Cathodic Protection Systems for Civil Works Structures

Florida Board of Professional Engineers
Approved Course No. 0010329

4 PDH Hours

A test is provided to assess your comprehension of the course material – 20 questions have been chosen from each of the above sections. You will need to answer at least 14 out of 20 questions correctly (>70%) in order to pass the overall course. You can review the course material and re-take the test if needed.

You are required to review each section of the course in its entirety. Because this course information is part of your Professional Licensure requirements it is important that your knowledge of the course contents and your ability to pass the test is based on your individual efforts.

Course Description:

This course is based entirely on the information published by the U.S. Army Corps of Engineers (USACE) in Engineering Manual EM 1110-2-2704: Cathodic Protection Systems for Civil Works Structures. Basic descriptions of Cathodic Protection Systems are included and the course will provide guidance and requirements for the selection, design, installation, operation, and maintenance of Cathodic Protection Systems used throughout USACE structures. The information found herein may also be applicable to other types of structures and components depending on the specific application.

How to reach Us …

If you have any questions regarding this course or any of the content contained herein you are encouraged to contact us at Easy-PDH.com. Our normal business hours are Monday through Friday, 10:00 AM to 4:00 PM; any inquiries will be answered within 2 days or less. Contact us by:

EMAIL: bajohnstonpe@aol.com
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Refer to Course No. 0010329

Cathodic Protection Systems for Civil Works Structures

How the Course Works…

What do you want To do?	LOOK For This!
Search for Test Questions and the relevant review section	**Q1** **Search the PDF for: Q1 for Question 1, Q2 for Question 2, Q3 for Question 3, Etc…** **(Look for the icon on the left to keep you ON Target!)**

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20 QUESTIONS

Q1: Corrosion is defined as the deterioration of material (typically a metal) that results from:

(A) a chemical reaction within the environment
(B) a biological reaction within the environment
(C) an electrochemical reaction within the environment
(D) A and C

Q2: Protective coatings alone (without cathodic protection) generally cannot offer complete corrosion protection because:

(A) imperfections exist including pinholes and scratches and over time these become permeable
(B) applicable coatings are not available
(C) the protection life of coatings is too short
(D) application limitations on coating systems

Q3: The most common type of Cathodic Protections System used for protection of structures is:

(A) galvanic systems
(B) impressed current systems
(C) oppressed current systems
(D) A and B

Q4: By weight – which type of anodes are consumed more rapidly:

(A) oppressed current anodes
(B) impressed current anodes
(C) galvanic anodes
(D) there is not relative difference in consumption different types of

Q5: Galvanic anodes for fresh water applications typically are composed of what material:

(A) zinc or magnesium-based alloys
(B) ferrous iron
(C) chromium-based alloys
(D) copper-based alloys

Q6: For large structures with significant expanses of bare or poorly coated metal a properly maintained impressed current system can provide effective corrosion protection:

(A) indefinitely
(B) 10 to 30 years
(C) 5 to 10 years
(D) reasonably up to 5 years

Q7: Disadvantages of an Impressed Current System include ALL of the following EXCEPT:

(A) higher design, maintenance, and installation costs
(B) higher total capacity (ampere-years)
(C) complexity of the installation itself
(D) creation of stray currents that may potentially corrode other nearby ferrous structures

Q8: For uncoupled coated metallic structures, the minimum current density to use is:

(A) 5 mA per square foot
(B) 6 mA per square foot
(C) 7 mA per square foot
(D) 8 mA per square foot

Q9: In areas where zebra mussel infestations can occur, Cathodic Protection System components may be at risk of failure or disruption. For control strategies, which technical guide is available for reference:

(A) Technical Note ZMR-3-05
(B) Technical Note ZMR-3-06
(C) Technical Note ZMR-5-03
(D) Technical Note ZMR-5-06

Q10: After acceptance of a new or repaired cathodic protection system, the system should be monitored and readings recorded on what interval:

(A) on a monthly basis until steady state conditions are reached
(B) after steady state is reached for 6-month intervals for a year or more
(C) minimum yearly intervals
(D) All of the Above

Q11: For system testing of a galvanic anode Cathodic Protection Systems, the negative polarized voltage measured between the structure and a saturated copper-copper-sulfate reference electrode should be at least:

(A) 450 mV
(B) 650 mV
(C) 850 mV
(D) there is no minimum voltage required

Q12: The reliability and effectiveness of any Cathodic Protection System depends on:

(A) proper design
(B) installation as per specifications
(C) proper operation and maintenance
(D) All of the Above

Q13: In all cases of corrosion of a submerged structure, there is a flow of electric current. Which best describes the current flow:

(A) current flows from the corroding area (cathodic area) into the electrolyte and returns to the structure at some other area (anodic area)
(B) current flows from the corroding area (anodic area) into the electrolyte and returns to the structure at some other area (cathodic area)
(C) current flows from the corroding area (anodic area) into the electrolyte and returns to another part of the structure where there is a larger area of corrosion (anodic area)
(D) current flows from the corroding area (anodic area) directly through the structure itself to another area (cathodic area)

Q14: All of the following variables are involved in determining the corrosivity of any electrolyte as part of a Corrosion Protection System EXCEPT:

(A) temperature
(B) pH
(C) suspended solids
(D) conductivity

Q15: What values must be known in order to calculate the estimated life of any galvanic anode:

(A) weight of the anode
(B) current output
(C) anode material
(D) All of the Above

Q16: In an application with water having a resistivity of >3500 Ohm-Cm, what is the best alloy anode to use:

(A) high potential magnesium
(B) H-1 alloy
(C) Grade B Magnesium
(D) High purity zinc

Q17: Refer to Appendix C - For galvanic anode systems, since the system has no adjustment capability anode selection must be based on:

(A) maximum (final) current requirement over the expected anode design life
(B) maximum (final) current requirement over an average 5 year anode design life
(C) maximum (final) current requirement over an average 10 year anode design life
(D) maximum (final) current requirement over an average 30 year anode design life

Q18: Which size of Extended Magnesium Rod Anodes are typically used on Civil Works structures because these are constructed with a 0.125 inch galvanized steel core wire:

(A) 2.00 inch
(B) 2.25 inch
(C) 2.50 inch
(D) A and C

Q19: High-Purity Cast Zinc Rods are usually only practical for use in waters with resistivities around:

(A) 10 – 50 ohm-cm
(B) 50 – 100 ohm-cm
(C) 100 – 2000 ohm-cm
(D) 2000 – 5000 ohm-cm

Q20: Refer to Appendix D - Design Adaptations required for use of High-Purity Zinc Bar Anodes v. use of magnesium rod anodes include:

(A) installation of plastolic coating
(B) required support methods are considerably more sturdy
(C) required support methods are considerably more flexible
(D) A and B

END OF TEST QESTIONS

EM 1110-2-2704

US Army Corps
of Engineers®

ENGINEERING AND DESIGN

Cathodic Protection Systems for Civil Works Structures

ENGINEER MANUAL

DEPARTMENT OF THE ARMY
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Engineering and Design

CATHODIC PROTECTION SYSTEMS (CPS) FOR CIVIL WORKS (CW) STRUCTURES

1. Purpose. This manual provides guidance and requirements for the selection, design, installation, operation, and maintenance of CPS for navigation lock gates and other U.S. Army Corps of Engineers (USACE) CW hydraulic steel structures (HSS). It may also be applicable to other types of structures and components depending on the specific application. This manual also discusses possible solutions to some of the problems with CPS that may be encountered at existing projects. For all Corrosion Prevention and Control (CPC) activities on HSS projects, it is critical to ensure compliance with this manual and other corrosion prevention criteria documents referenced below. This is to ensure that corrosion prevention activities, including selection and implementation of protective coatings, materials, and CPS, remain consistent across all USACE organizations.

2. Applicability. This manual applies to all USACE Commands having CW responsibilities.

3. Distribution Statement. Approved for public release; distribution is unlimited.

FOR THE COMMANDER:

13 Appendices
(See Table of Contents)

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COL, EN
Chief of Staff

* This manual supersedes EM 1110-2-2704, dated 12 July 2004

Contents

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Chapter 7: Corrosion, Corrosion Control, and Corrosion-Causing Issues

Appendixes

1. Purpose. This manual provides guidance and requirements for the selection, design, installation, operation, and maintenance of CPS for navigation lock gates and other USACE CW HSS. It may also be applicable to other types of structures and components depending on the specific application.

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3. Distribution Statement. Approved for public release; distribution is unlimited.

4. References. References are listed in Appendix A.

5. Records Management (Recordkeeping) Requirements. Records management requirements for all record numbers, associated forms and reports required by this regulation are included in the Army's Records Retention Schedule—Army. Detailed information for all record numbers, forms, and reports associated with this regulation are located in the Records Retention Schedule—Army at https://www.arims.army.mil/arims/default.aspx.

6. Background. The primary corrosion control method for HSS is a protective coating system or paint system. Where the paint system and structure are submerged in water (or buried in soil), a combination of the naturally existing anodic and cathodic areas on the metallic surface, the electrolyte (water or soil), and external electrical circuits (metal structure) form electrochemical corrosion cells, and corrosion naturally follows. CPS can supplement the coating system to mitigate corrosion damage.

Chapter 1
Introduction

1.1 Corrosion Protection. Engineer Manual (EM) 1110-2-3400 defines corrosion as the deterioration of a material (which is typically a metal) that results from a chemical or electrochemical reaction with its environment. Q1

a. In electrochemical reactions, positive ions are formed, or caused to be formed, at an anode in contact with an electrolyte and negative ions are formed, or caused to be formed, at a cathode in contact with an electrolyte. The positive ions of the anode attract free negative ions in the electrolyte.

b. If the positive ions of the anode combine with the negative ions in the electrolyte, the anode material undergoes an oxidizing reaction. In water, the most common negative ions are oxygen, and the most common positive ions are hydrogen. For metals, the reaction with the negative ions typically results in the formation of a metallic oxide (rust). Most common metals are not highly reactive with hydrogen, although there are certain conditions in which reactions with hydrogen become a concern. These conditions are addressed later in this manual.

c. Corrosion occurs on all metallic structures that are not adequately protected from corrosion. The cost of replacing a structure that may have been destroyed or weakened from excessive corrosion is substantial. A means should be taken to consistently prevent or mitigate this added cost through cathodic protection.

d. In addition to preparing and applying protective coatings to the surface of a structure, corrosion protection can be provided by applying a protective electric current to the structure surface which is immersed and in contact with an electrolyte. In the presence of certain other metals contacting the electrolyte near the structure, this technique transforms the structure into a cathodic electrode. A properly selected and designed CPS can prevent surface corrosion of the structure, or drastically reduce the rate at which it occurs.

1.2 USACE Experience with CPS. CPS have been used successfully on USACE CW projects for decades.

a. While many of the early CPS became inoperative because of design issues, materials selection, and installation techniques, improvements in design and installation techniques, along with improvements in materials, have made CPS highly reliable in a wide range of applications and environments.

b. CPS are used in combination with protective coatings to mitigate corrosion of hydraulic structures immersed in fresh, brackish, or salt water. While protective coatings are the primary corrosion control method for HSS, protective coatings alone generally cannot offer complete corrosion protection. This is because they usually contain some pinholes, scratches, and connected porosity, and over time these imperfections become increasingly permeable. Q2

c. As coatings degrade with time, these imperfections, commonly known as holidays, have a profound effect on overall coating integrity because of under film corrosion. CPS, when used in conjunction with protective coatings, have been effective in controlling corrosion. CPS utilize anodes that pass a protective current to the structure through the electrolyte environment.

1.3 Corrosion Prevention and Control Program and Plan.

a. CPC Coordinator. It is recommended that each District Dam Safety Officer, described in Engineer Regulation (ER) 1110-2-1156, designate a person who has experience and qualifications in corrosion control and cathodic protection techniques.

b. This person should serve as the District CPC Coordinator. The person designated to be the CPC Coordinator should be a National Association of Corrosion Engineers (NACE) Certified Corrosion Specialist, a NACE-Certified Cathodic Protection Specialist, or a licensed engineer with a minimum of 5 years of experience in the CPC of HSS operating in immersion service.

c. The District CPC Coordinator's responsibilities include ensuring that the CPS are evaluated and tested annually as described in ER 1110-2-1156 and other applicable CPC criteria, and that reports on the results of these evaluation surveys are prepared and maintained at the District Office and applicable site offices.

d. The CPC Coordinator should also ensure that the most current annual CPC survey report is included in the routinely scheduled and executed Periodic Assessment or Periodic Inspection Report for CW projects.

e. This action serves to provide a periodic record of each CPS inspection and to ensure that those records are available for review by management levels higher than the District level. In addition, the District CPC Coordinator should perform a complete corrosion and CPS inspection at each navigation lock or dam dewatering event and at other corrosion prevention activities as necessary.

f. CPC Program and Plans. The District CPC Coordinator should establish a CPC program encompassing HSS at all CW project sites within the District and develop a CPC Plan for each HSS.

g. CPC Plans form the basis for a budget used to secure necessary funding to implement annual activities required by the CPC program. The CPC Coordinator should submit a CPC program budget to the District Dam Safety Coordinator each year.

h. New, Replacement, and Rehabilitated HSS Projects. For new, replacement, or rehabilitated projects, the CPC plan should detail corrosion control measures to be implemented. It should include CPS design analysis with detailed calculations along with a discussion of material selection and protective coatings to be applied. The CPC plan for each new, replacement, and rehabilitated HSS should be included in the specific project Design Documentation Report.

i. Existing HSS Projects. For existing HSS projects, the CPC plan should include requirements for Annual Survey/Testing, Annual Report, and instructions for routine observations and equipment readings. CPC plans for existing HSS projects should consider the condition of existing structures, factors that affect the initiation and rate of corrosion, and methods of CPC such as protective coatings and cathodic protection.

1.4 Training and Available Services.

a. Training. Training should be provided for project designers, inspectors, and O&M personnel who are responsible for CPS in use at CW projects. District CPC Coordinators should arrange training with District Training Coordinators.

b. The training should include both corrosion control and CPS in general terms and report preparation. A Proponent Sponsored Engineer USACE Training (PROSPECT) Course on corrosion control is offered for USACE personnel. This course has a strong emphasis on corrosion control of HSS whereas commercially available courses, such as those offered by the NACE International, primarily emphasize the gas and oil pipeline industry, including off-shore oil structures.

c. The PROSPECT Course provides the required CPS training on design and testing for USACE employees not pursuing NACE International certification.

d. Available USACE Expertise and Services. Services are available on a cost reimbursable basis from the Corrosion Control and CPS Technical Center of Expertise (CCCP TCX).

e. This TCX is located in Mobile District (CESAM-EN-D), Mobile, Alabama, to assist Districts and Divisions in matters related to corrosion control and CPS. Services are also available for design, restoration, construction, O&M, and optimization adjustments of CPS.

f. Information and assistance on corrosion control via the use of protective coatings are available at the Paint Technology Center, also at the Engineer Research and Development Center Construction Engineering Research Laboratory (ERDC-CERL). Information and assistance on materials selection and uses for HSS are also available through ERDC-CERL. Appendix M includes CPS “Lessons Learned” in relation to HSS.

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Chapter 2
Cathodic Protection System Types

Q3

2.1 Cathodic Protection System Types. CPS can be one of two types. This includes galvanic systems and impressed current systems. Galvanic systems utilize galvanic or sacrificial anodes while impressed current systems utilize impressed current anodes. The two systems are further discussed below.

a. Galvanic Anode CPS. Galvanic anode CPS, also sometimes referred to as sacrificial CPS, employ galvanic anodes such as specific magnesium or zinc-based alloys, which are anodic relative to the ferrous structure they are installed to protect. This inherent material property provides the following CPS characteristics:

(1) Enables galvanic anodes to function without an external power source, so they generally need very little maintenance after installation.

Q4

(2) By weight, galvanic anodes are consumed more rapidly by corrosion than impressed current anodes. Consequently, their service life may be shorter than other types of anodes, and they must be replaced periodically to ensure continuing protection of the structure. Therefore, these anodes should be installed in accessible locations on the structure. Figure 2.1 shows a typical slab type anode.

Figure 2.1. Slab Type Anode

(3) Galvanic anode CPS are generally recommended for use with a well-coated structure that is expected to be well maintained or subjected to a minimum of damaging wear during its design life.

(4) Galvanic anode CPS help reduce surface corrosion of a metallic structure immersed in an electrolyte by coupling a less noble metal with the structure. Galvanic anode CPS work through the sacrifice of an anodic metal (i.e., one that has a negative electrochemical potential relative to the protected ferrous structure) to prevent deterioration of the structure through corrosion.

(5) Galvanic anodes for fresh water applications typically are composed of zinc or magnesium-based alloys. In the past, installation of galvanic anodes has often been done on an ad hoc basis, relying largely on the installer's individual knowledge and experience. However, recent research on galvanic anode materials has provided an improved engineering basis for designing applications of these systems.

Q5

b. Impressed Current CPS. These types of systems use direct current (DC) applied to an anode system from an external power source to drive the structure surface to an electrical state that is cathodic in relation to other metals in the electrolyte. These systems have the following characteristics:

(1) Various anode materials and geometries are used. Materials include mixed metal oxides, precious metals (e.g., platinum-clad titanium, niobium), and high-silicon chrome-bearing cast iron.

(2) The most common geometries are button anodes, flat disks anodes, rod anodes, and sausage or strings anodes as shown in Figures 2.2 through 2.5. Button and flat disk anodes are typically used on the skin plate of HSSs such as miter or sector gates. Rod and string anodes are typically located within the HSS such as inside quoin and girder compartments of a miter gate.

(3) Any anode mounted on the structure must be isolated with a dielectric shield to ensure effective current distribution. Impressed current systems employ anodes that are made of durable materials that resist electrochemical wear or dissolution. The impressed current is supplied by a power source such as a rectifier.

(4) All impressed current CPS require periodic maintenance because they employ a power supply and are more complex than sacrificial systems. However, impressed current CPS can be used effectively with bare or poorly coated structures because these systems include much flexibility in terms of the amount of protective current delivered and the ability to adjust it over time as conditions change.

