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Standard Practice

Corrosion Control of Submerged Areas of Permanently Installed Steel Offshore Structures Associated with Petroleum Production

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Foreword

Offshore structures represent large capital investments. Structures are being placed in offshore areas worldwide and are being designed to withstand forces resulting from hurricanes, arctic storms, tidal currents, earthquakes, and ice floes. Moreover, platform structures are currently being placed in deeper waters and, therefore, have become larger, more complex, and more expensive. Control of corrosion on structures is necessary for the economic development of oil and gas production, to provide safe support for working and living areas, and to avoid potential harm to the environment. For the purposes of this standard, offshore structures are considered to be stationary structures (platforms or subsea facilities) that are fixed to the sea floor by gravity, pilings, or mooring cables.

This NACE standard is intended for use by corrosion control personnel concerned with the corrosion of steel fixed offshore platforms associated with petroleum production. It outlines materials, practices, and methods for control of corrosion for steel fixed structures associated with petroleum production located in offshore areas. The purpose is to facilitate more effective corrosion protection of structures by the presentation of reliable information. Corrosion on offshore structures can be divided into three major areas: the submerged zone, the splash zone, and the atmospheric zone. The submerged zone also includes that portion of the structure below the mudline. This standard does not include procedures for the control of internal corrosion of wells, piping, and associated equipment that may be in use on the structure, but does include external protection of these items in the atmospheric zone on the structure.

This standard was originally issued in 1976 and revised in 1983 by Task Group (TG) T-1-2 on North Sea Corrosion Problems. It was revised in 1994 by TG T-1-5, and in 2003 and 2007 by TG 170 on Offshore Steel Platforms—Corrosion Control: Review of NACE Standard RP0176, which is administered by Specific Technology Group (STG) 30 on Oil and Gas Production—Cathodic Protection. All editions of this standard prior to 2007 included a section on coatings on offshore platforms. However, it was determined this subject would be more appropriately covered in another standard. Therefore, NACE TG 313 was formed to develop the standard on coatings.¹ TG 170 is sponsored by STG 02 on Protective Coatings and Linings—Atmospheric and STG 05 on Cathodic/Anodic Protection. This standard is issued by NACE under the auspices of STG 30.

In NACE standards, the terms *shall*, *must*, *should*, and *may* are used in accordance with the definitions of these terms in the NACE Publications Style Manual, 4th ed., Paragraph 7.4.1.9. *Shall* and *must* are used to state mandatory requirements. The term *should* is used to state something considered good and is recommended but is not mandatory. The term *may* is used to state something considered optional.

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Section 1: General

1.1 This standard provides guidelines for establishing minimum requirements for the control of corrosion on steel fixed offshore structures associated with petroleum production, and on the external portions of associated oil and gas handling equipment. Fixed structures include platforms, tension leg platforms (TLP), and subsea templates. This standard does not include guidelines for corrosion control of temporarily moored mobile vessels used in petroleum production.

1.2 For this standard, corrosion on structures is divided into three zones: the submerged, splash, and atmospheric zones. However, only the submerged zone is addressed in this standard. The atmospheric and splash zones are addressed in a standard that is currently a work in progress by NACE TG 313.

1.3 This standard does not designate guidelines for every specific situation because of the complexity of

environmental conditions. In many instances, the problem may have several solutions and, when appropriate, meritorious alternative solutions have been included.

1.4 This standard does not include guidelines for corrosion control of the internal portions of wells, piping, and associated equipment that may be installed on or attached to structures.

1.5 Underwater pipelines and pipeline risers are specifically excluded from this standard.

1.6 Alternative methods are acceptable to achieve a protected potential over an adequate design life; however, deviation should be made only if, in the opinion of a competent corrosion specialist, the objectives expressed in the standard have been achieved.

Section 2: Definitions

NOTE: Additional definitions for cathodic protection (CP) and coatings technology may be found in NACE SP0169,² the *NACE Corrosion Engineer's Reference Book*,³ and the *NACE International Glossary of Corrosion-Related Terms*.⁴

Anode: The electrode of an electrochemical cell at which oxidation occurs. Electrons flow away from the anode in the external circuit. Corrosion usually occurs and metal ions enter the solution at the anode.

Atmospheric Zone: The zone of the structure that extends upward from the splash zone and is exposed to sun, wind, spray, and rain.

Calcareous Coating or Deposit: A layer consisting of calcium carbonate and other salts deposited on the surface. When the surface is cathodically polarized as in cathodic protection, this layer is the result of the increased pH adjacent to the protected surface.

Cathode: The electrode of an electrochemical cell at which reduction is the principal reaction. Electrons flow toward the cathode in the external circuit.

Cathodic Protection: A technique to reduce the corrosion of a metal surface by making that surface the cathode of an electrochemical cell.

Coating: A liquefiable, or mastic composition that, after application to a surface, is converted into a solid protective, decorative, or functional adherent film.

Corrosion: The deterioration of a material, usually a metal, that results from a reaction with its environment.

Corrosion Specialist: A person who, by reason of education and experience, is qualified to evaluate and solve problems related to the corrosion of materials. In this standard, corrosion specialist refers to one who is qualified in the control of corrosion in marine environments.

Current: (1) A flow of electric charge. (2) The amount of electric charge flowing past a specified circuit point per unit time, measured in the direction of net transport of positive charges. (In a metallic conductor, this is the opposite direction of the electron flow.)

Current Density: The current to or from a unit area of an electrode surface.

Depolarization: The removal of factors resisting the current in an electrochemical cell.

Dielectric Shield: An electrically nonconductive material, such as a coating, sheet, or pipe, that is placed between an anode and an adjacent cathode, usually on the cathode, to improve current distribution in a cathodic protection system.

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Doubler Plate: An additional plate or thickness of steel used to provide extra strength at the point of anode attachment to an offshore platform.

Electrical Isolation: The condition of being electrically separated from other metallic structures or the environment.

Electrolyte: A chemical substance containing ions that migrate in an electric field.

Fairlead: A sheave over which an anchor chain or cable passes.

Foreign Structure: Any metallic structure that is not intended as a part of a system under cathodic protection.

Galvanic Anode: A metal that provides sacrificial protection to another metal that is more noble when electrically coupled in an electrolyte. This type of anode is the electron source in one type of cathodic protection.

Holiday: A discontinuity in a protective coating that exposes unprotected surface to the environment.

Impressed Current: An electric current supplied by a device employing a power source that is external to the electrode system. (An example is direct current for cathodic protection.)

Interference Current (Stray Current): Current through paths other than the intended circuit. For the purposes of this standard, interference current is current discharged to the electrolyte from a structure that may be either (1) not an intended part of the circuit or (2) an intended part of the circuit that is not adequately connected to the current source.

J Tube: A curved tubular conduit designed and installed on a structure to support and guide one or more pipeline risers or cables.

Mudline: The ocean floor at the location of interest.

Node: The point on an offshore structure at which two structural elements connect, for example, where a horizontal structural member is welded to the jacket leg.

Pipeline: A conduit for carrying produced oil, water, and gas between structures or between structures and onshore processing facilities.

Platform: An offshore structure used to accommodate oil and gas wells, related production equipment, pipelines, and living quarters.

Polarization: The change from the open-circuit potential as a result of current across the electrode/electrolyte interface.

Reference Electrode: An electrode whose open-circuit potential is constant under similar conditions of measurement, which is used for measuring the relative potentials of other electrodes.

Riser: (1) That section of pipeline extending from the ocean floor up to an offshore structure. (2) The vertical tube in a steam generator convection bank that circulates water and steam upward.

Silver/Silver Chloride Electrode: For the purposes of this standard, a reference electrode that uses seawater as the junction electrolyte, for example, the Ag/AgCl/ seawater electrode.

Splash Zone: The zone of the structure that is alternately in and out of the water because of the influence of tides, winds, and seas. Excluded from this zone are surfaces that are wetted only during major storms.

Structure: Stationary structure (platform or subsea facility) that is fixed to the sea floor by gravity, piling, or mooring cables.

Structure-to-Electrolyte Potential: The potential difference between the surface of a buried or submerged metallic structure and the electrolyte that is measured with reference to an electrode in contact with the electrolyte.

Submerged Zone: The zone that extends downward from the splash zone and includes that portion of the structure below the mudline.

Subsea Template: A structure intended to be placed on the sea floor to accommodate oil and gas wells, related production equipment, and pipelines.

Valve Reach Rod: A long valve stem extension that enables personnel on the surface to open and close a ballast control valve located near the bottom of the structure.

Voltage: An electromotive force, or a difference in electrode potentials, expressed in volts or millivolts.

Voltage Drop: The voltage across a current-carrying resistance in accordance with Ohm's Law.

Section 3: Structural Design for Corrosion Control

3.1 Introduction

3.1.1 This section recommends design features that simplify corrosion control of structural steel in the submerged zone of offshore structures. Corrosion control in the atmospheric and splash zones will be addressed by NACE TG 313. The structural design parameters that must be considered for an offshore structure to resist dynamic and static loads are the responsibility of civil and structural engineers and are not a part of this standard.

3.2 Splash Zone

3.2.1 This is the zone of an offshore structure that is alternately in and out of the water because of the influence of tides, winds, and seas. Excluded from this zone are surfaces that are wetted only during major storms. In the Gulf of Mexico, the splash zone typically covers an interval of about 2 m (6 ft); in Cook Inlet, Alaska, the interval approaches 9 m (30 ft); during winter storms the splash zone in the North Sea can be 10 m (33 ft).

3.2.2 Methods for controlling corrosion in the splash zone include both coatings and cathodic protection (CP). Coatings suitable for this application will be addressed by TG 313. CP can be used to supplement the protection from coatings in the tidal zone portion of the splash zone. The tidal zone is often considered to be that portion of the splash zone below the astronomical high tide mark that is intermittently submerged. CP does not provide protection to the portions of the splash zone that are kept wet due to sea spray or are only infrequently immersed.

3.3 Atmospheric Zone

3.3.1 This zone of an offshore structure extends upward from the splash zone. It is exposed to sun, wind, spray, and rain.

3.3.2 Corrosion in this zone is typically controlled by the application of a protective coating system (this is the subject of NACE TG 313).

3.4 Submerged Zone—External Areas

3.4.1 This zone extends downward from the splash zone and includes any portion of the structure below the mudline. Corrosion control for the external areas

of the submerged zone should be achieved through the application of CP or by CP in conjunction with coatings. To simplify the application of effective CP, the following design features are recommended:

3.4.1.1 Tubular members should be used wherever possible. Recessed corners in channels and I beams are difficult to protect. The crevice formed by placing angles or channels back-to-back may not be reliably protected, and such construction should not be used.

3.4.1.2 For structures in which fatigue or corrosion fatigue is a critical factor, welds may be stress relieved to reduce the likelihood of fatigue or corrosion fatigue failures in the heat-affected zone (HAZ). This may be important in cold-water environments, where polarization tends to develop slowly, or in partially shielded areas on a structure. See API⁽¹⁾ RP 2A-WSD⁵ and RP 2A-LRFD.⁶

3.4.1.3 All weld joints should be continuous. Skip and tack welding should not be used. If lap joints are used, both edges should be continuously welded. Bolted and riveted fittings should be avoided.

3.4.1.4 Ballast control valve reach rods should be designed so that they can be removed after a structure has been set, whenever practical. If left in place, they may shield adjacent structural members from the CP current. Loose reach rods can also cause chafing damage to the structure.

