results for coatings on steel panels are presented since very few tests have been made on steel piles. Any coating which fails on a steel panel should not be expected to protect a steel pile. In addition, coatings which perform well on panels should at least be considered good prospects for steel pile protection. Metallic coatings especially may be adversely affected by electrical currents caused by the pile passing through differing environments that may not exist in tests of panels.

Types of coatings in use today may be divided into a number of categories, two of which are metallic and nonmetallic. Some useful test information has been discovered on coatings and is presented under these two classifications. Since surface preparation is an important factor when coating steel for marine exposure, information thereon has been included under this heading.

The nonmetallic coatings may be further divided into organic and inorganic types.

a. Metallic Coatings. Several investigations have been made to determine the corrosion protection ability of metallic coatings on steel piling. The metals involved were flame-sprayed zinc and flame-sprayed aluminum. These metallic coatings have also been used in combination with other coatings.

(1) Flame-Sprayed Zinc. The U. S. Naval Engineering Laboratory has tested flame-sprayed zinc on steel piling (Alumbaugh, 1962).

The results of these tests are included in Tables II a and II b of Appendix A. These results show the flame-sprayed zinc coating to compare favorably with other high ranking coatings in the test except in the splash zone. Later tests of longer duration showed a number of other coatings to be quite superior to bare flame-sprayed zinc for protecting steel in seawater. The poor performance of zinc in the splash zone is probably due to the tendency of splashing water to erode the protective corrosion film formed on its surface. Figure 10 shows that the corrosion of zinc in seawater increases with water velocity at least within the velocity range of the test (Tuthill and Schellmoller, 1965).

Other tests involving steel panels coated with flame-sprayed zinc which were exposed by total immersion in seawater at mean tide level, and in the atmosphere, have been carried out at various locations by the American Welding Society (1962). It was concluded from these tests that flame-sprayed zinc coatings 3 mils in thickness exposed alternately to seawater and atmosphere will give less than 6 years of corrosion protection to steel, also that a 6-mil flame-sprayed zinc coating may give little more than 6 years of protection to steel exposed in the same manner. A later, 12-year report by the American Welding Society (1967) which gives results of a continuation of tests of totally immersed panels shows that flame-sprayed zinc coatings of 3 and 6 mils thickness have failed completely. Flame-sprayed zinc with thicknesses of 9, 12, 15 and 18 mils was still protecting the steel, however, the zinc was almost entirely coverted to corrosion products. Exposure at mean tide level produced similar results. The results of testing flame-sprayed zinc panels sealed with vinyl and chlorinated rubber are given in this section under "Vinyls" and "Chlorinated Rubber".

One paper (Horvick, 1964) suggests that for protecting steel continually immersed in low velocity seawater, under normal conditions, one mil of zinc coating should be specified for each year of protection required.

Steel panels with a flame-sprayed zinc coating were tested by alternate immersion and extraction at quarter-hourly periods in a solution of 20 grams of sodium chloride per liter of water for 2,390 hours (Orlowski, 1965). The thickness of these zinc coatings were in the order of 1.5, 3 and 5 mils. Some were sealed by cold phosphatization. A report on these tests states that:

1. There was no appearance of rust.

2. There may be a slight advantage resulting from sealing the zinc coatings by cold phosphatization.

3. The adhesion of vinyl paint to phosphatized paint is satisfactory.

Recent test results (Alumbaugh and Brouillette, 1966) report flame-sprayed aluminum to be far superior to flame-sprayed zinc in protecting steel

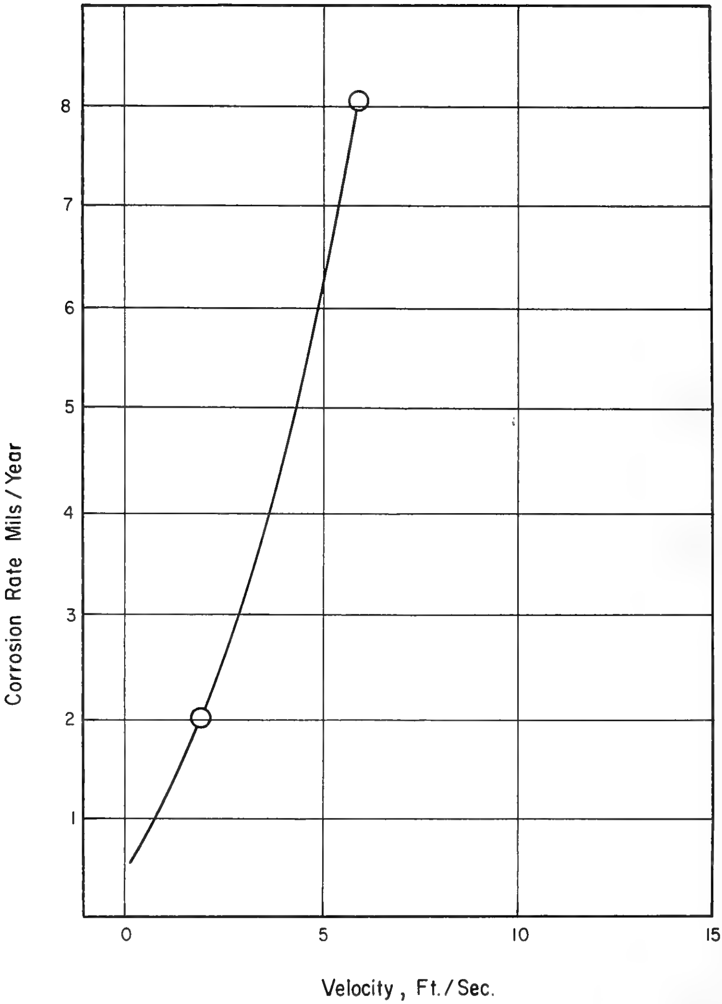


Figure 10. Effect of seawater velocity on corrosion rate of zinc at ambient temperature. (From Tuthill and Schellmoller, 1965)

piling from corrosion by seawater. The best flame-sprayed zinc coating of the test (5.5 mils thick) failed after 4 1/2 years, whereas one of the flame-sprayed aluminum coatings (4.5 mils thick) was still providing excellent protection after 11 1/2 years exposure in seawater. However, when sealed with other types of topcoats, the flame-sprayed zinc was far superior to the flame-sprayed aluminum. For a comparison of flame-sprayed zinc coatings with others, see Figures 11 a-c. Figure 11c shows that flame-sprayed zinc in combination with either saran, vinyl, epoxy, or furan have provided good protection to steel piling specimens for 10 1/2 years. Further testing will be required to determine the maximum duration that these coating systems are effective. Alumbaugh and Brouillette (1966) further report that when a phenolic mastic coating was applied to a flame-sprayed zinc coating blisters occurred before the test specimen was exposed to seawater.

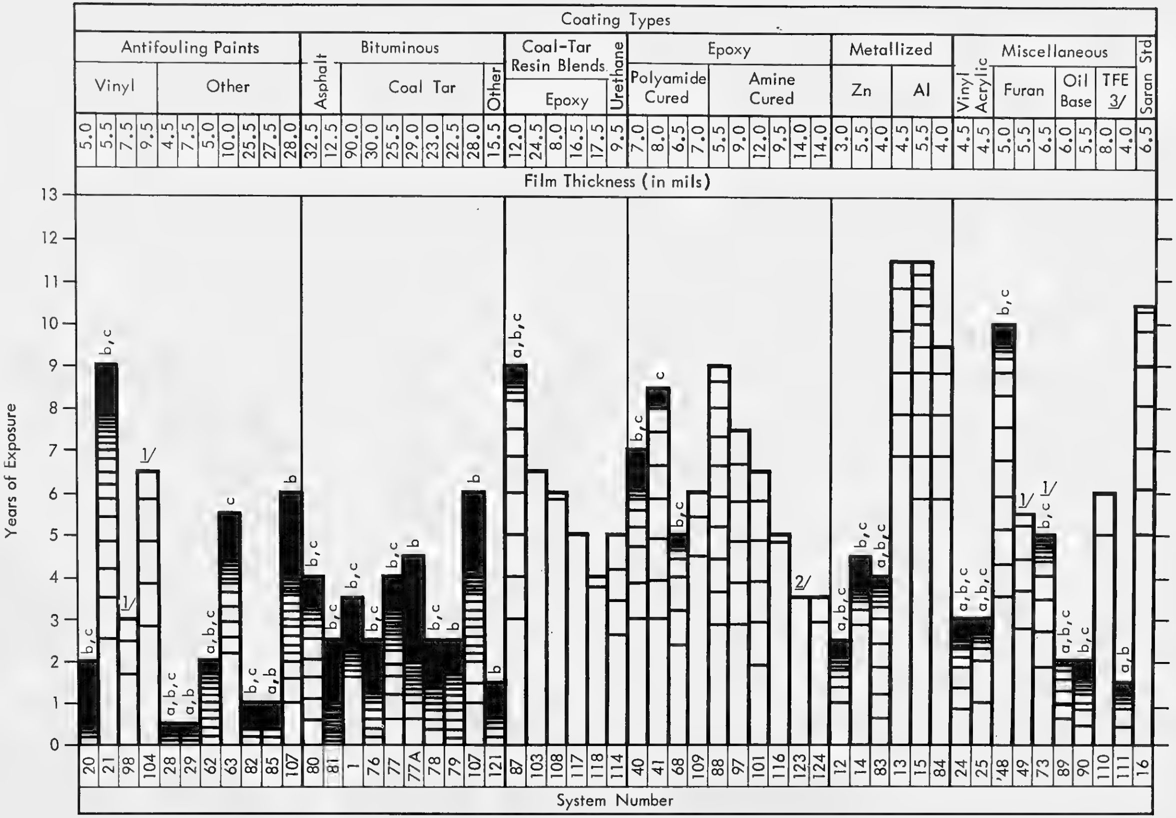
(2) Flame-Sprayed Aluminum. Flame-sprayed aluminum coatings 6, 9, 12, 15 and 18 mils thick on steel panels were evaluated after 6 and 12 years of exposure immersed in seawater at Freeport, Texas, and Wrightsville Beach, North Carolina. The results are given in reports by the American Welding Society (1962 and 1967). After 6 years there were small amounts of base metal corrosion on panels from both test sites (American Welding Society, 1962). Evaluation of the flame-sprayed aluminum coatings after 12 years of exposure revealed that all unsealed coatings had blistered, but that there were no pits in the steel under the blisters (American Welding Society, 1967).

Some steel panels coated with flame-sprayed aluminum and sealed with a wash primer and vinyl coat have been tested immersed in seawater for up to 12 years. The results of these tests are included under "Vinyl Coatings". Other steel panels with the flame-sprayed aluminum coating were exposed at meantide level for 12 years. The report of the 12-year inspection states that although mean tide level exposure is considered to be more severe in corroding bar steel than total immersion, it appeared to be no more severe for steel with flame-sprayed aluminum or zinc.

The results of a six-month test of flame-sprayed aluminum (Alumbaugh, 1964) are included in Table III.

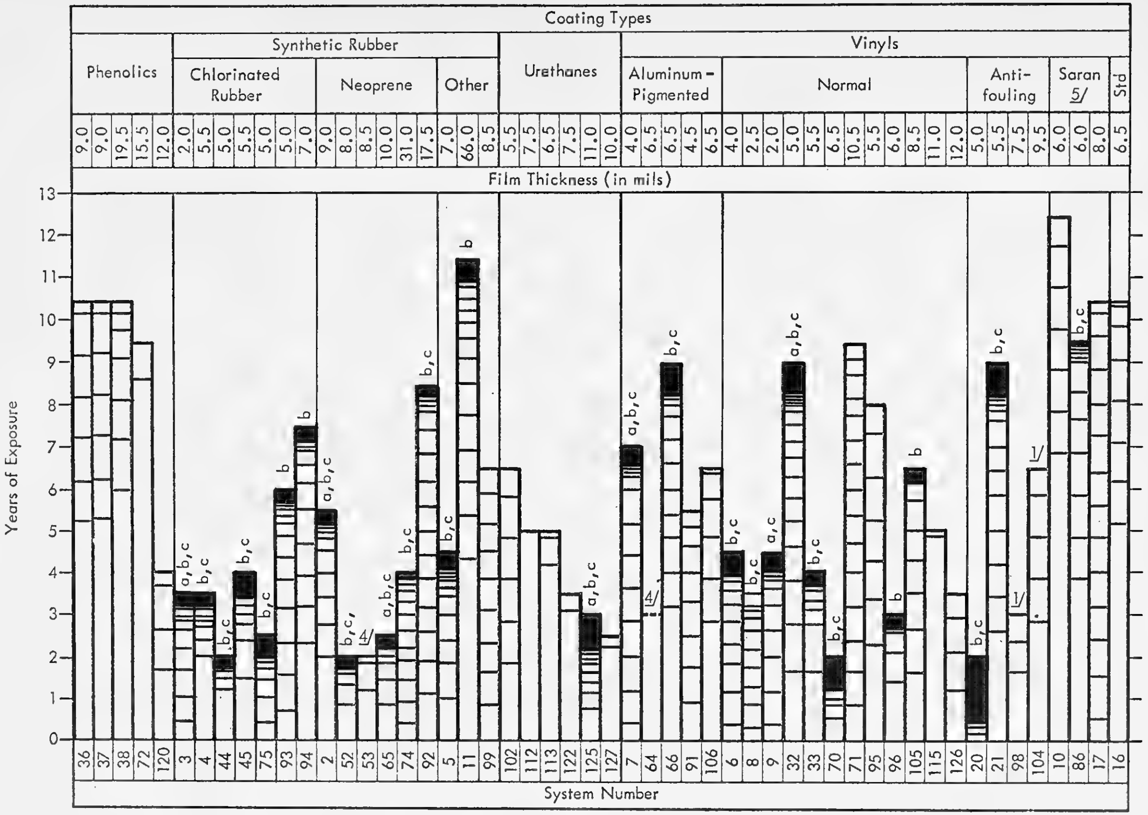
Alumbaugh and Brouillette (1966) report that a 4.5-mil flame-sprayed aluminum coating is still effectively protecting steel in seawater after 11 1/2 years of exposure. This process used powdered zinc. The fact that a thicker (5 mil) flame-sprayed aluminum coating using aluminum wire had practically failed after 11 1/2 years may or may not be of significance as to which is the better application method.

b. Non-Metallic Coating. This group comprises many coatings, including both organic and inorganic. The earlier non-metallic coatings for steel piling were generally coal tar or asphalt; neither of which has been very successful in seawater. One of the major problems is penetration of these coatings by fouling organisms. Coal-tar epoxy coatings



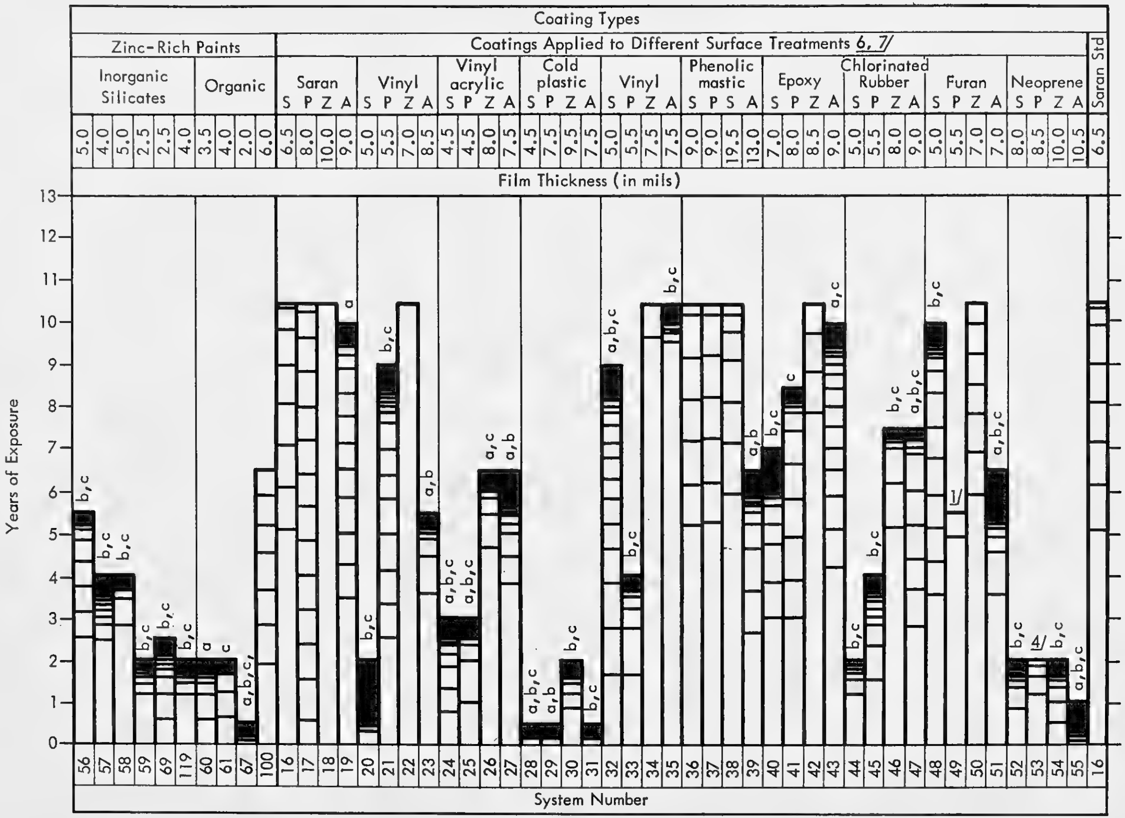
NOTES: See page 27 for footnotes. See Table XIV, Appendix A, for coating details.

Figure 11a. Comparative protection provided by the various systems to corrosion dock panels. (Sheet 1 of 3) (From Alumbaugh and Brouillette, 1966)



NOTES: See page 27 for footnotes. See Table XIV, Appendix A, for coating details.

Figure 11b. Comparative protection provided by the various systems to corrosion dock panels. (Sheet 2 of 3) (From Alumbaugh and Brouillette, 1966)



NOTES: See page 27 for footnotes. See Table XIV, Appendix A, for coating details.

Figure 11c. Comparative protection provided by the various systems to corrosion dock panels. (Sheet 3 of 3) (From Alumbaugh and Brouillette, 1966)

Footnotes for Figures 11a, 11b and 11c

1/ Vinyl system is still protecting the steel very well, but the primer and topcoat have lost adhesion and can be peeled from panel. Removed from test.

2/ Epoxy-phenolic.

3/ TFE (Tetrafluoroethylene), System 110, is System 109 with the TFE emulsion finish.

4/ Panel was lost.

5/ Saran is not actually a vinyl, but is included in this group since its properties are similar to those of a vinyl.

6/ The letters designate different surfaces over which the coatings were applied. S = bare sandblasted steel; P = pretreatment primer, Formula 117; Z = flame-sprayed zinc; A = flame-sprayed aluminum.

7/ Coatings in this group applied over bare steel and Formula 117 are also included under their particular generic types and are shown here for purposes of comparison.

Notes: 1. The letters a (atmospheric), b (tidal) and c (immersed) above the bar graph indicate the zone in which the coating failed.