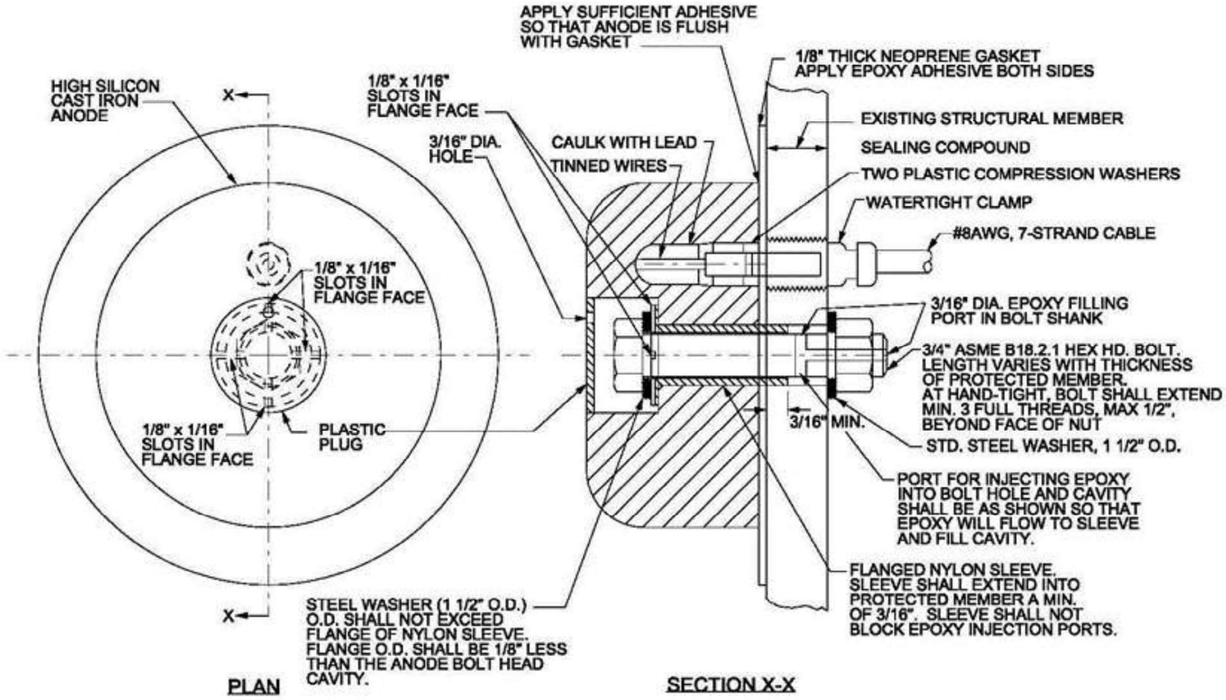

Figure 2.2. High Silicon Cast Iron (HSCI) Button Anode

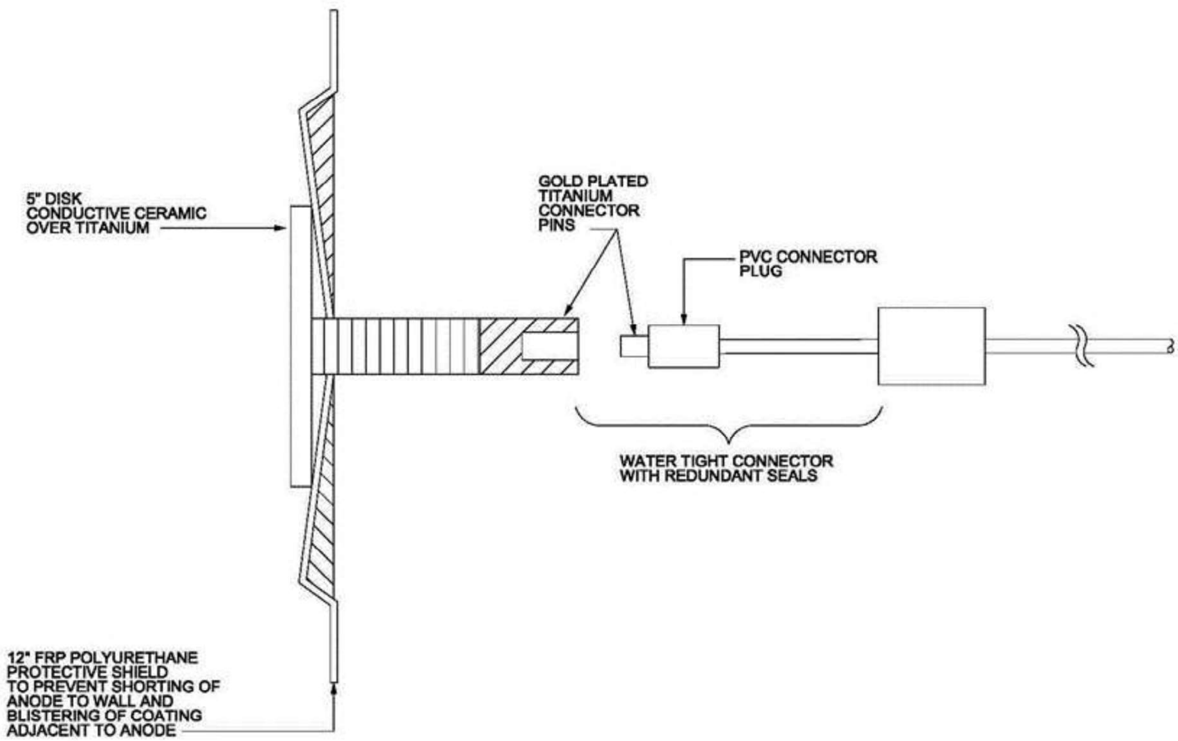

Figure 2.3. Ceramic Coated Flat Disk Anode

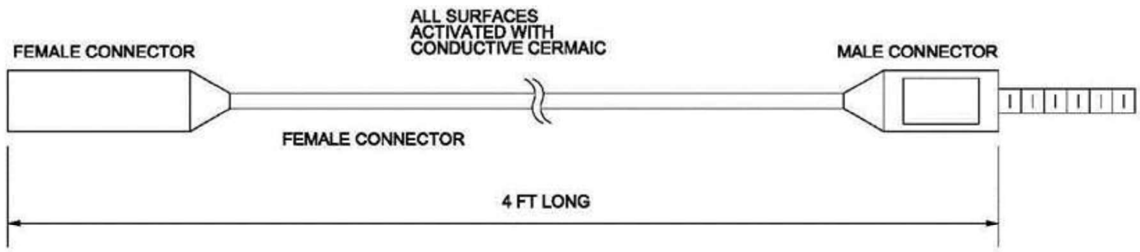

Figure 2.4. Rod Anode Segment

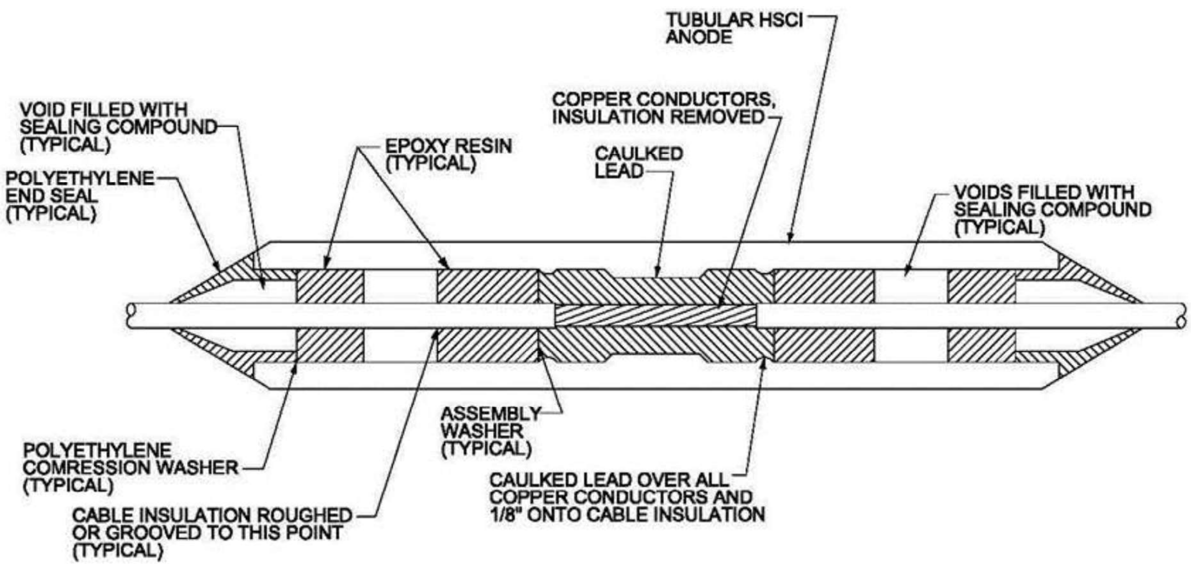

Figure 2.5. High Silicon Cast Iron Sausage or String Anode

Chapter 3
System Selection

3.1 CPS Selection. When selecting which type of system to use, the designer should consider the size of the structure to be protected and past project experience in operating and maintaining both types of systems.

a. Early in the selection process, it is useful to perform a current requirement test to help define the total amount of electrical current needed to protect the structure. For large structures with significant expanses of bare or poorly coated metal, where the total current requirement tends to be very high, a properly maintained impressed current system can provide 10 to 30 years of effective corrosion protection. **Q6**

b. Where current requirements are lower and the structure's protective coatings are well maintained, galvanic anode systems can be very effective. Improved modern coating systems and maintenance practices today allow for a wider use of galvanic anode CPS on large HSS than was the case in the past. For both types of systems, lifecycle cost comparisons, current output required, and overall design life should give an adequate indication of which system is preferable for the specific application. Other factors such as future maintenance needs, reliability, accessibility, and impact on operations may also warrant consideration.

c. Advantages of an Impressed Current System.

(1) Can be designed for a wider range of voltage and current applications.

(2) Higher total capacity (i.e., ampere-years) can be obtained from each installation.

(3) One installation can protect an extensive area of the surface of a metallic structure.

(4) Voltage and current can be varied to meet changing conditions, providing operational flexibility that is very useful to increase protection of the surface coating.

(5) Current requirement can be read and monitored easily at the rectifier.

(6) System can be designed to protect bare or poorly coated surfaces of metallic structures.

d. Disadvantages of an Impressed Current System. **Q7**

(1) Design, acquisition, maintenance and installation costs may be higher.

(2) Installation is complex because of the need for an external power supply, cabling, and numerous electrical connections.

(3) The system can create stray currents that may potentially corrode other nearby ferrous structures.

(4) If an excessive amount of current output is used, hydrogen gas may form between the substrate and coating, causing paint blistering or possible hydrogen embrittlement of high-strength steel.

e. Advantages of a Galvanic Anode System.

(1) External power source is not required.

(2) Installation is less complex since an external power source, including rectifier, is not required.

(3) The system works very well when electrolyte resistivity is low, surfaces are well coated, the structure is easily accessible, and significant deterioration of the coating is not expected within 5 to 10 years.

(4) The system is easier to install on moving complex structures such as tainter valves where routing of cables from an impressed current system could present a problem.

f. Disadvantages of a Galvanic Anode System.

(1) Current output per anode is low and may not be sufficient to protect large structures with significant expanses of uncoated or poorly coated bare metal.

(2) System generally cannot be economically justified where large surface areas of a poorly coated metallic structure require protection.

(3) Anode replacement expenses and/or the number of anodes required can be high compared with impressed current systems for structures with high current requirements.

(4) Current output cannot easily be adapted to seasonal changes in water resistivity or to unexpected changes in coating coverage caused by weathering, routine wear, or impact damage from debris, ice, or aquatic vessels.

(5) Because of the buildup of algae, silt, or other deposits on galvanic anodes, current output to the structure may be reduced.

(6) Monitoring system operation as described by NACE criteria is labor intensive and inconvenient because it requires that structure-to-electrolyte potential measurements be taken in the field.

Chapter 4
Cathodic Protection System Design

4.1 General. CPS must be designed to attain and maintain a level of protection of the structure per the USACE criteria presented in this manual and must be designed with a minimum service life of 20 years.

a. Appendices B through G include basic design formula and examples of design analysis and calculations used to develop subsequent design documents for impressed current or galvanic anode CPS for CW applications. These examples are provided as design guides only and should not be considered mandatory for use.

b. No CPS design is to be used as a standard design to be implemented for all HSS. Each CPS must be designed for the specific conditions of the HSS and its operating environment by a qualified Cathodic Protection Engineer. In addition to this manual, Unified Facilities Criteria (UFC) 3-570-01 can be useful in developing design calculations in conjunction with the criteria that follows.

4.2 USACE Criteria for HSS.

a. Maximum and Minimum Potentials. NACE has documented, empirical evidence that indicates effective corrosion control for steel structures in contact with an electrolyte can be achieved by maintaining a structure-to-electrolyte potential of –850 mV or more negative, as measured with respect to a saturated copper/copper sulfate (CSE) reference electrode.

b. USACE has therefore established a minimum structure-to-electrolyte potential of –850 mV, as measured with respect to a CSE reference electrode, as the basic protection criteria for CW HSS.

c. In addition, USACE has established a maximum structure-to-electrolyte potential of 1100 mV as the upper limit for cathodic protection for HSS. This upper limit was established in order to avoid other deleterious effects that can occur to the structure and the protective coating at higher structure-to-electrolyte potentials.

d. Current Density. For uncoupled coated metallic structures, the minimum current density to use in each CW' HSS CPS design must be no less than 7 mA/sq ft. USACE experience has indicated that this value is the minimum value that should be used for a CPS on any HSS to adequately control corrosion. With integration of stainless steels or other metals that are not commonly coated, this requirement is inadequate if coupled to a bare metal, especially stainless steel, or anodized aluminum. The proper current density in this case must be determined on a project basis. **Q8**

4.3 Design Calculations. To establish the CPS basis of design and to achieve the defined level of protection, the designer will perform a CPS design analysis to analyze the specific site conditions and parameters that the CPS design is to address and incorporate.

a. In addition, design calculations, must be performed to determine the number and types of anodes required. Such calculations must be based on the CPS determined to be necessary for the specific HSS. Calculations must use the design parameters defined in this manual or more stringent CPS design parameters.

b. These calculations must consider the total submerged, or periodically submerged, area of the structure to be protected, the resistivity of the electrolyte, the present condition of the protective coatings on the structure, the predicted deterioration of these coatings from physical damage, the normal paint change of state over at least a 20-year period, and the environment to which the structure will be subjected. Considerations for design calculations include, but are not limited to, the following:

(1) Water Resistivity/Conductivity. Obtain water quality data from the state Environment Management agency.

(2) Dimension and Geometry of HSS. Divide submerged portions of HSS to be protected into regions (areas), and determine surface area for each region. Regions to be protected by different types of anodes should be calculated as different areas. For example, miter gate skin plates to be protected using button anodes should be considered as different areas than downstream girder compartments typically protected using rod or string anodes.

(3) Coating Efficiency. Since structures are typically repainted every 5 to 10 years, assume 90% of the structure will remain coated at the end of its service life.

(4) Design Current Density. Typically use $7mA/ft^2$ for coated structures.

(5) Number of Anodes. Use surface area, coating efficiency, and current density to determine number of anodes required for each region.

(6) Calculate Resistance. Determine anode ground bed and conductor resistance.

(7) Select Rectifier. Use the highest voltage and add amperages per circuit to select rectifier.

4.4 Other Design Considerations.

a. Impact Protection for Cathodic Protection Components. Given their proximity to floating ice and debris, many cathodic protection components used to protect HSS are subject to severe damage from impact. Therefore, an assessment of impact protection needs to be considered. The following are examples of impact protection design features.

(1) Impact Protection for Button and Disk Anode Cables. Provide a 6-inch diameter by 8-inch long steel schedule 40 pipe with threaded pipe cap welded to the Hydraulic Steel Structure in back of each button or disk anode.

(2) A hole must be drilled in the side of this pipe and a thread-o-let fitting welded to the 6-inch diameter pipe at this point to receive the anode lead wire and conduit routed to the anode terminal box. The pipe and conduit are provided for impact protection of the anode cables and the anode bolt. Piping components must be galvanized and painted with 7 mil of the same used to protect the remaining HSS.

(3) Impact Protection for Rod and Sausage-String Anodes. As shown in Figures 4.1, 4.2, and 4.3, rod and sausage-string anodes used to provide cathodic protection for miter gates must be protected utilizing Schedule 80 polyvinyl chloride (PVC) piping installed through each girder web in the center of each chamber.

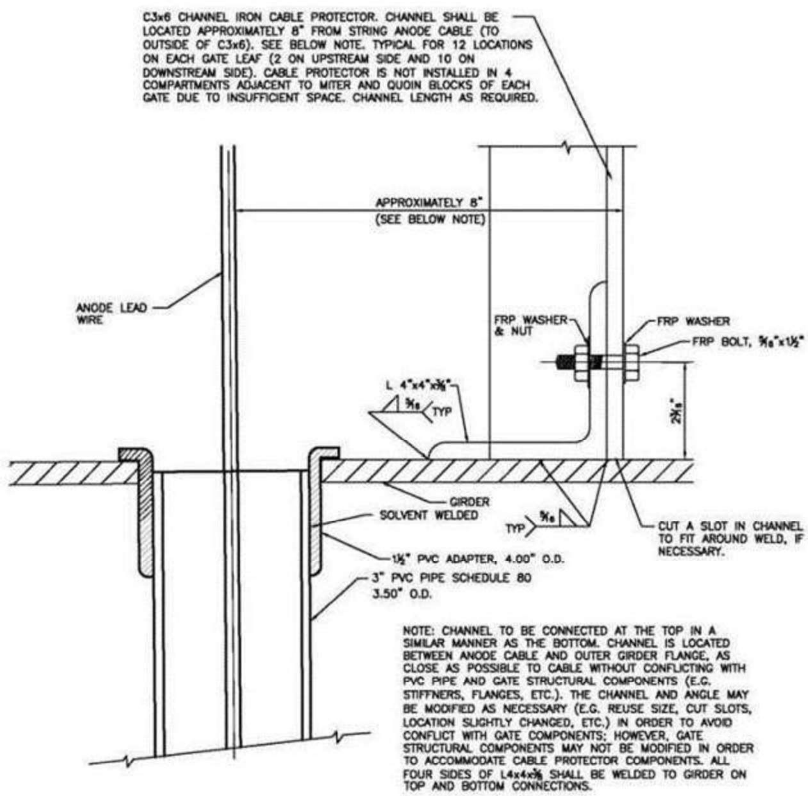

Figure 4.1. Anode Protection Pipe Upper Girder Termination

(4) The PVC piping must have an inside diameter that is at least 1-1/2 inches greater than the anode outside diameter. Piping should contain perforations with openings at least equal to the surface area of the anode material contained within the PVC pipe.

(5) Metal couplings must be installed through the girder webs on the compartment side of the gate (and where compartments are used on the skin plate side), where the PVC pipe penetrates the web. The steel coupling selected should have an interior diameter that will allow the plastic pipe and its associated couplings to pass through the coupling. These steel couplings should be aligned vertically to serve as vertical troughs for the plastic pipes.

(6) The full sections of PVC piping must be solvent welded together end to end. The protective PVC piping is also subject to damage from floating ice and/or debris; therefore, protective angle irons should be installed in front of the PVC pipe. These angle iron sections should be at least 1/4-inch thick with an angle leg length equal to outside diameter of the plastic pipe coupling.

(7) This angle iron should be welded to each girder passage pipe coupling and cover the full length of the PVC pipe. Metal piping components and angle irons must be painted with 7 mil of the same paint used to protect the remaining HSS.

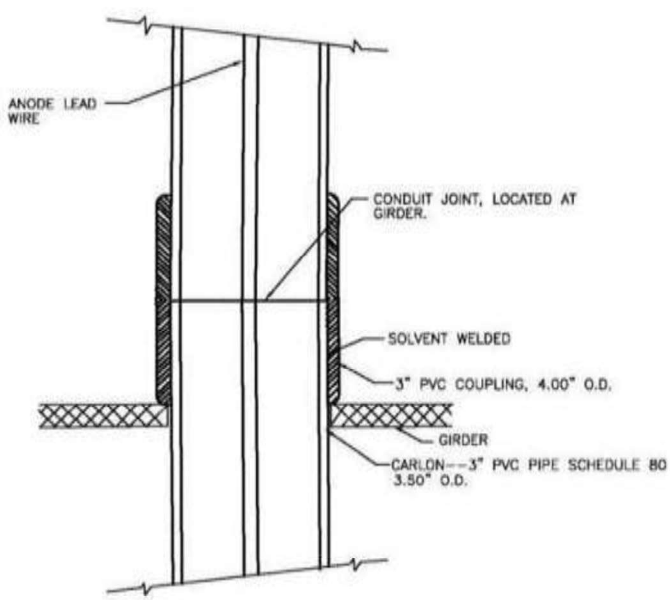

Figure 4.2. Anode Protection Pipe Girder Penetration

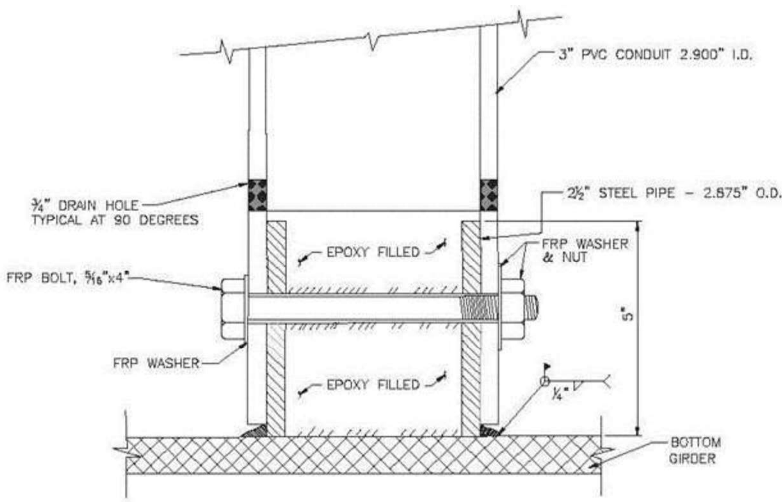

Figure 4.3. Anode Protection Pipe Bottom Girder Termination

b. Restoration Projects. Any inoperable CPS must be restored whenever possible and feasible. Restoration of a CPS is to be part of, and documented in, the CPC program. CPS restoration documentation is to include, but not be limited to, the following:

(1) A survey indicating the status and functional condition of rectifiers, anodes, terminal cabinets, anode system cables, and impact devices.

(2) A copy of the latest structure-to-reference-cell potential readings and associated report. Also, Appendix I contains a copy of the latest rectifier reporting record and an example weekly rectifier record (see Table I.6). Appendix B to this manual also contains an example CPS potential survey report and potential data.

(3) A copy of the latest corrosion control and CPS dewatering inspection report. Appendix K to this manual contains an example corrosion control and CPS lock dewatering report.

c. Zebra Mussel, Oyster, and Other Marine Growth Guidance.

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(1) In areas with potential for zebra mussel infestations, the CPS components may be at risk of failure or disruption. Design considerations in preventing these infestations should be included. For control strategies, refer to Zebra Mussel Research (ZMR) Technical Note ZMR-3-05, compiled by the Zebra Mussel Research Program at Waterways Experiment Station, Vicksburg, Mississippi.

(2) Oyster, barnacle and other marine growth can also adversely impact CPS components and the performance of CPS. Oyster, barnacle and other marine growth accumulation on CPS components must be considered in CPS design when it is a known issue. For further discussion, refer to the design analysis in Chapter 7 to this manual.

4.5 Construction Plans and Specifications. Before advertising an HSS project for immersion service, complete construction plans and specifications must be developed to form a basis for the CPS design and to specify CPS implementation on each new, replacement, or rehabilitated HSS.

a. Construction Drawings. Construction drawings should include plan and elevation views of the HSS showing locations of all CPS components including anodes, rectifiers, and cabling; assembly details; schematic wiring diagrams; and other information necessary to construct the CPS. Example CPS drawing details and plans, for both impressed current CPS and galvanic anode CPS, are available from the CCCP TCX.

b. Guide Specifications.

(1) UFGS 26 42 17.00 Cathodic Protection System (Impressed Current) must be used in preparing contract documents for procurement of all impressed current CPS used on HSS.

(2) This specification section, in addition to providing the technical requirements for various items of equipment for the CPS, addresses methods for protection of the CPS anodes and the electrical leads and connections to the anodes (button, string, and other anodes) from damage as a result of ice and various other debris.

(3) UFGS 26 42 13.00 20, “Cathodic Protection by Galvanic Anodes,” for use on underground piping and buried or submerged structure and HSS CPS using galvanic anodes systems.

(4) UFGS 26 42 14.00 10, “Cathodic Protection System (Sacrificial Anode),” for metal surfaces against corrosion by producing a continuous flow of DC from sacrificial anodes to the metal to be protected.

(5) UFGS 26 42 15.00 10, “Cathodic Protection System (Steel Water Tanks),” for a CPS using impressed current anodes for steel water tanks.

4.6 CPS Designer. The designer responsible for preparing the CPS design documents, whether USACE or a Corrosion Engineer hired by an Architect/Engineer firm or Construction Contractor, should be a NACE-Certified Corrosion Specialist, a NACE-Certified CP Specialist, or a licensed Professional Engineer with a minimum of 5 years of experience in the CPC of CW’ HSS operating in immersion service. Design work performed by a Corrosion Engineer hired by an Architect/Engineer firm or Construction Contractor, and installation/testing of the CPS should be reviewed/overseen by a USACE Corrosion Subject Matter Expert with comparable credentials.

