Causes and Prevention of Marine Corrosion

by

William M. Sackinger
Geophysical Institute
University of Alaska
Fairbanks, Alaska

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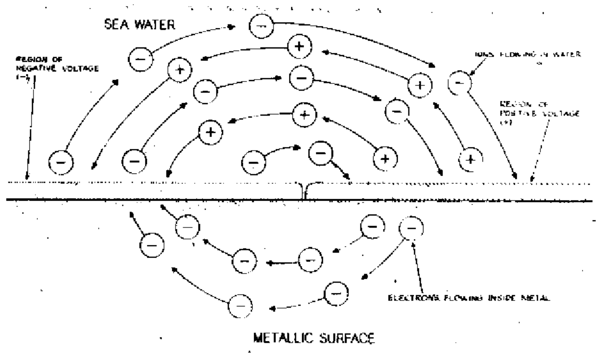

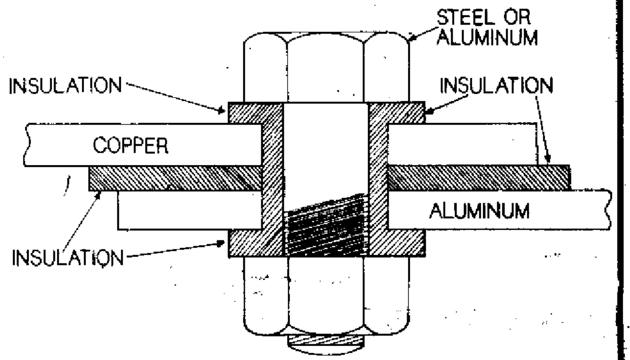

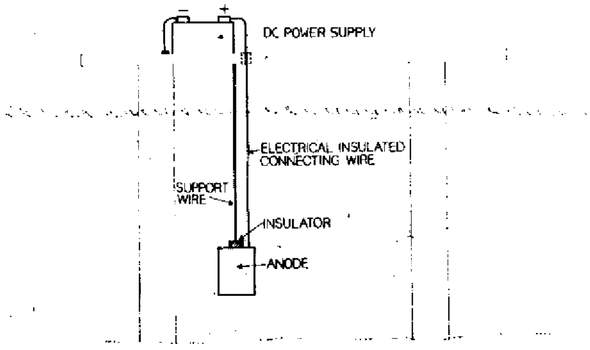

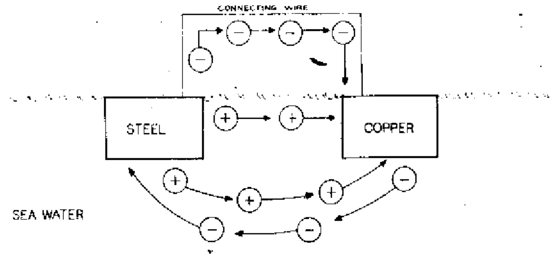

Alaska Sea Grant Program

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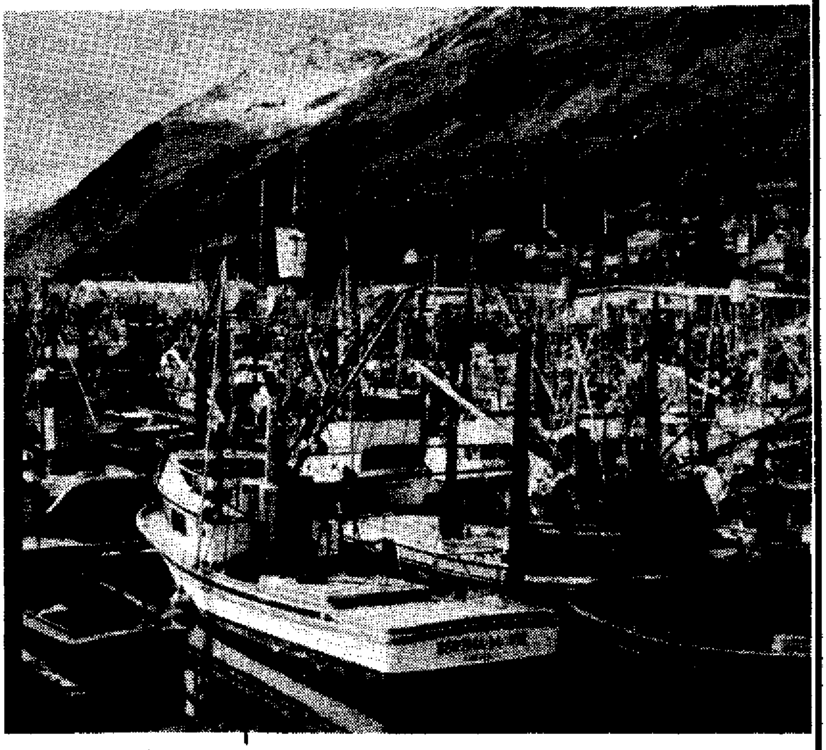
Corrosion costs the United States an estimated $ 70 billion each year, $ 14 billion of which is marine corrosion. Through the application of available technology, a major portion of these corrosion losses can be avoided. This publication explains the general principles of corrosion and its prevention. The first section discusses the chemical and electrical basis for corrosion. The section following uses those principles to explain various methods of prevention. In order to apply corrosion prevention techniques in a variety of marine situations, one must first understand the nature of the corrosion process.



The hundreds of boats docked here at Kodiak's harbor represent a multi-million dollar investment that is well worth protecting from corrosion. *Photo by Hank Pennington*

CAUSES OF CORROSION

Corrosion is usually defined as the destruction of a metallic surface by a chemical or electrochemical reaction produced by the environment. This should be distinguished from *erosion,* the physical damage of a surface by abrasive action of solid particles suspended in the water or air. Since corrosive chemical reactions involve transfer of electrical charge and movement of charged ions, it is convenient to think of corrosion in marine conditions as an electrical process acting on the surface of a metal.

With the exception of gold, platinum, and similar noble metals, all metals exist in nature in a chemically combined form, such as oxides or sulfides. These compounds are more stable than pure metals. Smelting and refining processes, which reduce metallic ore to pure metal, actually take considerable energy and result in a metallic form which is chemically less stable. Corrosion is the return of the metal to a chemically combined form as found in nature and is a natural chemical reaction. If the pure metal and oxygen are available, the result is a metallic oxide similar to the compound occuring in nature.

Adjacent regions of a metal surface have different conditions and different electrical voltages (Figure 1). These regions may be submicroscopic and the voltage difference may be a few millivolts or less. Voltage differences come about because of random variations in gas molecules, local impurity molecules on the surface, or from slight differences in surface composition of the metal from one point to another. Voltage differences can also be caused by surface stresses in the metal, by temperature differences from one location to another, by differences in oxygen concentration from one point to another, and by random variations of any sort. It is fair to say there will inevitably be random microscopic variations in some of these surface conditions, and these variations will be accompanied by voltage differences.

