Cathodic protection for boats in sea water: a review of recommendations
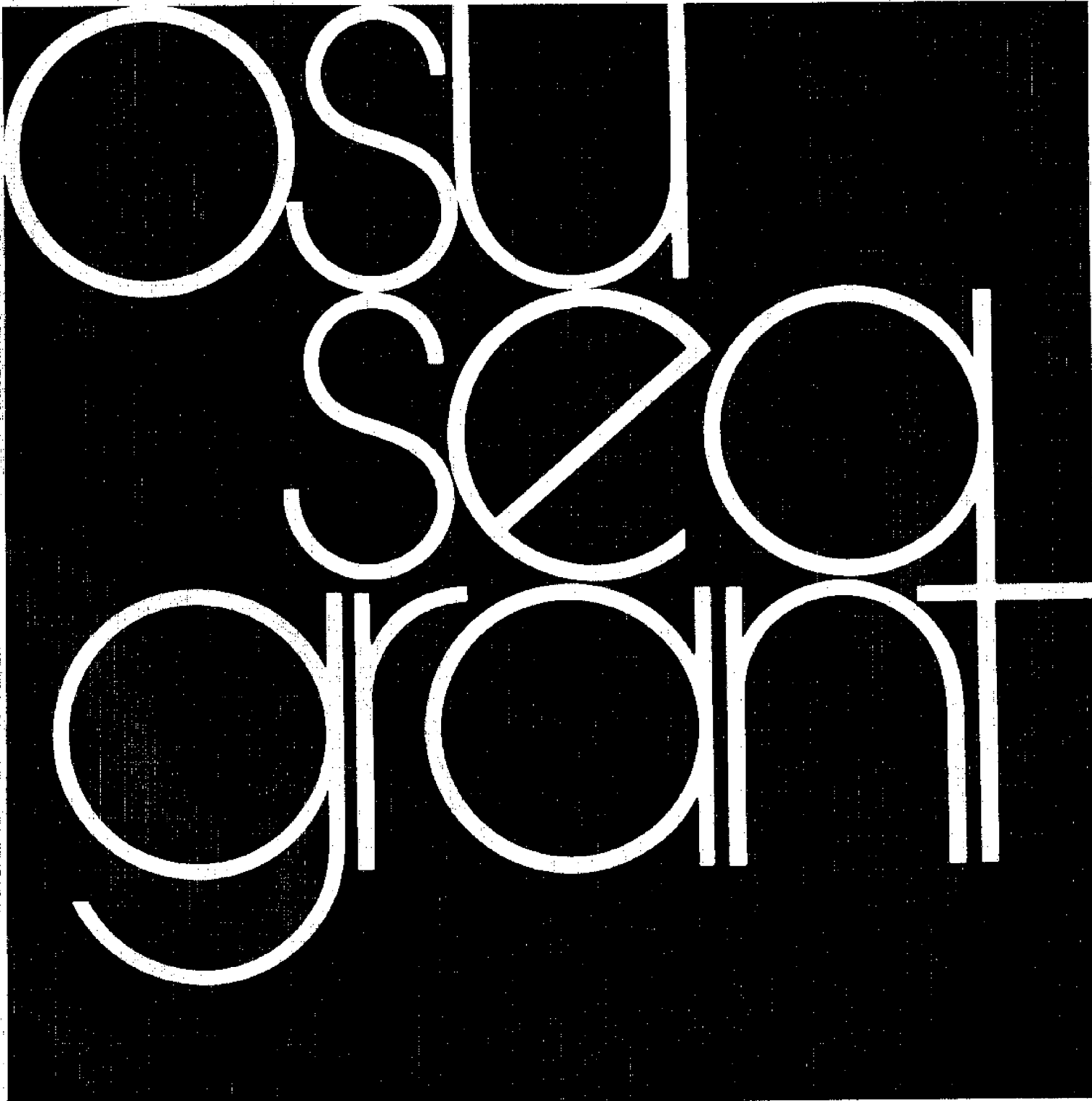
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Cathodic protection for boats in sea water: a review of recommendations

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acknowledgment

related publications

TRAWL CABLE CORROSION. Robert D. Malloch and Edward R. Kolbe. 1978. Publication no. ORESU-T-78-005. 29 pp. Price $2.50.

Results from a project which analyzed the nature of trawl cable corrosion on Oregon coastal trawlers to evaluate the feasibiltiy of corrosion control. The analysis leads to a detailed discussion of possible future experiments designed to accurately determine the amount and type of protection nedded. This report also discusses wire rope and general corrosion principles.

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contents

ABSTRACT

Two cathodic protection techniques are commonly used to control the corrosion of salt water vessels:
1) attaching sacrificial metals such as zinc;and
2) using impressed current devices which are driven from the vessel's power supply.

The advice of science and industry gained through interviews, a series of seminars, and a collection of literature is summarized in this publication. Recommendations on the application of these techniques are made. Several factors can significantly influence the success of these techniques. A few examples are: stray currents from faulty electrical systems on the boat or dock (leading to stray current corrosion), the quality and integrity of the the paint systems, types of metals and materials used, installation practices, hull materials, and water salinity.

I. INTRODUCTION

Corrosion in its many forms directly or indirectly accounts for a major portion of maintenance costs to salt water vessels. In addition, unnoticed or uncontrolled corrosion can cause the failure of critical equipment at sea.

Construction materials are selected with corrosion resistance and cost in mind. The front line of defense against damage to those materials is a good paint job. No coating is 100 percent effective, even when new. *Cathodic protection** is generally necessary to protect metals used in salt water. Paint system techniques and cathodic protection practices are interrelated but can be discussed separately. This report addresses the latter. It compiles the results of personal interviews, information gained through a series of workshops, and a study of the literature on subjects related to cathodic protection. This report is intended to be used by marine industry personnel, designers, engineers, boatyard operators, marine extension agents, and others with some scientific or technical background. The fundamental results are to be summarized in a separate extension bulletin (Mallon and Kolbe In Press).

Section I gives background information on electrical theory, electrochemistry of metals and important features of boat electrical systems; it is necessary to have some understanding of these subjects in order to understand cathodic protection.

Section II is concerned with practical aspects of corrosion control and gives recommendations to guide users in selection and installation of cathodic protection equipment.

Section III describes how other factors can affect hull protection. These include: electrical characteristics and problems, construction methods, and paint systems.

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*Terms in italics are ones that frequently appear in any discussion of corrosion and cathodic protection. Appendix B lists these terms with their definitions.

I.A. Basic Electricity and Electro-
   chemistry of Metals

Electrical *potential* or *voltage* is a
measure of potential energy per unit charge
(i.e. per electron) of a charged particle in
an electrical field. All of these terms
need not be defined or explained to under-
stand the key point: voltage is the driving
force (often likened to pressure) for flow
of charge in an electrical *circuit*.

The flow of charge induced by the presence
of a voltage difference between two points
in a circuit is called *current* and is pro-
portional to the voltage difference between
the two points. In the hydrodynamic analogy,
current is the flow rate of the fluid.
Direct current (D.C.) circuits are those in
which the current flows in one direction
only, depending on the *polarity* (which way
it is hooked up) of the voltage source.

In simple circuits, current is controlled
by *resistance* as well as voltage; resistance
is the proportionality constant between
voltage and current, and the statement of
this relationship is *Ohm's Law*: V=iR, where
V is the potential in *volts*, i is the current
in *amperes* and R is the resistance in *ohms*.
These units are defined such that one ampere
(or amp) is the current that flows through a
one ohm resistor which has a potential of one
volt impressed across it. Voltage is some-
times expressed in millivolts (mV); 1,000
mV = 1 volt. Ohm's law is generally valid
for all of a boat's electrical circuits
which affect corrosion phenomena. Resis-
tances are often called *loads* since they
draw power from the energy (or voltage)
source. The equivalent resistance of a com-
bination of resistors depends on whether
they are in series or in parallel (Fig. 1).
If in series, they add directly.

$$R_{eq} = R_1 + R_2$$

If in parallel, they add according to the
following formula,

$$R_{eq} = \frac{R_1 R_2}{R_1 + R_2}$$

where R_{eq} is the equivalent resistance of
the combination.

Power is consumed in resistive circuits
according to the formula,

$$P = i^2 R = iV = \frac{V^2}{R} .$$
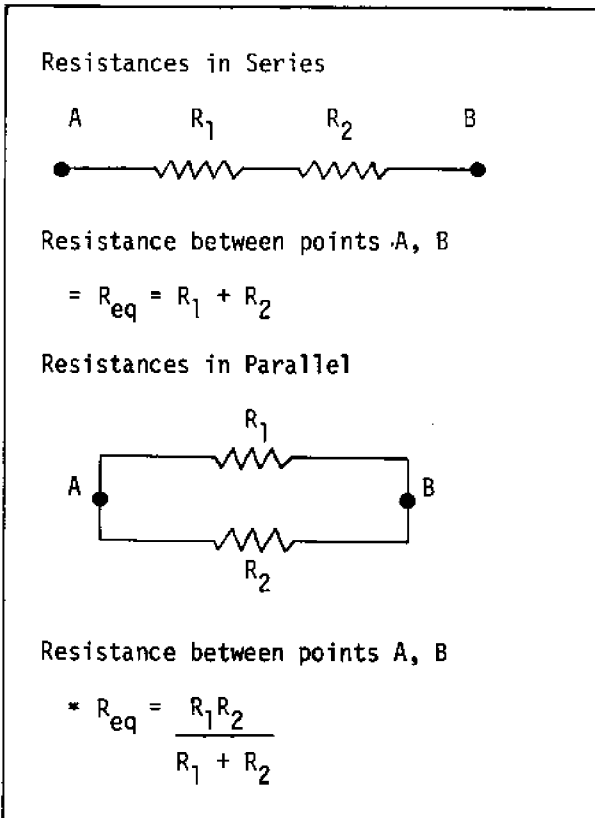
Fig. 1. Addition of circuit resistances

This power consumption is manifested as heat
unless some of it is used to do mechanical
work, such as in an electric motor.

Alternating current (A.C.) was developed
to facilitate power transmission over long
distances. A.C. voltages can be conveniently
stepped up and down using transformers; high
voltages (and thus low currents) are
necessary to cut power losses in transmission
wires. A.C. power as used on most boats
laying at the dock is a frequent source of
corrosion, as explained in section III.A.
The effect of resistances in A.C. circuits is
similar to that in D.C.; Ohm's law is still
valid. The polarity in an A.C. circuit
reverses every 1/120th of a second, making 60
cycles per second.

In corrosion processes, the sea water is
the resistance; the current flowing through
it can result from a voltage difference
between two pieces of submerged metal (such
as a propeller and a dock piling) which have
some external electrical connection. This
current, which relates to corrosion rate,
can severely damage the underwater fittings or
hull of a boat.

Corrosion is often broadly defined as the destruction or removal of a material by interaction with its environment. For the purpose of our more restrictive case of metals in sea water, corrosion may be thought of as the tendency of metals to return to their ores--the form in which they are found in nature. Ores (usually *oxides*), are more stable than their corresponding metals, since they consist of metal atoms in a positively charged state (*ions*) which are lower in energy--and hence more stable-- than the uncharged pure metal.* It takes a great deal of energy to convert ores to their metals--energy provided in smelting by high temperatures and in electrolytic reduction by electrical current.
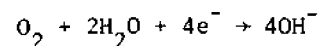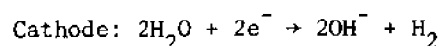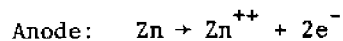
The rate at which metals corrode and reform their ores is governed by several factors, including the tendency to form "passive" layers of *oxidation* product, and the energy difference between the metal and the ore which is the *thermodynamic* driving force for the reaction. Energy differences such as those are tabulated in the *galvanic series* and manifest themselves in the electrical potential differences observed between different metals immersed in a *electrolyte* (see Fig. 2). Electrical potential is a convenient measure of energy in processes involving transfer of electrons. The potentials listed in figure 2 are referenced to a *calomel electrode*--common practice in sea water applications; use of a *silver-silver chloride electrode* will change these values by only a few millivolts. Likewise, changes in electrolyte, such as in moving from salt water to fresh water, change the voltage only slightly. Greater corrosion rates in salt water compared to fresh are due in part to the higher *conductivity* (lower resistance) of salt water which allows more current to flow.

Figure 3 shows a simplified arrangement of two dissimilar metals in sea water and the measurement of the potential difference between them. The galvanic series can be used to predict these theoretical voltage differences for any combination of metals listed. The exact voltage measured depends upon (1) the temperature, (2) the

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*The reason for this energy difference is properly explained in terms of quantum mechanics and cannot be quantitatively treated here, but it is related to the allowed configurations of electrons about the nucleus and the relative energies of these configurations.

concentration and composition of the electrolyte next to the electrode, (3) the nature of the surface of the metals, and (4) the nature of the measuring circuit. (Voltmeters with low sensitivity can cause inaccurate readings.) For this reason, the potentials listed in the galvanic series vary somewhat in practice.

If an appreciable current is allowed to flow in the circuit of figure 3, (for example by short-circuiting the two metals), several things begin to happen. Electrons begin to flow from the zinc to the copper where they are electrically attracted due to the higher (less negative) potential. For every electron freed, a zinc *ion* is simultaneously formed maintaining electrical neutrality. Since zinc ions are charged, and thus soluble in water, one atom of zinc goes into the solution as an ion. The zinc is corroded away at a rate proportional to the current. Principal electrode reactions are as follows:

$$\text{Anode:} \quad Zn \rightarrow Zn^{++} + 2e^-$$

$$\text{Cathode:} \quad 2H_2O + 2e^- \rightarrow 2OH^- + H_2$$

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

In this scheme, the electrons are transferred through the wire connecting the two metals. The *anode* is defined as the electrode at which *oxidation* or corrosion of metal takes place; *reduction*, primarily of water and oxygen to form *hydroxide* ion, (OH⁻), occurs at the *cathode*.

As positive zinc ions collect near the anode, they tend to decrease the strong negative potential of the zinc electrode (that is, make it more positive) and reduce the voltage of the galvanic cell, thus lowering the driving force for the reaction and decreasing the current in the external circuit. This effect is known as *polarization* (sometimes more specifically labeled "concentration polarization") and is an important factor in cathodic protection engineering. The effect is discussed further in section II.

To the corrosion engineer, the preceding discussion refers to a process called *galvanic action*. The reverse of this processes (one in which an externally impressed voltage is used to produce reactions at an electrode) is sometimes called *electrolysis*. For example, electrolysis is widely used commercially to plate one metal onto another (electroplating). Figure 4 shows a simplified scheme for electroplating copper onto steel. When

VOLTS: SATURATED CALOMEL HALF-CELL REFERENCE ELECTRODE

+ 0.3 + 0.2 + 0.1 0 −0.1 −0.2 −0.3 −0.4 −0.5 −0.6 −0.7 −0.8 −0.9 −1.0 −1.1 −1.2 −1.3 −1.4 −1.5 −1.6 −1.7

Magnesium

Zinc [1]

Beryllium

Aluminum Alloys [1]

Cadmium

Mild Steel Cast Iron

Low Alloy Steel

Austenitic Nickel Cast Iron

Aluminum Bronze

Naval Brass, Yellow Brass, Red Brass

Tin

Copper

Pb-Sn Solder (50/50)

Admiralty Brass, Aluminum Brass

Manganese Bronze

Silicon Bronze

Tin Bronze (G & M)

Stainless Steel — Types 410, 416

Nickel Silver

90-10 Copper-Nickel

80-20 Copper-Nickel

Stainless Steel — Type 430

Lead

70-30 Copper-Nickel

Nickel-Aluminum Bronze

Nickel-Chromium alloy 600

Silver Braze Alloys

Nickel 200

Silver

Stainless Steel—Types 302, 304, 321, 347

Nickel-Copper Alloys 400, K-500

Stainless Steel — Types 316, 317

Alloy "20" Stainless Steels, cast and wrought

Nickel-Iron-Chromium Alloy 825

Ni-Cr-Mo-Cu-Si Alloy 8

Titanium

Ni-Cr-Mo Alloy C

Platinum

Graphite

Alloys are listed in the order of the potential they exhibit in flowing sea water. Certain alloys indicated by the symbol: � in low velocity or poorly aerated water, and at shielded areas, may become active and exhibit a potential near −0.5 volts. Data is from Inco Bulletin A404, "Guidelines for Selection of Marine Materials".

[1] The metals are primarily for construction. Anode alloys may be expected to differ.

Fig. 2. Galvanic series (ref. SNAME, 1976. reprinted from report R-21, *Fundamentals of Cathodic Protection for Marine Service*, The Society of Naval Architects and Marine Engineers)
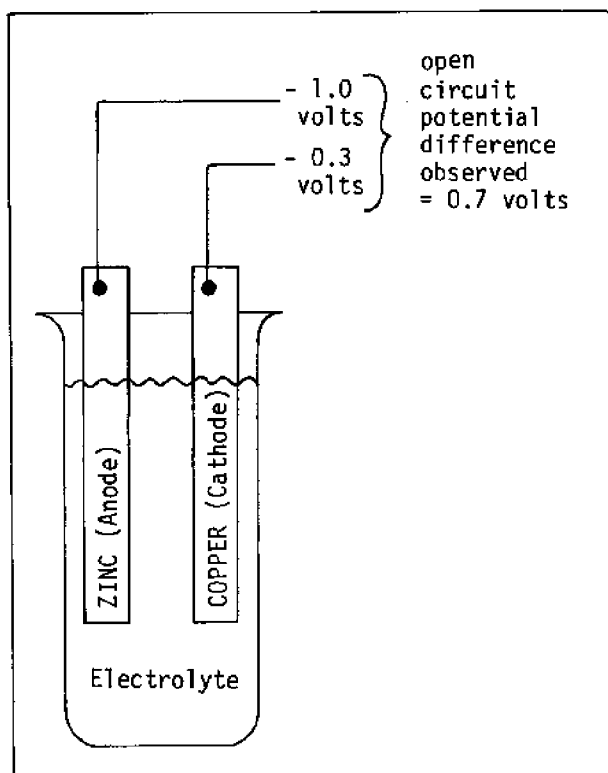
Fig. 3. Voltage measurement on a galvanic cell

Fig. 4. Electroplating

voltage is applied, the copper gives up an electron and "eats away" as the positive ions go into the solution. The battery essentially pumps the electrons into the steel electrode, which draws to its surface the copper ion in solution. On a boat, this kind of action is called *stray current corrosion* and can happen to underwater fittings that are accidentally given a voltage difference, relative to other nearby metals.