Chapter 5
System Testing and Optimizing

5.1 CPS Performance Testing. After the installation or repair of a CPS, the system must be measured to ensure compliance with contract acceptance testing requirements, ensure that sufficient benefits are obtained, and to determine if it has been optimized in accordance the guidance below. A system that does not meet the optimization criterion will not adequately protect the structure against corrosion.

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a. After acceptance of a new or repaired cathodic protection system, the system should be monitored and readings recorded on a monthly basis until steady state conditions are reached. Then, based on the judgment of the CPC Coordinator, tests should be performed at 6-month intervals for a year or more. Thereafter, tests are to be performed at yearly intervals. Critical or strategic structures should be monitored more frequently. Appendix L includes an example SOW for a contractor to accomplish CPS testing, evaluation, and reporting for a District's CPC Coordinator.

b. Personnel. All tests are to be performed or directly supervised by a NACE-Certified Corrosion Specialist, a NACE-Certified CP Specialist, or a licensed Professional Engineer with a minimum of 5 years of experience in the CPC, whether that individual be a contractor or an USACE employee. It is recommended that the USACE person accomplishing or supervising these tests also be the District CPC Coordinator.

c. Equipment. Test equipment is to consist of a fresh and calibrated copper/copper-sulfate reference cell, a submersible connection, cabling suitable for immersion use, and a high-impedance voltmeter capable of measuring cathodic protection potentials, and an interrupter or other equipment capable of interrupting the impressed current CPS rectifiers to enable measurement of the polarized or "instant off" potentials.

d. A more extensive list and description of recommended test equipment may be found in the example contractor SOW contained in Appendix L to this manual. Sensitivity of the voltmeter is to be more than 200,000 ohms per volt. The reference electrode is to be placed in the electrolyte adjacent to and within 0.5 to 3 in., if possible, to the face of the gate or other HSS.

5.2 Impressed Current CPS Criterion. The criterion of protection for use with impressed current CPSs relative to HSS is as follows: A voltage between negative 850 mV and negative 1100 mV as measured between the structure surface and a saturated copper/copper-sulfate reference electrode contacting the electrolyte directly adjacent to the structure. Determination of this voltage must be made with the CPS in operation. The number of hours of operation will be project specific and should be determined by the Cathodic Protection Engineer.

a. Voltage drops other than those across the structure-to- electrolyte boundary must be considered for valid interpretation of this voltage measurement. This will be done using of "instant off" measurements and current interruption as described in this paragraph. A minimum of negative 850 mV "instant off" potential between the structure being tested and the reference cell must be achieved over 95% of the submerged area of the structure (i.e., each separate area, such as skin plate side of gate, compartment side of miter gate or structural interior side of sector gate) without any of the "instant off" or polarized potentials being more negative than negative 1100 mV.

b. These "instant off" measurements must be obtained by interrupting the rectifier protective currents via use of government approved equipment. Generally, approved equipment would be use of a voltmeter and a CPS industry accepted means to interrupt the rectifier supplied currents to obtain the "instant off" measurements. This would be accomplished with use of synchronized current interrupters or government approved hard-wired connections with switching capability to enable the simultaneous "on" and "off" operation of multiple rectifiers. Examples would be in sector or miter gate impressed current CPS applications.

c. In relation to voltmeter reading displays during CPS testing, the "instant off" reading is herein defined as the second reading displayed on the voltmeter screen immediately after interrupting the rectifiers (i.e., immediately after turning the rectifiers off). The 100 mV polarization shift criterion described in NACE SP0169 is not to be used on HSS unless specifically authorized by the CPC Coordinator before its use.

d. An adequate number of measurements must be obtained over the entire structure to verify and record achievement of a polarized "instant off" potential between negative 850 mV and negative 1100 mV. Values between the submerged surface being tested and the reference cell must be achieved over 95% of the submerged area (i.e., each separate area, such as skin plate side of gate, each compartment on the compartment side of gate).

e. The designer must provide measurements of the structure to insure none of the potentials will exceed minus1100 mV. This should be done after consideration of voltage drops other than those across the structure-to-electrolyte boundary with respect to a copper/copper-sulfate reference electrode.

f. For miter gates, measurement locations are described in Paragraph L3 in the example SOW included in Appendix L to this manual. Appendix G to this manual includes sample measurement locations for sector gates. To ensure an adequate number of "ON" and "instant off" potential measurements are taken, a close interval potential survey is to be done.

g. The potential measurements are to be taken, at a minimum, on a grid of 3 ft vertical and 5 ft horizontal. The measurement grid will extend across the entire width of each side of each structure (or all along each structural member of the HSS, e.g., as in sector gate interiors) and from the surface of the water to deepest depth. If necessary, the rectifiers will be adjusted to obtain potentials between negative 850 mV and negative 1100 mV.

5.3 <u>Galvanic (Sacrificial) CPS Criterion</u>. The criterion of protection for use with galvanic anode CPSs in relation to submerged surfaces of HSS is as follows: a negative polarized voltage

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of at least 850 mV as measured between the structure and a saturated copper-copper-sulfate reference electrode contacting the electrolyte.

a. Determination of this voltage is to be made with the protective current applied ("ON" potentials) and after the CP system has been in operation for a suggested minimum of 168 hours. This minimum operation time will be project specific. Voltage drops other than those across the structure-to-electrolyte boundary must be considered for valid interpretation of this voltage measurement as described in NACE SP0169 and this manual.

b. For HSS, placing the electrode in close proximity to the painted surface is not considered adequate to meet the requirement of "consideration of voltage drops other than those across the structure-to-electrolyte boundary." The contractor's Corrosion Expert or the qualified and experienced USACE Engineer must establish that voltage drops other than those across the structure-to-electrolyte boundary (i.e., IR drop) have been properly considered by using the methodology described in the following paragraphs.

c. At a minimum of four locations on each submerged face or separate area of each HSS, temporary placement of portable steel coupons will be required for proper application of this criterion. For miter gates the locations are both upstream and downstream faces. For sector gates the locations are the skin plate side and structural interior side.

d. If the HSS is a new structure or if new steel plates are being used to repair existing HSS, then, if possible, these coupons are to be made of the same steel used for the structure. The locations of these portable steel coupons are to be as follows: two where the measured potentials are expected to be the lowest, i.e., at midpoints between anodes or at gate edges; and two at locations where the measured potentials are expected to be the highest, i.e., at anodes. Each coupon is to have an exposed surface area of 0.25 sq in.

e. The native potential of each temporarily placed coupon (i.e., the potential taken before the coupons are connected to the HSS) is to be measured and recorded after being immersed for a minimum of 30 minutes and each is then to be temporarily connected to the HSS. After allowing the coupon to be connected to the HSS for a suggest minimum of 168 hours (project specific), both "ON" and "instant off" potentials are to be measured and recorded, with the reference cell placed adjacent to the coupon.

f. Each "instant off" reading must be a minimum of negative 850 mV, with respect to a copper/copper- sulfate reference cell, at each test coupon location. These "instant off" measurements obtained at each coupon location are to be used to establish the IR drop (voltage drops other than those across the structure-to-electrolyte boundary).

g. The coupon "instant off" readings are to be properly applied and correlated with the required "ON" potential readings across the gate to substantiate that the "ON" readings meet the potential requirements described herein after voltage drops other than those across the structure-to-electrolyte boundary have been considered.

5.4 Optimizing System. Data collected during the test are to be reviewed, and any necessary adjustments are to be made. The system is to be properly optimized by adjusting each rectifier until 95% (per gate area or per DC circuit, whichever is or covers less surface area) of the polarized or "instant off" potentials fall within the range of between negative 850 mV and negative 1100 mV, with respect to a copper/copper-sulfate reference electrode, according to the criteria of protection defined in this Engineering Manual and NACE SP0169, as applicable. Where conflicts are found between other documents, including NACE SP0169 and this manual, this manual will take precedence.

5.5 Reporting. After the installation or a new CPS or repair of an existing system, a report on test results should be prepared and retained at the District. Subsequent inspections and reports on CP systems should be conducted annually as described in Chapter 6. Appendices I and J include examples of annual CPS testing and evaluation reports. Appendix I also includes an example weekly rectifier record (see Table I.6).

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6.1 O&M. The reliability and effectiveness of any CPS depends on its proper design and installation, and in the manner in which the system is operated and maintained.

a. O&M Manual. An O&M manual is to be provided for each new or rehabilitated CPS installed or repaired by a contractor. The district CPC Coordinator is to ensure that each O&M manual provided is consistent with the district CPC program.

b. This manual should provide instructions for testing and optimizing the system and should specify test equipment required. The example SOW included in Appendix L to this manual provides detailed testing procedures and a more detailed equipment list for CPS testing.

c. Copies of the structure-to-electrolyte potential measurements, obtained by the contractor at the time of acceptance of the system by the Government, should be included for reference. Blank data sheets should be provided for Government test personnel to record data obtained in future periodic testing of the CPS.

6.2 Troubleshooting Guide. A troubleshooting guide is to be provided for use with the CPS. This guide should address possible symptoms associated with failure of various items of equipment of the system. Recommendations and possible solutions should also be included. If the CPC Coordinator cannot resolve a problem, then it is recommended that the designer seek the assistance from the TCX in Mobile District addressed in Chapter 1 of this manual.

6.3 Annual Inspection and Testing. Based on the criteria of this manual, develop an annual Survey Inspection and Testing program for all HSS. During the inspection, if any inoperable or ineffective CPS is found, efforts should be taken to adjust or repair the system if possible, or plans made for its repair or replacement.

a. Annual Survey/Testing. A close interval survey of the structure-to-electrolyte polarized potentials is to be performed annually for each CPS. “Close interval” means that potential measurements are to be taken on a minimum of a 3-ft vertical and 5-ft horizontal grid. (See Chapter 5 for further details.) Cell placement must be as close to the protected structure as feasible to minimize voltage drop errors.

b. For impressed current CPS, “instant off” potentials are surveyed. For galvanic CPS, the ON potentials are to be correlated with the polarized potentials as described in Chapter 5. Potentials are to be taken with respect to a standardized reference cell, using a copper/copper-sulfate reference cell in fresh waters and a silver/silver chloride reference cells in salt water.

c. Any impressed current CPS failing to perform must be optimized by adjustment. Remedial actions are to be investigated and recommended for any galvanic CPS that fails to meet the criterion of protection as defined in this manual.

d. If the CPC Coordinator does not have sufficient in-house personnel to accomplish this work, then a contract may and should be considered to complete the work. The SOW in such a contract could include the completion of the annual surveys and the subsequent report, as necessary. Appendix L includes an example of such a SOW, which is provided for guidance only. Appendix J provides an example contractor's CPS survey report resulting from an SOW similar to that contained in Appendix L.

6.4 CPC Annual Reports. Subsequent to the annual survey and testing, prepare a CPC report documenting the condition of the CPSs and including any recommendations to repair the systems.

a. These reports should include a discussion and analysis of observations of structure deterioration, protective coating systems, and the CPS, measurements taken, graphical presentation of data obtained, and appropriate photographs.

b. The data accumulated in the CPC reports are to be retained to provide a database of current corrosion deterioration status of the structures for consideration of possible improvements to CPS techniques, and improvements to the CPC program.

c. The information contained in the reports can assist in work planning efforts before rehabilitation and/or dewatering activities. For examples of CPC Reports, see Appendices I and J for additional information on how CPC reports should be prepared and presented, see Appendix L, which contains a SOW explaining how a contractor is to prepare and present these reports.

6.5 Instructions for Routine Observations and Equipment Readings. The CPC Plan should also provide thorough direction to operators and other site office personnel to record the voltage and current outputs for each impressed current DC circuit CPS rectifier on a weekly basis. Electronic files of these rectifier reports are to be emailed weekly to the CPC Coordinator for review. Appendix I. includes an example rectifier report performed over a 1-month period by the Mobile District (see Table I.6).

6.6 Remote Monitoring. Experience has indicated that permanent reference electrodes mounted on HSS do not have a very long service life in the harsh environment to which they are subjected.

a. Consequently, auto-potential controlled rectifiers are not permitted for use for the automatic control of CPSs on HSS. In addition, reference electrodes mounted on the submerged surfaces of a HSS have not proven to be reliable for CPS potential monitoring purposes. They do not have a long service life and it is not practical to provide enough permanent reference electrodes to suffice for a close interval survey.

b. Therefore, under no circumstances will remote monitoring be substituted for the annual CPC potential survey. If remote monitoring is to be considered by the CPC Coordinator, the remote monitoring system is to only provide readings for each rectifier voltage and current outputs, and the data from each rectifier reviewed on a weekly basis by the CPC Coordinator, or a qualified and experienced person.

c. Any project requiring remote monitoring must meet requirements of UFC 4-010-06 Cybersecurity of Facility-Related Control Systems, ER 25-1-113, USACE Critical Infrastructure Cybersecurity Mandatory Center of Expertise, and ER 1110-2-1156, Chapter 20, and be coordinated with the Critical Infrastructure Cyber Security Center of Expertise.

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Chapter 7
Corrosion, Corrosion Control, and Corrosion-Causing Issues

7.1 Corrosion and Corrosion Control Objectives. This chapter contains additional information for review by those unfamiliar with corrosion, corrosion control, and corrosion-causing issues, specifically as pertaining to HSS. Following is a discussion of corrosion, its control, and various environmental, construction, and/or operational issues that cause corrosion to occur, as pertinent to HSS.

a. EM 1110-2-3400 defines corrosion as "the deterioration of a material, usually a metal, because of a reaction with its environment and which requires the presence of an anode, a cathode, an electrolyte, and an electrical circuit." In other words, the refined metal exhibits a tendency to change back into the form in which it existed in nature before it was refined.

b. In the electrochemical reaction, chemical changes and an exchange of electrical energy take place at the same time. In all cases of corrosion of a submerged structure, there is an accompanying flow of electric current. This current flows from the corroding area of the structure (anodic area), into the electrolyte, and returns to the structure at some other area (cathodic area). Q13

c. The electric current, flowing from the structure, carries metallic ions with it (i.e., ionic current flow or corrosion current). These metallic ions are changed by chemical reaction into oxides and are deposited, in the form of rust, on the structure at the anodic areas. These are the pits that are observed on the surface of the structure during inspection.

d. From an electrical circuitry perspective, the primary purpose of the conventional dielectric protective coating system is to limit the amount of current required to be supplied by the CPS to effectively prevent corrosion (i.e., the coating efficiency design parameter in the CPS calculations).

e. In addition, the coating system must have high dielectric strength characteristics and must be a good electrical insulator to electrically isolate, to the maximum extent possible, the metal substrate from the water (electrolyte). Provided that the coating system is properly selected, specified, and applied, it will also improve the protective current distribution from the CPS to the protected structure.

f. The objective of a properly designed, installed, operated, and maintained CPS is to adequately control the flow of electric current (which is described in the preceding paragraph) so that all electric current flows onto the submerged HSS from the anodes and no electric current is allowed to flow from the HSS into the water.

g. This objective can be effectively achieved when the CPS is capable (via proper design and installation), tested, and adjusted so as to provide the protective potentials, as defined in NACE SP0169 and further clarified for HSS in this manual, to all submerged surfaces of the HSS. If this objective is successfully achieved, then corrosion will be essentially eliminated on the submerged surfaces of the HSS.

7.2 Water Corrosivity. There are several variables involved in determining the corrosivity of any electrolyte environment; for CW' HSS, the relevant electrolyte is water (e.g., river, canal).

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a. Some of these variables are temperature, pH, dissolved oxygen content, chloride content, and conductivity. These will be briefly discussed in this section. While some chemical ions (e.g., chlorides) and activities (e.g., activity by microorganisms) may exist in an electrolyte that can affect the chemical reactions occurring in the water, thereby initiating corrosion, data, many times, may not be readily available on these possible corrosion-causing variables.

b. While it is generally true that chloride content would normally not pose a significant issue in fresh water and bacteria activity is difficult to confirm without laboratory analysis, these variables should not always be totally excluded from consideration during the CPS design.

c. The relationship between fresh water chloride content and conductivity deserves a word of caution. Some river systems, such as the Arkansas River, are known to have high levels of chlorides during some periods of the year. For example, some historical water quality data have indicated that the Arkansas River contained higher levels of chlorides in the month of January in one specific year than in other months of the same year, reportedly because of run off from salt flats.

d. Consequently, the conductivity for January (colder water temperature) was much higher than in June (warmer water temperature), which is opposite from that normally expected with fresh water. In addition, the water at some HSS projects, such as at Galveston District's Colorado River Locks' Project, has a very low average resistivity (very high average conductivity) because the locks are located in the Gulf Intracoastal Waterway (GIWW) near the Gulf of Mexico.

e. Therefore, as discussed further below, to the extent possible, it is critical that the CPS designer collect or gather water quality data (preferably over a several year period) specific to the water environment in which the HSS (to be cathodic protected) is, or will be, located. The matter of corrosion related to bacteria is briefly discussed below under "Special Corrosion Considerations."

f. To aid in the development of the CP design for a specific HSS, water quality data records can often be obtained from USACE, U.S. Geological Survey (USGS), the state department of environmental management, a local water commission agency, or some other local agency that may have water quality monitoring stations in the vicinity of the CW' project.

Appendix B
Sacrificial Cathodic Protection System Basic Design Formula and Reference Tables for Civil Works Applications

B.1 A study was performed to characterize the resistance and hence current output for the most common shapes and sizes of sacrificial anodes. Multiple measurements were taken at remote earth in waters with resistivity of 1250 ohm-cm and 4550 ohm-cm. The results are summarized in Figure B.1.[1]

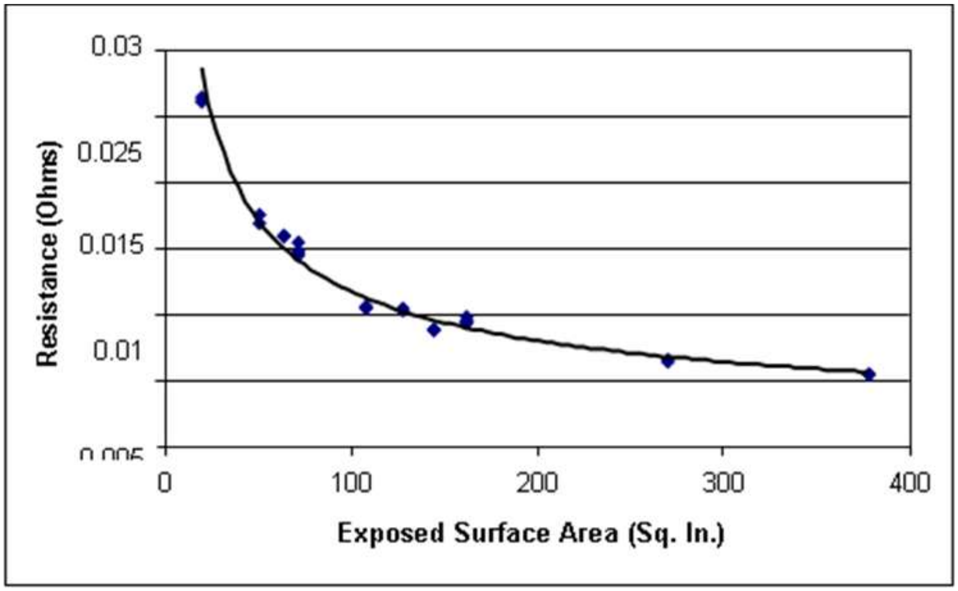

Figure B.1. Resistance vs. Anode Surface Area Normalized for 1 ohm-cm Resistivity Water

a. Table B.1 provides the average resistance values obtained on each of the two anode types that were evaluated. The anode specimen numbers were developed to indicate the dimensions of each anode, in inches, with each dimension being separated by an "x," followed by the anode style ("R" for round and "S" for slab), and then the edge condition ("BE" for bare edge and "CE" for coated edge). All anodes are coated on their back surfaces.

b. The current output calculations in Table B.1 are based on the structure being protected to a polarized potential of –0.85 volt with respect to a Cu-CuSO4 reference electrode. Further, the values for each alloy are based on the most commonly used potential values for each alloy vs. Cu-CuSO4 reference electrode of –1.80 volts for high-potential alloy magnesium, –1.55 Volts for H-1 alloy magnesium (Grade A or B only) and –1.1 Volts for high-purity Zinc.

[1] Marsh, Charles P., and J. B. Bushman. 2003. Direct Determination of Galvanic Anode Current Output for Common Shapes Used in Civil Works Applications. Tri-Service Corrosion Conference, Las Vegas, Nevada.

Table B.1
Current Output for Recommended Alloys of Magnesium and Zinc in 1 ohm-cm Resistivity Water

Anode Style No.	**Anode Type**	**Current Output in 1 ohm-cm Water Using High-Potential Mag (milliamperes)**	**Current Output in 1 ohm-cm Water Using H-1 Alloy Mag (Milliamperes)**	**Current Output in 1 ohm-cm Water Using High-Purity Zinc (Milliamperes)**
2x5RBE	Button	55,882	41,176	14,706
2x5RCE	Button	33,101	24,390	8,711
1x6x12SBE	Slab	84,070	61,947	22,124
1x6x12SCE	Slab	67,375	49,645	17,731
2x8x8SBE	Slab	92,233	67,961	24,272
2x8x8SCE	Slab	63,333	46,667	16,667
2x6x12SBE	Slab	98,958	72,917	26,042
2x6x12SCE	Slab	67,376	49,645	17,731
2x9x18SBE	Slab	139,706	102,941	36,765
2x9x18SCE	Slab	105,556	77,778	27,778
4x9x18SBE	Slab	166,667	122,807	43,860
4x9x18SCE	Slab	105,556	77,778	27,778

c. Table B.2 provides the approximate weight of each anode style in both magnesium and zinc alloys. Because the life of any galvanic anode is directly proportional to its weight and inversely proportional to its current output, both values must be known to calculate anode life.

