CATHODIC PROTECTION IN SHIPS

BY

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INTRODUCTION

In 1824, Sir Humphrey Davy established the principle of cathodic protection and demonstrated that corrosion of copper sheathed hulls could be prevented by the attachment of zinc or steel anodes to the hull.

Because of improved underwater paint systems from both the anti-fouling and anti-corrosive points of view, the docking interval of ships has been extended but because of the possibility of poor application, defective areas or damage in service, cathodic protection is used to supplement the protection provided by the paint film.

PRINCIPLE OF CATHODIC PROTECTION

When two metals are immersed in an electrolyte, a potential difference will exist between them causing a current to flow between them if they are electrically connected. The magnitude of this potential depends upon their separation in the electrochemical series (shown below), the further apart they are the greater the potential causing the current to flow from the anode to the cathode.

Galvanic Series of Metals and Alloys

Corroded end (ANODIC or least noble)

Magnesium

Magnesium Alloys

Zinc

Aluminium

Cadmium

Steel or Iron

Cast Iron

Chromium Iron (active)

18/8 Chromium-Nickel-Iron (Active)

18/8/3 Chromium-Nickel-Molybdenum Iron (Active)

Lead Tin Solders

Lead

Tin

Nickel (Active)

Cont'd/.. Inconel

Inconel (Active) Nickel-Chromium-Iron Alloy
Brasses
Copper
Bronzes
Copper-Nickel Alloys
Monel (Nickel-Copper Alloys)
Silver solder
Nickel (passive)
Inconel (passive) Nickel-Chromium-Iron Alloy
Chromium Iron (passive)
18/8 Chromium-Nickel-Iron (passive)
18/8/3 Chromium-Nickel-Molybdenum Iron (passive)
Silver
Graphite
Gold
Platimum

Protected End (CATHODIC or most noble)

Even where one metal surface is exposed to an electrolyte, because there will always be variations in the surface, for instance, surface composition, grain orientation, etc., one area of the exposed surface will become anodic to another.

At the anode, corrosion takes place by the metal atoms leaving the crystal lattice and entering the electrolyte as positively charged ions. In doing so, electrons are left behind on the metal.

$$M \longrightarrow M^+ + e^-$$

While this is proceeding at the anodes, at the other areas called cathodes, electrons are being consumed by the formation of hydroxyl ions.

$$O_2 + 2H_2O + 4e^- = 4OH^-$$

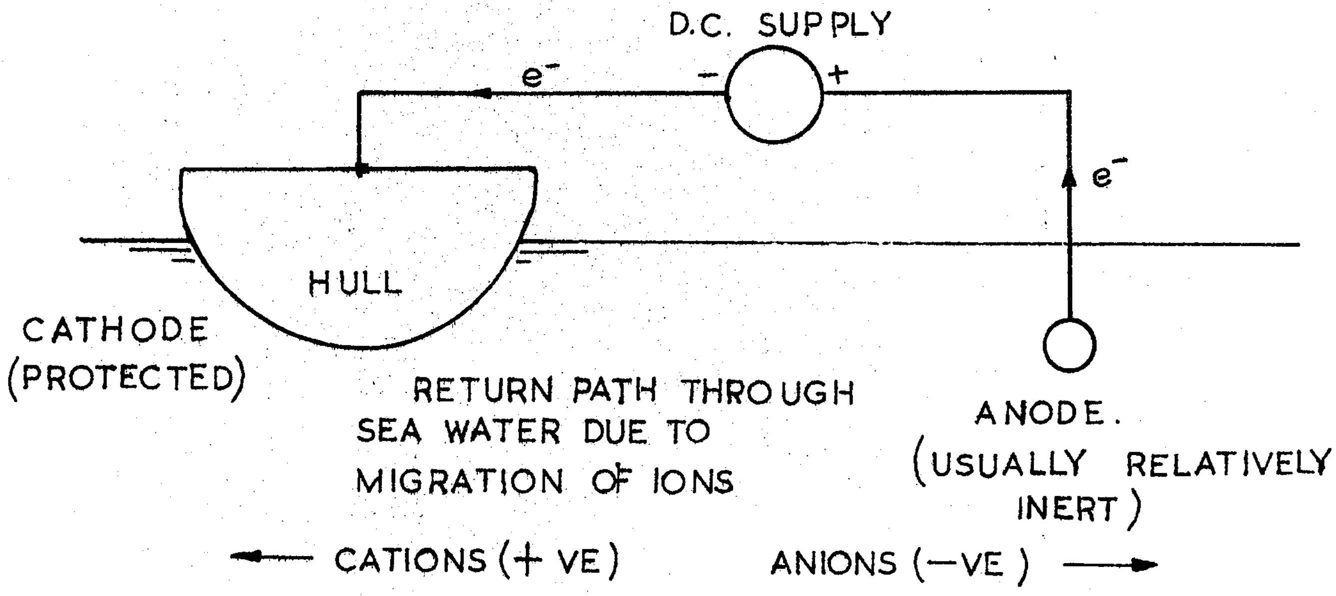
This is the principle reaction at the cathode in neutral or near neutral conditions and involves the reduction of dissolved oxygen to the hydroxyl ion. Since electrons

Cont'd/.. are being

are being produced at the anodes and consumed at the cathode, a stream of electrons will flow through the metal from anodes to cathodes. Notice since the electrons are negatively charged, this infers a flow of current from anode to cathode through the electrolyte, not through the metal.

The corrosion at the anode can be stopped if sufficient electrons are supplied from an external source to satisfy the cathode reaction. Thus the electrons provided by the anodes are not consumed by the cathode reaction and the anode reaction (ie) the corrosion, is stifled. The external source of the electrons can be provided by either a Galvanic or Impressed Current system.

With an inpressed current system, electrons are supplied by connecting the steel structure to the negative side of a low voltage D.C. supply. The positive side of the D.C. supply is connected to an anode which can be made from a variety of materials.