3.4.1.5 Piping, such as grout lines, well cutting lines, discharge lines, water supply casings, and pipeline risers, if clustered around a large structural member, can cause shielding and interfere with the flow of CP current. Piping not needed for continued operations should be removed if economically feasible. Lines not scheduled for removal should be located to avoid CP shielding. A minimum clear spacing of 1.5 diameters of the smaller pipe should be provided. Coatings may be used to minimize CP shielding.

3.4.1.6 Supplemental or replacement impressed current anodes are sometimes required after a structure has been placed in service. Designers should consider providing spare J tubes for

⁽¹⁾ American Petroleum Institute (API), 1220 L St. NW, Washington, DC 20005.

pulling cables for add-on anodes or providing brackets, guides, or clamps to facilitate such anode additions or replacement.

3.4.1.7 Structure pilings should be protected by the structure CP system. Piles driven through jacket legs are normally bonded to the jacket by welding, and thus receive CP. Skirt piles are typically driven inside submerged piling grout tubes and then are grouted in place. Skirt piles may be electrically connected to the jacket by means of guide shoes, centralizers, or other acceptable bonding methods. Corrosion rates below the mudline are considered to be low. However, mudline corrosion can be significant for structures with long lifetimes. All mudline members that are critical to the integrity of the offshore structure should be properly connected to the CP system.

3.4.1.8 Well casing conductors must be electrically connected to the structure when the well casing conductors are considered necessary to the integrity of the well casings.

3.4.1.9 All steel to be protected must have electrical continuity with the CP system (preferably by welded contact). This electrical continuity should be capable of lasting for the lifetime of the structure.

3.5 Submerged Zone—Internal Areas

3.5.1 Corrosion normally is negligible on the internal surfaces of structural members or in compartments that are sealed and have no contact with either the atmosphere or the seawater. Whenever possible, the design should provide for sealed compartments.

3.5.2 During offshore structure launching and tilt-up operations, some structural members are flooded and remain flooded for the life of the structure. To prevent internal corrosion, the flooding valves should be closed after flooding to isolate the flooded chambers from contact with atmospheric oxygen. In compartments in which circulation of seawater is possible, provisions should be made to curtail internal corrosion. CP or a combination of CP and coatings should be used. Tanks and compartments with a gas phase should be coated internally where condensation may occur and CP is not effective. The use of impressed current systems in these compartments should be avoided due to development of toxic and corrosive chlorine gas by the anode and possibly flammable quantities of hydrogen gas at the cathode.

3.5.2.1 Piping, valves, submerged pumps, and other special equipment must also be protected, particularly because when different metallic materials are used, there is high risk of galvanic corrosion. This is important, for example, when

corrosion-resistant alloy piping is routed through structural steel bulkheads.

3.5.3 In flooded compartments with a source of organic nutrients, bacterial growth may generate organic acids, carbon dioxide (CO₂), and hydrogen sulfide (H₂S) that can cause corrosion. Bacteria-related corrosion can be controlled by the use of internal CP, coatings, and microbiocides. **Warning:** *H₂S is toxic, even at low concentrations.*

3.5.4 Pipelines are sometimes installed in pull tubes or J tubes. To restrict contact with seawater and atmospheric oxygen, the pull tube annulus should be sealed at the above-water end with a suitable nonwicking packing after the lines have been pulled into position.

3.5.5 Floating production units have mooring systems intended for long-term service. Special considerations are required for the corrosion protection of these mooring lines.

3.5.5.1 Chains: Chains are protected by corrosion allowance. Corrosion allowance is added on the diameter of the chain (bar), such that at least twice the corrosion rate at the location must be used in calculating the additional material. In the splash zone, a higher corrosion allowance is required. Depending on chain handling, the wear could be substantial. Many permanent floating production units require minimal handling of the mooring systems. Instead of full corrosion allowance in the splash zone, the splash zone chain segment can be turned once during the lifetime; thus the submerged part becomes the splash zone part and vice versa after half the intended design life.

Experience has shown that CP on the structure is effective in protecting chains approximately 30 to 60 m (100 to 200 ft) out from the structure. The distance depends on the connection of the chain to the structure, the size of the chain, and the line tension. This CP should not be included in the mooring line design, but additional CP must be applied to prevent underprotection of the steel fairleads and steel structure.

3.5.5.2 Wire ropes: Wire ropes are normally made from galvanized wires and have an outer extruded corrosion protection jacket of polyurethane, polyethylene, or a similar material. In addition, grease is injected to prevent water from penetrating into the rope and to ease movement between the individual wires. Sacrificial zinc wires may be included. Because steel wires have very high strength, hydrogen effects should be evaluated as part of any CP of the ropes.

It is important that the external jacket completely cover the connection of the wire rope to the socket end and prevent water from penetrating into the wire rope.

3.5.5.3 For mooring lines and anchors, bacterial corrosion in the parts exposed to bottom sediments must be evaluated and, if necessary, protection measures taken in the form of CP, coating, or corrosion allowance.

Section 4: Criteria for CP

4.1 Introduction

4.1.1 This section lists criteria and related inspection methods for CP. Compliance with the criteria either separately or collectively indicates whether the structure is protected.

4.2 General

4.2.1 The objective of using CP is to control the corrosion of metallic surfaces in contact with electrolytes.

4.2.2 The criteria in Paragraph 4.3 have been developed through laboratory experiments or field experience. Structure protection need not be limited to these criteria if it can be demonstrated by other means that control of corrosion has been achieved.

4.2.3 The selection of a particular criterion for achieving the objective in Paragraph 4.2.1 depends, in part, on past experience with similar structures and environments in which the criterion has been used successfully.

4.2.4 No single criterion for evaluating the effectiveness of CP has proved to be satisfactory for all conditions. A combination of criteria may be needed for a single structure.

4.3 Criteria

4.3.1 Potential measurements

4.3.1.1 A negative (cathodic) voltage of -0.80 V or more negative measured between the structure surface in the submerged zone and a silver/silver chloride/seawater (See Paragraph 4.6.5) reference electrode (Ag/AgCl [sw]) contacting the water is necessary. Normally, this voltage should be measured with the protective current applied. This -0.80 V criterion does not include the voltage drop in the water (see Paragraphs 4.5.1.1 and 4.6.1).

4.3.1.2 The potential at which corrosion is controlled is a function of the temperature and the environment. In waters exposed to the air and at typical ambient temperatures, the criterion listed in Paragraph 4.3.1.1 has proved to be satisfactory. For other circumstances, the potential to control corrosion can be estimated using the Nernst equation.⁷

4.3.2 Visual inspection

4.3.2.1 Any visual inspection method (diver visual or feel, physical measurement, photography, or television) should indicate no progression of corrosion beyond limits acceptable for intended structure life throughout the structure. Guidance for this inspection is addressed in API RP 2A-WSD⁵ and RP 2A-LRFD.⁶

4.3.3 Coupons

4.3.3.1 Corrosion type and rate must be within limits acceptable for intended structure life. Steel coupons with metallurgy similar to that of the structure can be placed on a structure for later removal to determine the effectiveness of corrosion control measures. Coupons might be especially useful in areas suspected of being comparatively inaccessible to CP current.

4.4 Alternative Reference Electrodes

4.4.1 Other standard reference electrodes that may be substituted for the Ag/AgCl (sw) are listed below with their voltage equivalent to -0.80 V referred to a Ag/AgCl (sw):

4.4.1.1 Saturated copper/copper sulfate reference electrode (CSE): -0.85 V (or more negative for protection). NOTE: This electrode is not stable for long-term immersion service.

4.4.1.2 High-purity zinc electrode: +0.25 V (or less positive for protection) corresponding to ASTM⁽²⁾ B 418⁸ Type II, high-purity zinc having the following composition limits: aluminum: 0.005%

⁽²⁾ ASTM International, 100 Barr Harbor Dr., West Conshohocken, PA 19428.

maximum; cadmium: 0.003% maximum; iron: 0.0014% maximum; zinc: balance.

4.4.1.3 Saturated calomel reference electrode (SCE [saturated KCl]): -0.78 V (or more negative for protection).

4.4.1.4 MIL specification⁽³⁾ zinc reference electrode: +0.25 V (or less positive for protection) corresponding to MIL-A-18001⁹ having the following composition limits: aluminum: 0.10% to 0.50%; cadmium: 0.025% to 0.15%; iron: 0.005% maximum; lead: 0.005% maximum; copper: 0.005% maximum; silicon: 0.125% maximum.

4.4.1.5 Ag/AgCl (saturated KCl): -0.76 V (or more negative for protection).

4.5 Methods of Measuring and Evaluating CP

4.5.1 The most common and effective method of evaluating the CP level is to measure electrical potential between the structure and a suitable reference electrode.

4.5.1.1 Potential measurements should be made with the reference electrode located in the water as close as practicable to the structure to minimize included voltage drops. Measurements taken with the electrode close to a structure member but distant from anodes and in areas of greatest shielding should be given major consideration in evaluating the protective level of a structure.

4.5.1.2 The most frequently used method of measuring potentials involves suspending the reference electrode freely in the water from a designated location on the structure. The electrode is lowered to a specified series of depths for readings, and the process is repeated at other appropriate points on the structure. The location of the electrode may not be known because of drift resulting from water currents. This method is useful for determining the general condition of the CP system, but may not define problem areas on marginally protected structures.

4.5.1.3 The reference electrode may be carried by a diver or a remotely operated vehicle (ROV). This method provides excellent knowledge of electrode location and can result in a potential survey in any desired degree of detail. Diver safety must be considered during evaluation of impressed current protected structures. This may involve limiting the output from or deenergizing at least a part of the CP system for the duration of the measurements. If the CP system is

deenergized, the effect of the reduction on the level of protection should be considered during the evaluation of the potential measurements.

4.5.1.4 The reference electrode may be run down a guide wire for better control of its location. The guide wire may be permanently installed on the structure, or it may be temporarily installed with the aid of a heavy weight to anchor the guide wire at the bottom. If temporarily installed, the guide wire (if metallic) should be electrically isolated from the structure. The guided electrode is capable of providing more accurate potential information than the freely suspended electrode, depending on the proximity of the guide wire to the members of the structure.

4.5.1.5 A number of permanent reference electrodes may be mounted on a structure. 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 (sw) references into a single installed permanent unit also help to detect/reduce malfunctions.

4.5.1.6 In addition to reference electrodes, some structures have been equipped with permanent monitors to measure current density and current output from representative galvanic anodes. These devices are particularly useful when dealing with 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.

4.5.2 In addition to potential surveys, current density surveys can produce valuable data. Current density surveys utilize specially designed reference electrode arrays that measure the voltage gradient in the seawater around the structure. Although these surveys do not determine the level of protection present on the structure, they may be useful in determining current distribution and predicting remaining anode life.

4.5.3 Visual inspection is sometimes used to gain detailed knowledge not attainable by other means.

4.5.3.1 Divers may be employed to inspect visually or by feel if turbidity or light conditions dictate.

⁽³⁾ Military Specification, available from Government Printing Office, 732 North Capitol St. NW, Washington, DC 20401.

4.5.3.2 Visual inspection using suitable instruments may include physical measurements such as the crack length and depth, wall thickness, or pit depth, as well as anode size and condition.

4.5.3.3 Underwater photography may be used to provide a permanent record of conditions.

4.5.3.4 Underwater television can provide a running topside view if decisions must be made while underwater work is in progress. Videotapes can provide a permanent record of the underwater conditions.