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Table B.2
Approximate Anode Weight

Anode Style No.	**Anode Type**	**High-Potential and H-1 Alloy Magnesium Anode Weight (Pounds)**	**High-Purity Zinc Anode Weight (Pounds)**
2x5RBE	Button	2.5	10
2x5RCE	Button	2.5	10
1x6x12SBE	Slab	5	22
1x6x12SCE	Slab	5	22
2x8x8SBE	Slab	7.5	30
2x8x8SCE	Slab	7.5	30
2x6x12SBE	Slab	10	42
2x6x12SCE	Slab	10	42
2x9x18SBE	Slab	24	95
2x9x18SCE	Slab	24	95
4x9x18SBE	Slab	44	175
4x9x18SCE	Slab	44	175

d. Given the above information, the current output for any of the evaluated anode styles in different electrochemical environments can be calculated using the following formula:

$$I_a = I_{alloyI}/P$$

Where:

I_a = current output of anode in water surrounding structure to be protected

I_{alloyI} = current output of anode metal alloy selected from Table B.1 in 1 ohm-cm water (in milliamperes)

P = measured resistivity of water surrounding structure to be protected

e. As an example, for a lock gate immersed in 2700 ohm-cm water, the current output using a 2x9x18SBE high-potential magnesium alloy anode would be:

139,706 / 2700 = 51.74 mA

If H-1 magnesium alloy were used instead, the current output for this same style anode would be:

102,941 / 2700 = 38.13 mA

If high-purity zinc alloy were used instead, the current output for this same style anode would be:

36,765 / 2700 = 13.62 mA

f. Because the amount of bare submerged metal that can be protected is directly proportional to the current output of the anode, it can be seen that the high-potential magnesium alloy can protect 1.36 times as much surface area as the H-1 magnesium alloy and 3.8 times as much surface area as the high-purity zinc alloy.

g. Another consideration in anode selection is that the life of each anode is inversely proportional to the current output of the anode. Two different formulae, one for magnesium-based alloys and another for zinc-based alloys, are used for calculating anode service life. For magnesium-based anodes, the following formula applies:

$$Life_{mag(years)} = (116 \times W \times E \times UF)/I$$

Where:

$Life_{mag(years)}$ = years before anode is consumed to the point where its size has been reduced substantially by corrosion and its current output has reduced to the point where it is no longer considered an effective anode.

W = weight of magnesium metal in anode

E = efficiency in converting corrosion current to cathodic protection current = 50% for magnesium

UF = percentage anode used before it is no longer considered an effective anode = normally 85% for any galvanic anode

I = current output of single anode in milliamperes

h. For the 2x9x18SBE high-potential magnesium alloy anode example given above, installed in 2700 ohm-cm resistivity water, the life of the anode would be:

$$Life_{mag(years)} = (116 \times 24 \times 0.5 \times 0.85)/51.74 = 22.9$$

i. For the same anode using H-1 alloy magnesium, the 2x9x18SBE style anode installed in 2700 ohm-cm resistivity water, the life of the anode would be:

$$Life_{mag(years)} = (116 \times 24 \times 0.5 \times 0.85)/38.13 = 31.0$$

j. As noted above, a slightly different formula is used for zinc anodes:

$$Life_{mag(years)} = (42.4 \times W \times E \times UF)/I$$

Where:

$Life_{mag(years)}$ = years before anode is consumed to the point where its size has been reduced substantially by corrosion and its current output has reduced to the point where it is no longer considered an effective anode

W = weight of zinc metal in anode

E = efficiency in converting corrosion current to cathodic protection current = 90% for zinc

UF = percentage anode used before it is no longer considered an effective anode = normally 85% for any galvanic anode

I = current output of single anode in milliamperes

k. Therefore, for the same anode using high-purity zinc alloy, the 2x9x18SBE style anode installed in 2700 ohm-cm resistivity water, the life of the anode would be:

$$Life_{mag(years)} = (42.4 \times 95 \times 0.9 \times 0.85)/13.62 = 226$$

l. Given the anode lives calculated for each of the three examples, if a 20-year design life were desired, the high-potential alloy would not be acceptable in water of this resistivity while the H-1 alloy would have the desired life. The life of the high-purity zinc alloy anode in this style would be considered excessive, and an alternative style would be considered if zinc were the preferred anode material. However, as explained below, it should be noted that zinc anodes are not recommended for use in water exceeding 2500 ohm-cm resistivity.

m. Because the anode efficiencies for zinc and magnesium are known to be 0.9 and 0.5, respectively, and because a utilization factor of 0.85 is almost always applied by corrosion engineers in designing systems, a simple graph of anode life vs. current output can be made for magnesium (Figure B.2) and zinc (Figure B.3) alloy anodes.

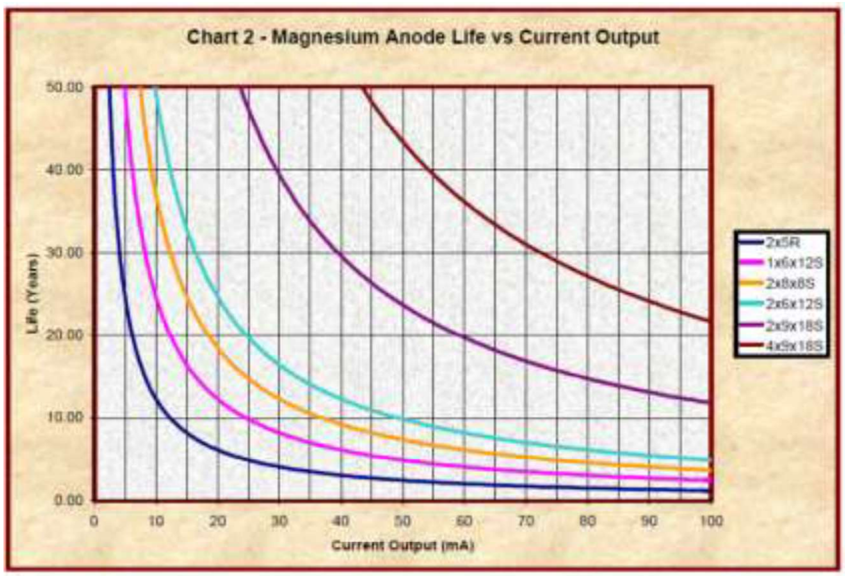

Figure B.2. Magnesium Anode Life vs. Current Output

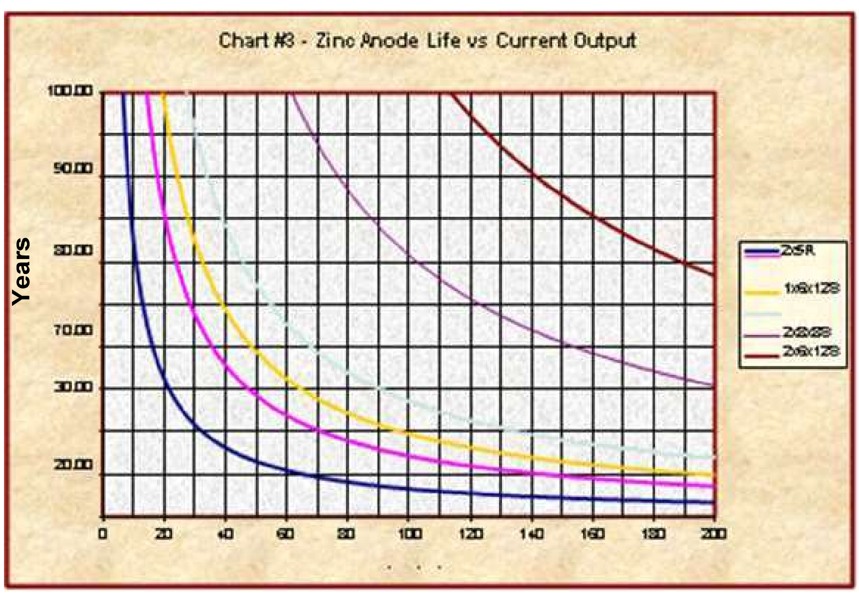

Figure B.3. Zinc Anode Life vs. Current Output

n. The Y-axis on both Figure B.2 and B.3 is in years and the X-axis in current output. As can be seen from Figures B.2 and B.3, only one magnesium anode style has a 20-year life at 100 mA current output. By comparison, there are five zinc anode styles with a 20-year life at 100 mA and two at 200 mA. However, zinc is capable of delivering this higher current only in very low-resistivity water (usually brackish or salt water).

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Table B.3
Preferred Alloys for Various Resistivity Waters

(Best = ✓✓✓)							
Water Resistivity (Ohm-Cm)	**< 500**	**>500 to 1000**	**>1000 to 1500**	**>1500 to 2000**	**>2000 to 2500**	**>2500 to 3500**	**>3500**
high-potential Magnesium				✓	✓✓	✓✓✓	✓✓✓
H-1 Alloy, Grade A or B Magnesium			✓	✓✓	✓✓✓	✓✓	✓
high-purity Zinc	✓✓✓	✓✓	✓✓	✓			

o. In summary, magnesium is preferred in higher resistivity waters (above 2000 ohm-cm) while zinc will almost always be preferred in waters below 1000 ohm-cm. For water above 3000 ohm-cm, high-potential magnesium will generally be preferred, and from 1500 to 2000 ohm-cm, H.1 alloy will almost always be preferred. Table B.3 will help in this general selection process.

p. With respect to current output of each anode style, charts can be developed for specific resistivity environments. Generally, fresh water river and lake water will have resistivity values between 1000 ohm-cm and 3000 ohm-cm. Tables B.4 through B.10 list in detail the current output for each anode style. These tables include a visual plot of the data for comparison purposes. The water resistivity values used in these tables range from 1000 ohm-cm to 4000 ohm-cm, in increments of 500 ohm-cm.

Table B.4
Anode Current Output in 1000 ohm-cm Resistivity Water

Anode Style	high-potential Mag	H-1 Mag	high-purity Zinc
2x5RBE	55.88	41.18	14.71
2x5RCE	33.10	24.39	8.71
1x6x12SBE	84.07	61.95	22.12
1x6x12SCE	67.38	49.65	17.73
2x8x8SBE	92.23	67.96	24.27
2x8x8SCE	63.33	46.67	16.67
2x6x12SBE	98.96	72.92	26.04
2x6x12SCE	67.38	49.65	17.73
2x9x18SBE	139.7	102.9	36.77
2x9x18SCE	105.6	77.78	27.78
4x9x18SBE	166.7	122.8	43.86
4x9x18SCE	105.6	77.78	27.78

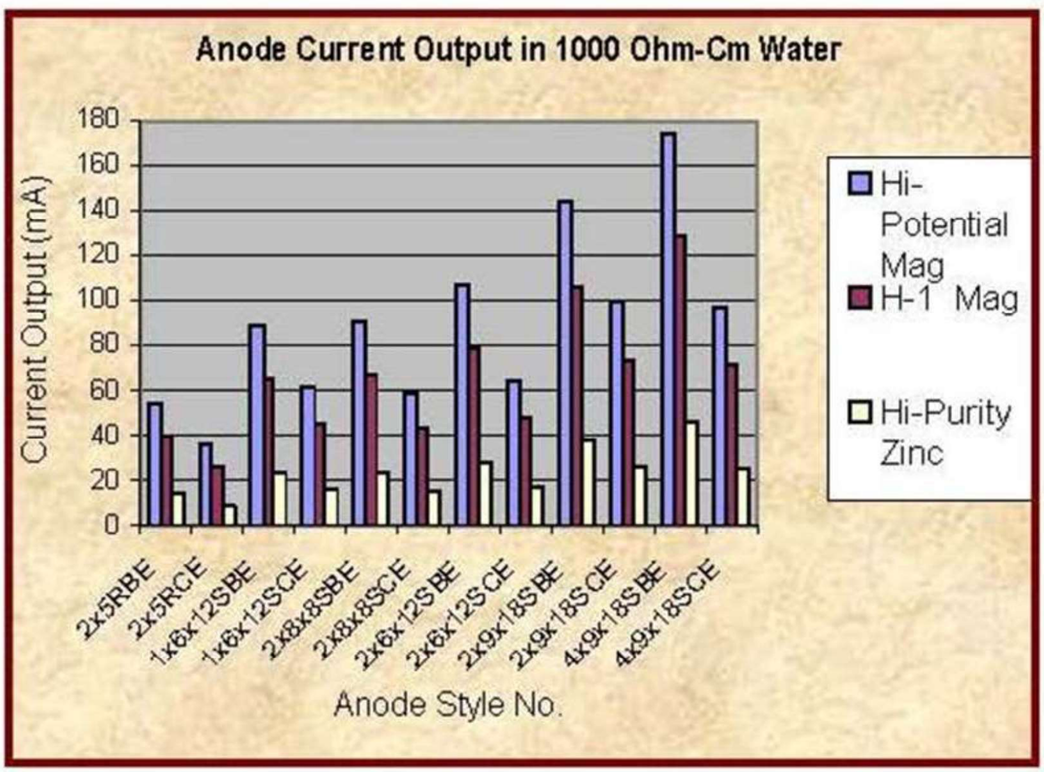


Table B.5
Anode Current Output in 1500 ohm-cm Resistivity Water

	high-potential Mag	H-1 Mag	high-purity Zinc
2x5RBE	37.25	27.45	9.80
2x5RCE	22.07	16.26	5.81
1x6x12SBE	56.05	41.30	14.75
1x6x12SCE	44.92	33.10	11.82
2x8x8SBE	61.49	45.31	16.18
2x8x8SCE	42.22	31.11	11.11
2x6x12SBE	65.97	48.61	17.36
2x6x12SCE	44.92	33.10	11.82
2x9x18SBE	93.14	68.63	24.51
2x9x18SCE	70.37	51.85	18.52
4x9x18SBE	111.1	81.87	29.24
4x9x18SCE	70.37	51.85	18.52

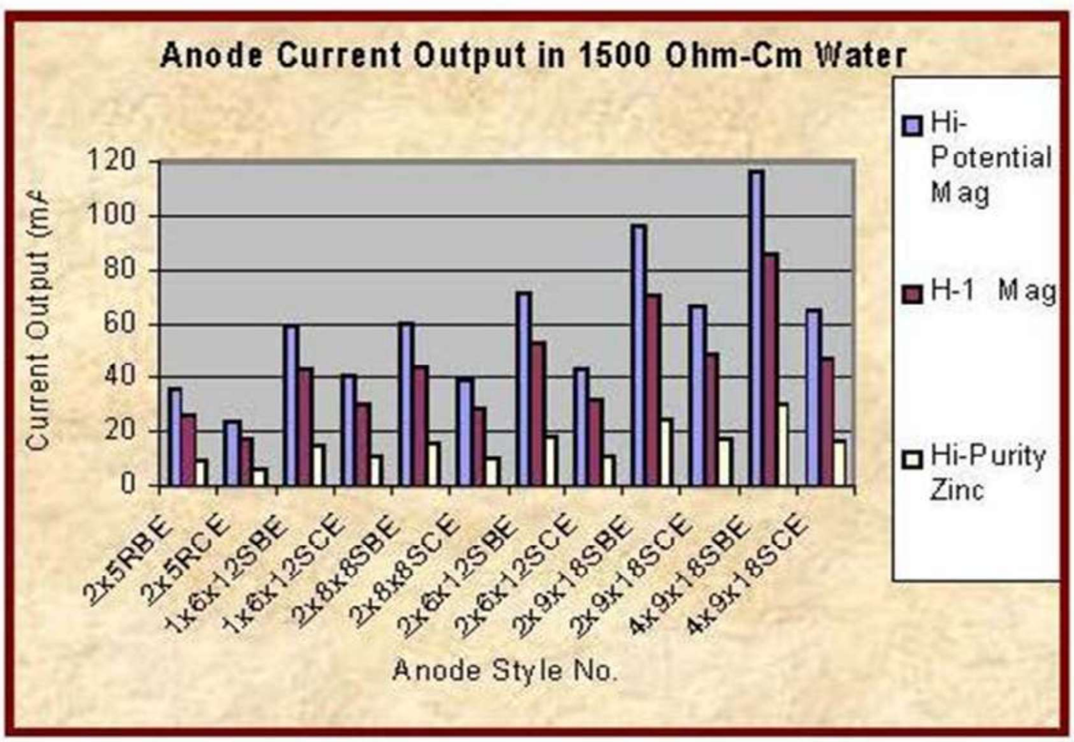
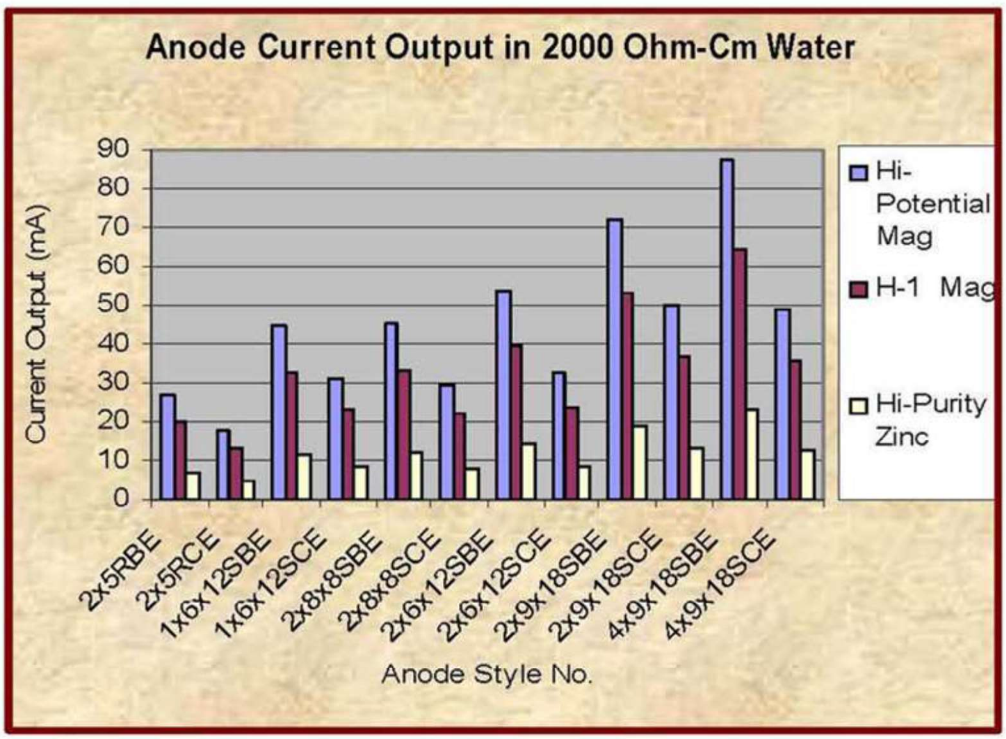


Table B.6
Anode Current Output in 2000 ohm-cm Resistivity Water

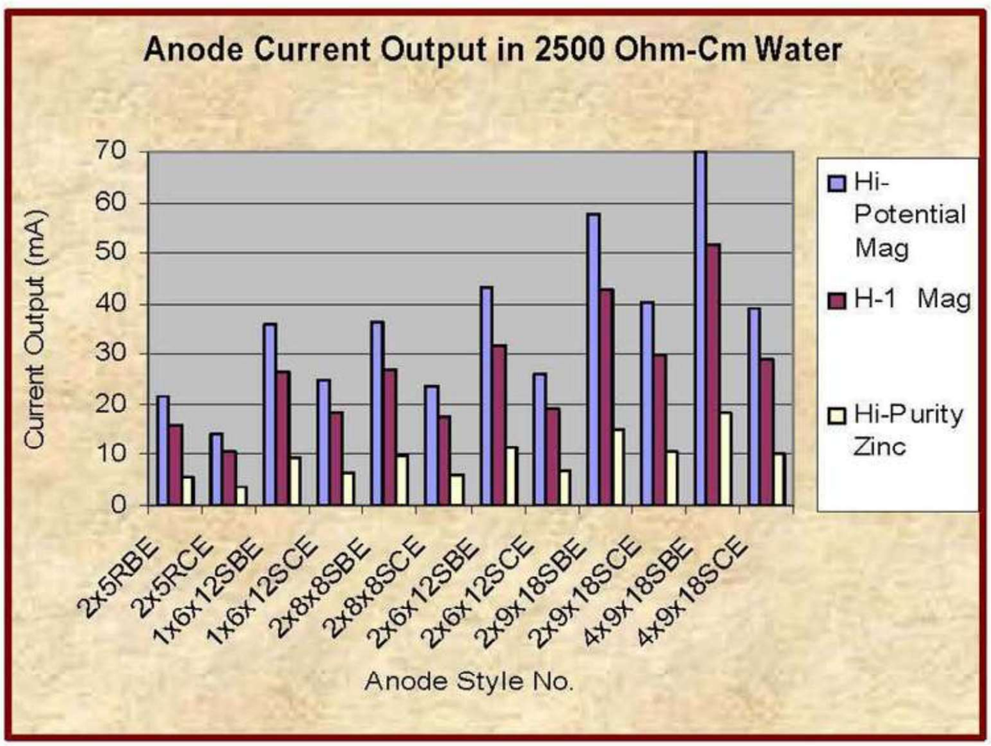
	high-potential Mag	H-1 Mag	high-purity Zinc*
2x5RBE	27.94	20.59	7.35
2x5RCE	16.55	12.20	4.36
1x6x12SBE	42.04	30.97	11.06
1x6x12SCE	33.69	24.82	8.87
2x8x8SBE	46.12	33.98	12.14
2x8x8SCE	31.67	23.33	8.33
2x6x12SBE	49.48	36.46	13.02
2x6x12SCE	33.69	24.82	8.87
2x9x18SBE	69.85	51.47	18.38
2x9x18SCE	52.78	38.89	13.89
4x9x18SBE	83.33	61.40	21.93
4x9x18SCE	52.78	38.89	13.89



* Use of zinc anodes in waters above 2000 ohm-cm is not recommended.

