



## **GUIDANCE NOTES ON**

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# **CATHODIC PROTECTION OF SHIPS**

**DECEMBER 2017**

**American Bureau of Shipping  
Incorporated by Act of Legislature of  
the State of New York 1862**

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## Foreword

Protective coatings are the most efficient way to protect ship steel structures from corrosion. However, cathodic protection, often in conjunction with protective coatings, is also used to protect immersed parts of bare steel surfaces (including coating damaged areas) from corrosion. This includes the external hull surface and the internal surfaces of tanks, such as ballast tanks.

Cathodic protection (CP) can be Impressed Current Cathodic Protection, Galvanic Anode Cathodic Protection or a combination of both. Cathodic protection controls corrosion by supplying direct current to the immersed surface of the structure, thus making the structure a cathode of a cell. The external hull of a ship is exposed to different waters with differing chemistries, which have a profound influence on the cathodic protection. These *Guidance Notes on Cathodic Protection of Ships* are developed to provide guidelines for ship CP design, installation, and maintenance. It is a common practice for a ship to have cathodic protection systems installed during its new construction.

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## SECTION 1 General

### 1 Scope

These Guidance Notes define the best practices and design recommendations for a ship's corrosion protection using cathodic protection (CP) systems and provide guidelines for ship CP design, installation, and maintenance.

Protective coatings are the most efficient way to protect ship steel structures from corrosion. However, cathodic protection, often in conjunction with protective coatings, is also used to protect immersed parts of bare steel surfaces (including coating damaged areas) from corrosion. This includes the external hull surface and the internal surfaces of tanks, such as ballast tanks. It is a common practice for a ship to have cathodic protection systems installed during its new construction.

External underwater surfaces include the underwater hull and all attachments and openings such as shafts, rudder, stabilizers, propeller, propeller bracket, sea chests, water intakes (up to the first valve), and scoops thruster).

The internal surfaces of various tanks include those of ballast water tanks, fresh water tanks, fuel storage tanks, crude oil tanks, bilges, etc. Pipes, such as condensers and heat exchangers, should also be protected cathodically.

Cathodic protection (CP) can be Impressed Current Cathodic Protection, Galvanic Anode Cathodic Protection or a combination of both. Cathodic protection controls corrosion by supplying direct current to the immersed surface of the structure, thus making the structure a cathode of a cell. The external hull of a ship is exposed to different waters with differing chemistries, which have a profound influence on the current distribution from the cathodic protection system. Thus, these Guidance Notes cover ships' cathodic protection only.

### 2 Materials

These Guidance Notes cover hulls fabricated principally from carbon manganese steels or low-alloy steels and appurtenances made of other ferrous or non-ferrous alloys such as stainless steels and copper alloys. It considers issues from dissimilar metals on ships. The cathodic protection system should be designed so that there is complete control over any galvanic coupling. These Guidance Notes do not cover hulls principally made of other materials such as aluminum alloys, stainless steels, or concrete.

The cathodic protection system for a ship is generally combined with a protective coating system, even though some appurtenances such as propellers are generally not coated. These Guidance Notes can be applied to both coated and bare hulls.

### 3 Personnel

Personnel responsible for the design, testing, measurements, monitoring, supervision of installation, supervision of operation, supervision of maintenance, and survey of cathodic protection systems are to have requisite experience and qualifications in cathodic protection. Personnel are to be trained and certified to reach and demonstrate the necessary competence levels for the tasks undertaken.

EN 15257 and the NACE Training and Certification Program provide a suitable method of assessing and certifying the competence of cathodic protection personnel.

## 4 Normative References

The following documents, in whole or in part, are normatively referenced in this document:

|             |                                                                                                                              |
|-------------|------------------------------------------------------------------------------------------------------------------------------|
| EN 12473    | General principles of cathodic protection in seawater                                                                        |
| EN 12496    | Galvanic anodes for cathodic protection in seawater and saline mud                                                           |
| EN 13509    | Cathodic protection measurement techniques                                                                                   |
| EN 15257    | CP personnel qualification                                                                                                   |
| EN 50162    | Protection against corrosion by stray current from direct current systems                                                    |
| EN 16222    | Cathodic protection of ship hulls                                                                                            |
| NACE SP0176 | Corrosion Control of Submerged Areas of Permanently Installed Steel Offshore Structures Associated with Petroleum Production |
| NACE SP0492 | Metallurgical and Inspection Requirements for Offshore Pipeline Bracelet Anodes                                              |
| NACE SP0387 | Metallurgical and Inspection Requirements for Cast Galvanic Anodes for Offshore Applications                                 |

## 5 Terms and Definitions

For the purposes of this document, the terms and definitions are given in the following:

*Anaerobic.* Lacking free oxygen.