4.5.4 Steel coupons with metallurgy similar to that of the structure can be placed on a structure for later removal to determine the effectiveness of corrosion control measures. Coupons might be especially useful in areas suspected of being comparatively inaccessible to CP current.

4.6 Precautionary Notes

4.6.1 Consideration should be given to voltage (IR) drops other than those across the steel/water interface when structure potential data are evaluated.

4.6.1.1 Changes in water resistivity from causes such as freshwater flow from a river or temperature variation affect the included voltage drop.

4.6.1.2 In impressed current systems, under conditions involving high-resistivity water or high current density, the voltage drop may be excessive. Potential measurements taken immediately after turning off the rectifier(s) may provide useful information by eliminating voltage drop in the water. (Instant-Off measurements typically are made between 0.2 and 1 second after switching the direct current (DC) circuit open. Switching the alternating current (AC) circuit may leave continuity between the anode and cathode and may result in erroneous data.)

4.6.1.3 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 SP0169²) to determine the true potential of the metal surface.

4.6.2 Storm waves or strong tides can produce high water velocities that tend to depolarize the structure.

Higher water levels also add additional areas of unprotected steel and increase the current required to produce protective potentials. Depolarization is less likely to be a problem for well-polarized structures with well-formed calcareous deposits or for coated steel structures.

4.6.3 Marine growth may mask the true condition of the steel surface during a visual inspection and must be removed from the areas being inspected. All potential measurements on the structure shall be made before removal of marine growth. The removal process could depolarize the steel and may result in erroneous measurements.

4.6.4 Coupons normally are small, and care must be taken in extending coupon data to cover other areas or the entire structure on protected structures.

4.6.5 The Ag/AgCl (sw) potential is somewhat affected by the resistivity, e.g., the chloride content, of the seawater in which the electrode is immersed. If the resistivity is known to differ appreciably from that of ordinary seawater (0.2 ohm-m at 20°C), the electrode reading should be corrected in accordance with the nomogram shown in Figure 1. For example, if brackish water of 1 ohm-m resistivity exists at the structure site, the minimum protective potential to Ag/AgCl (sw) electrode is -0.83 V, corresponding to -0.85 V to CSE.

4.6.6 At water depths progressively beyond 300 m (1,000 ft) and sometimes at shallower depths, seawater characteristics (dissolved oxygen, temperature, salinity, pH, sea currents, and fouling) may vary significantly from surface and shallow depths and affect cathodic polarization and calcareous deposit formation. A site-specific survey for CP performance and seasonal variation of seawater characteristics is helpful in the design of an effective CP system for deep water.

4.7 CP can affect the corrosion fatigue properties of the structure.

4.7.1 CP at typical potential values tends to restore the steel to the "in-air" fatigue value.

4.7.2 The rate of propagation of fatigue cracks may be accelerated in some steels with highly negative CP potentials. Fatigue crack growth data may be used to establish whether highly negative potentials are significant.

4.7.3 The calcareous coating may plug fatigue cracks, reducing crack growth.

4.7.4 Corrosion should be controlled in highly stressed locations to prevent pitting that might promote fatigue cracks.

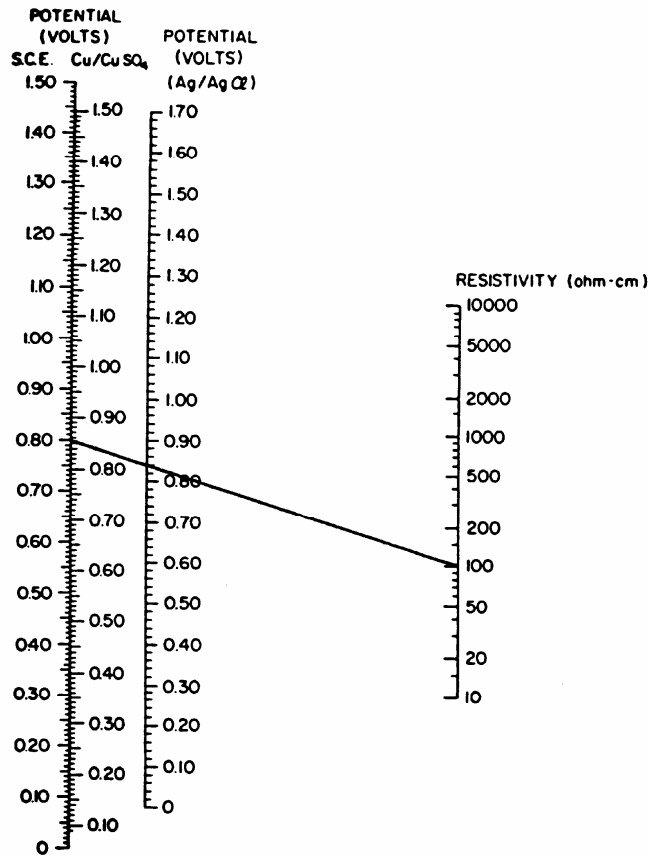


FIGURE 1: Nomogram for the correction of potential readings made with the Ag/AgCl electrode in waters of varying resistivity to the saturated calomel or Cu/CuSO₄ scale. All potentials shown are negative values.^{(4) 10}

Section 5: Design of Cathodic Protection Systems

5.1 Introduction

5.1.1 This section recommends procedures for designing CP systems that provide effective corrosion control for offshore structures.

5.1.2 In the design of an offshore CP system, environmental factors must be understood, and consideration should be given to the following:

5.1.2.1 Selection and specification of materials, equipment, and installation practices that ensure the safe installation and operation of the CP system.

5.1.2.2 Specification of materials and installation practices in conformance with applicable codes, regulations, and standards that may be issued by the following:

- (a) Structure operator,
- (b) NACE International,
- (c) API,
- (d) Government agencies,
- (e) National Electrical Code⁽⁵⁾ certifying agents, or

⁽⁴⁾ Nomogram courtesy of M.H. Peterson, Naval Research Laboratory, 4555 Overlook Ave. SW, Washington, DC 20375, and R.E. Groover, NRL Marine Corrosion Laboratory, Trumbo Point Annex, Bldgs. F-14, F-15, and F-1, Fleming Key, FL. 33041.

⁽⁵⁾ National Fire Codes, National Electrical Code 70 (National Fire Protection Association, 1 Batterymarch Park, Quincy, MA 02169).

(f) International standards bodies.

5.1.2.3 Selection and design of the CP system for optimum economy of installation, safety, maintenance, and operation.

5.1.2.4 Selection and specification of materials and installation practices that ensure dependable service for the operating life of the CP system.

5.1.2.5 Selection of a system to minimize excessive protective current densities or excessive earth (sea) potential gradients that may have detrimental effects on coatings or on neighboring buried or submerged foreign structures.

5.1.2.6 Initiation of cooperative investigations to evaluate the possible effects of the proposed CP system on the facilities of others (or their future expansion) in the general proximity.

5.2 Major Objectives of CP System Design

5.2.1 To deliver sufficient current for the design life of the facility, protect the structure, and distribute the current so that the selected criterion for CP can be efficiently satisfied for all parts of the structure intended to be protected.

5.2.2 To minimize the effect on associated pipelines or other neighboring metallic structures that may be caused by the operation of the proposed system.

5.2.3 To provide anode system design life commensurate with the design life of the protected structure or plan, and, when necessary, provide adequate rehabilitation procedures and appurtenances that may be used to simplify retrofits to the anode system and, for impressed current systems, their associated cables and power supplies.

5.2.4 To provide adequate allowance for anticipated changes in structure current requirements and anode current delivery capability from the standpoints of aging, additions to the structure, and possible changes in the environment.

5.2.5 To design and locate all CP system components such that the possibility of disturbance or damage is minimal.

5.3 Information Necessary or Useful for Offshore Structure CP System Design

5.3.1 Structure construction specifications and practices:

(a) Construction drawings,

(b) Onshore construction site, offshore construction practices, and probable construction dates,

(c) Number, size, and locations of riser pipes, including electrical cables,

(d) Coatings,

(e) Availability of electrical power,

(f) Corrosion control measurement points (test stations, electrical bond locations, etc.),

(g) Safety requirements,

(h) Installation accessibility and availability of structure equipment for possible use in system installation or replacement,

(i) Anticipated life of structure (design life),

(j) Water level,

(k) Pile guides removed after piling is completed or included in the CP design, and

(l) Location of isolation flanges or standoffs.

5.3.2 Offshore site conditions:

(a) Water depth, oxygen content, velocity, turbulence, temperature, water resistivity, tidal effects, silt, sand, and suspended solids (see nonmandatory Appendix A),

(b) Dependability of future monitoring and maintenance, including cost factors,

(c) Adjacent facilities, including pipelines,

(d) Existing and proposed CP systems, and

(e) Electrical isolation from foreign pipelines or structures.

5.3.3 Field survey data, corrosion test data, and operating experience:

(a) Protective current requirements to meet applicable criterion or criteria (see Paragraph 5.6),

(b) Water resistivity (considering possible stratification of water properties),

(c) Changes in construction specifications,

(d) Electrical isolation and continuity,

(e) Interference currents (see Section 7),

(f) Performance history of previous or existing CP systems in the same general environment,

(g) Maximum operating temperatures of pipeline risers, and

(h) Other maintenance and operating data.

5.3.4 Complete field survey work prior to actual application of CP is not always required if previous experience and test data are available for estimating current requirements and system performance.

5.4 Types of CP Systems

5.4.1 Galvanic anode systems

5.4.1.1 Galvanic anodes may be alloys of such active metals as magnesium, zinc, or aluminum. These alloys can be obtained in a variety of shapes and sizes to deliver protective current to a specific offshore structure with optimum current distribution. The method used to attach the anodes to the structure should be governed by their type and application, but low-resistance electrical contact must be maintained throughout the operating life of the anodes.

5.4.1.2 The performance of galvanic anodes in seawater depends critically on the composition of the alloy, particularly in the cases of zinc and aluminum (see nonmandatory Appendix B).

5.4.1.3 Magnesium anodes are very active and furnish high current outputs. For this reason, they can provide CP with a minimum number of anodes. Because of their properties, they usually are not used for long-life designs because they may cause excessively negative protection values, which may damage coatings and hydrogen-sensitive steels. Long-life designs can be achieved with remote magnesium anodes of the correct shape and weight.

5.4.1.4 For coated structures, the galvanic anode material should be capable of supplying current even after many years of very low anodic current density.

5.4.2 Impressed current anode systems

5.4.2.1 Impressed current anode materials may include lead-silver alloy, platinum over various substrates, mixed metal oxides, lead-platinum, graphite, or silicon-iron. These anodes should be connected with an electrically insulated conductor, either singly or in groups, to the positive terminal of a DC source such as a rectifier or generator. The structure to be protected should be connected to the negative terminal of the DC source.

5.4.3 Combination of galvanic anode and impressed current systems

5.4.3.1 A combination CP system provides protection during structure construction and during

times when the impressed current system is inoperative.

5.4.3.2 If the galvanic portion of the system is smaller than a conventional long-term system, it requires careful design to ensure adequate amount and distribution of current.

5.5 Considerations that Influence Selection of the Type of CP System

5.5.1 Availability of electrical power

5.5.2 Dependability of the overall system

5.5.2.1 Galvanic anode systems have shown dependability for long-term protection.

5.5.2.2 Impressed current systems are capable of providing long-term protection but are less tolerant of design, installation, and maintenance shortcomings than galvanic anode systems. Good service can be expected if proper attention is paid to mechanical strength, connections, cable protection (particularly in the wave or splash zone), choice of anode type, and integrity of power source. Adequate system monitoring should be provided.

