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Report 4200

Impressed-Current Cathodic Protection for Surface-Effect Ships

NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER
Bethesda, Md. 20034

IMPRESSED-CURRENT CATHODIC PROTECTION FOR SURFACE-EFFECT SHIPS

by

H. P. Hack, B. E. Miller,
and D. A. Davis

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Naval Ship Research and Development Center
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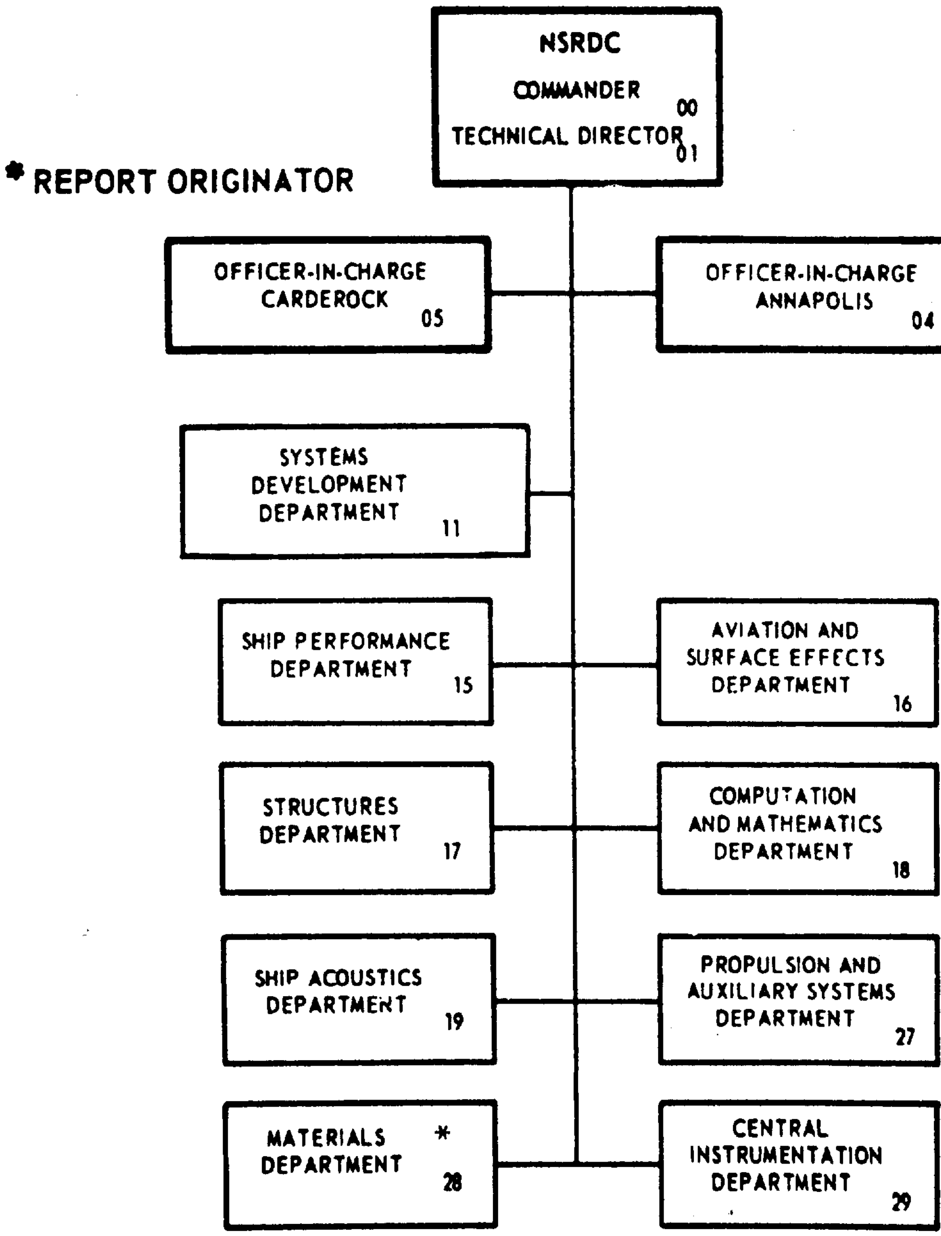

DEPARTMENT OF THE NAVY

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ABSTRACT

Impressed-current cathodic protection for surface effect ships is discussed from the viewpoint of the craft designers. After a brief explanation of the fundamental principles of cathodic protection, the function of an impressed-current system on surface-effect ships is discussed in general, and a design procedure is outlined and specifically applied to SES 100B. A brief discussion of commercially available cathodic-protection-system components is presented.

A laboratory investigation was conducted to provide background information for impressed-current cathodic protection of surface-effect ships. The optimum protection potential was identified by performing polarization experiments in flowing seawater (0-77 knots). Current requirements, at this potential level, were generated for SES 100B by combining the laboratory results with calculated surface areas of the wetted hull and appendage components.

ADMINISTRATIVE INFORMATION

This report was prepared under Work Unit 1-2813-154, Task Area S4629, for the Surface Effect Ships Program Office (SESPO) titled, "Galvanic Measurements of Surface Effect Ships." This is the final report of the program and constitutes milestone 4 of the 1 November 1973 Program Summary.

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INTRODUCTION

The 5000-series aluminum alloys are used on surface-effect ships and other weight-critical, high-performance craft. Although these aluminum alloys are, by nature, chemically reactive, an adherent oxide film renders them generally corrosion resistant in sea water. However, when electrically coupled to various corrosion-resistant appendage materials, such as titanium, stainless steels, and nickel alloys, accelerated corrosion of the aluminum will result. As it is difficult to avoid the use of these materials in high-performance craft, some form of protection system for the aluminum is advisable. One such system is called impressed-current cathodic protection (ICCP). The purpose of this report is to present the fundamentals of the theory, design, and application of such a system for use in surface-effect ships.

BASICS OF CATHODIC PROTECTION

This section describes the basic theory of galvanic corrosion and cathodic-protection systems. Those already familiar with these basic concepts can proceed to the next section.

Any metal when immersed in an electrolyte - in this case, sea water - will tend to establish itself at a specific electrical potential due to the chemical reactions occurring at the metal-electrolyte interface. The exact potential value depends on the nature and kinetics of these chemical reactions. As potential values are relative, not absolute, it is useful to establish a reference potential from which all other potentials can be measured. One such stable reference potential is generated when a mixture of silver and silver chloride interacts with chloride ions in sea water. A schematic example of these other materials generating stable potentials in sea water include copper/copper sulfate, special high-purity zinc, or saturated calomel (KCl). These stable materials are called reference cells or electrodes. The silver/silver chloride (Ag/AgCl) reference cell is used as a standard in sea water by arbitrarily assigning it a potential value of zero.

In practice, potentials of metals and alloys in equilibrium in sea water are established by comparison with a standard reference cell. These are called "open-circuit" potentials and can be used to position the various metals in a sea-water galvanic series. A metal's measured potential and location in the series depends upon its tendency to react or corrode in sea water. The difference in potential between two metals in the series is a measure of the galvanic energy, or driving force of the corrosion process, which results from electrically coupling the metals together.

A typical arrangement of common metals in a sea-water galvanic series appears in figure 1. In this arrangement, a more electronegative (or active) metal, such as aluminum, will suffer accelerated corrosion when coupled in sea water to a more electropositive (or noble) metal, such as titanium. The aluminum in such a couple is said to be anodic, and the titanium is said to be cathodic. Upon electrical coupling of dissimilar metals, electrons will be transferred from the more electronegative to the more electropositive materials, as illustrated in figure 2. This pair of dissimilar metals, electrically connected in sea water, is called a galvanic couple.

Charge neutrality is maintained by equal electron exchanges at the surface/water interfaces. As electrons flow out of the electronegative material (anode), it preserves charge neutrality by emitting positively charged metal ions into the sea water, thereby removing material and causing accelerated corrosion. In a galvanic couple, then, the anodic material experiences accelerated corrosion.

As a result of electron exchanges at the interfaces, the metal potentials, as measured against a standard reference cell, will change from the original open-circuit potentials. This change in potential, due to the current flow to or from the surface, is called polarization. Potential can be plotted against current to give a polarization curve. The shape of polarization curves can be influenced by environmental conditions, such as velocity and temperature. An example of polarization curves, shown in item (a) of figure 3, illustrates the type of behavior which occurs in galvanic coupling of dissimilar metals. The potential of a metal before any polarization is produced, called the open-circuit potential, occurs on its polarization curve near the y axis. The potentials of the anode and the cathode shift as the current is increased. The intersection of these curves defines the corrosion current, $I_{corrosion}$, and the potential of the galvanic couple, or mixed potential, $E_{corrosion}$. To prevent accelerated corrosion of the anode, it is necessary to shift the potential of the couple below the open-circuit potential of the anode (point A) which, in the case of an aluminum-titanium couple, would have to be less than -1000 mV.* Two approaches can be used to prevent galvanic corrosion at the anode. One is to isolate it electrically from the cathode. This approach is usually impractical on complex structures. The second is to apply cathodic protection to complex structures, an expedient which shifts the mixed potential of the couple below the open-circuit value of the more electronegative material.

Item (b) of figure 3 illustrates the cathodic polarization curves of the two coupled metals when cathodic protection is present. The intersection of each curve with the constant-potential cathodic protection line determines the current necessary to polarize that material to the specified protective level. Notice that the more noble material, titanium, requires more current than the less noble material, aluminum, to polarize it to the appropriate potential. Also, as the protection potential level becomes more negative, the current needed to polarize either material to that potential increases.

Both active and passive methods are used to apply cathodic protection. The passive method consists of adding a third, highly electronegative,material to the system. In the example of an aluminum-titanium couple, this would have to be a material that is more electronegative than aluminum, such as zinc. This material will then corrode in preference to the aluminum. Since it sacrifices itself to prevent corrosion of the other materials, this third material is called a sacrificial anode.

The active method to lower the potential of a couple is called ICCP. In this method, the sacrificial anode is replaced by an anode of an essentially inert material, such as platinum, to which an external voltage is applied. The basic components of an ICCP system are illustrated in figure 4. Voltage, supplied by a power supply to the anode, is regulated by the controller in order to hold the materials being protected at a constant potential. The potential difference between the reference cell and the metal near the cell is fed back to the controller. The current output required from the system to maintain a constant potential at the reference cell will vary with the conditions at the metal surface. Sea-water velocity is probably the most important variable, and generally, greater currents will be required at higher velocities.