To those concerned with marine corrosion, both galvanic action and stray current corrosion are sometimes erroneously referred to as *electrolysis*, since the symptoms are often the same. From a troubleshooting point of view, however, it is important to distinguish between the two processes. The term electrolysis is discouraged by industry personnel nowadays, so we will use the term *stray current corrosion* to refer to corrosion caused by battery or wiring voltages rather than by galvanic action. Stray current can be caused by both internally and externally impressed voltages, both D.C. and A.C. The bulk of this report deals with methods of controlling galvanic action.
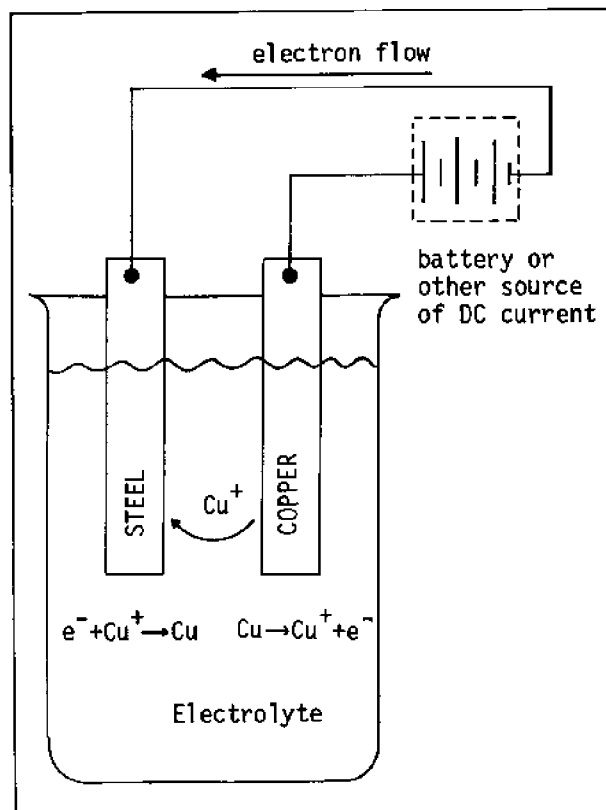
Stray current corrosion, however, is often the more significant cause of corrosion and is further discussed in section III.A.

I.B. Boat Electrical Systems

The purpose of this report is to describe various methods of providing cathodic protection for boats. In the usual case, these cathodic protection measures are meant to protect the boat against galvanic corrosion due to the interaction of dissimilar metals below the water line. In fact, stray current corrosion is often the most damaging process; it can only be avoided by the proper installation, maintenance, and use of the boat's electrical system and dockside wiring. The discussion in section II will assume that possible problems due to faulty electrical systems have been solved and that the electrical systems on the boat and adjacent dock are well designed and maintained.

Consideration of the following points is important.

9

Most experts agree that *bonding*, (the practice of electrically tying together all the metal parts of the boat), is essential for several reasons, one of which is to ensure that all metal parts are held at the same electrical potential so that no stray currents will flow through the water from one metal to the other. (There may still be currents due to galvanic action.) Bonding must be accomplished using very low resistance connections; often a wide copper strap is run down the center of the boat, and the individual metals are attached to this strap using heavy copper wire. Propellers and shafts are often difficult to bond because the film of lubricating oil in the gear box is nonconducting. For this reason, a *shaft brush* is often used. There are many types of shaft brushes, but they all consist of an assembly which makes good electrical contact with the rotating shaft. The shaft brush is then tied into the vessel's bonding system. A method for avoiding the use of a shaft brush using zinc shaft collars or wheel nut caps is discussed in section II.A. However, some engineers feel such devices do not provide protection as effective as a fully bonded, cathodically protected, system (Kurr 1978). All hull fittings need not necessarily be bonded, but such fittings require individual cathodic protection. Detailed discussions of bonding are available in various sources (Miller 1973, Kolbe et al. 1975, Cropsey 1976).

Details of boat wiring techniques are available in several references (Miller 1973, Cropsey 1976, ABYC 1977). D.C. wiring in boats is required to meet more stringent requirements than that in automobiles because of the corrosive nature of sea water and the need to prevent leakage of current through the low resistance sea water medium. Wiring must be of a larger size to minimize voltage drops. Connections must be more secure and well sealed from moisture to keep their resistance low. Unlike the wiring in automobiles, where the frame *ground* is used as one conductor, a two wire system must be used in boats. In the preferred method of **installation (Cunning 1978), three-wire** armored (shielded) cable is used to minimize radio interference and permit thorough bonding of all metal fittings. In this case the outer conducting shield is tied into the bonding system.

The difficulties of electrically insulating boats should be mentioned. Due primarily to the high electrical conductivity of salt water, incompletely sealed connections invariably lead to leakage current in places that salt water or spray can reach. Wet wood is a poor insulator, and current can travel along any surface which is damp with salt water. Thus it is recommended (Cunning 1978) that all terminals, connections, binding posts, etc. be thoroughly sealed with one of the commercially available products (such as Scotchkote or Silicone Seal).

Older boats often have positive grounding systems, i.e. the positive terminal of the battery is connected to the engine and bonding system (if one exists). This situation presents a corrosion hazard since any leakage currents from the negative terminal to grounded positive fittings through sea water would result in deterioration of the fittings. It is recommended (Cunning 1978, Anon. 1974, ABYC 1977) that such installations be converted to negative grounds.

Floating ground systems are sometimes used; in this case neither terminal of the battery is connected to the ground. Some experts (Cropsey 1976, Whitefish Authority undated), prefer this system, but modern engines and starting circuits are more conveniently wired with negative ground (Wilskey 1978, Cunning 1978).

Most boats utilize an internal A.C. wiring system for plugging in to dock power. For 115 volt A.C. service, the power cord from the dock consists of 3 wires: the hot wire (usually black or red), the neutral (white) and the grounding (green) wire. Figure 5 shows a simplified representation of a typical A.C. electrical system aboard a boat at dockside (Miller 1973). We have shown an isolation transformer in the circuit, an installation highly recommended (Cunning 1978, Miller 1973, Dodge 1978, ABYC 1977) for positive control of A.C. stray current corrosion. Note that the shore cord safety grounding conductor terminates at the transformer case and is not carried to boat ground.

Battery chargers are one of the most common A.C. appliances, especially on small boats. These devices should be approved marine types, never the "auto transformer" variety (Kolbe and Erickson 1976).

The relationship between A.C. power connection and corrosion phenomena will be discussed further in section III.A.
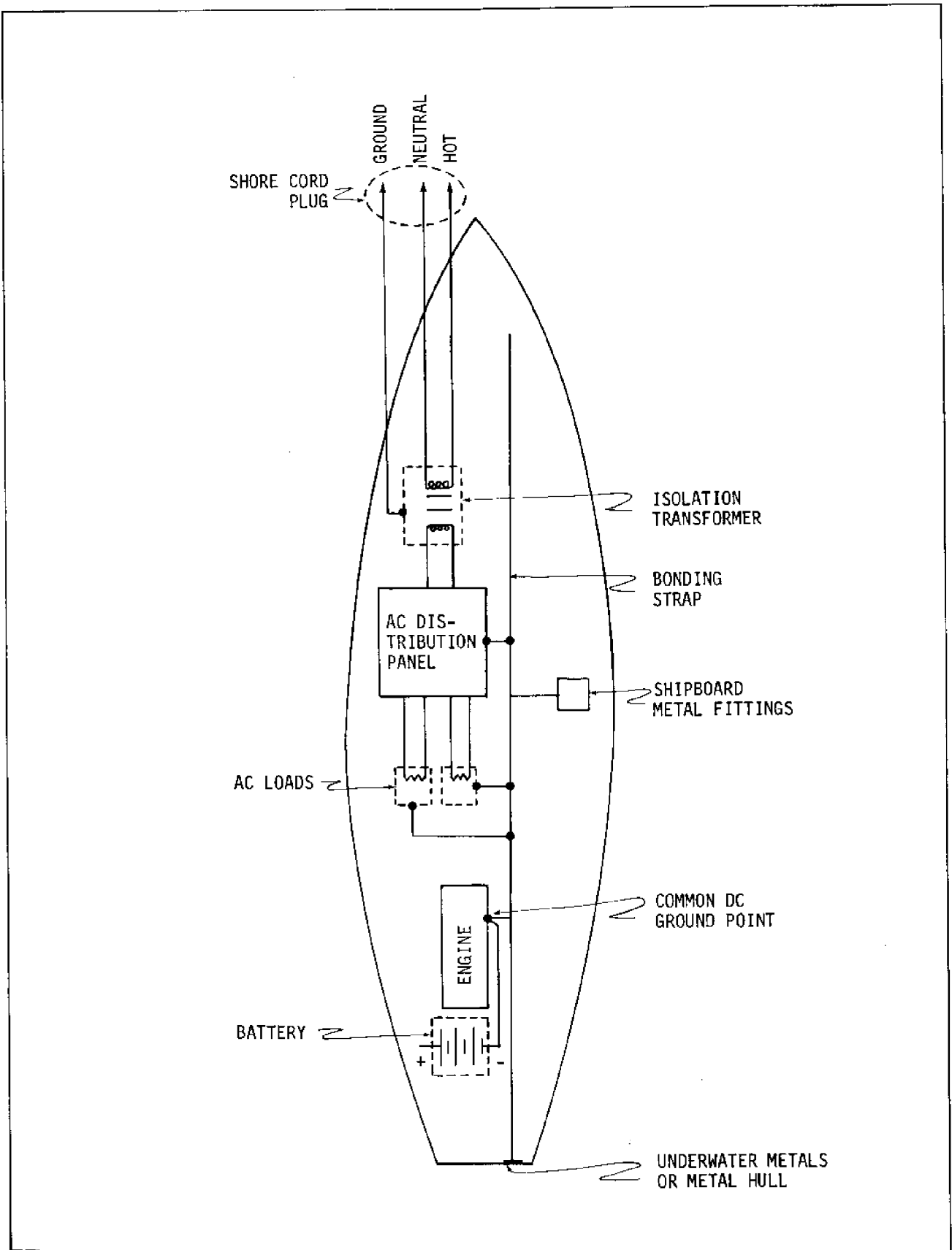
Fig. 5. Onboard AC power and its connection with the shore system

II. CATHODIC PROTECTION

II.A. *Sacrificial Metals*

The galvanic action discussed in section
I.A. is responsible in many instances for
electrochemical corrosion of hulls, under-
water metal fittings, propellers, shafts,
rudders and any other metals which are elec-
trically connected to a metal more *noble*
than itself, that is, more positive on the
galvanic series (Fig. 2). The foregoing
suggests, however, that the process might be
used to advantage by connecting the metal to
be protected to a metal more negative on the
galvanic series (less noble). In this
situation, the less noble metal becomes the
anode and corrodes, and the other metal
(being the cathode) is protected. That is,
of course, the basis for the widespread use
of zinc for corrosion protection, a common
practice for about 150 years. Sir Humphrey
Davy was the first to attach zinc plates to
the copper sheathing on the hulls of warships
(Davy 1824).

Consider the effect of adding increasing
amounts of zinc to a piece of copper immersed
in sea water, with a reference electrode and
voltmeter connected as shown in figure 6.
The reference electrode, often silver-silver
chloride, is used only to provide a point of
reference for the voltage measurement. With
little or no zinc attached, the voltage
measured will be close to the freely corrod-
ing potential of copper, -0.35 volts. As
more zinc is attached, the voltage will be-
come more negative, approaching the potential
of zinc, -1.03 volts. This example uses
copper and zinc, but the discussion is appli-
cable to other combinations of metals, for
example, a steel plate protected by an alumi-
num anode. Note that it is the *area* of metal,
not the weight, which determines the voltage
measured in figure 6. (For large areas, their
relative distribution is also important.)
Metal atoms that are not on the surfaces, do
not participate in galvanic action, except to
provide a pathway for flow of electrons with-
in the metal. The importance of electrode
areas will be discussed later in this section.
Figure 7 shows how the potential of freely
corroding metals in sea water moves toward

A) Area of copper very large compared to that of attached zinc

Voltmeter reading is slightly greater than (-0.35), the freely-corroding potential of copper alone

Reference cell Silver-Silver Chloride

COPPER ZINC REF. CELL

B) Areas of copper and zinc appropriately balanced for cathodic protection of copper

Voltmeter reading of (-0.60) volts indicates copper is properly protected

COPPER ZINC REF. CELL

C) Area of copper small compared to that of attached zinc

Voltmeter reading is approximately (-1.03), the freely-corroding potential of zinc alone
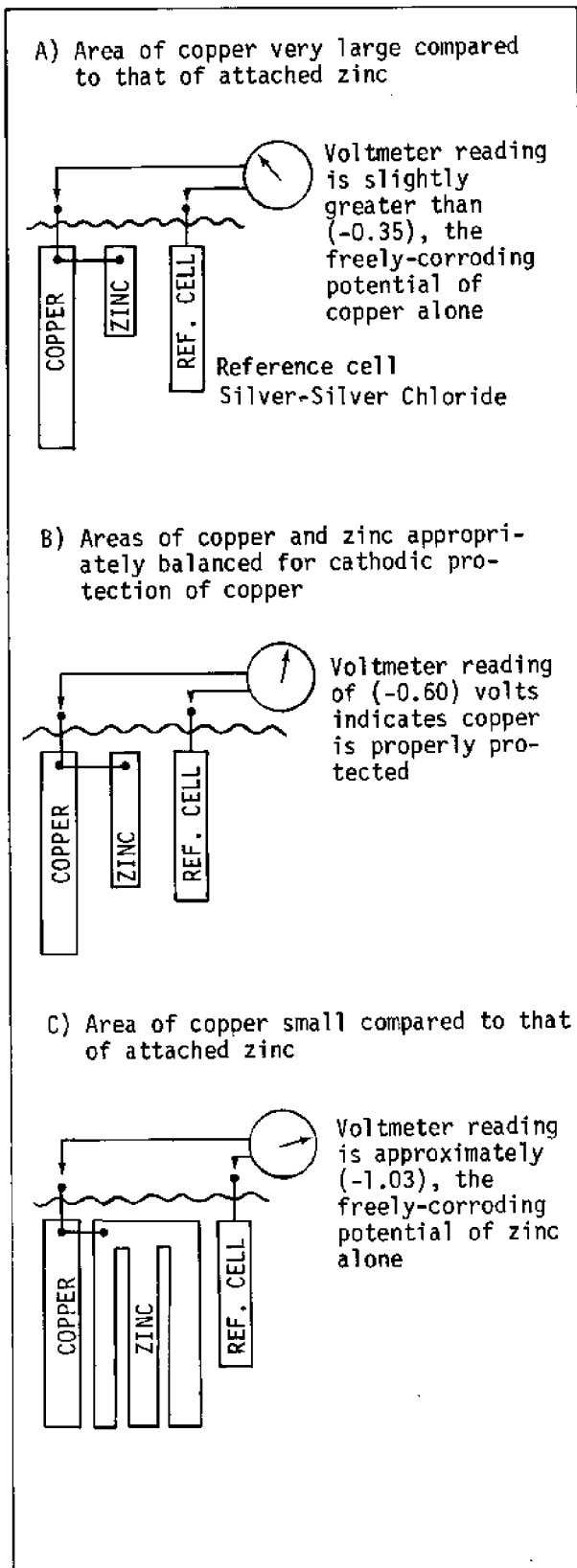
COPPER ZINC REF. CELL

Fig. 6. Varying the voltage of an underwater metal

that of zinc at -1.03 volts by attachment of zinc sacrificial anodes. Previous experiments (Dodge 1978, LaQue 1975, p. 206, Butler and Ison 1966, p. 225, Applegate 1960, p. 23) have shown us that the optimum potentials for protection are approximately 850 millivolts negative versus silver-silver chloride for steel, 650 millivolts negative for copper or copper alloys (such as bronze or brass) and 950 millivolts negative for the aluminum alloys used in boat building. Military specification zinc* also makes a convenient reference electrode and in this case the optimum potentials for protection would be approximately 200 millivolts positive with respect to zinc for steel, 400 millivolts positive for copper or copper alloys, and approximately 50 millivolts positive for aluminum alloys (Dodge 1978).

A good, straight-forward way to determine the amount of sacrificial anode metal needed has been suggested (Cunning 1978). It involves measurement of the *hull potential* versus a reference electrode and adjustment of the number of zincs to achieve the desired hull potential.** As more zinc is attached to the cathode, the cathode's potential is lowered toward the potential of zinc (Fig. 7). Thus to properly zinc a steel hull by this method, one would attached the negative lead of a VOM (Volt-ohm-milliammeter) to the hull via the bonding system and the positive lead to a silver-silver chloride reference electrode suspended in the water over the side. Zincs would then be attached to the hull until the meter reading changed from approximately -650 millivolts to about -850 millivolts. In practice this procedure would have to be carried out by trial and error, adding zincs one by one and making hull potential measurements periodically. These measurements should be made at various places around the hull; assuming a proper bonding system, measured potentials should not differ by more than about ten millivolts. If greater differences are observed, either the boat is improperly bonded, or a stray current situation is in effect and should be corrected before proceeding. Stray current phenomena will be discussed in a later section.***(page 15)

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*Military specification (MIL. SPEC.) refers to a composition of anodes which has been proven to corrode effectively and provide cathodic protection (Teel and Anderson 1956). This anode composition will be discussed later in greater detail.

**Note that voltage measurements with a reference electrode should only be made with a high resistance voltmeter.

APPROXIMATE FREELY CORRODING POTENTIALS
VOLTS RELATIVE TO ZINC

Ag-AgCl REFERENCE — 1.0

316,304 STAINLESS (passive) — 0.9

— 0.8

COPPER ALLOYS (eg. bronze) — 0.7

— 0.6

316,304 STAINLESS (active) — 0.5

STEEL

— 0.3

ALUMINUM ALLOYS — 0.2

ZINC — 0
ALUMINUM ANODE

PROTECTED POTENTIALS
(Dodge, 1978)

APPROXIMATE FREELY CORRODING POTENTIALS
VOLTS RELATIVE TO Ag-AgCl

Ag-AgCl REFERENCE — 0

316,304 STAINLESS (passive) — -0.1

— -0.2

COPPER ALLOYS (eg. bronze) — -0.3

— -0.4

316,304 STAINLESS (active) — -0.5

STEEL

— -0.7

ALUMINUM ALLOYS
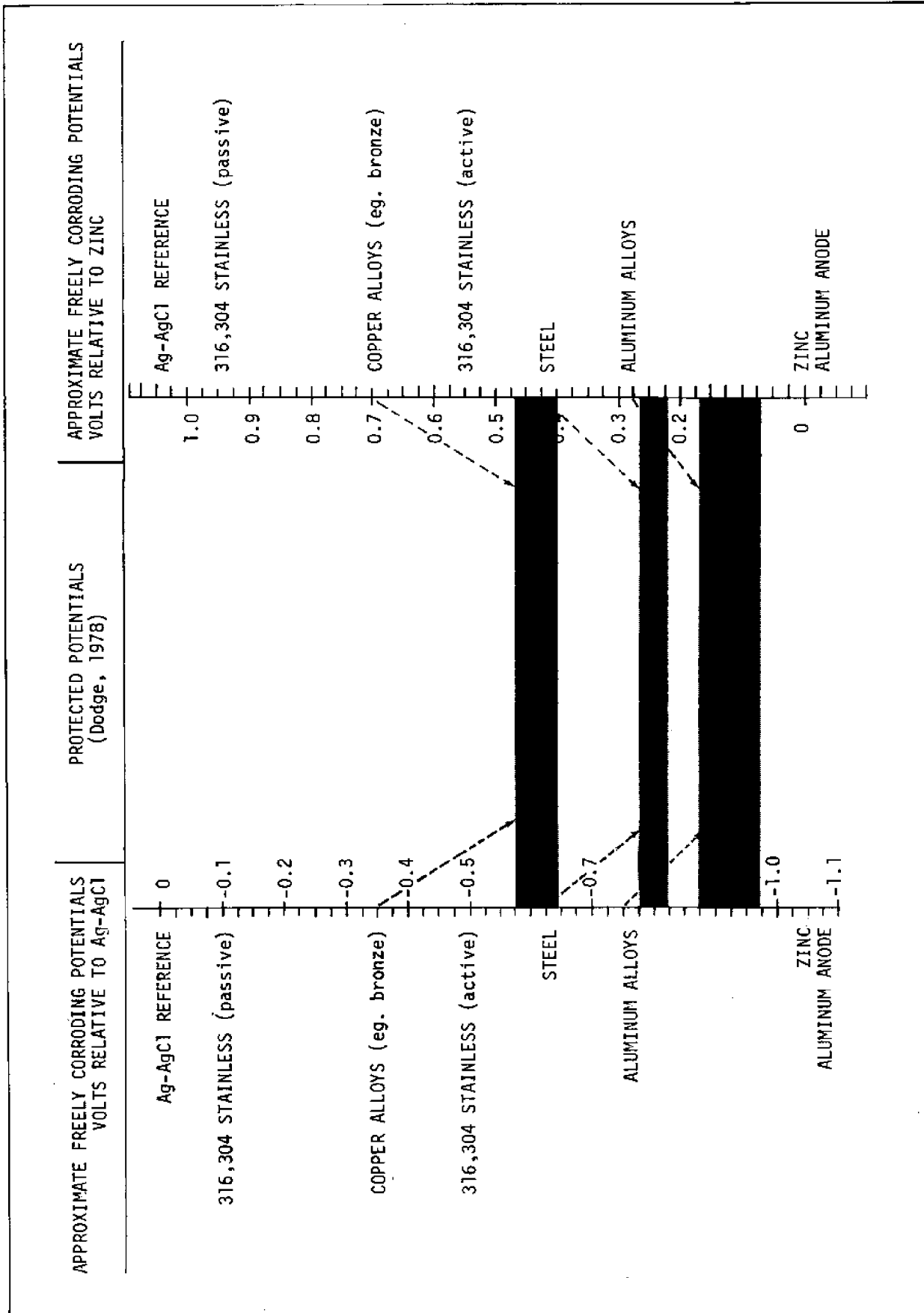
ZINC — -1.0
ALUMINUM ANODE — -1.1

Fig. 7. Protected potential ranges for underwater metals

Two considerations are extremely important when using zinc: purity and application. Table 1 gives the military specification (MIL-A-18001H) concerning the composition of zinc anodes necessary for proper corroding action (U.S. Navy 1968). Table 2 is a list of zinc anode manufacturers whose products are advertised as conforming to the military specification. Note the quantities of aluminum and cadmium in the zinc of Table 1, and notice also the extremely low level of allowable iron. It is the iron which prevents proper corroding action. This fact suggests that zinc which has been recycled by simply melting down and recasting may be contaminated with iron, especially if steel utensils have been used. Some re-melted anodes work fine; others do not. Corrosion engineers caution against using anodes made from recycled zinc, unless the producer can prove that the materials meet the requirements of MIL-A-18001H (Kurr 1978, Swartz 1978).