5.5.2.3 Built-in redundancy, the use of appropriate design margins, and provisions at the design stage for thorough maintenance can enhance the dependability of an impressed current system.

5.5.3 Total protective current required

5.5.4 Given the current required, the feasibility of protection with galvanic anodes and selection of anode material can be established by consideration of the following (see nonmandatory Appendixes A and B):

- (a) Resistivity of the electrolyte,
- (b) Anode-to-structure potential (when structure is at protected level),
- (c) Freedom from mechanical damage in installation, launching, and operation,
- (d) Useful life expectancy of anode material, and
- (e) Structure weight and structural limitations.

5.5.5 The physical space available for impressed current anodes placed on the ocean floor should be determined by the proximity of other structures and pipelines and by future construction and maintenance considerations.

5.5.6 The economics of capital investment, maintenance, inspection, depreciation, taxes, and corrosion losses should be considered over the entire

expected life of a CP system to assess the impact of the various alternatives properly.

5.5.6.1 A galvanic anode system requires a relatively large initial capital investment but little maintenance expense.

5.5.6.2 An impressed current anode system typically requires a lower initial capital investment with power and higher maintenance expenses added over the life of the system.

5.6 Factors Determining Total Current Requirements for CP

5.6.1 Total submerged areas:

5.6.1.1 Water-submerged area

5.6.1.1.1 For structures that are not coated in the submerged zone, the total protective current is determined from the design current density and the exposed surface area. However, for structures that have been totally or partially coated, the exposed surface area can be reduced accordingly. If the effective surface area is reduced to account for the use of a coating, the effect of coating breakdown over time should also be taken into consideration.

5.6.1.1.2 For structures, or elements of them, in which thermal spray aluminum (TSA) is used as a coating, a reduction in the exposed surface area cannot be taken for TSA because this coating is conductive and places a current demand upon the CP system.

5.6.1.2 Area below mudline

5.6.1.3 On structures that may contain wells, the actual anticipated number of conductors to be installed.

5.6.1.4 Uninsulated and unprotected foreign structures.

5.6.2 Anticipated minimum protective design (or maintenance) current density requirements of submerged structure area.

5.6.2.1 Typical long-term average water zone current densities for CP of open ocean structures that have been employed historically range from 54 to 430 mA/m² (5 to 40 mA/ft²). For values typical of 11 offshore production areas, see Appendix A (nonmandatory). Alternatively, based on service data from offshore structures and laboratory results from test specimens, Hartt and Lemieux¹¹ proposed that design mean current density, *i_m*, conform to the expression used in Equation (1):

$$i_m = \frac{10^{(a + c\sigma)} \times T_d}{b+1} \tag{1}$$

Where:

- i_m* = is the design mean current density
- T_d* is the standard deviation for the *i_m* data
- T_d* is design life
- c* is a safety factor multiple on *σ*
- a* and *b* are constants

Values for *a*, *b*, and *σ* were determined for cold and warm water locations as listed in Table 1. The magnitude for *c* is selected based on the factor of safety that is judged appropriate with credit being given for system redundancy. It was shown that the design *i_m* values in Appendix A (nonmandatory) for cold water locations correspond to *c* ~ 1, whereas the Appendix A (nonmandatory) current densities exceed the *i_m* projected by Equation (1) for warm water locations even with *c* = 2, which encompasses 97.5% of the data.

Table 1: Suggested Design Parameters for Equation (1)

	Warm/Shallow Parameters	Cold/Deep Water Parameters
<i>σ</i>	0.233	0.229
<i>a</i>	3.130	2.820
<i>b</i>	-0.410	-0.226

5.6.2.2 Typical mud zone protective current densities are 11 to 33 mA/m² (1 to 3 mA/ft²).

5.6.2.3 An allowance should be included in the total design current requirements to compensate for the current load imposed by the well casings below the mudline. Values typically range from

1.5 to 5 A per well. For tension leg platform and subsea production templates, the well casings may be coated or cemented from total depth (TD) to the seabed, and thus greatly reduce the bare steel areas that draw current. In these cases, consideration for the reduced surface area should be made, which may justify a reduction in the current allowance per well.

5.6.2.4 An allowance should be included in the total design current requirements to compensate for the current load imposed by pilings below the mudline. Values typically range from 1.5 to 5 A per piling. For subsea templates, this current demand may control the design.

5.6.3 Allowance for coatings, if any, on submerged portions of the structure

5.6.3.1 In the past, conventional protective coatings (other than anode shields) were seldom applied to structures below the splash zone. However, increased current requirements and anode weight restrictions can affect the decision to coat complex structures. Complex structures may include those that are to be installed in deeper waters with higher current density requirements, in shielded areas such as large conductor bundles, and on structures with extended design lives.

5.6.3.2 The current demand of a coated structure increases with time as the coating deteriorates. Enough CP capacity (anode current and life) should be provided to maintain protection as the coating deteriorates. Current demand may increase more or less rapidly than a visual inspection of the coating deterioration indicates.

5.6.3.3 Calcareous coatings, formed on the structure members by the application of CP current, reduce the current density required to maintain protective potentials and also improve current distribution (see Paragraph 5.6.4). Organic coatings also promote the formation of a dense calcareous deposit at coating holidays and bare areas because the initial current density may be relatively high at such locations. However, the solubility of potential film-forming calcareous deposits normally increases with decreasing temperature such that colder waters might not allow the formation of a protective calcareous coating or could require higher initial current density to achieve polarization.

5.6.4 Efficiency of current distribution

5.6.4.1 Current distribution efficiency can be improved by use of a greater number of anodes of lower individual output. Current distribution can also be improved by using a coating on the structure.

5.6.4.2 Galvanic anode systems, being made up of numerous distributed, small current sources (typically from 3 to 6 A each), achieve maximum efficiency of current distribution. When these anodes are mounted at least 300 mm (12 in.) offset from the structure members, a uniform current distribution is normally assumed for design purposes.

5.6.4.3 Impressed current anodes, being fewer in number and designed for larger current outputs than galvanic anodes, normally have a reduced current distribution efficiency. These anodes may be designed to discharge from 30 to more than 200 A each. The high current output usually results in overprotection of the nearest structure surfaces. To compensate for the inefficient distribution of current, an efficiency factor (usually in the range of 67 to 80%) should be used. The CP system should be sized to provide 1.25 to 1.50 times the calculated total current requirement, using the surface areas and selected design current densities.

5.6.4.4 With either galvanic or impressed current systems, the anodes should be distributed vertically and horizontally in accordance with the calculated current requirements of the structure members. Computer modeling can be used to verify proper current distribution.

5.7 Factors Determining Anode Current Output, Operating Life, and Utilization Factor

5.7.1 Various anode materials have different rates of consumption when discharging a given current density from the anode surface in a specific environment. Therefore, for a given current output, the anode life depends on the anode material as well as on its weight. Established anode performance data should be used to calculate the probable consumption rate (see nonmandatory Appendixes B and C).

5.7.2 Galvanic anodes and anode systems should be designed to provide sufficient exposed anode area to produce the required protective current for the life of the anode system. Two alternative protocols for calculating anode output capability are shown in nonmandatory Appendixes D and E. The anode system must also provide sufficient weight of anode material to supply current for the desired number of years of protection, based on established anode performance data.

5.7.3 Proper design of a galvanic anode system must consider structure-to-anode potential and resultant anode current output and, when applicable, anode lead wire resistance. The net driving voltage between a typical aluminum-zinc-mercury or zinc anode and a polarized structure at minimum protective level of -0.80 V (Ag/AgCl [sw] reference) is only 0.25 V (1.05 - 0.80),

although the initial net driving voltage is higher because the structure potential is more positive at this time.

5.7.4 The anode lifetime (L) of galvanic anodes may be determined using Equation (2):

$$L = \frac{W \times u}{E \times I} \quad (2)$$

where:

L = effective lifetime of the anodes in years

W = net mass of the anodes in kg or lb

u = utilization factor determined by the amount of anode material consumed when the remaining anode material cannot deliver the current required

E = consumption rate of the anode in kg/A-y or lb/A-y

I = mean current output during the lifetime in A

The shape of the anode affects the utilization factor. Proper selection of length, diameter, and core diameter can result in utilization factors ranging from 0.75 to almost 1.0. For standoff-type anodes, utilization factors of 0.90 to 0.95 are common. For bracelet anodes, values of 0.75 to 0.90 may be used.

5.8 Special Mechanical and Electrical Considerations

5.8.1 The performance of a CP system is dependent on the ability of the various components to withstand the physical stresses to which they are subjected. The type of system, the various components thereof, and the physical installation should all be durable and dependable.

5.8.2 Galvanic anode systems are relatively simple, but consideration must be given to the following:

5.8.2.1 Anodes should be located on the structure to ensure polarization of node welds as early as possible. Node welds are critical for structural strength of structures. Polarization of node welds is of primary importance to prevent development of unacceptable weld profiles such as undercutting in the HAZ and pitting in the weld. Both types of corrosion cause additional stress concentration that can lead to fatigue cracking. Nodes are also zones of high metal surface area and complex geometry, requiring greater current density for protection and to overcome the effects of shielding. Weld consumables that can cause welds to be anodic to the steel shall not be used. Tests shall be carried out as a part of the welding pre-qualification test (WPQT).

5.8.2.2 Anode cores must be structurally suitable for the anode weight and the forces to which the anode is subjected, both during structure setting and pile-driving operations and during storms and hurricanes. It is important that the core be able to withstand anticipated wave forces in the later

stages of anode consumption, when the body of the anode is no longer adding its strength to that of the anode core.

5.8.2.3 The core should be designed to maintain electrical integrity with the anode body for the full design life of the anode. A large-diameter core aids in achieving the required current output toward the end of the life of the anode.

5.8.2.4 Reinforcement to the structure members may be required to support the larger sizes of galvanic anodes. If so, it should be made at the point of anode attachment by gussets, doubler plates, or another approved method.

5.8.2.5 Because the efficiency of some aluminum alloys is adversely affected when they are covered with mud, attaching such anodes to structures located at or below the mudline should only be done after testing the anode in representative mud, or if experience shows that the intended anode material does not passivate when covered by mud. The reduction in the current output and efficiency from a galvanic anode covered by mud should also be considered if it is at or below the mudline.

5.8.2.6 Whenever practicable, larger sizes of galvanic anodes should be attached to the structure in such a manner that stresses are minimized at the point of attachment.

5.8.2.7 When larger offshore-type anodes are used, cracks may occur while cooling during casting because of the different coefficients of expansion of the anode and the core. These cracks are not detrimental, provided they do not converge in a manner to allow loss of anode material. Warpage is acceptable if it does not adversely affect the anode installation. More specific guidelines can be found in NACE SP0387.¹²

5.8.2.8 When galvanic anodes are mounted flush with the steel surface, either the back face of the anode or the surface of the steel should be coated or fitted with a dielectric shield to prevent premature consumption of the anode material from the back face and possible failure of the mount because of the pressure developed by the corrosion products of the anode.

5.8.3 Impressed current systems are more critical with respect to mechanical damage because relatively few anodes, each discharging a substantial amount of protective current, are involved. The loss of an anode can seriously reduce CP system performance.

5.8.3.1 The electrical connection between the anode lead cable and the anode body must be made watertight and mechanically sound.

5.8.3.2 Cable and connection insulating materials should be resistant to chlorine, seawater, hydrocarbons, and other deleterious chemicals.