*Abbreviations used in this text are from the GPO Style Manual, 1973, unless otherwise noted.

Before describing components that would be used for an ICCP system of a surface-effect ship, it is necessary to point out one special problem encountered with such systems on aluminum-hulled vessels. While some protection of an aluminum hull is required because of the galvanic coupling with noble metal appendages on the surface-effect ship, the problem of overprotection of aluminum must also be recognized. As indicated in figure 2, hydroxyl ions are generated at the cathode of a galvanic couple. Similarly, an alkaline solution can be generated at the surface of cathodically protected metals. Under conditions of overprotection, where the hull potential is driven too far negative, an excess of these hydroxyl ions will be generated, causing a condition of local alkalinity at the metal/sea-water interface. This highly alkaline environment will rapidly attack aluminum and other amphoteric* materials, causing a condition called overprotection corrosion. A steel-hulled ship would not corrode under similar conditions because iron is not an amphoteric metal. Since overprotection corrosion of aluminum can be very rapid, it is necessary to minimize the possibility of it occurring by care in the design of the system and selection of the components.

The basic components of an ICCP system for surface-effect ships are the power supplies, controllers, power generation equipment, the hull-mounted anodes surrounded by dielectric shields, and the hull-mounted reference cells. ICCP systems must employ dielectric shields to lower the current density delivered to the aluminum near the anode. The function of the shields will be further explained later in this section.

There are two main types of power supplies, saturable reactor (SR) and silicon-controlled rectifier (SCR). The SR type is most widely used for shipboard applications due to its availability and functional experience. This is the only type of unit readily available from commercial sources. However, it is bulky and heavy due to the large transformers used in the circuitry. Also, due to the operational characteristics of an SR, there is a minimum current which the power supply can deliver and a relatively long reaction time compared to SCR units. Extra circuitry can be installed to bypass this minimum current, but the equipment adds weight and requires more space. Unless careful selection is employed, this minimum current may

*Amphoteric - capable of reacting with either acids or bases.

still exceed ship demands under certain operational conditions. Overprotection corrosion or excessive degradation of coatings due to high cathodic potentials could occur under these circumstances.

The second type of power supply is the SCR. These units are smaller and lighter in weight and have no minimum current output; however, they are not standard commercial products and experience with their use is limited. Due to the rapid response of the SCR, interrupter reference measurement can be employed. In this potential measurement system, the anode current is momentarily cut off during the time that the hull potential measurements are made. Thus, the anode current will not influence the accuracy of the measurement, because the measurement time is so brief that the hull potential does not have an opportunity to return to the unprotected value. SCR units are sensitive to input power transients, which could occur on marine craft, and special overload protection must be employed to prevent damage to the solid-state components in the power supply.

The output from either type ICCP system will be a rectified a-c signal which will have ripple, the amount depending on how much attenuation has been incorporated into the design of the unit. Other instruments on the craft, especially those interfacing with the sea water, may be affected by this ripple, possibly causing erroneous readings. Certain a-c ripple frequencies, primarily from power generation harmonics, or induced electromagnetic interference generated by other on board electrical equipment, may also be transmitted to the sea water by the ICCP system. Due to the more rapid response of the SCR unit, it may be more likely to transfer these types of signals to the sea water. Troublesome ripple frequencies must therefore be filtered out by the use of extensive filtering circuitry or avoided by appropriate shielding.

The controller determines the variation between the preset protection potential and the actual hull potential at the reference cell, and generates a control voltage which signals the power supply to adjust the anode current accordingly. Controllers are available with dual outputs to control two power supplies at once, or with sensitivity adjustments, meters, etc. Many units can be modified to allow the use of a second reference electrode at the edge of the shield which will reduce power supply output if overprotection conditions are reached at this location.

Supplementary power generation equipment may be necessary if craft power is not available. This additional equipment will add weight, as well as operating, maintenance, and fuel supply problems to the craft. Generally, it is better to use the power generation equipment already installed in the craft, if possible, or to increase the capacity of this equipment where feasible to handle the extra load.

The reference cell most frequently used for marine craft is the Ag/AgCl type, due to its durability and adaptability to constant immersion conditions. This cell consists of silver screen or wire covered with partially reduced silver chloride and given complex stabilizing treatments. This screen is then placed in a nonconducting container with holes for water access, and the assembly is flush-mounted against the hull at the position where the hull potential can be best measured. Although only one reference cell is required for system control, more are usually employed. The others are used as spares or as a means of checking on proper operation of the cell controlling the system.

Current-delivering anodes are generally made of platinum-coated titanium or platinum-coated tantalum. Platinum, when made the anode of such a system, instead of releasing ions into the sea water will generate gases, such as chlorine, at its surface. Platinum-coated tantalum is normally preferred due to the resistance of tantalum to high voltages, permitting higher current densities at the anode. Two main types of hull-mounted anodes are commercially available. Round anodes are usually about 1 foot in diameter and flush-mounted against the hull. Strip anodes are generally available in 4- and 8-foot lengths and are less than 1-inch thick. They are usually surface mounted on the hull.

Surrounding each anode, for a distance of several feet, is a thick, waterproof, nonconductive material called the dielectric shield. In the absence of this shield, the anode current would follow the path of least resistance to the hull and would therefore be concentrated in the area near the anode. This high current density would generate an alkaline condition at the hull surface in this area, causing, in turn, overprotection corrosion. The shield increases the separation of anode and wetted hull. The resultant voltage drop through the water widely distributes the current and lowers the apparent anode potential at the hull beyond the shield. Since the current density is a function of $1/r^n$, where r is the distance from the anode and n is a geometrically dependent constant greater than 1, then the magnitude of the voltage gradient will be large near the anode and will constantly decrease as distance from the anode increases. The exact values will depend on the cathode surface geometry, seawater resistance, etc.

There are many types of dielectric shield materials, including epoxy mastics, coal-tar epoxy resins, polyurethane coatings, and rubber coatings. Integrity of the shields is critical, as even a small defect could lead to catastrophic overprotection corrosion of the aluminum beneath. Shield materials should have good adhesion, some resistance to mechanical damage, and the ability to withstand high anode potentials.

An alternate method for reducing overprotection near the anode is to mount the anode in a remote location, away from the aluminum hull. This approach, which eliminates the need for a dielectric shield, is discussed in appendix B.

METHODOLOGY - APPROACH TO DESIGN

The design of an ICCP system for a surface-effect ship can be accomplished in the following steps:

- Determination of current required, maximum and minimum.
- Selection of power supply and controller.
- Determination of number, size, type, and location of anodes.
- Determination of type and configuration of dielectric shield.
- Determination of type and location of reference cells.
- Alteration of ICCP system design to increase its compatibility with craft design.

To determine the current requirements for the system, a protection potential must first be chosen which will minimize galvanic effects of the appendage materials on the hull. The level chosen should be slightly more electronegative than the open-circuit potential of the aluminum hull. However, the effects of this potential on other materials in the system should be considered. For instance, 17-4 PH steel in some heat treatments experiences hydrogen embrittlement when coupled to aluminum, due to the generation of hydrogen at the cathodic

(17-4 PH) surface.[1] When protection is applied at a potential more electronegative than the mixed potential of aluminum coupled to 17-4 PH, excess hydrogen is produced, and the tendency for hydrogen embrittlement is intensified. After selecting the potential level, the approximate effective galvanic area of each material should be calculated under various operational conditions. Besides geometrical considerations, effective galvanic area is a function of the hull and appendage coatings used, the estimated rate of degradation of these coatings, and the frequency of coating repair. Also, if electrical isolation occurs, such as in certain propeller systems, the effective area must be reduced accordingly. It should be noted that the effective galvanic area of internal surfaces of piping may only extend several pipe diameters from the end of the pipe, due to IR drop.

The current demanded from the cathodic-protection system by each material is the product of its bare wetted area and the current density necessary to polarize it to the selected protection potential under the specific operational conditions involved. The total current demanded from the system is then the sum of the currents demanded by each material. This total current should be calculated for various operational modes, including dockside, cushionborne at low velocities, and cushionborne at high velocities. Values of minimum and maximum currents required from the system can thereby be determined.

Once these currents are known, a power supply and controller can be chosen. The power supply should be capable of converting ships' power into usable power for the anodes. It should have the capacity to supply the maximum current needed over long periods of time. It should also be able to limit its output to less than the minimum current previously calculated. The controller unit should be capable of controlling power supply output over its full range, with appropriate sensitivity to avoid slow reaction or overcompensation. A sensitivity adjustment is desirable.

Another necessary feature for any controller unit is fail-safe design, which will cause the controller output to reduce to the minimum value in case of system malfunction. This important feature can minimize the possibility of overprotection corrosion if a malfunction occurs which would otherwise drive the anode current above the level which causes overprotection,

[1] Jacobson, P. S., and D. D. Miller, "Preliminary Evaluation of Hydrofoil Base Metals and Coating Systems," The Boeing Co., Seattle, Wash. (1973)

such as open circuited or shorted anode or reference cell wires. Additional considerations in the selection of these two units include physical size and weights relative to ultimate location in the craft, ease of monitoring system function, reliability, and overhaul requirements. In addition, the controller must be stable and able to withstand marine atmospheres, vibration, and shock.

Shape and placement of anodes is critical in the design of an impressed-current system. Generally, anodes should be more concentrated in the vicinity of dissimilar metal appendages, since these will absorb a large portion of the anode current. They should be totally submerged under maximum velocity cushionborne operation to maximize their current-delivering capability. On surface-effect ships, limited submerged areas in the cushionborne mode place special requirements and limitations on the size, shape, and type of anodes needed. Other than this, anode placement and shape should be chosen to distribute the anode current evenly over the wetted surface areas. Due to the high speed of surface-effect ships, the anodes may need to be flush-mounted or faired into the hull. There is a possibility that no commercially produced unit will be satisfactory, and a special design will have to be used. Once the specific anode type is selected, its maximum current rating should be divided into the maximum controller output current to determine the number of anodes necessary. These should then be distributed around the hull according to the previously mentioned considerations. Placement in an unsymmetrical situation, such as near the water surface or next to a corner, should be avoided whenever possible to permit even distribution of the anode current. Consideration should also be given to remote mounting of the anodes, as discussed in Appendix B.