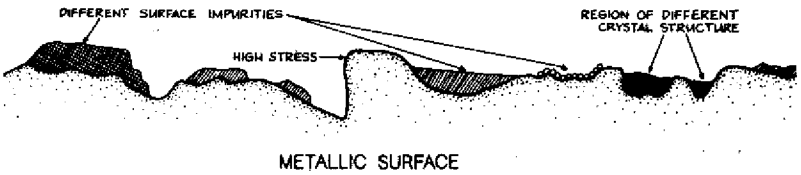


Figure 1. Random variations on a metallic surface.

Assume two parts of the surface with such a difference in voltage

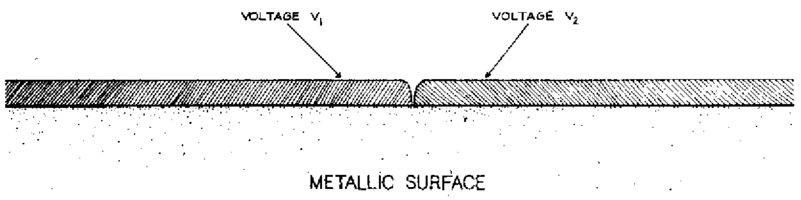


Figure 2. Simplified surface with two regions of different surface conditions having different voltages.

(Figure 2). Suppose in this example, that the voltage V_2 is more positive than V_1. Then, a miniature battery exists between the two regions. If charged carriers are available, current will flow. If the metal is immersed in sea water (Figure 3) positive sodium $(Na+)$ ions and negative chlorine $(Cl-)$ ions are available. There will then be an ion current in the sea water due to both (+) and (-) ion movement, as shown, and an electron current (-) in the metal itself. The positive region of the surface is called the *ANODE*, and the negative region of the surface is called the *CATHODE*. *CORROSION OCCURS AT THE ANODE*, where the atoms of the metal iron (Fe), for example, change from neutral atoms (Fe^0) to charged ions (Fe^{++}) which can enter the water and participate in the current flow. All metal ions do not usually make their way through the water to the cathode, but other natural ions in the sea water, such as sodium, calcium, and magnesium ions, do arrive at the cathode and form a complex chemical coating. Meanwhile, metal is being removed at the anode, and its corrosion continues.

After a limited period of time, metal removal at the anode will change surface conditions there, causing a different voltage. The deposition of other ions from the water on to the surface at the cathode will change the surface conditions there, resulting in a different voltage. This is continuously happening at small regions all over the surface. After a time, new regions take the anode role, and other new regions, the cathode role. Some parts of the surface which were formerly cathodes become anodes and suffer corrosion. These changes in voltage can go on indefinitely and are not well understood. However, it is a fact that metals immersed in sea water will have general surface corrosion with random pitting as well as overall corrosion.

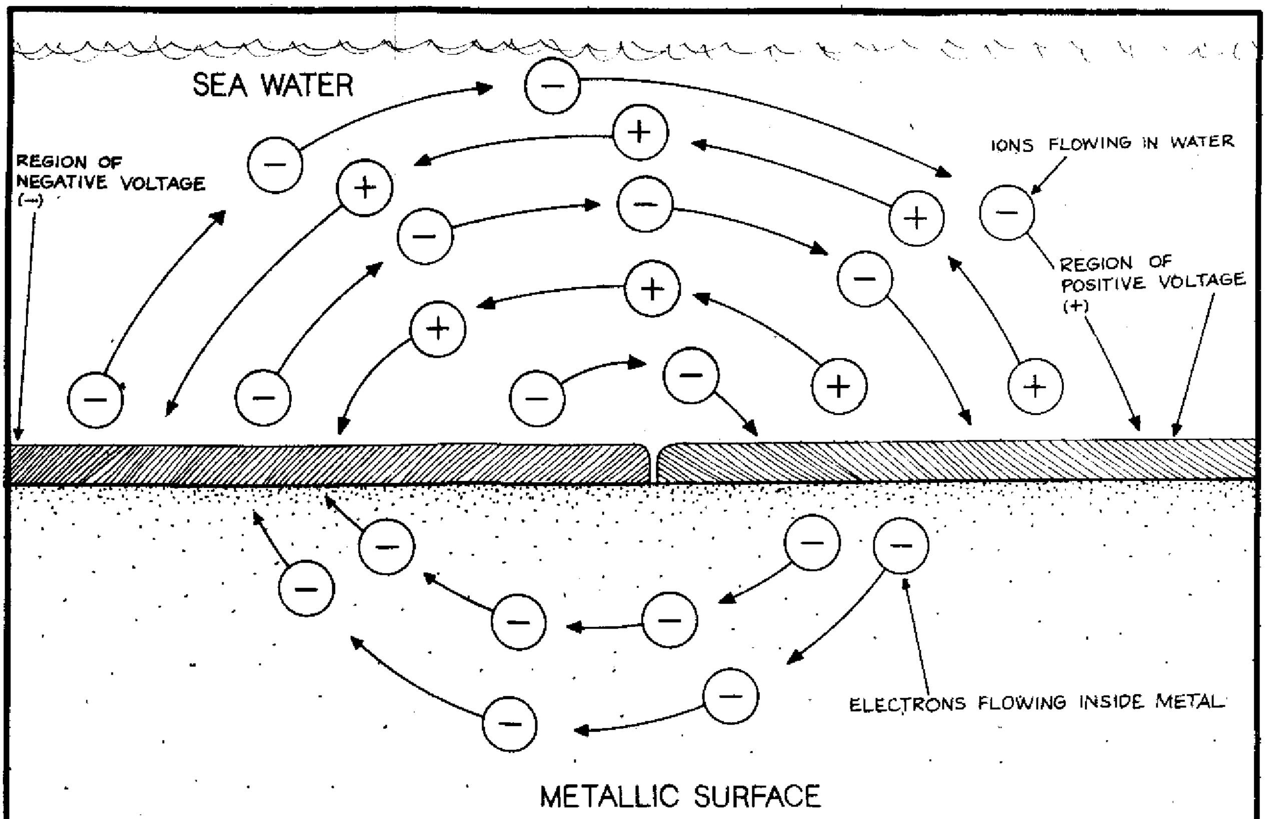


Figure 3. Ionic currents flowing in sea water; electron currents flowing within the metal.

The voltage between two metals differs greatly in comparison with voltage differences on one metallic surface. In Figure 4, corrosion currents exist between two different metals connected by a wire and immersed in sea water. For the example of steel and copper, steel is more positive and becomes the anode, while the copper is the cathode. The voltage between them is approximately 785 millivolts. The steel continues to corrode until it disappears.