The presence of aluminum and cadmium allows a somewhat higher tolerance for iron in the anode composition. One difficulty with this practice occurs in heat exchangers having temperatures greater than $120^{\circ}F$. Intergranular corrosion of aluminum results, and the anode crumbles away. For this reason, special zincs must be used in high temperature applications (Kurr 1978).

Figure 8 shows what a properly corroding zinc looks like. Bad zincs often form a scale on their surface which inhibits proper corrosion. According to the Navy (NAVSHIPS 1968):

"The inactive anode usually will have a hard, tenacious, dark grey or black film on the surface and the anode manufacturer's identification will still be prominent on the surface."

This scale can actually become cathodic to steel, thereby accelerating corrosion of nearby steel surfaces (Kurr 1978). In other words, bad zinc can be worse than no zinc at all.

The zinc anodes come in many different sizes and configurations, as shown in figure 9. The methods of attachment also differ. The best attachment is achieved with anodes having cast-in brackets or inserts, as shown in the figure. By casting a galvanized steel strap into the zinc itself, good electrical contact is ensured since the zinc-steel interface is totally enclosed within the zinc. With such anodes, the problem reduces to one of properly attaching the steel straps to the hull or bonding system. The best method of attachment is by welding directly to the hull in the case of a steel boat: properly made bolt-on connections are adequate. Cunning (1978) advises one to bolt on at least a few of the zincs. If zincs were rapidly expended in mid-season because of some electrical problem, one could replace them without putting the boat on dry dock.

Figure 10 depicts a problem that can occur if an anode lacks cast-in straps or inserts. Water can seep into crevices, causing corrosion products which prevent good electrical contact; corrosion of the zinc--and thus protection--stops. A procedure for mounting zincs which have no cast-in straps or inserts is to melt a small region on the zinc with a torch and then place the head of a bronze bolt in the puddle of molten zinc and allow it to solidify in place (Cunning 1978). The bolt then becomes a mounting stud.

Currently used methods of determining the number and placement of zinc anodes on a particular vessel are inexact. Widely varying conditions of water velocity, temperature, salinity, paint system condition, hull material composition, and other factors make it impossible to exactly specify the correct amount of zinc needed. Recommendations often assume some average state of these conditions; variations in these conditions can greatly affect zinc needs. The effect of these variations are discussed later in this report.

Table 3 is a summary of recommendations on zincing for seven typical boat sizes. The first part of the table gives the assumed hull dimensions and underwater metal areas which were used to calculate the zinc weights shown in the second part of the table. The

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***This discussion refers to the more common problem of protecting hulls and protruding metal fittings. In fact, underwater metal includes such integral things as heat exchangers, which can be linked to other metals via a common salt water path. This equipment is made of materials that are often dissimilar from the hull (e.g. copper, galvanized steel, tinned copper, cupro-nickel). Also such equipment may or may not be electrically well connected to the vessel's bonding system. As a result, heat exchangers can present unique corrosion control problems that may be best turned over to specialists (appendix D). Bilge water can represent a separate corrosion system and lead to another set of problems unless all metal is well bonded together.

Lead (max.) Percent	Iron (max.) Percent	Cadmium range Percent	Copper (max.) Percent	Aluminum range Percent	Silicon (max.) Percent	Zinc
0.006	0.005	0.025-0.15	0.005	0.10-0.50	0.125	Remainder

Table 1. Composition of "MIL-SPEC" zinc (from military specification MIL-A-18001H. U.S. Dept. of the Navy, 1968)

Manufacturer	Trade Name
Canada Metal Co., Ltd. Sales Office: P.O. Box 2012 Vancouver , B.C. V6B 3P8 (604) 683-1367	Canada Metal
Federated Metals Corp. Subsidiary of ASARCO Cathodic Protection Dept. P.O. Box 2600 Somerville, NJ 08876 Sales Office: P.O. Box 10326 Portland, OR 97210 (503) 227-1403	Hi- Amp FMD
Matthiessen & Hegeler Zinc Co. 1375 Ninth St. LaSalle, IL 61301 (815) 223-8600 (Note: Applicable marine products limited to zinc rod for heat exchangers)	
Pacific Smelting Co. 22219 S. Western Ave. Torrance, CA 90501 (213) 328-4811	PASCO
Rotometals 980 Harrison St. San Francisco, CA 94107 (415) 392-3285	Zincodes Cor-in
RSR Corp. Dallas, Texas Sales Office: 2700 16th Ave. SW Seattle, WA 98134 (206) 447-2700	RSR
Sentinal Anode Div. of Peco Mfg. Co. P.O. Box 02156 Portland, OR 97202 (503) 233-5314 (Note: Applicable marine products limited to small plugs, dies, rods for heat exchanger or similar use)	Sentinal Galvion

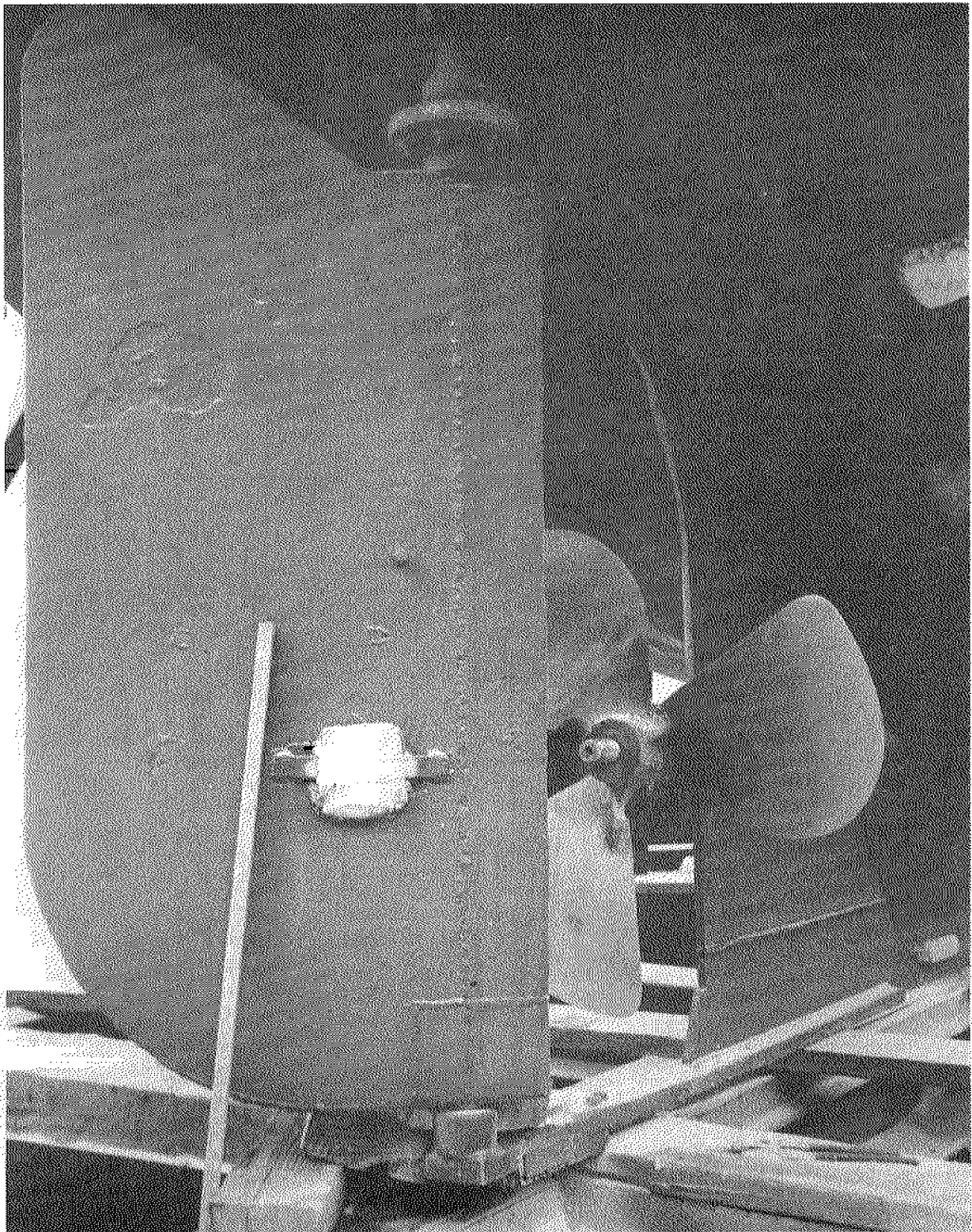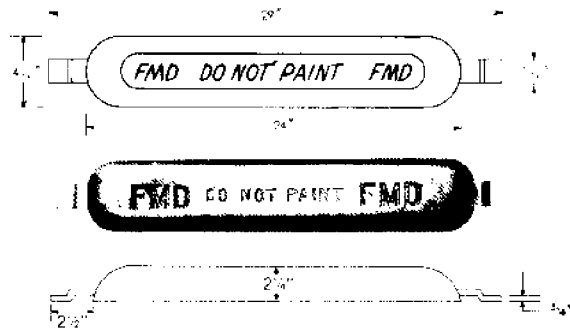Table 2. Some commercial zinc anodes conforming to MIL-SPEC A-18001H

Fig. 8. A properly corroding zinc anode

LL-26: 2¼" x 4½" x 14". Nominal weight. 26 lbs. Contains single galvanized steel longitudinal strap. Can be bolted or welded to hull. Particularly suited for smaller ships, coastal vessels, harbor tugs, etc. Current rating. 1 amp-yr.

LL-48: 2¼" x 4½" x 24". Nominal weight. 48 lbs. Contains single longitudinal galvanized steel strap for welding to hull. Particularly suited for major ships. 10.000 DWT and upward. Current rating, 2 amp-yrs.
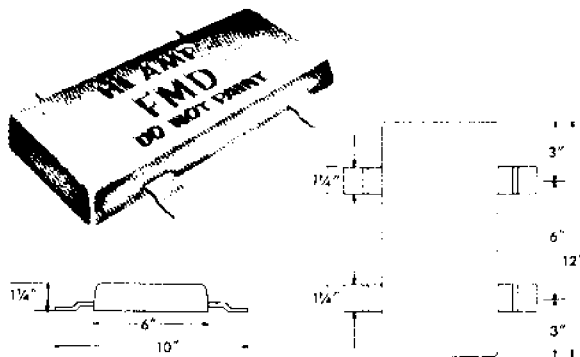
M-24: 6" x 12" x 1¼". Nominal weight. 22.5 lbs. Contains two cast-in galvanized steel mounting straps. Also available with brass straps. Current rating. 1 amp-yr.
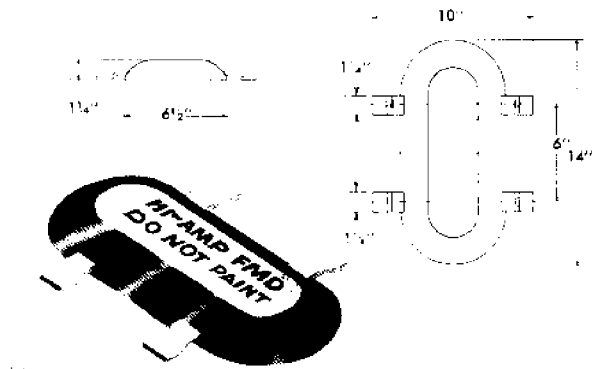
TAPERED M-24: 6½" x 14" x 1½". Nominal weight. 22.5 lbs. Contains two cast-in galvanized steel mounting straps. Current rating. 1 amp-yr.

M-6: 9" x 3" x 1¼" tear drop anode. Nominal weight, 5 lbs. Contains single cast-in galvanized steel strap with two ⅝" holes on 11" centers. Current rating. ¼ amp-yr.

Solid hull anodes without cast-in mounting straps.

Type	Size	Nom. Wt.	Current Rating
M-23	6" x 12" x 1¼"	22 lbs.	1 amp-yr.
M-19	6" x 12" x 1"	19 lbs.	¾ amp-yr
M-10	6" x 12" x ⅝"	10 lbs.	½ amp-yr.

Specialty plates: 3 sections ⅝" x 6" x 12" as shown. 4 sections also available.

M-12: 3" x 12" x 1¼". Nominal weight, 11.5 lbs. Contains single cast-in galvanized steel mounting strap 3/16" x 1¼" x 16". Current rating. ½" amp-yr.
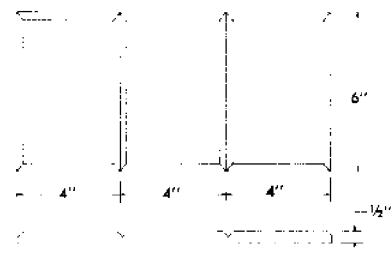
Fig. 9. Typical hull anode shapes and sizes (courtesy, Federated Metals Corp.)

18

Assumed Hull Dimensions and Characteristics

	22' OB Dory or I/O Cruiser	30' Inboard Troller	32' Auxiliary Sailboat	40' Troller	48' Troller or combination boat	58' combination boat	78' Dragger
Load waterline length (LWL) (ft.)	19	30	28	38	44	55	74
Beam, B (ft.)	8	11	11	13	16	19	22
Draft, D (ft.)	1	6	6	7	9	12	13
Underwater hull area using equation: $A=(LWL)\times(B+D)$, (ft.²)***	170	500	350	760	1100	1700	2600
Propeller Diameter (in.)	12	17	12	24	30	48	58
Propeller Area (ft.²)	1.5	3	1.5	6	10	24	36
Shaft and Strut Area (ft.²)	1.5	–	0.5	–	–	–	–
Rudder Area (ft.², painted steel 1 year old)	1.5	10	–	20	30	38	46
Radio Ground Plate Area (ft.²)	–	8	–	10	12	12	12
Other underwater metal area (ft.²) (e.g. copper alloy keel cooler)	–	–	–	10	10	12	15

***For the sailboat hull, 3/4 of this quantity was used (Duff 1973)

Pounds of zinc recommended by various sources*

Hull Material	Reference**	Water Velocity (Knots)	Service Life (Years)	22' OB Dory or I/O Cruiser	30' Inboard Troller	32' Auxiliary Sailboat	40' Troller	48' Troller or combination boat	58' combination boat	78' Dragger
Wood or Fiberglass	Woodcock[1]	0	–		3	0.5	8	10	14	18
	"	20	–		19	3	45	55	80	100
	NAVSHIPS[2]	>5	2	(5 sq. in.)	16	1.5	35	47	65	75
	Am. Zn. Inst[3]	–	3		42	8	100	126	188	246
	Kurr/SNAME[5]	<5	2		11	2	23	28	42	55
	"	>5	2		53	6	69	84	126	165
	RAN[6]	0	2		3	1	6	7	11	15
	"	12	2		30	10	60	70	110	150
	Duff[7]	–	1		18	5	30	34	62	90
	Local Practice[8]	–	–	1.5	18	–	40	66	101	172
Steel (1 year old paint job)	Woodcock[1]	0	–	12	34	22	55	78	119	178
	"	20	–	23	81	46	139	191	290	421
	NAVSHIPS[2]	–	2	23	66	44	101	146	225	340
	AZI[3]	–	3	34	137	74	245	334	509	738
	Birnbaum[4]	<5	3	34	98	67	152	220	338	512
	Kurr/SNAME[5]	<5	2	30	100	63	160	226	346	518
	"	>5	2	30	122	67	206	282	430	628

Table 3. Weight of zinc recommended for protection of boats

19

Amounts of zinc recommended by various sources*

Hull Material	Reference**	Service Life (Years)	Water Velocity (Knots)	22' OB Dory or I/O Cruiser	30' Inboard Troller	32' Auxiliary Sailboat	40' Troller	48' Troller or combination boat	58' combination boat	78' Dragger
Steel (1 year old paint job)	RAN[6]	2	0	20	62	42	97	139	214	324
	"	2	12	36	137	83	224	308	475	706
	Duff[9]	1	–	20	40	40	60	86	157	206
	Local Prac-tice[8]	–	–		80		105	192	330	705
Aluminum (1 year paint)	NAVSHIPS[2]	2	–	23	66	44	101	146	225	340
	Local Prac-tice[8]				10		28	55	100	223

* Calculation of weight is based on the use of 11 lb. rectangular anodes.
** Superscripts refer to reference number listed in the text, where method of calculation is explained. (pages 22 and 23)
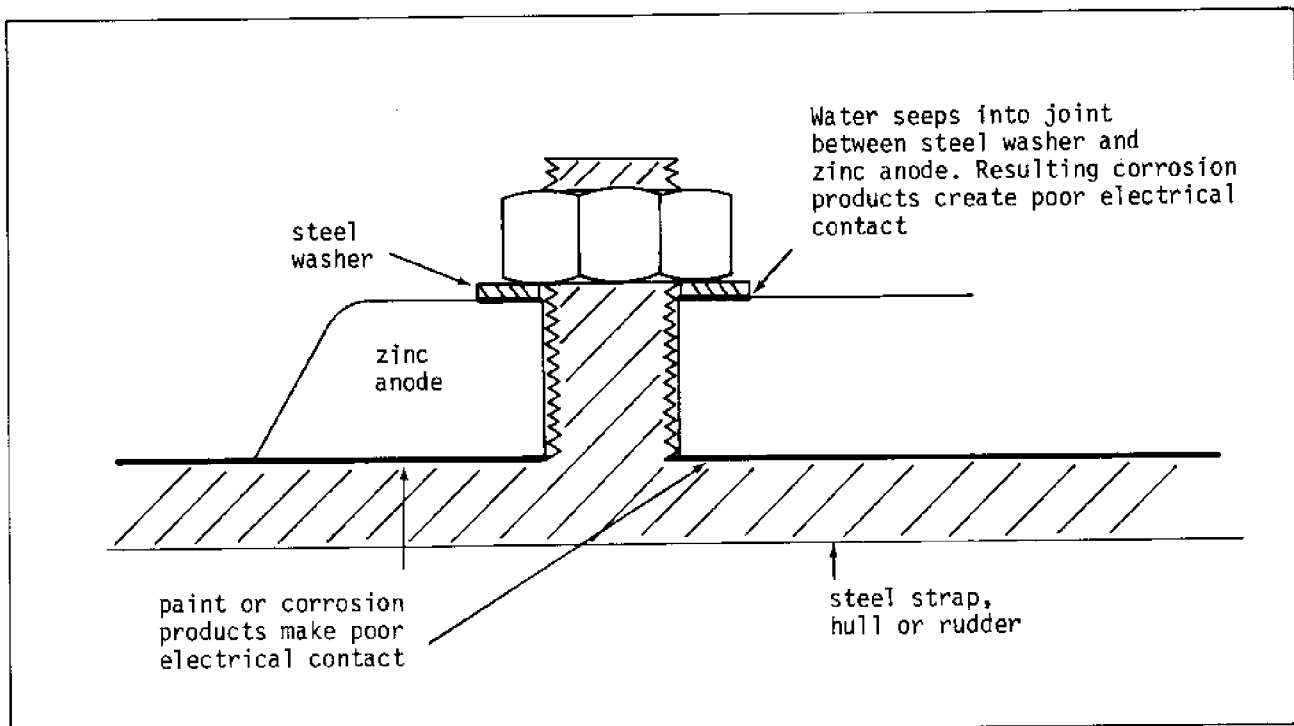
Table 3. Continued

Fig. 10. Danger of using zinc anodes having no cast-in straps or inserts

recommendations for zinc amounts are from a variety of sources, including individuals, boat yards, and industry publications.