The dielectric shield is the weakest link in the impressed-current system. As previously explained, this is particularly critical on an aluminum hull. Proper selection and design of the shields are necessary to prevent severe overprotection corrosion. The shield material selected must be able to withstand high velocity effects, including cavitation and erosion, and high anode voltages, without exhibiting any tendency towards disattachment or blistering. Of course, if the remote anode concept is utilized, the need for a dielectric shield is eliminated.

Design of the shield is as critical as selection of the material of which it is constructed. The shield is applied to the hull around the anode for a specified minimum distance which is dependent on maximum anode current. If noble metals are located near the anode, the shield should be slightly extended in their direction since the presence of these materials will tend to distort the potential profile around the anode due to the large amount of current these materials consume. Coated appendages will distort the field less than uncoated appendages. The best available conservative values for minimum dielectric shield distance from the anode were established for conventional craft, 7 feet for a 100-ampere anode and 11 feet for a 200-ampere anode.

Although a single reference cell is used to control the normal operation of the impressed-current system, usually a minimum of two are installed. The second is used as a spare and to check the stability of the controlling reference cell. Reliability of these cells is important. On craft with properly designed dielectric shields, reference cell failure may lead only to wasteful current excesses, but reference cell malfunction may increase the degree of overprotection corrosion experienced on an aluminum-hulled craft with shield deficiencies. Placement of the reference cells is also critical. Generally, they should be mounted well away from the anodes but not in areas that are completely sheltered from the anode current, for example, near corners or in areas near significant amounts of dissimilar metals, such as propellers. The general intent is to place the reference cells in an area well representative of overall hull potential. Additional cells may be mounted in areas of concern, for instance, near appendages, provided that they are not used to control the normal operation of the system but are for information and safety only. One such reference cell should be placed at the edge of the dielectric shield. This cell could act as a safety device to provide the controller with information concerning when overprotection conditions are reached at the shield edge, so that the anode current can be reduced accordingly.

There is essentially only one type of reference cell presently used for shipboard systems, Ag/AgCl. These cells have demonstrated their reliability, and therefore, there is presently no reason for using any other type. Different mounting configurations are available. The optimum configuration for an SES can be selected from knowing the sea-water flow characteristics and hull structure in the area in which the cell will be mounted. Cavitation must be avoided at the reference cell/sea-water interface, as the trapped air may eliminate the sea-water path necessary between the reference cell and the adjacent hull.

Once the system components have been selected and locations determined, many problems will appear which must be resolved before installation. Structural modifications to the hull may have to be performed in order to accommodate hull-mounted equipment. Space for hull-mounted and on-board equipment may be restricted, but adequate access space must still be provided, as the equipment must be monitored. Anode cable lengths should be kept to a minimum, and special procedures must be followed if the cables run through fuel tanks, such as shown in NAVSEC 9000-S6202-73980, section 2, sheet 155. If boat power is not available to drive the power supply, then the addition of an auxiliary generator will be necessary. High sea-water velocities may cause cavitation or erosion problems on hull-mounted equipment. In short, all aspects of the system must be considered before final equipment selection and installation.

METHODOLOGY - APPLICATION TO SES 100B

To apply the methodology outlined in the previous section to a 100-ton surface-effect ship (SES 100B), a series of laboratory exposures were conducted to establish the protection potential level and current requirements. These laboratory tests are detailed in appendix A.

Protection current and open-circuit potential data both lead to the conclusion that the protection potential at which the ICCP system operates should be -1150 mV. Protection current data in appendix A (table 5-A) show a protection value of 47% at the -1100 mV level in the last line and 100% at all other -1100 mV tests. This implies that a potential slightly more electronegative than this, i.e., -1150 mV, should produce 100% protection at all velocities and temperatures.

The control potential should be equal to, but not exceed, the most electronegative open-circuit potential expected of the aluminum hull. Although it is commonplace on steel vessels to suppress the steel corrosion by using potentials 50 to 100 mV more negative than the open-circuit potential, this practice is not recommended for aluminum-hulled craft, since aluminum cannot be cathodically protected to reduce its corrosion rate below the unprotected levels.* Data in table 5-A indicate that the corrosion rate of cathodically protected aluminum, at levels to -1150 mV, is at least as great as when unprotected. In addition, the arbitrary use of a -50 to -100 mV shift in control potential might increase the possibility of generating overprotection potentials at the hull, or of causing coating degradation associated with high current densities, especially on the noble metal appendages. The control potential should therefore be equal to the most electronegative open-circuit potential expected of the aluminum hull.

*Groot, C., "Cathodic Protection of Aluminum," Materials Protection, (Nov 1964).

The expected potential range of the hull can be found by consulting data in table 1-A of appendix A. Of the 161 aluminum open-circuit potential data points from which the average values were calculated, 9.3% were more electronegative than -1100 mV and 0.6% (one value, -1164 mV) were more electronegative than -1150 mV. Therefore, a choice of -1150 mV for the control potential appears to be reasonable.

Based on the above current and potential data, a cathodic-protection control potential of -1150 mV versus Ag/AgCl is recommended for surface-effect ships. Current data at this control potential are not available for design purposes; however, the data in table 4-A of appendix A at -1100 mV can be used as a reasonable approximation for the following reasons:

- Power supply current rating will probably exceed craft requirements due to a limited selection of available equipment.

- Actual current densities will probably be less than the maximums chosen in the design.

- Small specimens used for design may have greater potential and current fluctuations with greater resultant maximum values than large structures, such as the aluminum hull, due to an averaging effect of large areas.

- The critical estimate of 10% coating defects used later in this section may be larger than is actually present on the craft, especially due to the probable frequent maintenance required of an experimental craft.

- Areas under the dielectric shield coating should be essentially free of defects. The exposed area calculations for the hull do not deduct for the area of the defects which would be in the dielectric shield area in the absence of the shield.

The maximum and average current densities at -1100 mV are therefore to be used in the ICCP system design. These values, from appendix A, are summarized in table 1.

TABLE 1 - CURRENT DENSITIES
($AMPERES/FT^2$) AT -1100 MV

Material	Velocity, kn			
	0	28	55	77
17-4 PH Stainless Steel				
Maximum	0.14	4.91	5.73	5.97
Average	0.02	3.06	4.58	4.90
Ti-6Al-4V				
Maximum	0.09	3.04	4.85	1.83
Average	0.02	1.77	3.74	0.88
5456 Aluminum				
Maximum	0.010(1)	0.58	1.19	0.23
Average	0.007(1)	0.27	0.67	0.09

(1) Data from previous tests on hydrofoil materials.

Table 2 presents the calculations of wetted areas for the various components in the SES 100B at different keel depths. The area of each section was found by rough geometrical approximation taken directly from the craft blueprints. All areas were considered to be coated except the propeller and fairwater. A selection of 10% for the area of coating defects was made on the basis of craft observations and from a need to provide a margin of safety. The selection of a defect area is important to final system design and should be made after considering coating deterioration rates from craft service records, coating test data, and length of time between overhauls for coating repair. If the operational pattern of the craft permits frequent coating repair, then the 10% defect area can be reduced, lowering the current requirements.

Also of importance is the degree of electrical isolation between the propellers and the hull. As the propeller is not coated, it absorbs a great deal of current. If electrical isolation occurs, the maximum current needed from the system may be reduced. If tests verify that lubrication in the transmission gears electrically isolates the propellers while under way, the cathodic-protection system will not be required to deliver current to them, reducing the maximum current requirements of the system. Calculated wetted areas in table 2 are multiplied by the appropriate current densities of table 1 in order to obtain total current requirements under various operational conditions. The results are presented in table 3. The maximum controller current requirement for any operational mode, which appears in the next to the last column, is 378.5 amperes.

TABLE 2
WETTED AREAS

Section Description	No.	Area Each ft²					Total Exposed Area ft²					Effective Area After Coating,(1) ft²				
		Keel Depth, in														
		72	15	10	8	6	72	15	10	8	6	72	15	10	8	6
5456 Aluminum																
Outer sidewall	2	213.8	10	-	-	-	427.5	20.0	-	-	-	42.8	2.0	-	-	-
Inner sidewall	2	255.0	50	33.2	26.8	20.0	510.0	100.0	66.4	53.6	40.0	51.0	10.0	6.6	5.4	4.0
Lower sidewall	2	126.0	126	104.4	84.4	63.2	252.0	252.0	208.8	168.8	126.4	25.2	25.2	20.9	16.9	12.6
Nose section	1	132.0	-	-	-	-	132.0	-	-	-	-	13.2	-	-	-	-
Rear sidewall	2	9.0	-	-	-	-	18.0	-	-	-	-	1.8	-	-	-	-
Forward sidewall	4	61.5	7.9	2.5	1.9	1.1	246.0	31.6	10.0	7.6	4.4	24.6	3.2	1.0	0.3	0.4
Total							1585.5	403.6	285.2	230.0	170.8	158.6	40.4	28.5	23.0	17.1
Titanium																
Propeller blades	2	16.5	16.5	16.5	16.5	16.5	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0	33.0
Stabilizer fin	2	18.0	18.0	18.0	18.0	18.0	36.0	36.0	36.0	36.0	36.0	3.6	3.6	3.6	3.6	3.6
Rudder	2	13.5	13.5	13.5	13.5	13.5	27.0	27.0	27.0	27.0	27.0	2.7	2.7	2.7	2.7	2.7
Total							96.0	96.0	96.0	96.0	96.0	39.3	39.3	39.3	39.3	39.3
Stainless Steel																
Propeller hub	2	6.1	6.1	6.1	6.1	6.1	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2	12.2
Fairwater	2	3.6	3.6	3.6	3.6	3.6	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2
Gearbox housing	2	48.9	24.8	18.2	14.6	11.1	97.8	49.6	36.2	29.2	22.2	9.8	5.0	3.6	2.9	2.2
Total							117.1	69.0	55.6	48.6	41.5	29.2	24.4	23.0	22.3	21.6

(1) 10% defects.