Whenever any pair of dissimilar metals are connected, rapid corrosion must be expected because of their voltage differences. Table 1 gives the chemical order of positiveness associated with common metals in sea water. The more positive metal will be the anode. If two metals from separate lines in Table 1 are electrically connected and exposed to sea water (or even a thin moisture film in the atmosphere), corrosion of the more anodic (the more positive) metal is to be expected.

TABLE 1

Galvanic Series of Metals and Alloys in Sea Water

Positive (Anodic)

- **Magnesium and Magnesium alloys**
- **Zinc**
- **Aluminum**
- **Cadmium**
- **Aluminum alloys**
- **Iron, Steels, Cast Iron**
- **Active Stainless Steels (18/8)**
- **Lead, Tin, and Tin-lead solders**
- **Naval brass, 60/40 Brass**
- **Nickel and high-nickel alloys**
- **Copper, Admiralty and 70/30 Brass**
- **70/30 Cupro-nickels, Copper-nickel-iron alloys**
- **Silver solders**
- **Nickels and high-nickel alloys (passive)**
- **Passive Stainless Steels (18/8)**
- **Titanium**
- **Silver**
- **Platinum, Gold, (Graphite)**

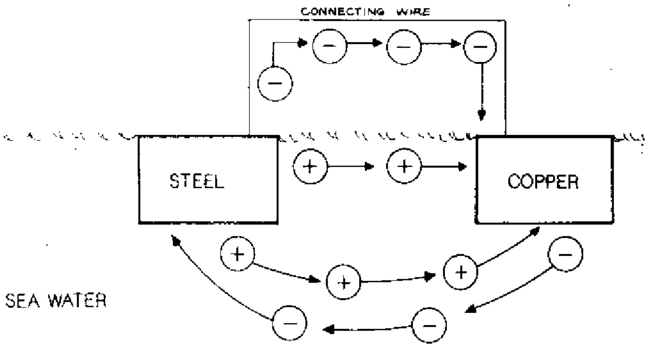


Figure 4. Corrosion of two different metals when connected electrically and immersed in sea water.

In calm seas, the dissolved oxygen concentration is higher near the surface, and at great depth there is much less oxygen available. If a metal is left for an extended period of time at great depth, the rate of corrosion will be limited at the cathode areas by available oxygen, and less overall corrosion would be expected than near the ocean surface. However, in the North Sea and other regions of the world with frequent storms and high seas, the resulting vertical mixing of the water keeps dissolved oxygen concentrations nearly uniform with depth. Furthermore, the colder water temperature permits more oxygen to be dissolved in the water. Anode-cathode corrosion cells are not limited by oxygen supply at the cathode and thus corrosion proceeds more rapidly in northern seas.

A more complicated type of corrosion is that associated with metal under high stress. This stress-corrosion effect causes cracking in regions of tension. The amount of time necessary for a cracking failure varies from one situation to another, for reasons that are not well understood. As a general rule, stress-corrosion cracking begins with the formation of microscopic cracks or defects on the surface. These cracks are selectively deepened

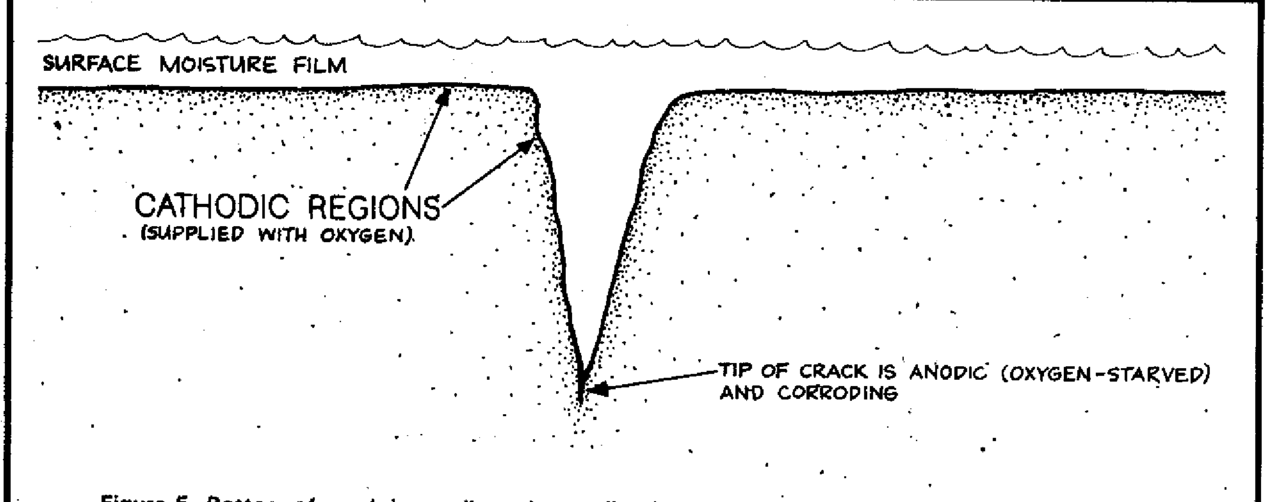


Figure 5. Bottom of crack is anodic and corroding because of a lack of dissolved oxygen there.

by the corrosion process. The most commonly used construction metals do not suffer stress-corrosion cracking in cold sea water.

Many factors can cause a voltage difference on two parts of the same metal. The most common condition is a difference in dissolved oxygen in the water between places on the metal surface. A common chemical reaction at the cathode is:

$$O_2 + 2H_2O + 4e^- \rightarrow 4(OH)^-$$

In this reaction, neutral oxygen atoms dissolved in the water combine with water and available electrons at the cathode to form negative hydroxyl (OH^-) ions. In locations where atmospheric oxygen cannot replace the dissolved oxygen as it is used, the region becomes anodic. For example, a crack or crevice in the surface of steel will usually be anodic at the bottom (Figure 5), because atmospheric oxygen is not readily available. As a result, the bottom of a crack or pit will corrode and the pit will grow deeper. This explains why pits and crevices corrode more rapidly than surrounding surfaces.

It is possible to limit corrosion rates by having a very low dissolved oxygen concentration everywhere; in closed cooling systems for boilers and power plants, oxygen scavengers are used to remove traces of dissolved oxygen. In the open conditions of marine operations this is usually not possible. Crevices under bolt heads or in threaded joints can corrode quickly because dissolved oxygen is less available there. A layer of loose paint or a layer of marine fouling can reduce the dissolved oxygen concentration beneath, allowing rapid corrosion. Mill-scale on steel, if not removed prior to painting, can cause pitting in seawater at rates as high as 0.25 inches per year (ipy). The mill-scale is a barrier to metal dissolution, and corrosion is therefore initially concentrated at breaks in the scale (Figure 6).

