CECW-CE

DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
Washington, DC 20314-1000

EM 1110-2-2704

Manual
No. 1110-2-2704

12 July 2004

Engineering and Design
CATHODIC PROTECTION SYSTEMS FOR CIVIL WORKS STRUCTURES

1. Purpose. This manual provides guidance for the selection, design, installation, operation, and maintenance of cathodic protection systems (CPSs) for navigation lock gates and other civil works hydraulic structures.

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

3. Discussion. The primary corrosion control method for civil works hydraulic structures is a protective coating system, most often paint. Where the paint system and structure are submerged in water, a combination of the anodic and cathodic properties of materials, the liquid electrolyte, and external electrical circuits combine to form electrochemical corrosion cells, and corrosion naturally follows. CPSs can supplement the paint coating system to mitigate corrosion damage.

4. Distribution. Approved for public release; distribution is unlimited.

FOR THE COMMANDER:

John R. McMahon

6 Appendixes
(See Table of Contents)

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Colonel, Corps of Engineers
Chief of Staff

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CHAPTER 1

INTRODUCTION

1-1. Purpose and Scope. This manual provides guidance for the selection, design, installation, operation, and maintenance of cathodic protection systems (CPSs) used to supplement paint systems for corrosion control on civil works hydraulic structures. It also discusses possible solutions to some of the problems with CPSs that may be encountered at existing projects.

1-2. Applicability. This manual applies to all USACE Commands having civil works responsibilities.

1-3. References.

a. MIL-HDBK-1004/10, Electrical Engineering Cathodic Protection.

b. EM 1110-2-3400, Painting: New Construction and Maintenance.

c. ETL 1110-9-10, Cathodic Protection Systems Using Ceramic Anodes.

d. UFGS-09965A, Painting; Hydraulic Structures and Appurtenant Works.

e. UFGS-13113A, Cathodic Protection Systems (Impressed Current) for Lock Miter Gates.

f. TN ZMR-3-05, Components of Hydropower Projects Sensitive to Zebra Mussel Infestations.

g. NACE International Recommended Practice RP0169-2002, Control of External Corrosion on Underground or Submerged Metallic Piping Systems.

h. PROSPECT course handbook 009, 2003-01 et seq., Corrosion Control.

i. ERDC/CERL TR-01-73, Low-Maintenance Remotely Monitored Cathodic Protection Systems Requirements, Evaluation, and Implementation Guidance (Vicki L. Van Blaricum, William R. Norris, James B. Bushman, and Michael J. Szeliga), November 2001.

j. Calculations of Resistances to Ground (H. B. Dwight), Journ. AIEE Trans., vol 55, 1939, pp 1319 – 1328.

1-4. Background.

a. General. USACE uses CPSs in combination with protective coatings to mitigate corrosion of hydraulic structures immersed in fresh, brackish, or salt water. Protective coatings alone generally cannot offer complete corrosion protection because they usually contain some pinholes, scratches, and connected porosity, and over time these imperfections become increasingly permeable. As coatings degrade with time, these imperfections, commonly known as holidays, have a profound effect on overall coating integrity because of underfilm corrosion. CPSs, when used in conjunction with protective coatings, have been effective in controlling corrosion. CPSs consist of anodes that pass a protective current to the structure through the electrolyte environment. CPSs can be one of two types, sacrificial anode or impressed current anode. Hybrid CPSs installed on structures can include both types of anodes to provide protective current.

(1) Sacrificial CPSs. Sacrificial CPSs, also referred to frequently as galvanic CPSs, employ sacrificial 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 enables sacrificial anodes to function without an external power source, so they generally need very little maintenance after installation. However, by design, sacrificial anodes are consumed by corrosion during their service life and must be replaced periodically in order to ensure continuing protection of the structure. Therefore, these anodes should be installed in accessible locations on the structure. Sacrificial anode CPSs 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. (Note that in this EM the terms “sacrificial” and “galvanic” may be used interchangeably.)

(2) Impressed current CPSs. 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. All impressed current CPSs require periodic maintenance because they employ a power supply and are more complex than sacrificial systems. However, impressed current CPSs 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.

b. Locations. Since 1950, USACE has used impressed current CPSs with graphite or high-silicon, chromium-bearing cast iron (HSCBCI) anodes. The first systems were installed on the Mississippi River near Rock Island, IL, on an experimental basis. Since then, CPSs have been used widely. About 22 CPSs were installed and are currently functioning on structures on the Tennessee-Tombigbee Waterway, the Alabama River, and the Black Warrior River in the Mobile District. CPSs have been used successfully on the Intercoastal Waterway on seven sector gates in the Jacksonville District and on miter gates in the New Orleans District. Impressed current systems have also been installed on three lock gates on the Columbia River in the Northwest.

Similarly, impressed current systems using both graphite and HSCBCI anodes were installed on lock gates on the Ohio River during the 1970s. However, ice and debris damage has made most of these systems inoperable. Since the early 1980s, a new type of ceramic-coated composite anode material has been used for various electrochemical processes, particularly in the electrolytic production of chlorine and cathodic protection systems, including off-shore, water tank, and groundbed applications. The mixed metal oxide ceramic-coated anodes consist of a conductive coating of iridium or ruthenium oxide (IrO2 and RuO2, respectively) applied by thermal decomposition onto specially prepared titanium substrates. The coatings are applied by spraying aqueous metallic salts onto the titanium substrates and heating to several hundred degrees Celsius. Multiple layers of coating material may be applied by the process to provide a maximum coating thickness of approximately 0.025 mm (1 mil). This type of impressed current CPS anode has been used at Pike Island and other locations with good results.

c. Inoperable impressed current systems. Most of the known inoperable impressed current systems utilized graphite anodes that were more than 20 years old. Only a few navigation structures have had systems that used ‘sausage string’ cast iron anodes provided with impact protection. Properly maintained and protected cast iron anode systems used in high-impact debris areas have provided good results. Graphite systems in low-impact debris areas have also shown good results.

d. Inoperable sacrificial anode systems. Zinc or magnesium sacrificial anodes provide some benefits, but they typically protect only smaller areas of bare metal and, consistent with their inherent material properties, they are consumed at higher rates than impressed current anodes. In order to be beneficial, sacrificial anodes must continue to apply current to the structure by design. Voltage testing must be conducted periodically and consumed anodes must be replaced promptly to keep the system operating in accordance with applicable criteria.

e. Solutions.

(1) Restoration of systems. Most existing inoperable CPSs at navigation structures can be restored. This approach is less expensive than installing complete new systems, and therefore should be considered first. When graphite anode strings are consumed or destroyed, they can be replaced with impact-protected cast iron sausage strings or ceramic-coated wire anodes. In many cases, anode strings can be replaced and systems can be repaired without dewatering a lock.

(2) New or replacement systems. Designers should use UFGS-13113A with this manual for new CPS installation or for complete system replacement when necessary.

f. Effective techniques. National Association of Corrosion Engineers (NACE) Recommended Practice RP0169-2002 specifies techniques for control of external corrosion on civil works hydraulic structures. It includes criteria for both coatings and cathodic protection, and should be used in conjunction with guidance in this manual and with painting design guidance in Engineer Manual EM 1110-2-3400. NACE RP0169-2002 should also be used as guidance unless noted otherwise, and designers should become familiar with it.

g. Resistivity policy. Cathodic protection should be provided on all submerged metallic structures. If, after performing a corrosion mitigation survey, an NACE-certified corrosion specialist or a professional engineer deems cathodic protection unnecessary due to a noncorrosive water, a statement to that effect should be prepared and sent to the district project manager as a part of the corrosion plan.

CHAPTER 2

CORROSION MITIGATION PLAN

2-1. Corrosion Protection Coordinator. Each district should designate a person who has experience and is familiar with cathodic protection techniques to serve as the district corrosion protection coordinator. Such a person may be a licensed professional engineer or a person certified as being qualified by NACE International as a cathodic protection specialist, corrosion specialist, or senior corrosion technologist. This individual will be responsible for ensuring that the CPSs are tested against the applicable corrosion protection criteria and for ensuring that reports on the results of these tests are prepared and maintained at the district for review and reference.

2-2. Plan.

a. Development. A corrosion mitigation plan should be developed by the district corrosion protection coordinator for each hydraulic structure.

(1) New projects. A corrosion mitigation plan should be developed and included in the design memorandum. For a previously completed design memorandum, the plan should be developed and submitted as a supplement to the design memorandum prior to completion of plans and specifications.

(2) Existing projects. A corrosion mitigation plan should be developed and presented as an appendix in a Periodic Inspection Report for reference in subsequent inspections. Corrosion mitigation plans should consider the condition of existing structures, factors that affect the rate of corrosion, methods of corrosion control, and cathodic protection of the structure.

b. Execution. The following policy on optimization, testing, and reporting of the CPS for each structure should be followed.

(1) A survey of the structure-to-electrolyte potential, using a standardized reference cell, should be performed. Any system failing to operate in accordance with established criteria should be optimized by adjustment.

(2) A report showing the condition of the CPSs and including any plans to repair the systems should be prepared and kept at the district for review.

(3) Any inoperable CPS should be repaired as needed.

2-3. Tests and Adjustments.

a. Tests, adjustments, and data collection. Tests should be performed in accordance with the corrosion mitigation plan. Rectifier voltages and currents should be recorded. There are no prescribed time intervals for testing new systems, but measurements should be taken and recorded monthly after initial energization or subsequent re-energization until steady-state conditions are reached. Then, based upon the judgment of the corrosion protection coordinator, tests should be performed at about 6-month intervals for a year or more, and thereafter at yearly intervals. It would be appropriate to monitor critical or strategic structures more frequently. Based upon the measurements taken, the rectifier current and voltage should be adjusted to produce either a negative polarized (cathodic) potential of at least 850 mV with the cathodic protection applied or other minimum cathodic polarization such as 100-mV polarization as described in NACE RP0169-2002 for steel and cast iron piping. This potential should be achieved over 90 percent of each face of each gate leaf. Readings should not exceed a polarized (cathodic) potential of 1200 mV at any location. Acceptance criteria for CPSs should be as defined in NACE RP0169-2002 unless otherwise noted in this manual.

b. Reports. Reports should be prepared and kept at the district. These reports should be prepared in a format similar to that shown in the miter gate sample and table in Appendix A, which presents measurements taken and data obtained. For other types of installations, the report should be modified to show similar data applicable to the respective installation. This report should be completed annually, not later than December.

c. Data. The data accumulated in these reports should be retained to provide a database for consideration of possible improvements to CPS techniques. Reports on the current corrosion deterioration status of the structures should be maintained.

CHAPTER 3

EXPERT ASSISTANCE

3-1. Background. Some USACE districts and laboratories have long been involved in planning, designing, procuring, installing, testing, operating, and maintaining various types of CPSs for navigation structures. Expertise is available to assist USACE elements in any of the above areas on a cost reimbursable basis. For further information about USACE expert assistance in the abovementioned areas, please contact the Corrosion Control and Cathodic Protection Systems Directory of Expertise (DX) at Mobile District or CECW-E at HQUSACE.

3-2. Expertise Required. District personnel who have limited experience and expertise in CPSs are encouraged to seek assistance from the Corrosion Control and Cathodic Protection Systems Directory of Expertise (DX) and/or laboratories through their Corrosion Protection Coordinator. The approval of a NACE-certified corrosion engineer is required for all new or replacement CPS designs.

3-3. Types of Assistance Available. The specific areas of assistance include initial planning, preparation and/or review of design and solicitation packages, review of design submittals, review of shop drawings or contract changes, training, and preparation of corrosion mitigation test plans. Assistance is also available, in troubleshooting, restoring, testing, and adjusting and optimizing CPSs.

3-4. Element Responsibility. USACE elements will be responsible for ensuring that all solicitations comply with current procurement policy, including consideration of the offeror′s experience and qualifications. Although the procurement method selected for any given project is at the discretion of the responsible element, the intent of this manual is to provide guidance so that all contractors in cathodic protection have qualifications which, as a minimum, meet the requirements in Chapter 6.

CHAPTER 4

TESTING AND OPTIMIZING

4-1. Equipment and Personnel. Test equipment should 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 polarized potentials with the CPS on. Sensitivity should be more than 5 meg-ohms per volt. The reference electrode should be placed in the electrolyte adjacent to and within 200 mm to the face of the gate at each test point. All tests should be supervised by an NACE-certified corrosion specialist, senior corrosion technologist, or cathodic protection specialist, a licensed corrosion engineer, or a Corps of Engineers representative assigned and qualified to do this work.

4-2. Optimizing System. Data collected during the test should be reviewed, and any necessary adjustments should be made. The system should be properly optimized by adjusting the rectifier until 90 percent of the potentials fall within the range of polarized (cathodic) potential of between negative 850 mV and negative 1200 mV, or 100-mV polarization according to NACE RP0169-2002. A report on test results should be prepared and retained at the district. Research and development work on low-cost remote monitoring systems has been performed recently to increase reliability, extend service life, minimize maintenance requirements, and automate CPS testing, evaluation, and diagnostic procedures in order to reduce CPS life-cycle costs (Van Blaricum et al. 2001). For further information about CPS remote monitoring systems, contact the Corrosion Control and Cathodic Protection Systems DX at Mobile District or CECW-E at HQUSACE.

CHAPTER 5

SYSTEM SELECTION

5-1. Corrosion Protection. Corrosion occurs on all metallic structures that are not adequately protected. The cost of replacing a structure which may have been destroyed or weakened due to excessive corrosion is substantial but avoidable, and means should be taken to consistently prevent or mitigate this added cost through cathodic protection. 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 cathodic protection system can prevent surface corrosion of the structure, or drastically reduce the rate at which it occurs.

5-2. Types of CPSs.

a. Sacrificial CPS. This type of system helps reduce surface corrosion of a metallic structure immersed in an electrolyte by coupling a less noble metal with the structure. Sacrificial CPSs 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. Sacrificial anodes for fresh water applications typically are composed of zinc- or magnesium-based alloys. In the past, installation of sacrificial anodes has often been done on an ad hoc basis, relying largely on the installer's individual knowledge and experience. However, recent research on sacrificial anode materials has provided an improved engineering basis for designing civil works applications of these systems.

b. Impressed current CPS. This type of system uses direct current 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. A number of impressed current 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. The most common geometries are slab or button anodes, rods, and strings. Any anode mounted on the structure must be isolated with a dielectric shield to assure effective current distribution.

5-3. 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. Early in the selection process, if practical, it is useful to perform a current requirement test to help define the total amount of electrical current needed to protect the structure (see PROSPECT Corrosion Control course handbook [009, 2003-01 et seq]). 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. Where current requirements are lower and the structure's protective coatings are well maintained, sacrificial anode systems can be very effective. Improved modern coating systems and maintenance practices today allow for a wider use of sacrificial CPSs on large civil works structures than was the case in the past. For both types of systems, preliminary design estimations and comparisons of costs, current output, 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.

a. Basis for selecting 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.

b. Basis for not selecting an impressed current system.

(1) First costs for design, acquisition, and installation are high.

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

(3) Maintenance costs can be high.

(4) System can create stray currents that may potentially corrode other nearby ferrous structures.

(5) 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.

c. Basis for selecting a sacrificial 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) System works very well when electrolyte resistivity is low, surfaces are well coated, structure is easily accessible, and significant deterioration of the coating is not expected within 5 to 10 years.

(4) 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.

d. Basis for not selecting a sacrificial 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 due to debris, ice, or aquatic vessels.