*Anode (in general).* An electrode, placed in the electrolyte, to apply cathodic protection to the structure.

*Anode Potential.* Anode-to-electrolyte potential.

*Cathode.* An electrode through which direct current leaves an electrolyte causing reduction reactions.

*Cathodic Disbonding.* Failure of adhesion between a coating and a metallic surface due to the effect of cathodic polarization.

*Closed Circuit Potential.* Potential measured at a galvanic anode when a current is flowing in between the anode and the surface being protected.

*Dielectric Shield.* Alkali-resistant organic coating applied to the structure being protected in the immediate vicinity of an impressed current anode to enhance the spread of cathodic protection and minimize the risk of hydrogen damage to the protected structure in the vicinity of the anode.

*Driving Voltage.* Also called driving potential. It is the difference between the structure/electrolyte potential and the anode/electrolyte potential when the cathodic protection is operating.

*Electrolyte.* A liquid in which electric current may flow by the movement of ions.

*Impressed Current (IC).* Direct current supplied by an external power source to cathodically protect a structure.

*Impressed Current Anode.* Anode in an impressed current installation, which is connected to the positive terminal of an impressed current power supply.

*Polarization.* Change in the potential of an electrode as the result of current flow to or from that electrode. Also, a change in the potential of a corroding metal from its natural steady-state value, as a result of current flow. "Depolarization" is the reverse process of Polarization.

*Reference Electrode.* An electrode which has a stable potential in one or more electrolytes at a given temperature, thus enabling it to be used in the measurement of other electrode potentials.

*Silver/Silver Chloride (Ag/AgCl) Reference Electrode.* Reference electrode consisting of silver, coated with silver chloride, in an electrolyte containing chloride ions. These are used mainly with seawater.

*Stray Current.* Current flowing through paths other than the intended circuit.

*Underwater Hull.* Part of the underwater hull may include that below the light waterline.



## SECTION 2 Design Criteria and Recommendations

### 1 General

A cathodic protection system uses galvanic anodes, an impressed current system, or a combination of both.

The cathodic protection system should provide sufficient and well-distributed currents to the ship hull steel surfaces so that the surfaces can be polarized to the potential within the limits given by the protection criteria (see Subsection 2/3) over the design life (see Subsection 2/2). The potential should be as uniform as possible over the entire submerged surface. This objective may only be approached by adequate distribution of the protective current over the structure during its normal service conditions. Special considerations should be given for areas such as water intakes, thrusters, and sea chests.

The design of the cathodic protection systems for the external hull should consider the anticipated service conditions and operating conditions such as the characteristics of the seawater (e.g., brackish/fresh water, temperature), the average and maximum anticipated speeds, and the lifetime associated with static (berthed) and dynamic (sailing) conditions.

The design of the cathodic protection systems for internal surfaces of ballast tanks should also consider the ballast period (wet/dry alternating period) and the influence of the ballast water treatment system.

### 2 Design Life of Cathodic Protection Systems

The cathodic protection system should be selected and designed either for the design life of the ship or on the basis of expected dry docking intervals, which are normally specified by the owner.

The design life should take into account any period of time when the cathodic protection system is active, including the ship's construction period.

### 3 Cathodic Protection Potential

#### 3.1 Cathodic Protection Potential Criteria

The accepted criterion for protection of carbon steels or low-alloy steels in aerated seawater is a protection potential of  $-0.80$  V or more negative measured with respect to Ag/AgCl/seawater reference electrode. With such polarization, the corrosion rate of the steel in seawater is suppressed to an acceptably low level. These criteria have been developed through laboratory experiments and field experience. However, structure protection does not need to be limited to these criteria if it can be demonstrated by other means that control of corrosion has been achieved.

In the case of mild steel with active sulfate-reducing bacteria (generally in anaerobic conditions), the potential for protection is  $-0.90$  V instead of  $-0.80$  V with respect to Ag/AgCl/seawater reference electrode.

With increasing negative potentials, there may be an adverse effect on fatigue properties and a risk of hydrogen embrittlement of susceptible steels. See 2/3.2.

A summary of the recommended potentials for protection of the various materials in seawater is given in Section 2, Table 1.