Most of the formulas and recommendations concerning amounts of zinc needed on a boat refer to the weight rather than the surface area of the anode. In fact surface area is the parameter most affecting adequate protective current, while weight gives an indication of how long the anode will last. As one might expect, a large thick anode will have a much lower surface-to-weight ratio than a small thin anode. Thus, merely specifying the weight of zinc will lead to protective voltage levels and currents which vary somewhat with the size of anode used.

The example calculations of this section and table 3 will assume the use of 11 pound rectangular anodes (denoted in figure 9 as "11.5 lb."). This is a compromise. Large vessels in the 50-80 foot range generally use larger (typically 22 pound) anodes. Because of the lower surface-to-weight ratio of these anodes, a large boat might need slightly higher weights of zinc than those shown in the table. Similarly, small boats which might typically use 5 pound anodes should use slightly smaller amounts than those shown in the table.

The following sample calculations show how we have converted the recommendations which were based on 22 pound anodes, to 11 pound anodes:

Suppose a corrosion specialist recommends that two 22 pound anodes be used to protect an underwater metal area. We've calculated that each 22 pound anode has a surface area of 110 square inches* so 220 square inches of zinc are needed to protect the area. Because an 11 pound anode has only 70 square inches of surface,* we would need 3.14

$$\left(= \frac{220 \text{ in}^2}{70 \text{ in}^2/\text{anode}}\right)$$ of the smaller anodes to protect the same area. The actual weight of zinc metal in the 11 and 22 pound anodes is 10.5 and 20.5 pounds respectively.** For this example then, table 3, which assumes use of 11 pound anodes, would list 33 pounds (= 3.14 anodes x 10.5 lb/anode)

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*Note that these calculations omit one side of the anode--it is assumed that the side adjacent to the hull will not corrode as the others do.

**Note that the "nominal weight" given in figure 9 includes steel straps which weigh approximately 1 pound each.

instead of 41 pounds (= 2 anodes x 20.5 lb/ anode).

Stern drives and outboards constitute a special case, and cathodic protection requirements for these units cannot realistically be specified in terms of weight of zinc. Most outboard motor and inboard-outboard drive unit manufacturers offer special zinc anodes for use on their equipment. Entries in the table for steel hulls include 1.5 pounds for protection of the aluminum drive unit.

Table 3 also includes the assumed areas of metal to be protected. Immersed area in square feet is calculated (Duff 1973) by multiplying the load waterline (in feet) times the sum of the beam and draft (feet) [LWL x (Beam + Draft)] for motor vessels, and as [3/4LWL x (Beam + Draft)] for medium displacement sailboats.

Propeller area is determined by calculating the area of a disc of equal diameter. For example, a 4 foot wheel would have an area of

$$(2 \text{ ft.})^2 \pi \times 2 \text{ sides} = 25.1 \text{ sq. ft.}$$

The sources of recommendation listed in the reference column of table 3, and their criteria are as follows: (Source number 1 corresponds to superscript "1" in the table, etc.)

1. Woodcock, Karl S. January 1969. Control of Corrosion of Underwater Metals. Department of Marine Resources, State House, Augusta, ME 04330. For stagnant conditions the criteria are as follows. One square foot of zinc will protect:

    800 square feet of freshly painted steel (vinyl paint)
    400 square feet of painted steel one year old (vinyl paint)
    250 square feet of bare steel or aluminum alloys, or
    100 square feet of copper or copper alloys
If the boat is in motion with a speed of twenty knots, the protection is reduced. One square foot of zinc will protect:
    400 square feet of freshly painted steel, (vinyl paint)
    200 square feet of painted steel one year old (vinyl paint),
    100 square feet of bare steel or aluminum alloys, or
    15 square feet of copper or copper alloys.
(Weight of zinc and thus service life of zinc not given.)
We have calculated that an 11 pound anode has an effective surface area (excluding back side) of 0.5 square feet.

2. Navy, U.S. Department of the. September 1968. (NAVSHIPS Technical Manual). Paints and Cathodic Protection. Preservation of Ships in Service. Chapter 9190. pp. 56-67. This reference is suitable primarily for larger vessels on which most of the protection needed is for the steel hull. For two year protection of painted steel or aluminum hulls, the specification is for one standard 22 pound zinc for each 150 square feet of underwater area. One zinc is needed for each 25 square feet of underwater metal area on wood-hulled ships. Water velocity is assumed to be greater than five knots.

The Navy further recommends two other cathodic protection measures not included in the calculations of table 3:
    a) for metal hulls having generally flooded bilges, bolt additional zinc anodes inside the hull, beneath the bilge water level; and
    b) for aluminum hulls, provide an additional five pound zinc anode on the external hull, for each five square feet of non-aluminum metal fittings.

3. American Zinc Institute, Inc. Undated. Zinc as a Galvanic Anode Underwater. 15 pp. Recommends "one 22 pound zinc for each 100 square feet of immersed steel hull area, and one for each five square feet of cathodic metal such as propellers, shafts, bearings, and rudders which may be fabricated from cathodic metals." (Three-year protection). We assume a steel rudder requires the same protection as a steel hull.

4. Birnbaum, Leon S., et al. 1971. Cathodic Protection. Reprinted from Naval Engineers Journal, April. pp. 13-24. Recommends one 22 pound zinc for each 100 square feet of immersed area. (Provides three years of protection for larger steel vessels.)

5. Kurr, G. 1978. Presentation on Cathodic Protection. O.S.U. Marine Technical Institute, Charleston, Oregon.

The following is a commercially used formula for determining total anode weight:

$$Wt\ (lb) = \left[\frac{(Life)\times(Area)\times\ density)\times\ \overset{(anode}{\overset{(current\ consump.}{rate)}}}{(Anode\ Utilization\ fraction)} \right]$$

where:

Life = service life of the anode, in years

Area = area being protected, in ft^2

Anode consumption rate = $24.8 \frac{lb}{amp\text{-}year}$ for zinc anodes, assuming 95% galvanic efficiency

Anode Utilization factor = .85 (assumed)

Current density = amount $(amps/ft^2)$ needed to protect metals under various conditions. The Society of Naval Architects and Marine Engineers (SNAME 1976) gives the following approximate levels of recommended protection:

2 mA/ft^2 needed on well-painted steel

5 mA/ft^2 needed on poorly painted steel

15 mA/ft^2 needed on bare bronze at water velocities less than 5 knots

45 mA/ft^2 needed on bare bronze at water velocities greater than 5 knots.

As an example, consider a 48-foot steel-hulled troller or combination boat, assume a two-year service life of the zinc anodes, and calculate the protection needed for water velocities greater than 5 knots.

The calculation of required zinc for this steel vessel will be a summation of two quantities: the amount needed to protect the steel hull and rudder, and the amount needed to protect the copper alloy material (bronze prop, keel cooler, etc.).* Assume that for the steel area, a current density of 3 mA/ft^2 is needed. Table 3 shows the painted steel area for this vessel to be:

Hull area = 1100 ft^2

Rudder area = 30 ft^2

Total area 1130 ft^2

So the weight of zinc needed for steel is:

$$Wt\ (lb) = \frac{(2\ yr)\ (1130\ ft^2)\ (.003\ \frac{amp}{ft^2})\ (24.8\ \frac{lb}{amp\ yr})}{.85} =$$

197.8 lb

For bare bronze, at velocities greater than five knots, a current density of 45 mA/ft^2 is needed. Table 3 gives the total copper alloy area of the propeller, radio ground plate, and keel cooler as 32 square feet.

So the weight of zinc needed for copper alloy is:

$$Wt\ (lb) = \frac{(2\ yr)\ (32\ ft^2)\ (.045\ amp/ft^2)\ (24.8\ lb/amp\ yr)}{.85} =$$

84.0 lb

Total zinc = 197.8 + 84 = 281.8 lb

11 pound anodes contain 10.5 pounds of zinc. Thus the required number would be

$$\frac{281.8\ lb}{10.5\ lb} = 27$$

22 pound anodes contain 20.5 pounds of zinc. The required number would be

$$\frac{281.8\ lb}{20.5\ lb} = 14$$

As anodes vary in size, their effective area and thus ability to supply current, also varies. An 11 pound anode can deliver up to 0.25 amperes at its polarized potential. A 22 pound anode can deliver up to 0.40 amperes at its polarized potential. For this sample boat, the total current draw is expected to be $(1130\ ft^2)$ x $(.003\ amps/ft^2)$ + $(32\ ft^2)$ x $(.045\ amps/ft^2)$ = 4.83 amps. For the 11 pound anodes, this will require $\frac{4.83\ amps}{27\ anodes}$ = .18 $\frac{amps}{anode}$. For the 22 pound anodes, this will require $\frac{4.83\ amps}{14\ anodes}$ = .35 amps/anode.

Thus either size anode could be used to protect the hull. Economics would favor use of the larger anodes, assuming current distribution is not a problem.

6. Royal Australian Navy Cathodic Protection Manual. 1977. ABR 5023. This manual lists recommended levels for protection:

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*Note that for vessels larger than those considered in table 3, calculations are generally based on steel area alone.

Type of Metal Surface Protective Coating	Current Density (mA/sq. ft.) to Maintain Potential of 820 mV	
	Stationary	12 Knots
Steel - Unpainted	4.0	30.0
Steel - Painted (Aluminum pigmented bituminous) - New	0.6	1.1
Steel - Painted (Aluminum pigmented bituminous) - 6 months old	1.0	1.8
Steel - Painted (Aluminum pigmented bituminous) - 1 year old	1.5	2.8
Steel - Oil Base painted - 6 months old	1.5	2.7
Steel - Oil Base painted - 1 year old	2.0	3.6
Stainless steel - Unpainted	4.0	30.0
Stainless steel - Painted (Vinyl)	1.5	2.8
Cooper alloy - Unpainted	4.0	40.0

Calculations for table 3 result from the formula given in the previous sections (Kurr 1978). For steel hulls, a coating equivalent to one year old oil base paint is assumed. Other values assumed are:

Anode consumption rate = $24.8 \frac{lb}{amp\text{-}year}$

Anode utilization factor = .85

7. Duff, M.G., and Partners Ltd. 1972. Cathodic Protection for Wood and GRP Hulled Yachts. M.G. Duff Marine, Ltd. Birdham, Chichester, Sussex, England.

Duff, M.G., Marine Ltd. 1970. Cathodic Protection for Motor Fishing Vessels. Same as above.

Recommendations by M.G. Duff, Ltd., are not based on underwater metal areas; sizes and numbers of zincs are specified for certain size and use classes of vessels. The criteria are too lengthy to reproduce here; the reader is referred to the original literature for detailed recommendations.

8. Local practice. The entries listed as "local practice" in table 3 are based on amounts of zinc used on the boats listed

in table 4. In many cases the amounts are estimates.

9. Duff, M.G., and Partners, Ltd. 1973. "C.P. for Steel Hulled Yachts." Same as above.

As indicated by tables 3 and 4, there is a shortage of data and experience for large aluminum hulls. Much of what we know about small aluminum hulls was learned from builders of Alaskan gillnetters and seine skiffs--many of which are typically in the water for a short period of time. Therefore use some caution when interpreting these recommendations for aluminum boats.

The only commonly used hull material not treated in table 3 is ferrocement. Experience and literature information are sparse for this material, but specialists (Wilskey 1978, Swartz undated) recommend that ferrocement be treated the same as steel. Care must be exercised to ensure that the steel skeleton of the hull has good electrical contact with the bonding and cathodic protection systems. Bronze fittings which pierce the hull must not contact the steel mesh.

In order to observe trends and patterns

24

Hull Material, Boat Type	Length Overall (ft.)	Wt. Zinc as Boat Came Off the Ways (lb.)	Wt. Zinc Replaced during Haulout (lb.)	% Consumption in One Year	Notes
Wood Charterboat	28	5			
" "	29	65		80	
" "	30	22			Bronze rudder and shoe
" Troller	30	15		30	Rudder corroding; zinc not corroding properly
" Charterboat	32	6		50	
" Troller	35	35		80	
" "	36	20			No radio ground plate
" "	40		14		
" "	40	18			
" "	40		28		
" Charterboat	40	50		70	
" Troller	42		35		
" "	45	40		80	Later increased to 80 lb. for troll wire voltage
" Fishing Vessel	48		95		
" Troller	49	34			Has radio ground plate
" "	50	100	35	35	Large amount considered necessary for troll wire voltage
" Fishing Vessel	52		45		
" "	56		20		
" "	58		63		
" "	62	70			
" Shrimper	62	158			
" Fishing Vessel	76		118		
Fiberglass Charterboat	32	18		50	
" "	32	18		50	
" "	35	18		50	
Aluminum gillnet boat	32	20			Practice of Hydraulic Fishing Supply, Seattle. Assumes unpainted 5086 alloy, stainless shaft, prop, rudder, fittings.
" "	32	0			Practice of ALFAB, Seattle. Hulls generally unpainted.
" "	32	~10			Practice of American Commercial Marine, Seattle. Zinc on stainless rudder only. Isolated bronze keel cooler must be separately protected. Boats generally in water only 2 mos.
" Fishing Vessel	40	60			
" "	56	110	38	35	
" "	58	0			
" Patrol Boat	64	76			Planing hull. Ref: (Leveau 1967)
" Fishing Vessel	67	250			

Table 4. Local practice of using zinc for cathodic protection

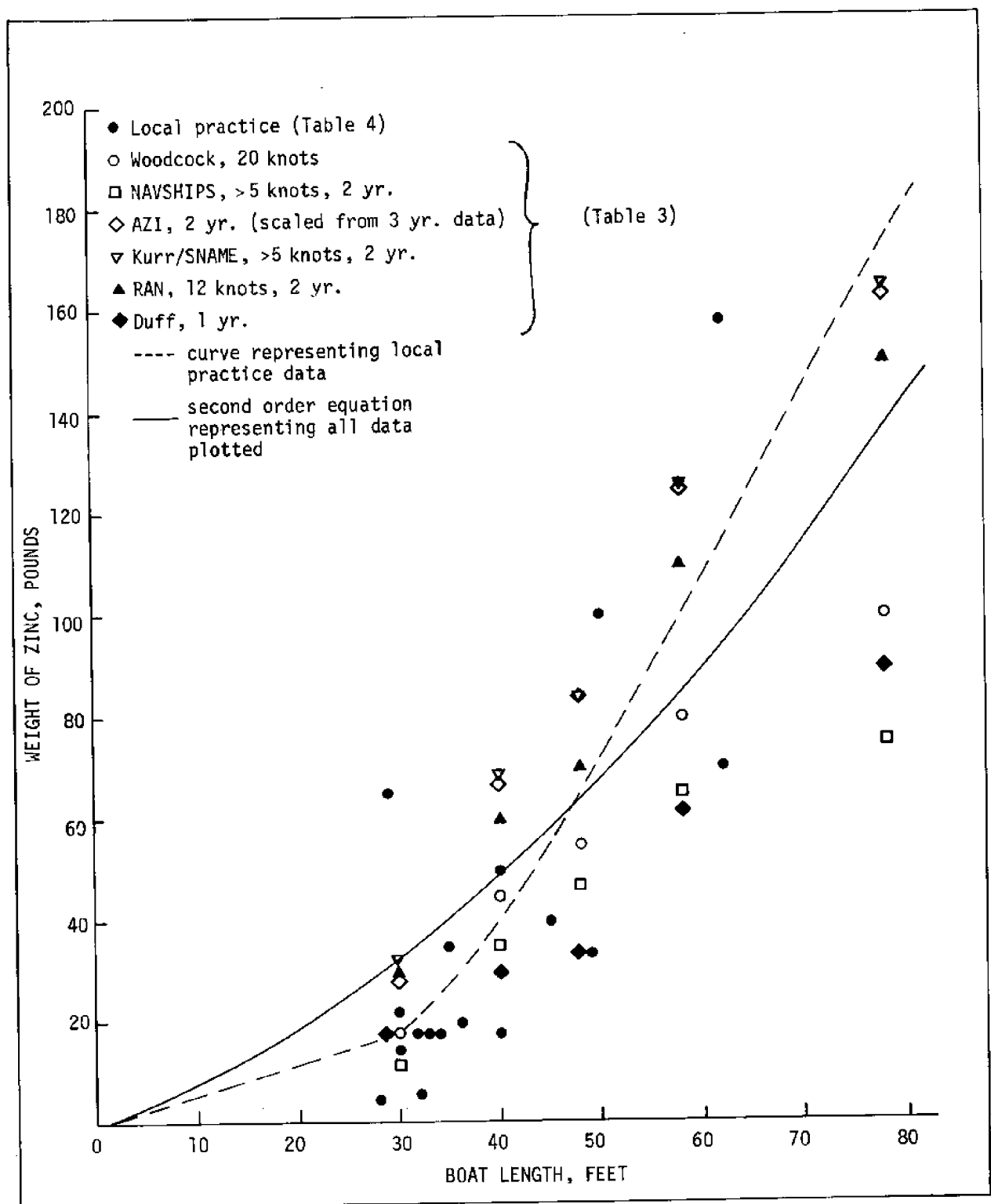| Hull Material, Boat Type	Length Overall (ft.)	Wt. Zinc as Boat Came off the Ways (lb.)	Wt. Zinc Replaced during Haulout (lb.)	% Consumption in One Year	Notes
Steel Tug	40		130		
"	50		144		
" Dredge Tender	50		144		
" Research Vessel	50	116			8 11# anodes plus 20# hub zinc
" Shrimper	53		180		
" "	53	288			
" "	58		322		
" "	58		286		
" Fishing Vessel	58	65			
" Dragger	60		120		
" Shrimper	64		252		
" "	68		293		
" "	68	660	348		Hull potential measured to be okay
" Fishing Vessel	72		384		
" King Crabber	75	530			
" Fishing Vessel	76	70			
" Dragger	78	575		50	
" Shrimper	78	754			
" Fishing Vessel	85		336		
" "	90		600		
" "	99		672		