TABLE 3
TOTAL CURRENTS

Keel Depth in	Velocity kn	Material	Area ft^2	Relevant Current Density amperes/ft^2		Total Current for Material amperes		Total Current for all Materials amperes	
				Maximum	Average	Maximum	Average	Maximum	Average
72	0	Aluminum	158.6	0.01	0.007	1.6	1.1	9.2	2.5
		Titanium	39.3	0.09	0.02	3.5	0.8		
		Stainless	29.2	0.14	0.02	4.1	0.6		
72	28	Aluminum	158.6	0.58	0.27	92.0	42.8	354.9	201.8
		Titanium	39.3	3.04	1.77	119.5	69.6		
		Stainless	29.2	4.91	3.06	143.4	89.4		
15	28	Aluminum	40.4	0.58	0.27	23.4	10.9	262.7	155.2
		Titanium	39.3	3.04	1.77	119.5	69.6		
		Stainless	24.4	4.91	3.06	119.8	74.7		
15	55	Aluminum	40.4	1.19	0.67	48.1	27.1	378.5	285.9
		Titanium	39.3	4.85	3.74	190.6	147.0		
		Stainless	24.4	5.73	4.58	139.8	111.8		
10	55	Aluminum	28.5	1.19	0.67	33.9	19.1	356.3	271.4
		Titanium	39.3	4.85	3.74	190.6	147.0		
		Stainless	23.0	5.73	4.58	131.8	105.3		
8	55	Aluminum	23.0	1.19	0.67	27.4	15.4	345.8	264.5
		Titanium	39.3	4.85	3.74	190.6	147.0		
		Stainless	22.3	5.73	4.58	127.8	102.1		
6	77	Aluminum	17.1	0.23	0.09	3.9	1.5	204.8	141.9
		Titanium	39.3	1.83	0.88	71.9	34.6		
		Stainless	21.6	5.97	4.90	129.0	105.8		

If the hull and appendage coatings have no defects, the exposed area of aluminum (from table 2) will be 0, titanium will be 33 ft^2 (propellers), and stainless steels will be 19.4 ft^2 (propeller hubs and fairwaters). At V = 0, the average current densities for titanium and stainless steels are 0.02 amperes/ft^2 giving an absolute minimum current rating of 0.66 + 0.39 = 1.05 amperes. The cathodic protection system must be controllable at this low current level, to minimize the possibility of overprotection of the aluminum.

On the basis of the calculated current requirements, a controller unit can be selected. The Engelhard model 50011-2 saturable reactor power supply, which supplies up to 450 amperes, best suits the requirements. To lower the minimum current produced by this supply, special circuitry is needed. The minimum can be dropped from 45 to 22 amperes by the manufacturer if the power supply is specified with an "L" suffix. The remaining 22 amperes must be bypassed by special circuitry provided by the manufacturer. This can be accomplished, but it may require an additional cabinet to house the equipment.

Engelhard controller model 36600 can be used in conjunction with this power supply. Filtering on this supply should be specified to provide an a-c ripple energy less than 1% of the total output, to minimize ICCP system electromagnetic interference with other craft systems. This unit will also have to be modified to provide an anode current limitation based on information provided by the reference cell at the edge of the dielectric shield.

At present, craft power is not available for these units. A separate power generator must therefore be supplied, or craft generation equipment increased to handle the added load. The generator must be capable of supplying 30 amperes, 440 volts, 60 Hz, 3-phase current (up to 10 kVA) for the power supply, and 10 amperes, 110 volts, 60-Hz, single phase current (up to 0.5 kVA) for the controller unit.

Anode number, type, and location can now be selected. An appropriate choice is two 200-ampere anodes located aft on the port and starboard sidewalls, since the dissimilar metal appendages are all located aft. As the craft draws only 6 inches at maximum velocity, selection of the shape and location of anodes is simplified. Strip anodes must be used, such as Engelhard model 37370 (figure 5) or Lockheed 96-inch "shipboard strip anode," and the location must be as close to the keel as possible to keep the anodes submerged. This can be accomplished only by affixing the anode to the lower slanted section of the keel. The exact location of the anodes will depend on structural considerations.

As no potential profiles of impressed current anodes operating at full current output are available, the size of the dielectric shield must be determined from the manufacturers' recommendations and some reasonable hypotheses. The 200-ampere anodes suggested for use on the SES 100B have a recommended minimum distance of 11 feet in all directions from the edge of the anode. This distance appears to be somewhat excessive since the majority of the current will be delivered to the appendages near the anodes, within the shield. Table 3 shows that the maximum current delivered to aluminum components in any operational mode is 92.0 amperes or about 50 amperes per anode. The actual figure should be somewhat less than this, due to the coverage of some aluminum by the "defect-free" dielectric shield material. Since the recommended minimum dielectric shield coating distance around an 8-foot anode delivering 100 amperes to a steel hull is 4 feet, a minimum distance of 4 feet should be ample for about half of this current delivered to an aluminum hull. A great deal of current should flow aft to the propellers and gearboxes. Therefore, it is recommended that the final shield start at least 4 feet forward of the anode and extend to the stern of the craft, with a minimum height of 4 feet above the keel.

To date, three materials appear to be reliable for dielectric shield applications. Material 1 is troweled on, and adequate smoothness to prevent cavitation may be difficult to obtain. Also, being an epoxy, it may experience brittle behavior if significant sidewall flexing is present. Material 2 was recently discovered to contain a carcinogenic solvent and therefore requires extreme care in application to meet occupational health standards. Although reformulation of the material is possible, retesting would have to be performed to confirm the similarity of properties to the original material. Material 3 is tough; and contains an antifoulant. The third is therefore recommended as the best state-of-the-art material to date for dielectric shields on surface-effect ships.

Type and location of reference cells must next be determined. Presently only one type of reference cell (figure 6) is approved for naval craft. This is a 9-inch (23 cm) diameter faired disk. This cell has proved to be stable and at present has the best streamlining of any cell commercially produced for large craft. One of these cells could be mounted in the lower slanted section of each sidewall a quarter of the boat length aft of the bow for normal control purposes, and a second cell mounted in each sidewall just outside the dielectric shield to monitor for overprotection. A third pair of cells should be mounted near the stern to check the system's effectiveness in polarizing the noble metal appendages. The third pair of cells is needed to obtain additional potential data for this experimental system, although not actually required for system control. Total weight of the system as described is as follows:

	Pounds
Power Generation Equipment	~ 1000
Power Supply	660
Controller	47
Anodes	120
Dielectric Shields	~ 300
Reference Cells	90
Other Equipment	~ 200
Total System Weight	~ 2417

The physical size of the units can be found in the next section of this report. The size and weight of the extra cabinet to contain current bypass circuitry is unknown, but the size should not exceed that of the power supply cabinet.

AVAILABLE COMMERCIAL UNITS

There are two major producers of ICCP system components for marine craft, Engelhard Industries, Division of Engelhard Minerals and Chemicals Corporation, and Lockheed Marine Services. Lockheed specializes in custom-designed and custom-built equipment, except for a small line of current-delivering anodes. Therefore, Engelhard is the main source for standard commercial power supplies, controllers, and reference cells. Several other suppliers produce power supply units.

Table 4 gives a list of power supplies and controllers available for large craft (greater than 100 amperes) and relevant data needed for component selection. All units are manufactured by Engelhard. Notice that all of the commercially available units are of the SR design, and that none of the units is designed to input 400-Hz current, which is attractive for use on surface-effect ships.

TABLE 4
POWER SUPPLIES AND CONTROLLERS

Model No.	Height in	Width in	Depth in	Weight lb	Power Input	Power Consumption	Power Output(1)	Control Range(2)	Circuit Description
						Power Supplies			
50011	36	24 3/4	18	660	440 volts, 3Ø, 60 Hz 380 volts, 3Ø, 50 Hz	0.14-13.9 kVA at 28 volts 0.12-12.0 kVA at 24 volts	450 amp 24-28 Vdc	50 volts, 225 amp 100 volts, 450 amp	SR, M 50 mV, 500 amp
50012	36	24 3/4	18	543	440 volts, 3Ø, 60 Hz 380 volts, 3Ø, 50 Hz	0.09-9.3 kVA at 28 volts 0.08-8.0 kVA at 24 volts	300 amp 24-28 Vdc	50 volts, 150 amp 100 volts, 300 amp	SR, M 50 mV, 300 amp
50013	36	24 3/4	18	538	440 volts, 3Ø, 60 Hz 380 volts, 3Ø, 50 Hz	0.06-6.2 kVA at 28 volts 0.05-5.3 kVA at 24 volts	200 amp 24-28 Vdc	50 volts, 100 amp 100 volts, 200 amp	SR, M 50 mV, 300 amp
50014	36	24 3/4	18	404	440 volts, 3Ø, 60 Hz 380 volts, 3Ø, 50 Hz	0.05-4.65 kVA at 28 volts 0.04-4.0 kVA at 24 volts	150 amp 24-28 Vdc	50 volts, 75 amp 100 volts, 150 amp	SR, M 50 mV, 300 amp
50135-1 50135-2	24 1/2	23	7 1/2	115	110 volts, 1Ø, 60 Hz	up to 0.6 kVA at 18 volts	.7-25 amp 12 Vdc 1-37.5 amp 18 Vdc	50 mV-5→100%	SR, M 1.5 volts, 50 amp Fail safe
50140-1 50140-2	24 1/2	23	7 1/2	180	110 volts, 1Ø, 60 Hz	up to 1.2 kVA at 18 volts	1.5-50 amp 12 Vdc 2-75 amp 18 Vdc	50 mV-5→100%	SR, M 1.5 volts, 100 amp Fail safe
50145-1 50145-2	24 1/2	23	7 1/2	230	100 volts, 1Ø, 60 Hz	up to 2.4 kVA at 18 volts	3-100 amp 12 Vdc 4-150 amp 18 Vdc	50 mV-5→100%	SR, M 1.5 volts, 200 amp Fail safe
						Controllers			
36600	20	16	7 1/2	47	105-125 volts, 1Ø, 50-60 Hz	.5 kVA max.	0-100 Vdc 4.5 amp	10 mV error- 75 Vdc out	Transistorized, Reference Cell & Output Check, Fail safe
36800	20	16	7 1/2	50	105-125 volts, 1Ø, 50-60 Hz	.5 kVA max.	0-100 Vdc 4.5 amp , Aux Pos 1:1 1:2, 1:3	10 mV error- 75 Vdc out	Transistorized, Reference Cell & Output Check, Twin, Fail safe
37460	20	16	7 1/2	52	105-125 volts, 1Ø, 50-60 Hz	1 kVA max.	0-100 Vdc 4.5 amp + 0-100 Vdc 4.5 amp	10 mV error- 75 Vdc out	Transistorized, Reference Cell & Output Check, Twin, Fail safe

(1) Minimum current outputs for all power supplies are 10% of the maximum. Adding an "L" suffix after the supply number specifies the reduced minimum output. Special current bypass circuits available. Standard a-c ripple energy is 5% total output; 1% is available if specified.
(2) Controllers can be modified for current limit control by means of a separate reference cell placed at the edge of the dielectric shield.
M - Contains monitoring meter, maximum meter readings follow. amp - amperes. SR - Saturable reactor.