**TABLE 1**  
**Summary of Potentials versus Ag/AgCl/Seawater Reference Electrode**  
**Recommended for the Cathodic Protection of Various Metals in Seawater**

| <i>Material</i>                                                                                                      | <i>Minimum Negative Potential<br/>volts</i>                                | <i>Maximum Negative Potential<br/>volts</i> |
|----------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------|---------------------------------------------|
| Iron and steel                                                                                                       | –0.80 for aerobic environment                                              | –1.10                                       |
|                                                                                                                      | –0.90 for anaerobic environment<br>(with active sulfate reducing bacteria) | –1.10                                       |
| High-strength steels<br>(yield strength > 690 MPa or hardness > 350 HV)                                              | –0.80                                                                      | –0.83 to –0.95 <sup>(1)</sup>               |
| Austenitic stainless steel for aerobic and anaerobic<br>conditions<br>$N_{PRE} = \% Cr + 3.3\% (Mo + 0.5W) + 16\% N$ | –0.30 for $N_{PRE} \geq 40$ <sup>(2)</sup>                                 | –1.10                                       |
|                                                                                                                      | –0.60 $N_{PRE} < 40$ <sup>(2)</sup>                                        | –1.10                                       |
| Duplex stainless steel for aerobic and anaerobic<br>conditions                                                       | –0.60 <sup>(2)</sup>                                                       | See Note 3                                  |
| Martensitic stainless steel (13%Cr) for aerobic<br>and anaerobic conditions                                          | –0.50                                                                      | See Note 5                                  |
| Nickel-based alloys                                                                                                  | –0.20                                                                      | See Note 4                                  |
| Copper alloys                                                                                                        | –0.45 to –0.60<br>for alloys with aluminum                                 | –1.10                                       |
|                                                                                                                      | –0.45 to –0.60<br>for alloys without aluminum                              | No limit                                    |

## Notes

- For high-strength steels susceptible to hydrogen-induced stress cracking (HISC), the maximum negative potential should be more positive (less negative) than –0.83 V (Ag/AgCl/seawater reference electrode).
- For most applications, these potentials are adequate for the protection of crevices, although higher (more negative) potentials may be considered.
- Forgings, castings, and welds are more prone to HISC than wrought materials due to the coarse microstructure allowing HISC propagating preferentially in the ferritic phase.
- High-strength nickel copper and nickel chromium iron alloys can be subject to HISC, and potentials that result in significant hydrogen evolution should be avoided.
- Depending on strength, specific metallurgic condition, and stress level encountered in service, those alloys can be susceptible to hydrogen embrittlement and cracking. If a risk of hydrogen embrittlement exists, then potential more negative than –0.80 V should be avoided.

The above potential criteria and limit values are “polarized” and do not include the voltage (IR) drop, which is generally considered insignificant in marine applications.

### 3.2 Detrimental Effects from Cathodic Protection

#### 3.2.1 Protective Coatings

The coatings to be used should be prequalified for resistance to cathodic disbonding.

#### 3.2.2 Mild Steels

With increasing negative potentials, there is an adverse effect on fatigue properties and a risk of hydrogen embrittlement of susceptible steels. For mild steel, a negative limit of –1.10 V (Ag/AgCl/seawater reference electrode) is generally accepted as the negative limit.

#### 3.2.3 High-strength Steels

For high-strength steels with yield strengths > 690 MPa (100 ksi) or hardness > 350 HV, it has been the practice to use potentials in the range of –0.80 V to –0.95 V (Ag/AgCl/seawater reference electrode). For high-strength steels susceptible to hydrogen-induced stress cracking (HISC), the maximum negative potential should be more positive (less negative) than –0.83 V (Ag/AgCl/seawater reference electrode).

### 3.2.4 Austenitic Stainless Steels and Nickel-Based Alloys

Austenitic stainless steels and nickel-based alloys in the solution annealed condition are generally considered immune to HISC for all practical applications. Moderate cold work would not induce HISC sensitivity of these materials except for UNS S30200 (AISI 302) and UNS S30400 (AISI 304) stainless steels. The same applies for welding or hot forming according to an appropriate procedure.

For certain nickel-based alloys, precipitation hardening may induce increased sensitivity to HISC. For precipitation hardened austenitic stainless steels, the susceptibility is low and a hardness of maximum 300 HV may be considered a reasonably safe limit, while component materials with a hardness higher than 350 HV should generally not receive CP. In the intermediate hardness range (i.e., 300 to 350 HV), precautions should be taken during design to avoid local yielding and/or to specify a qualified coating system for eliminating hydrogen absorption by CP. The qualified coating system should resist CP disbonding during service.

### 3.2.5 Ferritic and Ferritic-Pearlitic Steels (Stainless Steels)

Ferritic and ferritic-pearlitic structural steels with specified minimum yield strength (SMYS) up to 500 MPa (72 ksi) have proven in practice to have compatibility with marine CP systems. However, laboratory testing has demonstrated that steels which have passed their yield point have susceptibility to HISC. It is recommended that all welds should have 350 HV of hardness as an absolute upper limit. Within the range of 300 to 350 HV hardness, precautions should be applied during design to avoid local yielding and/or to specify a qualified coating system for eliminating hydrogen absorption by CP. Again, the qualified coating system should resist CP disbonding.