2. Increased concentration of horizontal lines in the bar graphs indicates increased deterioration of coating. Solid black areas indicate complete failure.

have been applied to many pile structures since 1955 and are proving to be more durable than ordinary coal tars. Many other non-metallic coatings such as vinyls, rubbers, phenolics, sarans, mica-filled asphalt emulsions, epoxies, urethanes, polyester-glass flake, and furan are being tested for service on steel piling by the U. S. Naval Civil Engineering Laboratory, the National Bureau of Standards and the Coastal Engineering Research Center. Information on non-metallic coatings from tests in progress or completed are presented in paragraphs to follow.

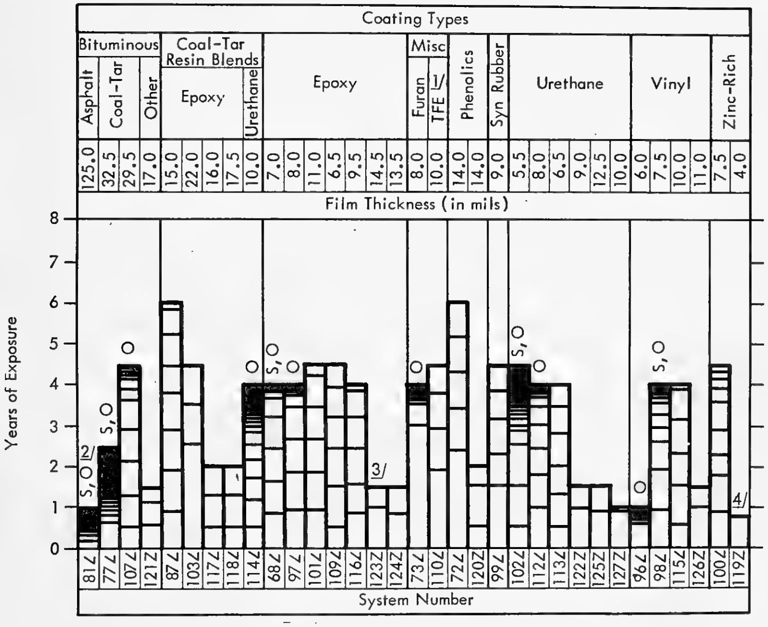
(1) Bituminus. A coal-tar coating cold-applied to steel piling for a test in seawater was in poor condition after 2 1/2 years in the zones that included the tide and sand abrasion. However, it was still effectively protecting the steel in the atmospheric and imbedded zone. The evaluation ratings given this coating at various test intervals up to 2 1/2 years are shown in Tables II a and II b.

Panels coated with a system consisting of a coal-tar primer, a coal-tar enamel and a natural resin anti-fouling topcoat were reported to be in "remarkably good" condition after 6 years immersion in tropical seawater. See Table IV. These coatings were applied very thick (70-100 mils). The same coating systems were considered inadequate for 6 years of exposure in seawater at mean tide level (Alexander, Forgeson, and Southwell, 1958).

Asphalt and coal-tar coatings on steel were tested in seawater at a harbor and a surf site at Port Hueneme, California. After exposures ranging up to 6 years, these coatings were found to be quite good for marine atmospheric exposure but did not show long-term durability in the tidal and submerged zones. One of the primary causes of failure was damage to the coatings by fouling organisms. Substantiating this theory is the fact that anti-fouling coal-tar coatings gave longer protection than other types in these tests (Alumbaugh and Brouillette, 1966). See Figures 11a and 12.

(2) Vinyl. Vinyl coatings are one of the more successful coatings for protecting steel in seawater. Of 83 coating systems tested on steel panels exposed to seawater in the tide zone for 6 years, 3 vinyl systems including a topcoat of anti-fouling paint were among the five best coating systems (Alexander, Forgeson, and Southwell, 1958). These coatings are included in Table V which lists the 5 coatings considered satisfactory for the mean tide zone after 3 years exposure. The vinyl coatings, however, were not considered to adequately protect the metal panels after 6 years immersion in seawater (see Table IV).

Vinyl coatings were included in coatings tested on piling driven in the surf zone at Port Hueneme, California (Alumbaugh, 1962). The ratings of the vinyl coatings (vinyl mastic and aluminum vinyl) after 2 1/2 years of exposure are shown in Tables II a and II b. These coatings were also tested on steel sheet piling and H piling driven at Cabras Island (off Guam) in the Marianas. The coating evaluation results of this test are given in Table VII.



Notes: *See Table XIV in Appendix A for coating system details. Increased concentration of horizontal lines in the bar graph indicate increased deterioration of coating. Solid black areas indicate complete failure.*

1/ *Same as 3/ above except 109∠ and 110∠*

2/ *S = coating failure on shore face of panel.*
O = coating failure on ocean face of panel.

3/ *Epoxy-phenolic.*

4/ *Panel was lost.*

Figure 12. Comparative protection provided by the various systems to angle iron panels.

Steel panels coated with flame-sprayed aluminum, a wash primer and vinyl topcoat were immersed in seawater at Freeport, Texas, and at Wrightsville Beach, North Carolina. Inspection of the panels at the end of 12 years revealed that protection of the steel was excellent with the exception of panels having aluminum 3 mils thick. The other aluminum thicknesses tested were 6, 9, 12, 15 and 18 mils. Panels with the same coating system were also placed at mean tide level for alternate immersion and atmospheric exposure. These panels appeared to be in the same general condition as the totally immersed panels (American Welding Society, 1967).

Of approximately 21 vinyl coating systems tested in Port Hueneme Harbor, a vinyl mastic had the longest exposure. After 9 1/2 years it was still providing a fair degree of protection to the steel (Alumbaugh and Brouillette, 1966). Two other vinyl systems with 6 1/2 and 8 years of exposure were performing very well. The performance of vinyl coatings and other types are given in Figures 11a-c and 12. Other findings from these tests were that aluminum pigmented vinyls showed no conclusive superiority and that failure of vinyl systems could usually be attributed to poor adhesion.

A coating system consisting of proprietary primer, vinyl, vinyl-alkyd and vinyl antifouling coats was rated in "good-fair" conditions after exposure for nearly 5 years on mooring buoys (Drisko, 1968). Three other vinyl coating systems (10, 11 and 12, Table VIII) performed poorly and were removed from the test due to failure after approximately 2 1/2, 1 1/2 and 4 1/2 years, respectively.

(3) Rubber. Short-term tests by the U. S. Naval Civil Engineering Laboratory showed neoprene synthetic rubber coatings to be relatively good for protecting steel piling from corrosion by seawater in each of the corrosion zones. Tables II a and II b show the ratings given to neoprene coatings after 2 1/2 years of testing on steel piling in the surf zone.

Steel panels coated with neoprene rubber were exposed in the atmosphere, at mean tide, and continuously submerged in seawater for 6 years along with 83 other coating systems. Alexander, Forgeson and Southwell, 1958 report that a neoprene rubber coating ranked second only to vinyl coatings with antifouling topcoats in the mean tide exposure. Mean tide was stated to be the most severe of the test zones. Table V gives the five top-ranking coatings in this zone. The synthetic rubber coating ranked highest in protecting the steel in the seawater immersion test. It should be noted that the coating was exceptionally thick.

Chlorinated rubber was used as a seal over flame-sprayed zinc applied to steel panels and exposed to seawater continuously immersed and at mean tide level (American Welding Society, 1962). After 6 years of exposure, an inspection of the panels revealed that the chlorinated rubber seal coat appeared to be completely gone from the specimens totally immersed and from those at mean tide level, and that some of the sealed panels showed more corrosion than the unsealed ones.

A chlorinated rubber coating over a red-lead primer was applied to steel piling and the test specimens exposed in the surf of the outer harbor at Port Hueneme, California. At the end of six months, the coating rated relatively low as shown in Table III.

A recent report (Alumbaugh and Brouillette, 1966) on tests including 16 synthetic rubber coating systems shows that 9 systems were considered to have failed or to be on the brink of failure by the end of four years exposure in seawater. Figure 11b shows that System No. 11 which consisted of a 77-mil thickness of flame-sprayed rubber powder gave steel the longest protection of the synthetic rubber coatings. This system did not fail until after approximately 11 years of exposure in seawater. A 17.5-mil coating system, consisting of a synthetic rubber primer and a neoprene finish coat plus accelerator, gave the second best performance of this generic group by protecting the steel for approximately 8 years.

(4) Phenolics. A phenolic mastic coating was tested on steel piling for 2 1/2 years (Alumbaugh, 1962) and according to test results as shown in Tables IIa and IIb performed quite well with the exception of Zone "B" which was in the lower part of the tide zone. Due to the depth of the water, Zone B was also in the sand-abrasion zone.

Phenolic mastic coatings were tested on mooring buoys for 5 years. The ratings of the coating at the end of 2 years was good-fair (Drisko, 1965). See Table VIII. The coating rating was also good-fair after 5 years (Drisko, 1968).

A phenolic resin mastic coating applied to sheet and H piling driven in the surf along the coast of the Marianas was reported to have performed adequately in protecting the piling for 4 years (Bureau of Yards and Docks, 1963). See Table VII.

In other tests at Port Hueneme, California, phenolic coatings performed better as a group than any other generic type (Alumbaugh and Brouillette, 1966). One phenolic mastic coating (System No. 72), given in Figure 11b, gave complete protection to steel for approximately 9 years. It was reported to be performing very well after 9 1/2 years of exposure. The same coating was also reported to have given the best performance on steel specimens subjected to the abrasive action of sand in the surf at Port Hueneme (Alumbaugh and Brouillette, 1966).

(5) Saran. After 2 1/2 years of testing on steel piling, a saran coating system rated quite good except in the sand-abrasion zone (Alumbaugh, 1962). Since saran was lower in cost than the other coating systems tested for 2 1/2 years, it was recommended as the most economical of the group to protect steel piling where sand abrasion does not exist. See Tables IIa and IIb.

Saran was tested on mooring buoys by the U. S. Naval Civil Engineering Laboratory (Drisko,1965). Ratings at the end of approximately 2 years are given in Table VIII. A later report on this test (Drisko, 1968) rated the saran to be in good-fair condition after 5 years of exposure. One source (Drisko and Brouillette, 1965) reports that saran has given excellent protection to steel panels exposed in shallow seawater for 4 years.

A 6.5-mil coating built up with alternate coats of orange and white Formula 113/40 saran applied over sand-blasted steel was reported to be giving good protection after 10 1/2 years of exposure in seawater (Alumbaugh and Brouillette, 1966). Saran applied over flame-sprayed zinc in the same tests was reported to be providing complete protection to the steel from rusting after 10 1/2 years. See Figures 11b and 11c.

(6) Asphalt Emulsion, Mica-Filled. Tests of a mica-filled asphalt emulsion showed it to be inadequate in two corrosion zones after 2 1/2 years of testing in seawater. This coating performed poorly in the upper tidal zone and afforded practically no protection in the abrasion zone at the end of 2 1/2 years according to the evaluation ratings (Alumbaugh, 1962).

(7) Coal-Tar Epoxy. Coal-tar epoxies are a blend of coal tar and epoxy resins. Although coal-tar epoxies have been rather extensively used as a coating on marine structures in the past few years, very little actual test data has been found concerning it. Table VIII gives the rating "good-fair" for coal-tar epoxy over an epoxy primer tested on a mooring buoy for over 2 years (Drisko, 1965). A later report (Alumbaugh, 1964) on this test also rates the coating "good-fair" after 5 years of service.

Two coats of catalyzed coal-tar epoxy primer and 1 coat of aluminum-filled catalyzed coal-tar epoxy topcoat giving a total thickness of 15 mils were applied to steel and tested in shallow seawater. This coating is reported to have given excellent protection to the steel for 3 years (Drisko and Brouillette, 1965).

Recent test data (Alumbaugh and Brouillette, 1966) shows coal-tar epoxies to hold considerable promise for protecting steel in seawater. A 12-mil coating did not fail until between 7 and 9 years of exposure. Thicker coatings (up to 24.5 mils) being tested are expected to be rated among the better coatings for protecting steel piling. See Figure 11a. Figure 12 shows that coal-tar epoxy coatings were also among the better coatings in withstanding sand abrasion in the surf zone.

(8) Epoxy. An epoxy coating has recently been developed which can be applied and cured on surfaces, under water, or dry. Based on short-term tests (Drisko and Brouillette, 1965),this coating is quite versatile. The coating is prepared for use by mixing two components and can be applied to surfaces under water or to dry surfaces by workmen using rubber gloves. Thicknesses exceeding 1/8 inch have been recommended for the coating.

Tests of six months' duration were made to determine the adhesive strength of epoxy coatings to bare steel and to other types of coatings. The findings and conclusions given in a report (Drisko, et al, 1964) resulting from this test are as follows:

(a) The four underwater-curing epoxies tested adhered well to sandblasted steel and to a variety of protective coatings.

(b) In general, the bonds formed by these epoxies lost no strength after the specimens were submerged for 6 months in flowing seawater.

(c) The bonded specimens with protecting coatings failed under applied stress in four different ways and under forces differing widely in magnitude.

(d) The four underwater-curing epoxies were similar in formulation; the major differences were in types and amounts of added fillers.

(e) In these tests, none of the four proprietary epoxies performed significantly better than the others.

(f) The underwater-curing epoxies tested can be used successfully to make underwater repairs to abrasion damage to recently applied protective coatings and to protect bare steel.

Table X gives the force required to break the bond between the four underwater-curing epoxies and other protective coatings. The results of these tests indicate that the underwater-curing epoxy coatings may be of considerable value for patching other types of coatings. The cost, however, may prohibit its use as a primary coating on most types of marine structures.

Polyamide- and amine-cured epoxy resin systems tested on steel in seawater performed quite well with the exception of systems 40, 41 and 68 shown in Figure 11a. System 88 in this test was giving good protection to the steel after 9 years of exposure in seawater (Alumbaugh and Brouillette, 1966). An epoxy coating system tested on mooring buoys was rated to be in "good" condition after 2 years of service (Drisko, 1965). See Table VIII. The coating was also rated good after 5 years of service (Drisko, 1968).

(9) Urethane. Very little test data was found for urethane coatings. However, one report (Drisko, 1965) rated a urethane coating "good-fair" after nearly 2 1/2 years exposure on a mooring buoy in seawater at San Diego, California. See Table VIII. The same coating rated fair-poor after nearly 5 1/2 years of exposure (Drisko, 1968). Tests by the U.S. Naval Civil Engineering Laboratory (Alumbaugh and Brouillette, 1966), indicated that, based on their condition after 5 to 6 years of exposure, urethane coatings should rate quite high for protecting steel piling. The urethane system affording the best protection except in the abrasion zone was applied over a vinyl primer.

(10) Glass Flake Polyester. No test data was found concerning the protective ability of this coating for steel piling. However, it was reported to be the best of a number of coatings tested for the protection of ship bottoms (Devoluy, 1965). Better resistance to abrasion and undercutting were claimed for this coating relative to others tested. Based on the above findings, it is felt that this coating may have some merit in protecting steel piling, especially in the sand abrasion zone.

(11) Furan. Four protective coating systems involving furan have been tested on bare steel for periods up to 10 1/2 years: Formula 117 pretreatment primer plus vinyl red lead, iron oxide primer, flame-sprayed zinc, and flame-sprayed aluminum. Of these systems, furan over flame-sprayed zinc has given good protection for 10 1/2 years (Alumbaugh and Brouillette, 1966). Furan's performance when applied over the other coating materials and applied on bare steel has been fair in comparison to other coatings tested. See Figures 11a, 11c and 12.

c. Surface Preparation for Coatings. The proper preparation of the metal surface is of primary importance when applying a protective coating of steel piling. Metal surface preparation methods include blast cleaning, pickling, solvent cleaning, hand tool cleaning, power tool cleaning and flame cleaning.

Blast cleaning is commonly used in the surface preparation of steel piling when significant quantities are involved. Although varying degrees of surface blast cleaning are used, a surface blasted to white metal can be expected to give best results. Blast cleaning to this extent, however, is usually not economical for many structures. Commercial blast cleaning which requires the removal of all oil, grease, mill scale, rust, and other surface contaminants is considered adequate for many of the protective coating systems.

Pickling is another method of metal surface preparation which promotes relatively long paint life for most coatings, when the proper procedures are used (Steel Structure Painting Council, Volume 2, 1964). However, facilities for pickling large structural items are rather limited.

Solvent cleaning, hand tool cleaning, power tool cleaning, and flame cleaning may also be used to prepare steel pile surfaces for coating. These methods are considered to be more limited in use and effectiveness than blast cleaning or pickling.

Specifications and details concerning the various metal surface preparation methods and their uses are contained in a report by the Steel Structures Painting Council, Volumes 1 and 2, (1964).

d. Primers for Steel Piling. Specially formulated coatings known as primers are often applied to bare metal surfaces before other coatings are applied. Prerequisites for maximum performance of primers as given in Jarboe (1964) are as follows:

1. Possess high specific adhesion, permitting satisfactory performance over clean sandblasted metal.

2. Have high chemical resistance.

3. Exhibit satisfactory wetting properties when applied to the metal to fill and penetrate rather than bridging crevices, pits, and pores found in most applications.

4. Contain high solids for coverage and provide adequate protection to sharp corners and edges.

5. Have minimum of drag in brush application and possess good spray properties.

6. Perform satisfactorily over old oxidized painted surfaces, rusty metallic surfaces, and even slightly damp surfaces.

7. Show compatibility with various generic types of topcoats.

8. Contain adequate amounts of inhibitive pigments.

9. Dry to a tack-free stage in a reasonably short time.

10. Possess satisfactory weatherability in the event finish coats are not to be applied for three to six months.

Although all of these characteristics may be difficult to obtain in a primer suitable for marine structures, they are, nevertheless, desirable.

Post curing inorganic primers such as zinc-lead silicate for steel are stated to have a long and proven record in corrosion prevention and to have performed outstandingly in the chemical and marine industries, either top-coated or bare (Gelfer, 1964). Other qualities stated for post-cured inorganic primers are: 1. excellent acceptability of topcoats; 2. ability to be cured quickly and effectively under varying conditions of temperature and humidity. The principal disadvantages of post-cured inorganic primers are the added cost and processing required in applying the curing agent and removing the residue from it before further coating can proceed.

A post-cured zinc-lead silicate primer performed satisfactorily for 18 months when used as a control for testing self-curing inorganic primers. Panels coated and scored showed little or no corrosion in the scored area and were otherwise unaffected (Gelfer, 1964).

In other tests by the U. S. Naval Civil Engineering Laboratory (Drisko and Brouillette, 1965), a post-cured inorganic zinc silicate primer has provided excellent protection to steel in shallow seawater for two years regardless of the deterioration of the topcoat during this period. In these tests, the vinyl phenolic primer coat did not adequately adhere to the zinc silicate primer.