Table 5 lists available anodes for large craft (greater than 50 amperes) and relevant data for each. All units are produced by Engelhard, except the shipboard Pt-Nb* anode, which is manufactured by Lockheed. Lockheed also manufacturers remote anodes, 100-400 amperes, which can be towed behind the craft. These are not listed in the table. Although not evident from the table, none of the anodes is streamlined for high-velocity operation.

TABLE 5 - ANODES

Model No.	Type	Configuration	Dimensions in	Weight lb	Current amperes	Minimum Distance Capastic Shield to Anode ft	Amount of 1/8-Inch Capastic Shield Recommended gal	Shield Weight lb
35559	Pt-coated	Disk	14D - 1T	25	50	3 1/2 (7)(1)	2 1/4(2)	34(3)
36460	Pt-coated	Strip	48 x 4 3/8 x 1	30	75 100	4 5	5 7	75 105
36470	Pt-coated	Strip	96 x 4 3/8 x 1	60	100 150	4 5 1/2	5 8 1/2	75 128
37370	Pt-coated	Strip	96 x 4 3/8 x 1	60	200	4 (11)	4 1/2(2)	68(3)
Shipboard	Pt-Nb	Strip	48L 96L		100 200			

(1) Distance for Tarset shield applied over Capastic.
(2) Plus 22-mil layer of Tarset.
(3) Plus weight of Tarset overlay.
D - Diameter
T - Thickness
L - Length

*Platinum coated Niobium

Table 6 lists the primary reference cell systems for marine craft along with pertinent data about each. All units are produced by Engelhard. The smaller disk electrode, model 37525, is primarily for small boats but is listed as a possible cell for noncontrolling applications where potential information is of interest but not essential.

TABLE 6
REFERENCE ELECTRODES

Model No.	Configuration	Dimensions in.	Weight lb
32622C	Recessed	1 1/2 D x 4L	11
37525	Disk	8D x 5/8 T	3 (small boat)
50910	Disk	9 D x 1 1/4T	15

D - Diameter; L - Length; T - Thickness

SUMMARY

This report discusses impressed current cathodic protection (ICCP) of surface effect ships from the viewpoint of the craft designers. After a brief explanation of the theory behind the use of an ICCP system, a system design methodology is developed which consists of six major steps as follows:

- Determination of current required, maximum and minimum.

- Selection of power supply and controller.

- Determination of number, size, type, and location of anodes.

- Determination of type and configuration of dielectric shield.

- Determination of type and location of reference cells.

- Alteration of ICCP system design to increase its compatibility with craft design.

These steps are further broken down and subsequently illustrated by application to the SES-100B. The major weak point of the ICCP system, the dielectric shield, is discussed along with an alternative approach, use of the remote anode concept. Failsafe features are emphasized.

The information presented in this report should aid the surface-effect-ship designers in developing a "feel" for the critical design parameters for impressed current cathodic protection systems.

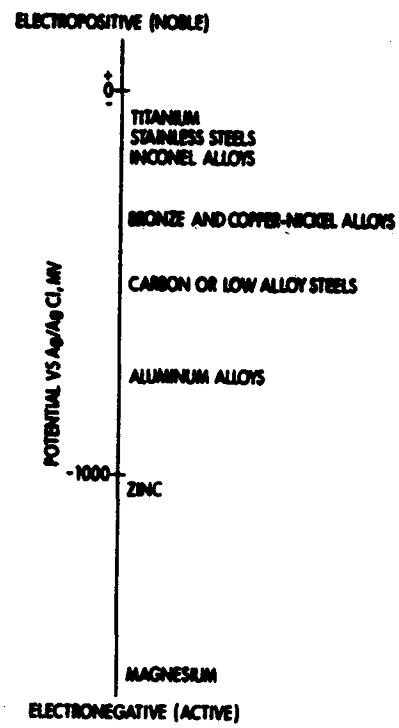


Figure 1 - Galvanic Series of Metals in Sea Water

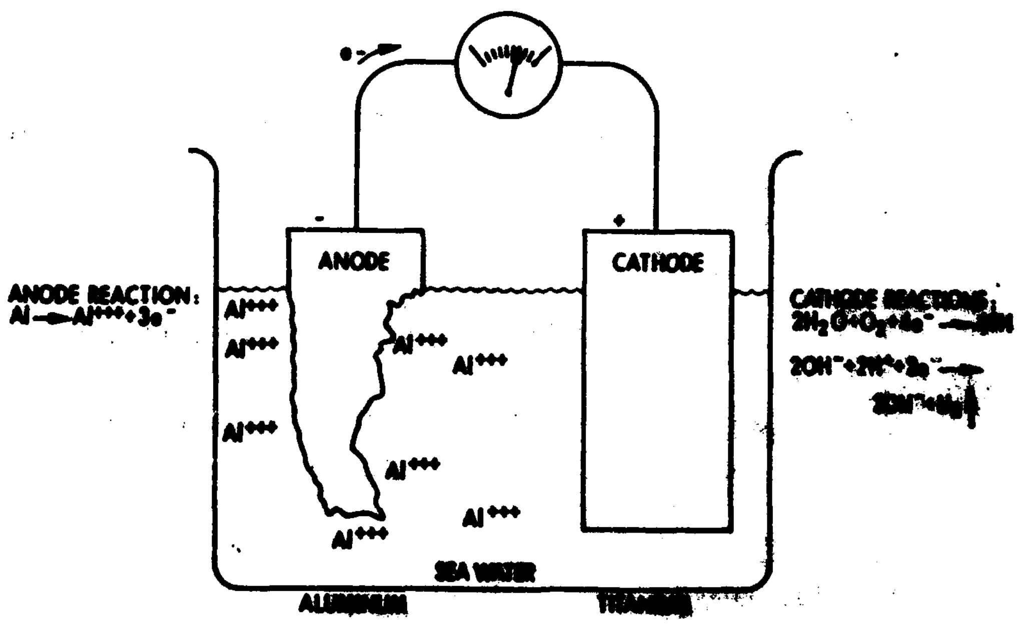
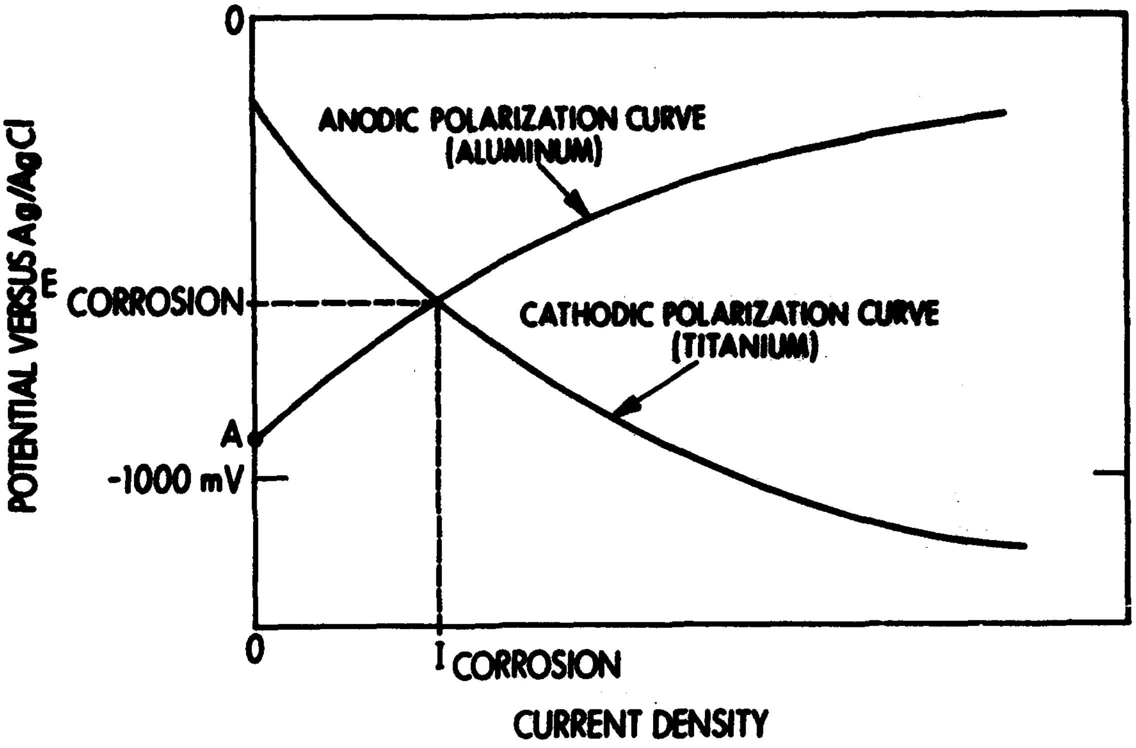