Table B.7
Anode Current Output in 2500 ohm-cm Resistivity Water

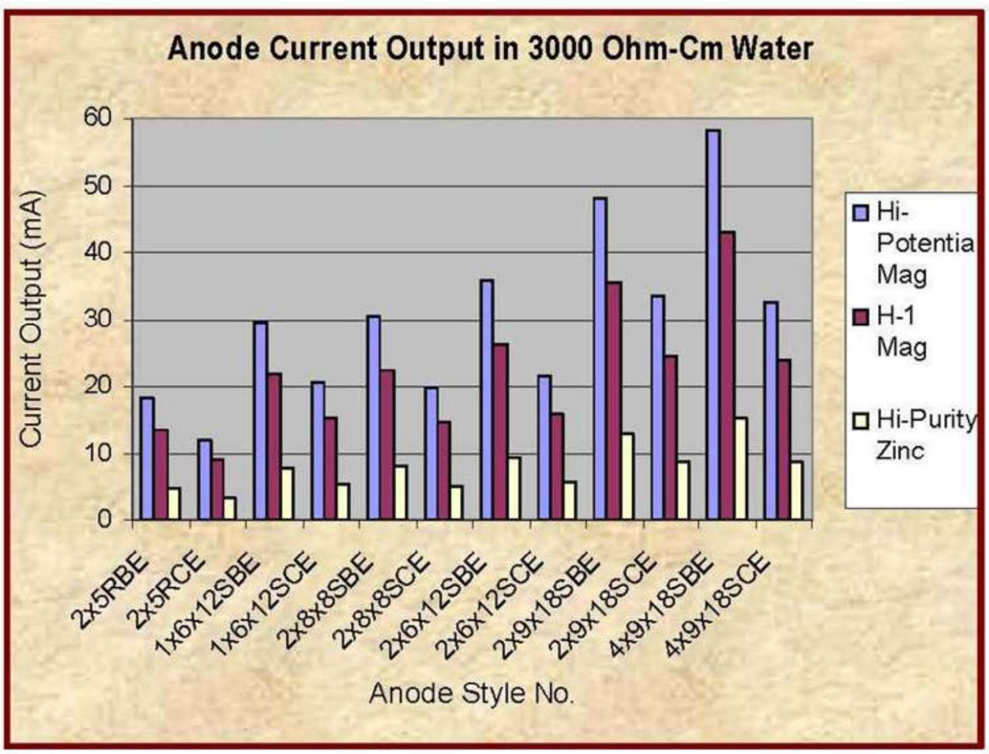
	high-potential Mag	H-1 Mag	high-purity Zinc*
2x5RBE	22.35	16.47	5.88
2x5RCE	13.24	9.76	3.48
1x6x12SBE	33.63	24.78	8.85
1x6x12SCE	26.95	19.86	7.09
2x8x8SBE	36.89	27.18	9.71
2x8x8SCE	25.33	18.67	6.67
2x6x12SBE	39.58	29.17	10.42
2x6x12SCE	26.95	19.86	7.09
2x9x18SBE	55.88	41.18	14.71
2x9x18SCE	42.22	31.11	11.11
4x9x18SBE	66.67	49.12	17.54
4x9x18SCE	42.22	31.11	11.11



* Use of zinc anodes in waters above 2000 ohm-cm is not recommended.

Table B.8
Anode Current Output in 3000 ohm-cm Resistivity Water

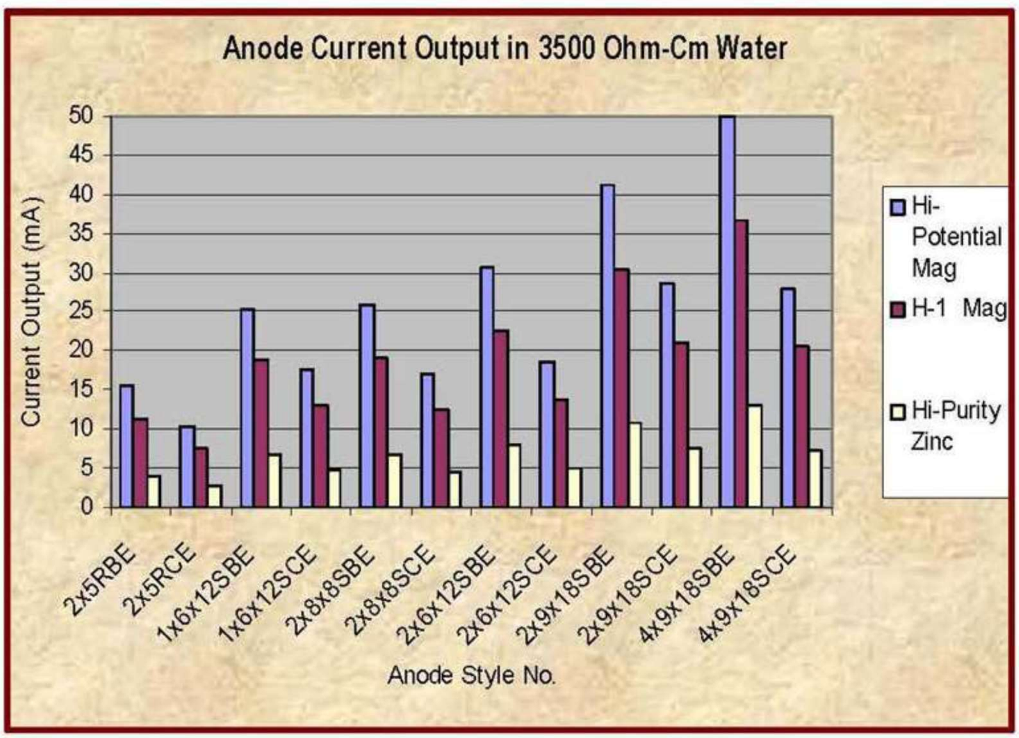
	high-potential Mag	H-1 Mag	high-purity Zinc*
2x5RBE	18.63	13.73	4.90
2x5RCE	11.03	8.13	2.90
1x6x12SBE	28.02	20.65	7.37
1x6x12SCE	22.46	16.55	5.91
2x8x8SBE	30.74	22.65	8.09
2x8x8SCE	21.11	15.56	5.56
2x6x12SBE	32.99	24.31	8.68
2x6x12SCE	22.46	16.55	5.91
2x9x18SBE	46.57	34.31	12.26
2x9x18SCE	35.19	25.93	9.26
4x9x18SBE	55.56	40.94	14.62
4x9x18SCE	35.19	25.93	9.26



* Use of zinc anodes in waters above 2000 ohm-cm is not recommended.

Table B.9
Anode Current Output in 3500 ohm-cm Resistivity Water

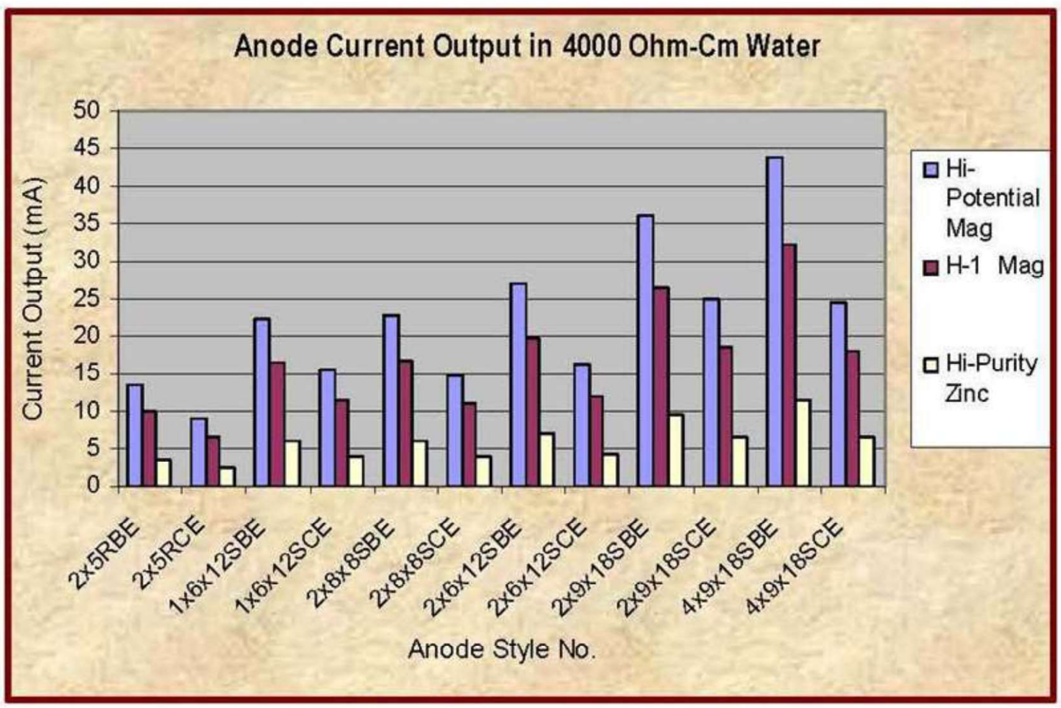
	high-potential Mag	H-1 Mag	high-purity Zinc*
2x5RBE	15.97	11.76	4.20
2x5RCE	9.46	6.97	2.49
1x6x12SBE	24.02	17.70	6.32
1x6x12SCE	19.25	14.18	5.07
2x8x8SBE	26.35	19.42	6.93
2x8x8SCE	18.10	13.33	4.76
2x6x12SBE	28.27	20.83	7.44
2x6x12SCE	19.25	14.18	5.07
2x9x18SBE	39.92	29.41	10.50
2x9x18SCE	30.16	22.22	7.94
4x9x18SBE	47.62	35.09	12.53
4x9x18SCE	30.16	22.22	7.94



* Use of zinc anodes in waters above 2000 ohm-cm is not recommended.

Table B.10
Anode Current Output in 4000 ohm-cm Resistivity Water

	high-potential Mag	H-1 Mag	high-purity Zinc*
2x5RBE	13.97	10.29	3.68
2x5RCE	8.28	6.10	2.18
1x6x12SBE	21.02	15.49	5.53
1x6x12SCE	16.84	12.41	4.43
2x8x8SBE	23.06	16.99	6.07
2x8x8SCE	15.83	11.67	4.17
2x6x12SBE	24.74	18.23	6.51
2x6x12SCE	16.84	12.41	4.43
2x9x18SBE	34.93	25.74	9.19
2x9x18SCE	26.39	19.44	6.94
4x9x18SBE	41.67	30.70	10.97
4x9x18SCE	26.39	19.44	6.94



* Use of zinc anodes in waters above 2000 ohm-cm is not recommended.

Appendix C
Detailed Galvanic Cathodic Protection Design Example Based on Pike Island Auxiliary Lock Gates Using Slab Anodes

C.1 Design for Lock Gates. Figure C.1 shows a Pike Island auxiliary miter gate. This gate is approximately 18.85 m (62 ft) long and 10.64 m (35 ft) high. With the river at normal water level, portions of each gate will always be submerged, and other portions may be submerged or exposed as lockages occur. During times of high water, more gate surfaces will be submerged, and under conditions of flood, the entire gates may be submerged. The usual water depth is 9.12 m (30 ft).

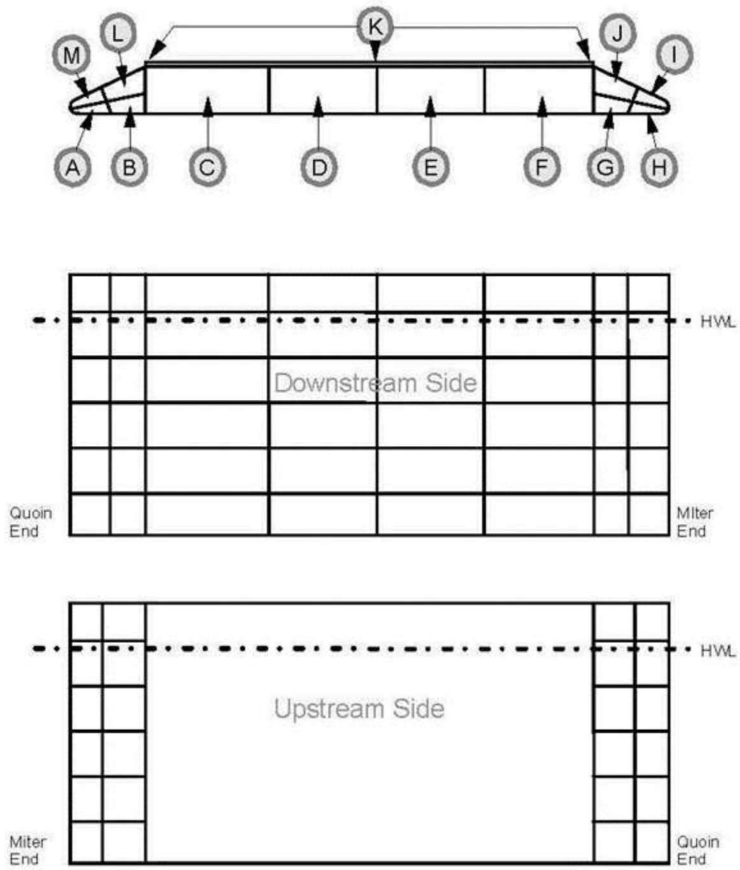


Figure C.1. Lock Gate Vertical, Downstream, and Upstream Structural Layout

a. The gates are constructed of welded structural steel, horizontally framed, with a cast pintle. The downstream side of the gate consists of a pattern of rectangular chambers closed on five faces and open to the water on the sixth face. The upstream face of the gate consists of a large skin plate (area K on sketch) over the major portion of the face and two columns of small chambers (chambers M, L, J, and I) at the quoin and miter ends of the gate.

b. The main (large) chambers (chambers C, D, E, and F) on the downstream face of the gate are set in four columns and are approximately 3.66 m (12 ft) wide, varying in height from 1.01 m (3 ft 4 in.) to 1.82 m (6 ft), with a depth of 1.06 m (3 ft 6 in.).

c. The two sets of vertically aligned chambers, at the quoin and miter ends of the gates (chambers A, B, G, and H), are much smaller and irregularly shaped. There are six horizontally aligned rows of chambers placed one above the other in each vertical column, giving a total of 48 chambers on the downstream side; however, only the five lower chambers are normally submerged.

C.2 Design Data. The following information, with values and assumptions included here for the current example, must be known in order to design any CPS for a lock gate structure:

a. The lock is located in fresh water with a resistivity of 1900 ohm-centimeters. Note: This information must be measured either onsite or from sample of water obtained onsite. Either should be obtained when water is at its highest resistivity (usually in the fall when rainfall and run-off are at their least).

b. Water velocity is less than 1524 mm/s (5 ft/s).

c. Water contains debris, and icing will occur in the winter.

d. The gate surfaces have a new vinyl paint coating, minimum of 0.15 mm (6 mils) thick, with not more than 1% of the area bare because of holidays in the coating.

e. The coating will deteriorate during 20 years of exposure. Based on the recent experience with the coating systems being applied to modern structures, it is reasonable and conservative to assume that 15% of the area will become bare in 20 years.

f. Design for 75.35 mA/m^2 (7.0 mA/ft^2) (moving fresh water).

g. Design for a 20-year life.

h. Design for normally submerged surface areas.

i. For galvanic anode systems, the anodes required must be based on the maximum (final) current requirement over the anode design life since the system has no adjustment capability. Q17

C.3 Computations.

a. Find the surface area to be protected.

(1) Upstream Side.

(a) Area of Skin Plate K. While the gate has an overall height of 10.64 m, it is normally submerged to a depth of 9.14 feet. The width of the gate covered by the skin plate is measured to be 14.50 m. Therefore, the submerged surface area of the skin plate = 14.50 m x 9.14 m = 132.53 m^2 (1,427 ft^2).

(b) Larger Chamber Areas J and L Adjacent to Skin Plate. Five each larger normally submerged chambers adjacent to skin plate each having 6.50 m^2 (70 ft^2) surface area. Note: the sixth chamber at top of each column of chambers is normally above the high-water line and will not be provided with protection.

(c) Smaller Chambers I and M Adjacent to Quoin and Miter End. Five each smaller, normally submerged chambers adjacent to skin plate each having 3.7 m^2 (40 ft^2) surface area. Note: The sixth chamber at top of each column of chambers is normally above the high-water line and will not be provided with protection.

(2) Downstream Side.

(a) Large Chambers C, D, E, and F. With five normally submerged chamber stacked in four columns, there are a total of 20 chambers. Note that the sixth chamber at top of each column of chambers is normally above the high-water line and will not be provided with protection.

(b) While their height varies slightly, the design will be based on the large chamber with greatest height (which has the largest surface area). The dimensions for the largest of these chambers is 3.66 m (12 ft) wide, 1.82 m (6 ft) high, and 1.06 m (3.5 ft) deep.

(c) Based on this information, the individual submerged area of chambers C, D, E, and F = area of both ends of the chambers + area of top and both of each chamber + area of back of chamber = (2 x 1.06 x 1.82) + (2 x 1.06 x 3.66) + (1.82 x 3.66) = 3.85 + 7.76 + 6.66 = 18.87 m^2 (203.2 ft^2).

(d) Small Chambers A, B, G, and H. With five normally submerged chambers stacked in four columns, there are a total of 20 chambers. Again, note that the sixth chamber at top of each column of chambers is normally above the high-water line and will not be provided with protection.

(e) The smallest chambers (A and H) have the same width of 0.9 meters each with an average depth of 0.2 meters while the two larger chambers (B and G) have a width of 1.1 meters each and an average depth of 0.4 meters. Each chamber will be designed on the chamber having the greatest height of 1.82 m.

(f) Thus, the area of the smallest chambers A and H = (2 x 0.2 x 1.82) + (2 x 0.2 x 0.9) + (1.82 x 0.9) = 0.78+ 0.36 + 1.64 = 2.78 m^2 (30 ft^2). The area of the next smallest chambers B & G = (2 x 0.4 x 1.82) + (2 x 0.4 x 1.1) + (1.82 x 1.1) = 1.46+ 0.88 + 2.0 = 4.34 m^2 (46.7 ft^2).

(g) Create a Summary Table of Area for Each Chamber (Table C.1).

Table C.1
Chamber Area Values

Chamber or Surface ID	Side of Gate	Type of Area	No. Submerged	Area Each m^2 (ft^2)	Area Total m^2 (ft^2)
A & H	Downstream	Chamber	5 x 2 = 10	2.78 (30)	27.8 (300)
B & G	Downstream	Chamber	5 x 2 = 10	4.34 (46.7)	43.4 (467)
C, D, E, & F	Downstream	Chamber	5 x 2 = 10	18.9 (203)	189 (2030)
I & M	Upstream	Chamber	5 x 2 = 10	3.7 (40)	37 (400)
J & L	Upstream	Chamber	5 x 2 = 10	6.50 (70)	65.0 (700)
K	Upstream	Skin Plate	1	133 (1,427)	133 (1,427)
Total Submerged Area					495.2 (5,324)

b. Calculate the Current Required for a Single Structure Component.

$$I = A \times I'(1.0 - C_E)$$

Where:

A = surface area to be protected

I' = required current density per bare ft^2 of steel submerged to adequately protect gate = 75.35 mA/m^2 = 7 mA/ft^2

C_E = coating efficiency (0.85 at end of 20 years' service)

Example calculation only for skin plate requirement:

$$I = 133\ m^2 \times 75.35\ mA/m^2 \times (1 - 0.85) = 1503\ mA$$

c. Create a Table of Current Requirements for Each Structure Component (Table C.2).

Table C.2
Current Requirements for Each Structure Component

Chamber or Surface ID	Side of Gate	Type of Area	Area Each m^2	Current Density I' (mA/m^2)	1 – CE	Min. No. Anodes*	Current Required per Unit (mA)	Current Required for All Units (mA)
A & H	Downstream	Chamber	2.78	75.35	.15	1	31.4	314.2
B & G	Downstream	Chamber	4.34	75.35	.15	1	49.1	490.5
C, D, E, F	Downstream	Chamber	18.9	75.35	.15	2	213.6	2136.0
I & M	Upstream	Chamber	3.7	75.35	.15	1	41.8	418.2
J & L	Upstream	Chamber	6.50	75.35	.15	1	73.5	734.7
K	Upstream	Skin Plate	133	75.35	.15	14	1503.2	1503.2
Total Current Required								5596.8

*To ensure uniform current distribution, it is normally good design practice to provide at least 1 galvanic anode per 10 m2 structure surface to be protected.

d. Select Anode Alloy. Refer to Table B.3 in Appendix B. Because the water resistivity is approximately 1900 ohm-cm, it is apparent that the preferred anode alloy material, considering both the current output available and anode life, is H-1 magnesium alloy (Grade A or B). If none of the available shapes provide sufficient current, re-evaluate using high-potential magnesium alloy anodes. If anode life proves too short with both magnesium alloys, then high-purity zinc alloy anodes should be considered.

e. Select Anode Size. Size is governed by the amount of current required for each size chamber and the skin plate. Because there are multiple chamber sizes to consider, start with the smallest surface and then sequentially evaluate the larger chambers. Designing the smaller components is simpler and will familiarize the designer with the process.

(1) Chambers A and H.

(a) Current required per unit = 31.4mA.

(b) Initial Anode Selection. Refer to Tables B.4 through B.10 in Appendix B. Select the table with the resistivity closest to that of the measured water resistivity. In this case, the water resistivity is 1900 ohm-cm, so the appropriate reference would be Table B.6, Appendix B, for 2000 ohm-cm resistivity water. The bar chart included in Table B.6 provides a visual aid to help quickly determine which anodes may be appropriate for this chamber. Based on Table B.6, the 1x6x12SBE, 2x8x8SBE, 2x9x18SCE, and 4x9x18SCE anode sizes appear to be the most appropriate.

(c) Anode Selection Based on Life. The desired anode life is 20 years. Using Figure B.2, Appendix B, only the 2x9x18 or 4x9x18 shapes have sufficient metal weight to meet the 20-year service life requirement at the 31.4 mA output desired. Because the 2x9x18SCE has sufficient life and will provide the desired current for this chamber, install one 2x9x18SCE plastisol-coated H-1 Alloy Grade A or B magnesium alloy anode for the 10 A and H Chambers. Also check and note that one anode per chamber is sufficient for good current distribution in these chambers (see Table C.2).