3. Concrete Jackets

A method sometimes used to protect steel in marine structures from corrosion is to encase or jacket the steel in concrete. Two methods of jacketing steel H piles with concrete as given by Ayers and Stokes (1961) are shown in Figure 13a. Figure 13b shows methods of protecting steel sheet piling in straight walls and cellular construction with concrete jackets. To effectively protect steel from corrosion, the concrete must be of good quality, properly placed and cured, and of adequate thickness. Ayers and Stokes (1961) show a minimum thickness of 4 inches for concrete jackets over steel.

When concrete is permeated by seawater due to use of a poor quality concrete or inadequate concrete thickness, corrosion of the steel occurs. Since the corrosion product volume is greater than the original steel volume, pressure is exerted on the surrounding concrete. If this pressure is greater than the opposing tensile strength of the concrete, the concrete will crack and eventually spall, exposing the steel. According to information in Griffin (1965), corroding metal can exert pressures up to about 4,700 pounds per square inch on the concrete.

Salt-free concrete has a pH value of about 13 (highly basic). Under this condition a tough corrosion film builds up on the surface of steel embedded in the concrete and the steel becomes passive in respect to further corrosion. When chloride ions enter concrete, the pH value is lowered and the passive film of corrosion products is destroyed, allowing further corrosion (Griffin, 1965).

A good quality concrete for jacketing steel in marine structures should have high strength, be relatively impermeable and have good bonding characteristics. Information by Finley in Wood (1963) recommends 7 1/2 bags of cement per cubic yard of concrete and 5 gallons of water per bag of cement for corrosion protection in splashing water or alkaline soil. Low water-cement ratios are desirable.

In areas where freezing and thawing exists, entrained air is recommended to prevent concrete deterioration. Mather (1957) reports that tests by the Portland Cement Association showed that proper use of air entrainment improved the performance of concrete with respect to freezing and thawing and to exposure to solutions of sulfate salt. Tests by the Corps of Engineers at Treat Island, Maine, also showed that the proper entrainment of air in concrete was the most important factor in improving the durability of concrete to severe weathering. Tyler (1962) reports that air entrainment in concrete aids by slowing the rate of seawater penetration. Lyse (1961) reports that the percent of air voids in concrete should be 10 to 12 percent for best resistance to freezing and thawing where exposed to seawater.

Another factor which may be important when considering concrete protection for steel piles is the rigidity of the structure. It seems quite possible that concrete jackets on seacoast pier piling, for example,

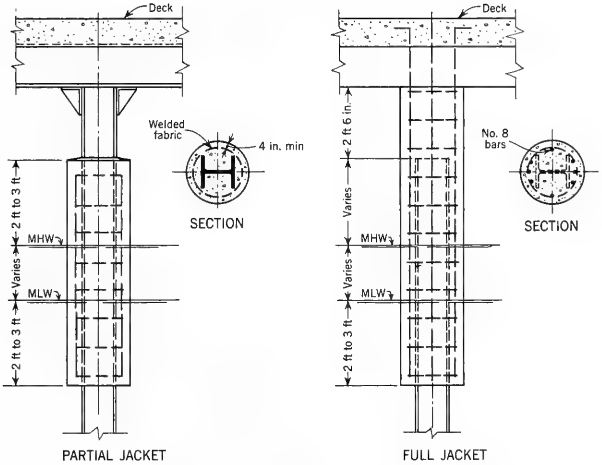
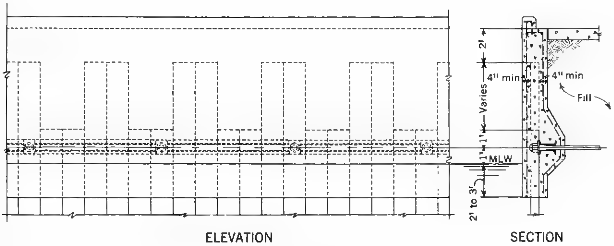
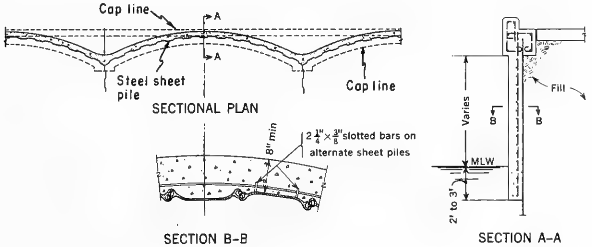


Figure 13a. Concrete jackets for steel H piles. (After Ayers and Stokes, 1961)



Steel sheet piling-straight wall construction



Steel sheet piling-cellular construction

Figure 13b. Concrete jackets for steel sheet piling. (After Ayers and Stokes, 1961) might be cracked due to flexing of the structure by the force of the waves.

Procedures suggested to minimize the deterioration of reinforced concrete should, in general, be applicable to concrete-jacketed steel piles. Some pertinent precautionary measures suggested in Mather (1957) from Warren (1956) for preventing deterioration of reinforced concrete in coastal structures are:

1. Careful selection of the cement. The most durable from the standpoint of chemical composition were said to be those with low tricalcium aluminate content, and the special aluminous cements.

2. Care with the aggregate, which must be tough and nonreactive to cement; and careful grading of aggregates.

3. High quality maximum density concrete. Rich mixtures - 1:1:3 or 1:1:2 were suggested.

4. Restriction of all working stresses to reasonable values.

5. Cover to be not less than 2 inches, preferably 3 inches; and square edges on beams and piles to be avoided.

6. Thorough curing in air before exposing to the tides or to splash, to obtain a hard outer skin.

7. Removal of mill scale from steel before installation.

8. Water/cement ratio to be as low as possible, with correction for the moisture content of the agregates.

9. Special care in placing the concrete to avoid segregation, particularly in underwater work.

10. Use of vibrators to obtain maximum consolidation.

The Corps of Engineers has conducted tests on over 2,500 concrete specimens at exposure stations located at Treat Island (Eastport), Maine, and St. Augustine, Florida. The tests were initiated in 1935. The concrete specimens were covered by seawater with the rising tides and exposed to atmosphere at low tides. Conclusions from these tests as given by Cook (1953) are as follows:

1. The entrainment of properly regulated quantities of air is the most important factor in the improvement of the durability of concrete under severe weathering conditions that has been developed by these investigations. At Treat Island, well-made concrete of good quality materials will not ordinarily withstand the exposure for more than one winter unless the concrete contains the proper amount of entrained air.

2. The use of various non-air-entraining admixtures did not appear to be of material benefit in increasing the durability of plain concrete but were not harmful in that they did not appear to decrease the durability of air-entrained concrete.

3. The use of air entrainment does not protect concrete which contains unsound aggregate.

4. The blending of natural cement with plain portland cement greatly improves the durability of concrete if by so doing the proper amount of entrained air is produced in the concrete.

5. No definite trends in the effect of curing conditions on durability have been revealed.

6. Aluminous cement produced highly durable concrete.

7. The use of absorptive form-lining improves the durability of concrete surfaces.

8. The quality of horizontal construction joints appears to be governed primarily by the quality of the concrete at the top of the lower lift.

9. The use of cement with a tricalcium aluminate content in excess of 12 percent has resulted in concrete that is non-durable in warm seawater. The use of Type II cement with a tricalcium aluminate content less than 8 percent appears warranted for such exposure.

Although the above conclusions were not based on tests of concrete jackets on steel piles, they should be considered when designing concrete jackets.

The literature surveyed did not indicate a life expectancy for steel piling with concrete jackets in the critical corrosion areas. Ayers and Stokes (1961) reported that concrete jacketing of steel piling has proven very effective when it extends from the top of the piling, above high tide to well below mean low water. They also concluded that concrete jackets in the tide range and cathodic protection below low tide was the most complete system for protecting steel piling. One publication reported that a reinforced concrete sheet pile wall at Neptune Beach, Florida, was still in good condition except for storm damage after 16 years of service, also that service records indicate that good concrete can endure for 50 years or more without excessive maintenance (Mather, 1957).

4. Cathodic Protection

a. General. Cathodic protection is another method of mitigating the corrosion of steel piling in seawater. This method is suitable for protecting the immersed zone of the piling. Protective coatings for steel are often used in combination with cathodic protection in order to reduce the area requiring protection.

b. Principle of Cathodic Protection. Corrosion of steel is an electrochemical process which takes place in a corrosion cell. Corrosion cells exist when a metal, or metals, which are electrically connected, have areas differing in electrical potential and are in contact with an electrolyte such as seawater. Electrodes of corrosion cells are either cathodic or anodic. The electric current leaves the metal surface at the anode and travels through the electrolyte to the cathode by ion transfer while electrons flow through the metal from the anode to the cathode. Corrosion of the metal occurs at the anode where the electric current leaves the metal. Cathodic areas of metal are usually unaffected by the entry of electric current, however, in some cases a protective film results on the metal surface such as calcareous deposits which may develop when seawater is the electrolyte.

Cathodic protection of a metal is based on forcing a reversal in the direction of electric current flow from that which normally occurs when the metal is corroding. The current must have sufficient magnitude and polarity to force the metal to be protected to become the cathodic electrode. Cathodic areas do not corrode when an adequate electric current flows to them. The current density required for the cathodic protection of steel varies with the type of steel being protected, its condition, and its environment. Field tests at the structure site and experience should be utilized in estimating current density requirements. The current density required for the corrosion protection of bare steel installed underground or in fresh water usually ranges from 1 to 6 milliamperes per square foot of surface area whereas from 3 to 10 milliamperes per square foot of surface area is usually required for installation in seawater. The range of current densities for coated steel sheet piling are usually within the range of 0.5 to 6.0 milliamperes per square foot for the seawater side and 0.95 to 1.0 milliampere per square foot for the land side. (U. S. Army Corps of Engineers, 1962).

c. Types of Cathodic Protection. Two types of cathodic protection systems are used - the galvanic system and the electrolytic system. The basic difference in these two systems is that, in the galvanic system, the source of the required electric current is the difference in electrical potential between two connected unlike metals in an electrolyte. The anodic metal corrodes as current flows to the cathode. The principle is illustrated in Figure 14. In the electrolytic system, direct current electricity of sufficient magnitude is supplied by an outside source. The source is usually a rectifier, which converts alternating current electricity to direct current which flows from one or more anodes through the electrolyte to the metal being protected.

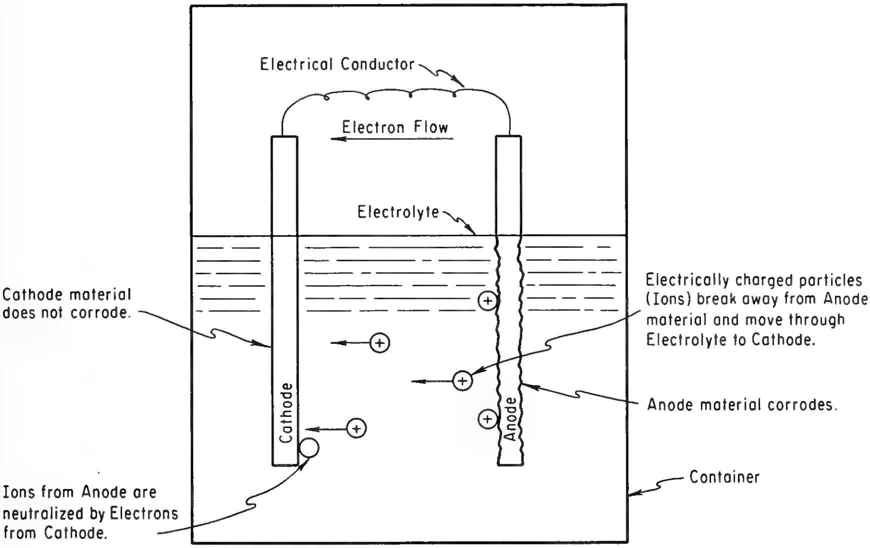


Figure 14. Example of Galvanic Corrosion Cell.

Characteristics of galvanic and rectifier cathodic protection systems compared by Husock (1962) follows:

	Galvanic	Rectifier
1.	Requires no external power	External power required
2.	Fixed driving voltage	Voltage can be varied
3.	Limited current	Can be designed for almost any current requirement
4.	Usually used in lower resistivity electrolytes	Can be used in almost any resistivity environment
5.	In underground applications interference with neighboring structures is usually negligible	Interference with neighboring structures must be considered

d. Galvanic System. In this system a galvanic corrosion cell is formed by installing an electrode which will be anodic to the metal to be protected (cathode) when the two are connected in an electrolyte. See Figure 14. The anodes are sacrificed to protect the cathodic metal. The anodes may be replaced periodically, if required.

(1) Galvanic Anodes for Steel. The principal materials which have been used for galvanic protection of marine structures of steel are magnesium and zinc. Although aluminum is anodic to steel, a surface film forms on the aluminum which hinders its generation of protective current when coupled to steel as sacrificial anodes. Aluminum alloy anodes have been developed and used in seawater applications (Husock, 1962). In laboratory tests, alloys of aluminum mercury and zinc have attained efficiences of 95 percent with potentials in the order of 1.05 volts. The electrical output per pound of metal consumed was 1,290 ampere hours (Reding and Newport, 1966). A comparison of zinc and magnesium anode characteristics from Husock (1962) is given below.

Characteristic	Zinc	Magnesium
Efficiency (approximate percent)	90	50
Theoretical consumption (lbs/ampere yr)	23.5	8.7
Approximate actual consumption (lbs/ampere yr)	26.0	17.0
Solution potential*	1.1	1.55

*Referred to a copper sulphate electrode.

Table XII gives the consumption rates in seawater, cost per pound and cost per ampere-year for magnesium, zinc and aluminum along with other anode materials suitable for impressed current systems.

The use of magnesium has been favored when higher driving forces are required. Hosford (1963) states that magnesium anodes in seawater tend to disintegrate rather rapidly unless restricted, therefore, zinc anodes are generally better in seawater environments.

e. Electrolytic (Impressed Current) System. This system is often employed in cathodic protection systems where it is desirable to use relatively high currents and voltages, where numerous galvanic anodes would ordinarily be acquired, where flexibility of voltage and/or current is desired, and where automatic control is desired. The source of current for impressed current systems is usually a rectifier if alternating current is available. Batteries or other direct current electrical sources can be used if necessary.

(1) Rectifiers. Rectifiers are used in impressed current systems to transform alternating current into direct current of the proper voltage. Rectifiers are also provided with a means of controlling the amperage. A rectifier consists basically of a circuit breaker, step-down transformer, stack, meters and a weatherproof enclosure. Selenium and silicon are the two materials generally used in constructing rectifier stacks. The selenium rectifier has been used extensively in cathodic protection systems in the past. Selenium rectifiers age with time. The aging consists of an increasing resistance in the direction of current flow and a decreasing resistance in the opposite direction. Selenium rectifiers are generally estimated to last 10 years when operated below maximum rating (National Association of Corrosion Engineers, 1965). Silicon rectifiers, however, offer the important advantages of apparently not being affected by age, increased efficiency, and compactness relative to selenium rectifiers. Figures 15 and 16 show efficiency curves for selenium and silicon rectifiers. On an operation basis, the National Association of Corrosion Engineers (1965) lists preferable types of rectifiers as follows:

Conditions	Type Rectifier
Above 30 volts d-c, single phase	Silicon
Above 44 volts d-c, three phase	Silicon
Below 30 volts d-c	Selenium

(2) Impressed-Current-System Anodes. Although there are numerous materials that can be used as anodes in impressed current systems, disadvantages encountered eliminate many for practical applications. The types of anodes generally used in impressed current systems protecting structures in seawater are graphite, high-silicon cast iron and various

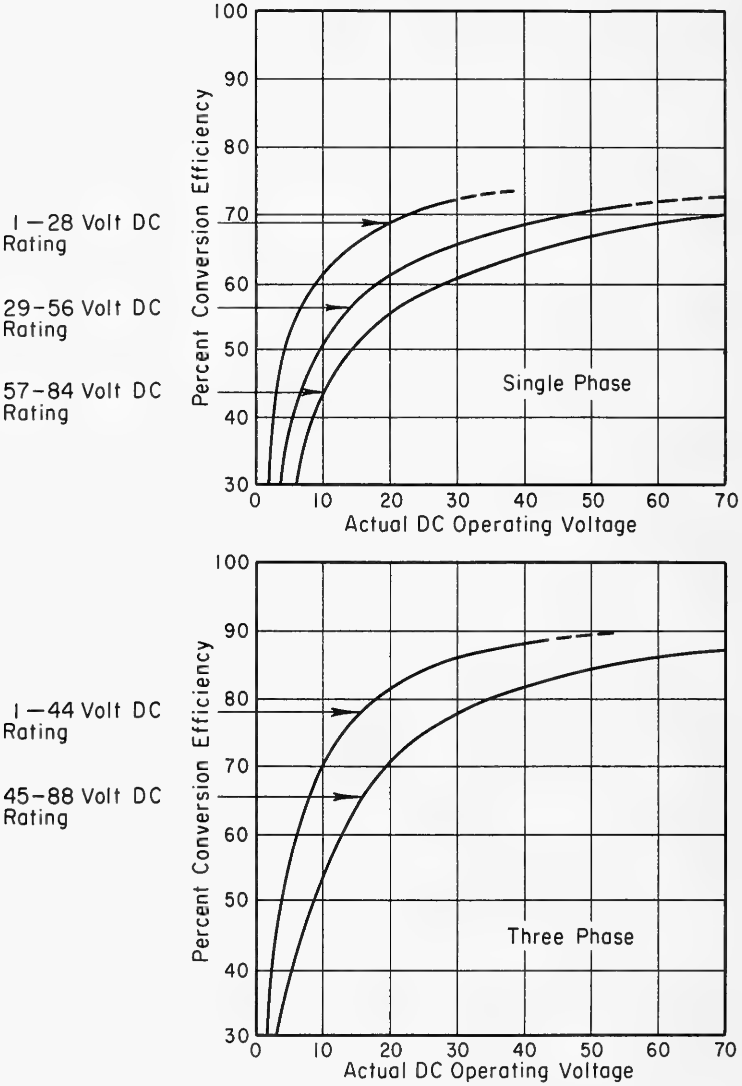


Figure 15. Efficiency vs. operating voltage for full wave selenium rectifiers. (After U. S. Army Corps of Engrs, 1962)

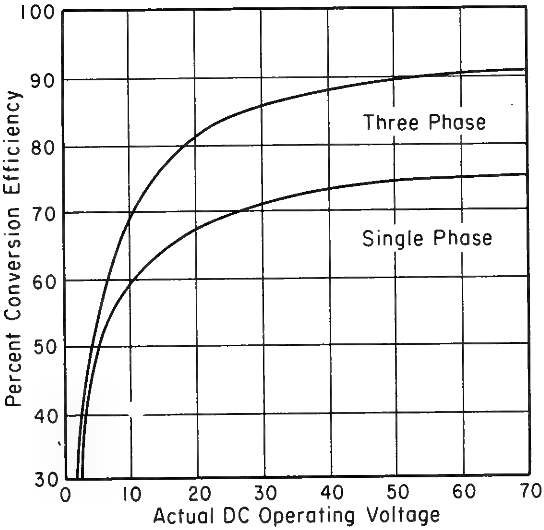


Figure 16. Efficiency vs. operating voltage for full wave silicon rectifiers. (After U. S. Army Corps of Engrs, 1962)

platinized metals. Graphite anodes are usually superior to high-silicon cast iron for seawater installations whereas high-silicon cast iron anodes are usually superior for fresh water installations (Husock, 1962). According to one report (Toncre and Rice, 1966), high-silicon iron anodes were selected over graphite anodes for brackish water installation after running tests on the two types. Composition changes are continually being made on basic anode materials to improve their performance. Therefore, information on the relative merits of each type should be checked just prior to selection.