Table 4. Continued

Fig. 11. Weight of zinc recommended for wood or fiberglass hulled boats
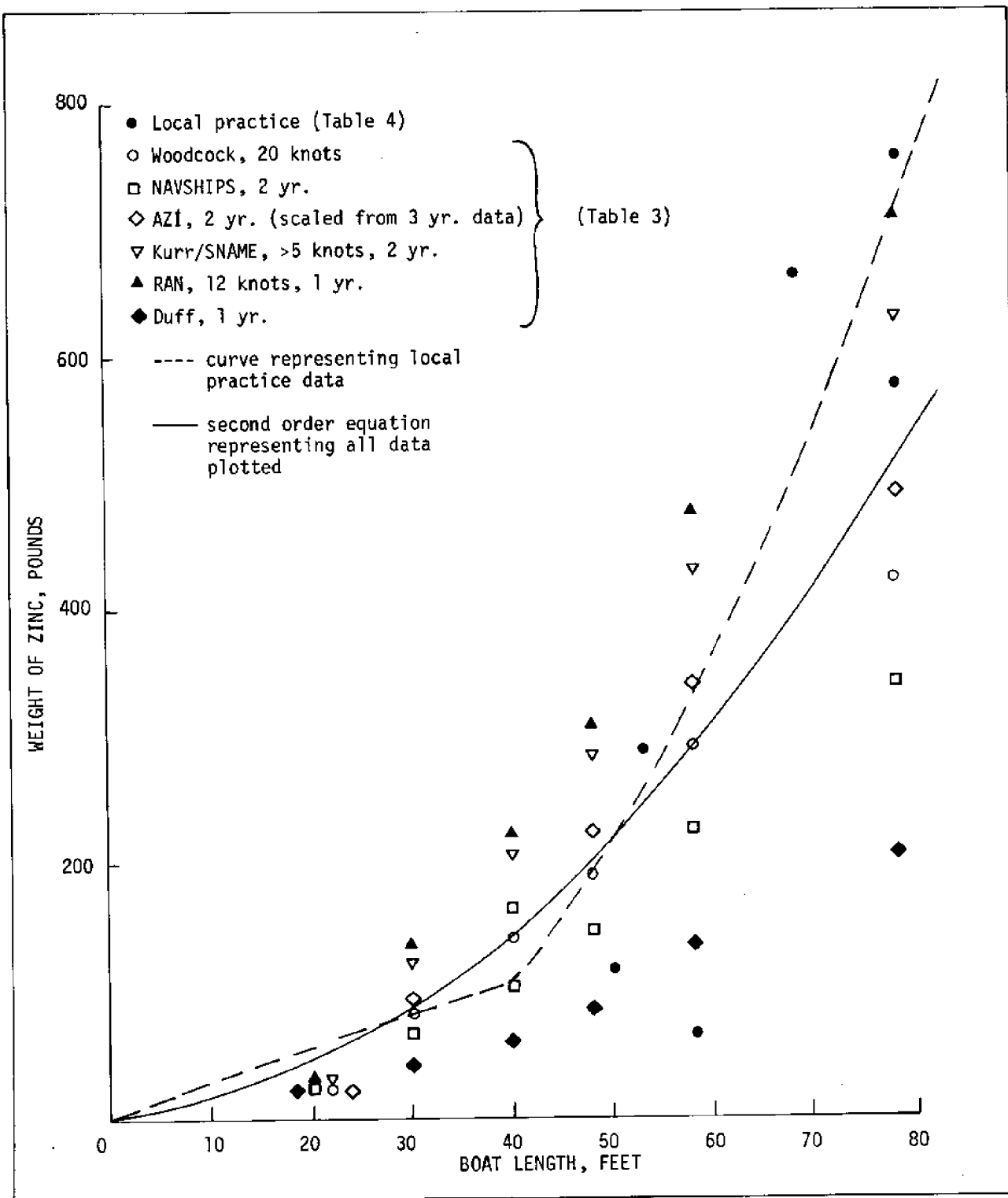
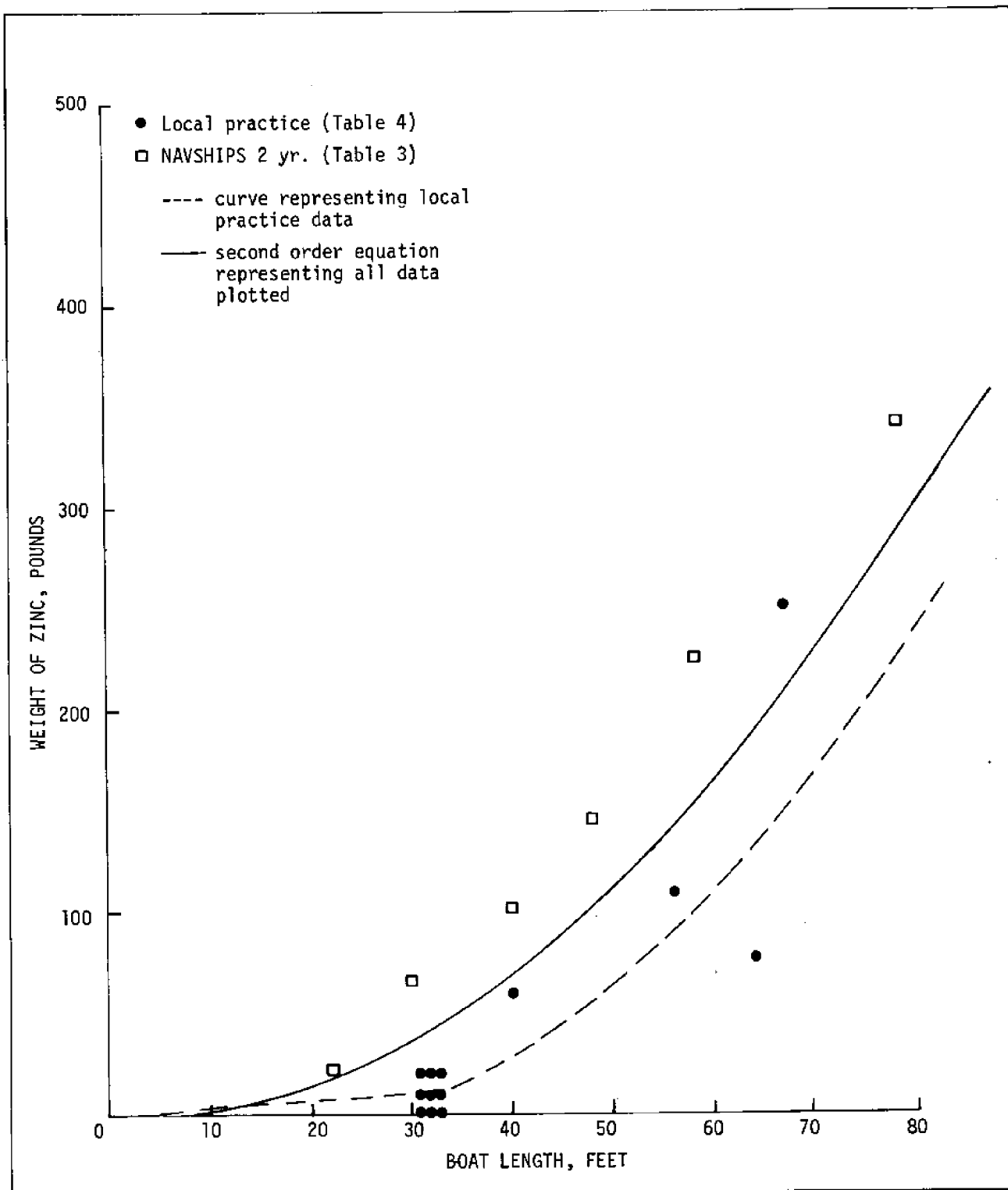Fig. 12. Weight of zinc recommended for steel hulled boats

Fig. 13. Weight of zinc recommended for aluminum hulled boats

to the recommendations detailed in table 3; some of the data is plotted in figures 11-13. Note that in general only the higher water velocity conditions are included in the graphs, thus indicating higher amounts more suitable perhaps for working vessels than pleasure craft. Note also that these example boats have fairly high amounts of exposed copper alloy material. Data was described by first representing local practice by the dotted curves shown in the figures. A least squares fit of all recommendations (with local practice treated as just one point) produced the solid curves shown. A range of approximately + 20 percent about these curves was used to itemize recommendations in the Extension bulletin summarizing this report (Mallon and Kolbe 1978).

In addition to the amount of zinc needed for cathodic protection, placement is also important. Placement of zincs should provide as broad a distribution of protective current as possible, taking into account ease of attachment, critical areas for protection, avoidance of high chafe areas, and any other practical considerations. Just under the turn of the bilge, along the side of the keel, under the transom, and on the bottom of the rudder or on the rudder face, are good places for zincs (Barber 1978). Propellers and shafts need extra protection because of high water velocity conditions and possible *stress corrosion* problems. Other hull fittings, such as keel coolers and radio ground plates are often protected with their own zincs, specified on the basis of their material and area (see table 3 and associated notes). In general, zincs are concentrated toward the stern of most vessels close to the unpainted critical metals (propellers, shafts, etc.). Keel coolers, bow irons, rudders, skegs, through-hull fittings, radio ground plates, and any other metal objects under water need protection and must be electrically connected, either directly or through the vessel's bonding system, to the proper amount of zinc. Figure 14 shows our recommendations for placement of zincs on a 65 foot steel shrimper. Configuration is based upon literature references, personal interviews, and direct observations of boats in dry dock.

For smaller wooden or fiberglass boats the main focus of protection is the shaft and propeller, for which there are three popular methods: the shaft collar, the wheel nut cap and the shaft brush (Fig. 15). Some interviewees report that shaft collars don't last long. They loosen and fall off after a short time. Those interviewed

attribute this loss to rapid rotation of the shaft and corrosion at the interface (Fig. 10). We have, however, observed a number of properly corroding shaft collars on sport boats and trollers. A zinc cap is often used on boats without exposed shafts; the cap fits over the wheel nut and must make good electrical contact with it. Wheels and shafts may also be protected by zincs attached to the vessel's bonding system, but in this method a shaft brush must be used to provide electrical contact between the shaft and the bonding system, since the lubricating oil in the gear box often insulates the shaft from the engine and therefore from the bonding system.

Zinc is not the only metal that can be used as a sacrificial anode; aluminum and magnesium are also used extensively in industrial applications such as pipelines and underground structures. Magnesium is generally unsuitable in saltwater applications due to its high negative potential (Fig. 2). In a good conductor such as sea water, these large voltage differences can cause excessive current densities at the anode. The dangers of such currents and consequent overprotection are discussed below. Magnesium anodes have, however, reportedly been used to protect galvanized sea water heat exchangers (Swartz 1978). Their use generally should be supervised by a corrosion engineer.

In recent years aluminum anodes have been used widely, particularly on offshore structures. Their chief advantages are lighter weight and lower cost. However, for small vessels aluminum anodes are not easily available and are thus less service-proven than zinc. As with zinc anodes, aluminum anodes must also be manufactured from a special alloy to ensure proper corroding action. Table 5 lists composition of several aluminum anodes and their manufacturers. (A zinc anode is listed at the bottom of the table, for comparison.) These aluminum alloys are anodic to the aluminum alloys used in marine construction, so that aluminum anodes could actually be used to protect aluminum hulls. (The Navy (NAVSHIPS 1968) however, recommends against using mercury-bearing aluminum anodes on aluminum hulls.)

As suggested previously, the current required for adequate cathodic protection varies greatly with water velocity, temperature, salinity, and the concentration of dissolved oxygen. The effect of moving water is to remove reaction products from the vicinity of the cathode (as shown in the reaction equations of section I.A.), thereby reducing polarization effects and maintaining
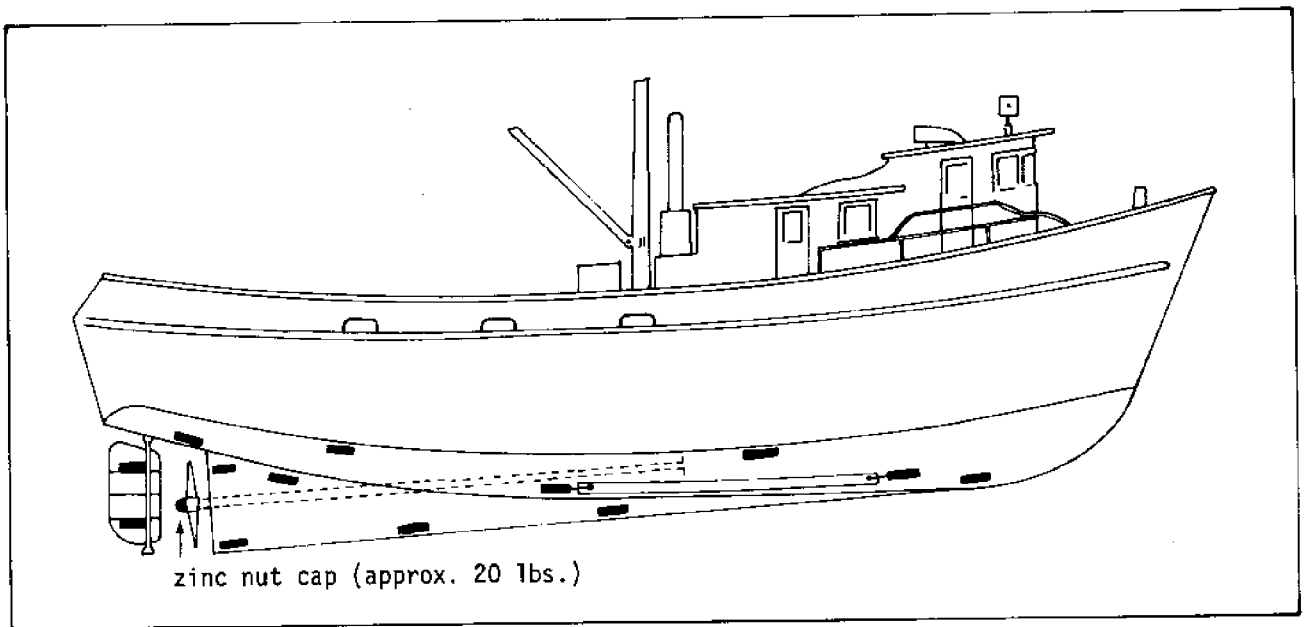
zinc nut cap (approx. 20 lbs.)

Fig. 14. Suggested placement of zinc anodes on each side of a 65 foot shrimper. (11 pound anodes represented by the symbol ▬)

full cell voltage. Thus the current drawn is greater under such conditions, and more zinc is required. (By Ohm's law, higher current is produced by higher voltage when the resistance is constant.) In a sense, zinc is self-regulating in that it puts out more current under conditions when more current is required. Note that in table 3, some sources give recommendations for both stationary and underway situations; in such cases the differences in recommended zinc are substantial.

Salinity also affects current output of a given amount of zinc; low salinity water has higher resistance than high salinity water and therefore allows less current to flow for a given voltage. Less cathodic protection is required in low salinity water, since corrosion by galvanic action is slowed down due to the increased resistance of the galvanic cell. This fact is another example of the self-regulating property of zinc sacrificial anodes; in low salinity water zincs put out less current and therefore last longer.

Likewise a good paint job on a metal surface causes a relatively small area of bare metal to be exposed, and this smaller surface area draws less current from a zinc.

In understanding galvanic action, it is

important to keep in mind the relative areas of the anodic and cathodic metal. Since the current flowing out of the anode must equal the current flowing into the cathode through the water, the *current density* at either electrode (the current per unit area of the electrode) depends on their relative areas. Figure 16 provides a schematic explanation of the relative area effect. One way to look at this effect is to consider what happens to the galvanic current when increasing amounts of zinc are attached to a piece of cathodic metal such as copper. (Compare with figure 6.) A greater surface area of zinc is now exposed to sea water and available for formation of zinc ions. Since the current in the circuit is governed by the rate of formation of these ions, the current increases. The area of copper, however, has not changed, but the current has increased, and therefore the current density at the copper is greater. High current density leads to high concentrations of hydroxide ions and hydrogen (see electrode reactions of section I.), which in some cases can cause a variety of problems, generally referred to as overprotection. Measuring the potential of the metal system versus a reference electrode will indicate whether the relative areas are correct for protection without overprotection (Fig. 7).