(2) Chambers B and G.

(a) Current required per unit = 49.1 mA.

(b) Initial Anode Selection. Refer to Tables B.4 through B.10 in Appendix B. Select the table with the resistivity closest to that of the measured water resistivity. As before, the water resistivity is 1900 ohm-cm, so the appropriate reference is Table B.6, Appendix B. Again, based on the data and bar chart visual aid, the only anodes to be considered are the 2x9x18SBE and the 4x9x18SBE.

(c) Anode Selection Based on Life. The desired anode life is 20 years. Using Figure B.2, Appendix B, only the 2x9x18 or 4x9x18 shapes have sufficient metal weight to meet the 20-

year life requirement at the 49.1 mA output desired. Again, because the 2x9x18SBE has sufficient life and will provide the desired current for this chamber, install one 2x9x18SBE, H-1 Alloy, Grade A or B magnesium alloy anode with bare sides and face for the 10 B and G Chambers. Also check and note that one anode per chamber is sufficient for good current distribution in these chambers (see Table C.2).

(3) Chambers C, D, E, and F.

(a) Current required per unit = 213.6 mA.

(b) Initial Anode Selection. Refer to Tables B.4 through B.10 in Appendix B. Select the table with the resistivity closest to that of the measured water resistivity. As before, the water resistivity is 1900 ohm-cm, so the appropriate reference is Table B.6, Appendix B.

(c) Based on the information gained from the designs for the previous smaller chambers, no single anode will be able to meet the current requirement for these large chambers. Instead, it would be preferable to use the least number of H-1 alloy magnesium anodes that will provide the desired current of 213.6 mA.

(d) Table B.6 shows that the 4x8x18SBE H-1 alloy magnesium anodes provides the highest current output of 64 mA. Four anodes of this model will provide 256 mA, which is sufficient to meet the design requirement. Also note that the 2x9x18SBE H-1 alloy magnesium anode provides a current output of 53 mA.

(e) Four anodes of this model will provide 212 mA, which is extremely close to the design current requirement. Both anodes may be considered, however, because the water resistivity is slightly lower than the 2000 ohm-cm value used in Table B.6. Therefore, both anodes (with four per chamber) would in fact meet the desired current requirement.

(f) Anode Selection Based on Life. As before, the desired anode service life is 20 years. Figure B.2 shows that only the 2x9x18 shape has sufficient magnesium metal weight to meet the 20-year service life requirement at the desired 53 mA/anode output. Thus, install four 2x9x18SBE, H-1, Grade A or B Alloy, magnesium anodes with bare sides and face for the 40 C, D, E, and F Chambers. It should be noted that the four anodes per chamber exceeds the minimum number of two anodes required for good current distribution (see Table C.2).

(4) Chambers I and M.

(a) Current required per unit = 41.8 mA.

(b) Initial Anode Selection. Refer to Tables B.4 through B.10 in Appendix B. Select the table with the resistivity closest to that of the measured water resistivity. As before, the water resistivity is 1900 ohm-cm, so the appropriate reference is Table B.6, Appendix B. Based on the data and bar chart visual aid, the only anodes to be considered are the 2x9x18SBE and the 4x9x18SBE.

(c) Anode Selection Based on Life. The desired anode life is 20 years. Using Figure B.2, Appendix B, only the 2x9x18 or 4x9x18 shapes have sufficient metal weight to meet the 20-year life at the 41.8 mA output desired. Because the 2x9x18SBE has sufficient life and will provide the desired current for this chamber, install one 2x9x18SBE H-1 Alloy Grade A or B magnesium alloy anode with bare sides and face for the 10 I and M Chambers. Also check and note that one anode per chamber is sufficient for good current distribution in these chambers (see Table C.2).

(5) Chambers J and L.

(a) Current required per unit = 73.5 mA.

(b) Initial Anode Selection. Again refer to Tables B.4 through B.10 in Appendix B. Select the table with the resistivity closest to that of the measured water resistivity. As before, the water resistivity is 1900 ohm-cm, so the appropriate reference is Table B.6, Appendix B. Based on the data and bar chart visual aid, it can be seen that none of the H-1 alloy magnesium anodes will provide the desired current. However, high-potential alloy magnesium anodes in configuration 2x9x18SBE provide 72 mA, which is very close to the calculated current, while the 4x9x18SBE will provide more than enough at 87 mA.

(c) Anode Selection Based on Life. The desired service life is 20 years. Figure B.2, Appendix B, shows that only the 4x9x18 shape has sufficient metal weight to meet the 20-year service life requirement at the 73.5 mA output desired. Thus, install one 4x9x18SBE high-potential alloy magnesium anode with bare sides and face for the ten J and L Chambers. Also check and note that one anode per chamber is sufficient for good current distribution in these chambers (see Table C.2).

(6) Surface K (Skin Plate).

(a) Current required = 1503.2 mA.

(b) Initial Anode Selection. Refer to Tables B.4 through B.10 in Appendix B. Select the table with the resistivity closest to that of the measured water resistivity. As before, the water resistivity is 1900 ohm-cm, so the appropriate reference is Table B.6, Appendix B.

(c) Based on the information gained from the designs for the previous smaller chambers, no single anode will be able to meet the current requirement for these large chambers. Instead, it would be preferable to use the least number of H-1 alloy magnesium anodes that will provide the desired current of 1503.2 mA. Table B.6 indicates that the 4x8x18SBE H-1 alloy magnesium anode provides the highest current output, 64 mA, while the 2x9x18SBE H-1 alloy magnesium anode provides current output of 53 mA.

(d) Note that the 2x9x18SCE high-potential alloy magnesium anode also will output 50 mA. Any one of these three anodes could be used, but the 4 in. thick H-1 alloy anode will cost almost twice as much as the 2 in. thick anode cast from the same alloy at the same width and length.

(e) An important consideration in anode selection for the skin plate is the value of Plastisol coating of the anode. Although the coating restricts current flow from the anode to the skin plate it in fact improves current distribution because the current from the sides of the anode cannot flow to the steel directly adjacent to the anode. With bare edge anodes it is necessary to place a neoprene rubber shield behind the anode to extend beyond the anode perimeter at least 2 in.

(f) This shield must be glued in place, typically with 100% silicone caulk. Unfortunately, this shielding material can be damaged by debris or ice floating down the river and impacting primarily on the exposed skin plate anodes.

(g) Consequently, for skin plate anodes only, if floating debris or ice are expected in the application, it is normally recommended that the entire anode be coated with Plastisol from which a window is cut to expose a limited operating surface.

(h) In the current example, for the skin plate galvanic anode system, use 30 2x9x18SCE high-potential Alloy plastisol-coated magnesium anodes. These will provide 1500 mA of current, which is extremely close to the design current requirement. Both anodes may be considered because the water resistivity is slightly lower than the values for chart's 2000 ohm-cm resistivity given in Table B.6, so 30 anodes will in fact meet the desired current requirement.

(i) Anode Selection Based on Life. The desired anode life is 20 years. Figure B.2 indicates that only the 2x9x18 shape has sufficient magnesium metal weight to meet the 20-year service life requirement at the 50 mA/anode output desired. Thus, install 30 2x9x18SCE high-potential Alloy, Plastisol-coated magnesium anodes with coated back and sides to protect the skin plate. It should be noted that the 30 anodes exceeds the minimum number of 1 to four anodes required for good current distribution (see Table C.2).

(j) Develop Anode Locations for Each Structure Element. Placement of anodes is simply a geometric process of distributing the anodes uniformly on each protected structural element to achieve good current distribution.

(7) Chambers A, B, G, H, I, J, L, and M. In this example, locating of the anodes in the chamber requiring only one anode is simple in that the anode will be placed on the back surface of each chamber, centered both vertically and horizontally.

(8) Chambers C, D, E, and F. Where more than one anode is required in each chamber, the anodes will be centered vertically within the chamber, but they must be evenly distributed along the side and back panels of the chamber to achieve uniform current distribution.

(9) This is done by "folding open" the three-sided box representing the anode into a flat rectangle, then mathematically distributing the anodes horizontally within that rectangle. The only chambers in this example requiring multiple anodes are the 20 large chambers whose depth is 1 meter and width is 3.7 meters. Because there are four anodes to be distributed around the vertical perimeter surface of the chamber, the overall perimeter dimension of 5.7 meters is first divided by the number of anodes, i.e., four in this case (5.7 m/4 = 1.43 m). This value is used for the center-to-center (c-c) spacing of the four anodes.

(10) Then divide the c-c value by 2 to arrive at the setback distance from the front edge of the chamber for the two outermost anodes (1.43 m/2 = 0.71 m). Because the height of the chambers varies from 1 m to 1.8 m, the vertical center point location of the anodes is shown as one-half of the chamber height. The locations for the anodes in the large chambers is shown in Figure C.2).

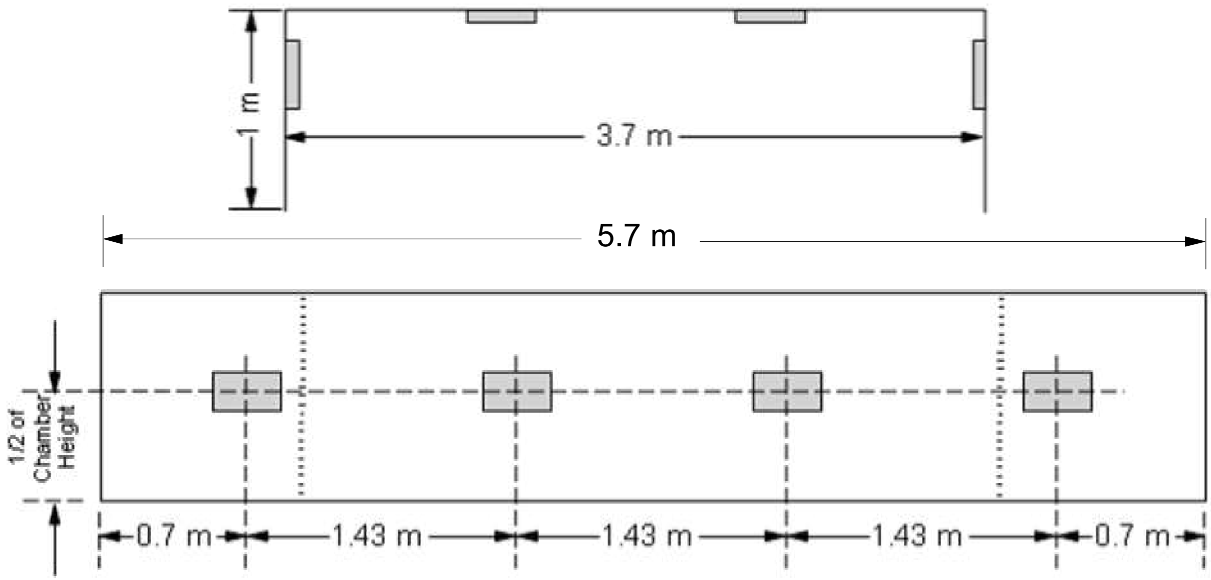


Figure C.2. Galvanic Slab Anode Locations in Largest Downstream Gate Chambers

(11) Skin Plate. Because the Skin Plate will usually require multiple anodes distributed uniformly both vertically and horizontally, the design procedure is somewhat different than it is for the chamber anode configuration. In this case, use the total square footage of the submerged skin plate surface (133 m^2) and divide by the number of anodes required to protect the skin plate (30 anodes) = 133 m^2/30 anodes = 4.43 m^2/anode. The width and height dimensions of each square area to be protected by each anode is the square root of that area. To calculate the width and height of the area to be protected by each anode, use the following formula:

$$W_{A1} = H_{A1} = \sqrt{A_{A1}}$$

Where:

W_{A1} = width of area protected by one anode
H_{A1} = height of area to be protected by one anode

A_{A1} = area to be protected by one anode

(12) For this particular skin plate, the height and width of the area to be protected by each anode is calculated below:

$$W_{A1} = H_{A1} = \sqrt{4.43} = 2.1\ meters$$

(13) The number of anodes in each row across the skin plate is calculated by dividing the width of the skin plate by the width of the area to be protected by a single anode. In this design, the skin plate width is 14.50 meters and the single anode area width is 2.1 meters, or 14.50/2.1 = 6.9 anodes.

(14) The number of anodes in each column across the skin plate is calculated by dividing the submerged height of the skin plate by the height of the rectangular area to be protected by a single anode. In this design, the skin plate submerged height is 9.12 meters and the single anode area height is 2.1 meters, or 9.12/2.1 = 4.32 anodes.

(15) To complete the calculation, round up both values to the next whole number. In this example, 6.9 becomes seven anodes equally spaced across the skin plate, and 4.32 becomes five anodes spaced equally down from the normal high-water line to the bottom of the skin plate.

(16) As in the case of the large chamber anodes, the horizontal spacing of the anodes is determined simply by dividing the number of seven horizontally spaced anodes (in this case) into the skin plate width of 14.5 meters = 14.5/7 = 2.071 meters. The vertical spacing of the anodes is determined simply by dividing the number of five vertically spaced anodes (in this case) into the skin plate submerged height of 9.12 meters = 14.5/7 = 1.824 meters. The layout for these anodes on the skin plate is shown in Figure C.3.

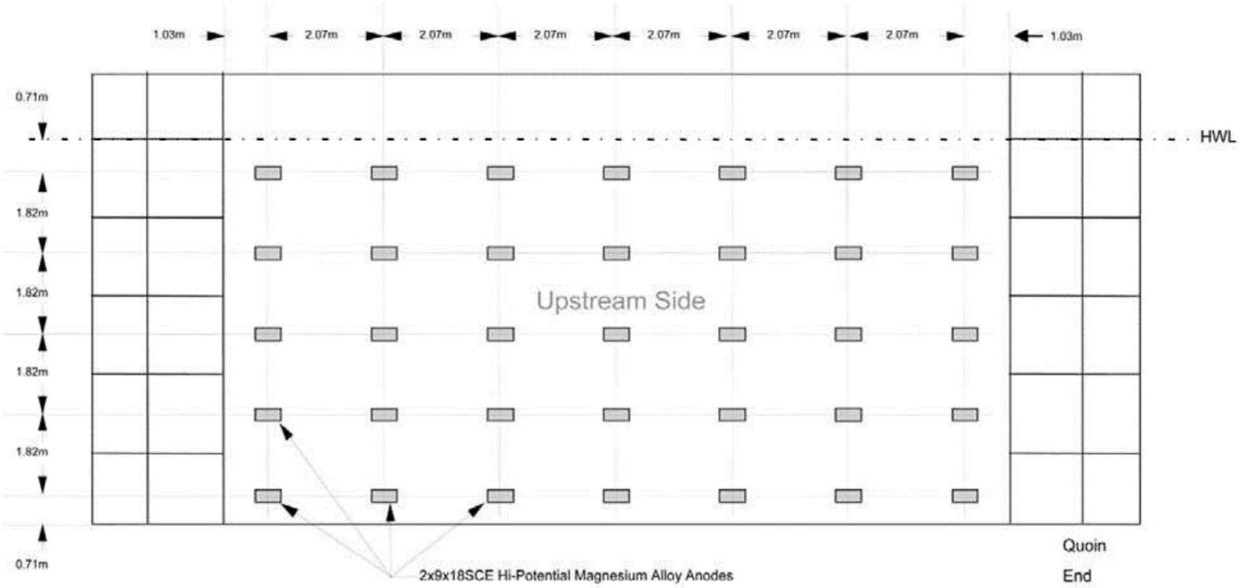


Figure C.3. Example Slab Anode Layout for Upstream Side (Skin Plate)

Appendix D
Detailed Galvanic Cathodic Protection Design Example Based on Pike Island Auxiliary Lock Gates Using Rod and Bar Anodes

D.1 Overview of Elongated Rod and Bar Galvanic Anodes for HSS. While the slab and disk galvanic anodes previously described in this manual are generally preferred for CW structures because of their inherent ruggedness and ease of installation, occasionally the elongated shape of the anodes described in this section may provide design solutions for some structures in higher resistivity environments.

a. Their elongated shape may provide better current distribution in some structure configurations and will usually deliver higher current output for the same weight of material. On the other hand, for magnesium anodes, this higher current output will result in reduced anode life.

b. For example, a 2-inch diameter magnesium rod anode 10-feet long installed in 1,000 ohm-cm water will generate 334 milliamperes DC current output, but the life of the anode will only be 3.69 years. Thus, magnesium rod anodes are normally only used in waters with resistivities in excess of 2000 ohm-cm (see Table B.3 in Appendix B).

c. Extended Magnesium Rod Anodes. High-potential magnesium anode rods are extruded in various diameters ranging from 0.5 –2.562 in. (Figure D.1). Only the 2.5 in. and 2 in. diameters (the two cross-sections at left in Figure D.1) are typically used on CW structures because these are the only sizes made with a 1/8 in. galvanized steel core wire. Q18

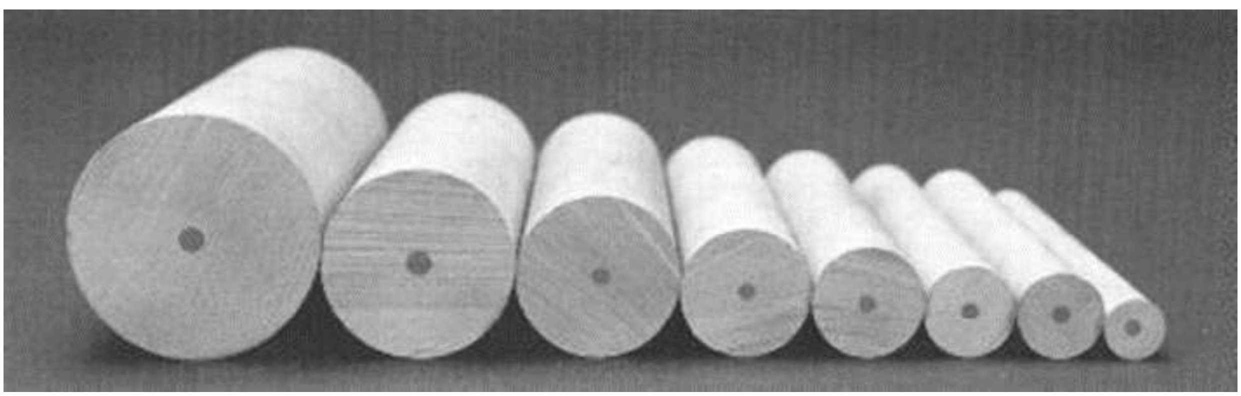


Figure D.1. DC-6722, DC-2375 (Left) and Other Extruded Magnesium Anode Cross-Sections Showing Galvanized Steel Core Wire at Center

d. All smaller diameters have a 1/16 in. or smaller diameter core wire, which is not strong enough to suspend the anodes on CW structures. These anodes are intended for vertical mounting only since the core wire is not strong enough to support the anode horizontally. Properties of the 2.5 in. and 2 in. rods are summarized in Table D.1.

Table D.1
Extruded Magnesium Rod Anodes Suitable for CW Structures

Shape identification number	Diameter, inches	Approx. Weight (lb/linear ft)	Core wire diameter, in.	Current Output "I" (mA) in 1000 ohm-cm Water per Anode Length "L" (inches)
DC-2375	2.024	2.5	0.188	$I = 8.3L^{0.7737}$
DC-6722	2.562	4.0	0.188	$I = 9.16L^{0.7623}$

e. The formulas for calculating current output of magnesium rod anodes 12 – 240 in. long in 1000 ohm-cm resistivity water were developed using Dwight's equation and Ohm's law, as shown in Tables D.2 and D.3. These tables list input variables, current output, and service life calculations for 2 in. and 2.5 in. diameter bare magnesium rods, respectively, using a calculating Microsoft Excel® spreadsheet.

f. The data from Tables D.2 and D.3 were used to generate graphs of current output vs. anode length for both diameters, which are shown in Figures D.2 and D.3. The Excel® trend line development function was then used to generate a curve of best fit using the power extrapolation method. The coefficient of determination for extrapolation was in excess of 99.5% for both curves.