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

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

CHAPTER 6

SYSTEM DESIGN, CONSTRUCTION, OPERATION, MAINTENANCE, AND RESTORATION

6-1. Design. For existing structures, a current requirement test should be made to accurately assess the overall system design. The designer should become familiar with the availability and suitability of types of commercially manufactured anodes which would satisfy the system requirements for cathodic protection. Chapter 5 provides guidance for selecting impressed current and sacrificial (i.e., galvanic) anode systems. The designer should become familiar with manufacturer recommendations for use and product performance claims. CPSs should be designed to attain and maintain a level of protection of the structure as defined in the section "Criteria and Other Considerations for Cathodic Protection" in NACE RP0169-2002. In order to achieve this level of protection, design calculations must be made to determine the number and types of anodes required. Examples of calculations can be found in Appendix B of this manual for impressed current cathodic protection design; in ETL 1110-9-10 for impressed current CPSs using ceramic anodes; and in MIL-HDBK-1004/10, "Electrical Engineering Cathodic Protection," which was developed from evaluations, surveys, and design practices of the Naval Facilities Engineering Command, other government agencies, and the private sector. Appendix C of this manual provides engineering formulae and reference tables for use in designing sacrificial CPSs for civil works applications, and Appendices D, E, and F present detailed examples of sacrificial anode CPS design for different types and sizes of structures using various anode geometries. MIL-HDBK-1004/10 can be a useful tool for design calculations in conjunction with the criteria that follow. These calculations must take into consideration the total 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 due to physical damage, the normal paint change of state over a 20-year period, and the environment to which the structure will be subjected. The design of CPSs should be accomplished under the supervision of a NACE-certified corrosion specialist, a cathodic protection specialist, or a professional engineer licensed in corrosion engineering.

a. Criteria. Design of civil works hydraulic structures shall conform to NACE RP0169-2002, paragraph 6.2.2 inclusive, "Steel and Cast Iron Piping." Those criteria are specifically included here by reference.

b. Guide specification. Unified Facilities Guide Specification UFGS-13113A, "Cathodic Protection Systems (Impressed Current) for Lock Miter Gates," should be used in preparing contract documents for procurement of CPSs. This specification, in addition to providing the technical requirements for various items of equipment for the CPS, addresses methods for protection from ice and various debris of the string anodes and the electrical leads to the button and string anodes. This specification is based upon the use of impressed current systems, which are normally used on hydraulic structures having large areas requiring corrosion protection.

Button anodes are normally used on the skin plate side of the gate, with rod or string anodes installed in the compartment areas of the gate; however, button anodes may also be used in the compartment areas if practical from an installation standpoint.

c. Zebra mussel guidance. 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 Technical Note ZMR-3-05, compiled by the Zebra Mussel Research Program at Waterways Experiment Station, Vicksburg, MS.

6-2. <u>Construction.</u> Installation of a CPS by a construction contractor should be accomplished under the supervision of an NACE-certified corrosion specialist, senior corrosion technologist, or cathodic protection specialist or a licensed corrosion engineer.

a. Services of corrosion engineer. The construction contractor should be required to obtain the services of a licensed corrosion engineer to supervise the installation and testing of the CPS. The term "corrosion engineer" refers to a person who has knowledge of the physical sciences and the principles of engineering and mathematics, acquired by professional education and related practical experience, and who is qualified to engage in the practice of corrosion control on metallic structures. Such person may be a licensed professional corrosion engineer or may be certified as being qualified by NACE International if such licensing or certification includes suitable cathodic protection experience.

b. Workmanship. All material and equipment shall be installed in accordance with the requirements of the specifications and as recommended by the corrosion engineer and approved by the Contracting Officer. The installation, including testing, should be performed by an organization that has had at least 3 years experience in this type of work.

6-3. <u>Operation and Maintenance.</u> The reliability and effectiveness of any CPS depend upon the manner in which it is operated and maintained, as well as its proper design and installation.

a. Performance testing prior to acceptance. The primary purpose for testing of a CPS is to determine if it has been optimized in accordance with and effectively meets design criteria (typically RP0169-2002). A system that does not meet these criteria will not adequately protect the structure against corrosion.

b. Operations and maintenance manual. An operations and maintenance manual should be provided for each CPS installed. This manual should provide instructions for testing and optimizing the system and should specify test equipment required. 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.

c. Troubleshooting guide. A troubleshooting guide should 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 a problem cannot be resolved by the corrosion protection coordinator, then it is recommended that the designer seek the assistance addressed in Chapter 3 of this manual.

6-4. Restoration. Existing inoperable CPSs should be restored whenever possible and feasible. Restoration of a CPS should be part of the corrosion mitigation plan and should include, but not be limited to, the following:

a. A list of materials and cost.

b. An assessment of impact protection and consideration of the need for additional impact protection devices.

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

d. A copy of the latest structure-to-reference-cell potential readings.

CHAPTER 7

TRAINING AND SERVICES

7-1. Training. Training should be provided for project designers, inspectors, and operation and maintenance personnel who are responsible for CPSs in use at projects. Corrosion protection coordinators should arrange with District Training Coordinators for this training. The training should include both cathodic protection in general terms and report preparation. A PROSPECT course on corrosion control is offered annually for district personnel. The course provides the required CPS training on design and testing.

7-2. Services. Services are available on a cost-reimbursable basis from the Corrosion Control and Cathodic Protection Systems DX at Mobile District, or the Engineer Research and Development Center – Construction Engineering Research Laboratory at Champaign, IL, to assist districts in matters related to corrosion control and cathodic protection. Services are also available for design, restoration, construction, operation and maintenance, and optimization adjustments of CPSs. Services inquiries may be referred to CECW-E at HQUSACE.

APPENDIX A

SAMPLE CORROSION MITIGATION PLAN

CESAM-EN-CE

TO: Chief, Engineering Division

SUBJECT: Corrosion Mitigation Plan for Lock B Miter Gates, Tenn-Tom Waterway

1. OBJECTIVE: The objective of the subject plan is to provide methods for corrosion mitigation of the submerged metallic structural components of the Lock B miter gates.

2. GENERAL: Lock B miter gates are located in a submerged corrosive environment in which the water resistivity varies, but generally ranges between 40,000-60,000 ohm-mm. Galvanic corrosion of the structural components of the lock miter gates can, and often does, result in deterioration of the structural integrity of the gates. This deterioration can affect the operation of the gates and often requires expensive repair and/or replacement of the gate or its structural components. Weakening of the structural components of the gates may also cause failure of seals, failure of gate alignment, or failure of quoin and miter blocks and a general deterioration of the lock gates.

3. CORROSION MITIGATION: Corrosion of the metallic components of the gates can be extensively reduced by the proper preparation and application of corrosion inhibiting coatings to the gate surfaces. In addition, corrosion of the gates can be further reduced, and the life of the applied coatings extended, by the installation of cathodic protection systems (CPSs).

a. Painting:

(1) Preparation of the ferrous surfaces of the gates and structural members, and the selection and application of protective coatings, should be accomplished in accordance with the requirements of UFGS-09965A, “Painting; Hydraulic Structures and Appurtenant Works.” The stringent requirements of the guide specification, including the Safety and Health Provisions detailed therein, should be adhered to.

(2) Ferrous surfaces of the gate structure should be cleaned to a grade approaching white metal grade in accordance with UFGS-09965A. The surface anchor pattern shall be consistent with the recommendations of the coating manufacturer. Quality control should be in accordance with the requirements of this guide specification, and the method and minimum thickness of application of the protective coatings specified therein should be adhered to. Proper surface preparation is essential for achieving a good coating life.

b. Impressed Current: Installation of a CPS utilizing sacrificial anodes is considered an inadequate method for cathodically protecting the Lock B miter gates. Impressed current cathodic protection should therefore be applied using the guidance of CW-16643.

(1) A separate impressed current CPS should be provided for each gate leaf. Each system should consist of a rectifier supplying protective current to anodes, which will distribute protective current to the gate structure. Cathodic protection should be installed on those portions of the gates submerged at normal pool levels. The faces of the gates should be protected to upper pool stages, except that the downstream face of the lower gates should be protected to the lower pool. Meters should be provided as part of the rectifier to monitor the CPS voltage and current.

(2) This navigation lock will be subject to flooding and floating debris; therefore, the CPS should be designed to permit for removal during periods of high water, and the anode cables and sausage-type anodes will require impact protection to prevent them from being damaged.

4. MAINTENANCE AND MONITORING: Maintenance and monitoring of the CPS (sacrificial or impressed current) are essential to ensure continuing corrosion protection. The areas of the lock gates to receive cathodic protection are those areas of the gates already stipulated in paragraph 3b(1). Monitoring and evaluations should be accomplished as follows:

a. The voltage and current readings of the rectifiers should be observed, monitored, and recorded daily. DC voltage and current data indicate that the rectifiers and CPS are working but do not guarantee that the system is properly optimized. Typical information on voltage and current data recordings is as follows:

GATE	VOLTS	AMPS
Upper - left leaf	14.5	0.3
Upper - right leaf	14.2	0.3
Lower - left leaf	11.4	0.6
Lower - right leaf	10.8	0.4

b. The evaluation of annual reference cell voltage data indicating the structure-to-electrolyte (lock-to-water) potential is the accepted method for determining the adequacy of corrosion protection provided by the CPS. Reference cell data are evaluated based on the design (anode locations), the voltage adjustments, and the adequacy of the test locations. Adjustments to the rectifier output can be made to improve the protective potentials applied to the gate leaves. Attached Table A-1 provides details on typical reference cell data.

(Name)

(Position)

TABLE A-1
(Impressed Current Installation)

RECTIFIER NO. 1
Upper Gate - Land Leaf - Upstream Side
Steel to Half-Cell Potentials[*]
Reports Control Symbol ENGW-E-7

Date of test: 1 Oct. 1991

Depth Below Water Surface mm	**Pre-Protection**			**Current On**			**Current Off**		
	Quoin End	**Middle**	**Miter End**	**Quoin End**	**Middle**	**Miter End**	**Quoin End**	**Middle**	**Miter End**
150	-0.500	-0.505	-0.495	-1.050	-1.000	-1.055	-0.655	-0.700	-0.650*
600	-0.500	-0.500	-0.500	-1.040	-1.030	-1.035	-0.700	-0.735	-0.705
1200	-0.500	-0.500	-0.500	-1.050	-1.085	-1.050	-0.825	-0.755	-0.815
1850	-0.500	-0.495	-0.495	-1.050	-1.100	-1.055	-0.855	-0.765	-0.850
2450	-0.495	-0.490	-0.490	-1.050	-1.085	-1.050	-0.865	-0.770	-0.850
3050	-0.490	-0.480	-0.485	-1.080	-1.110	-1.070	-0.880	-0.880	-0.850**
3650	-0.490	-0.480	-0.480	-1.070	-1.080	-1.060	-0.885	-0.880	-0.880
4250	-0.480	-0.479	-0.470	-1.070	-1.070	-1.065	-0.880	-0.885	-0.980
4900	-0.470	-0.464	-0.460	-1.000	-1.020	-1.030	-0.885	-0.890	-0.980
5500	-0.465	-0.455	-0.450	-1.000	-0.979	-1.050	-0.880	-0.885	-0.985
6100	-0.460	-0.445	-0.440	-0.950	-0.930	-1.000	-0.870	-0.875	-0.1075

Rectifier voltage = 2.10 volts
Rectifier current = 0.50 amps
Coarse tap position = L
Fine tap position = 2
Meter used 5 meg ohms/volt 2 volt scale
Half-cell 75 mm or less from lock steel
Resistance of circuit: E = IR
2.10 = .5R
R = 2.10/.5 = 4 ohms

NOTE: Include as many 600-mm (2-ft) increments as necessary to cover submerged depth of gate

* Unacceptable reading
** Acceptable reading

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[*] All potential measurements are expressed in units of direct current (DC) volts with respect to a copper/copper sulfate half cell.

APPENDIX B

DETAILED CATHODIC PROTECTION DESIGN PROCEDURES FOR PIKE ISLAND AUXILIARY LOCK GATES

Designs for Lock Gates.

Figure B-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).

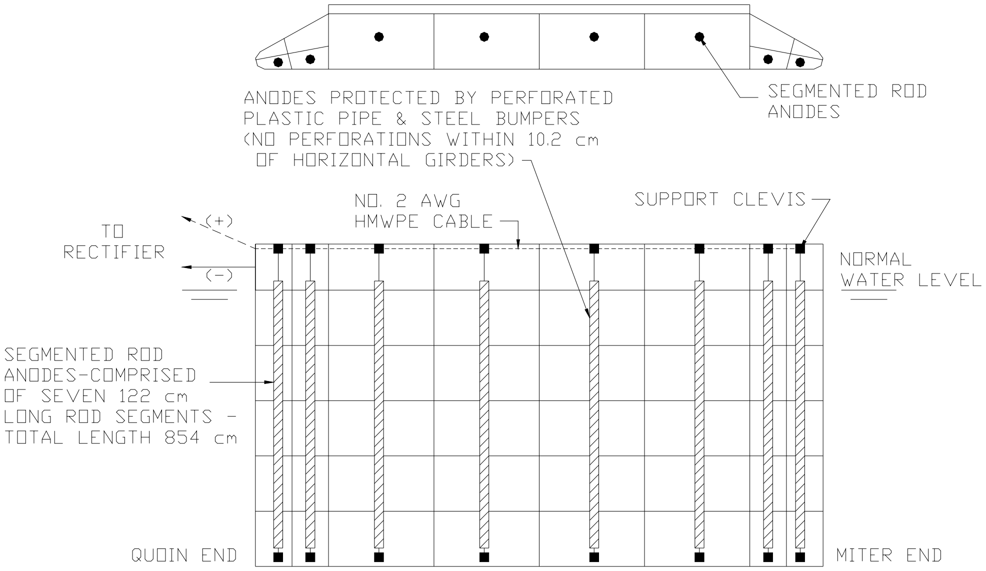

FIGURE B-1. PIKE ISLAND AUXILIARY LOCK MITER GATE

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 is made up of a large skin plate over the major portion of the face and two columns of small chambers at the quoin and miter ends of the gate.

The main (large) chambers 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.). The two sets of vertically aligned chambers, at the quoin and miter ends of the gates, are much smaller and irregularly shaped. There are 6 horizontally aligned rows of chambers placed one above the other in each vertical column, giving a total of 48 chambers on the downstream side.

Design Data.

a. The lock is located in fresh water with a resistivity of 3000 ohm-centimeters.

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 percent of the area bare because of holidays in the coating.

e. The coating will deteriorate significantly in 20 years of exposure. Experience shows that 30 percent 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. Electric power is available at 120/240 volts AC, single phase at the lock site.

h. Design for a 20-year life.

i. Design for entire surface of the gate to be submerged.

j. Base anode requirement on the average current requirement over the anode design life.

k. Base rectifier requirement on maximum (final) current requirement at end of anode design life.

Computations.

Find the surface area to be protected.

a. Upstream side

Area of skin plate: 14.51 m x 10.67 m = 154.82 m^2 (1666 ft^2)

Chamber areas at each end (same at each end):

- 6 chambers @ 6.50 m^2 = 39.02 m^2 (420 ft^2)
- 6 chambers @ 3.72 m^2 = 22.30 m^2 (240 ft^2)
- 6 chambers in each vertical column

b. Downstream side

Number of Chambers	Chamber Area m^2 (ft^2)	Total Area m^2 (ft^2)
4	5.85 (63)	23.41 (252)
4	6.60 (71)	26.34 (284)
4	7.06 (76)	28.24 (304)
4	8.08 (87)	32.33 (348)
4	8.55 (92)	34.19 (368)
4	13.47 (145)	53.88 (580)
4	14.68 (158)	58.71 (632)
4	15.51 (167)	62.06 (668)
4	16.63 (179)	66.52 (716)
2	17.28 (186)	34.56 (372)
4	18.12 (195)	72.46 (780)
2	19.14 (206)	38.28 (412)
2	21.18 (228)	42.36 (456)
2	22.20 (239)	44.40 (478)
Total number of chambers = 48 Total chamber area = 194.17 m^2 (2092 ft^2) Total area = 617.81 m^2 (6650 ft^2)		

2) Calculate the current requirements (I) from Equation 1.

$$I = A * I'(1.0 - C_E) \qquad [EQ\ 1]$$

where

A = surface area to be protected (varies depending on portion of structure)

I' = required current density to adequately protect gate 75.35 mA/m^2

C_E = coating efficiency (0.99 initial, and 0.70 final)

A) Upstream side

Skin plate current requirement

Calculate I

where A = 154.82 m^2 (1666 ft^2) (from computation step 1A).