5.8.3.3 Care must be taken to provide suitable mechanical protection for both the anode and its connecting cable. On suspended systems, the individual anodes or anode strings may be equipped with winches or other retrieval means as a damage-preventing measure during severe storms or for routine inspection and maintenance. The loss of protection during these periods should be considered.

5.8.3.4 Acceptable methods of installing fixed-type impressed current anodes include, but are not limited to, the following:

(a) Anodes can be installed at the lower ends of protective vertical steel pipe casings or conduits. Casings should be attached to above-water structure members and supported at repeating members below water. The anodes should be lowered through the casings (which protect the anode lead wires) and should be allowed to extend below a termination fitting at the bottom of each casing. This method provides a means of anode retrieval or replacement using the anode cable, without diver assistance. Marine growth or corrosion scale may make anode retrieval difficult.

(b) Anodes with essentially flat configuration-mounted, insulating-type holders can be attached directly to submerged structure members or to auxiliary structural members, such as vertical pipes, which can be removed for anode replacement. Properly designed systems of the latter type permit anode retrieval without diver assistance.

(c) Anodes can be installed on submerged structure members using offset steel structural supports attached to the structure members. Diver assistance is required for this type of anode replacement.

(d) Anodes may be bottom-installed on the ocean floor in special instances, such as in Cook Inlet, Alaska. Anodes are typically mounted on specially designed concrete sleds for stability; this minimizes the possibility of their becoming covered with mud or silt. Steel reinforcing in the concrete has been reported to be subject to interference current corrosion.

5.8.3.5 Impressed current anodes should be located as far as practical from any structure member (usually a minimum distance of 1.5 m [5 ft], but proportional to current magnitude [see Paragraph 8.5.2]). If a spacing of 1.5 m (5 ft) is not feasible, a dielectric shield should be used to minimize wastage of protective current by

localized overprotection. Anode holders should be designed to avoid such wastage and to minimize the possibility of a short circuit between the anode and the structure. NOTE: Satisfactory performance of coating materials used as cathode shields has not been fully demonstrated over long periods of time. Providing a suitable anode-to-cathode spacing is the preferred method of ensuring good anode current distribution.

5.8.3.6 Simple, rugged, easily maintained impressed current equipment should be used. Because conditions at an offshore location seldom vary, except for weather-related factors, manually adjustable oil-cooled rectifiers with both AC and DC overload protection are preferred. In certain special cases, either constant current or automatic potential control rectifiers may prove desirable, but the cost and maintenance of these units should be compared.

5.8.3.7 There may be a delay of several months to a year or more between the time a structure is set until permanent electrical power becomes available. Plans should be made for either temporary power and early energizing of impressed current systems or a short-term galvanic anode system. Otherwise, serious corrosion of structure members, as well as the underwater components of the impressed current system, can occur.

5.9 Design Drawings and Specifications

5.9.1 Suitable drawings should be prepared to designate the overall layout of the CP system and the location of significant items of hardware, corrosion test and monitoring stations, bond boxes, insulators, and neighboring buried or submerged metallic structures.

5.9.2 Layout drawings should be prepared for each impressed current CP installation, showing details and location of its components with respect to the structure to be protected.

5.9.3 The locations of galvanic anodes should be shown on drawings or recorded in tabular form with appropriate notes as to anode type, weight, shape, and location.

5.9.4 Specifications should be prepared for all materials and installation practices to be incorporated in construction, inspection, and operation of the CP system.

5.9.5 Suitable as-built drawings should be prepared during and at the completion of all installations. These drawings should include any deviations from original design.

5.9.6 Complete records should be maintained. Details of CP installations are necessary for routine

maintenance, troubleshooting, and future design (see Section 10).

5.10 Design of Companion Facilities

5.10.1 If the design of an offshore CP system incorporates the use of insulating flanges or unions, locating each insulating device in vertical piping minimizes internal shorting caused by accumulation of salts, metallic residue, or other conductive materials.

Such insulating devices should not be located below the water line (see Paragraph 6.7.1).

5.10.2 The potential sparking hazard of insulating devices should be recognized and considered in the design and location of such devices.

Section 6: Installation of Cathodic Protection Systems

6.1 Introduction

6.1.1 This section recommends procedures for installing CP systems in accordance with design considerations outlined in Section 5.

6.2 Construction Specifications

6.2.1 All construction work performed on CP systems should be done in accordance with drawings and specifications. The construction specifications should be in accordance with procedures and materials outlined in Sections 3, 4, and 5.

6.3 Construction Supervision

6.3.1 All construction work performed on CP systems should be done under the supervision of qualified personnel to verify that the installation is made in strict accordance with the drawings and specifications. Exceptions should be made only with the consent of the supervising corrosion specialist.

6.3.2 All changes from construction specifications should be noted on as-built drawings.

6.4 Galvanic Anodes

6.4.1 Inspection and handling

6.4.1.1 Specific guidelines can be found in NACE SP0387.¹²

6.4.1.2 Anodes should be inspected to ensure that dimensions and weight conform to design specifications and that any damage from handling does not affect application.

6.4.1.3 In the case of weld-on anodes, the steel cores should be inspected for conformance to specifications. If the anode cores have welded joints or connections, these should be inspected to ensure compliance with structure welding specifications.

6.4.1.4 When galvanic anode suspension cables are used for the lead wire, the cables should be inspected for strength, voltage drop, and good electrical contact with the anode. When separate suspension cables are used, care should be taken to ensure that anode lead wires are not in such tension as to damage the lead wires or connections.

6.4.1.5 If coatings are specified for anode supports or suspension cables, they should be visually inspected and repaired if damaged.

6.4.2 Installing anodes

6.4.2.1 Anodes should be installed according to construction specifications.

6.4.2.2 When anodes are welded directly to the structure, the welds should be inspected for conformance to the structure construction welding specifications.

6.4.2.3 Use of doubler or gusset plates should be considered for anodes mounted on standoff pipe cores and particularly for those weighing more than 230 kg (500 lb).

6.4.2.4 Doubler or gusset plates may be installed on anode supports at the time of anode installation. If installed as part of the anode fabrication, these plates may be subject to serious damage during anode hauling and handling.

6.4.2.5 Suspended galvanic anodes should be installed after the structure is set on location offshore, and the anode cables should be tested for good electrical contact to the structure after installation.

6.5 Impressed Current Systems

6.5.1 Inspection and handling

6.5.1.1 The rectifier or other power source should be inspected to ensure that internal connections

are mechanically secure and that no damage has occurred during shipping and handling. Nameplate and actual rating of the DC power source should comply with construction specifications.

6.5.1.2 Impressed current anodes should be inspected for conformance to specifications for anode material and size and length of lead wire and to ensure that the anode cap (if specified) is secure. Lead wires should be carefully inspected to detect possible insulation defects. Defects in the lead wires and anode caps must be properly repaired, or the anode must be rejected.

6.5.1.3 Care should be exercised in handling all impressed current system components prior to final installation.

6.5.2 Installation provisions

6.5.2.1 A rectifier or other power source should be installed out of the way of operational traffic and remote from areas of extreme heat or likely contamination by mud, dust, water spray, etc. In areas in which two or more rectifiers are installed, the rectifiers should be spaced for proper flow of cooling air.

6.5.2.2 Wiring to rectifiers shall comply with any applicable regulatory codes and with the operator's specifications. An external disconnect switch in the AC wiring to the rectifier should be provided. The rectifier case shall be properly grounded (electrical safety earth). Connecting the negative to the case prevents inadvertent reversal of polarity.

6.5.2.3 On thermoelectric generators, a reverse current device should be installed to prevent galvanic action between the anode and structure if the flame is extinguished.

6.5.2.4 Impressed current anodes should be installed in accordance with construction specifications. Special care should be taken to avoid damage to anodes and their lead wires during installation. Careful supervision of this phase is most essential to proper long-term performance of the CP system.

6.5.2.5 Conductor cable connections to the rectifier from the anode(s) and the structure must be mechanically secure and electrically conductive. Before the power source is energized, verification should be made that the negative (-) conductor is connected to the structure to be protected, that the positive (+) conductor is connected to the anode(s), and that the system is free of short circuits.

6.5.2.6 Connection between the positive header cable and lead wire(s) from the anode(s) should be mechanically secure and electrically conductive. The connections must be sealed to prevent moisture penetration and ensure electrical isolation from the environment. Submerged connections require seals suitable for the water pressures and environment to which they may be subjected.

6.5.2.7 When installing a suspended anode for which separate suspension is required, care should be taken that the lead wire is not in such tension as to damage the anode lead wire or connections.

6.5.2.8 Operating personnel should be trained in the function and need for such a system to ensure continued energization of the system.

6.6 Corrosion Control Test Stations, Connection, and Bonds

6.6.1 Installation provision

6.6.1.1 Test leads to pipelines associated with offshore structures must be mechanically secure and electrically conductive and should be readily accessible.

6.6.1.2 Both the pipe and the test lead wires should be clean, dry, and free of foreign material at points of connection when the connections are made. The complete connection should be coated to prevent atmospheric corrosion.

6.6.1.3 Conductive connections to other pipelines or across insulating joints should be installed in accordance with Paragraph 6.6.1.1. All bond connections should be readily accessible for testing. Cables should have welded connections. Care should be taken to ensure that all parts of the structure are in proper electrical contact with one another or are equipped with separate anodes.

6.7 Other Considerations

6.7.1 Insulating devices

6.7.1.1 Use of insulating flanges in pipelines associated with structures is covered in Paragraph 5.10.1. If insulating flanges above water are inaccessible, extension test leads should be installed in accordance with Paragraph 6.6.1.1 for test or bonding purposes.

Section 7: Control of Interference Currents

7.1 Introduction

7.1.1 The purpose of this section is to describe the possible detrimental effects of interference currents, sometimes called stray currents, and to recommend practices for their control.

7.1.2 Except during certain types of welding operations, the possibility of interference current corrosion on offshore structures is minimal.

7.2 Effects

7.2.1 Corrosion occurs in areas at which the interference current leaves the affected structure and enters the electrolyte as it returns to its source.

7.2.2 The degree of damage is directly related to:

- (a) the quantity of interference current and the current density,
- (b) the area of the affected structure where the current leaves to enter the electrolyte, and
- (c) the period of time when this effect occurs.

7.3 Short-Term Interference

7.3.1 The most common serious cause of short-term interference to a structure is welding operations when the welding machine is mounted on a barge or vessel with the machine's negative terminal grounded to the vessel and with the electrodes positive. Some operators have reported serious damage to structures with complete penetration of the submerged member as a result of welding current interference. The following measures should be implemented to prevent interference current during welding operations from a barge moored alongside during construction: (a) all welding machines should be electrically isolated from the barge, and (b) the grounding cable from each machine should be connected to the structure. Alternatively and preferably from a corrosion

standpoint, the barge operator should place the welding machines on the structure.

7.3.2 When negative welding leads are bonded to the structure, current return is ostensibly through negative leads or cables connected to the structure, but is also, to some degree, through the parallel water path from structure to barge hull if the precautions of Paragraph 7.3.1 are not followed. Current return through the water can be reduced by decreasing the resistance of the negative cables, by increasing their number or diameter, and by decreasing their length. Negative cables should be connected to the structure at a point as close to the barge as possible.

7.4 Long-Term Interference

7.4.1 There are normally no long-term interference sources that would cause significant corrosion on a structure, if all components of the structure are properly bonded.

7.4.1.1 The submerged, bare structure area is usually very large with respect to exposed pipeline areas; consequently, pipeline protection currents have a negligible interference effect on the structure.