Biological fouling is perhaps the most important factor in limiting corrosion in temperate waters. The detailed chemistry and the dissolved gases at the boundary between the metal and the fouling organisms have not been determined, so the reasons for this are not well understood.

In many practical cases, such as anchor chains and cables, the stress on metal surfaces is cyclic,

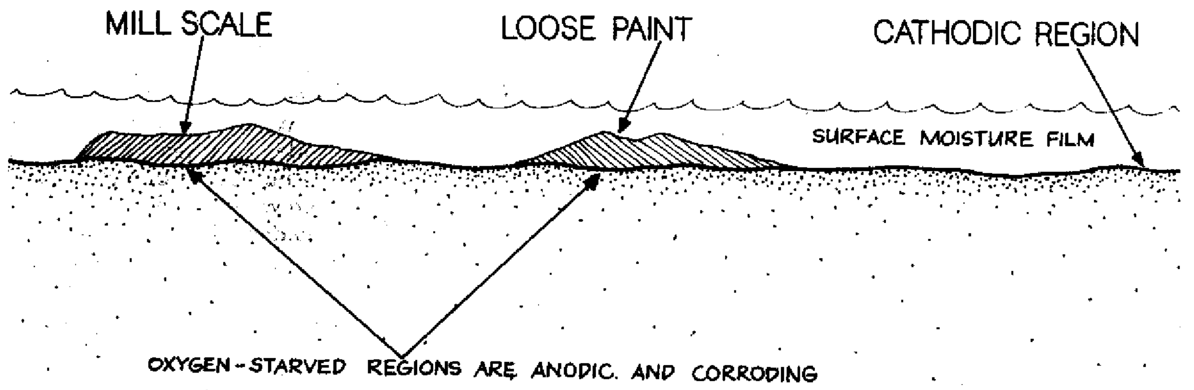


Figure 6. Regions under loose paint and mill scale are anodic and corroding because of a lack of dissolved oxygen

causing a gradual modification of the granular structure within the metal over millions of cycles. Metal-fatigue cracking occurs then, regardless of corrosion. When corrosion is present, it can reduce the expected useful life of equipment by a factor of 10 to 1,000 depending on the metal, stress and corrosion rates involved. This complicated problem in metallurgy is just now being investigated.

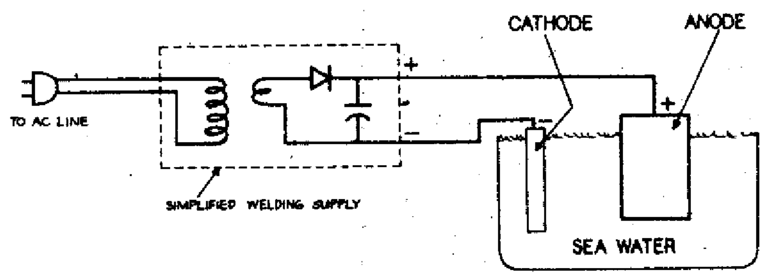


Figure 7. A DC voltage causes polarization and corrosion of the anode.

Microscopic bacteria can cause corrosion in sea water environments in several ways. In some cases, a layer of slime can contain bacterial colonies which will consume oxygen and cause a low oxygen concentration at the metal. As described above, the metal then becomes anodic and corrodes rapidly. These bacteria may also produce corrosive substances such as hydrogen sulfide, carbon dioxide, ammonia or acids as part of their metabolic cycle. Such substances enter into direct chemical reactions which corrode most metals. Damage to copper alloys caused by hydrogen sulfide from putrid water in idle cooling water systems (or polluted harbors) is perhaps the most common example of this.

A special class of bacteria, anaerobic bacteria, can exist in regions completely free of oxygen. These anaerobic bacteria live by reducing available sulfate ions to sulfides, a reaction in which iron, for example, can directly participate:

$$4Fe + 4H_2O + SO_4^{=} \rightarrow 3Fe(OH)_2 + FeS + 2(OH)^-$$

Neutral iron (Fe) is combined with water and sulfate ions ($SO_4^{=}$) to form iron hydroxide and iron sulfide (as corrosion products). This type of reaction is important in a region abundant in sulfates, such as polluted waters, but has also been observed in sea floor sediments and under layers of marine fouling on harbor structures. Higher temperature accelerates bacterial growth of all kinds and the corrosion which results from it.

In harbors, excessive corrosion is sometimes caused by incorrect grounding of shore-based electrical systems which are used to supply DC or AC power to a ship. The problem is related to the voltage difference between the ship and the shore-based electrical system.

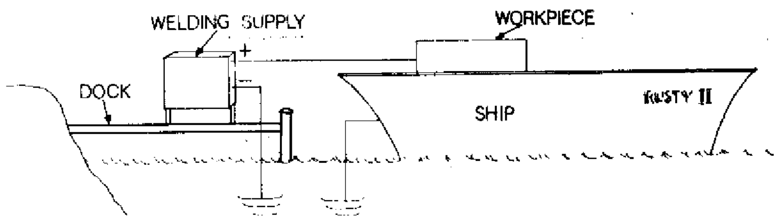


Figure 8. *INCORRECT* connection of welder to ship with both ship and welder grounded to the sea. Ship hull becomes anodic and corrodes rapidly.

A voltage difference produced by a DC power system can act just like a voltage difference from dissimilar metals. The more positive electrode becomes the anode, which corrodes (Figure 7). A DC welding generator can produce currents which are thousands of times larger than natural corrosion currents, creating serious corrosion in a short time if the ship (or any other metallic part immersed in the water) is allowed to be the anode in a sea water electrical ground return circuit (Figure 8). Even when AC electrical power is provided from a shore-based generator, there can be slight DC levels which lead to corrosion. If the sea water is used as an AC return, then during half of the AC cycle, the ship is anodic and corrosion occurs. During the other half of the AC cycle, the reverse polarity does not necessarily restore the lost metal back to its original surface. Ions from the sea are intermingled with it and net corrosion results. The safest rule is to provide insulated electrical cables for *all* ship-to-shore power connections. This is detailed in a later section of this paper.

For decades it has been known that corrosion of ships' hulls is greater when the ships are underway than when they are in port for extended periods. Several factors, such as marine fouling or polluted harbor waters could be responsible, but observation of accelerated corrosion on ship propellors and small orifices in piping systems has established that increased water velocity causes additional corrosion.

The corrosion part of this problem can be reduced with special materials for critical components like propellors, but the mechanical damage problem can only be partially solved with materials having high tensile strength and hardness. Complex alloys of cobalt, chromium, and tungsten ("stellites") have a high resistance to mechanical damage by cavitation, but are expensive for many uses. A better solution is often to modify designs to reduce velocity below the level where cavitation takes place; this is a special design problem for each instance. Fortunately, corrosion associated with fast-moving surfaces like propellors can be prevented with ordinary cathodic protection, the same used for other submerged surfaces. The section below, is a comprehensive survey of the methods available for corrosion prevention.