### 3.2.6 Martensitic Carbon, Low-alloy and Stainless Steels

For martensitic carbon, low-alloy, and stainless steels, failures of CP-induced HISC have occurred in materials with a yield stress of 690 MPa (100 ksi) and a hardness of 350 HV. It is widely recognized that untempered martensite is prone to HISC. Welds susceptible to martensite formation should receive post-welding heat treatment (PWHT) so as to reduce heat-affected zone (HAZ) hardness and residual stresses from welding. The same recommendations for hardness limits and design consideration for ferritic steels above apply.

### 3.2.7 Ferritic-austenitic ("Duplex") Stainless Steels

Ferritic-austenitic ("duplex") stainless steels should be regarded as potentially susceptible to HISC, independent of SMYS [typically 400 to 550 MPa (58 to 80 ksi)] or specified maximum hardness. Welding may cause increased HISC susceptibility in the weld metal and in the HAZ adjacent to the fusion line. This is related to an increased ferrite content rather than hardness. Qualification of welding should therefore prove that the maximum ferrite content in the weld metal and the inner HAZ (about 0.1 mm (0.004 in.) wide) can be efficiently controlled; contents of maximum 60 to 70% are typically specified. Forgings are more prone to HISC than wrought materials due to the coarse microstructure allowing HISC to propagate preferentially in the ferrite phase. Cold bent pipes with small diameters [uncoated and with mechanical connections (i.e., no welding)] have a proven record for CP compatibility when used as production control piping for subsea installations. Design precautions should include avoiding local plastic yielding and use of qualified coating systems.

### 3.2.8 Copper- and Aluminum-Based Alloys

Copper- and aluminum-based alloys are generally considered immune to HISC, regardless of fabrication modes.

## 3.3 Potential Measurements

The protection criteria and effectiveness of cathodic protection systems should be confirmed by direct measurement of the structure potential. However, visual observations of progressive coating deterioration and/or corrosion are indicators of possible inadequate protection. Steel plate thickness gauging can also indicate deficiencies in corrosion protection.

Potential measurements should be made with the reference electrode and a high impedance (minimum 10 MΩ). The reference electrode should be located in the seawater as close as practicable to the ship's hull to minimize voltage drops. The following should be considered when measuring the hull potentials:

- i) Potential measurement techniques can be referred to EN 13509 “Cathodic Protection Measurement Techniques”.
- ii) In areas of greatest shielding and/or in brackish waters, particular attention should be given in evaluating the protective level of ship hulls.
- iii) Changes in water resistivity from causes such as freshwater flow from a river or temperature variation can affect voltage level.
- iv) In impressed current systems under conditions involving high-resistivity water or high current density, the voltage drop may be excessive. Instant-off potential measurements can provide useful information by eliminating voltage drop in the water by switching off the direct current (DC).
- v) In conventionally designed galvanic anode protection systems, current-off readings are not possible. However, the included voltage drop is generally not significant in ordinary seawater if the reference electrode is placed close to the structure. The voltage drop may become significant in brackish waters. In such cases, it may be necessary to use interruptible coupons or other IR correction techniques (see NACE SP0169) to determine the true potential of the metal surface.

When permanent measurement electrodes are installed, they should be at locations representative of the most negative and the most positive potentials on the external hull surface. While the exact electrode locations are known, the information obtained from these electrodes is limited to the adjacent structure surfaces. Although this limitation holds true for any potential measurement, this method can provide a reproducible basis for comparing potentials at different times. The accuracy of permanent electrodes should be periodically checked against another electrode. Dual reference electrodes that combine zinc and Ag/AgCl/seawater references into a single, permanently-installed unit also help to detect/reduce malfunctions.

In the case of impressed current systems, reference electrodes should be fitted to the structure at suitable locations in order to automatically control the output of the anodes and maintain the polarization of critical areas within the set limits.

If this measurement circuit remains permanently connected, care should be taken that it does not draw excessive current (including when idle) from the reference electrode, which may become polarized and give false indications.

The use of portable coupons and electrical resistance probes can be considered for commissioning to allow readings to be made in areas where there is no permanent reference electrode installation. They can be particularly useful when establishing the effectiveness of the dielectric shields.

In addition to reference electrodes, some structures are equipped with permanent monitors to measure current density and current output from representative galvanic anodes. These devices are particularly useful when assessing new structure designs or new environments in which precise CP design criteria are not available. These devices typically use calibrated shunts to arrive at the current output or current density value. Signals are usually transmitted topside using hard-wired connections.