Figure 2
Galvanic Coupling

Item (a) Galvanic Couple



Item (b) Cathodic Protection

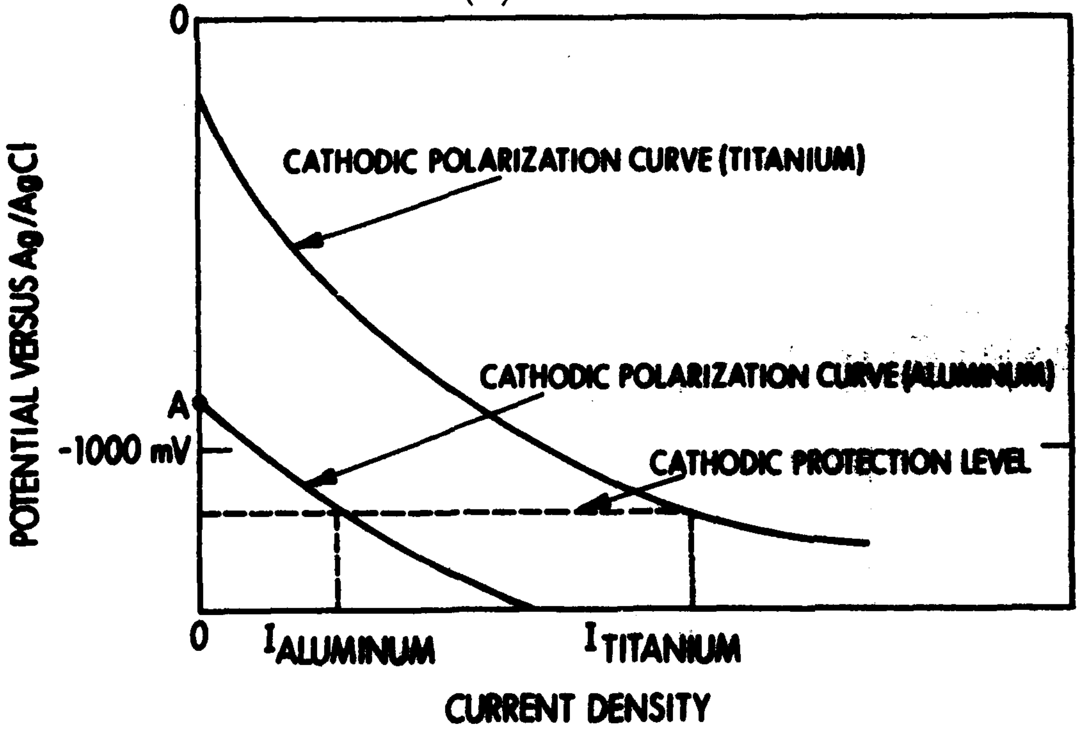


Figure 3
Polarization Curves

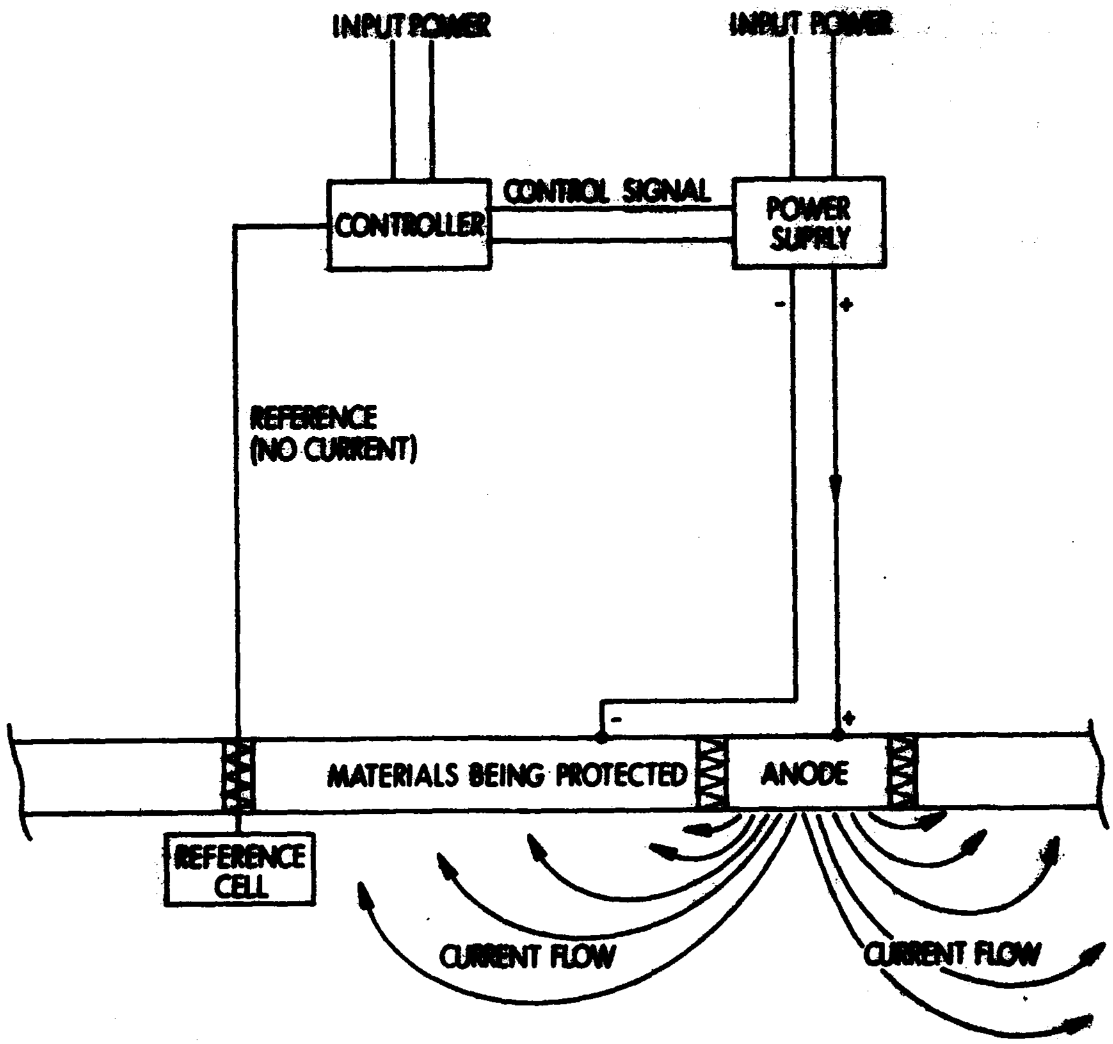
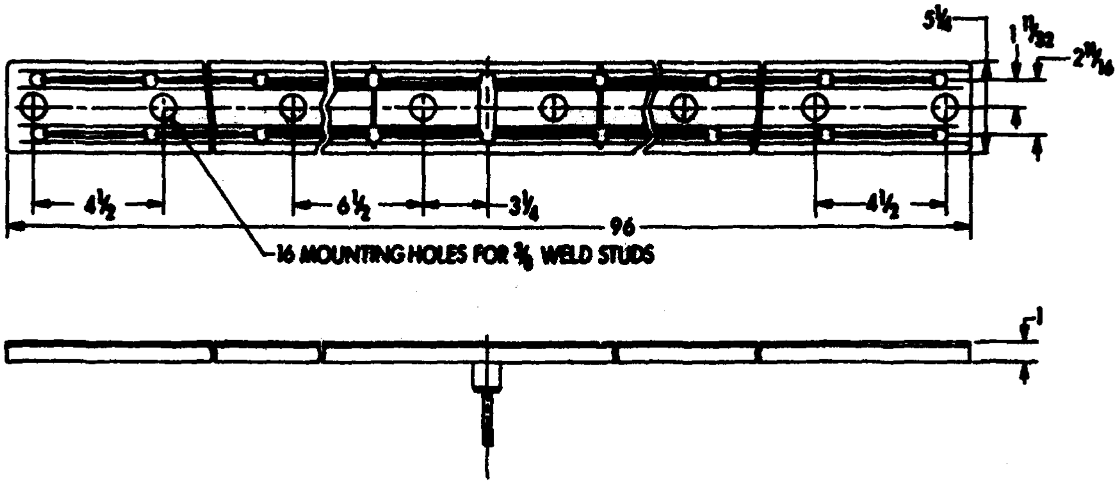
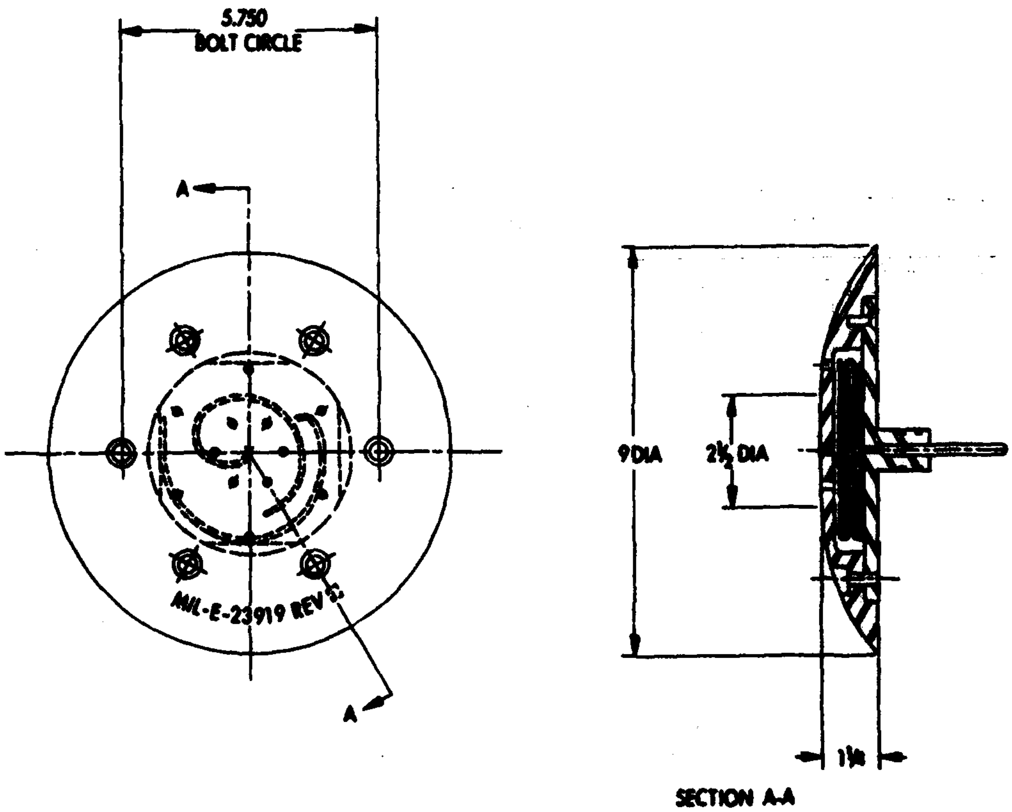


Figure 4
Generalized Impressed Current
Cathodic Protection System



Courtesy of Engelhard Industries (Drawing 37370)

Figure 5 - Anode Assembly



Courtesy of Engelhard Industries.

Figure 6 - Reference Cell Assembly

APPENDIX A

LABORATORY INVESTIGATIONS

The purpose of the laboratory investigation was to obtain open-curcuit potential and galvanic current data at high sea-water velocities to apply to the design of an ICCP system for surface-effect craft.