REACTION AT CATHODE

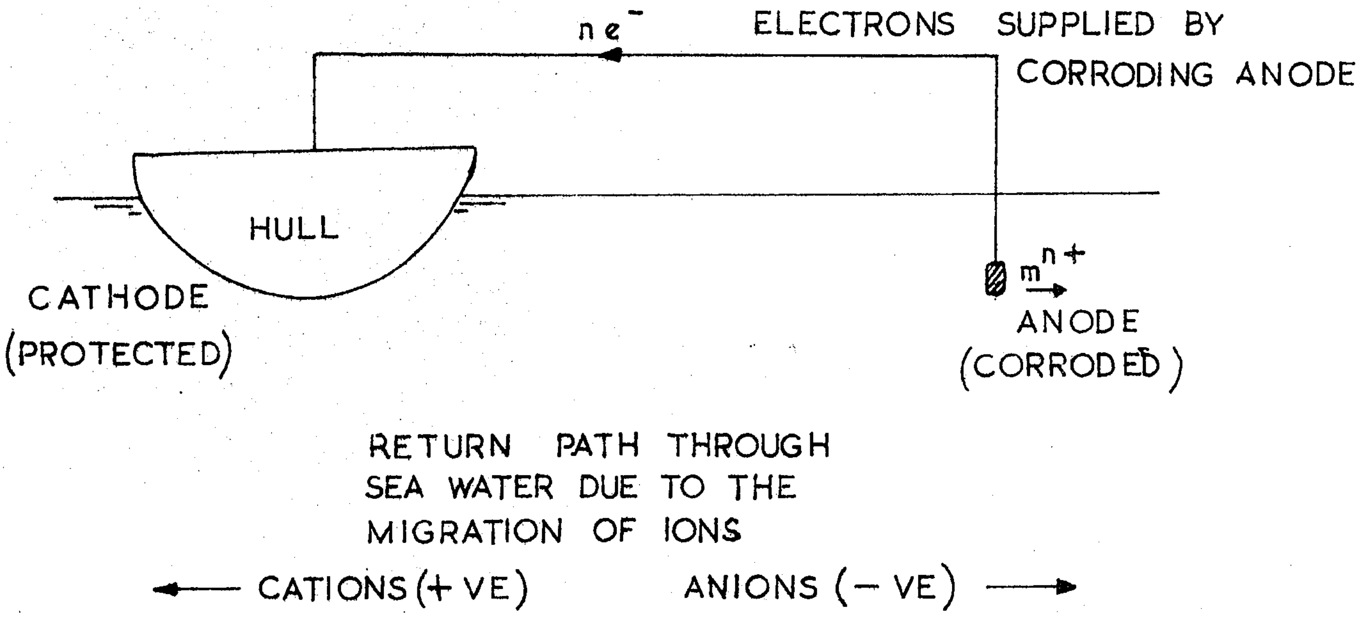
$O_2 + 2H_2O + 4e^- \text{ --- } 4OH^-$

(REDUCTION)

REACTION AT ANODE

OXIDATION REACTIONS DEPENDING ON ANODE MATERIAL

With a Galvanic system, a metal less noble in the galvanic series than the steel surface to be protected is joined directly to the steel surface. Active metals such as magnesium, alloys of zinc or alloys of aluminium will provide a source of electrons by virtue of the ease with which they corrode in electrolytes such as sea water.



REACTION AT CATHODE

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

(REDUCTION)

REACTION AT ANODE

$M \longrightarrow M^{n+} + ne^-$

(OXIDATION)

FOR ALUMINIUM ALLOY ANODES
$n = 3$
FOR MAGNESIUM ANODES
$n = 2$

Current Density Requirements and the Cathode Reaction

The current density required to cathodically protect a structure will depend on many factors including oxygen content, velocity and temperature of the water, the presence of deposits and the type and condition of the paint. These factors alter the current density requirement by their effect on the cathode reaction.

It has been shown that cathodic protection can be achieved if sufficient electrons are supplied to the structure to satisfy the cathode reaction. If the availability of oxygen at the metal-liquid interface is increased and the supply of electrons (ie) current density, from the external source is not correspondingly increased, then the electrons will be drawn from local anode sites and corrosion will again proceed. The current density required for complete cathodic protection is, therefore, dependent on the availability of oxygen at the metal interface. Since oxygen only reaches the metal interface by diffusion through the electrolyte, any factor which will vary the diffusion rate will alter the current density requirements for protection. Thus the need for higher current densities with increased water velocity can be appreciated. Conversely lower current densities can be used when the metal is covered by deposits or paint coatings.

Cont'd/.. The following

The following table shows the design current densities used for the various types of surfaces likely to be encountered on ships at zero speed and at 12 knots.

Type of Metal Surface or Protective Coating	Current Density mA/sq ft	
	Stationary	12 Knots
Steel - Unpainted	4.0	~ 30
Steel - Painted (Aluminium pigmented bituminous) New	0.6	1.1
Steel - Painted (Aluminium pigmented bituminous) 6 mths old	1.0	1.8
Steel - Painted (Aluminium pigmented bituminous) 12 mths old	1.5	2.8
Steel - Oil base painted 6 mths old	1.5	2.7
Steel - Oil base painted 12 mths old	2.0	3.6
Stainless Steel - Unpainted	4.0	~ 30.0
Stainless Steel - Painted (Vinyl)	1.5	2.8
Copper Alloy - Unpainted	4.0	~ 40

These figures were arrived at empirically from practical experience and laboratory work. Designed systems based on these values will provide full protection under normal conditions, but additional allowance should be made when continuous operation at speeds greater than 12 knots is envisaged.

A current density of 20 mA/sq ft may be initially required to protect bare steel in sea water but with time this value can be reduced to approximately 4 mA/sq ft. This is due to the cathode reaction producing hydroxyl ions (ie) alkalinity, and under these alkaline conditions soluble magnesium and calcium salts in sea water are precipitated on the steel surfaces as magnesium hydroxide and calcium carbonate and this calcareous deposit effectively decreases the current density requirements.

In both fresh and brackish harbour waters where oxygen content has been lowered by pollution etc., a lower current density may be required.

While the increase in alkalinity at the protected metal surface has been shown to produce some desired effects, it does impose conditions which are unfavourable to certain paint systems. Under alkaline conditions, oil based paints may be deteriorated by saponification of the oil and great care must be taken in such instances to avoid over-protection of the structure.