Corrosion of mild steel will increase with velocity, but steel is quite resistent to local turbulence attack. The latter phenomenon is more common in copper alloys. One explanation is that water movement erodes away any thin protective films which may form on small cathodic areas. At the same time, dissolved oxygen is usually supplied to corroding areas by the flow of water. Hence, a clean, active surface is exposed to aerated water and the conditions for corrosion are maximized. This type of attack can occur at speeds as low as 3 feet per second, and is even more severe if air bubbles are entrained in the water and strike the corroding surface. In heat exchangers cooled by sea water, the high velocity in constricted regions of the pipes can lead to a rapid pitting inside the pipes. Some alloys are more resistant to moving sea water. Table 2 is a rough guide to threshold velocities for this type of corrosion. The most resistant material is titanium, but less expensive alloys that form protective surface films (like stainless steels) can also be used. The other remedy for this type of attack is to design the system to avoid high velocities, possibly by enlarging orifices and pipes.

A similar type of corrosion is related to cavitation. If a rapidly moving surface (such as the tip of a propellor) increases pressure in a liquid then there will be parts of the surface with very low pressure. When the pressure is low enough, the liquid "boils" locally and a small pocket of vapor is formed for an instant. When this vapor pocket collapses, there is an immediate pulse of pressure which may be higher than 100,000 pounds per square inch at that location. This cavitation effect can clearly form pits, causing mechanical surface damage. The fresh, clean surface can then corrode rapidly, at a rate accelerated by the water moving past it.

CORROSION PREVENTION

Human and economic losses can be avoided by corrosion prevention. The cost of replacing a corroded component is not the only cost to be considered; the major cost in a productive ship or harbor system is the idle time during repair. Corrosion control often provides the opportunity to reduce maintenance costs, with an increase in initial capital expense. In a time of inflation, a capital investment in corrosion prevention can be attractive from an accounting standpoint. On the other hand, there is little reason to prolong the life of a ship or harbor structure beyond the point where it becomes technologically obsolete and unused. A balance must be achieved between expected useful life, maintenance expense and initial capital outlay, such that the economic costs, expressed in terms of constant dollars and present value, will be minimal. With this broad goal in mind, one can examine the technology available to prevent corrosion in the marine environment.

For surfaces in direct contact with liquids, one must distinguish between closed systems (such as boilers) and open systems (such as a ship's hull). Chemical inhibitors can be added to the closed systems in economical quantities to prevent internal cor-

TABLE 2

Approximate Threshold Values for Water Velocity Corrosion for Different Materials

Material	Threshold Water Velocity (ft/sec)
All low-alloy steels	0
Beryllium Copper	10
Other Copper	3-4
Admiralty Brass	5-6
Aluminum Brass	8
Naval Brass (wrought)	7-8
70/30 Cupro-nickel	15
Copper-Nickel-Iron Alloys	6(5% Ni)
High tin gunmetals	20
Stainless Steels	30
Titanium	Immune to corrosion
Phosphor Bronze	20

rosion. Basic water-soluble amines, such as morpholine or cyclohexylamine are sometimes added to neutralize the acidity from carbon dioxide. Octadecylamine and hexadecylamine can be added, in concentrations of 15 to 30 parts per million, to form water-repellent films on condensing surfaces in closed systems. Many inhibitors are effective only when optimum concentration is maintained and can cause chemical attack of the metals if concentrations are too low or too high. Some examples are sodium and potassium chromates, nitrites, phosphates, carbonates, benzoates, and silicates. These chemicals inhibit either the cathodic reaction or the anodic reaction; most of the compounds above prevent the anodic reaction. Sometimes the term "passivate" is used to indicate a surface chemical condition which prevents the anodic reaction. In boilers using fresh water as working fluid, additives are used to reduce the dissolved oxygen concentration or to increase the pH of the solutions to 11 or above, a value at which corrosion of iron and steel proceeds very slowly.

With open sea water exposure, however, the choice of proper materials and structural shapes is a major one in preventing marine corrosion. From Table 2, it is clear that titanium is immune to corrosion in sea water, as are the noble metals. For small fixtures and critical parts, where corrosion could lead to serious damage, gold electroplating can be cost-effective. For larger parts which are in standard forms such as sheets, tubes, and simple shapes, modern developments in the fabrication of titanium have led to relatively low cost and quick delivery. Castings and complex machined parts are generally not available in titanium however, so the more traditional materials must be used. If there is no flow of water past the metal surface, then copper and copper/nickel alloys (90/10 and 70/30) will withstand corrosion. A moderate water velocity causes corrosion to proceed (Table 2).

Generally speaking, all other common metals and alloys will suffer corrosion in sea water. The various forms of brass (copper/zinc alloys) will corrode unless cathodically protected. Bronze (copper/tin) alloys corrode at a slower rate as the percentage content of tin is increased. The aluminum bronze alloys (copper/aluminum) have excellent resistance to corrosion, as do the more complex nickel-aluminum bronzes, and aluminum-silicon bronzes.

Copper/nickel and copper/nickel/iron alloys corrode only very slowly and are often used for equipment in contact with sea water for extended periods. The Monel metals (70/30 nickel/copper) have a very high resistance to corrosion, particularly in highly aerated, fast-moving sea water. They may pit in areas that are stagnant or shielded since they rely upon an oxide layer at the surface for their protection, and adequate oxygen must be present. For many conditions in marine service the stainless steels (18/8 or 300 series) are subject to severe pitting to depths of as much as .050 inches per year in calm sea water. Their resistance to corrosion depends upon the thin passive surface oxide film and adequate dissolved oxygen must be present. Crevices are especially subject to attack, but stainless steel is well-protected when it is in physical contact with mild steel or another more anodic metal.

The use of non-metallic materials is possible in many cases. Plastics, (in some cases reinforced with fiberglas), are also replacing metal wherever strength considerations permit.

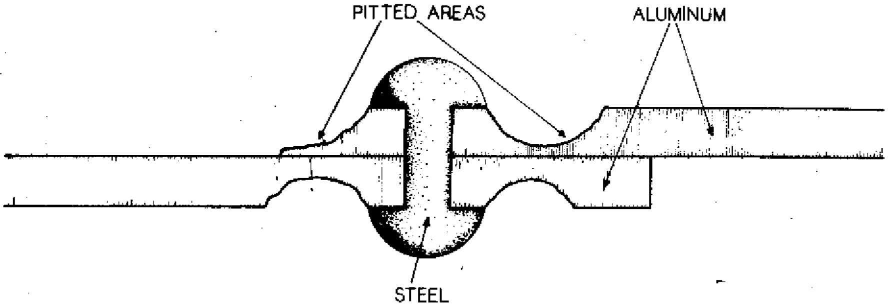


Figure 9a. Example of poor joining practice which causes corrosion due to the corrosion cell between dissimilar metals.