Cherry (1965) reports that graphite and silicon iron anodes suffer breakage when subjected to heavy seas. If these anodes are placed on the bottom, as is sometimes done to lessen their exposure to wave action, their efficiency may be impaired due to increased anode to electrolyte resistance caused by gas surrounding an anode which has been embedded in mud.

Platinized titanium anodes are apparently becoming popular in other countries. Platinized titanium anodes have been tested (Toncre and Rice, 1966) and are expected to cut initial costs and operating costs of cathodic protection systems. The long life of platinized titanium anodes and the relative ease with which they can be installed are the factors that are expected to reduce the costs of cathodic protection. Platinized titanium anodes are generally used in the form of long thin rods. Copper cores are used in platinized titanium anodes over 2 feet long to improve their conductivity (Lowe, 1966).

Toncre and Rice (1966) report that the copper cored platinized titanium anodes presently in use by one company are 1/8 inch in diameter and have platinum coatings 0.0001 to 0.0002 inch thick. The average current density was reported to be of the order of 120 amperes per square foot. These anodes, most of which were installed vertically, have been in operation for up to 33 months with no apparent loss in their current capacity. Laboratory tests were performed to discover why corrosion of the titanium allowed two anodes to fall to the bottom. Observations reported from these tests are that:

1. If the copper core is exposed to the electrolyte, there is no loss in anode efficiency when the copper core is consumed if the anode has no mechanical load below the exposed copper core.

2. If under the same conditions, a mechanical load is placed below the point of copper core exposure, the anode will dissolve anodically near the break and quickly fail.

Another report, Cherry (1965), states that after 5 years of service there are indications that platinized titanium anodes should last in excess of 10 years. The most successful suspension system for these anodes reportedly utilized steel pipe with an unplastisized polyvinyl chloride assembly at the bottom to hold the anode. The steel pipe was hinged at the top to permit easy inspection of the anodes. The anodes were placed about 2.5 feet from the side of the piles and about 6 feet below low water.

Direct current ripples, resulting from difficulty in producing constant voltage direct current from rectified alternating current electricity, are reported to be detrimental to the life of platinized titanium anodes (Lowe, 1966). However, the report states that on smaller systems it is usually more economical to use lower current densities and thicker platinum films instead of the expensive three-phase installations or voltage smoothing systems.

f. Anode Installation. Manufacturers produce a variety of sizes and shapes of galvanic anodes. Some are equipped with special facilities for mounting.

One of the primary design problems in cathodic protection systems is the provision of an arrangement of anodes which will adequately and efficiently protect the structure concerned and yet withstand destructive forces from wave action, ice, boats and floating debris. Cathodic systems designed to protect structures such as sheet pile bulkheads may be designed with anodes resting on the bottom. However, the useful life of anodes resting on the bottom may be reduced due to pitting caused by non-uniform environment. Also, unstable bottom conditions may cause excessive coverage of the anodes by sediments and reduce their effectiveness. These factors should be investigated if this type of installation is being considered. Systems designed to protect numerous vertical members, such as piling supporting a pier, may use anodes suspended between piling at a depth sufficient to lessen the possibility of damage by floating objects. Some of the more recent installations have anodes supported on pipes which are hinged at the top or mounted on cables that can be wound up on winches. These methods provide for easy removal of anodes for inspection and aid in prevention of storm damage.

Section VIII. CONCLUSIONS

The corrosion rate of steel piling in seawater varies considerably depending on water conditions and the zone of exposure on a given pile. According to information from various reports, the loss of steel thickness in seawater may vary from no loss to as much as 373 mils per year. The higher rate occurred where sand abrasion was present in steel sheet pile groins. The corrosion rate of bare steel submerged in normal seawater is generally considered to be 5 mils per year.

Since corrosion rates of steel piling may vary widely in seawater, the estimation of corrosion rates should be guided by test data from structures having as nearly as possible the same exposure conditions as the proposed structure. This survey indicates that more pile corrosion test data are needed for estimating corrosion rates, especially in colder waters.

Considerable progress is being made in the development of coatings capable of protecting steel piling in seawater. Partially completed tests indicate that such coatings as saran, phenolic mastic, coal-tar epoxy, epoxy, flame-sprayed aluminum coatings, and flame-sprayed zinc coatings topcoated with saran, vinyl, epoxy or furan, may effectively protect steel piling in seawater for 15 or more years provided severe conditions such as sand abrasion are not involved. Where sand abrasion exists, incomplete tests indicate that phenolic mastic and coal-tar epoxy coating systems, and possibly others, may approach 10 years of effective protection for steel in seawater. Coating systems consisting of flame-sprayed zinc topcoated with saran or vinyl appear to be two of the most effective coatings for steel tested to date.

Surface preparation of steel is very important when coatings are to be applied for seawater exposure. Blasting the surface with abrasive material and pickling are the generally accepted methods of surface preparation. Commercial blasting is considered adequate for many coatings. When better blasted surfaces are required, near white or white blasting of the steel is specified.

Cathodic protection systems, properly designed, and maintained are very effective in preventing the corrosion of steel immersed in seawater. Cathodic protection is often used in combination with protective coatings, the coatings protect the unsubmerged portion of the steel and reduce the area of submerged steel requiring cathodic protection.

Properly designed concrete jackets are reported to be very effective in protecting steel from corrosion by seawater, however, there is apparently very little data available for accurate evaluation.

There appears to be a great need for data to develop the initial cost, and cost per year of protection, for various corrosion protection methods. Such information is needed to determine the most economical protection system for a given structure.

LITERATURE CITED

Alexander, A. L., Forgeson, B. W. and Southwell, C. R. (1958), "Performance of Organic Coatings in Tropical Environments", paper presented at Northeast Region Meeting of National Association of Corrosion Engineers, Boston, Mass., 6-8 October 1958.

Alumbaugh, R. L. (1964), "Field Test Data on Coatings for Steel Piling in Sea Water", *Materials Protection*, pp. 34-45.

Alumbaugh, R. L. (1962), "Protective Coatings for Steel Piling: Results of 30-Month Tests", U. S. Naval Civil Engineering Laboratory, Technical Report R-194.

Alumbaugh, R. L. and Brouillette, C. V. (1966), "Protective Coatings for Steel Piling: Results of Harbor Exposure on Ten-Foot Simulated Piling", U. S. Naval Civil Engineering Laboratory, Technical Report R-490.

American Society for Testing and Materials, (1959), 1958 Book of ASTM Standards, Part 8, Philadelphia, Pennsylvania.

American Welding Society, Committee on Metallizing (1962), "Corrosion Tests of Metallized Coated Steel, 6-Year Report" AWS C2.8-62.

American Welding Society, Committee on Metallizing (1967), "Corrosion Tests of Metallized Coated Steel, 12-Year Report", AWS C2.11-67.

Ayers, J. R. and Stokes, R. C. (1961), "Corrosion of Steel Piles in Salt Water", Journal of Waterways and Harbors Division, WW3, *Proceedings of American Society of Civil Engineers.*

Baxter, J. F. and Steiner, L. E. (1960), *Modern Chemistry,* Prentice-Hall, Englewood, N. J.

Bethlehem Steel Corporation, "Steel H Piles", Handbook 2196, p. 32.

Brouillette, C. V. and Hanna, A. E. (1960), "Corrosion Survey of Steel Sheet Piling", U. S. Naval Civil Engineering Laboratory Technical Report 097.

Brouillette, C. V. and Hanna, A. E. (1966), "Second Corrosion Survey of Steel Sheet Piling", U. S. Naval Civil Engineering Laboratory Technical Report R-467.

Cherry, P. B. (1965), "Cathodic Protection of Jetties", *Corrosion Prevention and Control,* pp. 26-28. July 1965.

Cook, H. K. (1953), "Exposure Research on Concrete in Sea Water", *Proc. of Third Conference on Coastal Engineering* (October 1952), Council on Wave Research, pp. 217-230

Copson, H. R. (1952), "Effects of Velocity on Corrosion by Water", *Industrial and Engineering Chemistry*, Vol. 44, p. 1745.

Devoluy, R. P. (1965), "Protective Coatings for Ship Bottoms", *Materials Protection*. April 1965.

Drisko, R. W. (1965), "Protection of Mooring Buoys, Part VI. Result of Fifth Rating Inspection", U. S. Naval Civil Engineering Laboratory Technical Report R 385.

Drisko, R. W. (1968), "Protection of Mooring Buoys, Part XI. Results of Tenth (Final) Rating Inspection", U. S. Naval Civil Engineering Laboratory Technical Report R 585.

Drisko, R. W., and Brouillette, C. V. (1965), "Protective Coatings in Shallow and Deep Ocean Environments", paper presented at Western Region Conference, National Association of Corrosion Engineers, 8-12 November 1965, Honolulu, Hawaii.

Drisko, R. W., Cobb, J. W. and Alumbaugh, R. L. (1964), "Underwater-curing Epoxy Coatings", U. S. Naval Civil Engineering Laboratory Technical Report R 300, May 1964.

Fink, F. W. (1960), "Corrosion of Metals in Sea Water", U. S. Department of The Interior, Office of Saline Water, Research and Development Progress Report No. 46.

Gelfer, D. H. (1964), "Permanent Primers for Steel: Comparison of Self-curing and Post-curing Inorganic Zinc Coatings", *Materials Protection*, March 1964, pp. 54-61.

Griffin, D. F. (1965), "Corrosion of Mild Steel in Concrete", U. S. Naval Civil Engineering Laboratory, Port Hueneme, California, TR 306 Sup. August 1965.

Hosford, H. W. (1963), "Cathodic Protection of Marine Structures", The Harco Corporation, Paper No. HC-3, 25-638.

Horvick, E. W. (1964), "Specifications and Specifying", American Zinc Institute, Inc., Technical Seminar, May 27, 1964.

Husock, B. (1962), "Fundamentals of Cathodic Protection", American Institute of Electrical Engineers, conference paper, St. Louis, Missouri, Harco Corp. Paper No. DP-3.

Jarboe, E. D. (1964), "Organic and Inorganic Primers", *Materials Protection*, March 1964, pp. 14-21.

LaQue, F. L. and Cox, G. L. (1940), "Some Observations in the Potentials of Metals and Alloys in Sea Water", *Proceedings, American Society for Testing and Materials*, Volume 40.

LITERATURE CITED (Continued)

Lindahl, H. A. (1964), "Developments in Steel for Marine Applications", unpublished paper presented at American Shore and Beach Preservation Meeting, New York.

Littauer, E. L. (1966), "Impressed Current Systems for Corrosion Protection", *Geo-Marine Technology,* June 1966, pp. 17-23.

Lowe, R. A. (1966), "Platinized Titanium as Anode Materials", *Materials Protection,* April 1966, pp. 23-24.

Lyse, I. (1961), "Durability of Concrete in Sea Water", *Journal, American Concrete Institute,* June 1961.

Mather, B. (1957), "Factors Affecting the Durability of Concrete in Coastal Structures", U. S. Army Corps of Engineers, Beach Erosion Board, Technical Memorandum No. 96, 1957.

Muroaka, J. S. (1963), "The Effects of Fouling by Deep-Ocean Marine Organisms", *Undersea Technology,* May 1963, pp. 24-28.

National Association of Corrosion Engineers (1965), "What Field Personnel Should Know about Rectifiers", *Materials Protection,* April 1965, pp. 75-82.

Orlowski, P. (1965), "Protection by Metallization Against Corrosion and the Effects of Seawater Life", *Corrosion Prevention and Control,* February 1965, pp. 29-30.

Rayner, A. C. (1952), "Durability of Steel Sheet Piling in Shore Structures", U. S. Army Corps of Engineers, Beach Erosion Board Technical Memorandum No. 12, February 1952.

Reding, J. T. and Newport, J. J. (1966), "The Influence of Alloying Elements on Aluminum Anodes in Sea Water", *Materials Protection*, Vol. 5, No. 12, pp. 15-18, December 1966.

Ross, C. W. (1948), "Experimental Steel Pile Groins, Palm Beach, Florida", U. S. Army Corps of Engineers, Beach Erosion Board Technical Memorandum No. 10.

Shreir, L. L. (1963), *Corrosion,* John Wiley & Sons, New York, N.Y.

Snyder, R. M. and Hull, S. (1965), "Parametric Variables Affecting Corrosion", *Geo-Marine Technology,* July 1965, pp. 17-24.

Steel Structures Painting Council (1964), *Steel Structures Painting Manual,* Volume 1, 1964.

Steel Structures Painting Council (1964), *Steel Structures Painting Manual,* Volume 2, 1964.

Sverdrup, H. U., Johnson, M. W. and Fleming, R. H. (1942), *The Oceans*, Prentice-Hall, Inc., Englewood Cliffs, N. J.

Toncre, A. C. and Rice, L. (1966), "Impressed Current Anodes in Brackish Water", *Materials Protection,* April 1966, pp. 61-63.

Tuthill, A. H. and Schellmoller, C. M. (1965), "Guidelines for the Selection of Marine Materials", International Nickel Company, June 1965.

Tyler, I. L. (1964), "Concrete in Marine Environments", *Symposium on Concrete Construction in Aqueous Environments* (SP-8), American Concrete Institute.

Uhlig, H. H. (1948), *The Corrosion Handbook,* John Wiley and Sons, New York, N. Y.

United Kingdom, Department of Scientific and Industrial Research (1928), "Deterioration of Structures of Timber, Metal, and Concrete Exposed to the Action of Sea-Water", H. M. Stationery Office for the Department, Westminster, S.W. 1, England.

U. S. Army, Corps of Engineers, Office of the Chief of Engineers (1963), "Painting Hydraulic Structures and Appurtenant Works", CE-1409, October 1963.

U. S. Army, Corps of Engineers (1962), "Corrosion Control", TM-5-811-4, formerly EM 1110-1-184, August 1962.

U. S. Navy, Bureau of Yards and Docks (1963), "Long Range Systematic Study, Protective Coatings for Steel Piling, Four Year Evaluation Report", April 1963.

U. S. Steel Corporation (1964), "Mariner Steel Sheet and H-Piling", May 1964.

Warren, L. R. (1956), "Some Notes on the 1953 Congress of the Permanent International Association of Navigational Congresses", *Transactions of South African Institution of Civil Engineers,* Vol. 6, No. 10, October 1956, pp. 289-294.

Wood, L. E. (1963), "Protection of Reinforcing Steel", U. S. Army, Corps of Engineers, Ohio River Division Laboratories, Technical Report No. 2-30.

APPENDIX A

TABLES I THROUGH XV

TABLE I

Coating Description and Application Data(1) for Tables IIa and IIb

		Primer			Topcoats			Total
System Number(2)	Description	Type	No. of Coats	Thickness (mils)	Type(2)	No. of Coats	Thickness (mils)	Thickness (mils)
1	Aluminum Vinyl	Formula 117 Formula 119	1 4	0.5 4.0	Aluminum Vinyl	2	1.5	6.0
6	Vinyl Mastic	Vinyl Primer	2	2.0	Vinyl Mastic	2	10.0	12.0
7	Phenolic Mastic	Catalyzed Mica-Filled Phenolic Mastic Primer	1	10.5	Catalyzed Phenolic Mastic	1	9.0	19.5
9	Neoprene Brushing Composition	Neoprene Primer (B)	1	1.5	Catalyzed Neoprene	3	19.0	20.5
13	Cold-Applied Coal Tar Coating Comp.	Coal Tar Coating Compound (MIL-C-18480)(B)	3	19.5	Bituminous Emulsion Coating Compound (MIL-C-15203)(B)	3	12.0	31.5
16	Mica-Filled Asphalt Emulsion	Formula 117 Formula 84/47	1 1	0.5 1.0	Mica-Filled Asphalt Emulsion	6	28.0	29.5
20	Flame-sprayed Zinc	None	-	-	Flame-sprayed Zinc	1	5.0	5.0
23	Saran Formula 113/49(3)	None	-	-	Saran Resin Lacquer(alternate white & orange)	6	6.0	6.0

(1) Piles were prepared for painting by sandblasting the surface to a uniform, mat finish.

(2) All coatings except those marked with (B) were applied by spraying; (B) signifies that these coatings were applied by brush.

(3) Present designation is Formula 113/54 (MIL-L-18389).

From Alumbaugh (1962)

TABLE IIa

System Performance Ratings on Steel Sheet Piling After 12-, 18-, 24-, and 30-Month Exposures

System Number	Exposure Period (Months)	System Type	Ratings			
			Splash Zone	Tidal Zone		Embedded Zone
				Area "A"	Area "B"	
1	12	Aluminum Vinyl	9	9+	6	9
	18		9	9+	5	9
	24		9	9	3	9
	30		9	9	1	9
6	12	Vinyl	9	9+	9	9
	18		9	9	8	9
	24		9	9	7	9
	30		9	9	7	9
7	12	Phenolic Mastic	9	10	7	9+
	18		9	9+	7	9
	24		9	9+	5	9
	30		9	9+	4	9+
9	12	Neoprene	9	10	9+	9+
	18		9	9	9	9
	24		9	8	8	9
	30		9	8	8	9
13	12	Coal Tar	9	8	9	9+
	18		9	6	6	9+
	24		9	5	3	9
	30		9	4	1	9
16	12	Asphalt Emulsion	9	8	7	9+
	18		9	7	4	9+
	24		9	6	2	9+
	30		9	5	1	9+
20	12	Flame-Sprayed Zinc	9	10	9	10
	18		8	9	9	9+
	24		7	9	8	9+
	30		6	9	8	9+
23	12	Saran (Formula 113.49)	9	10	7	9
	18		9	9+	5	9
	24		9	9+	4	9
	30		9	9+	3	9

From Alumbaugh (1962)

Notes: 1. See Table I for coating system details.
2. See Table XIII for rating system note.

TABLE IIb

System Performance Ratings on Steel "H" Piling After 12-, 18-, 24-, and 30-Month Exposures

System Number	Exposure Period (Months)	System Type	Ratings			
			Splash Zone	Tidal Zone Area "A"	Tidal Zone Area "B"	Embedded Zone
1	12	Aluminum Vinyl	9	9+	8	9
	18		9	9	7	9
	24		9	9	7	9
	30		9	9	5	9
6	12	Vinyl Mastic	9	9+	9	9+
	18		9	9	8	9
	24		9	9	8	9
	30		9	9	7	9
7	12	Phenolic Mastic	9	10	9	9+
	18		9	10	9	9
	24		9	10	8	9
	30		9	10	7	9
9	12	Neoprene	9	10	9+	9+
	18		9	9	9	9
	24		*	9	9	9
	30		9	8	9	9
13	12	Coal Tar	9	8	9	9
	18		9	6	8	9
	24		9	5	6	9
	30		9	4	4	9
	12	Asphalt Emulsion	9	8	8	9+
	18		9	7	6	9+
	24		9	6	5	9+
	30		9	5	4	9+
20	12	Flame-Sprayed Zinc	9	10	9+	10
	18		8	9	9	9+
	24		7	9	9	9
	30		6	9	9	9
	12	Saran (Formula 113/49)	9	10	9	9
	18		9	9+	9	9
	24		*	9+	8	9
	30		9	9+	7	9

From Alumbaugh (1962)

*Due to equipment problems during driving operation these piles were driven to such a depth that no splash zone existed.