Initial current requirement (C_E = 99%):

I = 154.82 m^2 x 75.35 mA/m^2 x (1 - 0.99) = 116 mA (use 120 mA)

Final current requirement (C_E = 70%):

I = 154.82 m^2 x 75.35 mA/m^2 x (1 - 0.70) = 3498 mA (use 3500mA)

Average current requirement:

I = (120 + 3500)/2 mA = 1810 mA (use step 2A for skin plate)

End chamber current requirement

To be able to use the same anode assembly in each set of chambers, base the design on the larger of the two chambers at each end.

Calculate I

where A = 39.02 m^2 (420 ft^2) (from computation step 1A).

Initial current requirement (C_E = 99%):

I = 39.02 m^2 x 75.35 mA/m^2 x (1 - 0.99) = 29.4 mA (use 30 mA for 6 chambers)

Final current requirement (C_E = 70%):

I = 39.02 m^2 x 75.35 mA/m^2 x (1 - 0.70) = 882 mA (use 900 mA per 6 chambers)

Average current requirement:

I = (30 + 900)/2 = 465 mA per 6 chambers (use 0.5 per 6 chambers in a vertical column).

This is current requirement for one vertical column of 6 chambers. Total average current requirement is four times this amount:

I = 0.5 x 4 = 2.0 A for chamber

Total current requirement (I_T) for upstream side:

I_T = 120 mA + (4 x 30 mA) = 240 mA = 0.24 amps (initial)

I_T = 2.0 A + 2.0 A = 4.0 amperes (average)

I_T = 3500 mA + (4 x 900 mA) = 7100 mA = 7.10 amps (final)

B) Downstream side

Calculate I

where A = 22.20 m^2 (239 ft^2) (from computational step 1B).

Initial current requirement (C_E = 99%):

I = 22.20 m^2 x 75.35 mA/m^2 x (1 - 0.99) = 16.8 mA per chamber

Final current requirement (C_E = 70%):

I = 22.20 m^2 x 75.35 mA/m^2 x (1 - 0.70) = 502 mA per chamber

Average current requirement:

I = (16.8 + 502)/2 = 260 mA per chamber

Total current requirement for downstream side (48 chambers):

I_T = 16.8 mA/chamber x 48 chamber = 806 mA = 0.8 A (initial)

I_T = 260 mA/chamber x 48 chamber = 12,480 mA = 12.4 A (average)

I_T = 502 mA/chamber x 48 chamber = 224,096 mA = 24.2 A (final)

C) Total current requirement

Initial

Upstream side	=	0.24 amps
Downstream side	=	0.80 amps
		1.04 amps

Average

Upstream side	=	4.0 amps
Downstream side	=	12.4 amps
		16.4 amps

Final

Upstream side	=	7.1 amps
Downstream side	=	24.2 amps
		31.3 amps

Note: Average current requirements determine anode selection. Final current requirements determine rectifier selection.

3) Select the anode and calculate the number of anodes required (N) to meet the design life requirements.

Disk anodes such as those shown in Figure B-2 are considered best for the skin plate on the upstream side. Either 3.2-mm- (1/8-in.-) diam segmented rod anodes consisting of 1,219-mm (4-

ft) segments, as shown in Figure B-3, or continuous 3.2-mm- (1/8-in.-) diam prefabricated rod anodes are considered best for the chambers.

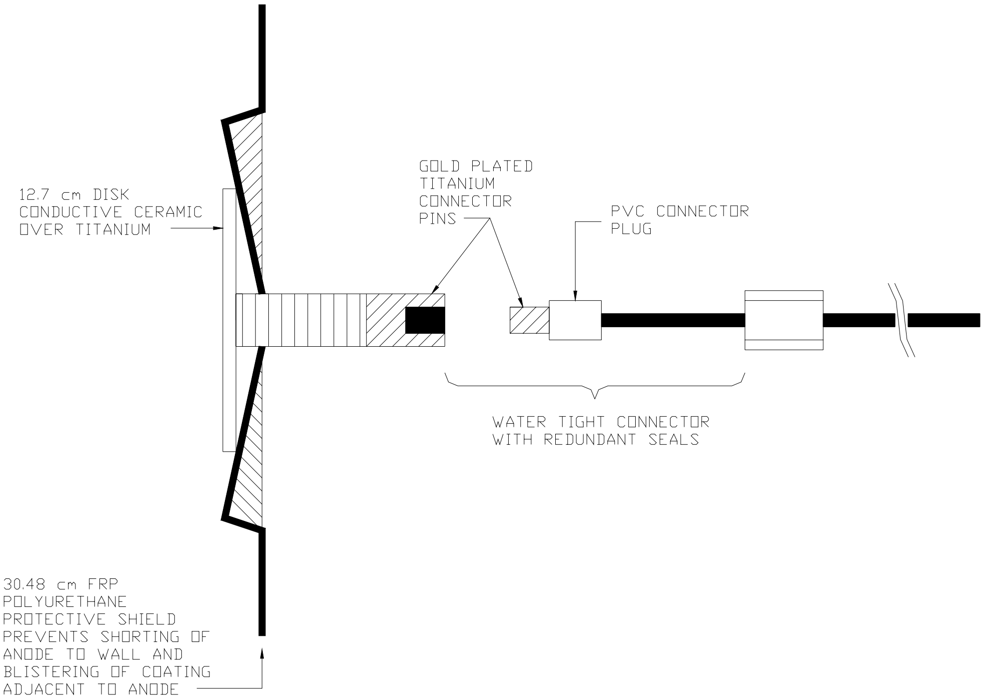

FIGURE B-2. TYPICAL CERAMIC-COATED FLAT DISK ANODE

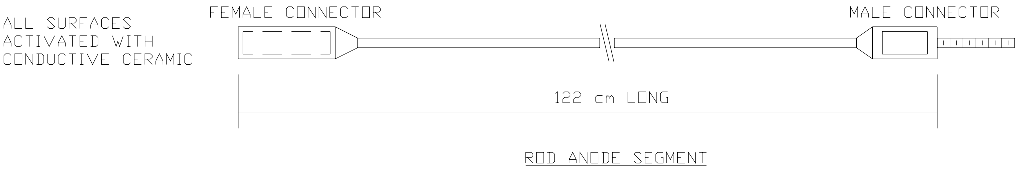

FIGURE B-3. TYPICAL CERAMIC-COATED ROD ANODE DESIGN

For this example, the design based on the 1219-mm (4-ft) segments. The design for the continuous rod material would be identical since they have the same amperage capacity per lineal foot of anode material. Number of anodes is calculated from Equation 2:

$$N = \frac{I}{I_A} \qquad \text{[EQ 2]}$$

where

I = total current requirement

I_A = average current per anode for the anode's desired life.

A) Upstream side

Skin plate - number of disk anodes

Calculate N where:

I = 2 A (from step 2A)

I_A = 0.84 A/disk anode

$$N = \frac{2}{0.84} = 2.4 \text{ anodes}$$

Use 3 disk anodes.

Chambers - number of segmented rod anodes

For each set of 6 chambers in a vertical column

Calculate N

$$N = \frac{0.5}{1} = 0.5 \text{ anodes}$$

where I = 0.5 A (from step 2A)

I_A = 1.0 A/1219-mm- (4-ft-) long segmented rod (from Table B-1M (Metric)/B-1 (U.S. Customary))

Use 1 segmented rod anode per 6 vertical chambers.

B) Downstream side

$I = 260$ mA per chamber

For each set of 6 chambers in a vertical column

$I = 6 \times 260 \text{ mA} = 1560 \text{ mA} = 1.56\text{A}$

$I_A = 1.0$ A/anode (from Table B-1M/B-1)

$N = \frac{1.56}{1} = 1.56$ anodes; use 2 segmented rod anodes per 6 vertical chambers

4) Select number of anodes to provide adequate current distribution.

A) Upstream side

Skin plate

Experience shows that an anode grid spacing of 3.048 to 3.658 m (10 to 12 ft) provides adequate coverage of protective current. Additional anodes are also needed along the bottom of the gate, as this is an area where coating damage occurs readily, thus exposing an appreciable amount of bare metal. Figure B-4 shows a suitable configuration using a combination of 19 disk anodes.

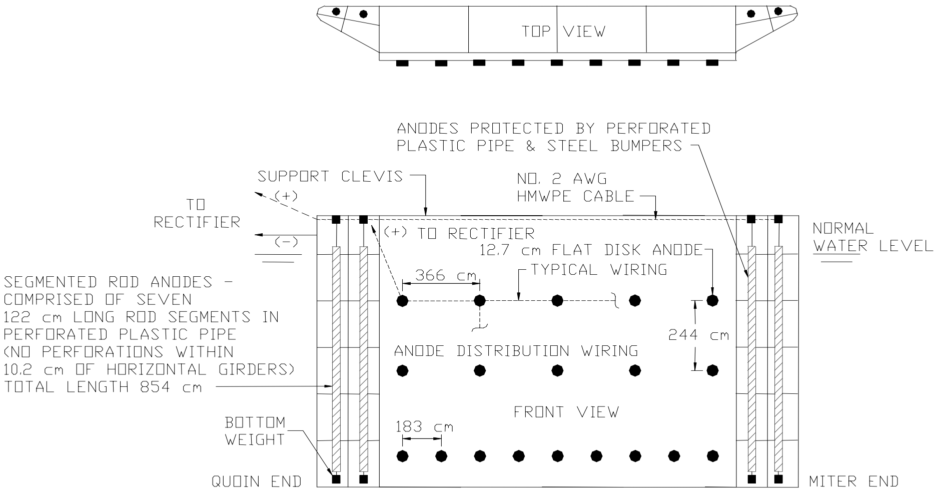

FIGURE B-4. AUXILIARY LOCK MITER GATE DESIGN AT PIKE ISLAND

TABLE B-1M (METRIC)
DIMENSIONS AND RATINGS OF CERAMIC ANODES

Underground Usage

Wire and Rod Anodes (Packaged)

Anode Element Dimension mm x mm	Package Size mm	Weight kg	Current Rating, amps				
			10-Year Design Life	15-Year Design Life		20-Year Design Life	
			HDC	HDC	SC	HDC	SC
3.2 x 610	51 x 762	13.22	1.3	1.10	0.6	0.9	0.5
1.6 x 1524	51 x 1829	30.86	1.5	1.25	0.7	1.0	0.6
1.6 x 1524	76 x 1829	57.32	1.5	1.25	0.7	1.0	0.6
3.2 x 1219	51 x 1524	26.45	2.7	2.2	1.2	1.8	1.0
3.2 x 1219	76 x 1524	48.50	2.7	2.2	1.2	1.8	1.0
6.4 x 1219	76 x 1524	48.50	5.5	4.4	2.4	3.5	2.0
3.2 x 1829	76 x 2438	77.16	4.0	3.3	1.8	2.7	1.5
9.5 x 1219	76 x 1524	48.50	7.5	6.0	3.6	5.1	3.0
12.7 x 1219	76 x 1524	50.70	10.0	8.0	4.8	6.8	4.0
19 x 1219	76 x 1524	55.11	15.0	12.0	7.2	10.0	6.0
3.2 x 1829	76 x 2438	77.16	4.0	3.3	1.8	2.7	1.5
6.4 x 1829	76 x 2438	77.16	8.2	6.6	3.6	5.3	3.0
3.2 x 2438	76 x 3048	97.00	5.4	4.4	2.4	3.6	2.0
6.4 x 2438	76 x 3048	97.00	11.0	8.8	4.8	7.0	4.0

Note: HDC = heavy duty coating tubular anodes (in coke breeze).
SC = standard coating tubular anodes (in coke breeze).

Anode Element Dimension, mm x mm	20-Year Design Life Current Rating, amps
25.4 x 250	2.00
25.4 x 500	4.00
25.4 x 1000	8.00
16 x 250	1.25
16 x 500	2.50
16 x 1000	5.00

TABLE B-1M (CONT'D)
FRESH AND SEAWATER USAGE

Wire and Rod Anodes (Bare)

Life (years)	**Fresh Water**	**Brackish Water**	**Seawater**
Maximum Current(A)/305-mm Length for 20-Year Design Life of 1.6-mm-diam Wire			
10	0.39	0.51	0.85
15	0.31	0.44	0.74
20	0.26	0.39	0.67
Maximum Current(A)/305-mm Length for 20-Year Design Life of 3.2-mm-diam Rod or Wire			
10	0.79	1.02	1.7
15	0.62	0.88	1.47
20	0.52	0.79	1.33
Maximum Current(A)/305-mm Length for 20-Year Design Life of 6.4-mm-diam Rod			
10	1.58	2.04	3.41
15	1.24	1.76	2.95
20	1.04	1.58	2.66
Maximum Current(A)/305-mm Length for 20-Year Design Life of 8.3-mm-diam Rod			
10	2.37	3.06	5.11
15	1.85	2.63	4.42
20	1.56	2.37	3.99
Maximum Current(A)/305-mm Length for 20-Year Design Life of 12.7-mm-diam Rod			
10	3.16	4.08	6.81
15	2.47	3.51	5.9
20	2.08	3.16	5.33
Maximum Current(A)/305-mm Length for 20-Year Design Life of 15.9-mm-diam Rod			
10	3.95	5.1	8.52
15	3.09	4.39	7.37
20	2.6	3.95	6.66
Maximum Current(A)/305-mm Length for 20-Year Design Life of 19-mm-diam Rod			
10	4.74	6.12	10.22
15	3.71	5.27	8.85
20	3.12	4.74	7.99

TABLE B-1M (CONT'D)
FRESH AND SEAWATER USAGE

Tubular Anodes (Bare)

Seawater - Current in amps per anode (15-year design life)	
25.4 mm x 500 mm	25 amps
25.4 mm x 1000 mm	50 amps
16 mm x 500 mm	15 amps
16 mm x 1000 mm	30 amps
Sea Mud - Current in amps per anode (20-year design life)	
25.4 mm x 500 mm	6 amps
25.4 mm x 1000 mm	12 amps
Fresh Water - Current in amps per anode (20-year design life)	
25.4 mm x 500 mm	4.00 amps
25.4 mm x 1000 mm	8.00 amps
16 mm x 500 mm	2.50 amps
16 mm x 1000 mm	5.00 amps

Current Density Limitations
Wire and Rod Anode

Anode Life Versus Maximum Current Density (amps per 0.0929 m^2)

Life, years	Coke	Fresh Water	Brackish Water	Seawater
10	19	24	31	52
15	15	19	27	45
20	13	16	24	41

Tubular Anodes

Anode Life Versus Maximum Current Density (amps per 0.0929 m^2)

Life, years	Fresh Water	Brackish Water	Seawater
20	9.3	9.3	56

TABLE B-1M (CONCLUDED)

Disk Anodes (see Figure B-2)

Size: 127 mm diam (typical - other sizes available) Active Area: 12,258 mm^2 Weight: 907 g		
	Fresh Water	Salt Water
Current capacity - 20-year life (amps/anode)	0.84	5.00
Operating voltage - 20-year life (V)	20.0	10.0

Segmented Rod Anodes (see Figure B-3)

Size: 1219-mm length; 3.5-mm diam Active Area: 14,194 mm^2 Weight: 65 g		
	Fresh Water	Salt Water
Current capacity - 20-year life (amps/anode)*	1.00	2.50
Operating voltage - 20-year life (V)	50.0	10.0

* Standard coating.