7.4.1.2 The location of interference current sources and the physical arrangement of a protected structure are usually such that there is no tendency for significant interference to exist.

7.4.2 In certain cases, interference may be produced on a foreign pipeline when it is electrically isolated from a protected structure because of the structure's CP system. Such interference can readily be controlled by the use of a current drainage bond from the pipeline to the structure, by installing CP on the isolated pipeline, or by upgrading the existing CP system on the pipeline. These mitigation procedures should be performed in cooperation with other companies or operators, when applicable.

Section 8: Dielectric Shields

8.1 Introduction

8.1.1 This section recommends practices for the selection and use of dielectric shields, including shield configurations and materials, for impressed current CP of structures.

8.2 General

8.2.1 The objective of dielectric shields, and coatings used as dielectric shields, is to prevent extremely high current densities and current wastage in the vicinity of the anodes. This serves to promote more uniform protective current distribution.

8.3 Use of a Dielectric Shield

8.3.1 Use of a dielectric shield depends on the CP design (see Section 5). Typically, dielectric shields are used in conjunction with an impressed current system because higher voltage gradients are generally used in such systems. A dielectric shield may also be used with a high-potential galvanic anode such as magnesium.

8.3.2 Specific uses of dielectric shields, including coatings used as dielectric shields, are as follows:

- (a) to cover cathode surfaces adjacent to anodes,
- (b) to provide a nonconducting extension to steel pipe conduits for impressed current anodes,
- (c) to afford a backing for flush-mounted galvanic anodes,
- (d) to minimize current demand by structure members in highly congested areas, and

(e) to restrict anode current output, i.e., reduce wastage of anode current to the structure in the immediate vicinity of the anode.

8.3.3 A general underwater coating may be considered as a type of dielectric shield and can be used either to reduce the required current or to extend the life of a CP system.

8.4 Types of Dielectric Shields

8.4.1 Various dielectric shields have been used in structure CP systems. These include yard-applied coatings, prefabricated plastic or elastomeric sheets, plastic pipe sleeves, and coated standoffs or supports for impressed current anodes.

8.5 Design Considerations

8.5.1 Electrochemical reactions at the anode and cathode produce corrosives and gases that may attack the dielectric shield or cause disbonding by gas formation under the dielectric shield. Materials selected should be suitable for the intended service.

8.5.2 For proper performance, the design of the dielectric shield (radius around the anode or distance from the anode to the nearest bare cathode surface) shall involve considerations of the anode current output, water resistivity, geometry of the structure, and location of other anodes.

8.5.3 Mechanical damage from environmental factors such as wave forces, water currents, floating debris, ice, and marine organisms must be considered. The design shall also include allowances for possible handling damage prior to structure placement.

8.5.4 The anticipated life or general deterioration of any dielectric shield material should be considered in the CP design (see Paragraph 5.8.3.4).

Section 9: Operation and Maintenance of Cathodic Protection Systems

9.1 Introduction

9.1.1 This section designates procedures for energizing and maintaining continuous, effective, and efficient operation of CP systems.

9.2 Electrical Measurements

9.2.1 Electrical measurements and inspections are necessary to determine that protection has been

established according to applicable criteria and that each part of the CP system is operating properly. Conditions that affect protection are subject to change with time. Corresponding changes are required in the CP system to maintain protection. Periodic measurements and inspections are necessary to detect performance changes in the CP system.

9.2.2 Care should be exercised in selecting the location, number, and type of electrical measurements used to determine the adequacy of CP (see Section 4).

9.2.3 Conditions may exist in which operating experience indicates that surveys and inspections should be made more frequently than recommended herein, such as following severe storms.

9.3 A survey should be conducted after each CP system is energized to determine whether it satisfies applicable criteria and operates effectively. This survey shall include structure/seawater potential measurements in sufficient detail to demonstrate conclusively that protection has been attained (see Section 4).

9.4 A periodic survey should be made to ensure the continuity of CP. The electrical measurements used in this survey should include structure potential measurements at locations selected for the earlier survey(s). The period between surveys should be determined as follows:

9.4.1 If previous survey data are not available, or no analysis of the previous data has been conducted, the survey should be performed at least annually.

9.4.2 For sacrificial anode CP systems, there are two critical periods of operation—initial operation of the system, demonstrating that the entire structure is polarized (see Paragraph 9.3); and final years of design life of the system, when the performance of the anodes can become more difficult to predict. Between these periods, structure potentials and anode wastage rates follow well-defined trends. Taking this into account, a risk-based approach to CP inspection can be adopted. Inspection frequency should be based on a five-year interval unless more frequent inspection is required because of any of the following conditions being present:

- Visual inspection reveals additional steelwork on the structure not included in the current structure CP drawings. This could include debris in electrical contact with the structure, new conductors, new caissons, new risers, etc. A CP survey should be carried out immediately, structure potentials measured, structure CP drawings updated, the impact on the structure anode design life assessed, and the need for any remedial work assessed (e.g., removal of debris, installation of additional anodes, etc.).

- Anodes are within two years of the end of their original design life. The CP survey should be carried out annually. If the required structure life is in excess of the remaining anode design life, the actual remaining life of the anode system should be reassessed (based on a survey of potentials and remaining anode mass) and the need for a retrofit

assessed. If the original CP design was conservative, the actual remaining anode life may be well in excess of two years. This actual remaining anode life can be used in scheduling future CP surveys (on the same five-year/two-year basis).

- Local regulatory requirements that require more frequent inspections (e.g., U.S. Minerals Management Service⁽⁶⁾—annual).

9.4.3 For impressed current cathodic protection (ICCP) systems, the initial operation of the system is critical, demonstrating that the entire structure is polarized (see Paragraph 9.3). After this, the performance of the ICCP system depends on proper operation and maintenance (see Paragraph 9.5). Taking this into account, a risk-based approach to CP inspection can be adopted. Inspection frequency should be based on a five-year interval unless more frequent inspection is required because of any of the following conditions being present:

- Visual inspection reveals additional steelwork on the structure not included in the current structure CP drawings. This could include debris in electrical contact with the structure, new conductors, new caissons, new risers, etc. A CP survey should be carried out immediately, structure potentials measured, structure CP drawings updated, the impact on the ICCP system assessed, and the need for any remedial work assessed (e.g., removal of debris, installation of additional anodes, modified anode currents, etc.).

- Operation and maintenance of the ICCP shows poor functionality, which indicates damaged anodes or cables.

- Local regulatory requirements that require more frequent inspections (e.g., U.S. Mineral Management Service—annual).

9.5 Inspection and tests of ICCP facilities should be made to ensure their proper operation and maintenance.

9.5.1 All sources of impressed current should be checked at intervals not to exceed two months. Evidence of proper functioning may be current output, normal power consumption, or satisfactory structure-to-seawater potentials on the protected structure.

9.5.2 All ICCP facilities should be inspected annually as part of a preventive maintenance program to minimize in-service failure. Inspection may include a check for electrical shorts, satisfactory ground and header cable connections, meter accuracy, rectifier efficiency, and overall circuit resistance.

⁽⁶⁾ U.S. Minerals Management Service (MMS), 1849 C St. NW, Washington, DC 20240.

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9.6 The test equipment used for obtaining each electrical value should be maintained in good operating condition and calibrated annually for accuracy. Reference electrodes should be cleaned and calibrated more frequently for possible inaccuracy because of contamination, bad electrical connections, or deterioration of wire insulations.

9.7 Diver-assisted or ROV inspections may be conducted in conjunction with other underwater work to ensure that the CP system is effective.

9.8 Remedial measures should be taken promptly when periodic surveys and inspections indicate that protection is

no longer adequate or will soon become inadequate. These measures may include:

9.8.1 Repairing, replacing, or adjusting components of CP systems.

9.8.2 Providing supplementary CP facilities in areas where additional protection is necessary.

9.8.3 Repairing defective insulating devices or continuity bonds.

Section 10: Corrosion Control Records

10.1 Introduction

10.1.1 This section describes a system of corrosion control records for documenting data pertinent to the design, installation, operation, maintenance, and effectiveness of the CP and coating systems.

10.1.2 Included in this section is an exhaustive listing of possible records. Each operator should decide which records are necessary for control of corrosion on the structure.

10.1.3 Information regarding the location of anodes, electrical leads, and rectifiers can be conveniently recorded on a drawing of the structure being protected. More of the potential survey data and results of maintenance inspections can be maintained in tabular form and kept up-to-date with periodic entries.

10.1.4 As-built drawings should reflect any changes from design specifications, particularly deviation in setting depth, which would alter the interval covered by the splash zone. Deviation in setting depth may occur through errors in water depth estimate (initial survey) or through settlement of the structure (possible over installed life).

10.2 CP Systems

10.2.1 Galvanic (sacrificial) anode system—The following should be recorded:

10.2.1.1 Design criteria used: design life, assumed anode output and consumption rate, and current density requirements.

10.2.1.2 Number, size, composition, and (if known) the manufacturer, cost, and supplier of the anodes.

10.2.1.3 Location of each anode, the method of attachment, and date of installation. If anodes are installed during structure construction, the date of

actual setting of the structure offshore should be recorded.

10.2.1.4 Number and location of anodes if checked either during construction or after setting on location, with all discrepancies noted.

10.2.2 Impressed current system—The following should be recorded:

10.2.2.1 Design criteria used (see Paragraph 10.2.1.1).

10.2.2.2 Number, size, composition, and (if known) the cost, manufacturer, and supplier of the anodes.

10.2.2.3 Location of each anode, method of attachment, and date of installation.

10.2.2.4 Specifications and locations of the DC source.

10.2.2.5 Composition and location of any dielectric shielding used.

10.2.2.6 Current and voltage output of each rectifier as called for in Paragraphs 9.3 and 9.5, noting any adjustments made.

10.2.3 Combination system

10.2.3.1 A combination system is one containing galvanic (sacrificial) anodes in addition to an impressed current system.

10.2.3.2 Records for a combination system must include complete information for each of the component systems.

10.2.4 Structure potential measurements

10.2.4.1 Each time the potential of the structure is measured, the type of reference cell and the measuring technique (diver-held, guided, permanent, or freely suspended) used should be recorded.

10.2.4.2 The structure potential should be recorded initially and at the time intervals specified in Paragraph 9.4.

10.2.5 Operation and inspection—The following should be recorded:

10.2.5.1 Results of underwater inspection of the anode system, noting all discrepancies such as missing anodes.

10.2.5.2 Location, size, and type of corrosion damage found during any underwater inspection, and location and general description of trash metal located on and around the base of the structure.

10.2.5.3 Size, composition, location, number, method of attachment, cost, supplier, and date of installation of all replacement anodes.

10.2.5.4 Any maintenance performed on the rectifier.

10.2.5.5 Downtime of the impressed current system, whenever possible.

10.2.5.6 Any enlargement of the structure or addition of pipelines and flowlines. Any deviation in setting depth (see Paragraph 10.1.4).

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⁽⁷⁾ John Wiley & Sons Inc., 111 River St., Hoboken, NJ 07030.

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Appendix A

Typical Design Parameters for Offshore Petroleum Production (Nonmandatory)

Structures in Selected Oil Provinces

The principal factor governing the minimum design current density at which polarization necessary for complete CP can be achieved in the open sea is the availability of corrosive (depolarizing) agents, principally oxygen, at the submerged structure surfaces. Lowering the water temperature increases both the water resistivity and oxygen solubility. Water turbulence, along with natural lateral flow, also maximizes the rate at which oxygen reaches the structure surfaces. Cook Inlet waters represent an environmental extreme; most of the above negative factors are present, in addition to scouring (mechanical depolarization) by suspended glacial silt in the swiftly flowing water.