Notes: 1. See Table I for coating system details.
2. See Table XIII for rating system note.

TABLE III

Coating System Description and Performance Ratings
Phase 1 - Six Month Test

SYSTEM	Number of Coats	Thickness (mils)	Total Thickness (mils)	Performance Ratings(1)
Vinyl Coatings				
1. Aluminum vinyl	--	---	---	8
MIL-C-15328 (Formula 117) wash prime	1	0.5	---	--
MIL-C-15929A (Formula 119) vinyl red-lead primer	3	3.0	---	--
Aluminum-pigmented vinyl finish	3	2.0	5.5	--
2. Vinyl	--	---	---	7
Vinyl-phenolic primer	1	1.0	---	--
Vinyl finish	3	4.5	5.5	--
3. Vinyl mastic	--	---	---	9
Vinyl-phenolic primer	1	1.0	---	--
Vinyl mastic finish	2	9.0	10.0	--
4. Saran(2)	--	---	---	9
Saran (Formula 113/49)	6	5.0	5.0	--
Metal Coatings				
5. Zinc pigmented polystyrene	3	2.0	2.0	5
6. Inorganic zinc silicate	1	2.5	2.5	7
7. Flame-sprayed zinc wire	1	5.0	5.0	9
8. Flame-sprayed aluminum wire	--	---	---	9
Flame-sprayed steel wire	1	0.5	---	--
Flame-sprayed aluminum wire	1	5.0	5.5	--

TABLE III (Cont.)

SYSTEM	Number of Coats	Thickness (mils)	Total Thickness (mils)	Performance Ratings(1)
Coal Tar Coatings				
9. Cold-applied coal tar	--	---	---	8
MIL-C-15328 (Formula 117), wash prime	1	0.5	---	--
MIL-C-18480 coal tar coating	2	28.0	---	--
MIL-C-15203, bituminous emulsion	1	3.0	31.5	--
10. Cold-applied coal tar	--	---	---	8
MIL-C-18480, coal tar coating	3	22.0	---	--
MIL-C-15203, bituminous emulsion	1	4.0	26.0	--
11. Cold-applied coal tar	--	---	---	8
MIL-C-15328 (Formula 117, wash prime	1	0.5	---	--
MIL-C-18480, coal tar coating	3	28.5	29.0	--
12. Cold-applied coal tar	--	---	---	8
MIL-C-18480, coal tar coating	5	25.0	25.0	--
13. Hot-applied coal tar	--	---	---	8
MIL-P-15147, coal tar primer	1	1.5	---	--
Hot-applied coal tar enamel	1	90.0	91.5	--
Asphalt Coatings				
14. Mica-filled asphalt emulsion	--	---	---	9
MIL-C-15328 (Formula 117), wash prime	1	0.5	---	--
JAN-P-735 (Formula 84), alkyd zinc chromate primer.	1	2.0	---	--
Mica-filled asphalt emulsion finish	6	29.0	31.5	--
15. Gilsonite asphalt	5	25.0	25.0	7

TABLE III (Cont.)

SYSTEM	Number of Coats	Thickness (mils)	Total Thickness (mils)	Performance Ratings(1)
Synthetic Rubber Coatings				
16. Neoprene bushing composition	--	---	---	9
Neoprene primer	1	1.5	---	--
Catalyzed neoprene finish	4	30.0	31.5	--
17. Chlorinated rubber	--	---	---	6
Red-lead primer	1	1.0	---	--
Chlorinated rubber finish	5	4.0	5.0	--
Miscellaneous Coatings				
18. Cold plastic antifouling paint	--	---	---	6
MIL-C-15328 (Formula 117), wash prime	1	0.5	---	--
MIL-P-18996 (Formula 14), anti-corrosive primer	1	4.5	---	--
Formula 145, cold plastic antifouling finish	4	17.0	22.0	--
19. Hot plastic antifouling paint	--	---	---	4
MIL-C-15328 (Formula 117), wash prime	1	0.5	---	--
MIL-P-18996 (Formula 14), anticorrosive primer	2	2.5	---	--
Formula 15 HP, hot plastic antifouling finish	1	31.0	34.0	--
20. Phenolic mastic	--	---	---	9
Catalyzed phenolic mastic primer	1	8.5	---	--
Catalyzed phenolic finish	1	9.0	17.5	--
21. Furan	--	---	---	7
Vinyl iron-oxide primer	1	1.0	---	--
Furan finish	6	6.0	7.0	--

TABLE III (Cont.)

	SYSTEM	Number of Coats	Thickness (mils)	Total Thickness (mils)	Performance Ratings[1]
22.	Epoxy	--	---	---	7
	Catalyzed epoxy red-lead primer	2	4.0	---	--
	Catalyzed epoxy finish	3	3.0	7.0	--
23.	Alkyd	--	---	---	4
	Alkyd iron-oxide-zinc chromate primer	2	2.0	---	--
	Alkyd finish	2	2.0	4.0	--

(1) Performance ratings were based on ASTM Photographic Reference Standards (ASTM Designation D610-43)

(2) Saran is not a vinyl but is included under this heading because it has similar properties.

From Alumbaugh (1964)

TABLE IV

Ratings for Coatings Immersed in Seawater

Number of Coats and Coating Description	Coating Thickness (mils)	Service Rating **			
		3 Years		6 Years	
		Unscribed	Scribed	Unscribed	Scribed
Phosphoric acid pretreatment 1. Coal-Tar Primer 2. Coal-Tar Enamel 304. Natural Resin A-F‡	80-100	10	10	9	8
Phosphoric acid pretreatment 1. Coal-Tar Primer 2. Coal-Tar Enamel 3-4. Natural Resin A-F*	70-85	10	10	8	8
Phosphoric acid pretreatment 1. Synthetic Rubber (Neoprene) 2-13. Synthetic Rubber (Neoprene)	40-55	10	10	8	9
Phosphoric acid pretreatment 1-2. Alkyd Primer 3. Hot Plastic A-F	41	10	10	0	1
Phosphoric acid pretreatment 1. Coal-Tar Primer 2. Coal-Tar Enamel 3. Hot Plastic A-F	85-115	10	10	7	5
Wash Primer Pretreatment 1-3. Vinyl Primer † 4-5. Vinyl A-F †	8.5	10	10	7	5
Wash Primer Pretreatment 1-2. Vinyl Primer † 3-8. Vinyl A-F †	18	10	10	3	6
Phosphoric acid pretreatment 1-2. Vinyl Primer 3-10. Vinyl Enamel	18-27	10	9	9	5

*Experimental NRL formula

** See Table VI for rating system details

‡ Navy cold plastic A-F paint.

† Similar competitive systems

From Alexander, et al (1958)

TABLE V

Ratings for Coated Panels Tested at Mean Tide

Number of Coats and Coating Description	Coating Thickness (mils)	Service Rating*			
		3 Years		6 Years	
		Unscribed	Scribed	Unscribed	Scribed
Wash primer pretreatment 1 Vinyl Primer 2 Vinyl A-F	7.5	7	8	2	2
Wash primer pretreatment 1-3 Vinyl Primer 405 Vinyl A-F	8	10	10	5	5
Wash primer pretreatment 1-3 Vinyl Primer 4-8 Vinyl A-F	18	10	10	6	6
Phosphoric acid pretreatment 1-3 Synthetic Rubber	2-250	8	9	5	5
1 Synthetic Rubber	25-35	10	10	7	5

*See Table VI for rating system notes

From Alexander, et al (1958)

TABLE VI

Description of Visual Rating System

Numerical Value	Condition of Coating and Panel
10	Perfect (no deterioration of any kind)
9	Slight deterioration of coating
8	Intermediate (between 7 and 9)
7	Deterioration evident with a few defects in coating; continued protection of underlying metal; coating considered satisfactory.
6	Moderate deterioration, some coating defects, slight corrosion of underlying metal surface. Some surface preparation and repainting necessary for continued protection. Coating considered unsatisfactory.

From Alexander, et al (1958)

TABLE VII

Fourth Year Coating System Ratings

	Coating Systems						
	Vinyl Mastic	Phenolic Resin Mastic	Neoprene Brushing Composition	Coal-tar base Cold-applied	Asphalt Emulsion, Mica-filled	Flame-sprayed Zinc	Saran Resin
Zone of Rating	Rating						
Atmospheric	Adequate	Adequate	Durable	Durable	Adequate	Durable	Durable
Tidal	Durable	Adequate	Inferior	Deficient	Deficient	Inferior	Adequate
Immersed	Durable	Adequate	Inferior	Adequate	Deficient	Adequate	Adequate
Embedded	Adequate	Adequate	Durable	Adequate	Durable	Durable	Adequate

From Bureau of Yards and Docks,
U. S. Dept. of the Navy (1963)

TABLE VIII

Overall Rating and Length of Service for Coated Buoys

Identification Number	Coating Description	Length of Service (days)	Overall Rating
1	Urethane	787	good-fair
2	Epoxy	747	good
3	Epoxy-Polyster	747	fair
4	Epoxy-Coal Tar Epoxy	787	good-fair
5	Coal Tar Epoxy-Phenolic	746	fair
6	Phenolic Mastic	745	good-fair
6C	Phenolic Mastic	746	good
7C	Phenolic	599	good-fair
8	Phenolic-Alkyd	600	good-fair
9	Vinyl	622	good
10	High-Body Vinyl	713	fair
11	Vinyl Mastic	-	removed from test
12	Inorganic Zinc Silicate - Vinyl Mastic	787	fair
13	Saran	746	good-fair
13C	Saran	753	good

See Table XI for details on coatings; see Table XIII for rating system details.

From Drisko (1965)

TABLE IX

Coating Descriptions and Thicknesses

System		Primer			Additional Coats			TOTAL
Number	Coating Description	Coating Type	No. of Coats	Thickness (mils)	Coating Type	No. of Coats	Thickness (mils)	Thickness (mils)
1	Urethane	Urethane	1	2	Urethane Epoxy	3 1	8 4	10 8-9
2	Epoxy	Epoxy	1	4-5	Epoxy Anti-fouling	1 1	3 4	11-12 15-16
3	Epoxy Polyester	Epoxy	1	4-5	Polyester Anti-fouling	2 1	5-6 4	9-11 13-15
4	Epoxy-Coal Tar Epoxy	Epoxy	1	4	Coal Tar Epoxy Epoxy Epoxy	1 1 1	4-5 4 4	8-9 12-13 16-17
5	Coal Tar Epoxy-Phenolic	Coal Tar Epoxy	1	5	Phenolic Phenolic	1 1	4-6 6-7	9-11 15-18
6 & 6C	Phenolic Mastic	Mica-filled Phenolic	1	10-11	Phenolic Mastic	1	8-9	18-20
7C	Phenolic	Wash Primer Phenolic	1 2	1/2 4 1/2	Phenolic Anti-fouling	1 1	2-3 3	7-8 8
8	Phenolic Alkyd	Wash Primer Phenolic	1 2	1/2 4 1/2	Alkyd Anti-fouling	1 1	2-3 3	7-8 8
9	Vinyl	Wash Primer Vinyl	1 4	1/2 6 1/2 - 7 1/2	Vinyl-alkyd Anti-fouling	3 2	4 4	11-12 11-12
10	High-body Vinyl	Vinyl	1	2	Vinyl Vinyl	2 1	5-6 2	7-8 9-10
11	Vinyl Mastic	Vinyl Phenolic	1	1-2	Vinyl Mastic	2	12-13	13-15
12	Inorganic Zinc Silicate-Vinyl Mastic	Inorganic Zinc Silicate Vinyl Phenolic	1 1	4 1-2	Vinyl Mastic	1	5-6	10-12
13 & 13C	Saran (Formula 113/54)	-	-	-	Saran	8	8	8

From Drisko (1965)

TABLE X

Force Required to Break Apart Bonded Panels

Breaking Force in Pounds Per Square Inch

Coating System	Epoxy A		Epoxy B		Epoxy C		Epoxy D	
	1 Week	6 Months	1 Week	6 Months	1 Week	6 Months	1 Week	6 Months
1 - Coal Tar	70cd*	70d	75cd	75cd	-	-	-	-
2 - Vinyl	-	-	610a	550a	670a	355a	-	-
3 - Saran	-	-	-	-	525d	390b	650d	1,095a
4 - Zinc Silicate - Vinyl Mastic	-	-	255ab	155c	-	-	455c	140c
5 - Phenolic Mastic	360b	615b	-	-	-	-	970a	850a
6 - Epoxy	510b	850b	-	-	670b	790a	-	-
7 - Mica-Filled Asphalt	40c	45c	75c	75c	50c	50c	45c	65c
8 - Epoxy	205c	180c	315c	310c	355c	355c	475c	340c
9 - Urethane	380b	600bd	620a	810a	635a	445a	1,030d	980d
10 - Coal Tar Epoxy	210c	225c	210c	180c	115c	220c	295c	230c
Sandblasted	320a	545a	255a	600a	460a	850a	265a	790a
Sandblasted (Duplicate)	600a	570a	370a	325a	285ab	790a	545a	845a

Note: See Table XI for details of coating systems. From Drisko, et al (1964)

*The lower case letters indicate type of failure as follows:

a = Epoxy separated from uncoated panel. b = Epoxy failed internally near the epoxy-coating interface.
c = Coating system failed internally. d = Coating system separated from underlying steel.

TABLE XI

Coating System Details for Table X

Coating System		Primer			Additional Coats			TOTAL
		Type	No. of Coats	Thickness (mils)	Type	No. of Coats	Thickness (mils)	Thickness (mils)
1	Coal Tar	MIL-C-18480 A	1	-	Coal Tar (MIL-C-18480 A)	2	-	42
2	Vinyl	Pretreatment Primer (MIL-P-15328 B) Vinyl (MIL-P-15929A)	1 5	1/2 6	Vinyl Alkyd Enamel (MIL-P-15936 B)	2	4	10 1/2
3	Saran	Saran	1	-	Same as primer Alternate coats of orange & white	4	-	6 1/2
4	Inorganic Zinc Silicate - Vinyl Mastic	Inorganic Zinc Silicate Vinyl-phenolic	1 1	2 1	Vinyl Mastic	2	10 1/2	13 1/2
5	Phenolic Mastic	Catalyzed Mica-filled Phenolic	1	10 1/2	Catalyzed Phenolic	1	8 1/2	19
6	Epoxy	Catalyzed epoxy	1	2 1/2	Catalyzed Epoxy Phenolic Topcoat	2	12 1/2	15
7	Mica-filled Asphalt Emulsion	Pretreatment Primer (MIL-P-15328 B) Phenolic (MIL-P-12742 A	1 2	1/2 4	Mica-filled Asphalt Emulsion	3	16	20 1/2
8	Epoxy	Catalyzed Epoxy	1	2 1/2	Catalyzed Epoxy	3	7 1/2	10
9	Urethane	Catalyzed Urethane	1	1 1/2	Catalyzed Urethane	3	8 1/2	10
10	Coal Tar Epoxy	Coal Tar Epoxy	2	9 1/2	Aluminum-filled Catalyzed Coal Tar	1	5 1/2	15
A	Epoxy	Two-package Epoxy with asbestos filler	1	187 1/2	-	-	-	187 1/2
B	Epoxy	Two-package Epoxy	1	187 1/2	-	-	-	187 1/2
C	Epoxy	Two-package Epoxy	1	187 1/2	-	-	-	187 1/2
D	Epoxy	Two-package Epoxy plus Copper Oxice	1	187 1/2	-	-	-	187 1/2

From Drisko, et al (1964)

TABLE XII

Sacrificial Anode Data

Material	Consumption Rate Lb. per Amp-Year	Cost per Pound	Cost per Amp-Year
Lead/Platinum			
Minimum	0.004		$0.0093
Maximum	0.013	$2.32	0.0301
Graphite (In coke breeze)			
Minimum	0.11		0.077
Maximum	0.44	0.70	0.308
Lead/Silver			
Minimum	0.10		0.217
Maximum	0.50	2.17	1.09
High Silicon Cast Iron			
Minimum	0.42		0.197
Maximum	2.42	0.47	1.14
Aluminum 80% Efficiency	8.1	0.50	4.05
Zinc 90% Efficiency	26.0	0.20	5.20
Magnesium 50% Efficiency	17.5	0.50	8.75

Platinum: Unqualified inclusion of platinum in this table is not realistic since the consumption rate is dependent upon the anode preparation technique. Thus, bulk platinum has an extremely low consumption rate, whereas platinum deposited onto an inert substrate such as titanium or tantalum is consumed at a rate of about 6 mg/amp-year at high current densities. Platinum is priced today at between $3.22 and $5.30 per gram.

From Littauer (1966)

TABLE XIII

Test Specimen Rating Systems for Tables IIa, IIb, and VIII

Table No.	Rating System	
IIa and IIb	Ratings are based on ASTM Photographic Reference Standards (ASTM Designation: D610-43) for evaluating the degree of resistance to rusting obtained with coatings on steel surfaces.	
VIII	Excellent	- Coating in essentially the same condition as when first placed in service.
	Good	- Coating has very minor deterioration.
	Fair	- A significant amount of coating deterioration and/or rusting, but still in serviceable condition.
	Poor	- Coating deterioration and rusting serious enough to lead to an early removal from service.