Cont'd/.. Although

Although it is true that an underwater hull devoid of paint can be successfully cathodically protected, this is only true if sufficient current is applied in a uniform distribution. Thus in a practical ship application if extensive loss of paint occurs, some corrosion of the hull will be experienced.

With impressed current systems, a dielectric shield (ie) a heavy duty coating of high electrical resistance, is provided around each anode to improve current distribution and reduce the possibility of local paint damage due to over protection.

CONTROL OF CATHODIC PROTECTION

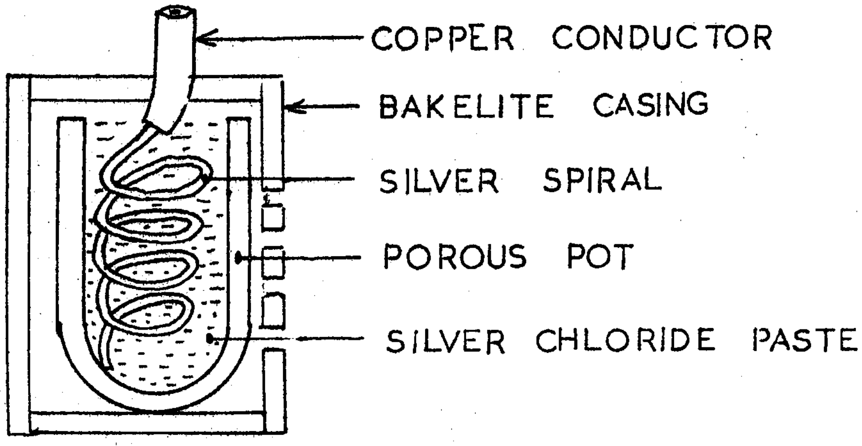
The method of determining complete cathodic protection is by measurement of the potential difference between the structure and some other electrode, the potential of which is known. Electrodes used for this purpose are for obvious reasons termed reference electrodes, the commonly used ones being silver-silver chloride, copper-copper sulphate and the calomel types.

The potentials of these reference electrodes with respect to a hydrogen electrode as zero are shown in this table:-

Reference Electrode	Potential (mV) at 25°C
Silver-Silver Chloride *	+ 248
Copper-Copper Sulphate	+ 316
Calomel (saturated)	+ 245

* The value for the silver-silver chloride electrode is based on its potential in sea water.

The basic design of a simple portable type of Silver-Silver Chloride reference electrode is shown in the sketch.



It consists of a centrally located strip of silver wound in a spiral form coated with an intimate mixture of silver chloride and silver powder. This assembly is placed inside a porous ceramic pot and the inside of the pot is filled with a silver-silver chloride paste. The pot is fitted inside a bakelite tube, and bakelite ends close the tube. The bakelite tube has several holes around its circumference to permit the entry of the sea water electrolyte.

When the electric cable from this electrode is connected to one side of a meter and the ship's hull electrically connected to the other, the potential difference between the two can be measured.

Most painted steel structures in sea water will have a potential of 600 to 650 mV negative to a silver-silver Chloride reference electrode. It has been well established that complete protection of steel in sea water is provided at a potential of approximately 800mV and the recommended potential control range for HMA Ships is 800 to 820 mV negative to the Silver-Silver Chloride reference electrode. Potentials more negative than 820mV (eg) 850mV are wasteful of current and may cause paint damage while potentials more positive than 800mV (eg) 750mV, indicate incomplete protection.

The limits of potential beyond which paint damage may occur are given for various paint systems in the following table:-

Anti-Corrosive Coating Type	Max. Permissable Hull Potential (mV)
Aluminium Bituminous	1000 *
Coal Tar Epoxy	1000 *
Vinyl	1000 *
Oleo resinous. All oil based paints.	820

* These materials are inherently alkali resistant. Potential control is not critical. This figure can be exceeded for short periods without detriment.

ELECTRICAL BONDING

The complete underwater area of a ship can be cathodically protected only if all exposed areas of the hull are secured to the main structure by a low resistance connection.

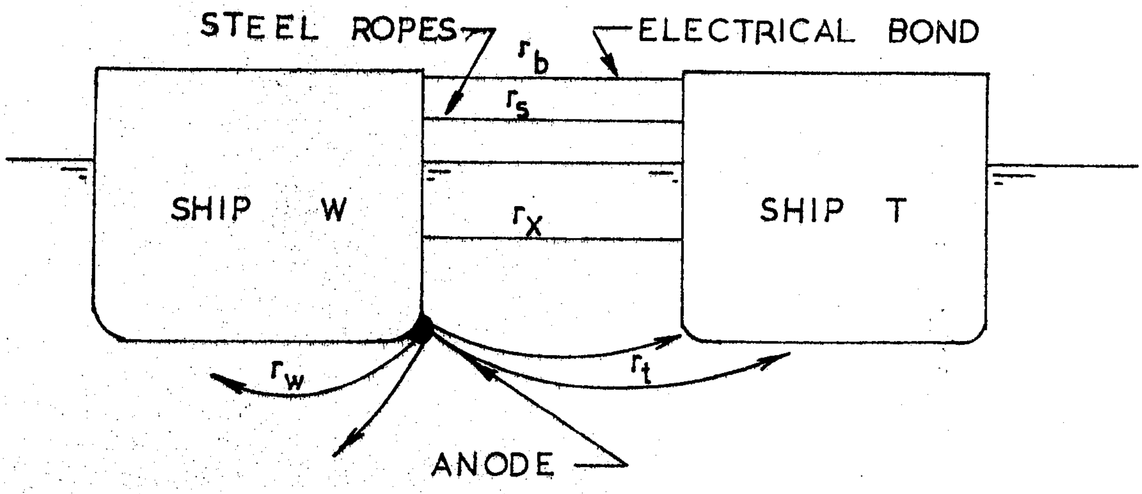
Cont'd/.. In the case

In the case of propellors and shafts it is likely that under stationary conditions there will be a fairly low resistance contact to the hull through the reduction gears and metal bearings. Under movement however, a high resistance contact to the hull is likely since gears and bearings will be essentially insulated by an oil film. Because of this and because shafts are generally wrapped with fibreglass epoxy, the propellor and shaft do not enter the calculations for the current requirement of the hull.