TABLE B-1(U.S. CUSTOMARY)
DIMENSIONS AND RATINGS OF CERAMIC ANODES

Underground Usage

Wire and Rod Anodes (Packaged)

Anode Element Dimension	Package Size, in.	Weight lb	Current Rating, amps				
			10-Year Design Life	15-Year Design Life		20-Year Design Life	
			HDC	HDC	SC	HDC	SC
1/8 " x 2'	2 x 30	6	1.3	1.10	0.6	0.9	0.5
1/16" x 5'	2 x 72	14	1.5	1.25	0.7	1.0	0.6
1/16" x 5'	3 x 72	26	1.5	1.25	0.7	1.0	0.6
1/8" x 4'	2 x 60	12	2.7	2.2	1.2	1.8	1.0
1/8" x 4'	3 x 60	22	2.7	2.2	1.2	1.8	1.0
1/4" x 4'	3 x 60	22	5.5	4.4	2.4	3.5	2.0
1/8" x 6'	3 x 96	35	4.0	3.3	1.8	2.7	1.5
3/8" x 4'	3 x 60	22	7.5	6.0	3.6	5.1	3.0
1/2" x 4'	3 x 60	23	10.0	8.0	4.8	6.8	4.0
3/4" x 4'	3 x 60	25	15.0	12.0	7.2	10.0	6.0
1/8" x 6'	3 x 96	35	4.0	3.3	1.8	2.7	1.5
1/4" x 6'	3 x 96	35	8.2	6.6	3.6	5.3	3.0
1/8" x 8'	3 x 120	44	5.4	4.4	2.4	3.6	2.0
1/4" x 8'	3 x 120	44	11.0	8.8	4.8	7.0	4.0

Note: HDC = heavy duty coating tubular anodes (in coke breeze).
SC = standard coating tubular anodes (in coke breeze).

Anode Element Dimension	20-Year Design Life Current Rating, amps
1" x 9.8"	2.00
1" x 19.7"	4.00
1 " x 39.4"	8.00
0.63" x 9.8"	1.25
0.63" x 19.7"	2.50
0.63" x 39.4"	5.00

TABLE B-1 (CONT'D)
FRESH AND SEAWATER USAGE

Wire and Rod Anodes (Bare)

Life (years)	Fresh Water	Brackish Water	Seawater
Maximum Current/l-ft Length for 20-Year Design Life of .0625-in.-diam Wire			
10	0.39	0.51	0.85
15	0.31	0.44	0.74
20	0.26	0.39	0.67
Maximum Current/l-ft Length for 20-Year Design Life of .125-in.-diam Rod or Wire			
10	0.79	1.02	1.7
15	0.62	0.88	1.47
20	0.52	0.79	1.33
Maximum Current/l-ft Length for 20-Year Design Life of .25-in.-diam Rod			
10	1.58	2.04	3.41
15	1.24	1.76	2.95
20	1.04	1.58	2.66
Maximum Current/l-ft Length for 20-Year Design Life of .325-in.-diam Rod			
10	2.37	3.06	5.11
15	1.85	2.63	4.42
20	1.56	2.37	3.99
Maximum Current/l-ft Length for 20-Year Design Life of .5-in.-diam Rod			
10	3.16	4.08	6.81
15	2.47	3.51	5.9
20	2.08	3.16	5.33
Maximum Current/l-ft Length for 20-Year Design Life of .625-in.-diam Rod			
10	3.95	5.1	8.52
15	3.09	4.39	7.37
20	2.6	3.95	6.66
Maximum Current/l-ft Length for 20-Year Design Life of .75-in.-diam Rod			
10	4.74	6.12	10.22
15	3.71	5.27	8.85
20	3.12	4.74	7.99

TABLE B-1 (CONT'D)
FRESH AND SEAWATER USAGE

Tubular Anodes (Bare)

Seawater - Current in amps per anode (15-year design life)	
1 in. x 19.7 in.	25 amps
1 in. x 39.4 in.	50 amps
0.63 in. x 19.7 in.	15 amps
0.63 in. x 39.4 in.	30 amps
Sea Mud - Current in amps per anode (20-year design life)	
1 in. x 19.7 in.	6 amps
1 in. x 39.4 in.	12 amps
Fresh Water - Current in amps per anode (20-year design life)	
1 in. x 19.7 in.	4.00 amps
1 in. x 39.4 in.	8.00 amps
0.63 in. x 19.7 in.	2.50 amps
0.63 in. x 39.4 in.	5.00 amps

Current Density Limitations
Wire and Rod Anode

Anode Life Versus Maximum Current Density (amps/sq ft)

Life, years	Coke	Fresh Water	Brackish Water	Seawater
10	19	24	31	52
15	15	19	27	45
20	13	16	24	41

Tubular Anodes

Anode Life Versus Maximum Current Density (amps/sq ft)

Life, years	Fresh Water	Brackish Water	Seawater
20	9.3	9.3	56

TABLE B-1 (CONCLUDED)

Disk Anodes (see Figure B-2)

Size: 5-in. diam (typical - other sizes available) Active Area: 19 sq in. Weight: 2.0 lb		
	Fresh Water	Salt Water
Current capacity - 20-year life (amps/anode)	0.84	5.00
Operating voltage - 20-year life (V)	20.0	10.0

Segmented Rod Anodes (see Figure B-3)

Size: 4-ft length; 0.138-in. diam Active Area: 22 sq in. Weight: 2.3 oz		
	Fresh Water	Salt Water
Current capacity - 20-year life (amps/anode)*	1.00	2.50
Operating voltage - 20-year life (V)	50.0	10.0

* Standard coating.

Chambers

A continuous length of screw-coupled segmented rod anodes is needed for each chamber column at the miter and quoin ends extending from the high-water line down to within 610 mm (2 ft) of the bottom girder. Each anode consists of 7 segments, each 1219 mm (4 ft) in length. Four segmented rod anode assemblies are thus required, comprising a total of 28 segments, each 1219 mm (4 ft) in length. See Figure B-5.

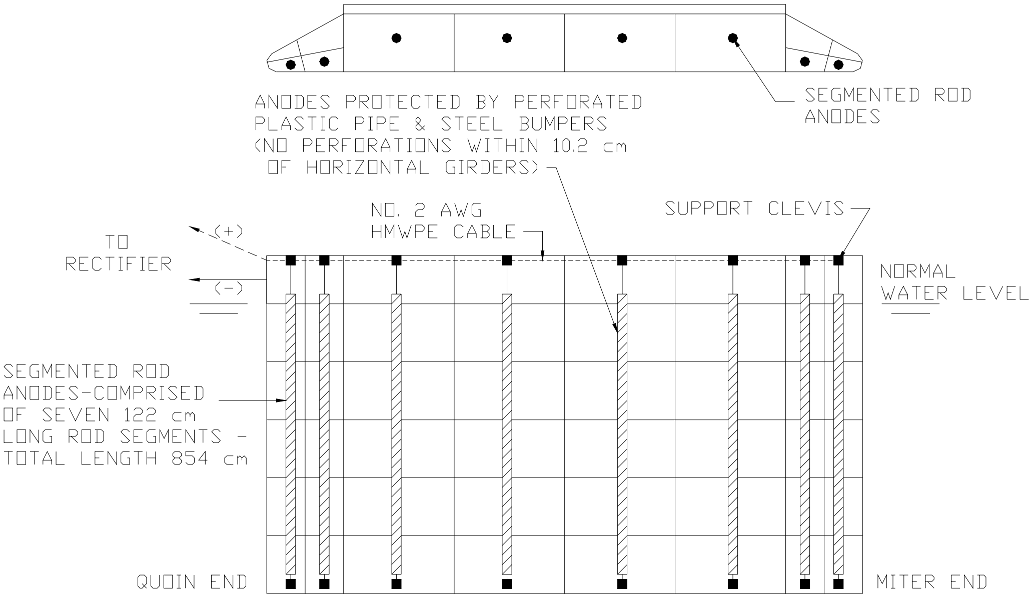

FIGURE B-5. AUXILIARY LOCK MITER GATE AT
PIKE ISLAND SHOWING ROD ANODE PLACEMENT

<u>Total anodes required for the upstream side:</u>

19 disk anodes

4 segmented rod anodes (28 individual rod segments)

B) Downstream side

One continuous length of screw-coupled segmented rod anodes is needed for each chamber column extending from the high-water line down to within 610 mm (2 ft) of the bottom girder. (Note: For the downstream side of the downstream gates, a much shorter anode length will be required since only the lower portions of this gate surface are ever submerged.) Each anode rod consists of 7 segments, each 1219 mm (4 ft) in length. Eight segmented rod anodes are thus required, comprising a total of 56 segments, each 1219 mm (4 feet) in length. See Figure B-5.

<u>5) Determine the anode-to-water resistance (R_A) of the individual anodes.</u>

<u>Disk anodes</u>

Empirical information indicates anode-to-water resistance (R_A) of a single 127-mm (5-in.) disk anode on a coated structure may be expressed by Equation 3.

$$R_A = \frac{p}{21.5} \qquad \text{[EQ 3]}$$

where p = 3000 ohm-cm (water resistivity from design item 1)

21.5 = Manufacturer correlation constant for 127-mm flat disk anode used to yield ohms

$$R_A = \frac{3000}{21.5} = 139.5\,\text{ohms}$$

The disk anode-to-water resistance (R_N) of the 19 disk anodes can be approximated from Equation 4.

$$R_N = R_A/N + (p * P_F)/C_C \qquad \text{[EQ 4]}$$

where: R_A = 139.5 ohms (disk anode-to-water resistance of individual disk anodes from previous calculation)

N = 19 (number of anodes, design step 4)

p = 3000 ohm-cm

P_F = 0.0427 (paralleling factor from Table B-2M (metric)/B-2

(U.S. customary)

C_C = 304.8 cm (10 ft) (center-to-center spacing of disc anodes).

R_N = 139.5/19 + (3000 x 0.0427)/(304.8 cm) = 7.7 ohms

At the maximum expected current of 3500 mA (3.5 amps), the voltage required for the disk anodes can be determined using Ohm's Law, Equation 5.

$$E = I \times R \qquad \text{[EQ 5]}$$

$$E = 3.5 \text{ x } 7.7 = 27 \text{ volts}$$

This is a reasonable voltage, so the 19 disk anodes are sufficient

<u>Segmented rod anodes</u>

The segmented rod anode-to-water resistance (RA) is calculated from Equation 6. the total length of anode is used, although a shorter length could be used if low water conditions were expected most of the time.

$$R_A = \frac{K \times p}{L} \times [\ln(8\,L/d) - 1] \qquad [\text{EQ } 6]$$

where p = 3000 ohm-cm (water resistivity from design item 1)

L = 853 cm (28 ft) (length of anode rod from design step 4)

d = 0.35 cm (0.0115 ft) (anode rod diameter)

K = 0.158 (metric)

K = 0.0052 (U.S. customary)

$$R_A = \frac{0.158 \times 3000}{853} \text{ x } \left(\ln \frac{8 \times 853}{0.35} - 1 \right)$$

$$R_A = 0.557\ (9.88 - 1) = 4.95 \text{ ohms}$$

TABLE B-2M (METRIC)
ANODE PARALLELING FACTORS FOR VARIOUS NUMBER OF

Anodes Installed in Parallel

N	**P**	**N**	**P**
2	0.0796	14	0.0512
3	0.0881	16	0.0472
4	0.0863	18	0.0442
5	0.0817	20	0.0411
6	0.0768	22	0.0390
7	0.0722	24	0.0369
8	0.0683	26	0.0347
9	0.0646	28	0.0332
10	0.0613	30	0.0317
12	0.0555		

Note: N = number of anodes; P = paralleling factors

TABLE B-2 (U.S. CUSTOMARY)
ANODE PARALLELING FACTORS FOR VARIOUS NUMBER OF

Anodes Installed in Parallel

N	**P**	**N**	**P**
2	0.00261	14	0.00168
3	0.00289	16	0.00155
4	0.00283	18	0.00145
5	0.00268	20	0.00135
6	0.00252	22	0.00128
7	0.00237	24	0.00121
8	0.00224	26	0.00114
9	0.00212	28	0.00109
10	0.00201	30	0.00104
12	0.00182		

Note: N = number of anodes; P = paralleling factors

Voltage for upstream side rod anodes

At the maximum expected current requirement for the upstream chambers of 900 mA per vertical column of 6 chambers, the voltage required for each rod anode can be determined using Ohm's Law, Equation 5.

$E = I \times R = 0.90 \text{ amps} \times 4.95 \text{ ohms} = 4.46 \text{ volts}$

This is a reasonable voltage, so the single anode per column of chambers is sufficient.

Voltage for downstream side rod anodes

At the maximum expected current of 251 mA per chamber, the current required for one vertical column of 6 chambers is:

$I = 6 \times 502 \text{ mA} = 3012 \text{ mA or } 3.0 \text{ amperes}$

The voltage required for each anode is found using Equation 5:

$E = I \times R = 3.0 \text{ amps} \times 4.95 \text{ ohms} = 14.9 \text{ volts}$

This is a reasonable voltage, so the single anode per vertical column of chamber is sufficient.

6) Determine total circuit resistance (R_T) using Equation 7.

$$R_T = R_N + R_W + R_C \quad \text{[EQ 7]}$$

where: R_N = anode-to-water resistance

R_W = header cable/wire resistance

R_C = tank-to-water resistance

A) Upstream side

Skin Plate

$R_N = 7.7$ ohms (anode-to-water resistance)

$R_W = 0.02$ ohms (wire resistance)

R_w depends on the actual wiring of the anodes, but the general arrangement would be to use a header cable from the rectifier to the center of the disk anode array and then distribute the current through a junction box to each anode. Wiring would be in a conduit on the inside of the gate. Assuming the rectifier is 8.53 m (28 ft) from the gate, there will be about 30.48 m (100 ft) of positive and negative header cable. No. 2 AWG, HMWPE insulated cable is selected. The resistance of the anode distribution wiring is considered negligible. The header cable resistance is calculated from Equation 8.

$$R_W = \frac{L_W R_{MFT}}{1000} \qquad \text{[EQ 8]}$$

where L_W = 30.48 m (100 ft) (header cable length (as noted above))

R_{MFT} = 0.159 ohms (resistance per 304.8 m (1000 linear ft) of No. 2 AWG HMWPE)

$$R_W = \frac{30.48 \text{ x } 0.159}{304.8} = 0.016 \text{ ohms; use 0.02 ohms}$$

R_C = 0.00 ohms (structure-to-water resistance)

R_C is considered negligible since the design maximum capacity is based on a 30 percent bare structure which would have negligible resistance.

The total resistance R_T of the skin plate disk anode system using Equation 7 is:

$R_T = R_N + R_W + R_C = 7.7 + 0.02 + 0.0 = 7.72$ ohms

Chambers

Total resistance of the 4 upstream chamber anodes (R_N) is calculated as follows: The four anode rods are in parallel. Total resistance can be determined from the law of parallel circuits. Since all four anodes have the same anode-to-water resistance, the calculation becomes Equation 9.

$$R_N = R_A / N = 4.95 / 4 = 1.24 \text{ ohms} \qquad \text{[EQ 9]}$$

where: R_N = total resistance of all four anodes

R_A = 4.95 (anode-to-water resistance)

N = 4 (number of anodes)

R_W = 0.01 ohms (wire resistance)

R_w consists of a No. 2 AWG, HMWPE insulated cable. The rectifier will be located about 7.62 m (25 ft) from the gate, requiring 15.24 m (50 ft) of positive and negative header cable to the gate.

There will be about 18.29 m (60 ft) of cable on the gate. One half of the cable resistance is used in the calculation to allow for distribution of current.

Total wire length then is: 15.24 m + 9.14 m = 24.38 m (80 ft)

Resistance, R_w, is calculated from Equation 8:

$$R_W = \frac{L_W R_{MFT}}{1000} \qquad \text{[EQ 8]}$$

where: L_w = 24.38 m (80 ft) (header cable length (as noted above))

R_{MFT} = 0.159 ohms (resistance per 304.8 m (1000 linear ft) of No. 2 AWG HMWPE)

$$R_W = \frac{24.38 \text{ x } 0.159}{304.8} = 0.01 \text{ohms}$$

R_C = 0.00 ohms (structure-to-water resistance is negligible)

Total resistance (R_T) of the upstream chamber system then from Equation 7:

$$R_T = R_N + R_W + R_C \quad \text{[EQ 7]}$$

R_T = 1.24 + 0.01 + 0.0 = 1.25 ohms

B) Downstream side

Calculations are similar to those from the upstream chambers. Anode-to-water resistance, R_N, from Equation 9 is:

$R_N = R_A/N$

where: R_A = 4.95 ohms (from design step 5).

N = eight anode rods (from design step 3).