31

Manufacturer	Trade Name	Composition	Efficiency %	Current Capacity A-H/lb	Consumption Rate lb/Amp-year	Potential, vs Cu-CuSO$_4$ ref. in Seawater, Volts
Federated Metals, Somerville, NJ Cathodic Protection Service, Houston, TX	Galvalum*I	Zinc .45% Mercury, .045% Aluminum, remainder	95	1280	6.8	-1.1
Cathodic Protection Service, Houston TX	Galvalum*III	Zinc Indium Aluminum				
Federated Metals, Somerville, NJ	Hi-Amp	Zinc, 4.5% Indium, .02% Cadmium, .01% Impurities, "controlled" Aluminum, remainder	84.4	1102	8	-1.1
Kaiser Magnesium Div., Tulsa, OK	Kaiser KA90	Zinc Tin Aluminum	87	1176	7.4	-1.11
Kaiser Magnesium Div., Tulsa, OK	Kaiser KA95	Zinc Mercury Aluminum	95	1285	6.8	-1.05
Reynolds Aluminum Richmond, VA	Reynode					
Zinc Anode for Comparison (Lennox 1962)		Aluminum, .1-.5% Cadmium, .025-.15% Lead, .006% max. Iron, .005% max. Copper, .005% max. Silicon, .125% max. Zinc, remainder	95	372 (ideal)	23.5 (ideal)	-1.1

*Registered Trademark of Dow Chemical

Table 5. Composition and manufacturers of some aluminum anodes. (data taken from manufacturers' literature)
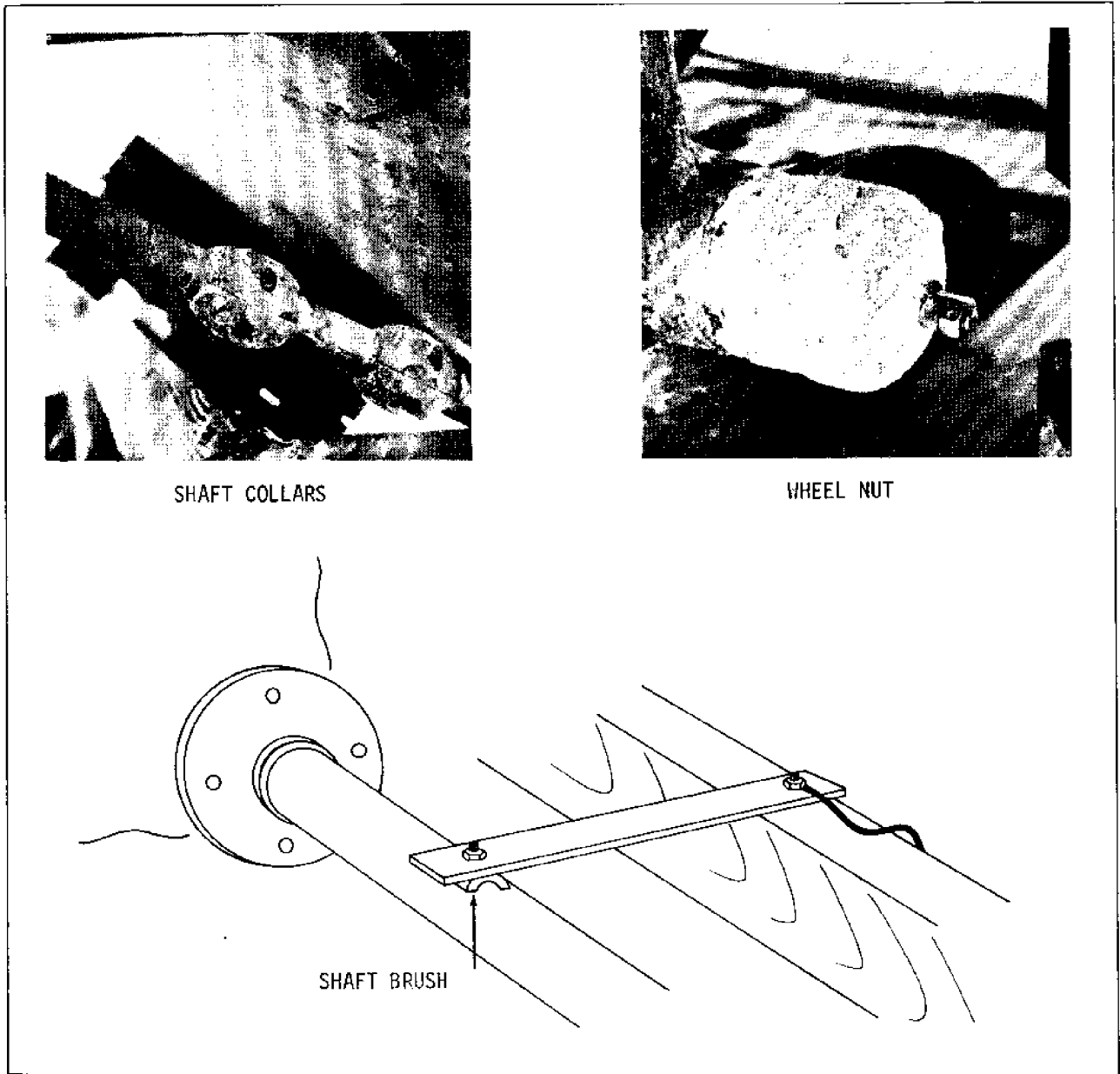
SHAFT COLLARS   WHEEL NUT

SHAFT BRUSH

Fig. 15. Equipment to protect shaft and propeller

Another important facet of the relative area effect is the fact that fastenings must always be, if anything, more noble than the metal that they are fastening. Otherwise they, being small, will corrode away very quickly. There are instances where vessels have been lost due to such an oversight. For example the yacht *Sea Call* sank many years ago because some of the monel hull plating was riveted with mild steel rivets. These rivets corroded away because they were anodic to the monel (LaQue 1975, p. 19).

A frequently asked questions is, "Can one overprotect a boat?". Under some conditions, the answer is yes. Despite the tendency for self-limitation in zinc anodes, overprotection can still occur. Excess hydroxide ions can react with oil based paint in a saponification reaction which renders the paint water soluble and causes it to be washed away (Brown 1969). Hydroxide ions can also attack aluminum, and for this reason overprotection must be avoided on aluminum hulls, outboards and outdrives (Swartz undated, Woodcock 1969). Wood electrolysis can result from overprotection in wooden boats (Fig. 17). This effect is actually an alkaline attack on the wood

A) Area of exposed copper is very large compared to that of attached zinc

Ammeter reading shows very low current flow between zinc and copper

current density at copper is very low

B) Areas of copper and zinc appropriately balanced for cathodic protection of copper

Ammeter reading shows medium rate of current flow

medium current density at copper results from proper cathodic protection

C) Area of zinc much larger than that required for adequate cathodic protection

Ammeter reading shows high rate of current flow

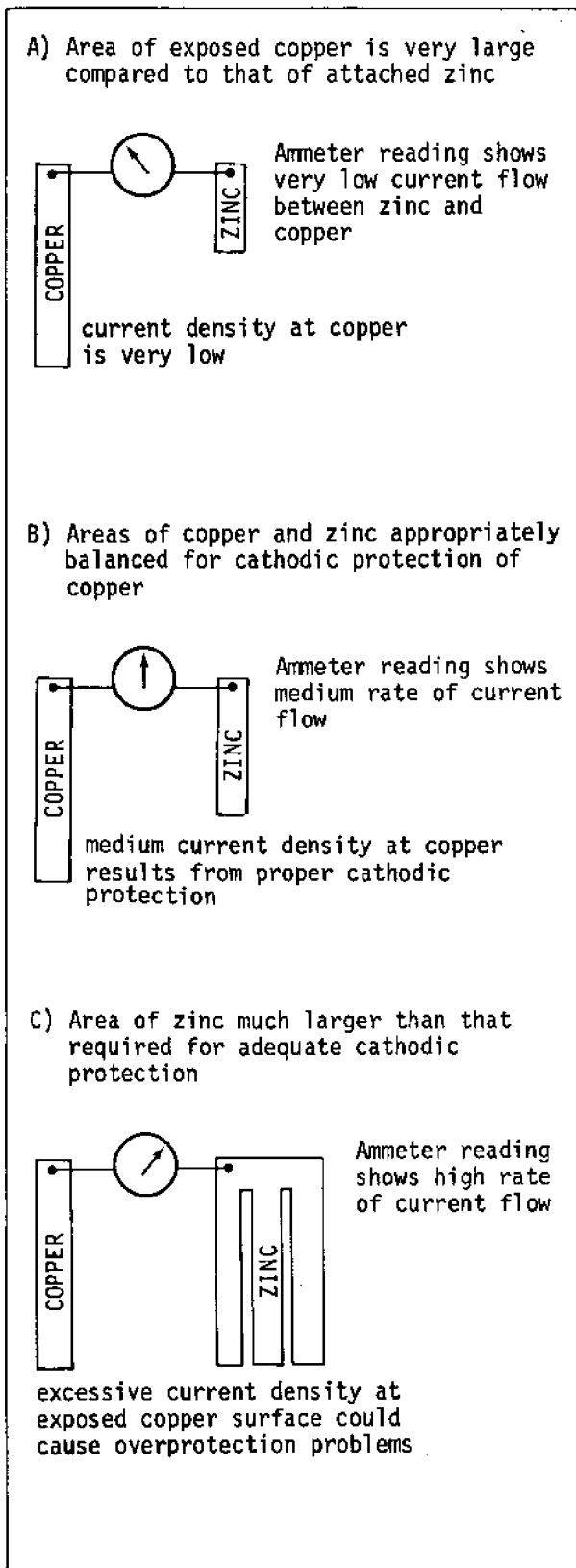excessive current density at exposed copper surface could cause overprotection problems

Fig. 16.   Relative area effect

fibers by the hydroxide ions produced in the cathode reaction (Swartz undated). The process is similar to that used in commercial pulping of wood to produce paper. Wood electrolysis is evident as a white deposit around fittings on the inside of the hull, and is characterized by the bitter taste of lye (sodium hydroxide) as opposed to the taste of salt (sodium chloride). Destructive action of the lye may be temporarily checked by brushing the deposits away and washing the affected area with distilled white vinegar (Swartz undated). Excess hydrogen produced in the cathode reaction can also damage paint; often an overprotected hull will exhibit paint blisters under which the metal will be clean and uncorroded (Swartz 1978). Hydrogen is also a well known cause of embrittlement in stainless steel (LaQue 1975, p. 215). Apart from hydrogen embrittlement, which is a well established phenomenon, some specialists claim that it is impossible to over zinc a steel hull (Swartz 1978).

The foregoing discussion has covered some of the factors influencing hull protection and some consequences of using inadequate or excessive amounts of zinc under various conditions. It is possible to take the guesswork out of hull protection by frequently measuring hull potential relative to a standard reference cell. Such frequent monitoring is necessary to ensure that the hull potential falls within the voltage levels recommended in an earlier section. It will warn against excessive galvanic action and with proper monitoring you can tell when zincs are expended, are not working properly, have fallen off, or have lost good electrical contact. In addition, hull potential monitoring can warn of stray current situations. Most experts recommend installation of a permanent hull potential meter and a permanently mounted reference electrode--either military specification zinc or silver-silver chloride.

. Some manufacturers of hull potential meters are:

Bartell Corporation, Newport Beach, Calif.
Electro-Guard, San Diego, Calif.
Engelhard Corporation, Union, N.J.

Figure 18 shows a typical unit manufactured by the Electro-Guard Company.

Even with hull potential monitoring, it will often be found that a boat will be underprotected while underway and overprotected when stationary. This inherent limitation of cathodic protection using directly connected zinc may be overcome by

Excessive protection, or high voltage, creates excessive current flow at fitting. Resulting production of hydroxide ions in water-soaked planking leads to wood electrolysis.
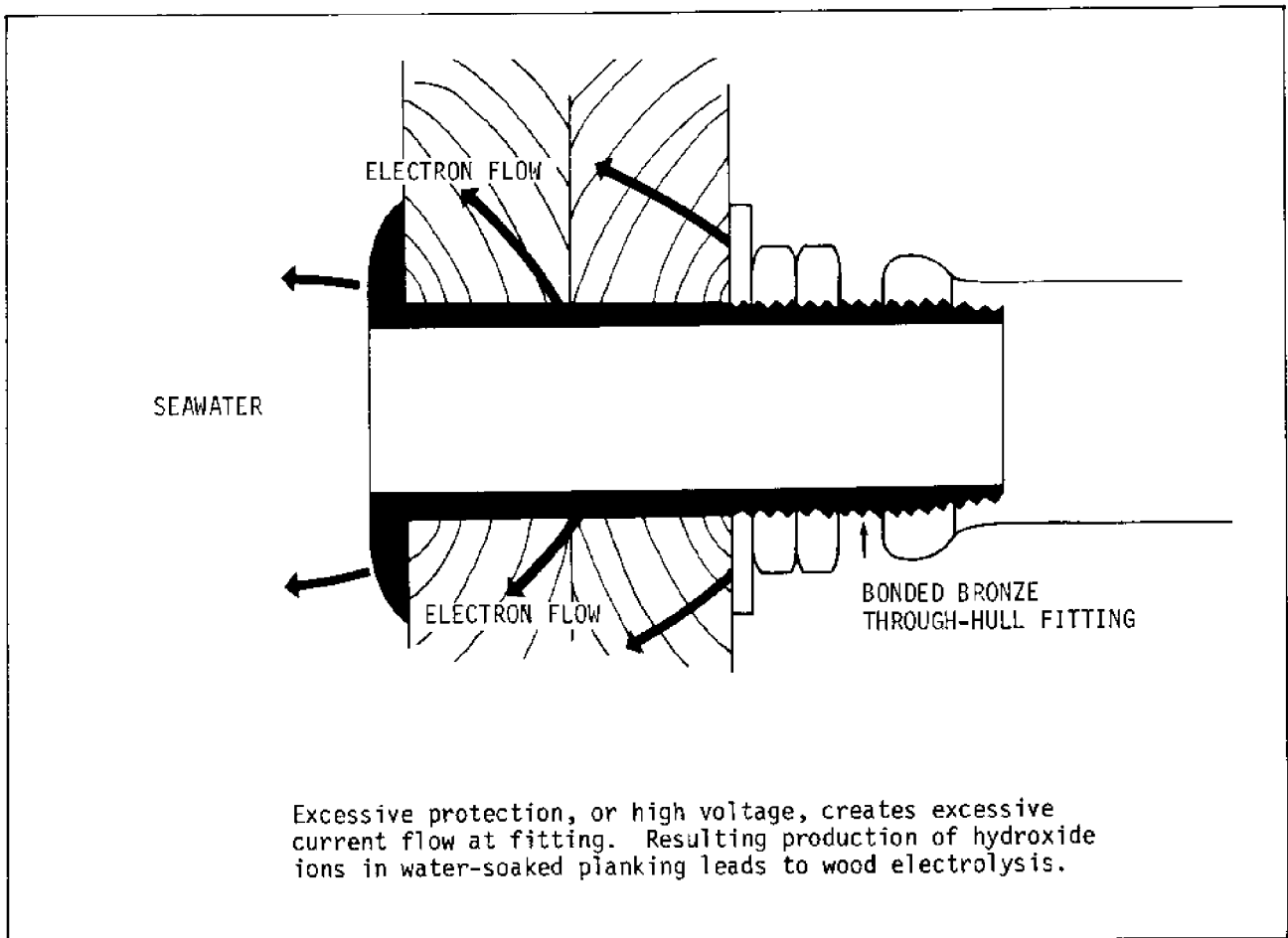
Fig. 17. Wood electrolysis

manually or electronically controlling the current in the external circuit from the hull to the zinc. Instead of attaching zinc directly to the metal to be protected or to the bonding system, the current is routed through a controller which adjusts the current to give optimum hull potential (Fig. 7). Such devices are manufactured by Bartell Corporation, 1577 Monrovia Avenue, Newport Beach, Calif. 92660 and Electro-Guard Corrosion Control Systems, P.O. Box 6187, San Diego, Calif. 92106. The systems also include hull potential monitors and zinc reference electrodes. These systems are said to provide adequate, but not excessive protection. They will extend the useful life of the zinc, and will reduce replacement costs.

One final variation on the zinc sacrificial anode technique is provided by the "Inter-zinc," manufactured for small craft by Intercontinental Factors, Inc., 1019 Santa Fe Avenue, Los Angeles, Calif. 90021.

This unit consists of a small zinc anode encased in, but insulated from, a copper tube containing an electrolyte. The copper is attached to the engine block and the zinc to the underwater fittings. These devices are not common in the Northwest, and we have no user information on which to base an evaluation.

II. B. Impressed Current Systems

The actual function of the sacrificial anodes in cathodic protection systems is to provide a source of current that will maintain hull potential at a protected value. Lennox (1977) describes cathodic protection in these terms:

"Cathodic protection functions by supplying sufficient current to ship hulls so that all areas on the hull assume relatively uniform potentials and thus effectively eliminate local anodes on the hull.

35

Monitor Meter
MODEL 110
- Aluminum Model 110A
- Steel Model 110S
- Bronze & Stainless Model 110 BR
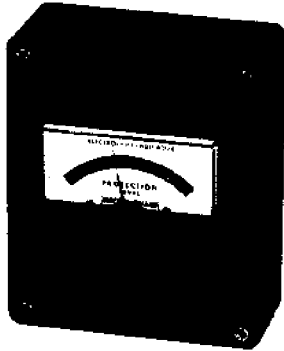
This unit is for all sizes of steel and aluminum hulls, ferro-cement boats and boats with I/O drive units. Coupled with the proper hull coatings and anti-fouling paint, it provides a complete anti-corrosion system for such vessels. The meter indicates at a glance how much corrosion protection is on the hull, and warns of any failure in the paint system protecting the hull. It also indicates immediately when zincs are lost, expended or contact to them is broken. It shows the presence of stray currents which may be the result of electrical leaks from other boats, the battery system, chargers, generators, or dockside current. The reference cell with insulated bolt for hull mounting is suitable for hulls up to 1½ inches thick. A portable model of this unit also is available for both aluminum and steel hulls.

Fig. 18. Hull potential monitor (courtesy of Electro-Guard Co.)

active (anodic) and corrode while other areas are inactive (cathodic) and do not corrode. By supplying D.C. current, the hull polarizes until the potentials of the local cathodes become as negative as the local anodes. Under these conditions, the discreet anodes and cathodes are eliminated, and corrosion does not occur on the structure."

It is possible to provide this current from the boat's battery. In these *impressed current devices*, a portion of the battery voltage is applied to the underwater metal and electronically controlled at a pre-selected value chosen for the type of metal to be protected (see figure 7 and associated discussion in section II.A.). These systems are commercially available; figure 19 shows the schematic installation of a typical small boat impressed current device manufactured by Engelhard Industries and labeled a *CAPAC* system (Cathodic Protection Automatically Controlled). *CAPAC* is described in the Engelhard literature:

"The Model 90W12D system is composed of four major components: the reference cell, the controller, the anode(s) and the CAPAC Monitor. These units perform the following functions:

(a)   The reference electrode produces a voltage which is related to the amount of protection received by the hull.

(b)   The controller compares the voltage produced by the reference cell with an internal voltage set by the factory. The output of the controller is automatically adjusted to keep the reference voltage at the same value as the factory set voltage.

(c)   The anode is an electrically insulated element located outside the boat's hull through which current flows from the controller into the water and back into the hull or bonded fittings.

The amount of anode current delivered by the controller is dependent upon factors such as: the physical dimensions of the hull, the condition of the paint on the hull, conductivity of the sea water, and the speed of the boat. For this reason, the operating current of the controller is difficult to predict.

(d)   The CAPAC Monitor is a panel mounted meter which is used to monitor the level of cathodic protection on a submerged metallic surface."

These systems have many advantages. They automatically sense hull potential and maintain current output from the anodes at the optimum level. They require no periodic replacement of anodes. Impressed current devices are widely used on larger vessels and ships, but have not enjoyed widespread acceptance among small boat owners. Chief
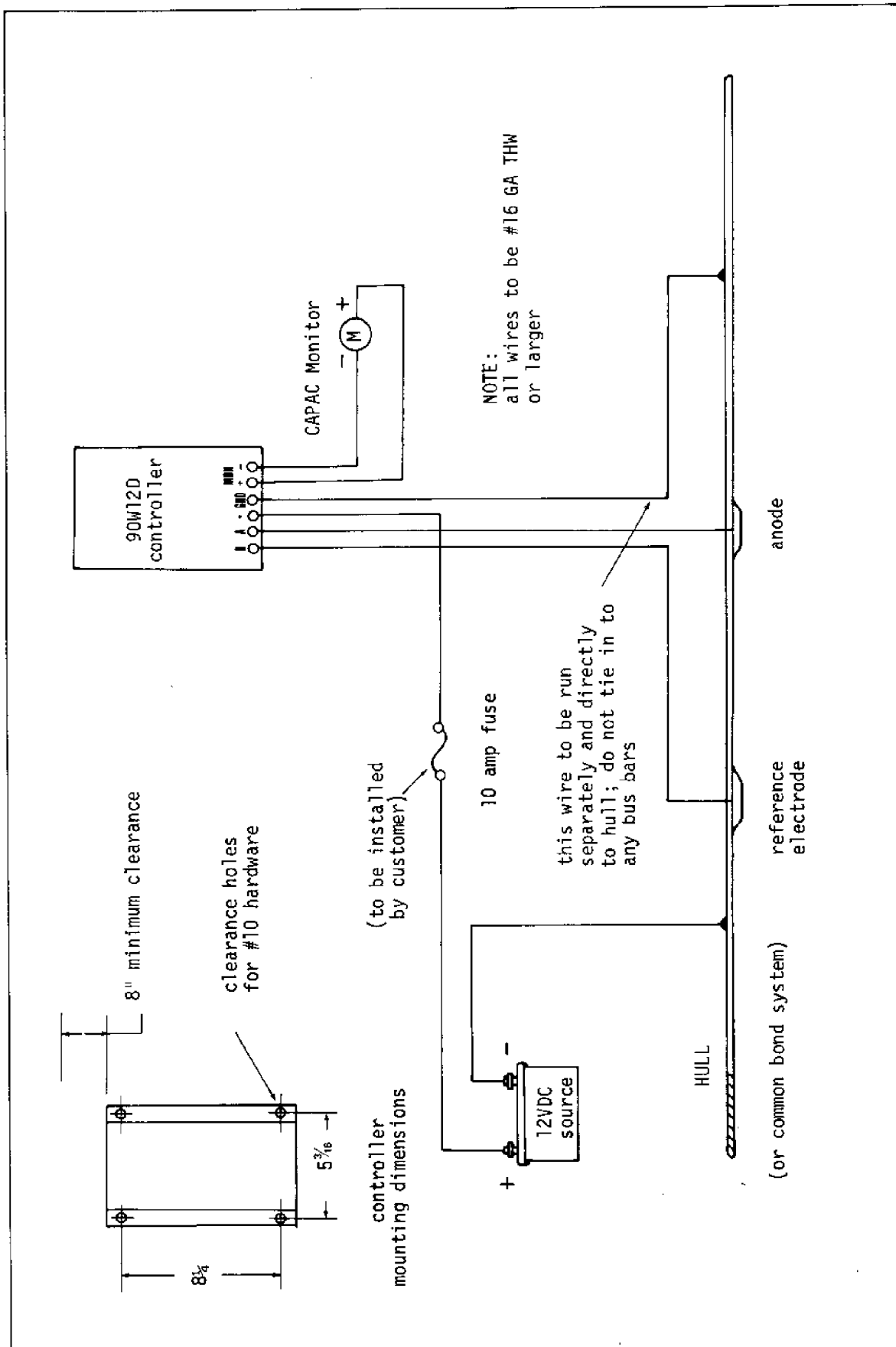
Fig. 19. Schematic for an Impressed Current System (courtesy, Engelhard Industries)

37

criticisms are that they require some under-
standing, maintenance, and monitoring on the
part of the operator for reliable service,
their initial cost is much greater than that
of a zinc sacrificial anode system, and that
they continually draw power from batteries
or power system. Without regular battery
recharging, an impressed current device can
run a battery dead within a few weeks.