APPARATUS

The high-velocity tests were conducted in a specially designed apparatus illustrated in figure 1-A. The specimen, 1 x 4 x 3/16 inch, is supported by a slot in a hollow cylindrical nylon holder. Sea water is pumped across the specimen faces at velocities up to 77 knots, controlled by different sized orifices in the nozzle assembly. The leading edge of the specimen is rounded to minimize turbulence. The specimen holder has platinized titanium anodes integrally mounted parallel to the water flow opposite each specimen face. Small holes drilled in the nylon holder near the specimen faces are attached to tubing which feeds into a small container holding the Ag/AgCl reference cells, making a salt-bridge arrangement for impressed-current-system control. The salt bridge permits sensing of metal potential information from a remote location by establishing an isolated sea-water path between the reference cell and the area of interest. Electrical contact is made to the specimen by means of a contact screw of the same material, threaded through the specimen holder.

MATERIALS

Materials tested were 5456-H117 aluminum for hull applications, and 17-4PH stainless steel, titanium 6Al-4V, and Inconel 625 for appendage applications. Nominal composition of these alloys are:

5456 Aluminum	- 5.25Mg, 0.8Mn, 0.1Cr, Bal Al
17-4PH Stainless Steel	- 15.5-17.5Cr, 3.0-5.0Ni, 3.0-5.1Cu, .15-.45Nb+Ta, Bal Fe
Titanium 6Al-4V	- 5.75-6.75Al, 3.5-4.5V, Bal Ti
Inconel 625	- 20.0-23.0Cr, 8.0-10.0Mo, 3.15-4.15 Nb+Ta, 5.0 max Fe, Bal Ni

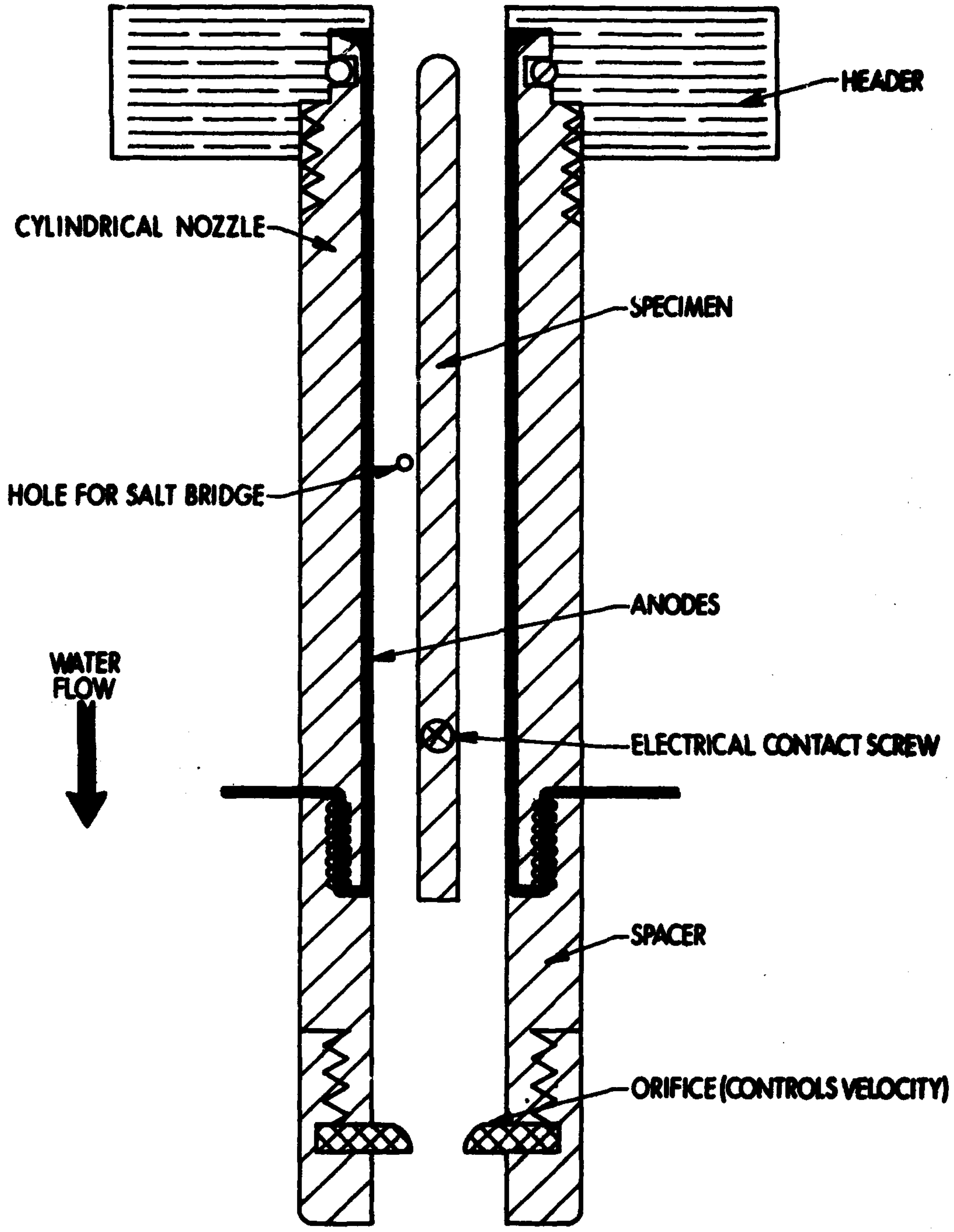


Figure 1-A
High-Velocity Test Apparatus

INVESTIGATION

Tests were conducted to determine the maximum open-circuit potentials of the SES hull and appendage materials and the maximum protection current densities at various sea-water velocities and protection potentials. The effect of water temperature on the above parameters was also investigated. These tests were conducted in the high-velocity apparatus at velocities of 28, 55, and 77 knots, and protection potential levels of -950, -1025 and -1100 mV. Test duration was 30 days.

Low-velocity tests (quiet sea water) were conducted to determine the minimum protection current demanded by the SES appendage materials at various levels of cathodic protection. These studies were conducted by immersing 1/4-inch plate specimens, 3 x 4 inches, in natural sea water for 30 days at -950, -1025, and -1100 mV. Electrical contacts were isolated from the sea water by a silicone adhesive. Only the appendage materials 17-4 PH stainless steel. titanium 6A1-4V, and Inconel 625 were tested, since the minimum current output of an impressed-current system would be calculated on the assumption that no coating defects are present. The only areas not coated are certain appendages; therefore, assuming no coating defects, the appendage materials are the only materials in contact with the sea water.

The final laboratory study was conducted to determine the resistance of various dielectric shield materials to high anode voltages. Aluminum specimens, 4 inches square, were coated with shield materials 2, 3, and 4, plus material 4 with anti-foulant. In addition, larger panels coated with Material 1 were tested. All panels were affixed in a test apparatus which allowed only the coated face to come in contact with the sea water, and half of the coatings were pierced with a pinhole sized drill to simulate a coating flaw. The racks were immersed in natural sea water, and the panels held at -12 volts relative to platinized titanium anodes mounted nearby. Total test time was 6 months.

RESULTS AND DISCUSSION

Results of the high- and low-velocity tests appear in tables 1-A to 4-A. Table 1-A presents open-circuit data taken before and after constant potential tests on 18 aluminum specimens at three velocities, and four aluminum and three appendage material control specimens exposed concurrent with constant potential tests.

TABLE 1-A
OPEN-CIRCUIT POTENTIALS AND CORROSION RATES
30-DAY TESTS

Material	Potential mV Versus Ag/AgCl at the Velocity of:			Corrosion Rate mils/year at the Velocity of:		
	28 kn	55 kn	77 kn	28 kn	55 kn	77 kn
5456 Aluminum[1]						
Maximum	-630	-627	-876	-	-	-
Average	-910	-858	-1017	77	150	139
Minimum	-1129	-897	-1164	-	-	-
17-4PH Stainless						
Maximum	-	-	+329	-	-	-
Average	-	-	+197	-	-	0.42
Minimum	-	-	+26	-	-	-
Ti-6Al-4V						
Maximum	-	-	+558	-	-	-
Average	-	-	+110	-	-	0.68
Minimum	-	-	-102	-	-	-
Inconel 625						
Maximum	-	-	+184	-	-	-
Average	-	-	+66	-	-	0.22
Minimum	-	-	-102	-	-	-

(1) Potential data considers 30-day tests and readings from first 2 days of constant potential tests before potentials were applied.

The average aluminum potentials ranged from -858 to -1017 mV, with no systematic dependence on velocity. Of the 161 aluminum open-circuit data points from which this table was made, 9.3% were more negative than -1100 mV, and 0.6% (one value, -1164 mV) were more negative than -1150 mV. Tables 2-A through 4-A present current density data. Generally, the amount of protection current was higher at more negative potentials. Although the protection current increased with increasing sea-water velocity up to 55 knots as expected, in many cases the current was less at 77 knots than at 55 knots. Current requirements for polarizing all of the appendage materials to the protection potential generally differed by no more than a factor of two for a given velocity and potential, while the current requirements for the aluminum were usually more than an order of magnitude lower.

TABLE 2-A
CONSTANT POTENTIAL
30-DAY TEST DATA (-950 MV)

Material	Current Densities amperes/ft^2 at the Velocity of:				Corrosion Rate mils/year at the Velocity of:			
	0 kn	28 kn	55 kn	77 kn	0 kn	28 kn	55 kn	77 kn
5456 Aluminum								
Maximum	-	0.06	0.34	0.28	-	-	-	-
Average	-	0.0043	0.078	0.046	-	96	161	190
Minimum	-	0.0	0.0	0.0	-	-	-	-
17-4PH Stainless								
Maximum	0.073	2.31	4.22	4.38	-	-	-	-
Average	0.023	1.30	2.98	3.20	nil	0.06	0.13	0.39
Minimum	0.011	0.60	1.35	2.25	-	-	-	-
Ti-6Al-4V								
Maximum	0.058	2.86	1.70	1.09	-	-	-	-
Average	0.025	1.14	1.67	0.77	nil	0.01	0.13	0.49
Minimum	0.010	0.44	0.60	0.42	-	-	-	-
Inconel 625								
Maximum	0.068	1.41	3.88	4.93	-	-	-	-
Average	0.024	1.00	2.55	3.66	nil	0.03	0.11	0.46
Minimum	0.010	0.17	0.50	1.27	-	-	-	-

TABLE 3-A
CONSTANT POTENTIAL
30-DAY TEST DATA
(-1025 MV)

Material	Current Densities amperes/ft² at the Velocity of:				Corrosion Rate mils/year at the Velocity of:			
	0 kn	28 kn	55 kn	77 kn	0 kn	28 kn	55 kn	77 kn
5456 Aluminum[1]								
Maximum	-	0.34	0.79	0.29	-	-	-	-
Average	-	0.12	0.34	0.094	-	95	183	188
Minimum	-	0.0	0.028	0.0	-	-	-	-
17-4PH Stainless								
Maximum	0.094	3.24	5.29	6.75	-	-	-	-
Average	0.019	2.04	4.47	3.96	nil	0.02	0.11	0.23
Minimum	0.007	0.60	4.34	3.34	-	-	-	-
Ti-6Al-4V								
Maximum	0.063	3.28	3.72	3.72	-	-	-	-
Average	0.019	2.06	2.90	1.49	nil	0.05	0.07	0.42
Minimum	0.006	0.60	1.83	1.19	-	-	-	-
Inconel 625								
Maximum	0.194	1.85	4.14	6.29	-	-	-	-
Average	0.026	1.01	3.13	4.53	nil	0.07	0.14	0.37
Minimum	0.006	0.44	0.76	1.17	-	-	-	-

[1] Weighted average of values at -950 and -1050 mV.