Table D.2
Magnesium Anode Resistance: Current Output and Life Calculations for 2-Inch Diameter Bare Rod

Variables	**Value**	**Term**	
Soil Resistivity	1000	ohm-cm	
Anode Metal	Mg		
Anode Alloy	High-Potential		
Anode Model No.	DC-2375		
Anode Weight/Foot	2.5	Pounds	
Anode Faradaic Consumption Rate	8.5	Lb/Amp-Yr.	
Anode Efficiency (Percent used to provide CP Current)	50.0%	% Eff.	
Utilization Factor	85.0%	UF	
Anode Potential (vs. Cu-CuSO4)	1.75	Volts	
Desired Cathode Potential (mV vs. Cu-CuSO4)	0.85	Volts	
Net Anode-to-Structure Driving Potential	0.90	Volts	
Anode Diameter	2	Inches	
Length of 2 in. Diameter High-Potential Magnesium Rod Anode (in.)	**Package Resistance (Ohms)**	**Total Current Output in 1000 ohm-cm Resistivity Water(mA)**	**Mag Anode Life (Years)**
12	14.9590	60	2.05
24	9.2851	97	2.54
36	6.8942	131	2.82
48	5.5454	162	3.04
60	4.6688	193	3.19
72	4.0490	222	3.33
84	3.5853	251	3.44
96	3.2241	279	3.53
108	2.9341	307	3.61
120	2.6955	334	3.69
132	2.4956	361	3.76
144	2.3254	387	3.82
156	2.1786	413	3.88
168	2.0506	439	3.93
180	1.9379	464	3.98
192	1.8378	490	4.02
204	1.7482	515	4.07
216	1.6677	540	4.11
228	1.5947	564	4.15
240	1.5283	589	4.19

Table D.3
Magnesium Anode Resistance: Current Output and Life Calculations for 2.5-Inch Diameter Bare Rod

Variables	Value	Term	
Soil Resistivity	1000	ohm-cm	
Anode Metal	Mg		
Anode Alloy	High-Potential		
Anode Model No.	DC-6722		
Anode Weight/Foot	4.0	Pounds	
Anode Faradaic Consumption Rate	8.5	Lb/Amp-Yr.	
Anode Efficiency (Percent used to provide CP Current)	50.0%	% Eff.	
Utilization Factor	85.0%	UF	
Anode Potential (vs. Cu-CuSO4)	1.75	Volts	
Desired Cathode Potential (mV vs. Cu-CuSO4)	0.85	Volts	
Net Anode-to-Structure Driving Potential	0.90	Volts	
Anode Diameter	2.5	Inches	
Length of 2.5 in. Diameter High-Potential Magnesium Rod Anode (in.)	**Package Resistance (Ohms)**	**Total Current Output (mA)**	**Mag Anode Life (Years)**
12	13.7964	65	3.03
24	8.7038	103	3.83
36	6.5067	138	4.29
48	5.2547	171	4.61
60	4.4363	203	4.86
72	3.8552	233	5.08
84	3.4192	263	5.25
96	3.0788	292	5.4
108	2.8049	321	5.53
120	2.5793	349	5.65
132	2.3899	377	5.75
144	2.2286	404	5.86
156	2.0892	431	5.95
168	1.9676	457	6.04
180	1.8604	484	6.11
192	1.7651	510	6.19
204	1.6798	536	6.25
216	1.6031	561	6.33
228	1.5335	587	6.38
240	1.4702	612	6.44

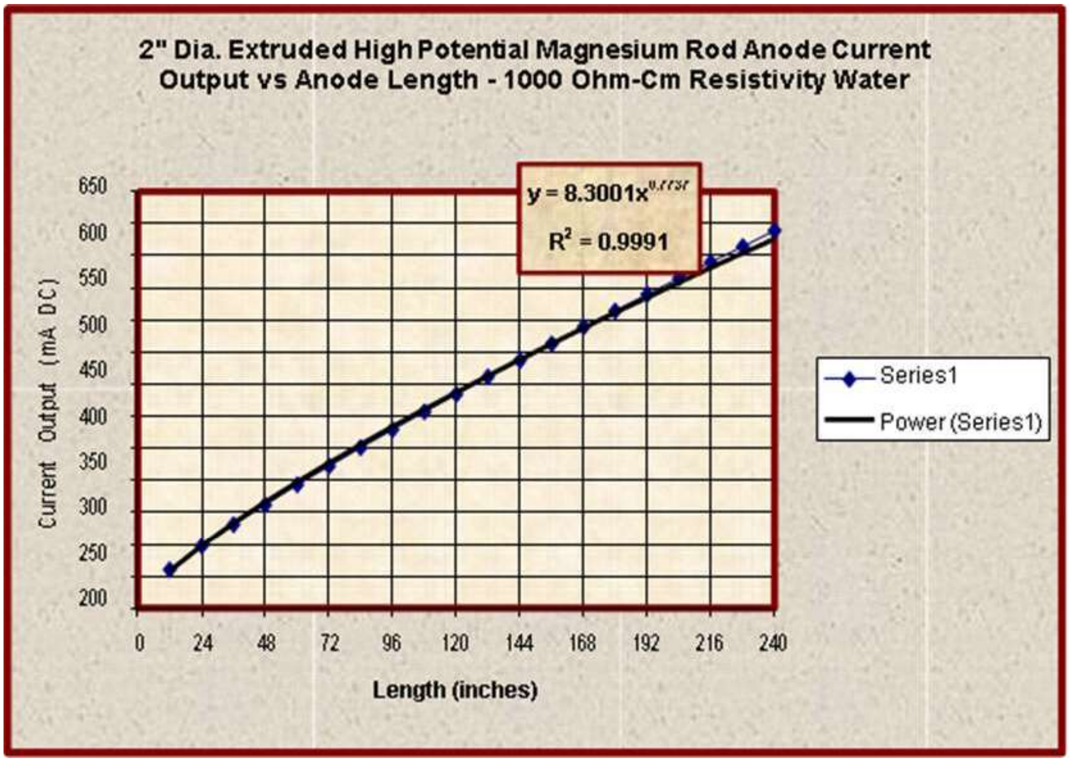


Figure D.2. Current Output vs. Anode Length for 2-Inch Diameter High-Potential Magnesium Rod Anodes

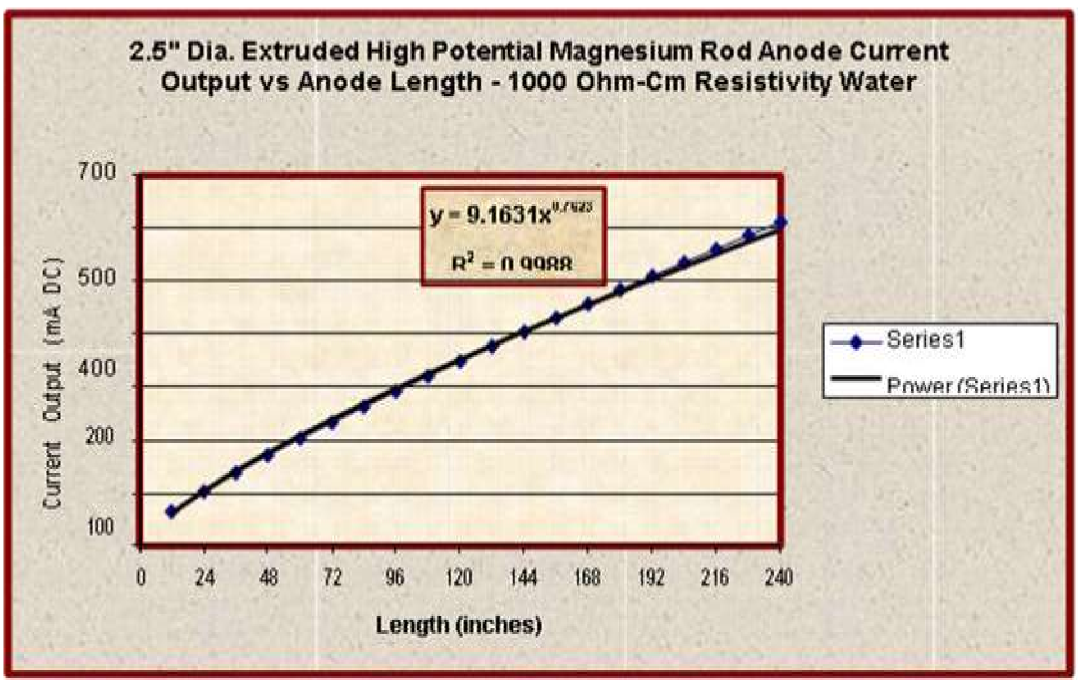


Figure D.3. Current Output vs. Anode Length for 2.5-Inch Diameter High-Potential Magnesium Rod Anodes

g. For any magnesium anode to provide protection, a positive electrical connection must be established and maintained between the anode and the structure being protected. The standard end configurations used on CW structures are three 6 in. x 1/8 in. threaded core extended one end only.

h. This threaded rod can then be used to suspend the rod vertically from a suitable support bracket. Generally, this connection is made by threading a standard galvanized steel nut and washer on the rod (Figure D.4) and then inserting the rod up through a support bracket (minimum 1/4 in. thick) or suitable plate on the structure.

i. The wire core should be extended at least 6 in. so the anode material is at least 5 in. from the metal mounting bracket or structure surface to ensure good anode current distribution. A galvanized steel star washer followed by a standard washer and nylon insert lock nut are then used to fasten the rod in position. The star washer improves the electrical contact to the structure. The entire connection must be properly coated to prevent corrosion of the connection.

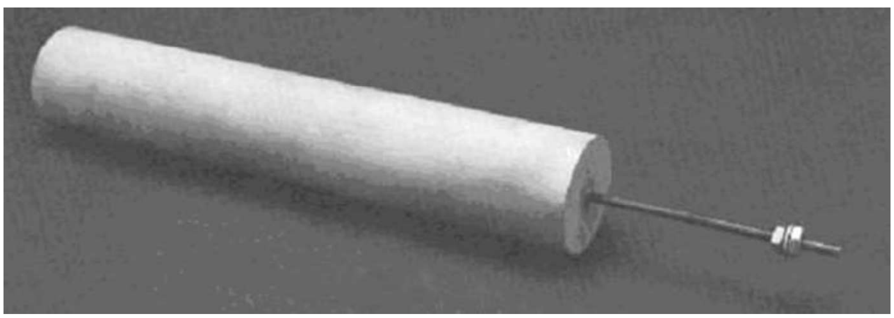


Figure D.4. Magnesium Rod Anode Showing Threaded Core Wire, Double Nuts, and Washers

j. High-Purity Cast Zinc Rods. Zinc rod anodes suitable for use on CW structures are cast in molds around their core rod. They are usually only practical for use in waters with resistivities from 100 to 2000 ohm-cm. Waters with higher resistivities will provide relatively low current to the protected structure although providing a theoretical service life well in excess of 100 years. **Q19**

k. In waters below 100 ohm-cm these anodes will have a service life of less than 10 years. In terms of material properties, this anode is inherently more rugged and impact-resistant than the extruded magnesium rod anode. The most commonly used shape has either a 2 in. or 2.5 in. square cross-section with a standard length of either 5 ft or 6 ft.

l. These anodes are cast with a 1/2 in. diameter straight electro-galvanized steel core rod for direct welding or assembly to two flat attachment bars with U bolts to facilitate routine replacement, as shown in Figure D.5. The U bolts clamp the anode core in place and provide electrical continuity to the support bar and structure.

m. These U bolts are held in place with nylon insert galvanized steel lock nuts and washers on the back side of the plate. Either connection should be thoroughly coated to prevent corrosion attack in any crevices created by the connection. The steel support plate must be welded to the structure and is typically ¼ in. thick x 2 in. wide x 8 in. long. The core is usually extended 6 in. on both ends and is fastened to the plate so that end of the anode material is at least 5 – 6 in. from the mounting plate and also 4 in. away from the structure to provide good current distribution to the structure being protected.

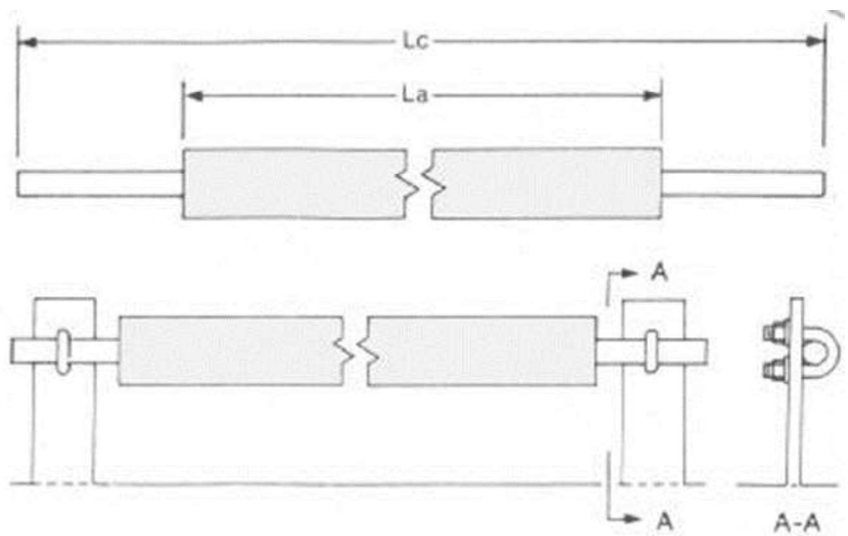


Figure D.5. Connection Schematic for High-Purity Cast Zinc Bar Anodes

n. The current output of each style anode was calculated using Dwight's equation and Ohm's law using a computing Excel® spreadsheet specifically designed for this purpose. Tables D.4, D.5, and D.6 show the computations for the three different zinc rod anodes available.

Table D.4
High-Purity Zinc Anode Resistance: Current Output and Life Calculations for 1.4-Inch Cross-Section Bare Bar

Variables	**Value**	**Term**	
Soil Resistivity	1000	ohm-cm	
Anode Metal	Zn		
Anode Alloy	Hi-Purity		
Anode Model No.	TZ-27		
Anode Weight/Foot	6.75	Pounds	
Anode Faradaic Consumption Rate	23.5	Lbs./Amp-Yr.	
Anode Efficiency (Percent used to provide CP Current)	90.0%	% Eff.	
Utilization Factor	85.0%	UF	
Anode Potential (vs. Cu-CuSO4)	1.10	Volts	
Desired Cathode Potential (mV vs. Cu-CuSO4)	0.85	Volts	
Net Anode-to-Structure Driving Potential	0.25	Volts	
Anode Square Dimensions	1.40		
Anode Effective Circular Diameter	1.57976	Inches	
Length of 1.4 x 1.4 in. High-Purity Zinc Bar Anode (in.)	**Bare Anode Resistance (Ohms)**	**Total Current Output (mA)**	**Zinc Anode Life (Years)**
12	16.1879	15	14.65
24	9.8996	25	17.58
36	7.3039	34	19.39
48	5.8526	43	20.44
60	4.9146	51	21.54
72	4.2538	59	22.35
84	3.7609	66	23.31
96	3.3777	74	23.76
108	3.0706	81	24.41
120	2.8184	89	24.69
132	2.6074	96	25.18
144	2.4279	103	25.60
156	2.2732	110	25.97
168	2.1384	117	26.29
180	2.0198	124	26.58
192	1.9146	131	26.84
204	1.8205	137	27.27
216	1.7359	144	27.47
228	1.6594	151	27.65
240	1.5898	157	27.99

Table D.5
High-Purity Zinc Anode Resistance: Current Output and Life Calculations for 2-Inch Cross-Section Bare Bar

Variables	Value	Term	
Soil Resistivity	1000	ohm-cm	
Anode Metal	Zn		
Anode Alloy	Hi-Purity		
Anode Model No.	TZ50 & TZ60		
Anode Weight/Foot	12.5	Pounds	
Anode Faradaic Consumption Rate	23.5	Lbs./Amp-Yr.	
Anode Efficiency (Percent used to provide CP Current)	90.0%	% Eff.	
Utilization Factor	85.0%	UF	
Anode Potential (vs. Cu-CuSO4)	1.10	Volts	
Desired Cathode Potential (mV vs. Cu-CuSO4)	0.85	Volts	
Net Anode-to-Structure Driving Potential	0.25	Volts	
Anode Square Dimensions	2.00		
Anode Effective Circular Diameter	2.2568	Inches	
Length of 2 x 2 in. High-Purity Zinc Bar Anode (in.)	**Bare Anode Resistance (Ohms)**	**Total Current Output (mA)**	**Zinc Anode Life (Years)**
12	14.3296	17	23.94
24	8.9704	28	29.07
36	6.6845	37	32.99
48	5.3880	46	35.38
60	4.5430	55	36.99
72	3.9441	63	38.75
84	3.4954	72	39.56
96	3.1454	79	41.21
108	2.8641	87	42.09
120	2.6326	95	42.83
132	2.4384	103	43.46
144	2.2730	110	44.39
156	2.1302	117	45.21
168	2.0056	125	45.57
180	1.8959	132	46.24
192	1.7984	139	46.84
204	1.7112	146	47.38
216	1.6327	153	47.87
228	1.5616	160	48.32
240	1.4969	167	48.73

Table D.6
High-Purity Zinc Anode Resistance: Current Output and Life Calculations for 2.5-Inch Cross-Section Bare Bar

Variables	Value	Term	
Soil Resistivity	1000	ohm-cm	
Anode Metal	Zn		
Anode Alloy	Hi-Purity		
Anode Model No.	TZ70 & TZ100		
Anode Weight/Foot	17.5	Pounds	
Anode Faradaic Consumption Rate	23.5	Lbs./Amp-Yr.	
Anode Efficiency (Percent used to provide CP Current)	90.0%	% Eff.	
Utilization Factor	85.0%	UF	
Anode Potential (vs. Cu-CuSO4)	1.10	Volts	
Desired Cathode Potential (mV vs. Cu-CuSO4)	0.85	Volts	
Net Anode-to-Structure Driving Potential	0.25	Volts	
Anode Square Dimensions	2.50		
Anode Effective Circular Diameter	2.821	Inches	
Length of 2.5 x 2.5 in. High-Purity Zinc Bar Anode (in.)	**Bare Anode Resistance (Ohms)**	**Total Current Output (mA)**	**Zinc Anode Life (Years)**
12	13.1670	19	29.98
24	8.3892	30	37.98
36	6.2969	40	42.73
48	5.0974	49	46.50
60	4.3104	58	49.11
72	3.7503	67	51.02
84	3.3293	75	53.17
96	3.0001	83	54.91
108	2.7349	91	56.34
120	2.5163	99	57.54
132	2.3327	107	58.57
144	2.1761	115	59.44
156	2.0408	123	60.21
168	1.9226	130	61.35
180	1.8184	137	62.37
192	1.7258	145	62.86
204	1.6428	152	63.71
216	1.5681	159	64.49
228	1.5004	167	64.81
240	1.4387	174	65.48

o. Data from Tables D.4, D.5, and D.6 were used as inputs for Table D.7, which lists the standard size zinc rod anodes cast by several manufacturers.

Table D.7
Current Output for Available Sizes of High-Purity Zinc Rod Anodes Suitable for CW Structures

Anode	Lb	W & H	La	Lc	Current Output (mA) in 1000 ohm-cm Water
TZ-27	27	1.4"	48"	60"	34
TZ-50	50	2"	48"	60"	46
TZ-60	60	2"	60"	72"	55
TZ-70	70	2 1/2"	48"	60"	49
TZ-100	100	2 1/2"	60"	72"	58

D.2 Design and Input Data for Lock Gate Using High-Potential Magnesium Rod Anodes. The support means for magnesium rod anodes are inherently more fragile than for slabs and buttons. Generally, they are used only in sheltered areas where waterborne debris will not impact against the anode.

a. This design example uses the same structure used in Appendices C and E (see Figure C.1), and the coating and environment conditions are the same as those used in Appendix C.

b. Therefore, the design input data will not be replicated here because they are identical to those given in Appendix C, Section C.2. In the current case, however, the use of the rod anodes will only be applied to the chamber side of the gate.

D.3 Computations and Current Requirements for Each Structure Component. These data are the same as those used in Appendix C, Section C.3. For this example, we need only the first three rows of the existing current requirements table (see Table C.2) because this design is for the downstream side only. Therefore, the requirements are as shown in Table D.8.

Table D.8
Current Requirements for Each Downstream Structure Component

Chamber or Surface ID	Side of Gate	Type of Area	Area Each m^2	Current Density I' (mA/m^2)	$1 - C_E$	Min. No. Anodes*	Current Required per Unit (mA)	Current Required for All Units (mA)
A & H	Downstream	Chamber	2.78	75.35	.15	1	31.4	314.2
B & G	Downstream	Chamber	4.34	75.35	.15	1	49.1	490.5
C, D, E, & F	Downstream	Chamber	18.9	75.35	.15	2	213.6	2136.0

D.4 Anode Design Based on Using Magnesium Rod Anodes.

a. Select Anode Alloy. The only available option is high-potential magnesium alloy.

b. Select Anode Size Based on Current Requirement for Each Size Chamber.

(1) Chambers A and H. Current required = 31.4 mA.

(a) Initial Anode Selection. Refer to Tables D.1, D.2, and D.3. We note that the water resistivity of 1900 ohm-cm will reduce the anode current output for a given anode length based on the following formula.

$$Current\ Output = \frac{Current\ Output\ (in - 1000\ ohm - cm)}{Environment - resistivity\ (ohm - cm)} \times 1000$$

(b) The rod anodes are designed for vertical suspension. The overall gate height is 18.85 m (35 ft) divided into 6 uniform height chambers with an internal height of approximately 1.8 m (5.83 ft). Thus, the maximum anode length in each chamber is approximately 1.5 m (5ft). We calculate that a 30 cm (12 in.) anode 5 cm (2 in.) in diameter will put out 31.5 milliamperes DC (60x1000/1900 = 31.5) while the same length anode 6.4 cm (2.5 in.) in diameter will put out 34.2 ma (65x1000/1900 = 34.2). Either size would meet the current required to protect this size chamber.

(c) Anode Selection Based on Life. We want the anode to last 20 years. Using Tables D.2 and E.3 (magnesium anode life column), we see that neither anode will provide the desired life. The maximum life available can be calculated by the following formula.

$$Current\ Output = \frac{Anode\ Life\ (in - 1000\ ohm - cm)}{1000} \times Environment - resistivity\ (ohm - cm)$$

(d) Per the above, the maximum life would be provided by the 6.4 cm (2.5 in.) diameter by 30 cm (12 in.) long rod which would have a life of 5.7 years. Based on this, a decision will either have to be made to use a different style or alloy anode. Alternatively, a plan for replacing the anodes in the chamber every 6 years could be developed. Since replacing the anodes is fairly easy to do on the downstream side, this may be a practical solution.

(2) Chambers B and G. Current required = 49.1 mA.

(a) Initial Anode Selection. Refer to Tables D.1, D.2, and D.3. We note that the water resistivity of 1900 ohm-cm will reduce the anode current output for a given anode length based on the following formula.

$$Current\ Output = \frac{Current\ Output\ (in - 1000\ ohm - cm)}{Environment - resistivity\ (ohm - cm)} \times 1000$$

(b) The rod anodes are designed for vertical suspension. The overall gate height is 18.85 m (35 ft) divided into six uniform-height chambers with an internal height of approximately 1.8 (5.83 ft). Thus, the maximum anode length in each chamber will be approximately 2.8m (5 ft). We calculate that a 64 cm (24 in.) anode 5 cm (2 in.) in diameter will put out 51 milliamperes DC (97x1000/1900 = 51) while the same length anode 6.4 cm (2.5 in.) in diameter will put out 54 ma (65x1000/1900 = 54). Either size would meet the current required to protect this size chamber.