From Alumbaugh (1962); Drisko (1965)

TABLE XIV

Description of Coatings in Figures 11a-c and 12

System and Color	No. of Coats	Thickness (mils)
SERIES 1		
1. Hot-applied coal-tar enamel - 34Yb (black)		
Cold-applied coal-tar primer	1	
Hot-applied coal-tar enamel	1	90.0
		Total 90.0
2. Neoprene brushing compound (black)		
Neoprene primer	1	
Neoprene finish plus accelerator	6	9.0
		Total 9.0
3. Aluminum-pigmented chlorinated rubber (aluminum)		
Chlorinated rubber red-lead primer	1	
Aluminum-pigmented chlorinated rubber finish	2	2.0
		Total 2.0
4. Chlorinated rubber (gray)		
MIL-C-15328 (Formula 117), pretreatment primer	1	
Chlorinated rubber intermediate	2	
Chlorinated rubber finish	2	5.5
		Total 5.5
5. Thiokol-vinyl resin blend (black)		
Thiokol-vinyl resin finish	3	7.0
		Total 7.0
6. Vinyl (gray)		
Vinyl resin finish	4	4.0
		Total 4.0
7. Aluminum-pigmented vinyl (aluminum)		
Pretreatment primer	1	
Vinyl red-lead primer	1	
Aluminum-pigmented vinyl finish	1	4.0
		Total 4.0
8. Vinyl (gray)		
MIL-C-15328 (Formula 117), pretreatment primer	1	
Anticorrosive intermediate	2	
Vinyl finish	2	2.5
		Total 2.5

From Alumbaugh and Brouillette (1966)

TABLE XIV Continued

	System and Color	No. of Coats		Thickness (mils)
9.	Vinyl (gray)			
	Single package pretreatment primer	1		
	Stainless-steel-pigmented intermediate	2		
	Clear vinyl finish	1		2.0
			Total	2.0
10.	Saran (orange)			
	Saran (alternate white and orange coats)	5		6.0
			Total	6.0
11.	Flame-sprayed Thiokol (black)			
	Flame-sprayed Thiokol powder	1		66.0
			Total	66.0
12.	Flame-sprayed zinc (gray)			
	Flame-sprayed zinc powder	1		3.0
			Total	3.0
13.	Flame-sprayed aluminum (aluminum)			
	Flame-sprayed aluminum powder	1		4.5
			Total	4.5
14.	Flame-sprayed zinc (gray)			
	Flame-sprayed zinc wire	1		5.5
			Total	5.5
15.	Flame-sprayed aluminum (aluminum)			
	Flame-sprayed aluminum wire	1		5.0
			Total	5.0
	SERIES 2			
16.	Saran (white)			
	Saran (Formula 113/49), alternate orange and white coats	7		6.5
			Total	6.5
17.	Saran (white)			
	MIL-C-15328 (Formula 117), pretreatment primer	1		0.5
	Saran (Formula 113/49), alternate orange and white coats	8		7.5
			Total	8.0

TABLE XIV Continued

	System and Color	No. of Coats	Thickness (mils)
18.	Saran (white)		
	Flame-sprayed zinc wire	1	2.5
	Saran (Formula 113/49), alternate orange and white coats	7	7.5
	Total		10.0
19.	Saran (white)		
	Flame-sprayed aluminum wire	1	3.5
	Saran (Formula 113/49), alternate orange and white coats	7	5.5
	Total		9.0
20.	Vinyl antifouling (black)		
	MIL-P-15929 (Formula 119), vinyl red-lead primer	2	2.0
	MIL-P-16189 (Formula 129), vinyl antifouling finish	3	3.0
	Total		5.0
21.	Vinyl antifouling (black)		
	MIL-C-15328 (Formula 117), pretreatment primer	1	0.5
	MIL-P-15929 (Formula 119), vinyl red-lead primer	2	2.0
	MIL-P-16189 (Formula 129), vinyl antifouling finish	3	3.0
	Total		5.5
22.	Vinyl (orange)		
	Flame-sprayed zinc wire	1	2.5
	MIL-P-15929 (Fornula 119), vinyl red-lead primer	5	4.5
	Total		7.0
23.	Vinyl (orange)		
	Flame-sprayed aluminum wire	1	4.5
	MIL-P-15929 (Formula 119), vinyl red-lead primer	5	4.0
	Total		8.5
24.	Vinyl-acrylic lacquer (clear)		
	Vinyl-acrylic lacquer finish	6	4.5
	Total		4.5
25.	Vinyl-acrylic lacquer (clear)		
	MIL-C-15328 (Formula 117), pretreatment primer	1	0.5
	Vinyl-acrylic lacquer finish	6	4.0
	Total		4.5

TABLE XIV Continued

	System and Color	No. of Coats		Thickness (mils)
26.	Vinyl-acrylic lacquer (clear)			
	Flame-sprayed zinc wire	1		3.0
	Vinyl-acrylic lacquer finish	8		5.0
			Total	8.0
27.	Vinyl-acrylic lacquer (clear)			
	Flame-sprayed aluminum wire	1		2.5
	Vinyl-acrylic lacquer finish	8		5.0
			Total	7.5
28.	Cold plastic antifouling (black)			
	Formula 145, cold plastic antifouling finish	4		4.5
			Total	4.5
29.	Cold plastic antifouling (black)			
	MIL-C-15328 (Formula 117), pretreatment primer	1		0.5
	Formula 145, cold plastic antifouling finish	4		7.0
			Total	7.5
30.	Cold plastic antifouling (black)			
	Flame-sprayed zinc wire	1		3.0
	Formula 145, cold plastic antifouling finish	4		6.5
			Total	9.5
31.	Cold plastic antifouling (black)			
	Flame-sprayed aluminum wire	1		3.0
	Formula 145, cold plastic antifouling finish	4		4.5
			Total	7.5
32.	Vinyl (gray)			
	Vinyl finish	6		5.0
			Total	5.0
33.	Vinyl (gray)			
	MIL-C-15328 (Formula 117), pretreatment primer	1		0.5
	Vinyl finish	5		5.0
			Total	5.5
34.	Vinyl (gray)			
	Flame-sprayed zinc wire	1		2.5
	Vinyl finish	5		5.0
			Total	7.5

TABLE XIV Continued

System and Color	No. of Coats	Thickness (mils)
35. Vinyl (gray)		
Flame-sprayed aluminum wire	1	3.0
Vinyl finish	5	4.5
		Total 7.5
36. Phenolic mastic (gray)		
Catalyzed phenolic mastic primer	1	4.5
Catalyzed phenolic mastic finish	1	4.5
		Total 9.0
37. Phenolic mastic (gray)		
MIL-C-15328 (Formula 117), pretreatment primer	1	0.5
Catalyzed phenolic mastic primer	1	4.5
Catalyzed phenolic mastic finish	1	4.0
		Total 9.0
38.* Phenolic mastic (gray)		
Catalyzed mica-filled phenolic mastic primer	1	11.0
Catalyzed phenolic mastic finish	1	8.5
		Total 19.5
39. Phenolic mastic (gray)		
Flame-sprayed aluminum wire	1	3.0
Catalyzed phenolic mastic primer	1	5.0
Catalyzed phenolic mastic finish	1	5.0
		Total 13.0
40. Epoxy (white)		
Catalyzed epoxy red-lead primer	2	3.5
Catalyzed epoxy finish	2	3.5
		Total 7.0
41. Epoxy (white)		
MIL-C-15328 (Formula 117), pretreatment primer	1	0.5
Catalyzed epoxy red-lead primer	2	4.0
Catalyzed epoxy finish	2	3.5
		Total 8.0
42. Epoxy (white)		
Flame-sprayed zinc wire	1	3.0
Catalyzed epoxy finish	2	5.5
		Total 8.5

---

*This system was not compatible with the flame-sprayed zinc coating and reacted chemically when applied as a topcoat. Consequently, the phenolic mastic was not tested over the flame-sprayed zinc wire.

TABLE XIV Continued

	System and Color	No. of Coats	Thickness (mils)
43.	Epoxy (white)		
	Flame-sprayed aluminum wire	1	2.5
	Catalyzed epoxy finish	2	6.5
			Total 9.0
44.	Chlorinated rubber (red)		
	Chlorinated rubber red-lead primer	2	2.0
	Chlorinated rubber finish	3	3.0
			Total 5.0
45.	Chlorinated rubber (red)		
	MIL-C-15328 (Formula 117), pretreatment primer	1	0.5
	Chlorinated rubber red-lead primer	2	2.0
	Chlorinated rubber finish	3	3.0
			Total 5.5
46.	Chlorinated rubber (red)		
	Flame-sprayed zinc wire	1	2.0
	Chlorinated rubber finish	5	6.0
			Total 8.0
47.	Chlorinated rubber (red)		
	Flame-sprayed aluminum wire	1	3.5
	Chlorinated rubber finish	5	5.5
			Total 9.0
48.	Furan (gray)		
	Vinyl red-lead, iron oxide primer	2	1.5
	Furan finish	3	3.5
			Total 5.0
49.	Furan (gray)		
	MIL-C-15328 (Formula 117), pretreatment primer	1	0.5
	Vinyl red-lead, iron oxide primer	2	1.5
	Furan finish	3	3.5
			Total 5.5
50.	Furan (gray)		
	Flame-sprayed zinc wire	1	3.0
	Furan finish	3	4.0
			Total 7.0

TABLE XIV Continued

System and Color	No. of Coats	Thickness (mils)
51. Furan (gray)		
Flame-sprayed aluminum wire	1	3.0
Furan finish	3	4.0
		Total 7.0
52. Neoprene brushing composition (black)		
Synthetic rubber primer	2	3.0
Neoprene finish plus accelerator	3	5.0
		Total 8.0
53. Neoprene brushing composition (black)		
MIL-C-15328 (Formula 117), pretreatment primer	1	0.5
Synthetic rubber primer	2	3.0
Neoprene finish plus accelerator	3	5.0
		Total 8.5
54. Neoprene brushing composition (black)		
Flame-sprayed zinc wire	1	3.0
Synthetic rubber primer	1	1.0
Neoprene finish plus accelerator	3	6.0
		Total 10.0
55. Neoprene brushing composition (black)		
Flame-sprayed aluminum wire	1	3.0
Synthetic rubber primer	1	1.0
Neoprene finish plus accelerator	3	6.5
		Total 10.5
SERIES 3		
56. Zinc inorganic silicate (gray)		
Zinc inorganic silicate (post-cured)	2	5.0
		Total 5.0
57. Zinc inorganic silicate (gray)		
Zinc inorganic silicate (post-cured)	1	4.0
(Panel contained window)*		Total 4.0
58. Zinc inorganic silicate (gray)		
Zinc inorganic silicate (post-cured)	2	5.0
(Panel contained window)*		Total 5.0

---

*Before coating, a piece of 1-inch by 6-inch masking tape was applied to the middle of the tidal zone on one face of these sandblasted panels. After the coatings were cured, the masking tape was removed leaving a "window" of uncoated sandblasted metal to be exposed to the tidal environment.

TABLE XIV Continued

System and Color	No. of Coats	Thickness (mils)
59. Zinc inorganic silicate (gray)		
Zinc inorganic silicate (post-cured)	1	2.5
		Total 2.5
60. Zinc-dust-pigmented polystyrene (gray)		
Zinc-dust-pigmented polystyrene	2	3.5
		Total 3.5
61. Zinc-dust-pigmented polystyrene (gray)		
Zinc-dust-pigmented polystyrene	2	4.0
(Panel contained window)*		Total 4.0
62. Copper antifouling paint (brown)		
Iron oxide, zinc chromate primer	1	1.0
Mica-pigmented insulating coat	2	2.0
Antifouling finish	2	2.0
		Total 5.0
63. Copper antifouling paint (brown)		
MIL-C-15328 (Formula 117), pretreatment primer	1	0.5
Iron oxide, zinc chromate primer	2	1.5
Mica-pigmented insulating coat	2	2.0
Antifouling finish	2	2.0
		Total 6.0
64. Aluminum-pigmented vinyl (aluminum)		
Flame-sprayed aluminum wire	1	3.5
Aluminum-pigmented vinyl finish	3	3.0
		Total 6.5
65. Neoprene (black)		
Neoprene primer	2	2.5
Neoprene finish plus accelerator	3	7.5
		Total 10.0
SERIES 4		
66. Aluminum-pigmented vinyl (aluminum)		
MIL-C-15328 (Formula 117), pretreatment primer	1	0.5
MIL-P-15929 (Formula 119), vinyl red-lead primer	2	4.0
Aluminum-pigmented vinyl finish	2	2.0
		Total 6.5

---

*Before coating, a piece of 1-inch by 6-inch masking tape was applied to the middle of the tidal zone on one face of these sandblasted panels. After the coatings were cured, the masking tape was removed leaving a "window" of uncoated sandblasted metal to be exposed to the tidal environment.

TABLE XIV Continued

	System and Color	No. of Coats	Thickness (mils)
67.	Zinc-dust-pigmented polystyrene (gray)		
	Zinc-dust-pigmented polystyrene	2	2.0
			Total 2.0
68-	Epoxy (white)		
684.	Catalyzed epoxy red-lead primer	2	3.0(2.5)*
	Catalyzed epoxy finish	2	3.5(4.0)
			Total 6.5
69.	Zinc inorganic silicate (gray)		
	Zinc inorganic silicate (post-cured)	1	2.5
			Total 2.5
70.	Vinyl (gray)		
	Vinyl-phenolic strontium chromate, iron oxide primer	1	1.0
	Vinyl finish	2	5.5
			Total 6.5
71.	Vinyl mastic (black)		
	Vinyl-phenolic strontium chromate, iron oxide primer	1	1.5
	Vinyl mastic finish	2	9.0
			Total 10.5
72-	Phenolic mastic (gray)		
724.	Catalyzed mica-filled phenolic mastic primer	1	10.5 (6.0)
	Catalyzed phenolic mastic finish	1	5.0 (8.0)
			Total 15.5(14.0)
73-	Furan (black)		
734.	Vinyl red-lead, iron oxide primer	1	1.0(1.5)
	Furan finish	5(4)	5.5(6.0)
			Total 6.5(7.5)
74.	Neoprene brushing compound (black)		
	Synthetic rubber primer	1	2.0
	Neoprene finish plus accelerator	3	29.0
			Total 31.0

---

*Where there are differences between the number of coats or coating thicknesses applied to the 4-inch by 10-foot panels and the angle iron panels, the values for the angle iron panels are given in parentheses in this appendix.

TABLE XIV Continued

	System and Color	No. of Coats		Thickness (mils)
75.	Chlorinated rubber (red)			
	Chlorinated rubber red-lead primer	1		0.5
	Chlorinated rubber finish	4		4.5
			Total	5.0
76.	Cold-applied coal tar (black)			
	MIL-C-15328 (Formula 117), pretreatment primer	1		0.5
	MIL-C-18480 coal-tar coating compound	3		25.5
	MIL-C-15203 bituminous emulsion finish	1		4.0
			Total	30.0
77- 77L.	Cold-applied coal tar (black)			
	MIL-C-18480 coal-tar coating compound	3(4)		21.5(18.5)
	MIL-C-15203 bituminous emulsion finish	1(3)		4.0(14.0)
			Total	25.5(32.5)
78.	Cold-applied coal tar (black)			
	MIL-C-15328 (Formula 117), pretreatment primer	1		0.5
	MIL-C-18480 coal-tar coating compound	3		22.5
			Total	23.0
79.	Cold-applied coal tar (black)			
	MIL-C-18480 coal-tar coating compound	3		22.5
			Total	22.5
80.	Mica-filled asphalt emulsion (black)			
	MIL-C-15328 (Formula 117), pretreatment primer	1		0.5
	JAN-P-735* (Formula 84/47), alkyd zinc chromate primer	1		1.5
	Mica-filled asphalt emulsion finish	7		30.5
			Total	32.5
81- 81L.	Gilsonite asphalt (black)			
	Gilsonite asphalt	5		125.0
			Total	125.0
82.	Cold plastic antifouling (black)			
	MIL-C-15328 (Formula 117), pretreatment primer	1		0.5
	MIL-P-18996 (Formula 14), anticorrosive primer	2		3.5
	Formula 145, cold plastic antifouling finish	4		21.5
			Total	25.5

---

*Current designation is TT-P-645.

TABLE XIV Continued

	System and Color	No. of Coats	Thickness (mils)
83.	FlameOsprayed zinc (gray)		
	MIL-M-3800 zinc wire, flame-sprayed	1	4.0
			Total 4.0
84.	Flame-sprayed aluminum (aluminum)		
	MIL-M-3800 aluminum wire, flame-sprayed	1	4.0
			Total 4.0
85.	Hot plastic antifouling (red-brown)		
	MIL-C-15328 (Formula 117), pretreatment primer	1	0.5
	MIL-P-18996 (Formula 14), anticorrosive primer	2	4.0
	Formula 15 HP, hot plastic antifouling finish	1	23.0
			Total 27.5
86.	Saran (white)		
	Saran (Formula 113/49)*, alternate orange and white coats	6	6.0
			Total 6.0
	SERIES 5		
87- 87L.	Coal-tar epoxy (black)		
	Catalyzed coal-tar epoxy	3	12.0(15.0)
			Total 12.0(15.0)
88.	Epoxy (gray)		
	Catalyzed epoxy primer	1	1.5
	Catalyzed epoxy finish	2	4.0
			Total 5.5
89.	Oil-base (gray)		
	Oil-base red-lead primer	1	2.0
	Oil-base cement-pigmented finish	2	4.0
			Total 6.0
90.	Oil-base (gray)		
	Oil-base lead suboxice, iron oxide primer	1	1.0
	Oil-base lead suboxide finish	3	4.5
			Total 5.5
91.	Aluminum-pigmented vinyl (aluminum)		
	Pretreatment primer	1	0.5
	Vinyl red-lead primer	1	1.0
	Aluminum-pigmented vinyl finish	2	3.0
			Total 4.5

---

*Current designation is MIL-L-18389 (Formula 113/54).