The formation of a calcareous deposit also affects the current requirement by reducing the ability of oxygen to reach the metal surface. The calcareous deposit precipitates from seawater because of the alkaline shift in pH that results from the polarization of the metal surface. Because the beneficial qualities of the calcareous deposit are reduced by decreasing water temperature and lower current densities, a relatively high initial current provision for CP can reduce the long-term current demand to maintain protection.

Laboratory and field tests have shown that rapid polarization of a steel cathode upon immersion to potentials of -0.9 to -1.0 V (Ag/AgCl [sw]) generates a more protective calcareous deposit than is achieved by slower polarization. High current densities are required to achieve these results, but current demand decreases (by as much as a factor of 10) quickly as the protective calcareous deposit is formed.

At the launch of a structure, the potential difference between the sacrificial anode system and the unpolarized steel may be around 0.45 V, which enables the sacrificial system to generate a very high current density on the cathode. After polarization, this potential difference decreases to 0.25 V or less with an accompanying decrease in current density.

This polarization process normally results in a linear relationship between steel potential and current density, the slope of the line being the design slope. For any given location, galvanic anode designs with similar design slope values result in similar long-term current densities. The relationship between design slope and maintenance current density can be established by on-site experiments or by review of experience at that location.

The CP current density is strongly dependent on water temperature. For deep-water structures, different design values should be used for different temperature zones. To optimize the design, the structure should be split up into separate zones over which the temperature does not vary by more than 5°C (9°F). The average temperature of each interval should be used to assess the required current densities.¹³ The same approach can apply to resistivity assessment.

Table A1 presents a general guide to the design of CP systems in major offshore petroleum producing areas. These data may be used as a starting point for investigation prior to selection of final design parameters for a specific application. Table A1 also presents equivalent design values for the same producing areas.

**Table A1
Design Criteria For Cathodic Protection Systems**

Production Area	Water Resistivity ^(B) (ohm-m)	Water Temp. (°C)	Environmental Factors ^(A)		Typical Design Current Density ^(C)			Typical Design Slope ohm-m ² (ohm-ft ²)
			Turbulence Factor (Wave Action)	Lateral Water Flow	mA/m ² (mA/ft ²)			
					Initial ^(E)	Mean ^(F)	Final ^(G)	
Gulf of Mexico Deep water	0.20	22	Moderate	Moderate	110 (10)	54 (5)	75 (7)	4.1 (44)
GOM	0.29	4-12	Low	Varies	194 (18)	75 (7)	86 (8)	
U.S. West Coast	0.24	15	Moderate	Moderate	150 (14)	86 (8)	100 (9)	3.0 (32)
Cook Inlet	0.50	2	Low	High	430 (40)	380 (35)	380 (35)	1.0 (11)
Northern ^(D)	0.26-0.33	0-12	High	Moderate	180 (17)	86 (8)	120 (11)	2.5 (27)
North Sea ^(D)	0.26-0.33	0-12	High	Moderate	150 (14)	86 (8)	100 (9)	3.0 (32)
Southern ^(D)								
North Sea ^(D)	0.15	30	Moderate	Low	130 (12)	65 (6)	86 (8)	3.5 (37)
Arabian Gulf								
Southeast Australia	0.23-0.30	12-18	High	Moderate	130 (12)	86 (8)	86 (8)	3.5 (37)
Northwest Australia					120(11)	65 (6)	65 (6)	
Brazil	0.20	15-20	Moderate	High	180 (17)	65 (6)	86 (8)	2.5 (27)
West Africa	0.20-0.30	5-21	Low	Low	130 (12)	65 (6)	86 (8)	3.5 (37)
Indonesia	0.19	24	Moderate	Moderate	110 (10)	54 (5)	75 (7)	4.1 (44)
South China Sea	0.18	30	Low	Low	100 (9)	32 (3)	32 (3)	

^(A) Typical values and ratings based on average conditions, remote from river discharge.

^(B) Water resistivities are a function of both chlorinity and temperature. In the reissued *Corrosion Handbook*¹⁴ by H.H. Uhlig, the following resistivities are given for chlorinities of 19 and 20 parts per thousand (ppt):

**Resistivities (ohm-m)
Temperature (°C [°F])**

Chlorinity (ppt)	0 (32)	5 (41)	10 (50)	15 (59)	20 (68)	25 (77)
19	0.351	0.304	0.267	0.237	0.213	0.192
20	0.335	0.290	0.255	0.227	0.203	0.183

^(C) In ordinary seawater, a current density less than the design value suffices to hold the structure at protective potential once polarization has been accomplished and calcareous coatings are built up by the design current density. CAUTION: Depolarization can result from storm action.

^(D) Conditions in the North Sea can vary greatly from the northern to the southern area, from winter to summer, and during storm periods.

^(E) Initial and final current densities are calculated using Ohm's Law and a resistance equation such as Dwight's¹⁵ or McCoy's¹⁶ equation with the original dimensions of the anode. An example of this calculation is given in Appendix D (nonmandatory), which uses an assumed cathode potential of -0.80 V (Ag/AgCl [sw]).

^(F) Mean current densities are used to calculate the total weight of anodes required to maintain the protective current to the structure over the design life. Examples of these calculations are given in Appendixes D and E (nonmandatory).

^(G) Final current densities are calculated in a manner similar to the initial current density, except that the depleted anode dimensions are used. An example of this calculation is given in Appendix D (nonmandatory).

Figure A1 presents the current density curves based on the temperature of the seawater.

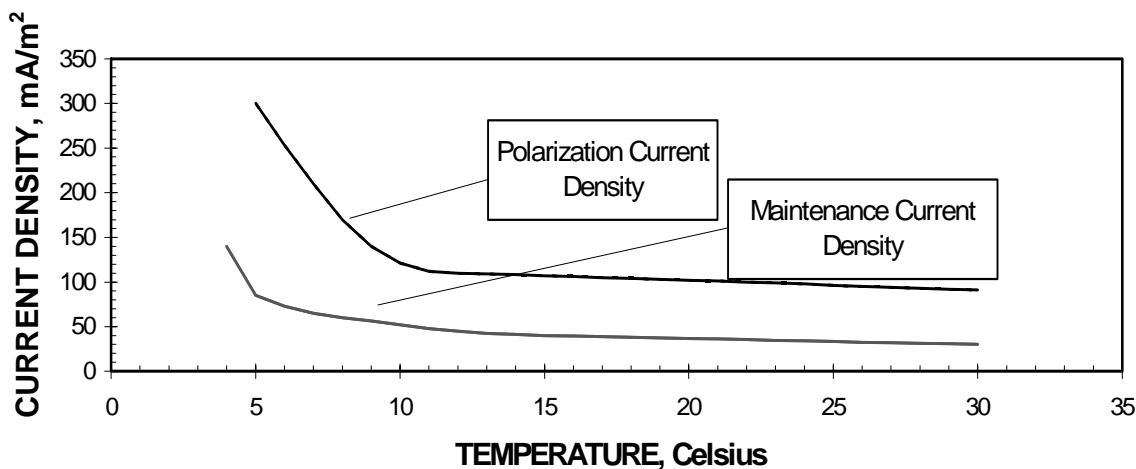


FIGURE A1: Current Density/Temperature Curves

Appendix B

Energy Capabilities and Consumption Rates of Various Commercial Galvanic Anodes Available for Cathodic Protection of Offshore Structures (Nonmandatory)

The energy capability of a given galvanic anode material is usually expressed in terms of ampere-hours per kg (lb) of material. This figure, when divided into the number of hours per year (8,760), gives the anode consumption rate in kg (lb) per ampere-year, a more useful form of energy rating to the design engineer.

The energy capability of any galvanic anode material selected for use in offshore CP design should be previously established through controlled laboratory and field tests at an anode current density normally expected in field applications, i.e., approximately 2.2 to 7.5 A/m² (200 to 700 mA/ft²) of anode surface. Table B1 lists the established energy capabilities of some of the more commonly used galvanic anode materials at anode output current densities of 2.2 to 7.5 A/m² (200 to 700 mA/ft²). The ranges shown for any one material are attributed to variations in composition and heat treatment offered by the various

manufacturers. Table B1 also lists the corresponding anode consumption rates, calculated as stated above. Therefore, it is prudent in design of galvanic CP systems to consider that anode capacity may be less than is predicted from short-term testing.

Segregation of some minor alloys and impurities during cooling can alter the galvanic properties of the anode material. Any potential segregation is more pronounced on the interior portions of larger anodes because of slower cooling after casting.

Any anode material must be capable of a sufficient driving voltage to provide the necessary design current output. A check for proper driving voltage of an anode can be made by measuring the closed circuit potential of the anode, using a suitable reference cell.

Table B1: Energy Capabilities and Consumption Rates of Galvanic Anode Materials in Seawater

Galvanic Anode Material ^(A)	Energy Capability ^(B) A-h/kg (A-h/lb)	Consumption Rate kg/A-y (lb/A-y)	Anode Potentials, ^(C) Negative Volts (Ag/AgCl [sw])
Aluminum-zinc-indium	2,290 to 2,600 (1,040 to 1,180)	3.8 to 3.4 (8.4 to 7.4)	1.05 to 1.10
Zinc (MIL-A-18001) ⁸	770 to 820 (350 to 370)	11.2 to 10.7 (25.0 to 23.7)	1.0 to 1.05
Magnesium (H-1 alloy)	1,100 (500)	8.0 (17.6)	1.4 to 1.6

^(A) Aluminum alloys with mercury and tin additions have been utilized in the past and may be found on existing structures. These alloys are not believed to be commercially available.

^(B) The above data show ranges that are taken from field tests at Key West, Florida, by Naval Research Laboratory, Washington, DC,¹⁷ and from manufacturers' long-term field tests. Modification to these numbers will be made only by recommendation from NACE STG 30 on Oil and Gas Production—Cathodic Protection.

^(C) Measured potentials can vary because of temperature and salinity differences.

Appendix C
**Consumption Rates in Seawater of Various Commercial Types of Impressed
 Current Anodes Available for Cathodic Protection of Offshore Structures
 (Nonmandatory)**

Impressed current anodes, unlike galvanic anodes, can be driven over a wide range of anode current densities, depending on the designer's preferences and the demands of a particular application. Because anode current loadings have a definite bearing on consumption rates, any meaningful listing of consumption rates for various anode materials must necessarily include the approximate anode current density at which such rates have been established.

Table C1 lists consumption rates of various impressed current anode materials used for CP systems on offshore structures. If titanium is used as the substrate for a platinum-type anode, anode/electrolyte voltage must be limited to about 8 V. For niobium substrates, laboratory data indicate that voltages as high as 100 V are satisfactory; however, field experience shows that 50 V is a more reliable and practical limit.

Table C1: Consumption Rates of Impressed Current Anode Materials

Impressed Current Anode Material	Typical Anode Current Density in Saltwater Service A/m ² (A/ft ²)	Nominal Consumption Rate g/A-y (lb/A-y)
Pb-6%Sb-1%Ag	160 to 215 (15 to 20)	14 to 90 (0.03 to 0.2 ^(A))
Pb-6%Sb-2%Ag	160 to 215 (15 to 20)	14 to 27 (0.03 to 0.06 ^(B))
Platinum (on Titanium, Niobium, or Tantalum substrate) or Titanium mixed metal oxide	540 to 3,230 (50 to 300)	3.6 to 7.3 (0.008 to 0.016 ^(B))
Graphite	11 to 43 (1 to 4)	230 to 450 (0.5 to 1.0)
Fe-14.5%Si-4.5%Cr	11 to 43 (1 to 4)	230 to 450 (0.5 to 1.0)

^(A) Very high consumption rates of Pb-Ag anodes have been experienced at depths below 30 m (100 ft).