$R_N = 4.95/8 = 0.62$ ohms

$R_W = 0.01$ ohms wire resistance (wire length and resistance is the same as the upstream side).

Total resistance (R_T) from Equation 7:

$R_T = R_N + R_W + R_C = 0.62 + 0.01 + 0.0 = 0.63$ ohms

7) Determine required rectifier voltage (V_{REC}) and current.

A) Upstream side

Skin plate

Maximum current required: 3.50 A (step 2A)

Resistance: 7.72 ohms (from step 6A)

Voltage required, Equation 5: E = I x R = 3.5 x 7.72 = 27 volts

Chambers

Maximum current required: 3.6 amperes (from step 2A)

Resistance: 7.72 ohms (from step 6A)

Voltage required, Equation 5: E = I x R = 3.6 x 1.25 = 4.5 volts

B) Downstream side

Maximum current required: 24.2 amperes (from step 2B)

Resistance: 0.63 ohms (from step 6B)

Voltage required, Equation 5: E = I x R = 24.2 x 0.63 = 15.3 volt

Selection of Rectifier

The largest design voltage requirement is 27 volts. Using a factor of safety of 120 percent, rectifier voltage is calculated:

27 volts x (120%) = 33 volts

Total current required:

Upstream skin plate = 3.50 amperes

Upstream chambers = 7.1 amperes

Downstream chambers = 24.2 amperes

34.8 amperes

For a commercially available rectifier having an output of 40 volts, 40 amperes is chosen. Because of the different circuit resistances, separate control over each circuit is required. This is best handled by a rectifier having 3 separate automatic constant current output circuits. Figure B-6 shows the circuitry.

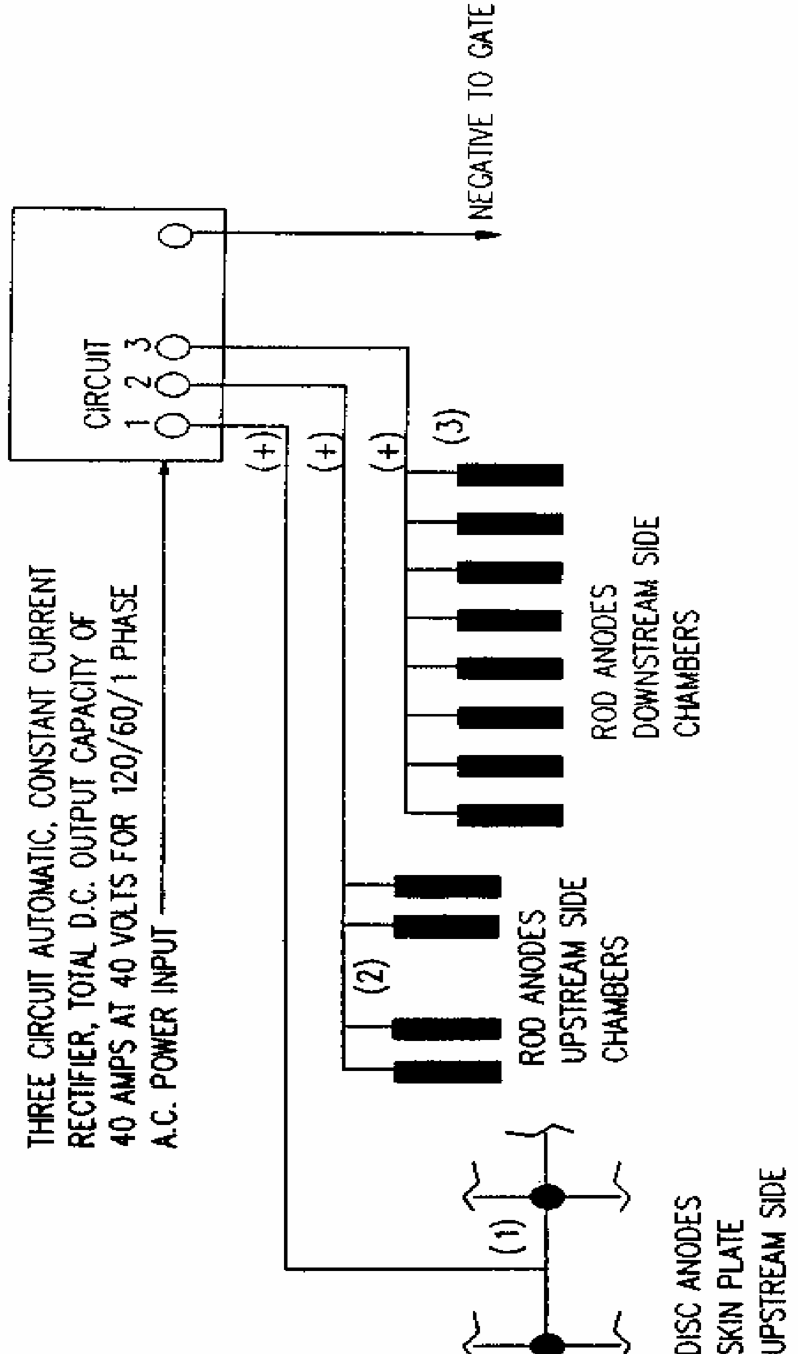

FIGURE B-6. CIRCUIT DIAGRAM FOR LOCK MITER GATE

Rod Anode Installation

Rod anodes can be supported by the cable from a clevis at the top of the gate. Since ice and debris are expected, the anodes need to be protected. This is best done by installing them within perforated polyethylene or fiberglass pipes. A steel half-pipe bumper is used outside the plastic pipe. The anodes may be secured at the bottom using a stabilizing weight or stand off device.

Other Gate Applications

Anode configurations for a Cordell Hull tainter gate and a Cape Canaveral sector gate are shown in Figures B-7 and B-8.

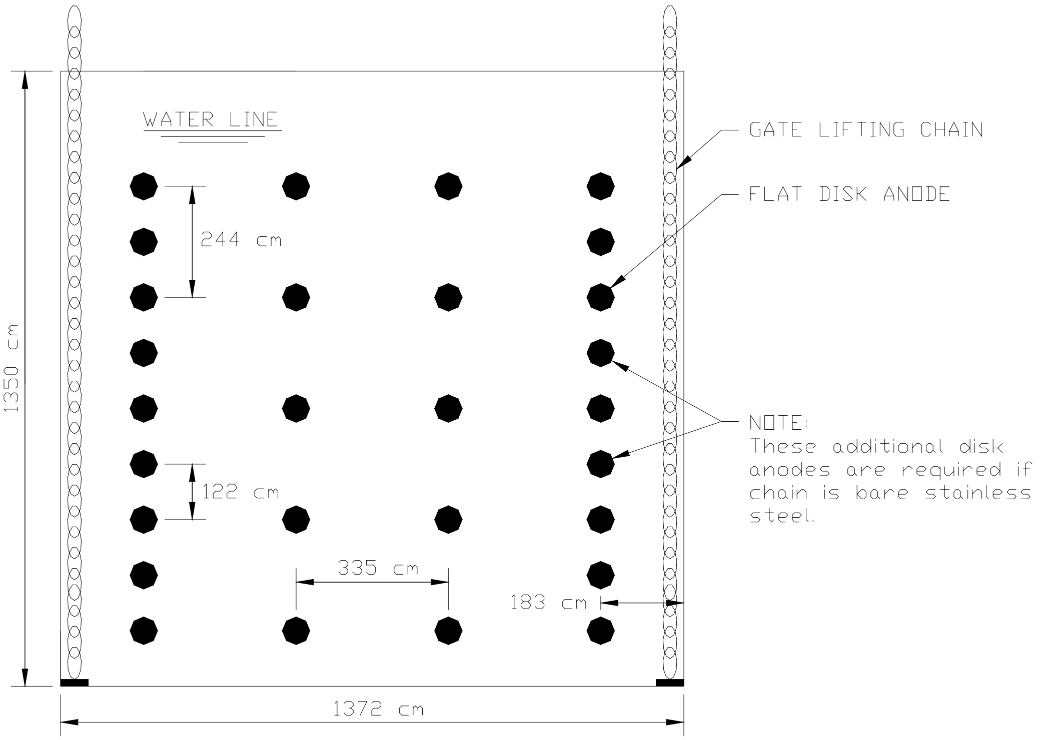

FIGURE B-7. TAINTER GATE DESIGN AT CORDELL HULL SHOWING FLAT DISK ANODE PLACEMENT

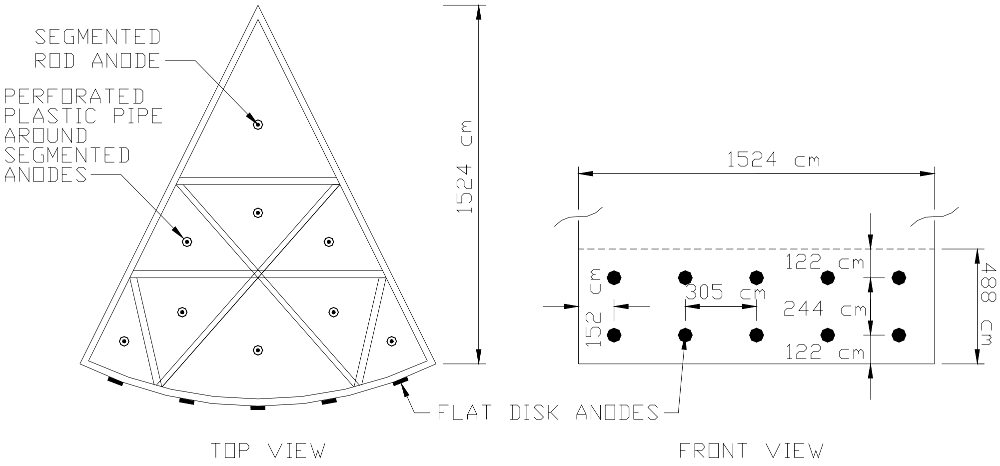

FIGURE B-8. SECTOR GATE DESIGN AT CAPE CANAVERAL
SHOWING FLAT DISK ANODE PLACEMENT

APPENDIX C

SACRIFICIAL CATHODIC PROTECTION SYSTEM BASIC DESIGN FORMULAE AND REFERENCE TABLES FOR CIVIL WORKS APPLICATIONS

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 C-1.* Table C-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 in., 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.

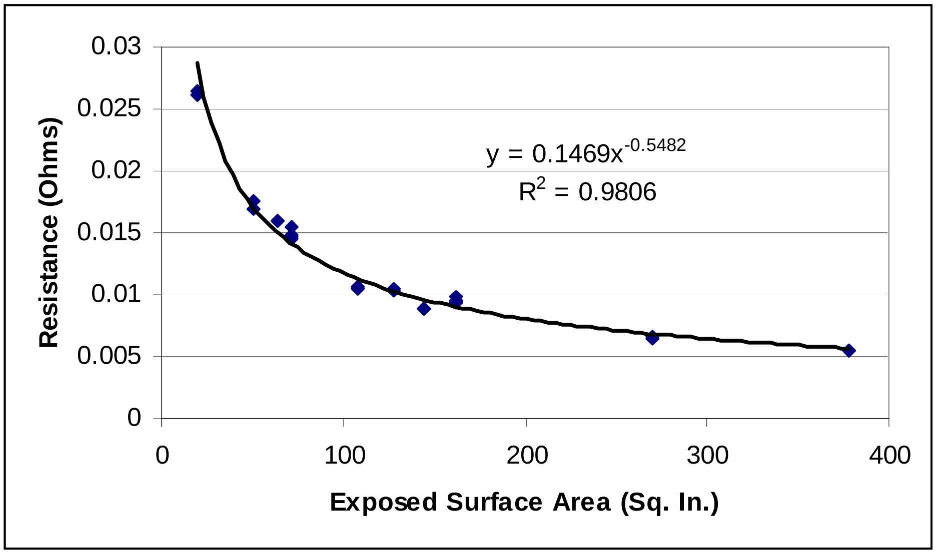

FIGURE C-1. RESISTANCE VS ANODE SURFACE AREA NORMALIZED FOR 1 OHM-CM RESISTIVITY WATER

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* Marsh, Charles P., and J. B. Bushman, "Direct Determination of Galvanic Anode Current Output for Common Shapes Used In Civil Works Applications," presented to the Tri-Service Corrosion Conference (21 November 2003, Las Vegas, NV).

TABLE C-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

The current output calculations in Table C-1 are based on the structure being protected to a polarized potential of -0.85 volt with respect to a Cu-$CuSO_4$ reference electrode. Further, the values for each alloy are based on the most commonly used potential values for each alloy versus 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.

Table C-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.

TABLE C-2. APPROXIMATE ANODE WEIGHT

Anode Style No.	**Anode Type**	**High-Potential And H-1 Alloy Magesium 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

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

$$I_a = \frac{I_{alloy1}}{P}$$

where:

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

I_{alloy1} = current output of anode metal alloy selected from Table 2 in 1 ohm-cm water (in milliamperes)

P = measured resistivity of water surrounding structure to be protected

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:

$$\frac{139{,}706}{2700} = 51.74mA$$

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

$$\frac{102{,}941}{2700} = 38.13mA$$

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

$$\frac{36{,}765}{2700} = 13.62mA$$

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.

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:

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

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 long considered an effective anode = normally 85% for any galvanic anode

I = current output of single anode in milliamperes

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:

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

$$Life_{mag(years)} = 22.9$$

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:

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

$$Life_{mag(years)} = 31.0$$

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

$$Life_{zinc(years)} = \frac{42.4 \times W \times E \times UF}{I}$$

$Life_{mag(years)}$ = 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 long considered an effective anode = normally 85% for any galvanic anode

I = current output of single anode in milliamperes

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:

$$Life_{Zinc(years)} = \frac{42.4 \times 95 \times 0.9 \times 0.85}{13.62}$$

$$Life_{Zinc(years)} = 226$$

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.

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 versus current output can be made for magnesium (Figure C-2) and zinc (Figure C-3) alloy anodes.

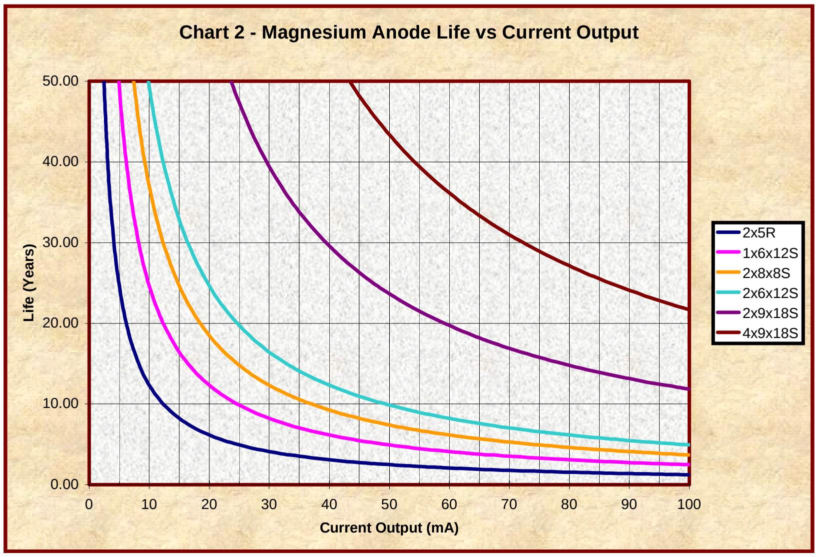


FIGURE C-2. MAGNESIUM ANODE LIFE VERSUS CURRENT OUTPUT

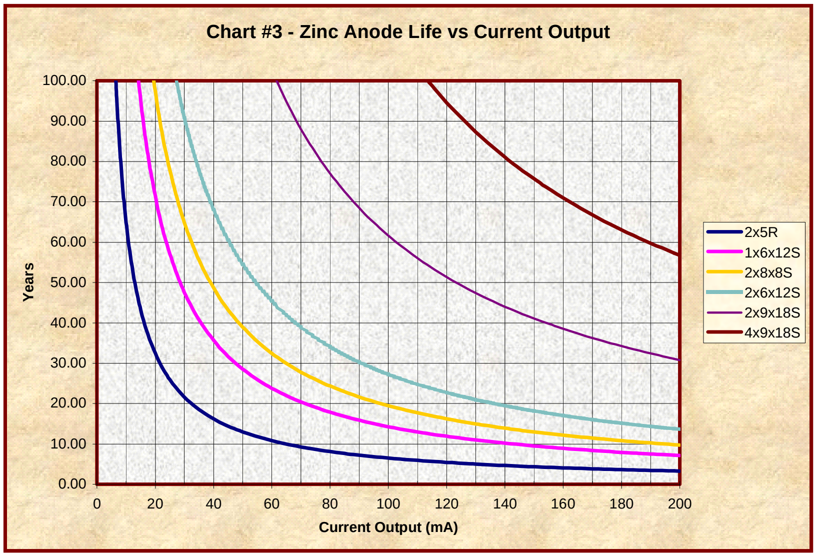


FIGURE C-3. ZINC ANODE LIFE VERSUS CURRENT OUTPUT

As can be seen from Figures C-2 and C-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).