The exception to this is in the case of grease packed white metal bearings where intermittent electrical contact between the rotating shaft and bearings can cause severe pitting of the shafts. To avoid this, the current picked up by the propellors and shafts is shunted direct to the hull by a low resistance brush gear. In this case the propellor area does enter the current requirement calculations.

For similar reasons rudders are bonded directly to ships structure by fitting a flexible electrical cable between the rudder post and hull.

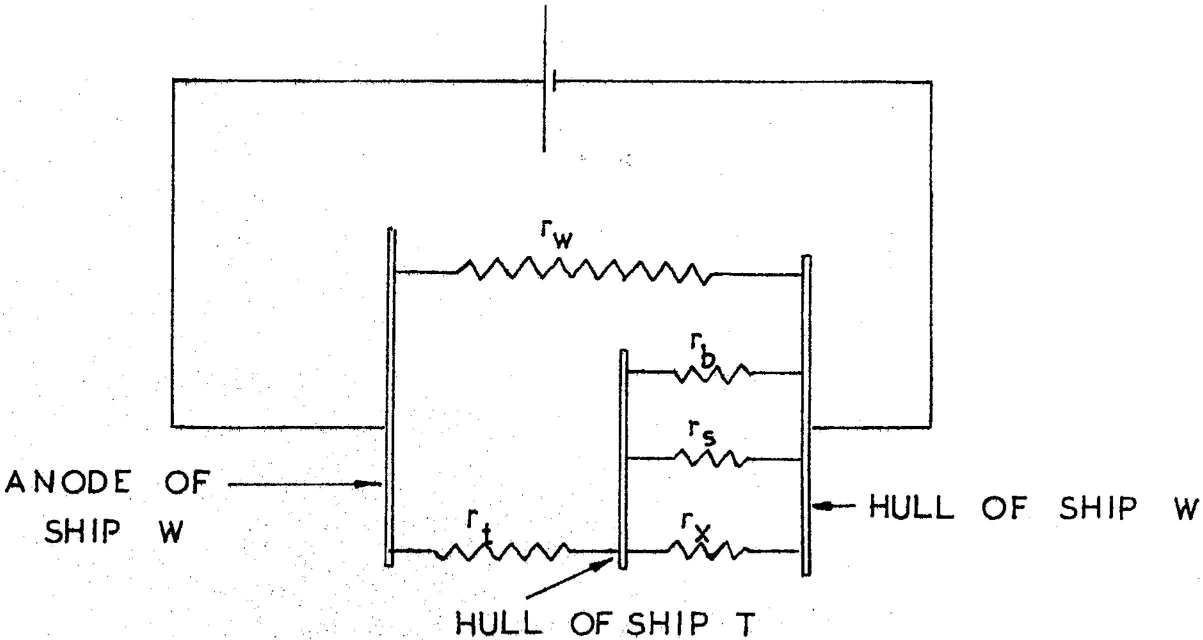
When a cathodically protected marine structure is in close proximity to an unprotected structure, there is a danger of corroding the latter by stray currents originating from the anodes of the protected structure. For example, a cathodically protected ship lying alongside an unprotected ship and not bonded to it could cause accelerated corrosion of the unprotected ship.



The diagram shows the various possible current paths from the anode of the cathodically protected ship W. Current leaving this anode will flow to the hull of ship W and some may flow to the neighbouring ship T and return by various paths such as sea water, steel securing ropes or an electrical bond. Current returning through the sea water path of

Cont'd/.. resistance

resistance r_x will cause corrosion of the ship T at the position the current leaves the hull.



From the above electrical representation of the previous sketch it can be appreciated that the current flow through r_x will be small if either the resistance in the steel rope connection r_s, or the resistance of the electrical bond r_b is small compared with r_x. r_x is the resistance of the sea water path from anode to hull W and r_t is the resistance of the sea water path from anode to hull T.

Measurements have shown that the resistance of a steel rope connection is not sufficiently low and it is therefore necessary to fit an electrical bond between the ships, the resistance of which must not exceed 0.001 ohms.

By this means, corrosion of a neighbouring unprotected ship can be reduced. When such a bond is applied, however, the potential of the protected ship will fall below the protective limit and because the cathodic protection is now being applied to two hulls it is necessary to increase the anode current considerably.

MATERIALS FOR GALVANIC SYSTEMS

The most commonly used materials for galvanic or sacrificial anodes are alloys of zinc, magnesium and aluminium. These alloys have been developed to give a better performance than the base metal. The following table lists the more important properties of the galvanic anode materials.

Material	Sol'n Pot'l Volts V Ag/AgCl ref	Driv'g Voltage with resp to prot'ctd structure at 0.8 V	Cur. Output Amp hrs/ lb.	Anode Consumption lbs per amp yr.	Density lbs/in^3
Magnesium Alloy 6% Al, 3% Zn, Mg remainder	1.5	0.7	500 @ 50% effcy	17 @ 50% effcy	0.063
Zinc Alloy (0.3 % Al, 0.05 Cd, 0.003% Fe (max) Zn remainder	1.0	0.2	370 at 100% effy	24 at 100% effcy	0 . 26
Aluminium Alloy (0.4% Zn, 0.04% Hg, Al remainder	1.05	0.25	1250 @ 95% effcy	7 @ 95% effcy	0.1

The zinc alloy and aluminium alloy compositions quoted are the standard compositions used in the RAN.