TABLE 4-A
CONSTANT POTENTIAL
30-DAY TEST DATA
(-1100 MV)

Material	Current Densities amperes/ft² at the Velocity of:				Corrosion Rate mils/year at the Velocity of:			
	0 kn	28 kn	55 kn	77 kn	0 kn	28 kn	55 kn	77 kn
5456 Aluminum[1]								
Maximum	-	0.58	1.19	0.23	-	-	-	-
Average	-	0.27	0.67	0.095	-	95	159	167
Minimum	-	0.07	0.20	0.0	-	-	-	-
17-4PH Stainless								
Maximum	0.141	4.91	5.73	5.97	-	-	-	-
Average	0.020	3.06	4.58	4.90	nil	0.02	0.09	0.36
Minimum	0.004	1.73	1.57	3.18	-	-	-	-
Ti-6Al-4V								
Maximum	0.089	3.04	4.85	1.83	-	-	-	-
Average	0.016	1.77	3.74	0.88	nil	-.01	-.02	0.41
Minimum	0.003	0.48	2.69	0.40	-	-	-	-
Inconel 625								
Maximum	0.272	1.99	7.00	4.69	-	-	-	-
Average	0.047	1.08	4.44	3.51	nil	0.11	0.15	0.40
Minimum	0.012	0.44	1.75	0.86	-	-	-	-

[1] Average of values at -1050 and -1150 mV.

Table 5-A presents a summary of constant potential data aluminum. The data have a greater dependence on velocity and temperature than upon the level of cathodic protection. The comparison of constant potential tests with control tests having no potential applied suggests that the corrosion of the aluminum is at least as great when cathodically protected at any level up to -1150 mV as when unprotected. Cathodic protection is not effective in decreasing the corrosion rate of uncoupled aluminum hulls but can only be used to suppress undesirable galvanic effects caused by the dissimilar metal appendages.*

TABLE 5-A
CONSTANT POTENTIAL
30-DAY TESTS OF ALUMINUM - SUMMARY

Velocity (Kn)	Average Temperature (° F)	Constant Potential (mV vs Ag/AgCl)	Corrosion Rate (mils/year)	Percent Protection Current Flow[1]
77	81.4	-950	190	45
77		-1050	188	91
77		-1150	146	95
77		none[2]	139	-
77	60.8	-950	76	20
77		-1025	74	100
77		-1100	74	100
77		none[2]	60	-
55	81.4	-950	161	49
55		-1050	191	100
55		-1150	128	100
55		none[2]	150	-
55	60.8	-950	66	0
55		-1025	66	40
55		-1100	55	100
28	81.4	-950	96	13
28		-1050	95	96
28		-1150	95	100
28		none[2]	81	-
28	60.8	-950	47	0
28		-1025	45	100
28		-1100	51	47

(1) Percentage of data points with current flow from the ICCP system. Zero current is assumed to mean that a galvanic couple with that aluminum specimen would not have had its galvanic corrosion completely suppressed.
(2) Control specimen with no applied potential.

*Groot, C., "Cathodic Protection of Aluminum," Materials Protection (Nov 1964).

Results of the dielectric shield tests are not yet complete. After 2 weeks in test, all dielectric shield materials are behaving similarly, with no evidence of blistering, peeling, or disbonding of the coatings. Previous tests conducted on material 1 at -6.0 volts resulted in no visible deterioration of the shield material after 1 year in test. No definite conclusions are possible at this stage regarding dielectric shield materials. Results of these tests will be presented in a later report.

APPENDIX B

REMOTE ANODE

Due to the proximity of the hull-mounted anodes to the aluminum hull material of surface-effect ships, it is necessary to use dielectric shields to redistribute the anode current to prevent overprotection. The hull-mounted configuration may present additional problems that have not been encountered on conventional ships. As previously discussed, the high operating speed of the craft can affect both the anode and the dielectric shield material. Additionally, the geometric configuration and limited area available on submerged surfaces may be inadequate for the utilization of a hull-mounted anode configuration.

An alternate approach, illustrated in figure 1-B, is to suspend the anodes from a remote location, such as the space between the sidewalls of the surface-effect ship, thereby assuring the existence of the necessary physical separation between the anodes and the hull without the need for a dielectric shield. Such an anode system offers several distinct advantages, but also some disadvantages over the conventional hull-mounted system as shown in table 1-B.

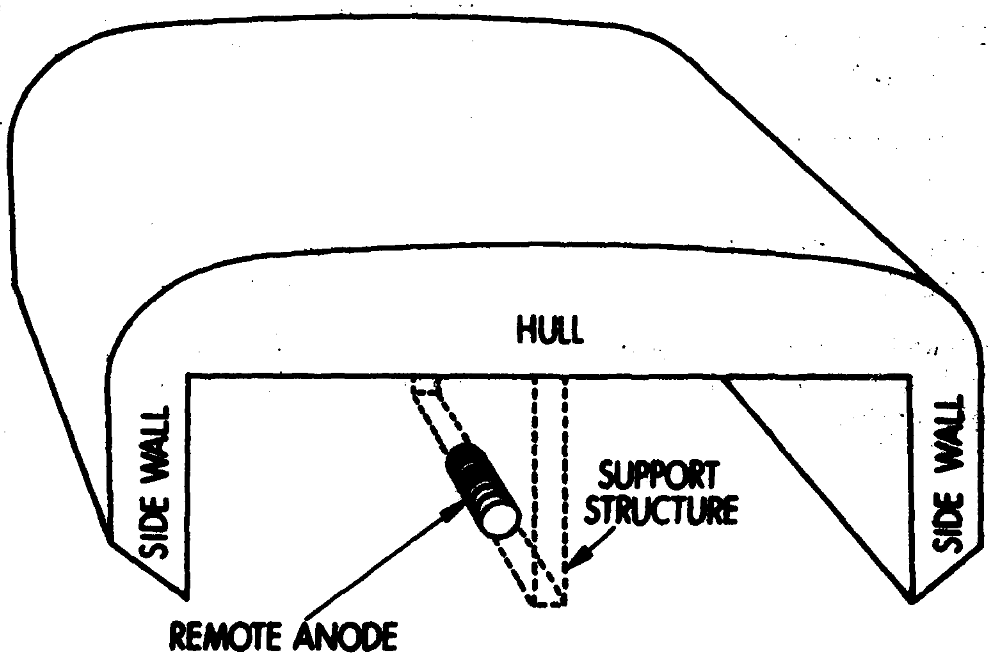


Figure 1-B
Remote Anode Schematic

TABLE 1-B - ADVANTAGES AND DISADVANTAGES OF REMOTE ANODE SYSTEM

Advantages	Disadvantages
1. Eliminates danger of overprotection due to shield failure.	1. No commercial units available; all units must be specially designed and custom built.
2. More even current distribution to hull.	2. No operational experience has been gained with such systems.
3. Reduces through-hull wiring penetrations.	3. Design difficulties for rigid lightweight anode supporting structure.
4. Reduces complexity of running wires through or around fuel tanks in sidewalls.	4. Design difficulties in insulating anode from support structure.
5. Eliminates cost of dielectric shield materials, application and maintenance.	5. May add more hydrodynamic drag than conventional hull-mounted anodes.
6. Eliminates dielectric shield weight.	6. May increase draft of craft.
7. Fewer reference cells required.	7. More susceptible to damage from floating or partially submerged debris.
8. Adequate protection by single anode.	8. Loss of anode might result in damage to rear skirt.
9. Sidewall structure not affected as with hull-mounted anodes.	

To deliver a current of 400 amperes to the hull, a remote anode made from platinized titanium would have to have a surface area of 4 ft^2, and an anode of platinized tantalum requires an area of 60 in^2. This could be in the form of a hydrodynamically efficient teardrop or foil shape, a long bar or tube, or a plate similar to the stabilizers or rudders. It would have to be suspended even with, or below, the keel, with the optimum position being 2-3 feet below the keel. In this position, the anode would be less affected by wave action.

The anode supporting structure would probably have to be braced from the sidewalls. This structure must be capable of withstanding the thwartships force on the anode in extreme turns, the drag force at maximum craft velocity, and have the minimum of submerged frontal area during high velocity operation to minimize drag. Retractability for emergency high-speed operation, or to avoid damage by floating debris, may be necessary.

The remote anode concept appears to be a feasible approach to cathodic protection of surface-effect ships. Further studies, principally structural and hydrodynamic, will have to be conducted to determine the specific effects of each type of anode configuration on craft performance. Also, studies must be made to determine the expected current-delivering lifetime of various anode materials, such as platinum-coated tantalum, under high-speed conditions.

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13. ABSTRACT

A laboratory investigation was conducted to provide background information for impressed-current cathodic protection of surface-effect ships. The optimum protection potential was identified by performing polarization experiments in flowing seawater (0-77 knots). Current requirements, at this potential level, were generated for SES 100B by combining the laboratory results with calculated surface areas of the wetted hull and appendage components. Impressed-current cathodic protection for surface effect ships is discussed from the viewpoint of the craft designers. After a brief explanation of the fundamental principles of cathodic protection, the function of an impressed-current system on surface-effect craft is discussed in general, and a design procedure is outlined and specifically applied to SES 100B. A brief discussion of commercially available cathodic-protection-system components is presented.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Galvanic series						
Electrical coupling						
Corrosion						
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Impressed current						
Coating defects						
Shielding						

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