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 C-3 will help in this general selection process.

TABLE C-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	✓✓✓	✓✓	✓✓	✓			

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 C-4 – C-9 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 C-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

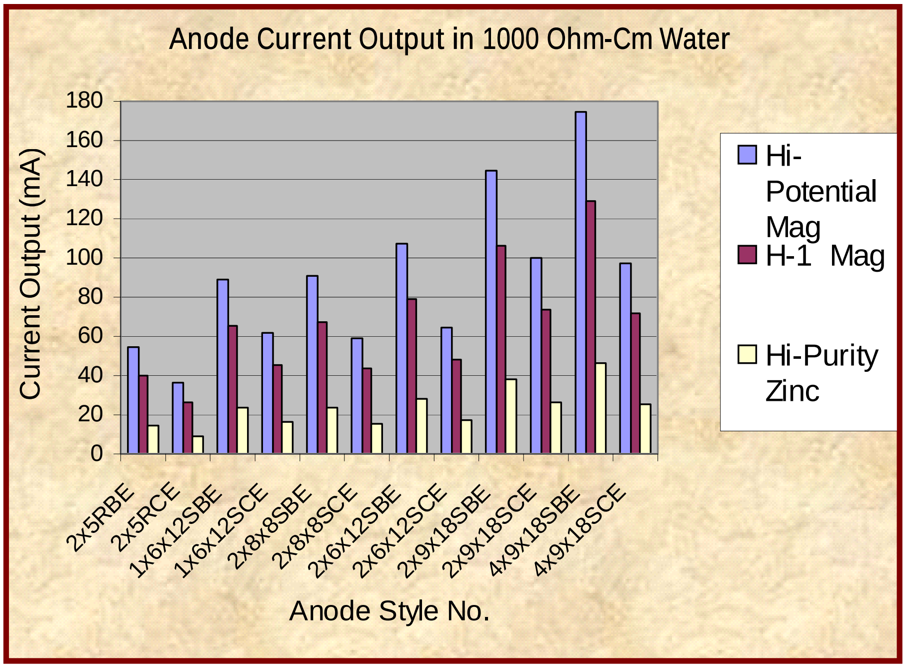


TABLE C-5. ANODE CURRENT OUTPUT IN 1500 OHM-CM RESISTIVITY WATER

	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

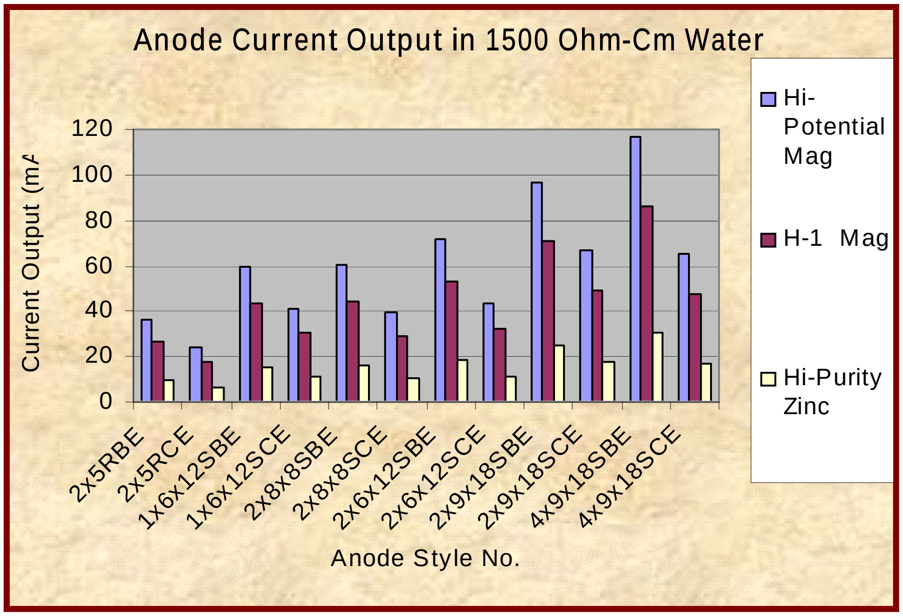
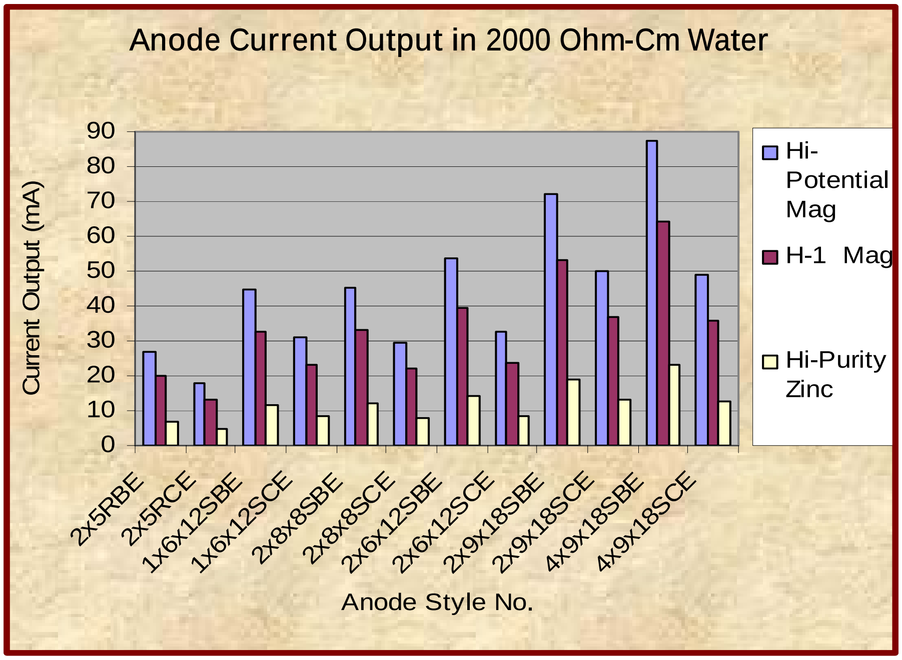


TABLE C-6. ANODE CURRENT OUTPUT IN 2000 OHM-CM RESISTIVITY WATER

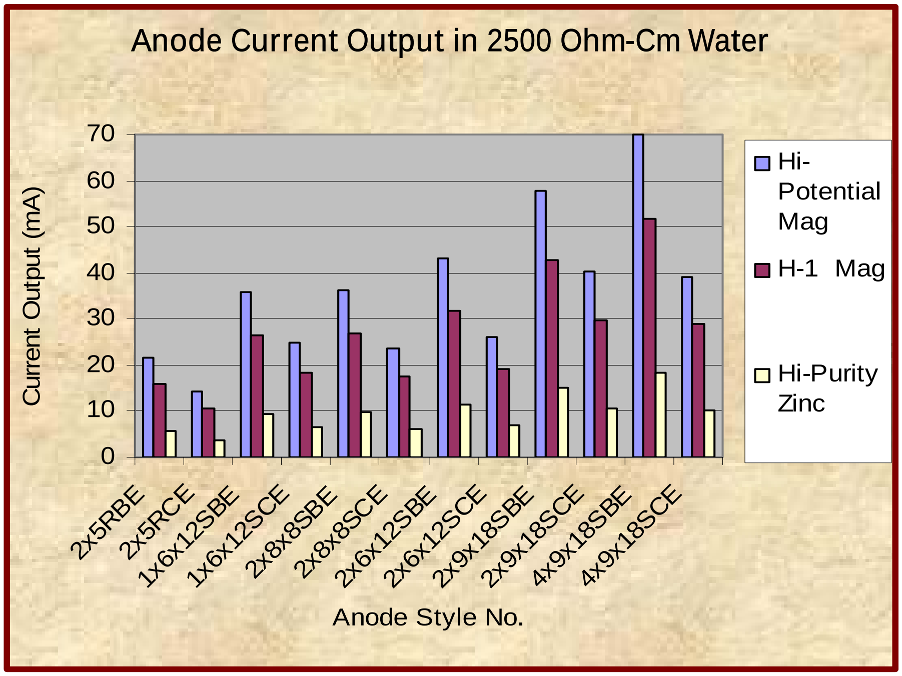
	high-potential Mag	**H-1 Mag**	**high-purity Zinc***
2x5RBE	27.94	20.59	7.35
2x5RCE	16.55	12.20	4.36
1x6x12SBE	42.04	30.97	11.06
1x6x12SCE	33.69	24.82	8.87
2x8x8SBE	46.12	33.98	12.14
2x8x8SCE	31.67	23.33	8.33
2x6x12SBE	49.48	36.46	13.02
2x6x12SCE	33.69	24.82	8.87
2x9x18SBE	69.85	51.47	18.38
2x9x18SCE	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 C-7. ANODE CURRENT OUTPUT IN 2500 OHM-CM RESISTIVITY WATER

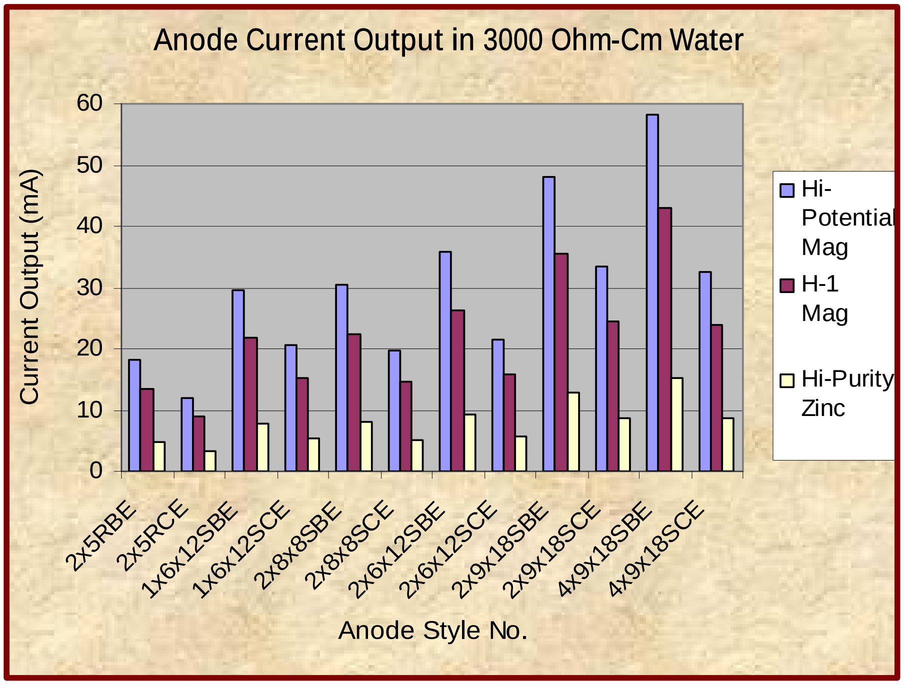
	high-potential Mag	**H-1 Mag**	**high-purity Zinc***
2x5RBE	22.35	16.47	5.88
2x5RCE	13.24	9.76	3.48
1x6x12SBE	33.63	24.78	8.85
1x6x12SCE	26.95	19.86	7.09
2x8x8SBE	36.89	27.18	9.71
2x8x8SCE	25.33	18.67	6.67
2x6x12SBE	39.58	29.17	10.42
2x6x12SCE	26.95	19.86	7.09
2x9x18SBE	55.88	41.18	14.71
2x9x18SCE	42.22	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 C-8. ANODE CURRENT OUTPUT IN 3000 OHM-CM RESISTIVITY WATER

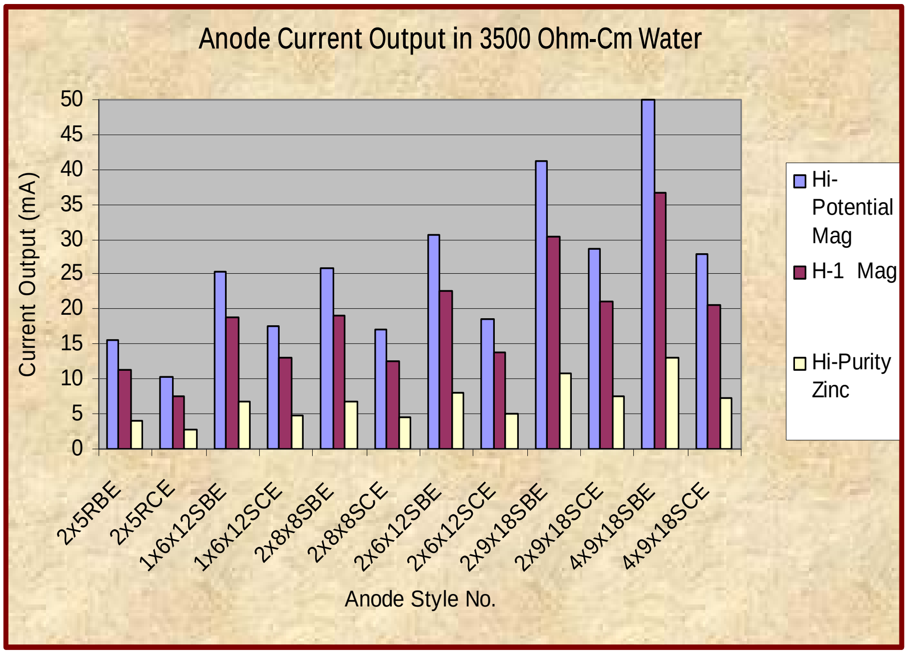
	high-potential Mag	**H-1 Mag**	**high-purity Zinc***
2x5RBE	18.63	13.73	4.90
2x5RCE	11.03	8.13	2.90
1x6x12SBE	28.02	20.65	7.37
1x6x12SCE	22.46	16.55	5.91
2x8x8SBE	30.74	22.65	8.09
2x8x8SCE	21.11	15.56	5.56
2x6x12SBE	32.99	24.31	8.68
2x6x12SCE	22.46	16.55	5.91
2x9x18SBE	46.57	34.31	12.26
2x9x18SCE	35.19	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 C-9. ANODE CURRENT OUTPUT IN 3500 OHM-CM RESISTIVITY WATER

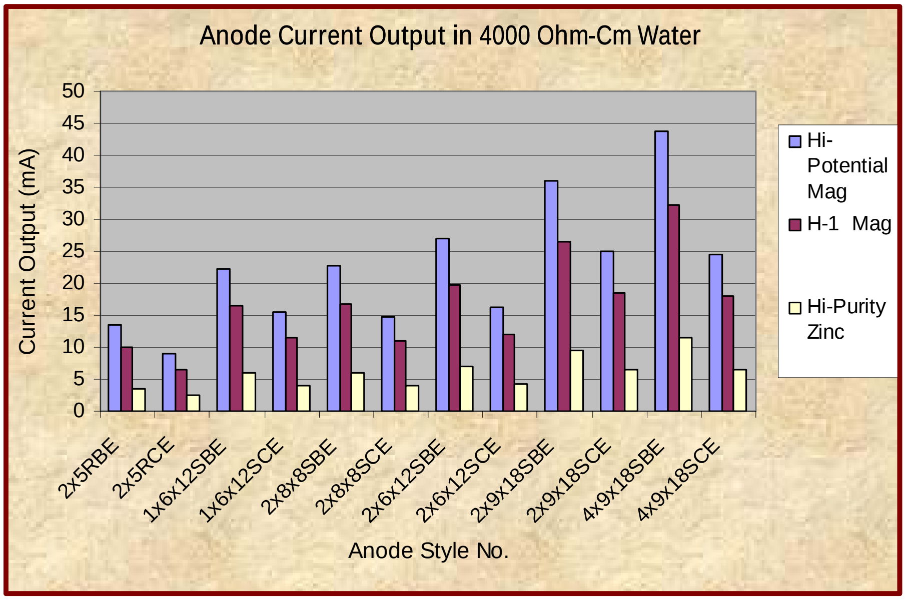
	high-potential Mag	**H-1 Mag**	**high-purity Zinc***
2x5RBE	15.97	11.76	4.20
2x5RCE	9.46	6.97	2.49
1x6x12SBE	24.02	17.70	6.32
1x6x12SCE	19.25	14.18	5.07
2x8x8SBE	26.35	19.42	6.93
2x8x8SCE	18.10	13.33	4.76
2x6x12SBE	28.27	20.83	7.44
2x6x12SCE	19.25	14.18	5.07
2x9x18SBE	39.92	29.41	10.50
2x9x18SCE	30.16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

DETAILED GALVANIC CATHODIC PROTECTION DESIGN EXAMPLE BASED ON PIKE ISLAND AUXILIARY LOCK GATES USING SLAB ANODES

D-1. Design for Lock Gates

Figure D-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).