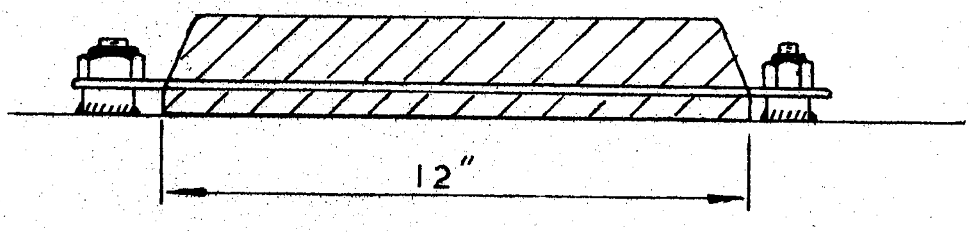
ZINC ALLOYS

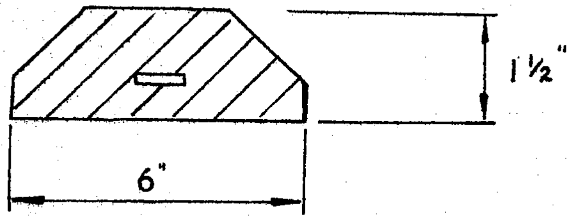
The early use of commercial quality zinc was found to be quite unsatisfactory due to the formation of surface films which severely limited the current output. Inclusion of iron was the primary cause of film formation and early specifications limited iron content to 0.0014%. However, extensive research has shown that the effect of iron impurity can be overcome by additions of aluminium with silicon or aluminium with cadmium, to the alloy. The standard zinc alloy anodes used in the RAN are designated Types 1, 2 and 3, the details of which are shown below.

Nom. Composition	Designation & Size	Mean Currnt Output(amps)	Nom life (yrs)	Wt (lbs
99.6% Zinc 0.3% Aluminium 0.05% Cadmium 0.003%(Max) Iron	Type 1 - 12" x 6" x 1½"	0.5	1	18.5
	Type 2 - 12" x 6" x 2¼"	0.5	2	25.5
	Type 3 - 6" x 2½" x 1½"	0.2	1	4.2

Cont'd/.. A zinc alloy

A zinc alloy anode in sea water has a potential of approximately - 1000mV with reference to a Silver-Silver Chloride electrode and thus has a driving voltage of only 200mV over a cathodically protected structure at -800mV. This makes it imperative to ensure a low resistance connection between the anode and the hull, and for this reason, the earlier method of bolting through the anode material has been discontinued. The anodes are now cast around galvanised straps which can be welded or bolted to the structure. This ensures a low resistance connection between the zinc alloy and the structure, for the complete life of the anode. An advantage of the low driving voltage is that it provides useful self limitation of the current output which is dependent on the potential of the structure. Also dielectric shielding is unnecessary. This sketch shows the cross-section of a Type 1 anode:

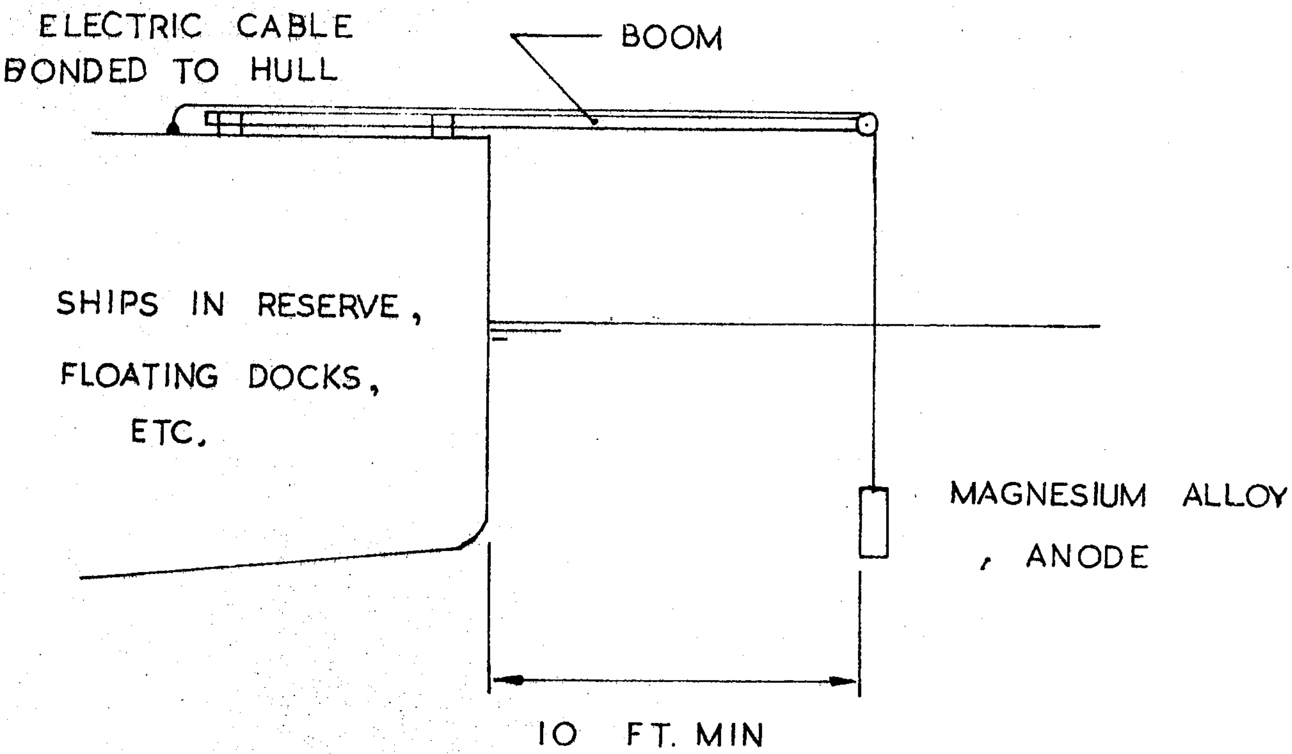




MAGNESIUM ALLOYS

Because of the higher driving voltage (700mV), magnesium alloy anodes are the most important galvanic anodes used industrially for the protection of underground pipelines where the resistivity of the soil is much higher than that of sea water.