Several manufacturers of impressed
current devices are:

Calpico, Inc., San Francisco, Calif.
Corrosion Control Associates, Richmond,
    Calif.
Engelhard Industries Div., (CAPAC),
    Union, N.J.
Mercury Marine (Quicksilver)*, Fond
    duLac, Wis.
Norton Corrosion Ltd., Woodinville, Wash.
Outboard Marine Corp. (ECP Corrosion
    Prevention Kit)*, Galesburg, Ill.
Wilson Walton International Inc. (Aqua-
    matic), Hoboken, N.J.

Table 6 summarizes information on some of
the commercially available impressed current
systems suitable for small boats.

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*Application limited to small boats having
outboards or sterndrives.

Manufacturer	Model No.	Max. Current (Amps)	Boat Categories Suitable Hull Material	Size	No. of Anodes*	1978 Hardware Costs	Source of Information
Engelhard "CAPAC"	90W12D	7 1/2	Steel	22' OB or I/O	1	$510	Steve Dodge, Corrosion Control Assoc.
			Steel	32' Troller	2	$625	
			Steel	40' Troller	3	$740	
			Steel	48' Fishing Boat	4	$855	
			Wood or Fiberglass	22'-40' I/O, Troller, Sailboat	1	$510	
			Wood or Fiberglass	48'-78' Fishing Boat	2	$625	
Corrosion Control Assoc.	Mark IB	5 1/2	Steel	22' OB or I/O		$475	Steve Dodge, Corrosion Control Assoc.
			Steel	32' Troller		$540	
			Steel	40' Troller		$655	
			Wood or Fiberglass	22'-40' I/O, Troller, Sailboat		$475	
			Wood or Fiberglass	48'-78' Fishing Boat		$540	
OMC	172372	1/2	Wood or Fiberglass	22' OB or I/O, 32' Sailboat**	1	$ 80	Dick Hamilton, OMC
Mercury Marine	C-66632A2 C-91-68086Al	1/2	Wood or Fiberglass	22' OB or I/O, 32' Sailboat**	1	$ 95 (includes monitor)	

* In addition to anodes, each system in this table uses one permanently mounted reference electrode.
** OMC and Mercury system suitable for 32' sailboat only under special circumstances.

Table 6. Examples of impressed current systems

III. OTHER FACTORS AFFECTING HULL PROTECTION

III.A. Stray Current Corrosion

Section I made some marine wiring recommendations to avoid electrolytic corrosion. Stray current corrosion, if it occurs, is usually more damaging to underwater metals than is galvanic action. Three forms of this phenomenon are discussed below.

The first, termed "D.C. stray current corrosion", occurs when unwanted direct currents flow between two points on the same boat. Usually this occurs because of faulty or inadequate wiring, poor insulation, or wet connections, which allow current to leak through highly conductive sea water. Figure 20 shows one example. A positive battery cable which passes through bilge water would have a similar affect. Any imperfection in the insulation could cause current to flow from the battery cable through the water to the hull of a steel boat. Regions of the hull receiving current would be more positive than other regions, and therefore would corrode by the principles of electrolysis explained in section I. Shielded wiring of adequate size, well insulated and sealed connections, and thorough bonding of the boat will usually eliminate D.C. stray current corrosion.

A second form of stray current corrosion is due to shore power effects. Shore power connections are a notorious source of corrosion and can be the major cause of underwater metal loss. If dockside wiring is inadequate to carry the currents required, voltage drops in the A.C. system will occur from one end of the dock to the other. When a voltage difference is applied to two boats by connection to the bonding system or boat ground of each, then current will flow through the water from one boat to the other, thereby causing rapid corrosion on one or both of the boats (Fig. 21).

Some docks do not have a separate safety grounding conductor, but simply tie the green safety ground wire from the boat shore cord to the neutral conductor within the
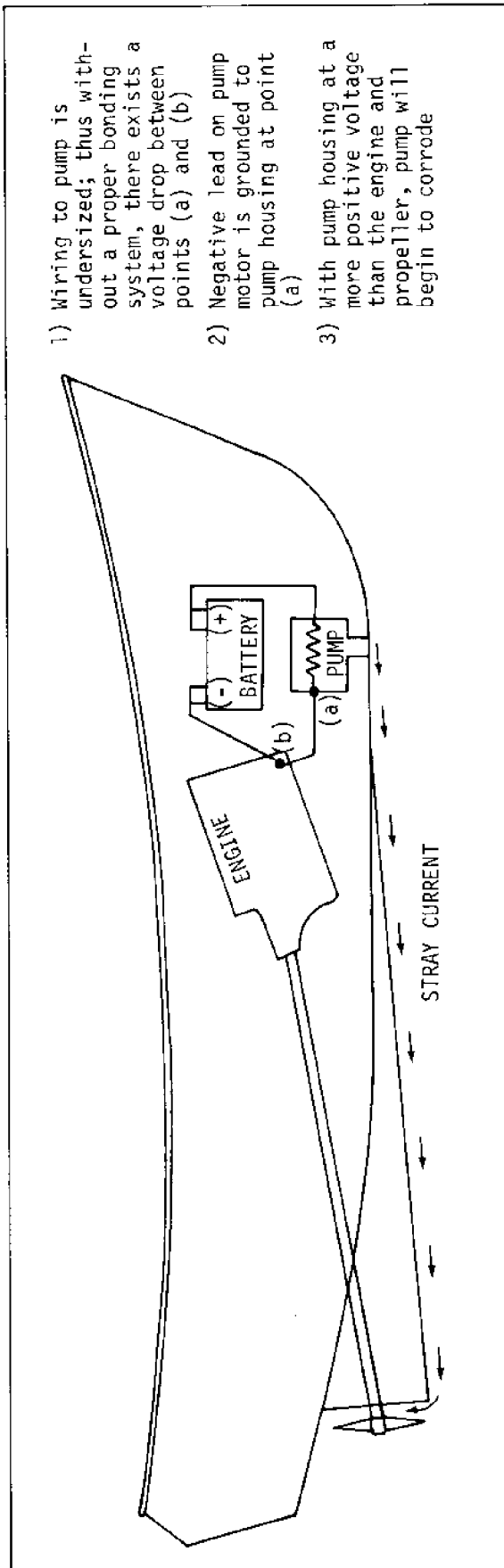
1) Wiring to pump is undersized; thus without a proper bonding system, there exists a voltage drop between points (a) and (b)

2) Negative lead on pump motor is grounded to pump housing at point (a)

3) With pump housing at a more positive voltage than the engine and propeller, pump will begin to corrode

BATTERY

ENGINE

PUMP

STRAY CURRENT

Fig. 20. DC stray current corrosion example (Miller 1973)

receptacle on the dock (Fig. 21). This situation invites corrosion whenever high power consumption on the dock causes appreciable current to flow in the neutral wire. Flow of current is associated with potential differences, and in such a case this potential difference would be impressed between the two boats tied into the shore power system. A preferred dock wiring system would incorporate a separate safety grounding conductor and would employ larger gauge wiring in the neutral leg to reduce voltage drops in this wire.

As mentioned in section I, an isolation transformer is the best insurance against A.C. stray current corrosion for the individual boat owner. Another device which is often used to reduce electrical shock hazard, the ground fault circuit interrupter (GFCI), can also protect against some forms of stray current corrosion. The GFCI senses even small currents indicative of leakage in the safety grounding conductor and automatically shuts off the A.C. power. A third device, called an "isolator", is less desirable than an isolation transformer but is capable of blocking stray D.C. voltages while at the same time allowing any dangerous A.C. currents to pass to ground. The isolator will not, however, prevent A.C. stray current corrosion. Likewise, the GFCI suffers from the disadvantage that it is impractical to protect an entire boat with a GFCI; they are suitable primarily for use on individual applicances, such as power tools (Miller 1973).

Some battery chargers can cause electrolytic corrosion. One particularly bad type does not isolate the primary from the secondary windings. Such units are called auto transformers and should not be used in marine applications (Kolbe and Ericksen 1975). Since stray currents can exist within a boat and cause corrosion even with a good battery charger, many persons disconnect both terminals of the battery as a precaution during charging (Cropsey 1976).

One more example of vessel corrosion related to shore power connections appears in figure 22. Two adjacent vessels plugged into the dock A.C. circuit could have their underwater fittings connected, as described in figure 21. Suppose boat A (Fig. 22) has a positive-to-ground D.C. system. Suppose further that boat A has some electrical leakage problem--perhaps poor wiring insulation is causing current to leak from a hot wire (in boat A's case, negative) to an underwater fitting. As a result, not only will the other underwater fittings on boat A be relatively *positive* and thus begin to rapidly corrode, but the underwater fittings on boat
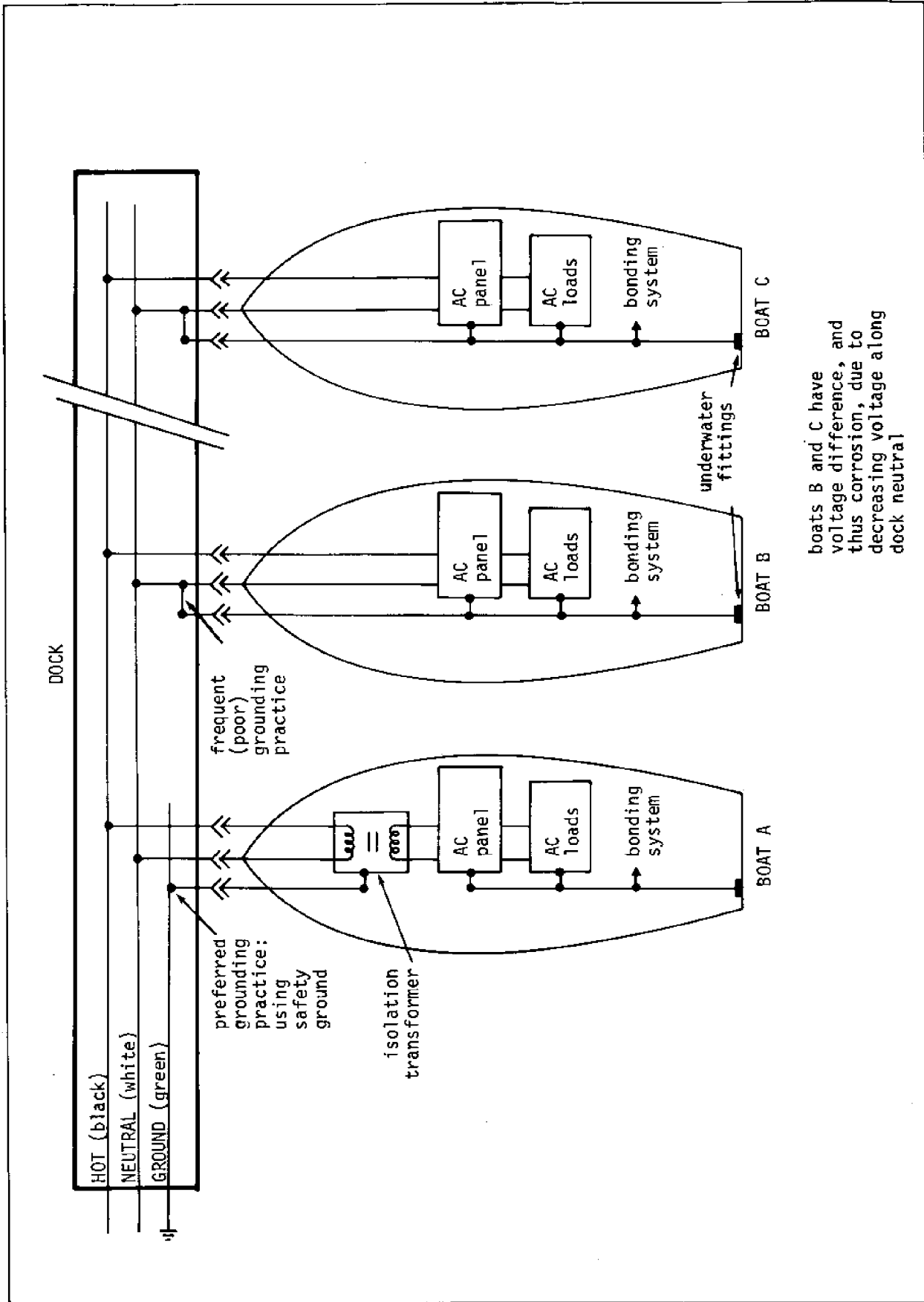
DOCK

HOT (black)
NEUTRAL (white)
GROUND (green)

preferred grounding practice: using safety ground

frequent (poor) grounding practice

isolation transformer

AC panel

AC loads

bonding system

BOAT A

AC panel

AC loads

bonding system

BOAT B

AC panel

AC loads

bonding system

BOAT C

underwater fittings

boats B and C have voltage difference, and thus corrosion, due to decreasing voltage along dock neutral

Fig. 21. Example of stray current corrosion due to inadequate AC wiring (Cunning, 1978)
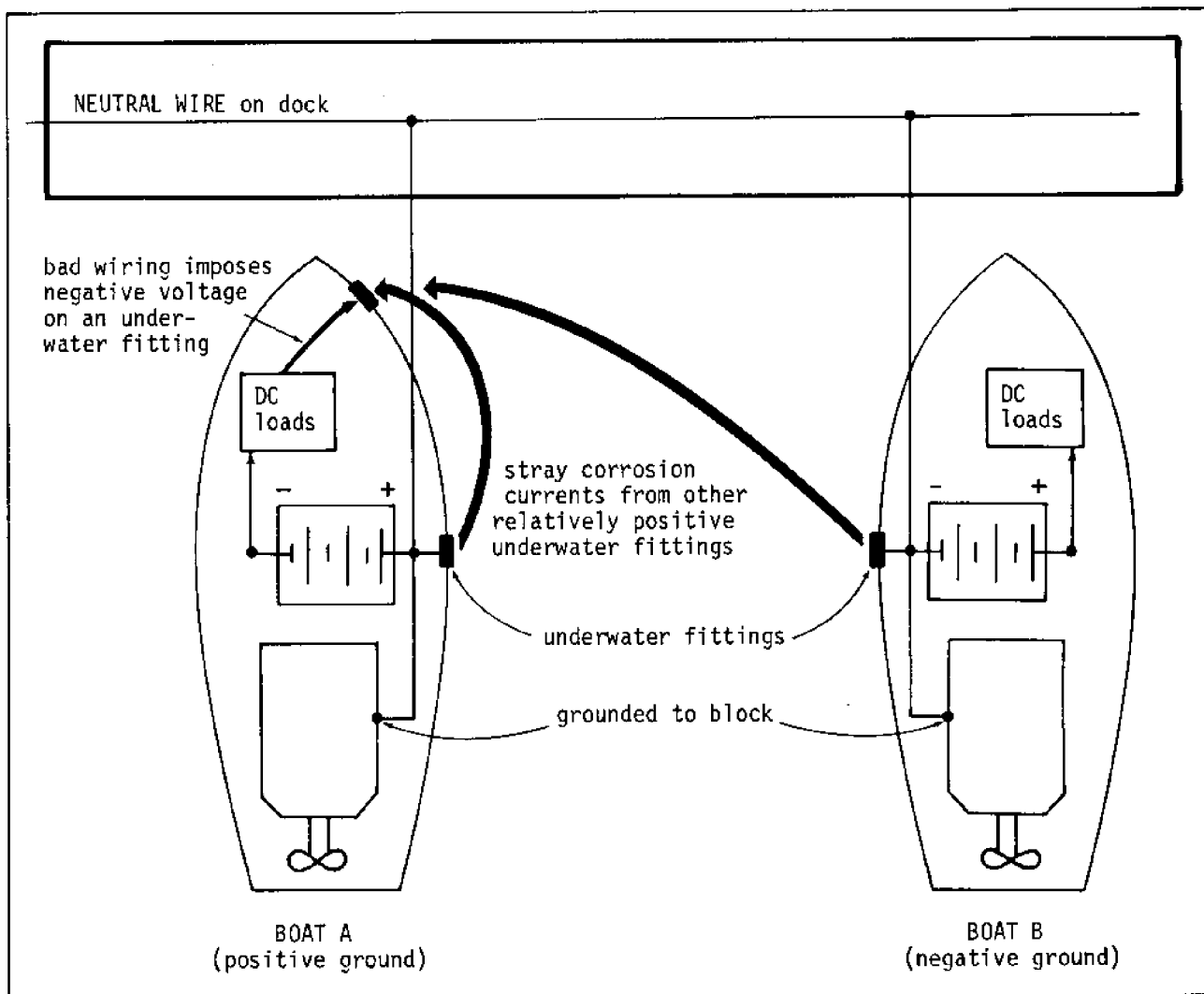
Fig. 22. Stray current corrosion resulting from a failed positive-to-ground system

B will also be relatively positive, and also rapidly corrode.

A third form of stray current corrosion results from electric fields set up in the water next to a moorage. Currents flowing through the water from one region to another will be concentrated in the higher conductivity material of a boat moored in the path of the current (Fig. 23). (An analogous phenomenom occurs in magnetic fields, where flux lines are concentrated by ferromagnetic materials.) The boat in the middle could be damaged, even if that boat has no shore cord connection (Cunning 1978, Dodge 1978).