^(B) This figure can increase when current density is extremely high and in low-salinity waters.

Appendix D Typical Method for Calculation of Galvanic Anode Current Output Using Initial, Maintenance, and Final Current Densities (Nonmandatory)

This method has been commonly employed in the past for CP design, so practitioners tend to be familiar with it. The disadvantage is that it is based on an algorithm rather than being first principles-based and can lead to unnecessary over-design compared to the slope parameter method (see Appendix E [nonmandatory]). The over-design can be minimized if a range of anode sizes is considered, and the size selected on the one that gives the lowest installed cost.¹⁸ From a modification of Dwight's equation,¹⁵ the resistance of a cylindrically shaped anode to the electrolyte in which it is placed is equal to the product of the specific resistivity of the electrolyte and certain factors relating to the shape of the anode, as given in Equation (D1):

$$R = \rho \frac{K}{L} \left[\ln \left(\frac{4L}{r} \right) - 1 \right] \quad (D1)$$

where:

R = anode-to-electrolyte resistance in ohms
 ρ = resistivity of the electrolyte in ohm-m. (See Table A1)
 K = 1,000/(2π) or 159 if L and r units are in mm or 0.00627 if L and r units are in inches
 L = length of anode in millimeters (inches)
 r = radius of anode in millimeters (inches) (for other than cylindrical shapes, r = C/2π, where C = cross-section perimeter.)

Thus, for a 250 x 250 mm (10 x 10 in.) cross-section, C = 1,000 mm (40 in.) and r = 159 mm (6.27 in.).

To determine the current output from an anode, use Ohm's Law: I = E/R.

For a typical calculation for an anode in the Gulf of Mexico, the number of anodes required for protection must satisfy three different calculations. There must be enough anodes to polarize the structure initially (initial current density from Table A1) to produce the appropriate number of amps of current over the design life of the structure (mean current requirement), and to produce enough current to maintain protection at the end of the design life (final current requirement). For this exercise, the following information is given:

Structure surface area = 9,300 m² (100,000 ft²)

Design life = 20 years

ρ = 0.20 ohm-m (from Table A1).

Based on this information, select an anode with the following characteristics:

Material: Aluminum-Zinc-Indium alloy

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E = 0.30 V driving force between an aluminum or zinc anode and a protected steel structure at -0.80 V (Ag/AgCl [sw])

L = 3,660 mm (144 in.) anode length,

r = 159 mm (6.3 in.) anode radius initially for a 250 x 250 mm (10 x 10 in.) anode on a 100-mm (4-in.) pipe core, Wt = 540 kg (1,200 lb) weight per anode,

CC = 2,530 A-h/kg (1,150 A-h/lb) for current capacity for Al-Zn-In alloy anodes,

r_{core} = 57 mm (2.25 in.), which is one-half the OD of an 100-mm (4-in.) Schedule 80 pipe.

Therefore, the initial current output per anode is as shown in Equation (D2):

$$I = \frac{E}{R} = \frac{0.30 \text{ V}}{\frac{0.20 \Omega\text{m} \times 159}{3,660 \text{ mm}} \left[\ln \left(\frac{4 \times 3,660 \text{ mm}}{159 \text{ mm}} \right) - 1 \right]} = \frac{0.30 \text{ V}}{0.0310 \text{ ohm}} = 9.8 \text{ A} \quad (D2)$$

The number of anodes required to protect a structure with 9,300 m² (100,000 ft²) of exposed surface area with a

required initial current density of 110 mA/m² is as shown in Equation (D3):

$$N = \frac{\text{Initial Current Density (110 mA/m}^2) \times \text{Surface Area (9,300 m}^2)}{\text{Amps output per anode (9.8) x 1,000 mA/A}} = 104 \text{ anodes} \quad (D3)$$

In order to meet the second current density requirement for the structure, which determines the number of kg (lb) of anode material required to protect the structure over the 20-

year design life with a mean current design requirement of 54 mA/m² (see Table A1), use Equation (D4):

$$N = \frac{54 \text{ mA/m}^2 \times 9,300 \text{ m}^2 \times 20 \text{ yr} \times 8,760 \text{ h/y}}{2,530 \text{ A h/kg} \times 540 \text{ kg/anode} \times 1,000 \text{ mA/A}} \quad (D4)$$

N = 64 anodes

current requirement, except that the expended dimensions of the anode are used to represent the anode at the end of its life [see Equation (D5)].

Lastly, the number of anodes to provide the final current requirement is calculated in a manner similar to the initial

$$r_{\text{expended}} = r_{\text{initial}} - (r_{\text{initial}} - r_{\text{core}}) \times 0.9 = 159 - [(159 - 57) (0.9)] = 67 \text{ mm} \quad (D5)$$

where 0.9 is the anode utilization factor for a standoff anode.

and the number of anodes required to protect a structure with 9,300 m² (100,000 ft²) of exposed surface area and a final current density requirement of 75 mA/m² (see Table A1) is as shown in Equations (D5.5 and D6):

L_{expended} = 3,660 mm (144 in.) (no change in length)

$$I = \frac{E}{R} = \frac{0.30 \text{ V}}{\frac{0.20 \Omega\text{m}}{1} \frac{159}{3,660 \text{ mm}} \left[\ln \left(\frac{4 \times 3,660 \text{ mm}}{67 \text{ mm}} \right) - 1 \right]} = \frac{0.30 \text{ V}}{0.038 \text{ ohm}} = 7.87 \text{ A} \quad (D5.5)$$

$$N = \frac{\text{Final Current Density (75 mA/m}^2) \times \text{Surface Area (9,300 m}^2)}{\text{Amps output per anode (7.87) x 1,000 mA/A}} = 89 \text{ anodes} \quad (D6)$$

The initial current calculation required 104 anodes, the mean current density requirement required 64 anodes, and the final current calculation required 89 anodes. For this application, the proper number of anodes to use would be 104 anodes. However, the difference between this value

and the calculated mean current requirement of 66 anodes is significant. Another anode shape that provides less variation between the three requirement values is often more economical to install. In this particular case, use of an anode that is 2,440 mm (96 in.) in length that weighs 330 kg

(725 lb) will provide a more optimal solution, where the number of anodes required to satisfy the three calculations is more consistent.

Dwight's equation is valid when $4L/r \geq 16$; for anodes when $4L/r < 16$ or for anodes that do not approximate cylindrical shapes, equations such as McCoy's¹⁶ (see Equation [D8]) or other versions of Dwight's¹⁵ may better predict the actual current output of the anodes. Theoretically, for a deep sea submerged cylindrical anode, a more nearly correct equation would be as shown in Equation (D7):

$$R = \rho \frac{K}{L} \left[\ln \left(\frac{2L}{r} \right) - 1 \right] \quad (D7)$$

However, Equation (D1) is more widely used in CP practice. Notes:

(a) For practical designs and to ensure adequate current to protect the structure during the life of the anode, the length (L) and radius (r) should be selected to show the

condition of the anode when it is nearly consumed. For an elongated anode, the change in length may be ignored.

(b) If the structure potential rises more negative than the minimum protection potential of -0.80 volt (Ag/AgCl [sw]), E becomes less than the calculated driving voltage. This decreases anode current output and increases anode life.

(c) The anode net weight must be sufficient to provide the calculated current for the design life of the system, in accordance with the actual consumption rate of the anode material selected (see Appendix B and Table B1).

(d) McCoy's¹⁶ formula is shown in Equation (D8):

$$R = \frac{0.315 \rho}{\sqrt{A}} \quad (D8)$$

where:

R = resistance in ohms
 ρ = resistivity of water in ohm-m
 A = area of exposed anode in m²

Appendix E Typical Method for Calculation of Galvanic Anode Current Output Using Design Slope and Maintenance Current Density (Nonmandatory)

This method is proposed as an alternative to calculation of the initial, mean, and final current densities (Appendix D). It affords the advantage of being first principles-based such that undisclosed over-design, as may be inherent to the preceding method, may be avoided. This CP system design for the seawater-exposed sections of an uncoated structure using the design slope follows these steps¹⁸:

1. Determine the required design life for the structure, T.
2. Based on the anode material to be used and the application environment, select a value for the anode consumption rate, k (Note: a different symbol for anode consumption rate is used in Appendix D).
3. Specify the water resistivity, ρ. For large structures that span zones of varying resistivity, separate designs should be executed for different regions of the structure, e.g., when the current requirement changes by more than 10 percent.
4. Based on prior experience or on experimental data at the site of interest, select values for the design slope, S, and for the maintenance current density, i_m, which results from that design slope. Again, separate designs should be executed for different regions of the structure.
5. Determine the value of the right-hand side of Equation (E1). This value then describes the anode size and shape

alternatives that may be used to achieve the selected design, as dictated by the left-hand side.

$$R_a w = i_m T k S \quad (E1)$$

where:

R_a = resistance of single anode to remote seawater (for example, Equation [D1]) in ohms
 w = mass of a single anode in kg
 i_m = maintenance current density in A/m²
 T = design life in years
 k = anode consumption rate in kg/A-y (example values are shown in Table B1)
 S = design slope in ohm-m² (example values are shown in Table A1)

6. Iteratively determine a suitable anode for the application:

- (a) Select a candidate anode, and from its dimensions calculate its resistance, R_a, and its mass, w.
- (b) Check whether for this anode, the left-hand side of Equation (E1) is equal to the right-hand side.
- (c) If there is no match, two options exist. First, the anode can be modified and steps 6a and 6b repeated to optimize the anode to meet the design criteria. (Although an infinite

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number of anodes that will satisfy Equation (E1) can be designed, there is a smaller subset that is practical to manufacture and install.) Alternatively, the selected anode may be accepted, and Equation (E1) may be rearranged, as shown in Equation (E2), to determine the actual design life that will result.

$$T = \frac{R_a w}{i_m k S} \quad (E2)$$

7. Once the anode has been sized, Equation (E3) can be used to calculate the surface area that each anode will protect.

$$A_1 = \frac{S}{R_a} \quad (E3)$$

where:

A_1 = area protected per anode

8. Determine the total surface area for the structure or zone to be protected and divide by the area protected by each anode to determine the number of anodes needed, as shown in Equation (E4).

$$N = \frac{A_{total}}{A_1} \quad (E4)$$

where:

N = total number of anodes

A_{total} = total surface area for structure or zone to be protected

9. Determine whether the design slope based on final conditions (90% anode consumption) is acceptable but using the value of R_a for an expended anode. R_a of an expended anode can be calculated using the same procedure described to determine the current output of an expended anode in Equations D5 and D5.5. The long-term potential of the anode might be different from the value exhibited during the polarization process, so that the design line may shift up or down on the polarization graph.

If a large number of designs will be done for structures in similar conditions, steps 1 through 7 and 9 of this procedure may need to be followed only once. A standard anode that will protect a certain cathode area, A_1 , on each structure, is thereby defined.

If a design requires that different sizes and shapes of anodes be used because of complex structure geometry, then each anode type should be independently determined to satisfy the design equation in step 6 above. The area protected by each anode type is different.