Their main use in a marine environment is in remote systems (ie) systems where the anode is placed some distance from the structure to be protected but still connected electrically to it. This sketch shows the usual method of rigging such anodes:



The details of the magnesium alloy anodes used in the RAN are as follows:

Composition	Size	Mean Current Output (amps)	Nominal life(yrs)	Wt lbs.
90% Magnesium 6% Aluminium 3% Zinc	30" x 9" dia.	With no resistance - 6.0 With 0.25 Ω resistance - 3.0	1 2	120

As illustrated, the current output of the anode can be reduced (therefore increasing the life of the anode) by inserting a resistance in series with the anode.

They have not been adopted for the protection of active ships for the following reasons:-

(a) their higher driving voltage does not permit effective self limitation of current output, which makes it difficult to produce a design which will give complete protection without overprotection under both stationary and moving conditions.

(b) it is necessary to fit small dielectric shields.

(c) these anodes are expensive.

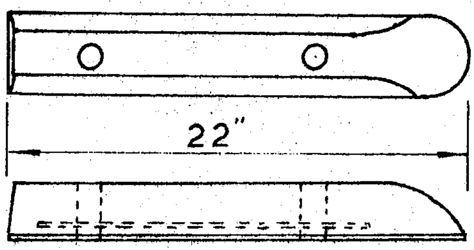
Cont'd/.. Because

Because magnesium and its alloys can produce sparks on contact with bare or rusted steel, the use of these anodes in tanks or confined spaces associated with combustable fumes is strictly forbidden.

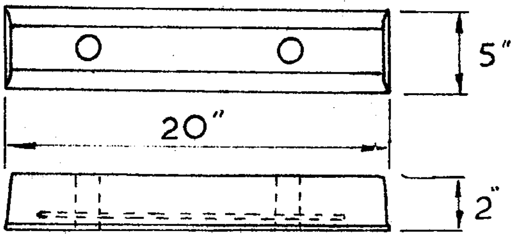
ALUMINIUM ALLOYS

A very satisfactory aluminium alloy containing mercury and zinc as the main alloying elements is now available commercially and this material has been chosen to replace the zinc alloy as the standard material in the RAN for external hull galvanic anodes.

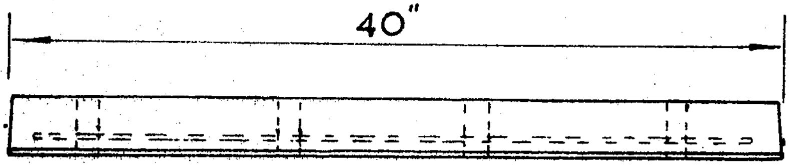
Extensive tests in Australia and overseas have shown that this material has a high electrochemical efficiency and a much greater current output than the zinc alloy. The driving voltage is similar to that of the zinc alloy so the points mentioned previously for the zinc alloy (ie) low resistance connection between anode and hull imperative and no dielectric shielding necessary, apply to these anodes. The details of these anodes are shown below:-



TYPE 4 A



TYPE 4 B



TYPE 4 C

Nominal Composition	Designation and Size	Mean Current Output(amps)	Nominal life(yrs)	Weig (lb
99.5% Aluminium 0.4% Zinc 0.05% Mercury	Type 4A - 22" x 5" x 2" faired end	0.9	2	17
	Type 4B - 20" x 5" x 2" square ends	0.9	2	16
	Type 4C 40" x 5" x 2" square ends	1.3	3	32

Cont'd/.. It should

It should be noted that these current output and nominal life figures quoted will be modified when these anodes are used in butted in line arrays.

The following table illustrates how these figures are modified:

Anode Type	Anode Array Size		
	2-3 anodes	4-8 anodes	10 or more anodes
Type 4A	0.64	0.45	0.36
Type 4B	0.64	0.45	0.36
Type 4C	0.90	0.66	0.53

The considerable advantage of these anodes when compared to zinc anodes is with respect to their weight and life. For a given electrical output the use of aluminium alloy anodes can result in a 60-70% weight saving and a long life system.

Because aluminium and its alloys can produce sparks on striking rusted steel at sufficiently high velocity, when aluminium alloy anodes are mounted in tanks containing petroleum products, they must not be placed in a position where their potential energy exceeds 200 ft. lbsf.

IMPRESSED CURRENT SYSTEMS

The components of such a system are a d.c. power source, means of controlling and measuring the current, suitable anodes and dielectric shielding (for hull mounted systems).

There are 2 types of impressed current systems used, manually and automatically controlled ones.

With impressed current systems, both hull mounted and portable reference electrodes are used to check the potential of the hull.

With manually controlled systems, the potential of the hull is merely indicated on a meter which is checked periodically and the current output from the d.c. supply adjusted accordingly. With automatically controlled systems, this hull potential signal is fed via a meter into an amplifier and transformer rectifier and continuously controls the current output by variation of the A.C. input into the rectifier.

ANODE MATERIALS

A wide variety of materials may be used as anodes for inpressed current systems, including mild steel, silicon iron, lead alloy, graphite, platinim and platinum plated titanium.

Cont'd/.. Mild Steel

Mild Steel is an expendable anode material while the remainder are generally classed as insoluble. Mild steel anodes are generally operated at low current densities where the anode efficiency is 100%, the anode reaction being the formation of iron ions:

$$Fe \text{ ------ } Fe^{++} + 2e^{-}$$

This means that the supply of electrons to the structure is accompanied by the equivalent electrochemical loss of iron from the anode. For the insoluble anodes, however, the anode reaction is essentially the discharge of oxygen and chlorine, in addition to which there may be some small loss of anode material. This loss varies with material and is virtually zero for platinim.

It is emphasised that whereas in galvanic systems care must be taken to ensure a good electrical contact between the anode and the hull, with impressed current systems, the anode must be well insulated from the hull.

The following table lists the consumption rates for the impressed current anodes operating in sea water at the specified current densities. The consumption rate varies markedly with current density.