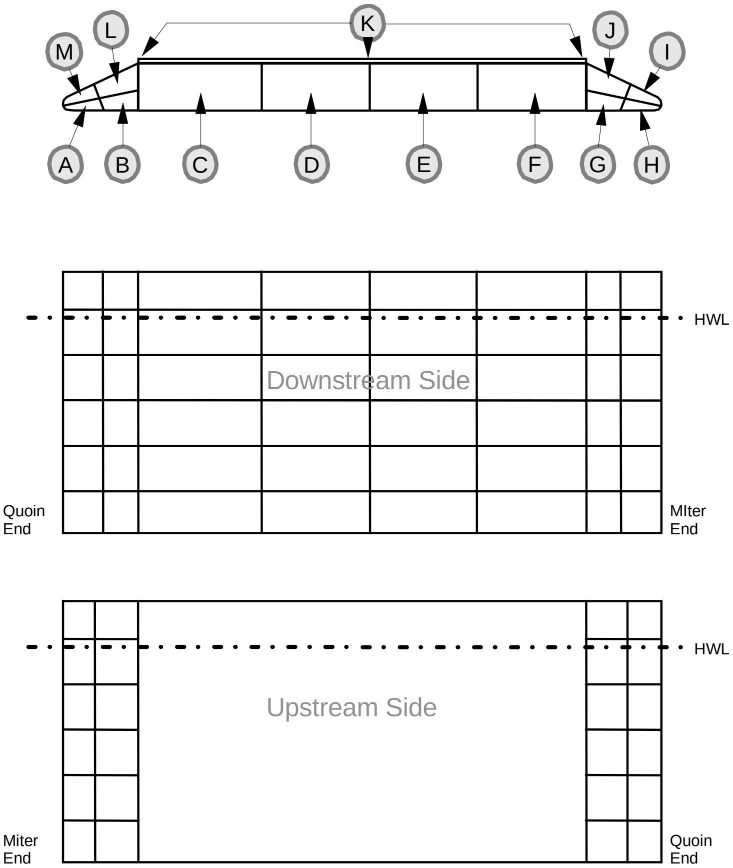


FIGURE D-1. LOCK GATE VERTICAL, DOWNSTREAM AND UPSTREAM STRUCTURAL LAYOUT

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 & I) at the quoin and miter ends of the gate.

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.). The two sets of vertically aligned chambers, at the quoin and miter ends of the gates (chambers A, B, G, & 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.

D-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 on-site or from sample of water obtained on-site. Either should be obtained when water is at it’s highest resistivity (usually in fall when rainfall is least and run-off is 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 percent 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 percent 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.

D-3. Computations

a. Find the Surface Area to be Protected

(1) Upstream Side

i. *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).

ii. *Larger chamber areas J & L adjacent to skin plate*: 5 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.

iii. *Smaller chambers I & 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

i. *Large chambers C, D, E, & 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. 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 1.06 m (3.5 ft) deep. 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).

ii. *Small chambers A, B, G & 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. 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. 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).

(3) Create a Summary Table of Area for Each Chamber (Table D-1)

TABLE D-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

$$I = A \times I'(1.0 - C_E) \qquad \text{[EQ 1]}$$

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 x 75.35 mA/m^2 x (1 – 0.85) = 1503 mA

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

TABLE D-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 - 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
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 m^2 structure surface to be protected.

d. Select Anode Alloy

Refer to Table C-3 in Appendix C. 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

i. Current Required per unit = 31.4 mA

ii. Initial Anode Selection: Refer to Tables C-4 through C-10 in Appendix C. 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 C-6, Appendix C, for 2000 ohm-cm resistivity water. The bar chart included in Table C-6 provides a visual aid to help quickly determine which anodes may be appropriate for this chamber. Based on Table C-6, the

1x6x12SBE, 2x8x8SBE, 2x9x18SCE, and 4x9x18SCE anode sizes appear to be the most appropriate.

iii. Anode Selection Based On Life: The desired anode life is 20 years. Using Figure C-2, Appendix C, 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 D-2).

(2) Chambers B and G

i. Current Required per unit = 49.1 mA

ii. Initial Anode Selection: Again refer to Tables C-4 through C-10 in Appendix C. 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 C-6, Appendix C. Again, based on the data and bar chart visual aid, the only anodes to be considered are the 2x9x18SBE and the 4x9x18SBE.

iii. Anode Selection Based On Life: The desired anode life is 20 years. Using Figure C-2, Appendix C, 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 D-2).

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

i. Current Required per unit = 213.6 mA

ii. Initial Anode Selection: Again refer to Tables C-4 through C-10 in Appendix C. 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 C-6, Appendix 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. Table C-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. 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 C-6. Therefore, both anodes (with four per chamber) would in fact meet the desired current requirement.

iii. Anode Selection Based On Life: As before, the desired anode service life is 20 years. Figure C-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 D-2).

(4) <u>Chambers I and M</u>

i. Current Required per unit = 41.8 mA

ii. Initial Anode Selection: Again refer to Tables C-4 through C-10 in Appendix C. 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 C-6, Appendix C. Based on the data and bar chart visual aid, the only anodes to be considered are the 2x9x18SBE and the 4x9x18SBE.

iii. Anode Selection Based On Life: The desired anode life is 20 years. Using Figure C-2, Appendix C, 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 D-2).

(5) <u>Chambers J and L</u>

i. Current Required per unit = 73.5 mA

ii. Initial Anode Selection: Again refer to Tables C-4 through C-10 in Appendix C. 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 C-6, Appendix C. 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.

iii. Anode Selection Based On Life: Again the desired service life is 20 years. Figure C-2, Appendix C, 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 10 J and L Chambers. Also check and note that one anode per chamber is sufficient for good current distribution in these chambers (see Table D-2).

(6) Surface K (Skin Plate)

i. Current Required = 1503.2 mA

ii. Initial Anode Selection:

(a) Again refer to Tables C-4 through C-10 in Appendix C. 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 C-6, Appendix 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 C-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. 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.

(b) 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. This shield must be glued in place, typically with 100% silicon 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. 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. 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 C-6, so 30 anodes will in fact meet the desired current requirement.

iii. Anode Selection Based On Life: The desired anode life is 20 years. Figure C-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 1four anodes required for good current distribution (see Table D-2).

f. 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.

(1) 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.

(2) 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. 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. 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 D-1).

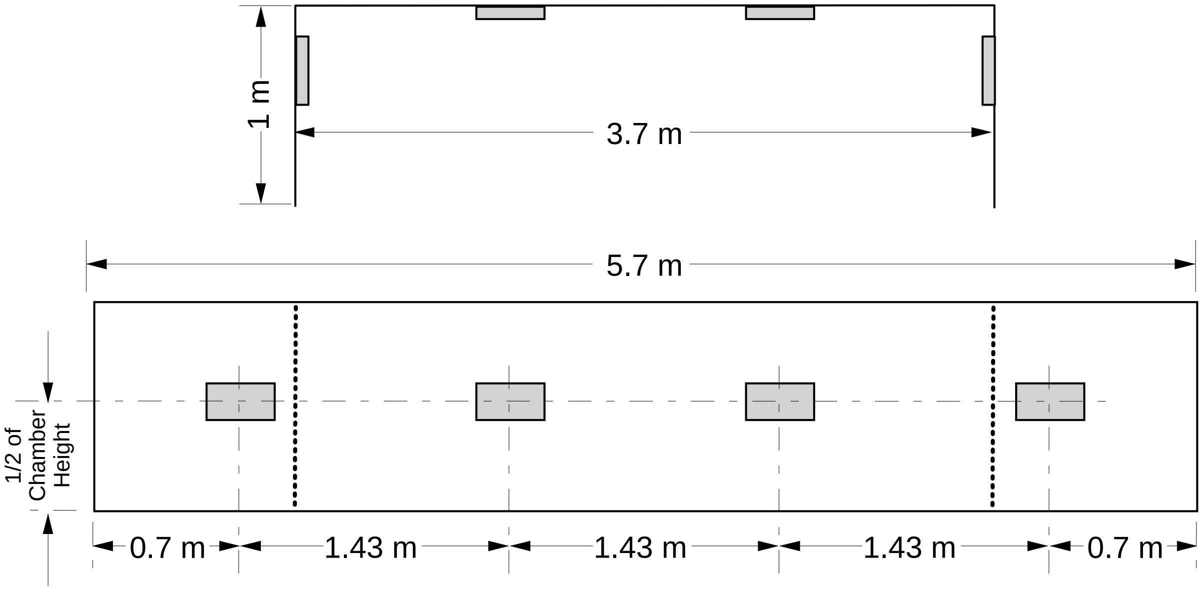


FIGURE D-1. GALVANIC SLAB ANODE LOCATIONS IN LARGEST DOWNSTREAM GATE CHAMBERS

(3) *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

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

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

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.

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.

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. 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 D-2.

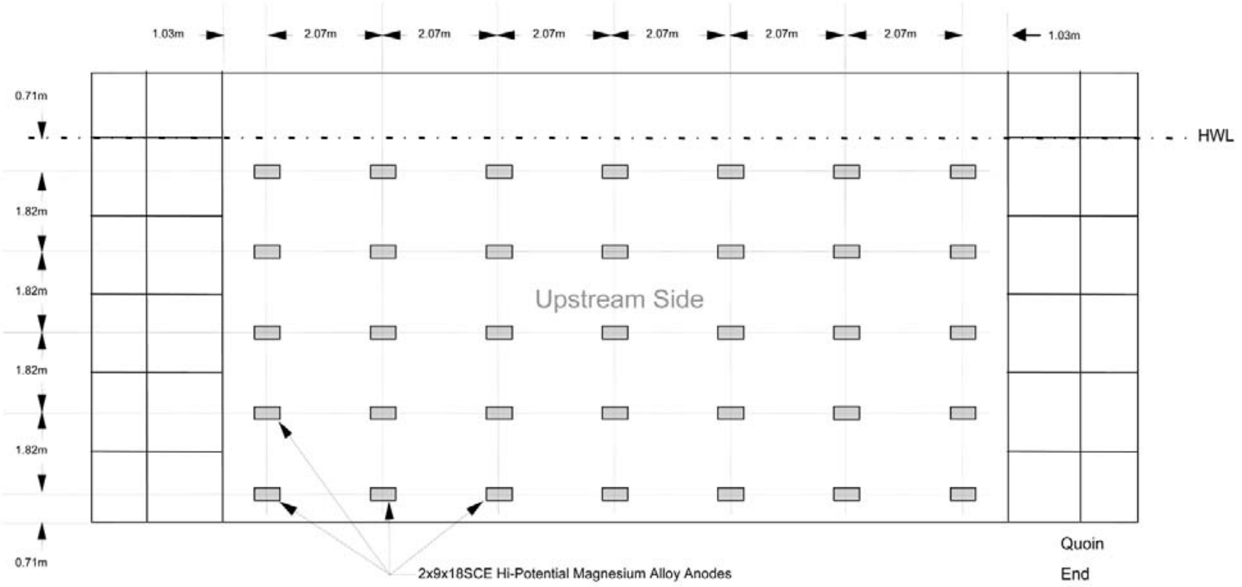


FIGURE D-2. EXAMPLE SLAB ANODE LAYOUT FOR UPSTREAM SIDE (SKIN PLATE)

APPENDIX E

DETAILED GALVANIC CATHODIC PROTECTION DESIGN EXAMPLE BASED ON PIKE ISLAND AUXILIARY LOCK GATES USING ROD AND BAR ANODES

E-1. Overview of Elongated Rod and Bar Galvanic Anodes for Civil Works Structures

While the slab and disk galvanic anodes previously described in this manual are generally preferred for civil works structures due to 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. 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. For example, a 2 in. diameter magnesium rod anode 10 ft long installed in 1000 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 C-3 in Appendix C).

a. Extruded Magnesium Rod Anodes

High-potential magnesium anode rods are extruded in various diameters ranging from 0.5 –2.562 in. (Figure E-1). Only the 2.5 in. and 2 in. diameters (the two cross sections at left in Figure E-1) are typically used on civil works structures because these are the only sizes made with an 1/8 in. galvanized steel core wire. All smaller diameters have a 1/16 in. or smaller diameter core wire, which is not strong enough to suspend the anodes on civil works 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 E-1.

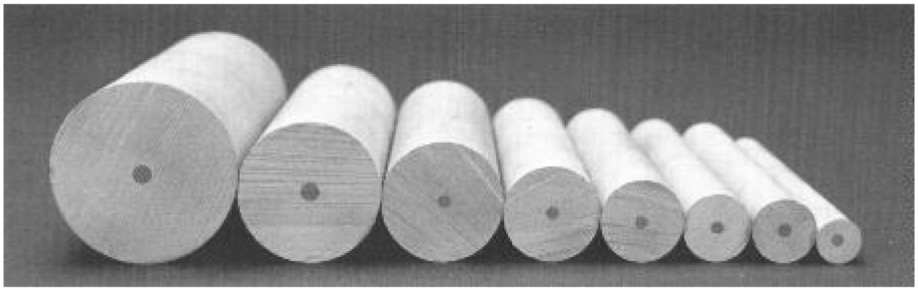


FIGURE E-1. DC-6722, DC-2375 (LEFT) AND OTHER EXTRUDED MAGNESIUM ANODE CROSS SECTIONS SHOWING GALVANIZED STEEL CORE WIRE AT CENTER

TABLE E-1. EXTRUDED MAGNESIUM ROD ANODES
SUITABLE FOR CIVIL WORKS 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	$I = 9.16L^{0.7623}$

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 E-2 and E-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.