### 3.4 Reference Electrode

The polarized potential of the steel surface in its environment (such as seawater) is measured relative to the potential of a reference electrode. Consequently, no equipment item is of more fundamental importance to the cathodic protection (CP) system than the reference electrode.

The most commonly-used reference electrode in marine environments is the solid junction (SJ) silver/silver chloride (SSC) electrode in direct contact with seawater. However, the potentials of a SJ Ag/AgCl/seawater electrode can be affected by the chloride concentration and temperature of the seawater in which it is immersed. It is also affected by light (photo-sensitive) and contaminants in its environments. These are most likely to affect reference electrodes which operate in a variety of environments and permanent electrodes on ships sailing in different waters (seawater, brackish, and fresh water).

The reference potential will vary as the logarithm of the concentration of active species, which is especially significant in dry electrodes. This effect is minimized by the use of wet electrodes.

Temperature has direct and indirect effects on the reference electrode. The direct effect is a linear variation of potential with temperature [provided with temperature coefficient – mV/°C (mV/°F)]. The indirect effect is a function of the increased quantity of salt able to be dissolved at higher temperatures. These temperature effects are large enough to produce a significant error in potential measurements if left uncompensated.

The effect of temperature on reference electrode potential can be calculated by the following equation:

$$E_t = E_{SHE \text{ at } 25^\circ\text{C}} + k_t (T - 25^\circ\text{C})$$

$$E_t = E_{SHE \text{ at } 77^\circ\text{F}} + k_t (T - 77^\circ\text{F})$$

where

$E_t$  = reference potential at temperature,  $T$

$E_{SHE \text{ at } 25^\circ\text{C}}$  = reference potential at 25°C (see Section 2, Table 2)

$E_{SHE \text{ at } 77^\circ\text{F}}$  = reference potential at 77°F (see Section 2, Table 2)

$k_t$  = temperature coefficient, in mV/°C (mV/°F)

$T$  = actual temperature, in °C (°F)

Other standard reference electrodes may be substituted for the Ag/AgCl (seawater) with their protection potential equivalent to –800 mV referred to an Ag/AgCl (seawater):

- Saturated copper/copper sulfate reference electrode (CSE [saturated CuSO<sub>4</sub>]): –860 V (or more negative) for protection. This electrode is not stable for long-term immersion service.
- High-purity zinc electrode

**TABLE 2**  
**Common Reference Electrodes and Their Potentials and Temperature Coefficients**

| Electrode                                                | Potential Relative to SHE [at 25°C (77°F)] mV | Protection Potential Reading [at 25°C (77°F)] mV | Temperature Coefficient $k_t$ mV/°C (mV/°F) | Typical Usage      |
|----------------------------------------------------------|-----------------------------------------------|--------------------------------------------------|---------------------------------------------|--------------------|
| CSE (Cu/CuSO <sub>4</sub> /Saturated CuSO <sub>4</sub> ) | +316                                          | –860                                             | +0.90 (+0.5)                                | Soil, fresh water  |
| SSC (SJ Ag/AgCl/0.6M (3.5%) NaCl)                        | +256                                          | –800                                             | –0.33 (–0.18)                               | Seawater, brackish |
| SSC (LJ Ag/AgCl/0.5M KCl)                                | +256                                          | –800                                             | ---                                         | ---                |
| SSC (LJ Ag/AgCl/KCl saturated)                           | +199                                          | –743                                             | –0.70 (–0.39)                               | ---                |
| SCE (Saturated Calomel Electrode)                        | +0.244                                        | –788                                             | –0.70 (–0.39)                               | Water, laboratory  |
| Steel protection potential                               | –544                                          | ---                                              | ---                                         | ---                |
| ZRE (Zinc Reference Electrode)                           | –780                                          | +244                                             | ---                                         | Seawater           |

### 3.5 Factors Affecting CP Potential

Ships are exposed to water under varying temperatures and environments. The potential at which corrosion is controlled is a function of the temperatures and the environments. In seawater exposed to the air and at typical ambient temperatures, the criterion listed in 2/3.1 has proved to be satisfactory. For other circumstances, the potential to control corrosion can be estimated using the Nernst equation:

$$E = E^0 + \frac{RT}{nF} \ln \left( \frac{[a_M^{+ne}]}{[a_m]} \right)$$

where

|             |   |                                                 |
|-------------|---|-------------------------------------------------|
| $E^{\circ}$ | = | standard state potential                        |
| $E$         | = | electrode potential                             |
| $a_M^{+ne}$ | = | activity of metal ions                          |
| $a_m$       | = | activity of metal (1 for pure metal)            |
| $R$         | = | gas constant (8.31431 joules/(°K • mole))       |
| $T$         | = | absolute temperature (298.2°K)                  |
| $n$         | = | number of electrons transferred                 |
| $F$         | = | Faraday's constant (96,500 Coulombs/equivalent) |