Material	Anode Consumption lbs/amp. yr	Density lbs/in^3
Mild Steel	20 at 1 amp/ft^2	0.28
Silicon Iron	1.5 at 5-10 amps/ft^2	0.25
Lead-Silver-Antimony Alloy	0.2 at 5-10 amps/ft^2	0.4
Graphite	1.2 at 5-10 amps/ft^2	0.08
Platinim plated Titanium	Negligible	1.16

STEEL ANODES

Early attempts to use steel anodes for the protection of HMA active Ships were not entirely successful. Anodes were mounted on wooden fairings on the bilge keels but difficulty was experienced in obtaining a satisfactory current distribution to the forward and aft areas. Wooden mountings proved unsatisfactory due to the insulation difficulties and these fittings were cumbersome and difficult to maintain. A better current distribution could be achieved using several small anodes placed around the hull but due to their high consumption rate, this was not possible. Mild steel anodes are, however, still used in some remote systems.

Cont'd/.. SILICON

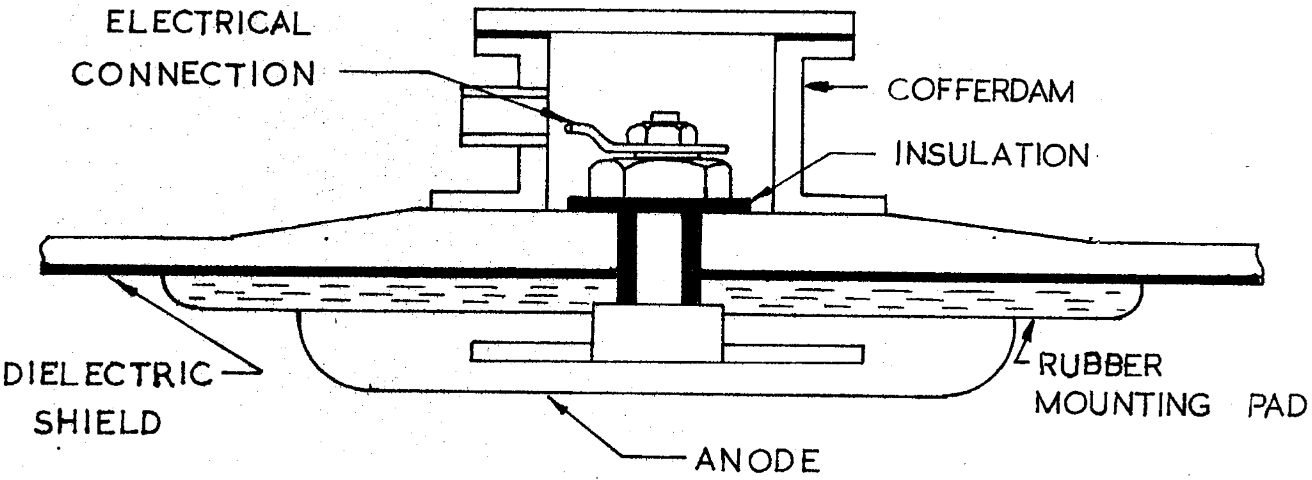
SILICON IRON

This ferrous alloy should contain at least 14.3% silicon since the consumption rate increases rapidly if the silicon content is reduced below this value. Although this material is cheap and in rod form is used in some remote systems, it is not used on fast ships since the consumption rate at higher water speeds is too high.

LEAD-SILVER ALLOYS

This material was developed in the U.K. and is essentially a lead alloy containing 1% silver and 6% antimony. These anodes should not be operated at current densities greater than 25 amps/sq ft due to the development of passivity which severely restricts the flow of current from the anode. This material is the standard RAN impressed current anode material.

STANDARD LEAD SILVER ANTIMONY IMPRESSED CURRENT ANODE



OTHER MATERIALS

Graphite has been used by the U.S. and Canadian navies for both hull mounted and remote systems but because of their relative fragility, the RAN does not use these anodes. Platinim plated Titanium anodes with a 0.0001" thick platinim coating have been tried in the RAN but because of stripping of the coating after 3 to 4 years, the thickness has been increased to 0.0002". These anodes have performed satisfactorily for several years but owing to their high cost, they are not generally used.

DIELECTRIC SHIELD MATERIALS

Dielectric shields are thick coatings of heavy duty organic materials applied to the hull around impressed current and magnesium galvanic anodes. For impressed current systems, the shield must extend at least 5 ft from the anode centre and have a minimum thickness of 0.040". Since the

Cont'd/.. anode

anode reaction of the insoluble anodes involves the discharge of oxygen and chlorine, the shield materials must be resistant to these gases at quite moderate concentrations. Additionally, any defects in the shield will be subject to a high current density with consequent development of highly alkaline conditions at the metal interface. Thus the bond between shield and the metal interface must also be resistant to these conditions. Other desirable features for these materials are low water transmission rate, good adhesion to steel, resistance to shock, vibration and flexing, compatability with anti fouling paints and ease of application. Of the wide range of materials tested under service conditions, the epoxy resin - fibreglass layup has been selected by the RAN as the most suitable material for dielectric shields.

REMOTE GROUND BED SYSTEM

This system uses steel anodes located on the sea bed in the vicinity of the structures to be protected. It is used to protect ships fitting out, ships in reserve, floating docks or other stationary vessels, and provided there is a reasonable depth of water, the system can provide a uniform current distribution.

COMPARISON OF CATHODIC PROTECTION SYSTEMS

The advantages and disadvantages of the various types of cathodic protection systems are shown in the following table:-

Type of System	Advantages	Disadvantages
Hull Mounted Galvanic (Overall Protection)	Simple to fit. Low initial cost. Little maintenance required. Suitable for any paint system. No power required.	High running cost. Requires 1 or 2 yearly renewal. Increased hull resistance and noise.
Hull Mounted Galvanic (Stern Area Protection)	As above. Lower cost for fitting and maintenance.	Slight hull resistance increase. Requires 1 or 2 yearly renewal. Only protects Stern area.
Remote Galvanic Overall Protection	No power required. Low initial cost. Excellent current distribution. Renewal without docking. No anode shielding necessary. Controllable, Little Maintenance.	High running cost.

Table Cont'd.

Type of System	Advantages	Disadvantages
Hull Mounted Impressed Current. Overall protection. Manual or Automatic Control	Low running cost. Low maintenance costs. Yrs of life without renewal. Controllable. Little effect on hull resistance and noise.	High initial cost. Skilled control necessary. Unsuitable for oil based paints.
Remote Impressed Current Overall protection. Manual Control.	Medium installation costs. Low operating costs. Controllable No anode shielding necessary. Excellent current distribution. Renewable without docking.	Not mobile.