If dissimilar metals are used and electrically connected, then a corrosion cell will be formed. Steel is found in those parts of ships and marine structures exposed to sea water and is often connected mechanically to other metals. Special insulator designs can be used in some cases to allow two dissimilar metals to be mechanically connected but electrically isolated. An example of a riveted joint which includes a corrosion cell is shown in Figure 9a. Figure 9b shows a bolted joint properly insulated to prevent corrosion. When insulated sections are not possible because of the mechanical stresses in the joints, the first alternative is to apply an insulating layer over the joint to prevent access by sea water and to increase the distance between anode and cathode.

The use of marine paints and coatings to prevent corrosion has been common practice for centuries. It has always achieved a modest degree of success, but has fallen short of perfection because of small defects or "pinholes" in the coatings. Such defects are usually caused by evaporation of the solvent which is put into the paint to make possible its application. The subject of marine paints and coatings is a very broad one and cannot be adequately treated here. However, it is safe to say that paints without solvents, such as epoxy paints, are relatively free of pinholes and defects depending upon the method of application of heat. An airless-sprayed layer applied to a properly-prepared clean surface and followed by a proper curing temperature will generally be satisfactory protection against corrosion. Mechanical abrasion, however, can remove such coatings locally and corrosion will then occur. To rely upon coatings as the sole protection against corrosion is not a wise choice, unless the coatings can be periodically renewed. The combination of paint and cathodic protection is safe and economical.

The most effective and widely-used method of marine corrosion prevention today is cathodic protection. A corrosion cell is deliberately created between a sacrifical anode and the other metal parts in contact with the sea water. The current in this cell is superimposed upon small local corrosion cells and current is injected from the sea water into the protected cathodic surfaces.

The current density required will depend upon the surface coating; bare steel normally is protected

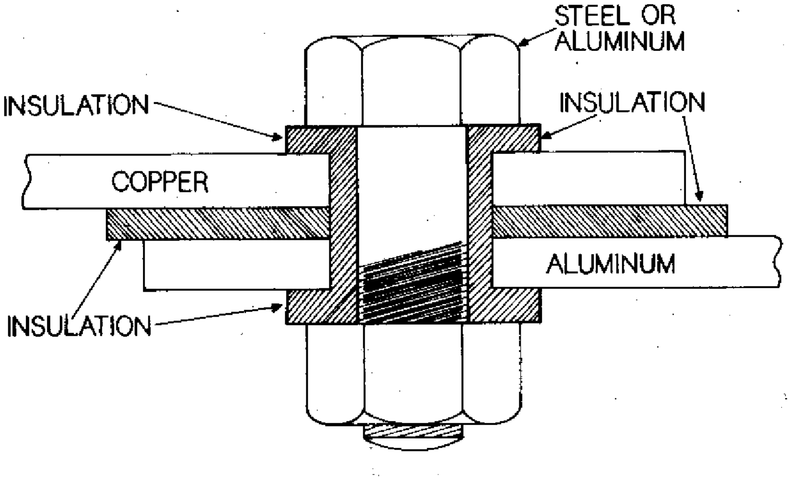


Figure 9b. A bolted joint between two dissimilar metals which is electrically insulated to prevent corrosion.

at a current density of 10 milliamperes per square foot. As soon as a protective calcareous scale has formed on the cathodic areas, only 3 mA/ft^2 may be needed. For newly-painted surfaces the current required may be 0.1 mA/ft^2 or lower. For very aggressive conditions of cold, aerated water at moderate velocity, such as Cook Inlet, Alaska, values of the order of 100 mA/ft^2 may be required. These values cannot be predicted from theoretical calculations, but must be established based upon a measurement of the potential difference between the cathodic surface and the surrounding sea water. High purity zinc or a silver/silver chloride reference cell is used to measure potential. A cathode potential of -0.75 volts with respect to the silver/silver chloride cell is the minimum value for adequate protection; in practice, -.80 volts to -.85 volts are used. This corresponds to .22 to .25 volts when measured with reference to the high-purity zinc. Self-contained, portable measurement devices are now available commercially and used by divers to make corrosion surveys.

The conductivity of sea water is great enough that the voltage drop mentioned is primarily in the interface layer coating the ship or structure. This layer is a combination of calcareous coatings and marine fouling. If it is continually removed by scouring of sea ice or silty water, a larger protective current density will be needed — about 100 mA/ft^2.

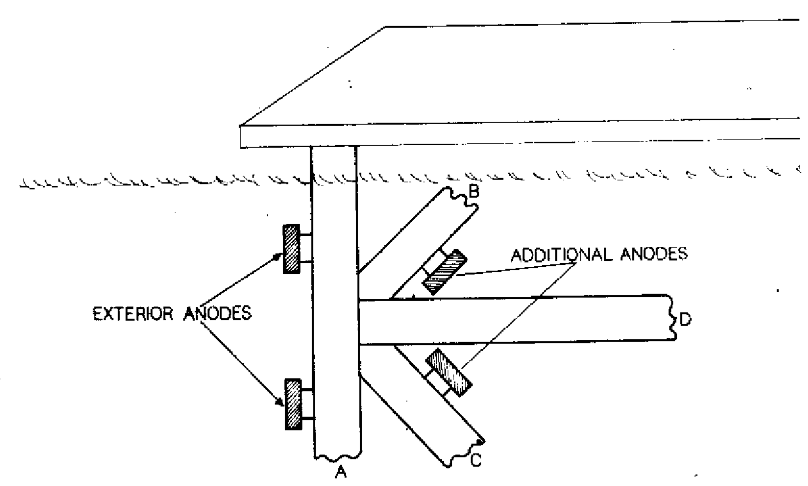


Figure 10. Cathodic protection of recessed areas with adjacent sacrificial anodes.

Placement of sacrificial anodes at regular intervals along a structure is important especially on those having recesses and complicated shapes. An approximate but oversimplified rule of thumb for proper placement of sacrificial anodes relies upon the analogy of a light source illuminating the structure. Placing the light source at certain points would illuminate the structure uniformly. If the sacrificial anodes are placed in the same positions as those imagined light sources, uniform cathodic protection will occur. Assume an offshore structure with sacrifical anodes mounted on the outside of the legs (Figure 10). However, the interior of the node formed at the junction of the tubular members (B-C-D) is not illuminated directly by the exterior anodes and may be inadequately protected. Additional anodes placed near the interior of the junction are a possible solution to the problem. Detailed calculations and surveys have shown that the current does go around corners and edges to a larger extent than this analogy indicates, giving an extra margin of confidence in this approach.