Factors that affect the degree of cathodic protection needed:

- *Water Velocity.* Cathodic protection current needs increase with water velocity past the hull. The necessary current can be as high as 30 times that for still water
- *Vessel Usage.* More frequently operated vessels need more cathodic protection than vessels infrequently used.
- *Conductivity of the Water.* As the conductivity increases, the rate of galvanic activity increases.
- *Salinity (Fresh and Seawater).* Current needs increase with salinity, but higher driving potentials are needed in fresh water.
- *pH of the Water.* As pH decreases (acid rain lakes), the corrosion rate increases.
- Dissolved oxygen content
- Temperature
- Marine growth
- *Deterioration of Protective Coatings.* Current needs increase as protective coatings deteriorate.

The above factors are interrelated and vary with geographical location and season. It is not feasible to give an exact relation between the seawater environmental parameters indicated above and cathodic current demands to achieve and to maintain CP. To rationalize CP design for marine applications, default design current densities,  $i_c$ , are defined based on vessel speed.

## 4 Design Current

### 4.1 General

To achieve the protection potential criteria denoted in Subsection 2/3, the appropriate design current density for each component or area with respect to the environmental and service conditions should be used during design.

The selection of design current densities may be based on either experience gained from similar ships operating in a similar manner or specific tests and measurements.

The current demand of each metallic component or area of the structure is the result of the product of its surface area multiplied by the protection current density for the bare steel and the coating breakdown factor.

### 4.2 Structure Subdivision and Surface Area Calculations

#### 4.2.1 Submerged Surfaces of Ship Hull

In the CP design, the submerged surfaces of a ship hull can be divided into different cathodic protection zones, which are then considered to be independent for cathodic protection design, although they are not electrically isolated.

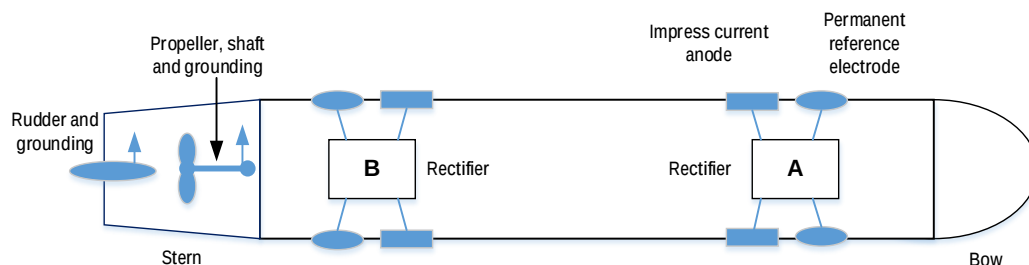
For instance, the underwater hull can be divided into two main cathodic protection zones: the forward (or bow) zone and the aft (or stern) zone, shown in Section 2, Figure 1. This subdivision is related to the high current demand of the aft zone due to high water flow rates, turbulence, and the presence of dissimilar metals due to the propeller(s). The aft cathodic protection zone includes the aft part of the hull, propeller(s), shaft(s), rudder(s), etc.

Some specific components may constitute a cathodic protection zone, such as openings of sea chests, thrusters, rudders, and propellers. The cathodic protection system is determined and dedicated for each cathodic protection zone. Each component should be fully detailed in the design including material, surface area and coating characteristics (coating type, design life and coating breakdown factor).

Special considerations should be given for areas such as water intakes, thrusters, and sea chests:

- Electrochemical marine growth prevention systems (MGPS) often used within sea chests to prevent fouling of seawater intake systems. They may interact with the cathodic protection system. This effect should be considered in the design and installation of the anti-fouling system.
- Cathodic protection within sea chests may adversely affect box coolers in sea chests if the box coolers are electrically isolated from the sea chest. The possible effect should be taken into account in designing the cathodic protection for sea chests.

**FIGURE 1**  
**Typical Arrangement for Two Impressed Current Systems for Ship Hulls**



#### 4.2.2 Internal Surfaces

For internal surfaces, complex geometries can exist within tanks (e.g., stiffeners and heating coils). Lower sections of tanks not fully drained within stiffeners can also constitute discrete cathodic protection zones to be considered.

Each component of a cathodic protection zone should be fully detailed in the design. This should include:

- Material type
- Specific potential limit (if applicable)
- Complexity of the structure
- Surface area
- Coating characteristics, including type, predicted lifetime, anticipated coating breakdown.

Having component areas in the zone and current density needed regarding the component coating condition and service condition, the current demand for each zone can be determined.

It is acceptable to simplify calculations of the surface areas of complex geometries, provided that the simplification is conservative.