In the initial introduction of cathodic protection into the RAN it was thought that small impressed current systems with anodes mounted well towards the stern area would provide a relatively cheap system primarily concerned with the providing complete stern area protection only. However, accumulated experience has shown that complete or almost complete protection of all the underwater hull was being achieved. Thus for impressed current systems, the distinction between overall and stern area protection is no longer made. A convenient method of classification now used is that for ships with a wetted area of less than 15,000 sq ft, the impressed current anodes should all be located in the stern area whereas for larger ships, the anodes should be evenly distributed throughout the ships length.

The "throw" of protective current from a galvanic system is less than that from an impressed current system and hence the distinction between "overall" and "stern area" protection is maintained.

Due to the better current distribution that can be obtained using remote systems, these systems will operate on a lower total current than the equivalent hull mounted system.

The RAN policy for new construction is to fit automatically controlled impressed current systems to combatant ships and other ships where water silence is an operational requirement (eg) Oceanographic Ships.

DESIGN OF CATHODIC PROTECTION SYSTEMS

Having determined the type of system to be used, the amount of current needed to protect the hull is determined from the underwater area of the hull including rudders and bilge keels, the paint system used and the likely

Cont'd/.. cruising

cruising speed. Whether or not the propellor current is included, dependson whether or not the propellor is bonded to the hull. From the total current needed, the number of anodes needed is determined.

For galvanic anodes the current output per anode is determined primarily on the sea water path which is in turn dependent on the surface area of the anode and not directly on its weight. Some modification of current output can be caused by current crowding (ie) the effect of one anode on another in the immediate vicinity.

Knowing the current output for the given shape of anode, the effective life can be calculated from the following expression.

$$M_{lbs} = I_{amps} \times T_{years} \times E$$

where

M = weight of metal consumed
I = Average current output
T = effective life
E = consumption rate in lbs/amp year

For example, a Type 1 zinc alloy anode, with a current output of ½ amp, will lose 12 lbs of metal in one year, and therefore, since it weighs 20 lbs, will adequately maintain this current for 1 year. Similarly, a Type 2 anode will have an effective life in excess of 2 years. This is achieved by increasing the weight with a minimum increase in surface area (ie) the current output remains similar to a Type 1 anode. Some excess of anode material is required above the minimum quantity to ensure adequate current output towards the end of the design life since current output falls at an increasing rate as the anode approaches complete consumption.

The distribution of galvanic anodes is a compromise between the current crowding effect, overall current distribution, increase in hull resistance and increase in underwater noise.

The new type of aluminium alloy anodes, TYPES 4A, 4B and 4C now being specified for overall hull protection of ships to be fitted with a galvanic system, have been designed to butt together to form in-line arrays thus reducing the increase in hull resistance and noise. However, because of the current crowding effect, the current output per anode is reduced and therefore more anodes are required so again a compromise must be reached.

With impressed current systems, the number of hull penetrations for anodes and reference electrodes must be minimised, but anodes must be provided in pairs, port and starboard (to ensure symmetry of coverage) and must be situated to give satisfactory coverage to the hull. Reference electrodes should be placed mid-way between anodes

Cont'd/.. and both

and both electrodes and anodes should be placed halfway between the keel and the deep waterline. Another factor to be considered in the placing of anodes is the dielectric shield which is a 12 ft square centred on the anode. This should not be penetrated by hull openings or lie in way of bilge keels or chines.

No matter whether the system chosen is an impressed current system or a galvanic system, it is necessary to provide extra protection to rudders, stern tubes and eddy plates, inlets, discharges and recesses, by the fitting of additional galvanic anodes in these areas.

Because the corrosion pattern of aluminium alloy anodes is very severe and it is possible for pieces of anode material to become separated from the anode body, aluminium alloy anodes are not used in inlets or recesses where mechanisms might be interfered with by small pieces of anode material. In these areas, zinc alloy anodes which corrode in a much more even manner should be used.

As an example consider a Guided Missile Destroyer

Underwater Wetted Area is Deep Condition = 21,300 sq ft
Propellor Area (Unbonded) = 450 sq ft
Paint System Used - Aluminium pigmented Bituminous

For this type of ship the design is based on a 12 month old paint system at ship speed of 12 knots.

∴ Current Density required by hull = 2.8 mA/sq ft

∴ Hull Current needed $= \frac{21,300 \times 2.8}{1000} = \underline{60 \text{ amps}}$

If the propellors had been bonded, the additional current required would have been given by:

Current density required to protect copper alloys = 40mA/sq ft.

∴ Additional propellor current $= \frac{450 \times 40}{1000} = 18$ amps

Now consider an impressed current system is required. Design Output from one standard lead silver antimony impressed current anode = 12 amps.

∴ No. of anodes needed $= \frac{60}{12} = 5.$

∴ Nearest greater even number = 6.

∴ System would comprise of 3 pairs of anodes distributed evenly throughout the length of the ship.

Additional galvanic anodes would have to be fitted to the bottoms of rudders, on the inside of eddy plates, inlets, discharges and sonar recesses.

Now consider a galvanic system using Type 4 aluminium alloy anodes is required.

From before, hull current required = 60 amps.

Assume anode groups of 10 or more anodes will be needed.
Output per anode (Type 4A or 4B) = 0.36 amps.
∴ No. of anodes needed $= \frac{60}{0.36} = 167.$

This could be made up of a pair of anode arrays at the forward end of the bilge keels, and another pair of arrays at the aft end of the bilge keels. Each array would consist of 2 Type 4A anodes and 28 Type 4B anodes (or 14 Type 4C). **A further pair of anode arrays should be sited in the stern area, each stern array consisting of 24 anodes, 2 TYPE 4A + 22 TYPE 4B (or 12 TYPE 4C).**

Additionally, extra anodes should be fitted to the bottoms of rudders, on the inside of eddy plates, inlets, discharges and sonar recesses. Note that zinc anodes would have to be used in inlets and sonar recesses.