In another example, a shielded region is formed within steel pilings supporting a dock (Figure 11). Anodes should be placed outside and inside this dock, located flush with the edge of the dock to prevent mechanical damage to anodes by nearby ships. In order for an anode to protect adjacent steel pilings, all pilings should be electrically connected.

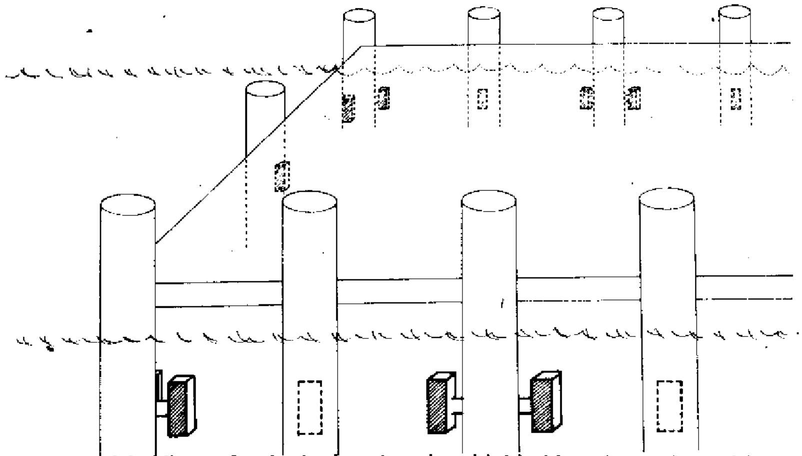


Figure 11. View of a dock showing the shielded interior region with sacrificial anodes on *both exterior and interior*. Steel pilings should be electrically connected.

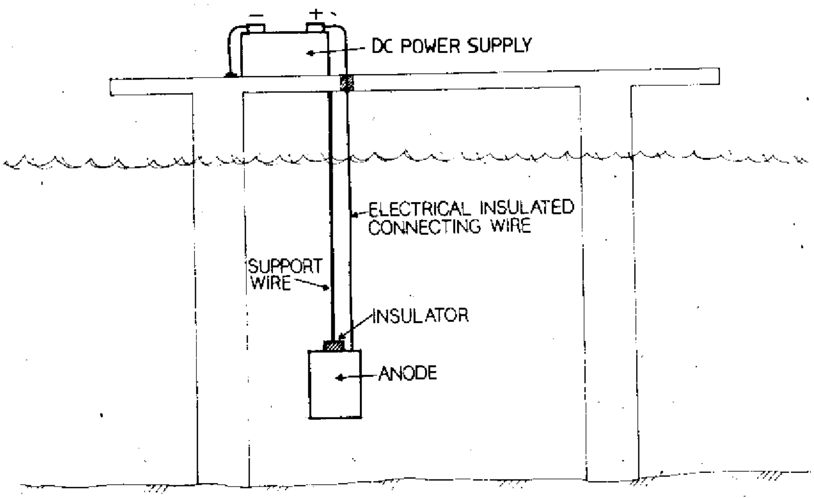


Figure 12. Suspended impressed-current electrodes for cathodic protection of a dock.

The two most common materials for sacrificial anodes are zinc alloys and aluminum alloys. The advantage of using sacrificial anodes to prevent corrosion is that protection can be built into the structure permanently. That protection can be expected to last for the useful life of the structure.

On the other hand, there are problems with sacrificial anodes, including instances of inadequate protection after installation. For offshore structures in deep water, the weight of sacrificial anodes can be a factor, contributing heavily to structural loading. Protruding anodes on docks are dangerous to ships and led to development of flush placement. Ships which travel in waters of varying characteristics require flexibility in voltage protection, and more frequently use an impressed-current corrosion protection system.

Impressed-current systems are also used on coastal and offshore structures (Figure 12). An adjustable DC power supply provides low-voltage (high-current) protection, since it is connected between the steel members of the dock and the anodes, which are gradually consumed. Since the voltage is controllable, any convenient material can be used for the anodes.

Recent development of platinized titanium and platinized niobium have led to long anode lives, but lead/silver and other materials are frequently used with good results. If steel anodes are used, they are consumed at a rate of about 20 pounds per ampere-year. Silicon-iron and graphite have been successfully used, but both are brittle and susceptible to mechanical damage.

The proper voltage for adequate protection of steel is about -0.85 volts when using a silver/silver chloride anode. For aluminum adequate protection is achieved at approximately -0.98 volts. If the voltage of the anode is increased significantly beyond this value, hydrogen gas is produced at the cathode. Hydrogen gas can lead to brittleness in the steel of the cathode. It can also remove paints and other protective surface coatings. Its presence interferes with uniformity of current flow into the cathode. Therefore, it is important to con-

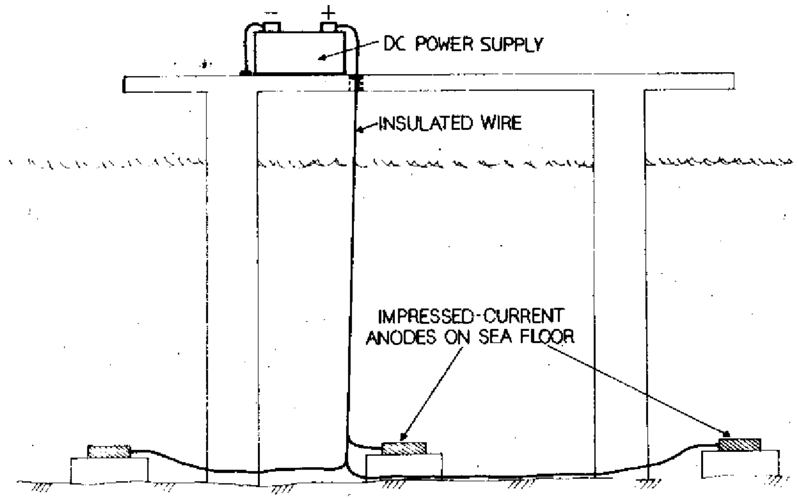


Figure 13. Impressed-current electrodes placed on sleds located on sea floor.

trol the voltage applied to the impressed-current anode carefully, keeping it between the mentioned limits. In some cases, it is difficult to control all parts of the cathode surface. Parts which are very close to the anode have a higher voltage and more current than those further away.

Dielectric shield coatings on the cathode near the anode have been used to prevent excessive hydrogen evolution, but the best solution is to place impressed current anodes away from steel to be protected (Figure 13). The electrodes are placed on sleds on the sea floor some distance from the structure. A classic method, now obsolete, for ship protection is to tow a long wire behind the ship as an anode (Figure 14). Flush mounted electrodes are also used on ships, and dielectric shielding is then necessary.