TABLE XIV Continued

	System and Color	No. of Coats	Thickness (mils)
92.	Neoprene (black)		
	Synthetic rubber primer	2	0.5
	Neoprene finish plus accelerator	7	17.0
			Total 17.5
93.	Chlorinated rubber-vinyl (gray)		
	MIL-C-15328 (Formula 117), pretreatment primer	1	0.5
	MIL-P-15929 (Formula 119), vinyl red-lead primer	2	1.5
	Chlorinated rubber-vinyl finish	3	3.0
			Total 5.0
94.	Aluminum-pigmented chlorinated rubber (aluminum)		
	Chlorinated rubber red-lead primer	2	1.5
	Aluminum-pigmented chlorinated rubber finish	3	5.5
			Total 7.0
95.	Vinyl (gray)		
	Aluminum-pigmented vinyl-Thiokol primer	3	2.5
	Vinyl finish	2	3.0
			Total 5.5
96- 96L.	High-build vinyl (gray)		
	Vinyl-phenolic, strontium chromate, iron oxide primer	1	1.0
	High-build vinyl finish	2(3)	5.0
			Total 6.0
97- 97L.	Epoxy (gray)		
	Catalyzed epoxy primer	1	1.5(1.0)
	Catalyzed epoxy body coat	2	3.5(3.0)
	Catalyzed epoxy finish	2	4.0
			Total 9.0(8.0)
98- 98L.	Vinyl antifouling (red-brown)		
	MIL-C-15328 (Formula 117), pretreatment primer	1	0.5
	MIL-P-15929 (Formula 119), vinyl red-lead primer	2	2.5(2.0)
	MIL-P-15931 (Formula 121), vinyl anti-fouling finish	2	4.5(5.0)
			Total 7.5

TABLE XIV Continued

	System and Color	No. of Coats	Thickness (mils)
99- 99∠.	Chlorosulfonated polyethylene (gray)		
	Vinyl red-lead, iron oxide primer	2	1.5
	Catalyzed chlorosulfonated polyethylene finish	5	7.0
		Total	8.5
100- 100∠.	Zinc-filled modified epoxy (gray)		
	Catalyzed zinc-filled modified epoxy	3	6.0(7.5)
		Total	6.0(7.5)
101- 101∠.	Epoxy (gray)		
	Catalyzed epoxy primer	1	3.0 (2.0)
	Catalyzed epoxy finish	2	9.0
		Total	12.0(11.0)
102- 102∠.	Aluminum-pigmented urethane (aluminum)		
	Catalyzed urethane red-lead primer	2(3)	1.5
	Catalyzed urethane intermediate	1	1.5(1.0)
	Catalyzed aluminum-pigmented urethane finish	4	2.5(3.0)
		Total	5.5
103- 103∠.	Aluminum-pigmented coal-tar epoxy (aluminum)		
	Catalyzed coal-tar epoxy red-lead primer	1	7.5 (5.5)
	Catalyzed coal-tar epoxy intermediate	2	14.5(15.5)
	Catalyzed aluminum-pigmented coal-tar epoxy finish	1	2.5 (2.0)
		Total	24.5(23.0)
104.	Vinyl antifouling (red-brown)		
	Pretreatment primer	1	0.5
	Vinyl red-lead primer	1	1.5
	Vinyl intermediate (black)	1	2.5
	Vinyl antifouling finish	2	5.0
		Total	9.5
105.	Vinyl (gray)		
	Pretreatment primer	1	0.5
	Vinyl red-lead primer	2	1.5
	Vinyl intermediate (black)	1	2.0
	Vinyl finish	2	4.5
		Total	8.5

TABLE XIV Continued

	System and Color	No. of Coats	Thickness (mils)
106.	Aluminum-pigmented vinyl (aluminum)		
	Pretreatment primer	1	0.5
	Vinyl red-lead primer	2	1.5
	Aluminum-pigmented vinyl finish	3	4.5
			Total 6.5
77a.	Cold-applied coal tar (black)		
	MIL-C-18480 coal-tar coating compound	5	19.5
	MIL-C-15203 bituminous emulsion finish	2	9.5
			Total 29.0
107- 107L.	Cold-applied coal-tar antifouling (black)		
	MIL-C-18480 coal-tar coating compound	5(5)*	21.0(22.5)*
	MIL-C-15203 bituminous emulsion finish (top 1/3)	1(0)	5.0 (0)
	Coal-tar antifouling finish (bottom 2/3)	1(1)	7.0 (7.0)*
			Total 26.0(top 1/3) 28.0(bottom 2/3)
108.	Coal-tar epoxy (black)		
	Catalyzed coal-tar epoxy	2	8.0
			Total 8.0
109- 109L.	Epoxy (cream)		
	Catalyzed epoxy primer	1	1.0
	Catalyzed epoxy intermediate	1	2.5
	Catalyzed epoxy finish	1	3.5(3.0)
			Total 7.0(6.5)
110- 110L.	Tetrafluoroethylene (blue-green)		
	Catalyzed epoxy primer	1	1.5 (2.0)
	Catalyzed epoxy intermediate	1	2.0 (3.5)
	Catalyzed epoxy finish	1	4.0 (3.0)
	Tetrafluoroethylene emulsion finish	1(2)	0.5 (1.5)
			Total 8.0(10.0)
111.	Tetrafluoroethylene (blue-green)		
	MIL-C-15328 (Formula 117), pretreatment primer	1	0.5
	Tetrafluoroethylene emulsion finish	4	3.5
			Total 4.0

---

*System 107L consisted of five coats of MIL-C-18480 over the entire panel to give 22.5 mils and one coat of the antifouling coating on the top half of the panel for a total film thickness of 29.5 mils.

TABLE XIV Continued

	System and Color	No. of Coats		Thickness (mils)
112-	Urethane (green)			
112Z.	Vinyl red-lead, iron oxide primer	1		2.5(2.0)
	Catalyzed urethane finish	2		5.0(6.0)
			Total	7.5(8.0)
113-	Urethane (green)			
113Z.	Pretreatment primer	1		0.5
	Catalyzed urethane finish	3		6.0
			Total	6.5
114-	Coal-tar urethane (black)			
114Z.	Catalyzed coal-tar urethane finish	2		9.5(10.0)
			Total	9.5(10.0)
115-	Vinyl (gray)			
115Z.	Pretreatment primer	1		0.5
	Vinyl iron oxide primer	1		2.0
	Vinyl finish	2		8.5 (7.5)
			Total	11.0(10.0)
116-	Epoxy (gray)			
116Z.	Catalyzed epoxy zinc chromate primer	1		4.5
	Catalyzed epoxy finish	2		5.0
			Total	9.5
117-	Coal-tar epoxy (black)			
117Z.	Catalyzed coal-tar epoxy finish	3		16.5(16.0)
			Total	16.5(16.0)
118-	Coal-tar epoxy (black)			
118Z.	Catalyzed coal-tar epoxy finish	3		17.5
			Total	17.5
119-	Zinc inorganic silicate (gray)			
119Z.	Zinc inorganic silicate (self-cured)	1		4.0
			Total	4.0
120-	Modified phenolic (gray)			
120Z.	Catalyzed modified-phenolic primer	1		6.0
	Catalyzed modified-phenolic finish	2		6.0 (8.0)
			Total	12.0(14.0)

TABLE XIV Continued

	System and Color	No. of Coats	Thickness (mils)
121- 121Z.	Polystyrene-pyrobitumen mastic (black)		
	Phenolic red-lead primer	1	1.0
	Polystyrene-pyrobitumen mastic finish	2	14.5(16.0)
			Total 15.5(17.0)
122- 122Z.	Urethane (gray)		
	Catalyzed urethane zinc chromate primer	1	1.0(1.5)
	Catalyzed urethane finish	7(6)	6.5(8.0)
			Total 7.5(9.5)
123- 123Z.	Epoxy phenolic (gray)		
	Catalyzed epoxy primer	1	3.0 (3.5)
	Catalyzed epoxy-phenolic finish	3	11.0
			Total 14.0(14.5)
124- 124Z.	Epoxy (white)		
	Catalyzed epoxy zinc chromate primer	1	3.5 (4.0)
	Catalyzed epoxy finish	1	10.5 (9.5)
			Total 14.0(13.5)
125- 125Z.	Urethane (gray)		
	Catalyzed urethane zinc chromate primer	1	1.5 (2.0)
	Catalyzed urethane finish	3	9.5(10.5)
			Total 11.0(12.5)
126- 126Z.	Vinyl-alkyd (black)		
	MIL-C-15328A (Formula 117), pretreatment primer	1	0.5
	MIL-P-15929A (Formula 119), vinyl red-lead primer	5	6.5 (5.5)
	MIL-E-15932A (Formula 122-1), vinyl-alkyd finish	2	5.0 (4.5)
			Total 12.0(10.5)
127- 127Z.	Urethane (black)		
	Catalyzed epoxy zinc chromate primer	1	2.5(3.0)
	Catalyzed urethane finish	3	7.5(7.0)
			Total 10.0
	SERIES 6		
128- 128Z.	Coal-tar epoxy (black)		
	Zinc inorganic silicate (self-cured)	1	2.5
	Catalyzed coal-tar epoxy finish	1	9.0
			Total 11.5

TABLE XIV Continued

	System and Color	No. of Coats	Thickness (mils)
129-	Vinyl-alkyd (gray)		
129Z.	Zinc inorganic silicate (self-cured)	1	3.0
	MIL-P-15328B (Formula 117), pretreatment primer	1	0.5
	MIL-P-15929B (Formula 119), vinyl red-lead primer	3	6.0
	MIL-E-15936B (Formula 122-27), vinyl-alkyd finish	2	4.5
			Total 14.0
130-	Epoxy (gray)		
130Z.	Zinc inorganic silicate (post-cured)	1	3.0
	Catalyzed epoxy lead-silico-chromate primer	1	2.0
	Catalyzed epoxy intermediate	1	4.0
	Catalyzed epoxy finish	1	2.0
			Total 11.0
131-	Vinyl-alkyd (gray)		
131Z.	Zinc inorganic silicate (post-cured)	1	3.0
	MIL-P-15328B (Formula 117), pretreatment primer	1	0.5
	MIL-P-15929B (Formula 119), Vinyl red-lead primer	5	5.0
	MIL-E-15936B (Formula 122-27), vinyl-alkyd finish	2	5.5
			Total 14.0
132-	Epoxy (gray)		
132Z.	Zinc inorganic silicate (self-cured)	1	5.0
	Catalyzed epoxy mastic iron oxide and chromate primer	2	5.0
	Catalyzed epoxy finish	1	2.5
			Total 12.5
133-	Vinyl-alkyd (gray)		
133Z.	Zinc inorganic silicate (self-cured)	1	4.0
	MIL-P-15328B (Formula 117), pretreatment primer	1	0.5
	MIL-P-15929B (Formula 119), vinyl red-lead primer	3	5.5
	MIL-E-15936B (Formula 122-27), vinly-alkyd finish	2	5.0
			Total 15.0

TABLE XIV Continued

	System and Color	No. of Coats	Thickness (mils)
134- 134Z.	Vinyl (gray)		
	Zinc inorganic silicate (post-cured)	1	2.0
	Vinyl mastic iron oxide and chromate primer	1	1.5
	Vinyl mastic intermediate	1	4.0
	Vinyl finish	1	2.5
			Total 10.0
135- 135Z.	Vinyl-alkyd (gray)		
	Zinc inorganic silicate (post-cured)	1	2.0
	MIL-P-15328B (Formula 117), pretreatment primer	1	0.5
	MIL-P-15929B (Formula 119), vinyl red-lead primer	3	6.5
	MIL-E-15936B (Formula 122-27), vinyl-alkyd finish	2	6.0
			Total 15.0
136- 136Z.	Epoxy (gray)		
	Zinc inorganic silicate (self-cured)	1	4.0
	Catalyzed epoxy lead-silico-chromate primer	1	2.0
	Catalyzed epoxy intermediate	1	5.0
	Catalyzed epoxy finish	1	3.0
			Total 14.0
137- 137Z.	Vinyl-alkyd (gray)		
	Zinc inorganic silicate (self-cured)	1	4.5
	MIL-P-15929B (Formula 119), vinyl red-lead primer	3	5.5
	MIL-E-15936B (Formula 122-27), vinyl-alkyd finish	2	4.0
			Total 14.0
138- 138Z.	Epoxy (gray)		
	Zinc inorganic silicate (self-cured)	1	4.0
	Acrylic zinc chromate, zinc oxide primer	1	1.0
	Catalyzed epoxy finish	1	10.0
			Total 15.0
139- 139Z.	Vinyl-alkyd (gray)		
	Zinc inorganic silicate (self-cured)	1	3.5
	MIL-P-15328B (Formula 117), pretreatment primer	1	0.5
	MIL-P-15929B (Formula 119), vinyl red-lead primer	3	6.5
	MIL-E-15936B (Formula 122-27), vinyl-alkyd finish	2	4.0
			Total 14.5

TABLE XIV Continued

	System and Color	No. of Coats	Thickness (mils)
140-	Aluminum-pigmented hydrocarbon resin (aluminum)		
140Z.	Zinc inorganic silicate (self-cured)	1	3.0
	Modified phenolic-epoxy red iron oxide tie coat	1	1.0
	Aluminum-pigmented hydrocarbon resin finish	3	9.0
			Total 13.0
141-	Vinyl-alkyd (gray)		
141Z.	Zinc inorganic silicate (self-cured)	1	3.0
	MIL-P-15328B (Formula 117), pretreatment primer	1	0.5
	MIL-P-15929B (Formula 119), vinyl red-lead primer	3	6.0
	MIL-E-15936B (Formula 122-27), vinyl-alkyd finish	2	4.5
			Total 14.0
142-	Aluminum-pigmented hydrocarbon resin (aluminum)		
142Z.	Zinc inorganic silicate (post-cured)	1	2.0
	Modified phenolic-epoxy red iron oxide tie coat	1	1.0
	Aluminum-pigmented hydrocarbon resin finish	3	8.0
			Total 11.0
143-	Vinyl-alkyd (gray)		
143Z.	Zinc inorganic silicate (post-cured)	1	2.5
	MIL-P-15328B (Formula 117), pretreatment primer	1	0.5
	MIL-P-15929B (Formula 119), vinyl red-lead primer	4	6.0
	MIL-E-15936B (Formula 122-27), vinyl-alkyd finish	2	6.0
			Total 15.0
144-	Vinyl-alkyd (gray)		
144Z.	MIL-P-15328B (Formula 117), pretreatment primer	1	0.5
	MIL-P-15929B (Formula 119), vinyl red-lead primer	4	6.0
	MIL-E-15936B (Formula 122-27), vinyl-alkyd finish	2	4.0
			Total 10.5

From Alumbaugh and Brouillette (1966)

TABLE XV

Galvanic Series in Seawater

Magnesium
Magnesium alloys

Zinc
Galvanized steel or galvanized wrought iron

Aluminum 5052-H
Aluminum 3004
Aluminum 3003
Aluminum 1100
Aluminum 6053-T

Cadmium

Aluminum 2117-T
Aluminum 2017-T
Aluminum 2024-T

Mild steel
Wrought iron
Cast iron

Ni-Resist

13% chromium stainless steel type 410 (active)

50-50 lead tin solder

18-8 stainless steel type 304 (active)
18-8-3 stainless steel type 316 (active)

Lead
Tin

(Continued from previous column)

Muntz metal
Manganese bronze
Naval brass

Nickel (active)
Inconel (active)
Yellow brass
Admiralty brass
Aluminum bronze
Red brass
Copper
Silicon bronze
Ambrac
70-30 copper nickel
Comp. G-bronze
Comp. M-bronze

Nickel (passive)
Inconel (passive)

Monel
18-8 stainless steel type 304 (passive)
18-8-3 stainless steel type 316 (passive)

After LaQue and Cox (1940)

APPENDIX B

GLOSSARY OF CORROSION TERMS

Terms used in corrosion prevention and maintenance techniques are defined below.

Adsorption. The taking up of one substance at the surface of another is termed adsorption. It is the tendency exhibited by all solids to condense upon their surfaces a layer of any gas or solute with which such solids are in contact.

Aeration cell (oxygen cell). An aeration cell is an electrolytic cell, the e.m.f. of which is caused by a difference in air (oxygen) concentration at one electrode as compared with that at another electrode of the same material.

Aggressive carbon dioxide. Free carbon dioxide in excess of the amount necessary to prevent precipitation of calcium as calcium carbonate is termed aggressive carbon dioxide.

Amphoteric corrosion. Amphoteric materials are those materials that are subject to attack from both acid and alkaline environments. Aluminum and lead, commonly used in construction, are subject to amphoteric corrosion in highly alkaline environments. Such corrosion is usually caused by a chemical reaction resulting from a concentration of alkaline products formed by the electrochemical process. The use of cathodic protection in highly alkaline environments, therefore, intensifies the formation of alkaline products.

Anaerobic. Anaerobic means free of air or uncombined oxygen.

Anion. A negatively charged ion of an electrolyte which migrates toward the anode under the influence of a potential gradient.

Anode. The electrode of an electrolytic cell at which oxidation occurs. In corrosion processes, usually the electrode that has greater tendency to go into solution. Typical anodic processes are anions giving up electrons, metal atoms becoming ions in solution or forming an insoluble compound of the metal, and the oxidation of an element or group of elements from a lower to a higher valence state.

Anode corrosion efficiency. The ratio of the actual corrosion of an anode to the theoretical corrosion calculated from the quantity of electricity that has passed or discharged from the anode.

Anodic polarization. That portion of the polarization of a cell that occurs at the anode.

Anolyte. The electrolyte of an electrolytic cell that is adjacent to the anode.

Calomel electrode. A half-cell consisting of mercury, a paste of mercury and calomel (mercurous chloride), and a standard solution of potassium chloride saturated with calomel. It is used as a standard electrode in potential difference measurements.

Cathode. The electrode of an electrolytic cell at which reduction occurs. In corrosion processes, usually the area that is not attacked. Typical cathodic processes are cations taking up electrons and being discharged, oxygen being reduced, and the reduction of an element or group of elements from a higher to a lower valence state.

Cathodic corrosion. Corrosion resulting from a cathodic condition of a structure, usually caused by the reaction of alkaline products of electrolysis with an amphoteric metal.

Cathodic polarization. That portion of the polarization of an electrolytic cell which occurs at the cathode.

Cathodic protection. Reduction or prevention of corrosion of a metal surface by making it cathodic to the electrolyte, for example, by use of sacrificial anodes or impressed electrical currents.

Catholyte. The electrolyte of an electrolytic cell adjacent to the cathode.

Cation. A positively charged ion of an electrolyte which migrates toward the cathode under the influence of a potential gradient.

Caustic embrittlement. Embrittlement of a metal resulting from contact with an alkaline solution.

Cavitation erosion. Damage of a metal associated with the formation and collapse of cavities in the liquid at a solid-liquid interface.

Chalking. The development of loose removable powder at, or just beneath, a coating surface.

Checking. The development of slight breaks in a coating that do not penetrate to the underlying surface. Checking may be described as visible (as seen by the naked eye) or as microscopic (as seen under the magnification of ten diameters).

Chemical conversion coating. A protective or decorative coating produced in situ by chemical reaction of a metal with a chosen environment.

Coating resistance. The electrical resistance of a coating to the flow of current. Unit of measurement is ohms for one square foot of coating. Typical values range from less than 1,000 ohms to more than 1,000,000 ohms for one square foot.

Coefficient of corrosion. A term used in applied cathodic protection. The reciprocal of anode corrosion efficiency.

Concentration cell. An electrolytic cell, the e.m.f. of which is the result of a difference in concentration of the electrolyte or active metal at the anode and the cathode.

Concentration polarization. That portion of the polarization of an electrolytic cell produced by concentration changes resulting from passage of electric current through the electrolyte.

Contact corrosion (crevice corrosion). Corrosion of a metal at an area where contact is made with a material usually nonmetallic.

Corrosion. Destruction of a metal by chemical or electro-chemical reaction with its environment.

Corrosion fatigue. Reduction of fatigue durability by a corrosive environment.

Corrosion fatigue limit. The maximum repeated stress endured by a metal without failure in a stated number of stress applications under defined conditions of corrosion and stressing.

Corrosion mitigation. The reduction of metal loss or damage through use of protective methods and devices.

Corrosion prevention. The halting or elimination of metal damage through use of corrosion-resisting materials, protective methods, and protective devices.

Couple. A pair of dissimilar conductors in electrical contact.

Couple action. (See galvanic corrosion.)

Cracking (of coating). Breaks in a coating which extend through to the underlying surface. Observation under a magnification of ten diameters is recommended where there is difficulty in distinguishing between cracking and checking.

Crazing. Crazing is a network of checks and cracks appearing on a surface.

Critical humidity. The relative humidity above which the atmospheric corrosion rate of a given metal increases sharply.

Current density. The current per unit of cross-sectional area. In cathodic protection work, the current density is usually expressed in milliamperes per square foot.

Deactivation. The process of prior removal of the active corrosion constituents, usually oxygen, from a corrosive liquid by controlled corrosion of expendable metal or by other chemical means.

Decomposition potential (or voltage). The practical minimum potential difference necessary to decompose the electrolyte of a cell at a continuous rate.

Depolarization. The reduction of counter e.m.f. by removing or diminishing the causes of polarization.

Deposit attack. Corrosion occurring under or around a discontinuous deposit on a metallic surface.

Dezincification. Corrosion of a zinc alloy, usually brass, involving loss of zinc and a residue or deposit that remains in situ of one or more less-active constituents, usually copper.