Isolation transformers, permanently mounted hull monitors, adequate vessel wiring and bonding systems, and sound dock wiring are all important in preventing these stray

current situations. The individual boat owner can check out a few things on tying up. First, hull potential can be measured with a meter and portable reference electrode placed at various positions around the boat. Potentials measured should not differ by more than about ten millivolts (Cunning 1978). Hull potential measurement on both sides of the boat as well as fore and aft will alert the boat owner to potentially damaging electrical fields in the water. Second, under some conditions, it is important to check shore cord polarity (Miller 1973, ABYC 1977). This can be determined either by measurement with a multimeter or by using a polarity indicator. This precaution will prevent accidental reversal of the shore cord plug (either by incorrect receptacle wiring or by actual physical reversal) which under some
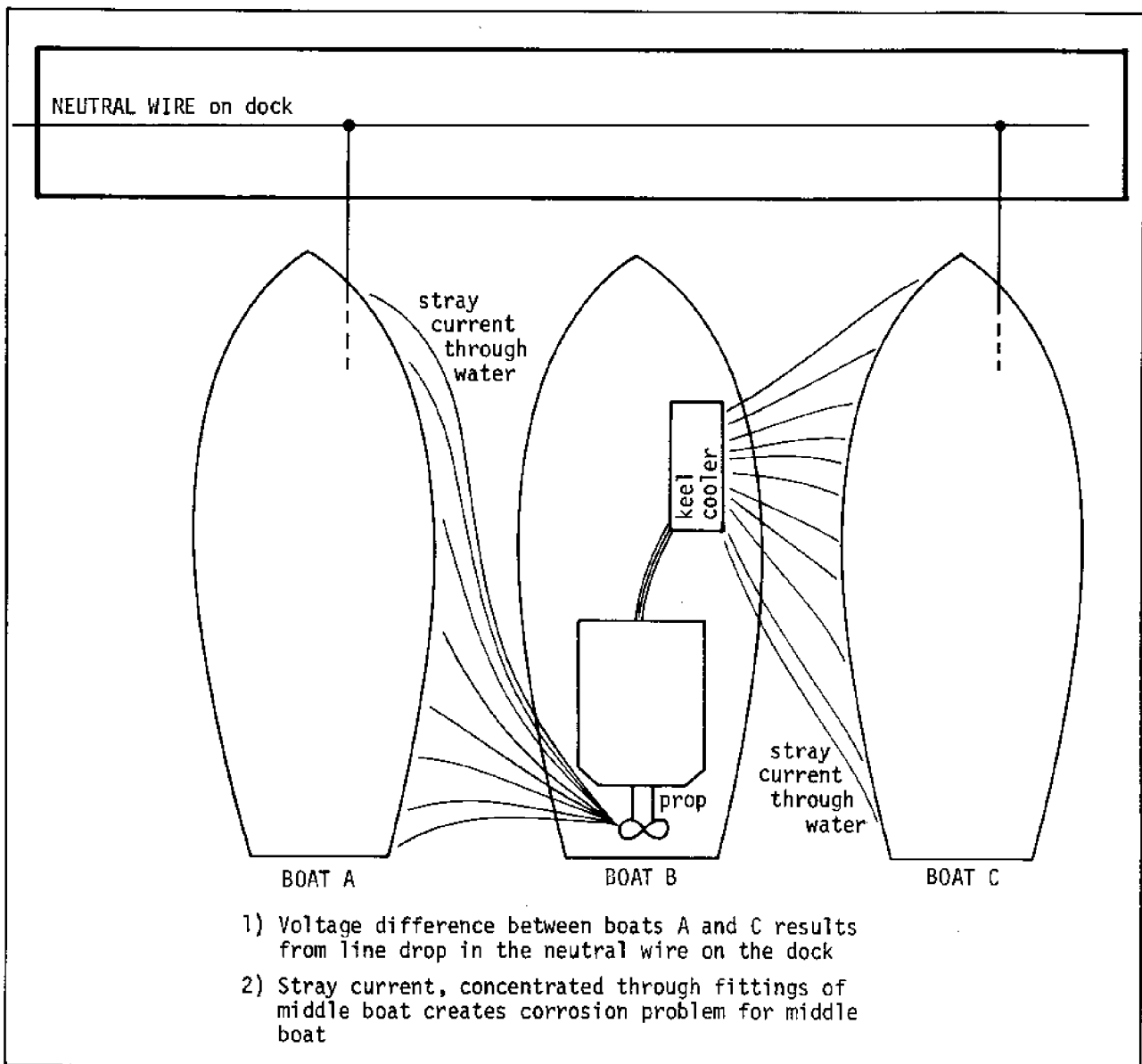
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Fig. 23. Concentration of stray current through an isolated boat

circumstances could cause the hot conductor to be carried to boat ground. Only high resistance polarity indicators should be used; ABYC requires that these devices have an impedance of at least 100,000 ohms (ABYC 1977). Otherwise they can draw appreciable current and give rise to stray current corrosion themselves.

The areas of cathodic protection, stray current corrosion, and electrical trouble-shooting are all related and can be complex. Frequently, one runs into situations requiring the services of a corrosion engineer or marine electrical specialist.

Appendix D gives a list of some industry specialists who have advertised services for marine corrosion control and electrical troubleshooting, and are accessible by the Oregon fleet.

III.B. Troll Wire Voltage Controllers

Many salmon trollers attempt to adjust troll wire voltage by first isolating the steel wire from the boat and then imposing a small positive voltage. This is done by either adjusting the number of zincs on the hull, or by installing any one of a number of commercially available electronic devices

driven by the vessel's battery. The practice originated in Canada (Kolbe et al. 1975), and is widely used. No scientific evidence has been reported to determine its effectiveness.

An important question is: How does the adjustment of this voltage affect the cathodic protection of the boat? If one is not using the electronic controller, line voltage increases as more zinc anodes are added to the hull. If there is more zinc than needed to protect the hull and underwater fittings, overprotection occurs.

If an electronic controller is used to impose positive line voltage, there will be little if any effect on the cathodic protection of the hull (Cunning 1978, Dodge 1978). A more rapid deterioration of the stainless steel trolling wires will occur, however.

III.C. Welding and Construction

Welding on boats must often be done without bringing the welding unit on board. In this event, great care must be taken to provide extremely low resistance ground paths from the boat to the shore. The cable must be attached to the boat as close as possible to the site of the weld. Ideally, this connection should be made to a special lug welded to the hull (Wilskey 1978). Very large currents are generated in arc welding and can flow from hull to ground through the water unless an adequate ground cable is provided.

Mill scale is cathodic to steel; if not removed by the builder, pitting can occur (Kurr 1978). Also, some experts have suggested that hull plating from different manufacturers or from different batches of steel can have different galvanic potentials and can therefore give rise to galvanic corrosion when welded together (Cunning 1978, Wilskey 1978).

III.D. Paint Systems

This report will not discuss paint systems in detail--but will relate basic paint characteristics to cathodic protection. Well-painted surfaces allow only very small regions of metal to contact sea water. These regions are often microscopic in size and are frequently called holidays. The current required to cathodically protect a surface has been monitored with ammeters on vessels protected by impressed current devices. For well-painted hull surfaces, it

is quite low. As the surface coating ages and slowly deteriorates, the current climbs gradually. If the coating becomes damaged due to abrasion or collision, the required current can rise dramatically.

Figure 24 demonstrates this behavior by showing current vs. time for a tug used in the area of Cook Inlet, Alaska (Barber 1978). Current climbed gradually as the epoxy coating aged but jumped dramatically when it encountered heavy ice and suspended silt during one winter's operation.

Other examples can be found. SNAME and Australian Navy tables reproduced in section II.A. show dependence of current density requirements on both *type* and *age* of the paint system.

Another example appears in table 7 which gives cathodic protection current requirements for proper design of a merchant ship system (Norton Corrosion undated). Note that current densities depend upon both the type of paint used, and on the expected service of the ship.

Certain types of paint and combinations of paint must be avoided in some situations. For example, copper-containing bottom paint should never be used on aluminum hulls, or attack on the aluminum by the more cathodic copper will result. Tin-containing bottom paints are recommended for use on aluminum hulled vessels (Holm and DeFarrari 1974, Lennox 1977).

Copper-containing bottom paints can also cause pitting on steel hulls. Copper should be avoided unless an insulating barrier is applied between the hull and the bottom paint (Lenk 1977, SNAME 1976). Organo-tin based bottom paints and others containing less soluble copper compounds such as hydroxides are recommended for steel hulls (Devoluy 1967). On wooden or fiberglass hulls, copper-containing bottom paints are quite common and are often applied directly to the hull after suitable surface preparation.

Some sources claim that cathodic protection reduces the effectiveness of copper antifoulants. Since the bottom paint works by slowly dissolving to form copper ions which are toxic to attacking organisms, the use of cathodic protection might be expected to slow down this dissolving process and thereby reduce the effectiveness of the antifoulant. Other sources, however, claim that there is little or no effect on antifouling by cathodic protection (Chandler 1977, Hillstrom 1978).

The use of zinc rich in primers on steel hulls is also an area of controversy; hy-droxide ions formed at the cathode are thought to attack the zinc (Devoluy 1967).
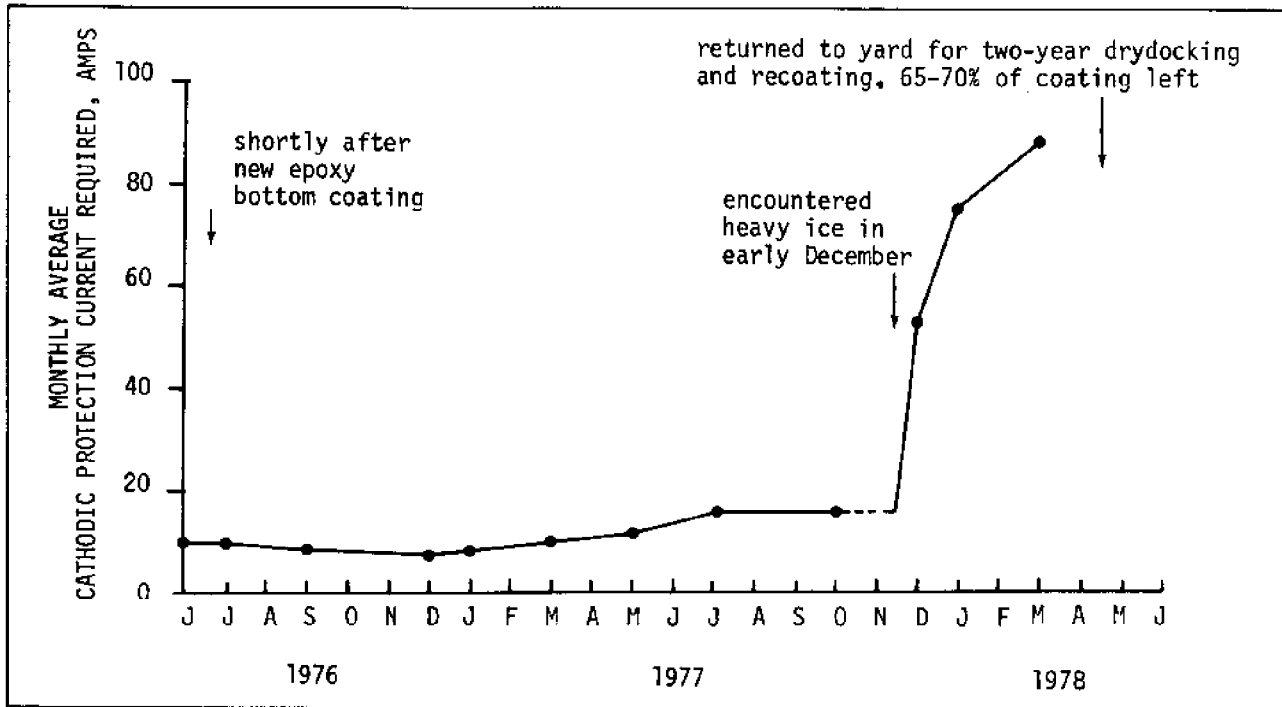

Fig. 24. Cathodic protection current needed for the Alaska-based tug "Alaska Husky" (courtesy of Mr. Wally Barber, Foss Tug and Launch Co., Seattle)

Since hull roughness control and corrosion control are equally important when designing cathodic protection systems, current requirements must be chosen carefully. The following table gives representative requirements.

CURRENT DENSITY TABLE* - MERCHANT SHIPS**

BOTTOM PAINT

New Ships	Coal Tar Epoxy	Vinyl Chlorinated Rubber	Conventional Primer and Top Coat		Bare or Primed Areas
Old Ships Service		Coat Tar Epoxy	Vinyl Chlorinated rubber	Conventional Primer and Top Coat	Bare or Primed Areas
Deep Port to	3.3 ma/ft.^{2}	3.7 ma/ft.^{2}	4.7 ma/ft^2	5.6 ma/ft.^{2}	11.2 ma/ft.^{2}
Deep Port	35 ma/M^2	40 ma/M^2	50 ma/M^2	60 ma/M^2	120 ma/M^2
General	3.7 ma/ft.^{2}	4.7 ma/ft.^{2}	5.6 ma/ft.^{2}	5.6 ma/ft.^{2}	11.2 ma/ft.^{2}
(some channels)	40 ma/M^2	50 ma/M^2	60 ma/M^2	60 ma/M^2	120 ma/M^2
Occasional bars and some scrap-	5.1 ma/ft.^{2}	5.6 ma/ft.^{2}	6.5 ma/ft.^{2}	6.5 ma/ft.^{2}	11.2 ma/ft.^{2}
ing	55 ma/M^2	60 ma/M^2	70 ma/M^2	70 ma/M^2	120 ma/M^2

* Minimum size system when anodes are not well distributed: mean requirement when they are well distributed.
** Tug boats and faster small vessels require much higher current densities.

Table 7. Cathodic protection current requirements (courtesy, Norton Corrosion Limited, Woodinville, Wash.

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APPENDIX B.   GLOSSARY OF TERMS

ampere: The unit of flow rate of electrical charge (often abbreviated amp).

anode: The electrode of an electrochemical cell at which oxidation is the principal reaction. Also the electrode which corrodes in a sacrificial metal cathodic protection system or in other galvanic action.

bonding: The practice of using very low resistance conductors to electrically tie together all the metal parts of a boat.

calomel electrode: A reference electrode similar to Ag-AgCl; differs in potential by only a few millivolts.

cathode: The electrode of an electrochemical cell at which reduction is the principal reaction. Also the protected metal in a cathodic protection system.

cathodic protection: The practice of protecting underwater metal parts by making them cathodes, either by connecting them to sacrificial anodes of a less noble metal, or by using an impressed current device.

circuit: A system of conductors and other electrical components in which current flows.

conductivity: Ability to carry current; the reciprocal of resistance.

current: The flow of electrical charge in a circuit. Units are amperes or amps.

current density: Current per unit area (i. e., area through which the current flows).

electrode: A component of a circuit, usually metal, which is immersed in the electrolyte.

electrolysis: Traditionally, a term used to describe all forms of electrochemical corrosion, including both galvanic action and stray current corrosion. Chemically, the producing of chemical changes by passage of an electric current through an electrolyte.

galvanic action: The corrosion which occurs when two dissimilar metals are electrically connected and immersed in an electrolyte.

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

ground: Electrical connection to the earth. (Sometimes used to refer to a connection to a common conducting framework, such as an automobile frame or appliance chassis.)

hull potential: Potential of hull (metals) with respect to a standard reference electrode.

hydroxide ion: OH^-

impressed current device: A device, usually electronically controlled, which takes a portion of a boat's power supply and applies it to the hull in such a way that the hull is negative and therefore protected.

ion: An atomic or molecular species which has either an excess or deficit of electrons, rendering it charged.

load: A circuit component which draws current from a voltage source.

ohm: The unit of resistance to flow of electrical charge.

noble: Metals generally less prone to corrosion are said to be more noble than others (also more cathodic).

Ohm's law: $V=iR$, $i=\frac{V}{R}$ or $R=\frac{V}{i}$, where V is the voltage, i is the current in amperes (or amps), and R is the resistance in ohms (Ω). A voltage of one volt placed across a resistance of one ohm will cause a current of one ampere to flow.

oxidation: Loss of electrons.

oxide: A chemical compound consisting of positive ions (usually metal ions) bonded to negative oxygen ions.

polarization: A change in potential (in our context, by reason of electrochemical action).

polarity: The identification of the positive and negative terminals.

potential: (see voltage).

reduction: Gain of electrons.

resistance: The opposition to current flow by a circuit component when voltage is applied.

shaft brush: A device used to provide good electrical contact with a rotating propellor shaft, for purposes of bonding.

silver-silver chloride electrode (Ag-AgCL): A commonly used reference electrode for measurement of potentials in an aqueous solution.

stray current corrosion: Corrosion caused by unintentionally impressing a voltage, either A.C. or D.C. on an underwater metal component.

stress corrosion: Mechanical stress has the effect of making a metal more anodic, thus accelerating its corrosion.

thermodynamics: A branch of physical science which deals with heat transfer and energetics of processes.

volt: The unit of electrical potential or voltage (given the symbol V).

voltage: (Also potential) A measure of the driving force for flow of current. Often compared to hydraulic pressure.

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   INTEREST

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APPENDIX D. SOME CORROSION CONTROL SERVICES
AND MARINE ELECTRICAL CONTRACTORS, SAN
FRANCISCO TO SEATTLE*

Code identifying type of service:

1 - Cathodic protection consulting service
2 - Hull potential measurement
3 - Boat electrical wiring
4 - Electrical troubleshooting
5 - Sales of sacrificial anodes
6 - Sales of impressed current devices

Name/address	Type of Service

California

Calpico, Inc. 185 T Harbor Way San Francisco, CA 94124 (415) 588-2241	1,2,4,5,6
Corrosion Control Associates Steve Dodge 5601 Doremus Avenue Richmond, CA 94085 (415) 233-6061	1,2,4,5,6
Carranza Marine Electronics Fred Sundquist 317 W. 17th Eureka, CA 95501 (707) 445-2224	1,2,4,6
South Bay Marina Bill Donahue Foot of C. Street Fields Landing (Eureka), CA 95501 (707) 442-4571	3,4,5

Name/address	Type of Service

Oregon

Hillstrom Shipbuilding Co. Ron Halbritter P.O. Box 477 Coos Bay, OR 97420 (503) 269-1115	1,3,4,5
Marine Electrical Conrad Muller P.O. Box 5648 Charleston, OR 97420 (503) 888-9202	1,2,3,4,6
Mid Coast Marine Jack Wilskey P.O. Box 692 Coos Bay, OR 97420 (503) 269-5101	1,3,4,5
Bayside Machine Works, Inc. Mark Chandler Yaquina Bay Road Newport, OR 97365 (503) 265-5241	1,3,4,5
Yaquina Bay Marine Supply Ray Carter 424 SW Bay Blvd. Newport, OR 07365 (403) 265-5143	2,5,6
Astoria Marine Construction Co. 403 SW Front Street Astoria, OR 97103 (503) 325-4121	3,4,5
Bumble Bee Shipyard and Machine Shop Mel Hjorten P.O. Box 60 Astoria, OR 97103 (503) 325-5252	3,4,5

Washington

| Boat Electric Co. Ray Bunn 6303 Seaview Avenue NW Seattle, WA 98107 (206) 784-5908 | 1,2,3,4,5,6 |

*This list of companies or individuals is
not complete and does not constitute an endorse-
ment by Oregon State University. The list
results from commonly known or advertised
services which are available to Oregon boat
owners and companies.

Name/address	Type of Service
Foss Shipyard Wally Barber 660 W Ewing Street Seattle, WA 98119 (206) 281-3872	1,2,3,4,5,6
Harris Electric, Inc. Fishermen's Terminal Seattle, WA 98119 (206) 282-8080	3,4
Hendricks Electric, Inc. Stan Hendricks Fishermen's Terminal Bldg. C-10 Seattle, WA 98119 (503) 284-8840	3,4
Lunde Electric Co., Inc. 2401 NW Market Street Seattle, WA 98107 (206) 783-6800	1,2,3,4
Norton Corrosion, Ltd. Roy Casper Woodinville, WA 98072 (206) 486-9126	1,2,4