All calculations of surface areas and current demand should be documented in the CP design report.

### 4.3 Design Current Density for Bare Steel

The protection current density of bare steels and other metals (i.e., cuprous alloys) depends on the kinetics of electrochemical reactions on the surface. It varies with the material, potential, surface condition, dissolved oxygen content in seawater, flow rate, sailing speed, and temperature. For each particular environmental and service condition, protection current density should be evaluated.

As guidance, typical design current densities for protecting bare steel are given in Section 2, Table 3.

**TABLE 3**  
**Typical Design Current Densities**

| <i>Situation<br/>m/s (knots)</i> | <i>Design Current Densities<br/>for Bare Steel<br/>mA/m<sup>2</sup> (mA/ft<sup>2</sup>)</i> | <i>Design Current Densities<br/>for Coated Steel<br/>mA/m<sup>2</sup> (mA/ft<sup>2</sup>)</i> |
|----------------------------------|---------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|
| $V \leq 1$ (2 knots)             | 100-200 (9.3-18.6)<br>without tidal influence                                               | 5-15 (0.5-1.4)                                                                                |
|                                  | 150-250 (13.9-23.2)<br>with tidal influence                                                 | 7-20 (0.7-1.9)                                                                                |
| $1 < V < 10$ (20 knots)          | 220-350 (20.4-32.5)                                                                         | 11-28 (1.0-2.6)                                                                               |
| $V \geq 10$ (20 knots)           | 350-500 (32.5-46.5)                                                                         | 18-40 (1.7-3.7)                                                                               |
| Vessels in ice                   | 500-750 (46.5-69.7)                                                                         | 35-90 (3.3-8.4)                                                                               |
| Propeller surface                | $\geq 500$ (46.5)                                                                           |                                                                                               |

Protective current density for the areas of bow thrusters, water-jet drives, etc., should be determined individually in each case.

In addition to the calculated underwater hull area, other cathodic protection zones (such as the appendages, propellers, shafts, sea chests, thrusters, etc.) should be calculated separately.

### 4.4 Design Current Density for Coated Steel

The cathodic protection system is generally combined with suitable protective coating systems, which act as the primary method for corrosion prevention.

Most protective coatings are organic and not conductive. These coatings can reduce the protection current demand tremendously and can also improve the current distribution over the surface. However, the coatings deteriorate with time because of aging and physical damage, and thus the protection current demand of coated steel also increases with time.

An initial coating breakdown factor is used to present initial coating damages and defects when the ship is put into service. An annual coating deterioration rate is used to describe an increase of the coating breakdown factor over time during the design life of the ship's cathodic protection system or during a period corresponding to the drydocking interval (at least 2 years).

For each individual component or cathodic protection zone (area and condition), the design current density needed for the protection of coated steel,  $J_c$ , is equal to the product of the current density for bare steel (see 2/3.2),  $J_b$ , and the coating breakdown factor,  $f_c$ :

$$J_c = J_b \times f_c \quad \text{A/m}^2 \text{ (A/ft}^2\text{)}$$

where

- $J_c$  = protection current density for coated metal, in A/m<sup>2</sup> (A/ft<sup>2</sup>)
- $J_b$  = protection current density for bare metal, in A/m<sup>2</sup> (A/ft<sup>2</sup>)
- $f_c$  = coating breakdown factor which varies with time due to ageing and mechanical damage.  $f_c = 0$  for a perfectly insulating coating and  $f_c = 1$  for no coating or a coating with no insulation properties

This formula should be applied for each individual component or cathodic protection zone.

The  $f_c$  values are strongly dependent on the actual construction and operational conditions. For reference, guidelines for the values of coating breakdown factors for conventional paint systems are given in Section 2, Table 4. For high-speed vessels (speed above 25 knots) and vessels in harsh or ice service, the annual depletion rate may be higher.

**TABLE 4**  
**Values of Coating Breakdown Factors for Conventional Paint Systems for Ship Hulls**

|                                                                                                                         |                                         |                     |
|-------------------------------------------------------------------------------------------------------------------------|-----------------------------------------|---------------------|
| Initial coating breakdown factor                                                                                        |                                         | 1% to 2%            |
| Indicative annual deterioration rates for durability defined ISO 12944 for seawater or brackish water immersion service | Using low durability coating systems    | 3% per year         |
|                                                                                                                         | Using medium durability coating systems | 1.5% per year       |
|                                                                                                                         | Using high durability coating systems   | 0.5% to 1% per year |

Another approach for the estimation of the protection current density for coated structures may be considered when values for design parameters are well known from past experience. In this approach, an average value of this protection current density ( $J_g$ ) is considered. Detailed documentation regarding the class of vessel and service and the satisfactory cathodic protection performance is needed to be evaluated for this approach.