The advantages and disadvantages of the sacrificial anode method compared with the impressed-current approach are listed below (after F.L. LaQue):

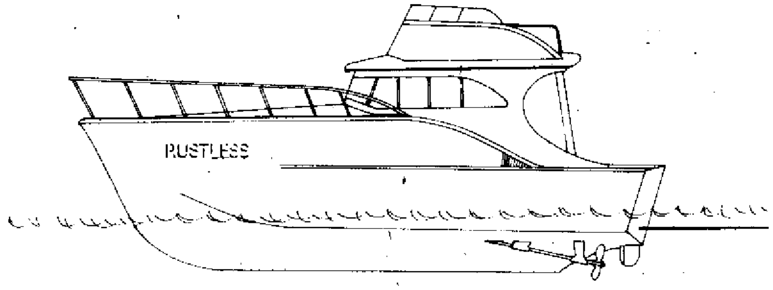


Figure 14. Impressed-current corrosion protection of a ship underway with a trailing anode wire.

Sacrificial Anodes

Advantages

1. Does not require electric power
2. No initial outlay for power equipment
3. Little supervision required
4. Current cannot be supplied in the wrong direction
5. Simple installation
6. Cathodically protected anode leads

Disadvantages

1. Available current depends on anode area, implying large electrodes for large ships
2. Energy stored in refined anodes is expensive
3. In large arrays, high current requires large connecting wires

Impressed Current Systems

Advantages

1. Protection current can be increased to necessary level
2. Smaller diameter leads, because voltage drops in lead wires can be compensated by power supply

Disadvantages

1. Requires continuous DC power
2. Possibility of connection with wrong polarity
3. Trained supervisory personnel required
4. Anode leads have to be insulated and waterproofed to prevent their corrosion
5. Depending on geometry, current shields may be needed
6. Possibility of damage to coatings, and hydrogen embrittlement from overvoltages.

Most small boats have a DC electrical system. It is important that the negative terminal of the battery be used as 'ground'. Care must also be taken to ensure that specific low-resistance electrical connections be made between the negative battery terminal and all metallic parts of the boat that are exposed to sea water. With this common connection, either a sacrificial or an impressed-current system of cathodic protection can be used. If fact, a dual or a combination system could be used (Figure 15), where a sacrificial anode is available to provide protection when the boat is moored and the ignition switch is turned off. A redundant approach includes the advantages of both systems.

The protection of several ships in a harbor is best done by connecting all the ships through a low resistance wire to a negative terminal on the dock. The necessary cathodic protection may be supplied from an anode at the dock. If supplied from one of the ships, current will automatically be shared with adjacent ships, protecting them as well. If several ships are moored and their adjustable voltage sources are active, peculiar effects could arise as their voltage sources are coupled through adjacent sea water contact. For this reason, a single set of protective anodes from a single shore-based supply voltage is preferable.

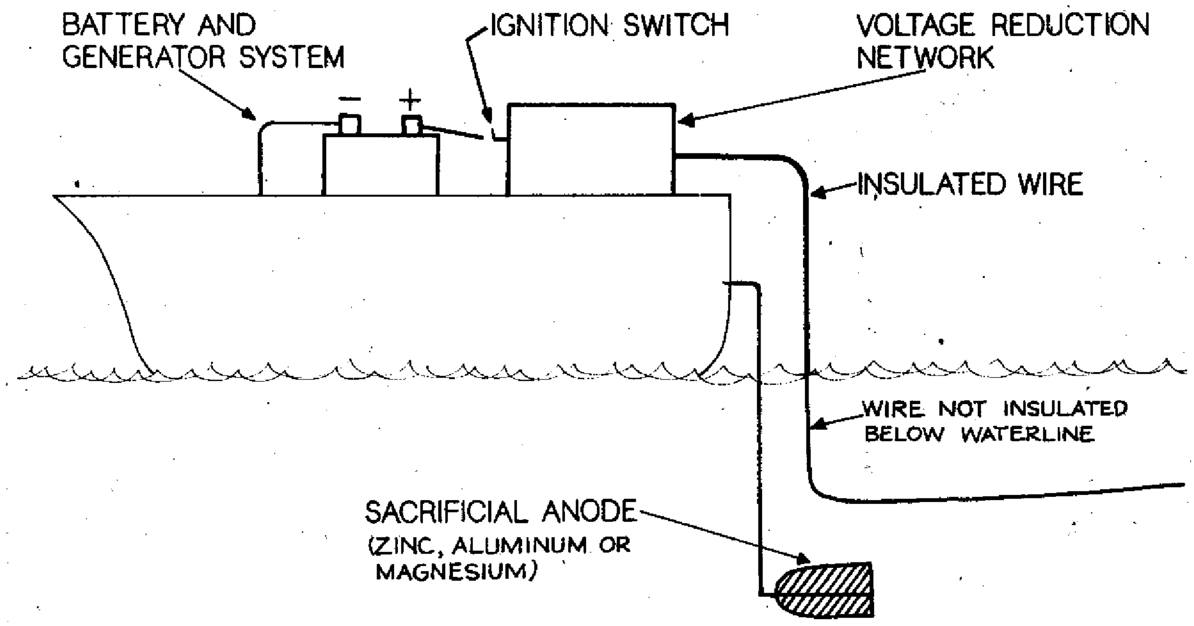


Figure 15. Example of a redundant cathodic protection approach for small boats using both sacrificial anodes and impressed current.

To generalize, the most effective ways of preventing marine corrosion are:

1. Use corrosion-resistant alloys where cost permits.
2. Electrically isolate dissimilar metals, in most cases, but also make wise use of dissimilar metal contact cathodically to protect vital small parts such as bolts, valve seals, spindles, thermometer wells, etc.
3. Apply protective insulating coatings to large areas that are exposed to sea water.
4. Install cathodic protection for all areas exposed to sea water.

With these precautions and attention to the effects of geometry, voltage differences, coatings and the effectiveness of cathodic protection, losses to marine corrosion can be avoided.

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For your information, marine advisory bulletins (MABs) on the following subjects are available through the Alaska Sea Grant Program:

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Marine Advisory Program
Bld. "H"
University of Alaska
2651 Providence Avenue
Anchorage, AK. 99504
Phone: 263-1890

John Doyle, Program Leader
John Ball, Safety Specialist
Don Kramer, Seafood Specialist
C.L. Kerns, Aquaculture Specialist

Atmautluak

Marine Advisory Program
Atmautlauk, AK 99559
Phone: Radio Station
KYUK 543-2103 and leave message

Alexi Pavilla, Agent

Kodiak

Marine Advisory Program
Pouch "K"
Kodiak, AK 99615
Phone: 486-3599

Hank Pennington, Agent

Cordova

Marine Advisory Program
P.O. Box 521
Cordova, AK 99574
Phone: 424-3446

Craig Weise, Agent

Petersburg

Marine Advisory Program
Box 1329
Petersburg, AK 99833
Phone: 772-3381

Brian Paust, Agent

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