Differential aeration cell. (See aeration cell.)

Drainage. Conduction of current (positive electricity) from an underground metallic structure by means of a metallic conductor.

a. Forced drainage. Drainage applied to underground metallic structures by means of an applied e.m.f. or sacrificial anode.

b. Natural drainage. Drainage from an underground metallic structure to a more negative structure, such as the negative bus of a trolley substation.

Driving force (driving potential). The electromotive force generated in a galvanic cell or the electromotive force applied to an electrolytic cell.

Electroendosmosis. (See electroosmosis.)

Electrolysis. The production of chemical changes in an electrolyte resulting from the passage of electricity.

Electrolyte. A chemical substance or mixture, usually liquid, containing ions that migrate in an electric field.

Electromotive force series (e.m.f. series). A list of elements arranged according to their standard electrode potentials, the sign being positive for elements having potentials that are cathodic to hydrogen and negative for those elements having potentials that are anodic to hydrogen. (This convention of sign, historically and currently used in European literature, has been adopted by the Electrochemical Society and by the National Bureau of Standards, and it is employed in this publication. The opposite convention of G. N. Lewis has been adopted by the American Chemical Society.)

Electronegative potential. A potential corresponding in sign to those of the active or anodic members of the e.m.f. series. Because of the existing confusion of sign in the literature, it is suggested that "anodic potential" be used whenever "electronegative potential" is implied. (See Electromotive force series.)

Electroosmosis. The flow of a liquid in the soil solution or membrane because of difference in electrical potential on the two sides of the membrane. As a result, the soil dries out at or near the anode, causing an increase in soil resistivity. The principle has been used to migrate considerable volumes of water to dry out and stabilize soil during construction.

Electropositive potential. A potential corresponding in sign to potentials of the noble or cathodic members of the e.m.f. series. It is suggested that "cathodic potential" be used whenever "electropositive potential" is implied. (See e.m.f. series.)

Embrittlement. Severe loss of ductility of a metal or alloy.

Erosion. Destruction of a metal or other material by the abrasive action of liquid or gas, usually accelerated by the presence of solid particles of matter in suspension, and sometimes accelerated by corrosion.

Exfoliation. Scaling off a surface in flakes or layers is termed exfoliation.

Film. A thin, not necessarily visible, layer of material.

Fogged metal. A metal the luster of which has been sharply reduced by a film of corrosion products is termed fogged metal.

Fretting corrosion. Corrosion at the interface between two contacting surfaces, accelerated by relative vibration between them of an amplitude that is high enough to produce slip.

Galvanic cell. A cell consisting of two dissimilar conductors in contact with an electrolyte, or two similar conductors in contact with dissimilar electrolytes. More generally a galvanic cell converts energy liberated by a spontaneous chemical reaction directly into electrical energy.

Galvanic corrosion. Corrosion associated with the electric current of a galvanic cell that consists of dissimilar electrodes. It is also known as couple action.

Galvanic series. A list of metals and alloys arranged according to their relative potentials in a given environment.

Graphitization (graphitic corrosion). Corrosion of gray cast iron in which the metallic iron constituent is converted into corrosion products, leaving the graphite intact.

Half-cell. A conducting material (usually metallic) in contact with an electrolyte. It is used as a standard reference in potential tests. For further explanation, reference is made to paragraph 8-01 g. in this manual.

Hydrogen embrittlement. Hydrogen embrittlement is caused by the entrance of hydrogen into the metal, for example, through pickling or cathodic polarization.

Hydrogen overvoltage. Overvoltage associated with the liberation of hydrogen gas is termed hydrogen overvoltage.

Impingement attack. Corrosion associated with turbulent flow of a liquid. For some metals the action is considerably accelerated by entrained bubbles in the liquid.

Inactive. (See passivity.)

Inhibitor. As applied to corrosion, an inhibitor is a chemical substance or mixture that if added to an environment (usually in small concentration) effectively decreases corrosion.

Intercrystalline corrosion. (See intergranular corrosion.)

Intergranular corrosion. Preferential corrosion at grain boundaries of a metal or alloy. It is also called intercrystalline corrosion.

Internal oxidation. The precipitation of one or more oxides of alloying elements beneath the external surface of an alloy as a result of oxygen diffusing into the alloy from the external source. It is also known as subscale formation.

Ion. An electrically charged atom or group of atoms.

Local action. Corrosion caused by local cells on a metal surface.

Local cell. A cell the e.m.f. of which is due to difference of potential between areas on a metallic surface in an electrolyte.

Long-line current. Current flowing through the earth, from an anodic to a cathodic area that returns along an underground metallic structure. Usually occurs where the areas are separated by considerable distances and where the current results from concentration cell action. (See positive electricity.)

Matte surface. A surface of low specular reflectivity.

Metallizing. The process of spraying a surface with a metal.

Metal replacement. The deposition of a metal from a solution of its ion on a more anodic metal accompanied by the solution of the latter metal. It is also called "immersion plating."

Mill scale. The heavy oxide layer formed during hot fabrication or heat-treatment of metals. The term is applied chiefly to iron and steel.

Molality. Molality is the concentration of a solution expressed as the number of gram molecules of the dissolved substance per 1,000 grams of solvent.

Noble metal. A metal which in nature occurs commonly in the free state, or a metal or alloy whose corrosion products are formed with a low negative or a positive free-energy change.

Noble potential. A potential substantially cathodic to the standard hydrogen potential.

Open-circuit potential. The measured potential of a cell during which no significant current flows in the external circuit.

Overvoltage. The difference between the potential of an electrode at which a reaction is actively taking place and another electrode at equilibrium for the same reaction.

Oxidation. Loss of electrons by a constituent of a chemical reaction.

Parting. Parting refers to the selective corrosion of one or more components of a solid-solution alloy.

Parting limit. The maximum concentration of a more noble component in the alloy, above which parting does not occur within a specific environment.

Passivator. An inhibitor which appreciably changes the potential of a metal to a more cathodic value.

Passive-active cell. A cell the e.m.f. of which is due to a potential difference between a metal in an active state and the same metal in a passive state.

Passivity.

a. An active metal in the e.m.f. series, or an alloy composed of such metals, is considered passive if its electrochemical behavior becomes that of an appreciably less active or noble metal.

b. A metal or an alloy is passive if it substantially resists corrosion in an environment where, thermodynamically, there is a large free-energy decrease associated with its passage from the metallic state to appropriate corrosion products.

Patina. A green coating, consisting principally of basic sulfate and occasionally containing small amounts of carbonate or chloride, which forms on the surface of copper or copper alloys exposed to the atmosphere for a long time.

pH. A measure of hydrogen ion activity defined by $pH = \log_{10}(1/aH+)$ where aH = hydrogen ion activity = the molal concentration of hydrogen ions multiplied by the mean ion activity coefficient.

Pickle. A solution or process used to loosen or remove corrosion products, such as scale and tarnish, from a metal.

Pitting erosion. (See cavitation erosion.)

Pitting factor. The depth of the deepest pit resulting from corrosion, divided by the average penetration as calculated from weight loss.

Polarization. The production of a counter e.m.f. by the products formed or by the concentration changes resulting from passage of current through an electrolytic cell.

PPM. Parts per million.

Positive electricity. A body is said to possess positive electricity when it has a deficiency of electrons.

Potential. When a point is said to be at a certain potential, the meaning is that there is a voltage difference of that amount between the point concerned and a given reference. See also standard electrode potential.

Prime coat. A first coat of paint, originally applied to improve adherence of the succeeding coat, but now frequently containing a corrosion inhibitor.

Reaction limit. The minimum concentration of an alloy component below which appreciable attack of an alloy takes place in a given environment, but above which the alloy is corrosion resistant.

Redox. The term "redox" is an abbreviation of oxidation-reduction potential, used to determine whether soil is aerobic or anaerobic. The redox-potential is obtained between a platinum electrode and a calomel half-cell.

Reduction. Gain of electrons by a constituent of a chemical reaction.

Relative humidity. The ratio, expressed as a percentage, of the amount of water present in a given volume of air at a given temperature to the amount required to saturate the air at that temperature.

Remote electrode (remote earth). The potential of a structure-to-earth will change rapidly near the structure, and if remote earth is reached, there will be little or no variation in the voltage. Remote earth is any location away from the structure at which the potential gradient of the structure to earth is constant.

Resistivity. The specific resistance of a material. It is defined as the resistance in ohms of a centimeter cube of material, measured across opposite faces. Since the resistance of a material varies directly with length and inversely with area, the resistance (R) can be written in an equation $R = \rho(l/a)$. By rearrangement solving for ρ, $\rho = R(l/a)$; where R is in ohms, l is in centimeters and a is in square centimeters. Thus the units of resistivity are $\frac{\text{ohm x cm.}^2}{\text{cm.}}$ or ohm-cm.

Rusting. Corrosion of iron resulting in the formation of products on the surface, consisting largely of hydrous ferric oxide.

Scaling. The formation of partially adherent layers of corrosion products on a metal surface at high temperature.

Season cracking. Cracking resulting from a combination of corrosion and internal stress. A term usually applied to stress-corrosion cracking of brass.

Self-corrosion. (See local action.)

Slushing compound. A nondrying oil, grease, or similar organic compound that, when coated over a metal, affords at least temporary protection against corrosion.

Spalling. The chipping or fragmenting of a surface or surface coating caused, for example, by differential thermal expansion or contraction.

Stray current corrosion. Corrosion caused by an electric current through paths other than the intended circuit or by an extraneous current in the earth.

Stress corrosion. Corrosion of a metal accelerated by stress.

Stress corrosion cracking. Cracking resulting from the combined effect of corrosion and stress.

Subscale formation. (See internal oxidation.)

Tarnish. Discoloration of a metal surface as the result of formation of an adherent continuous film of corrosion products.

Tuberculation. The formation of localized corrosion products scattered over the surface in the form of knoblike mounds.

Underfilm corrosion. Corrosion that occurs under lacquers and similar organic films in the form of randomly distributed hairlines (most common) or spots.

Weld decay. Corrosion notably of austenitic chromium steels at specific zones away from a weld.

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Coastal Engineering Research Center (CERC) Corps of Engineers, Department of the Army Washington, D.C.	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE

CORROSION AND PROTECTION OF STEEL PILING IN SEAWATER

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

5. AUTHOR(S) *(First name, middle initial, last name)*

Laverne L. Watkins

6. REPORT DATE May 1969	7a. TOTAL NO. OF PAGES 99	7b. NO. OF REFS 55

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S) Technical Memorandum No. 27
b. PROJECT NO.	
c.	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d.	

10. DISTRIBUTION STATEMENT

This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY

13. ABSTRACT

The report, based on a survey of literature, assembles much of the current knowledge concerning corrosion and protection of steel piling in seawater. Causes of corrosion and effects of environmental conditions are presented. Results of tests on protective coatings for steel are included. Corrosion rates of bare steel piles and the factors involved in the use of cathodic protection and concrete jackets are explained. References surveyed show that flame-sprayed zinc sealed with vinyl is possibly the best coating system tested. More data is needed from which to determine the most economical method of protecting steel piling in seawater.

UNCLASSIFIED
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
steel piling						
corrosion						
protective coatings						
concrete jackets						
flame-spraying						
vinyl						
epoxy						

UNCLASSIFIED
Security Classification

U. S. ARMY COASTAL ENGRG RESEARCH CENTER, CE
WASHINGTON, D. C. 20016

CORROSION AND PROTECTION OF STEEL PILING IN SEAWATER by L. L. Watkins. 99 pp. including 16 Figures and 2 Appendixes. May 1969

TECHNICAL MEMORANDUM No. 27 UNCLASSIFIED

1. Corrosion prevention
2. Steel Piling
3. Cathodic protection
4. Concrete jackets
5. Protective coatings

I. Title
II. Watkins, L. L.

The report, based on a survey of literature, assembles much of the current knowledge concerning corrosion and protection of steel piling in seawater. Causes of corrosion and effects of environmental conditions are presented. Results of tests on protective coatings for steel are included. Corrosion rates of bare steel piles and the factors involved in the use of cathodic protection and concrete jackets are explained. References surveyed show that flame-sprayed zinc sealed with vinyl is possibly the best coating system tested. More data is needed from which to determine the most economical method of protecting steel piling in seawater.

U. S. ARMY COASTAL ENGRG RESEARCH CENTER, CE
WASHINGTON, D. C. 20016

CORROSION AND PROTECTION OF STEEL PILING IN SEAWATER by L. L. Watkins. 99 pp. including 16 Figures and 2 Appendixes. May 1969

TECHNICAL MEMORANDUM No. 27 UNCLASSIFIED

1. Corrosion prevention
2. Steel Piling
3. Cathodic protection
4. Concrete jackets
5. Protective coatings

I. Title
II. Watkins, L. L.

The report, based on a survey of literature, assembles much of the current knowledge concerning corrosion and protection of steel piling in seawater. Causes of corrosion and effects of environmental conditions are presented. Results of tests on protective coatings for steel are included. Corrosion rates of bare steel piles and the factors involved in the use of cathodic protection and concrete jackets are explained. References surveyed show that flame-sprayed zinc sealed with vinyl is possibly the best coating system tested. More data is needed from which to determine the most economical method of protecting steel piling in seawater.

U. S. ARMY COASTAL ENGRG RESEARCH CENTER, CE
WASHINGTON, D. C. 20016

CORROSION AND PROTECTION OF STEEL PILING IN SEAWATER by L. L. Watkins. 99 pp. including 16 Figures and 2 Appendixes. May 1969

TECHNICAL MEMORANDUM No. 27 UNCLASSIFIED

1. Corrosion prevention
2. Steel Piling
3. Cathodic protection
4. Concrete jackets
5. Protective coatings

I. Title
II. Watkins, L. L.

The report, based on a survey of literature, assembles much of the current knowledge concerning corrosion and protection of steel piling in seawater. Causes of corrosion and effects of environmental conditions are presented. Results of tests on protective coatings for steel are included. Corrosion rates of bare steel piles and the factors involved in the use of cathodic protection and concrete jackets are explained. References surveyed show that flame-sprayed zinc sealed with vinyl is possibly the best coating system tested. More data is needed from which to determine the most economical method of protecting steel piling in seawater.

U. S. ARMY COASTAL ENGRG RESEARCH CENTER, CE
WASHINGTON, D. C. 20016

CORROSION AND PROTECTION OF STEEL PILING IN SEAWATER by L. L. Watkins. 99 pp. including 16 Figures and 2 Appendixes. May 1969

TECHNICAL MEMORANDUM No. 27 UNCLASSIFIED

1. Corrosion prevention
2. Steel Piling
3. Cathodic protection
4. Concrete jackets
5. Protective coatings

I. Title
II. Watkins, L. L.

The report, based on a survey of literature, assembles much of the current knowledge concerning corrosion and protection of steel piling in seawater. Causes of corrosion and effects of environmental conditions are presented. Results of tests on protective coatings for steel are included. Corrosion rates of bare steel piles and the factors involved in the use of cathodic protection and concrete jackets are explained. References surveyed show that flame-sprayed zinc sealed with vinyl is possibly the best coating system tested. More data is needed from which to determine the most economical method of protecting steel piling in seawater.

U. S. ARMY COASTAL ENGRG RESEARCH CENTER, CE
WASHINGTON, D. C. 20016

CORROSION AND PROTECTION OF STEEL PILING IN
SEAWATER by L. L. Watkins. 99 pp. including
16 Figures and 2 Appendixes. May 1969

TECHNICAL MEMORANDUM No. 27 UNCLASSIFIED

1. Corrosion prevention
2. Steel Piling
3. Cathodic protection
4. Concrete jackets
5. Protective coatings

I. Title
II. Watkins, L. L.

The report, based on a survey of literature, assembles much of the current knowledge concerning corrosion and protection of steel piling in seawater. Causes of corrosion and effects of environmental conditions are presented. Results of tests on protective coatings for steel are included. Corrosion rates of bare steel piles and the factors involved in the use of cathodic protection and concrete jackets are explained. References surveyed show that flame-sprayed zinc sealed with vinyl is possibly the best coating system tested. More data is needed from which to determine the most economical method of protecting steel piling in seawater.

U. S. ARMY COASTAL ENGRG RESEARCH CENTER, CE
WASHINGTON, D. C. 20016

CORROSION AND PROTECTION OF STEEL PILING IN
SEAWATER by L. L. Watkins. 99 pp. including
16 Figures and 2 Appendixes. May 1969

TECHNICAL MEMORANDUM No. 27 UNCLASSIFIED

1. Corrosion prevention
2. Steel Piling
3. Cathodic protection
4. Concrete jackets
5. Protective coatings

I. Title
II. Watkins, L. L.

The report, based on a survey of literature, assembles much of the current knowledge concerning corrosion and protection of steel piling in seawater. Causes of corrosion and effects of environmental conditions are presented. Results of tests on protective coatings for steel are included. Corrosion rates of bare steel piles and the factors involved in the use of cathodic protection and concrete jackets are explained. References surveyed show that flame-sprayed zinc sealed with vinyl is possibly the best coating system tested. More data is needed from which to determine the most economical method of protecting steel piling in seawater.

U. S. ARMY COASTAL ENGRG RESEARCH CENTER, CE
WASHINGTON, D. C. 20016

CORROSION AND PROTECTION OF STEEL PILING IN
SEAWATER by L. L. Watkins. 99 pp. including
16 Figures and 2 Appendixes. May 1969

TECHNICAL MEMORANDUM No. 27 UNCLASSIFIED

1. Corrosion prevention
2. Steel Piling
3. Cathodic protection
4. Concrete jackets
5. Protective coatings

I. Title
II. Watkins, L. L.

The report, based on a survey of literature, assembles much of the current knowledge concerning corrosion and protection of steel piling in seawater. Causes of corrosion and effects of environmental conditions are presented. Results of tests on protective coatings for steel are included. Corrosion rates of bare steel piles and the factors involved in the use of cathodic protection and concrete jackets are explained. References surveyed show that flame-sprayed zinc sealed with vinyl is possibly the best coating system tested. More data is needed from which to determine the most economical method of protecting steel piling in seawater.

U. S. ARMY COASTAL ENGRG RESEARCH CENTER, CE
WASHINGTON, D. C. 20016

CORROSION AND PROTECTION OF STEEL PILING IN
SEAWATER by L. L. Watkins. 99 pp. including
16 Figures and 2 Appendixes. May 1969

TECHNICAL MEMORANDUM No. 27 UNCLASSIFIED

1. Corrosion prevention
2. Steel Piling
3. Cathodic protection
4. Concrete jackets
5. Protective coatings

I. Title
II. Watkins, L. L.

The report, based on a survey of literature, assembles much of the current knowledge concerning corrosion and protection of steel piling in seawater. Causes of corrosion and effects of environmental conditions are presented. Results of tests on protective coatings for steel are included. Corrosion rates of bare steel piles and the factors involved in the use of cathodic protection and concrete jackets are explained. References surveyed show that flame-sprayed zinc sealed with vinyl is possibly the best coating system tested. More data is needed from which to determine the most economical method of protecting steel piling in seawater.