For reference, typical average current densities for cathodic protection of coated hulls of ships are given in Section 2, Table 5.

**TABLE 5**  
**Typical Average Current Densities of Coated Hulls for Cathodic Protection**

| Docking Periods<br>months | Current Densities<br>$\text{mA/m}^2$ ( $\text{mA/ft}^2$ ) |
|---------------------------|-----------------------------------------------------------|
| Up to 18                  | 15-25 (1.4-2.3)                                           |
| 19-36                     | 26-45 (2.4-4.2)                                           |
| 37-60                     | 46-75 (4.3-7.0)                                           |

#### 4.5 Current Demand

The current demand for each zone can be determined once component areas and current densities are available.

The design of impressed current systems is based on the maximum current demand. The design of galvanic anodes systems is based on the maximum current demand and mean current demand.

If typical average current densities in Section 2, Table 5 are not adopted for the design, two different values, maximum current demand  $I_{\max}$  and mean current demand  $I_{\text{mean}}$ , should be considered:

- $I_{\text{mean}}$  is used to calculate the minimum mass of galvanic anode material or life of impressed current anodes necessary to maintain cathodic protection throughout the design period.
- $I_{\max}$  corresponds to the most severe working conditions (e.g., dynamic conditions, end of life coating breakdown factor, and worst case environmental conditions) and is used to design the maximum current capacity of the cathodic protection system.

For each component, these two protection current demands can be determined according to the following formula:

$$I_{i, \max} = S_i \times f_{c, \max} \times J_{bd} \quad \text{amperes}$$

$$I_{i, \text{mean}} = S_i \times f_{c, \text{mean}} [t \times J_{bd} + (1 - t) \times J_{bs}] \quad \text{amperes}$$

where

|                      |   |                                                                                                                                                        |
|----------------------|---|--------------------------------------------------------------------------------------------------------------------------------------------------------|
| $I_{i, \max}$        | = | maximum protection current demand for a component, in amperes (A)                                                                                      |
| $I_{i, \text{mean}}$ | = | mean protection current demand for a component, in amperes (A)                                                                                         |
| $S_i$                | = | area of the submerged zone (component under full load conditions including the underwater hull and boot topping), in m <sup>2</sup> (in <sup>2</sup> ) |
| $f_{c, \max}$        | = | maximum coating breakdown factor for the concerned service period. $f_{c, \max} = 1$ for bare steel surface                                            |
| $f_{c, \text{mean}}$ | = | mean coating breakdown factor for the concerned service period. $f_{c, \text{mean}} = 1$ for bare steel surface                                        |
| $J_{bd}$             | = | current density for bare metal in dynamic conditions, in A/m <sup>2</sup> (A/in <sup>2</sup> )                                                         |
| $J_{bs}$             | = | current density for bare metal in static conditions, in A/m <sup>2</sup> (A/in <sup>2</sup> )                                                          |
| $t$                  | = | fraction of time associated to dynamic conditions                                                                                                      |

Consequently, for each CP zone, the protection current demand values are given by the sum of all components in the zone.

$$I_{\max} = \sum I_{i, \max}$$

$$I_{\text{mean}} = \sum I_{i, \text{mean}}$$

When the average current density approach for each component is used, referring to Section 2, Table 5, a unique current demand  $I = J_g \sum S_i$  is considered for each cathodic protection zone.

## 5 Circuit Resistance

The number and location of the anodes determines an electrical current distribution for achieving the protection potential level over the whole steel structure surface. The potential drop from cathodic protection circuit resistance should be considered for applied potential to the steel structure surface.

For cathodic protection systems using galvanic anodes, the optimum anode dimensions may be determined using Ohm's law of cathodic protection circuit:

$$I = \frac{\Delta E}{R}$$

where

|            |   |                                                                                                                                              |
|------------|---|----------------------------------------------------------------------------------------------------------------------------------------------|
| $I$        | = | current output from anode, in amperes                                                                                                        |
| $\Delta E$ | = | driving voltage between anode and structure, in volts                                                                                        |
| $R$        | = | circuit resistance, which is sum of anode-to-electrolyte resistance, electrolyte resistance and structure-to-electrolyte resistance, in ohms |

The circuit resistance,  $R$ , is assumed to be approximately equal to the anode/electrolyte resistance, which is called "anode resistance", as the structure-to-electrolyte resistance and the electrolyte resistance are generally very small.

$\Delta E$  is generally taken as the potential difference between the polarized potential of the steel and the operating potential of the particular anode alloy in seawater.

The anode resistance is a function of the anode geometry and the resistivity of the electrolyte. Empirical formulae given in the following Subsection may be used to calculate the anode resistance.