(c) Anode Selection Based on Life. We want the anode to last 20 years. Using Tables D.2 and D.3 we see that neither anode will provide the desired life. The maximum life available can be calculated by the following formula.

$$Current\ Output = \frac{Anode\ Life\ (in - 1000\ ohm - cm)}{1000} \times Environment - resistivity\ (ohm - cm)$$

(d) Per the above, the maximum life would be provided by the 6.4 cm (2.5 in.) diameter by 61 cm (24 in.) long rod which would have a life of 7.2 years. Based on this, a decision will have to be made to either use a different style anode or plan on replacing the anodes in the chamber every 7 years. Since this is fairly easy to do on the downstream side, this may be a practical solution.

(3) Chambers C, D, E, and F. Current required = 213.6 mA.

(a) Initial Anode Selection. Refer to Tables D.1, D.2, and D.3. We note that the water resistivity of 1900 ohm-cm will reduce the anode current output for a given anode length based on the following formula.

$$Current\ Output = \frac{Current\ Output\ (in - 1000\ ohm - cm)}{Environment - resistivity\ (ohm - cm)} \times 1000$$

(b) The rod anodes are designed for vertical suspension. The overall gate height is 18.85 m (35 ft) divided into 6 uniform height chambers with an internal height of approximately 1.8 m (5.83 ft). Thus, the maximum anode length in each chamber will be approximately 150cm (5ft).

(c) A quick check of Tables D.2 and D.3 reveals that a single anode of either diameter will not put out sufficient current. We calculate that a 150 cm (60 in.) anode 5 cm (2 in.) in diameter will put out 101 milliamperes DC (193x1000/1900 = 101) while the same length anode 6.4 cm (2.5 in.) in diameter will put out 107 ma (203x1000/1900 = 107). Based on the current requirement of 213.6 ma, we would need either three of the 5 cm diameter anodes per large chamber or two of the 6.4 cm diameter rods.

(d) Anode Selection Based on Life. We want the anode to last 20 years. Using Tables D.2 and D.3 we see that neither anode will provide the desired life. The maximum life available can be calculated by the following formula.

$$Current\ Output = \frac{Anode\ Life\ (in - 1000\ ohm - cm)}{1000} \times Environment - resistivity\ (ohm - cm)$$

(e) Since we will only need 2 of the larger diameter rods, we will check its life. Per the above, the maximum life would be provided by the 6.4 cm (2.5 in.) diameter by 152 cm (60 in.) long rod which would have a life of 9.3 years. Based on this, a decision will have to be made to either use a different style anode or plan on replace the 6.4 cm diameter anodes in each chamber every 9 years. Since this is fairly easy to do on the downstream side, this may be a practical solution.

(f) Develop Anode Locations for Each Structure Element. Locating anodes is simply a geometric process of distributing the anodes uniformly on each structure element to achieve good current distribution.

(4) Chambers A, B, G, H, I, J, L, and M. In this example, locating of the anodes in the chamber with one anode only is simple in that the anode will be located in the center horizontally and at a distance 1/3 of the chamber depth from the back surface of each chamber. The top of the anode threaded rod will be fastened so that the anode magnesium body will be approximately 10 cm (4 in.) down from the chamber top plate to enhance current distribution.

(5) Chambers C, D, E, and F. Where more than one anode is required in each chamber, the anodes again will again all be placed at a distance 1/3 of the chamber depth from the back surface of each chamber.

(6) In addition, the top of the anode threaded rod will be fastened so that the anode magnesium body will be approximately 10 cm (4 in.) down from the chamber top plate and at least 10 cm (4 in.) up from the chamber bottom plate (this latter distance will be a function of the anode body length but should be no less than 10 cm) to enhance current distribution. The locations for the anodes in the large chambers is shown in Figure D.6.

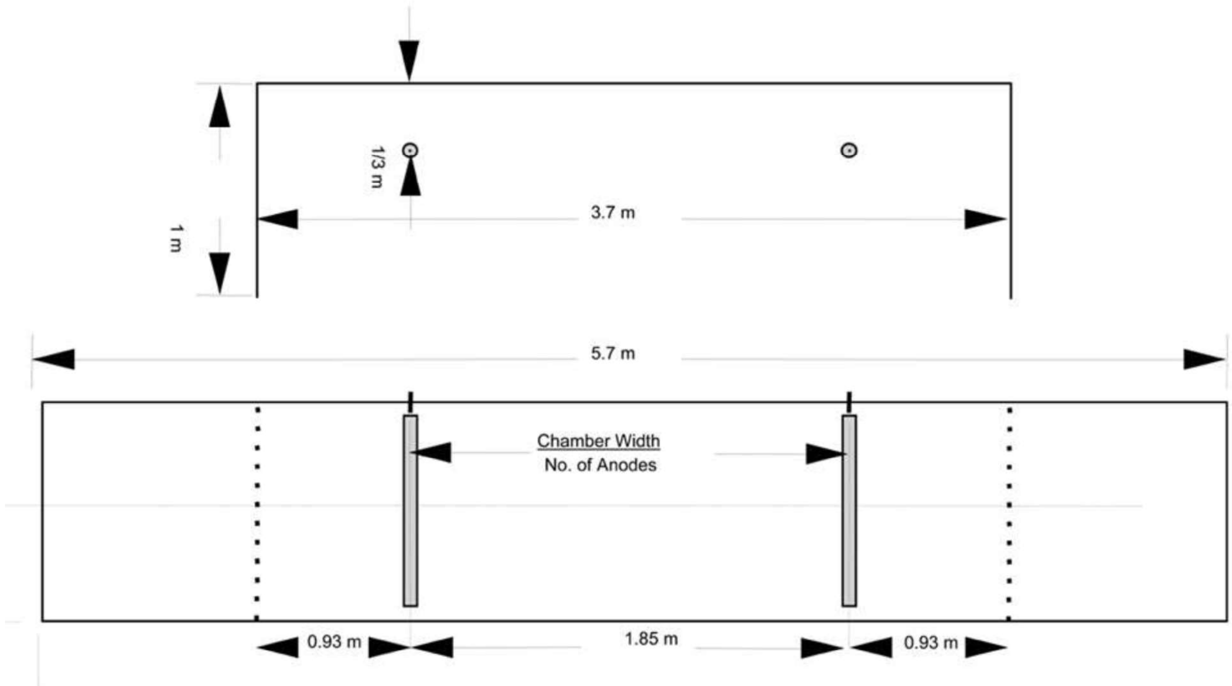


Figure D.6. Rod Galvanic Anode Locations in Largest Downstream Chambers

(7) Multiple anodes must be evenly distributed from the side panels of the chamber to achieve more uniform current distribution. In order to ensure good current flow also to the chamber end plates, the anode spacing is modified so that the center-to-center spacing between the anodes is equal to the chamber width divided by the number of anodes per chamber.

(8) In this design example, with two anodes per large chamber, the chamber width of 3.7 m is divided by 2 so that the center-to-center spacing between the two anodes would be 1.85 m and the distance between the anodes and their adjacent chamber walls is half this distance or 0.93 m.

(9) Note if three anodes were required in this same size chamber, the center-to-center spacing would be 1.23 m (3.7/3 = 1.23) and the outermost anodes to adjacent chamber walls would be half this spacing or 0.62 m (1.23/2 = 0.62).

D.5 <u>Design Adaptation for Using High-Purity Zinc Bar Anodes</u>. The support method for the high-purity zinc bar anodes is considerably sturdier than that used in magnesium rod anodes. However, like magnesium rods, the zinc bar anodes must be offset from the gate structure by at least 12.7 cm (5 in.) to achieve effective current distribution. They also are typically used in sheltered areas where waterborne debris will not impact them. Q20

a. This zinc bar example shares the same structure, coating, environment, and other assumptions used in the high-potential magnesium rod anode design, so the first three design step are identical to those described in Sections D.2 and D.3 above. As in the magnesium rod example, this design example only addresses the downstream side of the gate. It begins at design Step 4, in which the logic for anode selection is presented.

b. Based on using the same data, we can go to Step 3 in the previous example where we created a current requirement chart for each chamber (in this design, only for the downstream chambers). We will use the same steps thereafter for the downstream side only.

c. Select Anode Alloy. The cast zinc bar anodes are available only as high-purity zinc alloy with a cross-section of either 3.6 cm (1.4 in.), 5.0 cm (2.0 in.) and 6.4 cm (2.5 in.). Their active zinc anode length is either 121 cm (48 in.) or 152 cm (60 in.) with a solid steel core having a diameter of 1.3 cm (0.5 in.). This core extends 15 cm (6 in.) from each end of the bar.

d. Select Anode Size Based on Current Requirement for Each Size Chamber.

(1) Chambers A and H. Current required = 31.4 mA.

(a) Initial Anode Selection. Refer to Tables D.4 through D.7. We note that the water resistivity of 1900 ohm-cm will reduce the anode current output for a given anode length based on the following formula.

$$Current\ Output = \frac{Current\ Output\ (in - 1000\ ohm - cm)}{Environment - resistivity\ (ohm - cm)} \times 1000$$

(b) The zinc bar anodes are designed for either vertical or horizontal suspension. Since these small chambers are less than 1 meter in width, the anodes will have to be installed vertically. The overall gate height is 18.85 m (35 ft) divided into six uniform-height chambers with an internal height of approximately 1.8 m (5.83 ft).

(c) Thus, the maximum anode length in each chamber is approximately 1.5 m (5 ft). We calculate that even the highest-output anode with zinc bar dimensions of 6.4 cm (2.5 in) square by 152 cm (60 in.) long will only put out about 30.5 milliamperes DC (58x1000/1900 = 30.5). Since this does not quite meet our minimum current requirement, we will need to use to smaller anodes.

(d) We then calculate that the smallest available zinc bar anode with zinc bar dimensions of 3.6 cm (1.4 in.) square by 91 cm (36 in.) long will put out about 17.9 milliamperes DC (34x1000/1900 = 17.9). Thus, two mounted vertically and spaced laterally as far apart as possible will generate the desired current.

(e) Anode Selection Based on Life. We want the anode to last 20 years. Using Table D.4 we see that this anode will have a life of 19.4 years in 1000 ohm-cm resistivity water. The maximum life available can be calculated by the following formula.

$$Current\ Output = \frac{Anode\ Life\ (in - 1000\ ohm - cm)}{1000} \times Environment - resistivity\ (ohm - cm)$$

(f) Per the above, the maximum life provided by the 3.6 cm (1.4 in.) square by 91 cm (36 in.) long zinc bar would be approximately 37 years. Based on this, a decision will have to be made to either use a different alloy, different style anode, or accept a design with an unusually long life. Because this service life is not unrealistically long, the anode will be used for the design in this example.

(2) Chambers B and G. Current required = 49.1 mA.

(a) Initial Anode Selection. Refer to Tables D.4 through D.6. We note that the water resistivity of 1900 ohm-cm will reduce the anode current output for a given anode length based on the following formula.

$$Current\ Output = \frac{Current\ Output\ (in - 1000\ ohm - cm)}{Environment - resistivity\ (ohm - cm)} \times 1000$$

(b) The zinc bar anodes are designed for either vertical or horizontal suspension. Again, since these relatively small chambers are less than 1.2 meter in width, the anodes, the shortest of which is slightly more than 1.2 meters, will have to be installed vertically. The overall gate height is 18.85m (35 ft) divided into six uniform height chambers with an internal height of approximately 1.8 m (5.83 ft).

(c) Thus, the maximum anode length in each chamber is approximately 1.5 m (5 ft). We calculate that even the highest-output anode with zinc bar dimensions of 6.4 cm (2.5 in.) square by 152 cm (60 in.) long will only put out about 30.5 milliamperes DC (58x1000/1900 = 30.5). Since this does not nearly meet our minimum current requirement for chambers B and G, we will need to use two anodes.

(d) We then calculate that the smallest available zinc bar anode with zinc bar dimensions of 3.6 cm (1.4 in.) square by 91 cm (36 in.) long will put out about 17.9 milliamperes DC (34x1000/1900 = 17.9). Thus, even two mounted vertically and spaced laterally as far apart as possible will not generate the desired current.

(e) We then re-calculate based on the next largest available zinc bar anode with zinc bar dimensions of 5.0 cm (2 in.) square by 122 cm (48 in.) long will put out about 24.2 milliamperes DC (46x1000/1900 = 24.2). Thus, even two of these next size anodes will not generate the desired current (48.4 ma vs. a minimum requirement of 49.1 ma).

(f) By selecting the next size up zinc bar anode with dimensions of 5.0 cm (2 in.) square by 152 cm (60 in.) long will put out about 28.2 milliamperes DC (46x1000/1900 = 28.9). Thus, two 5.0 cm (2 in.) square by 152 cm (60 in.) long zinc bar anodes mounted vertically and spaced laterally as far apart as possible will generate the desired current.

(g) Anode Selection Based on Life. We want the anode to last 20 years. Using Table D.5 we see that this anode will have a life of 37 years in 1000 ohm-cm resistivity water. The maximum life available can be calculated by the following formula.

$$Current\ Output = \frac{Anode\ Life\ (in - 1000\ ohm - cm)}{1000} \times Environment - resistivity\ (ohm - cm)$$

(h) Per the above, the maximum life provided by the 5.0 cm (2.0 in.) square by 152 cm (60 in) long zinc bar would be approximately 70.3 years. Based on this, a decision will have to be made to either use a different alloy, different style anode, or accept a design with an unusually long life. Because this service life is not so unrealistically long, the anode will be used for the design in this example.

(3) Chambers C, D, E, and F. Current required = 213.6 mA.

(a) Initial Anode Selection. Refer to Tables D.4 through E.6. We note that the water resistivity of 1900 ohm-cm will reduce the anode current output for a given anode length based on the following formula.

$$Current\ Output = \frac{Current\ Output\ (in - 1000\ ohm - cm)}{Environment - resistivity\ (ohm - cm)} \times 1000$$

(b) The zinc bar anodes are designed for either vertical or horizontal suspension. Since these are much larger chambers with a width of 3.7 meters (12.1 ft) and a height of 1.8 meters (5.83 ft), the anodes could either be installed horizontally or vertically. The overall gate height is 18.85m (35 ft) divided into six uniform-height chambers with an internal height of approximately 1.8 m (5.83 ft).

(c) For vertical placement, the maximum anode length in each chamber is approximately 1.5 m (5 ft). For horizontal placement, not only is there no limit in anode length based on those commercially available, but up to three of the 91 cm (36 in.) anodes could be placed end-to-end inside each chamber.

(d) We then calculate that the smallest available zinc bar anode with dimensions of 3.6 cm (1.4 in.) square by 91 cm (36 in.) long will put out about 17.9 milliamperes DC (34x1000/1900 = 17.9). The total number of this size anode required per chamber can be calculated by dividing the total current per chamber of 213.6 ma by the current per anode of 17.9 which equals 11.9 anodes.

(e) Thus, our design will utilize 12 anodes mounted horizontally in four rows of three each mounted end-to-end with one row mounted on the chamber bottom, two rows on the chamber back wall, and the final row on the underside of the chamber top.

(f) Anode Selection Based on Life. We want the anode to last 20 years. Using Table D.4 we see that this anode will have a life of 19.4 years in 1000 ohm-cm resistivity water. The maximum life available can be calculated by the following formula.

$$Current\ Output = \frac{Anode\ Life\ (in - 1000\ ohm - cm)}{1000} \times Environment - resistivity\ (ohm - cm)$$

(g) Per the above, the maximum life provided by the 3.6 cm (1.4 in.) square by 91 cm (36 in.) long zinc bar would be approximately 37 years. Based on this, a decision will have to be made to either use a different alloy, different style anode, or accept a design with an unusually long life. Because this life is not so long as to be totally unrealistic, the anode will be used for the design in this example.

e. Develop Anode Locations for Each Structure Element. Locating anodes is simply a geometric process of distributing the anodes uniformly on each structure element to achieve good current distribution.

(1) Chambers A and H. Where more than one anode is required in each chamber, the anodes will be mounted to the back surface of each chamber held off the surface approximately 15 cm (6 in.) by mounting brackets. Multiple anodes must be evenly distributed from the side panels of the chamber to achieve more uniform current distribution.

(a) To ensure good current flow to the chamber end plates, the anode spacing is modified so that the center-to-center spacing is equal to the chamber width divided by the number of anodes per chamber. In this design example, with two anodes per small chamber, the chamber width of 1 m is divided by 2 so that the center-to-center spacing between the two anodes would be 0.5 m and the distance between the anodes and their adjacent chamber walls is half this distance, or 0.25 m.

(b) Note that if three anodes were required in this same size chamber, the center-to-center spacing would be 0.33 m (1/3 = 0.33) and the outermost anodes to adjacent chamber walls would be half this spacing, or 0.17 m (0.33/2 = 0.17). Note that this spacing from the end walls should never be less than 0.15 m (6 in.) to ensure that current distribution will relatively uniform.

(2) Chambers B and G. Where more than one anode is required in each chamber, the anodes will be mounted to the back surface of each chamber held off the surface approximately 15 cm (6 in.) by mounting brackets.

(a) Multiple anodes must be evenly distributed from the side panels of the chamber to achieve more uniform current distribution. In order to also ensure good current flow to the chamber end plates, the anode spacing is modified so that the center-to-center spacing is equal to the chamber width divided by the number of anodes per chamber.

(b) In this design example, with two anodes per small chamber, the chamber width of 1.1 m is divided by 2 so that the center-to-center spacing would be 0.55 m and the distance between the anodes and their adjacent chamber walls is half that distance, or 0.23 m. Note if three anodes were required in this same size chamber, the center-to-center spacing would be 0.37 m (1.1/3 = 0.37) and the outermost anodes to adjacent chamber walls would be half that spacing, or 0.19 m (0.37/2 = 0.19). Note that this spacing from the end walls should never be less than 0.15 m (6 in.) to ensure that current distribution will relatively uniform.

(3) Chambers C, D, E, and F. In this design, zinc bar anodes are to be mounted horizontally in two parallel rows of three anodes each installed end-to-end. Each chamber is approximately 1 m (3.3 ft) deep by 1.8 m (5.8 ft) by 3.7 m (12.2 ft).

(a) Since each anode is 1.2 m (4 ft) long, the anodes will barely fit end-to-end in a horizontal row. To fit the three anodes into this chamber, a mounting hole will be drilled into each chamber end plate to receive one end of the nearest anode.

(b) The other threaded end of the anode will be held in place by a mounting plate placed 1.21 m from each end plate. The mounting plate must have a slot into which this 2nd end of the anode support rod can be fitted to be held in place by a nut and bolt.

(c) The center anode in each chamber will also have to mount into these same chamber support plates either by mounting them into the same support slots or by cutting an additional slot immediately adjacent to the support slot for the end anode rods. The two rows of anodes would be spaced equally away from the top and bottom of each chamber.

(d) In this design example, with two horizontal rows of anodes per large chamber, the chamber height of 1.8 m is divided by 2 so that the center-to-center spacing between the two rows of anodes would be 0.9 m and the distance between the anodes and their adjacent chamber top and bottom walls is half that distance, or 0.45 m.

(e) If three anodes were required in this same size chamber, the center-to-center spacing would be 0.6 m (1.8/3 = 0.6) and the outermost anodes to adjacent chamber walls would be half that spacing, or 0.3 m (0.6/2 = 0.3).

(f) Note that this spacing from the end walls should never be less than 0.15 m (6 in.) to ensure that current distribution will relatively uniform. The locations for the anodes in the large chambers is shown in Figure D.7. As is the case with all galvanic anode designs on CW structures, the intent is to deploy the anodes in a way that distributes their protective current uniformly for each similar current density surface area.

(g) For a structure where significantly different densities were required for protection, however, more anodes would be concentrated in the high-current density areas with fewer distributed uniformly in the lower current density areas (proportionate to the relative current densities required).

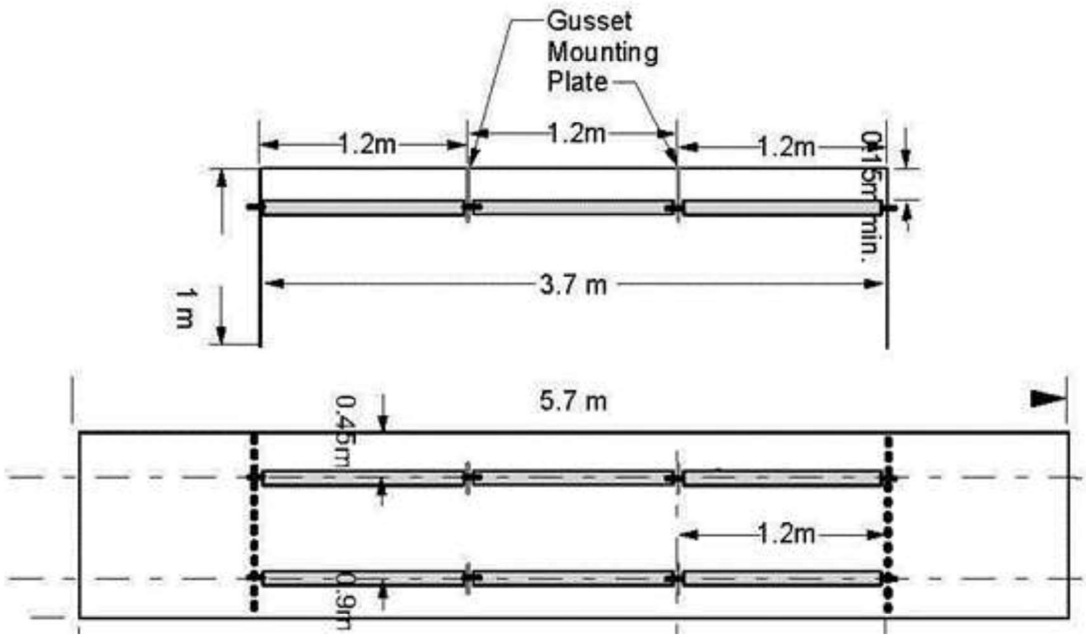


Figure D.7. Zinc Bar Galvanic Anode Locations in Largest Downstream Gate Chambers