The data from Tables E-2 and E-3 were used to generate graphs of current output versus anode length for both diameters, which are shown in Figures E-2 and E-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 E-2. MAGNESIUM ANODE RESISTANCE – CURRENT OUTPUT AND LIFE CALCULATIONS FOR 2 IN. 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 E-3. MAGNESIUM ANODE RESISTANCE – CURRENT OUTPUT AND LIFE CALCULATIONS FOR 2.5 IN. 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

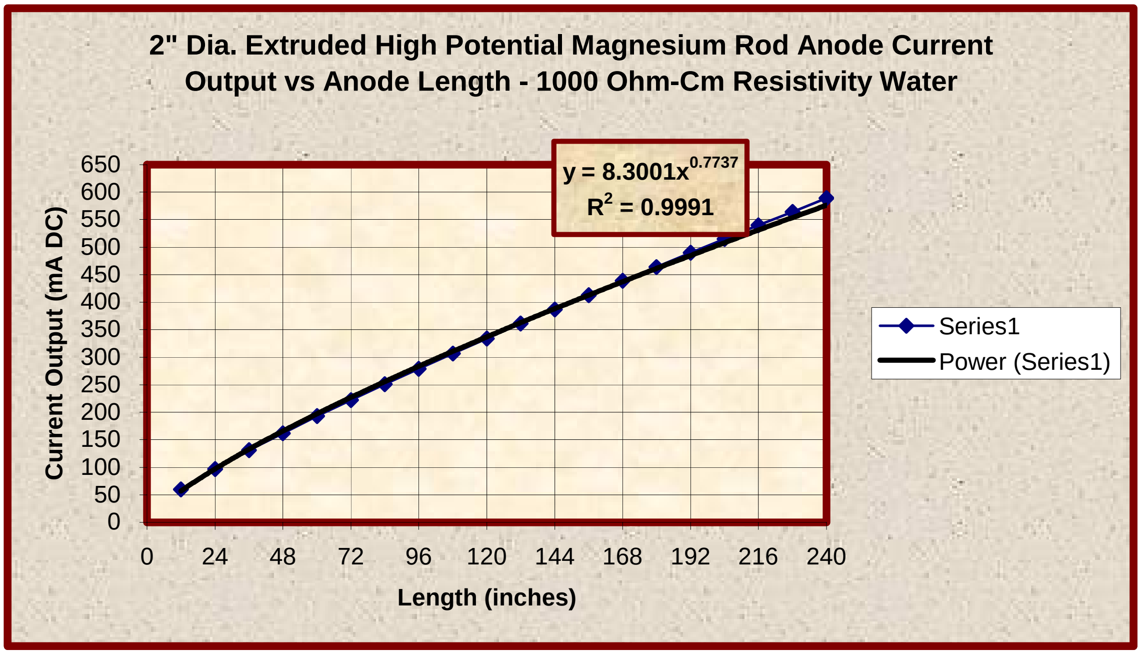


FIGURE E-2. CURRENT OUTPUT VERSUS ANODE LENGTH FOR 2 IN. DIAMETER HIGH-POTENTIAL MAGNESIUM ROD ANODES.

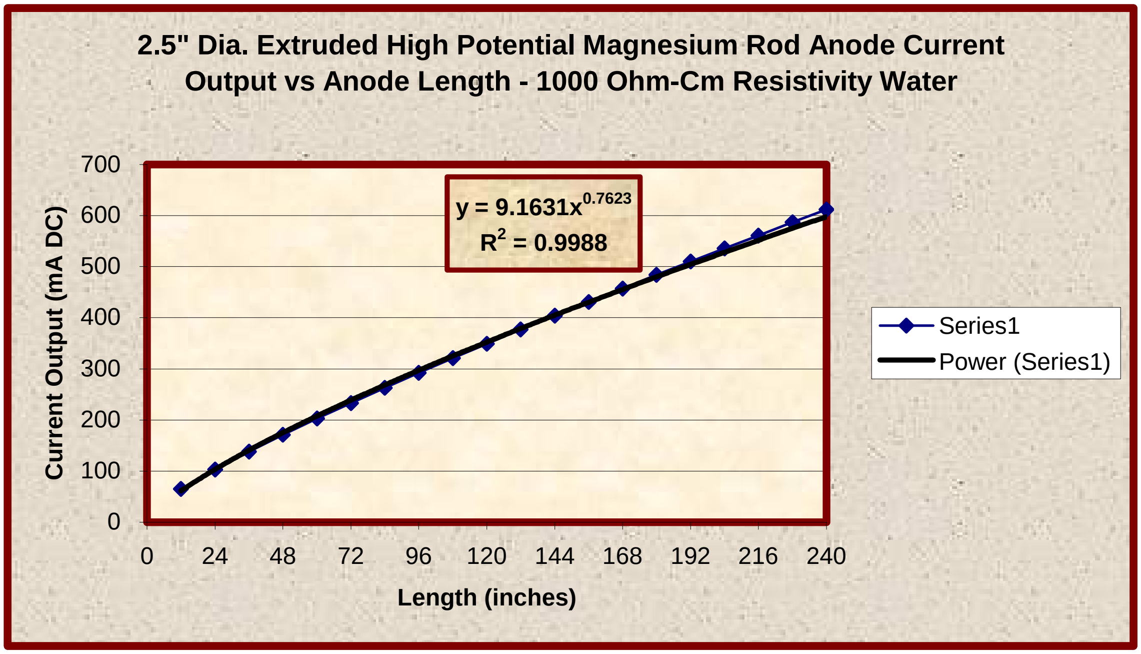


FIGURE E-3. CURRENT OUTPUT VERSUS ANODE LENGTH FOR 2.5 IN. DIAMETER HIGH-POTENTIAL MAGNESIUM ROD ANODES.

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 civil works structures are 3 – 6 in. x 1/8 in. threaded core extended one end only. 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 E-4) and then inserting the rod up through a support bracket (minimum 1/4 in. thick) or suitable plate on the structure. 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 assure 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.

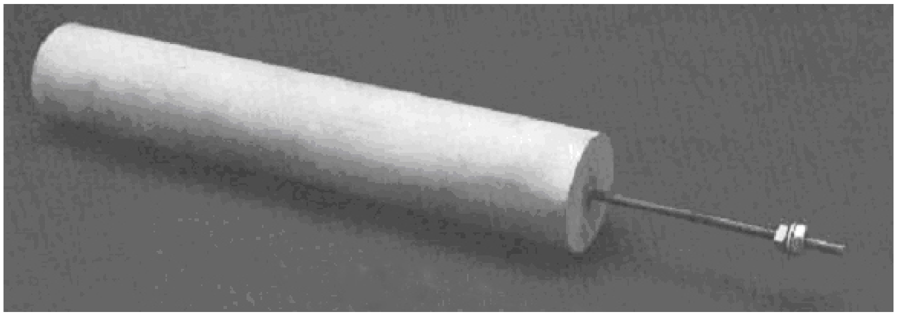


FIGURE E-4. MAGNESIUM ROD ANODE SHOWING THREADED CORE WIRE, DOUBLE NUTS, AND WASHERS

b. <u>High-Purity Cast Zinc Rods</u>

Zinc rod anodes suitable for use on civil works 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. 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.

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 E-5. The U bolts clamp the anode core in place and provide electrical continuity to the support bar and structure. 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.

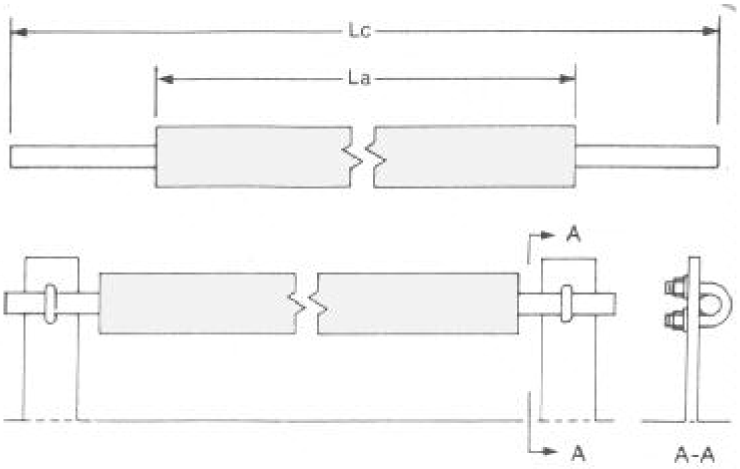


FIGURE E-5. CONNECTION SCHEMATIC FOR
HIGH-PURITY CAST ZINC BAR ANODES.

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 E-4, E-5, and E-6 show the computations for the three different zinc rod anodes available.

TABLE E-4. HIGH-PURITY ZINC ANODE RESISTANCE – CURRENT OUTPUT AND LIFE CALCULATIONS FOR 1.4 IN. 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 E-5. HIGH-PURITY ZINC ANODE RESISTANCE – CURRENT OUTPUT AND LIFE CALCULATIONS FOR 2 IN. 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 E-6. HIGH-PURITY ZINC ANODE RESISTANCE – CURRENT OUTPUT AND LIFE CALCULATIONS FOR 2.5 IN. 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

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

TABLE E-7. CURRENT OUTPUT FOR AVAILABLE SIZES OF
HIGH-PURITY ZINC ROD ANODES SUITABLE FOR CIVIL WORKS 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

E-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. This design example uses the same structure used in Appendices B and D (see Figure D-1), and the coating and environment conditions are the same as those used in Appendix D. Therefore, the design input data will not be replicated here because they are identical to those given in Appendix D, Section D-2. In the current case, however, the use of the rod anodes will only be applied to the chamber side of the gate.

E-3. Computations and Current Requirements for Each Structure Component

These data are the same as those used in Appendix D, Section D-3. For this example we need only the first three rows of the existing current requirements table (see Table D-2) because this design is for the downstream side only. Therefore, the requirements are as shown in Table E-8:

TABLE E-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

E-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

i. Current Required = 31.4 mA

ii. Initial Anode Selection: Refer to Tables E-1, E-2, and E-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:

$$CurrentOutput = \frac{CurrentOutput(in - 1000ohm - cm)}{environment - resistivity(ohm - cm)} \times 1000$$

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.

iii. Anode Selection Based On Life: We want the anode to last 20 years. Using Tables E-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.

$$CurrentOutput = \frac{AnodeLife(in - 1000ohm - cm)}{1000} \times environment - resistivity(ohm - cm)$$

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

i. Current Required = 49.1 mA

ii. Initial Anode Selection: Refer to Tables E-1, E-2, and E-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:

$$CurrentOutput = \frac{CurrentOutput(in - 1000ohm - cm)}{environment - resistivity(ohm - cm)} \times 1000$$

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.

iii. Anode Selection Based On Life: We want the anode to last 20 years. Using Tables E-2 and E-3 we see that neither anode will provide the desired life. The maximum life available can be calculated by the following formula.

$$CurrentOutput = \frac{AnodeLife(in - 1000ohm - cm)}{1000} \times environment - resistivity(ohm - cm)$$

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

i. Current Required = 213.6 mA

ii. Initial Anode Selection: Refer to Tables E-1, E-2, and E-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:

$$CurrentOutput = \frac{CurrentOutput(in - 1000ohm - cm)}{environment - resistivity(ohm - cm)} \times 1000$$

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). A quick check of Tables E-2 and E-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.

iii. Anode Selection Based On Life: We want the anode to last 20 years. Using Tables E-2 and E-3 we see that neither anode will provide the desired life. The maximum life available can be calculated by the following formula.

$$CurrentOutput = \frac{AnodeLife(in-1000ohm-cm)}{1000} \times environment-resistivity(ohm-cm)$$

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.

c. 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.

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 the 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.

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 the each chamber. 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 E-6.

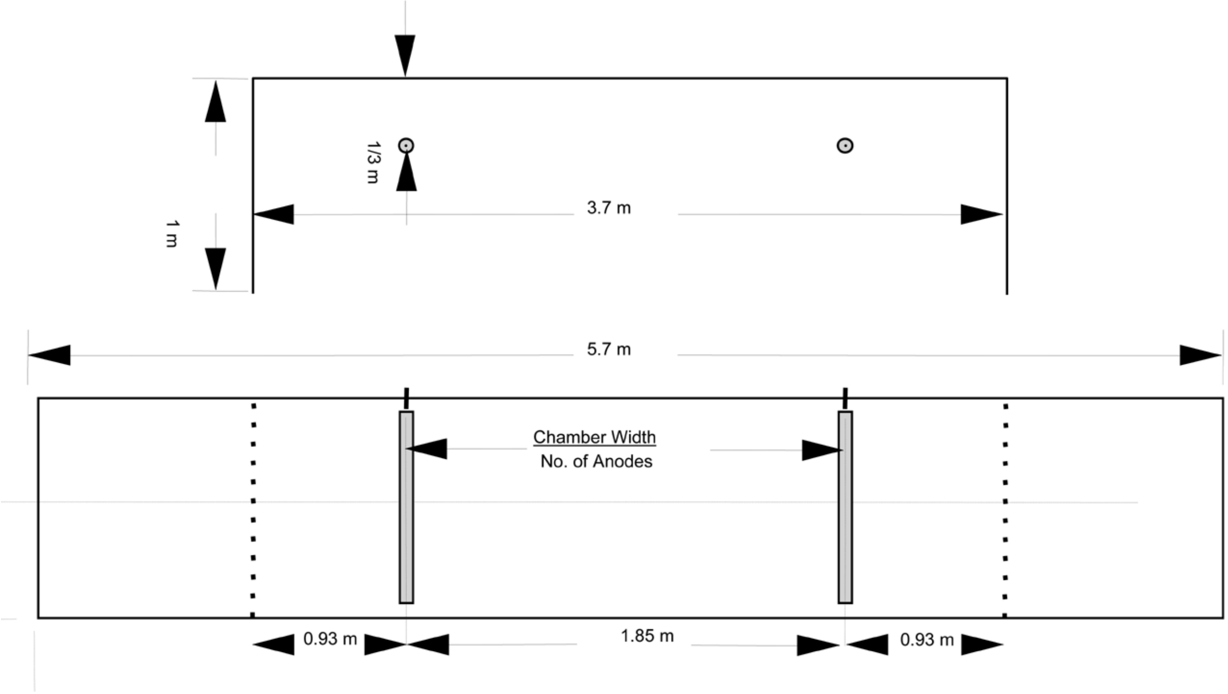


FIGURE E-6. ROD GALVANIC ANODE LOCATIONS
IN LARGEST DOWNSTREAM CHAMBERS

Multiple anodes must be evenly distributed from the side panels of the chamber to achieve more uniform current distribution. In order to assure 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. 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.

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).

E-5. Design Adaptation for Using High-Purity Zinc Bar Anodes

The support method for the high-purity zinc bar anodes is considerably more sturdy 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.

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 E-2 and E-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.

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.

a. 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.

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

(1) Chambers A and H

i. Current Required = 31.4 mA

ii. Initial Anode Selection: Refer to Tables E-4 through E-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:

$$CurrentOutput = \frac{CurrentOutput(in-1000ohm-cm)}{environment-resistivity(ohm-cm)} \times 1000$$

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). 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. 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.

iii. Anode Selection Based On Life: We want the anode to last 20 years. Using Table E-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.

$$CurrentOutput = \frac{AnodeLife(in - 1000ohm - cm)}{1000} \times environment - resistivity(ohm - cm)$$

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) *<u>Chambers B and G</u>*

i. Current Required = 49.1 mA

ii. Initial Anode Selection: Refer to Tables E-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:

$$CurrentOutput = \frac{CurrentOutput(in - 1000ohm - cm)}{environment - resistivity(ohm - cm)} \times 1000$$

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). 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. 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. 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 versus a minimum requirement of 49.1 ma). 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.

iii. Anode Selection Based On Life: We want the anode to last 20 years. Using Table E-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.

$$CurrentOutput = \frac{AnodeLife(in-1000ohm-cm)}{1000} \times environment-resistivity(ohm-cm)$$

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) <u>Chambers C, D, E, and F</u>

i. Current Required = 213.6 mA

ii. Initial Anode Selection: Refer to Tables E-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:

$$CurrentOutput = \frac{CurrentOutput(in-1000ohm-cm)}{environment-resistivity(ohm-cm)} \times 1000$$

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). 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. 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. 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.

iii. Anode Selection Based On Life: We want the anode to last 20 years. Using Table E-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.

$$CurrentOutput = \frac{AnodeLife(in - 1000 ohm - cm)}{1000} \times environment - resistivity(ohm - cm)$$

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.

c. <u>Develop Anode Locations for Each Structure Element</u>

Locating anodes is simply a geometric process of distributing the anodes uniformly on each structure element to achieve good current distribution.

Chambers A and H: Where more than one anode is required in each chamber, the anodes will be mounted to the back surface of the 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. In order to also assure 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.

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.

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. Multiple anodes must be evenly distributed from the side panels of the chamber to achieve more uniform current distribution. In order to also assure 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 1.1 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.

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). 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. 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. 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.

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. 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). 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 E-7.

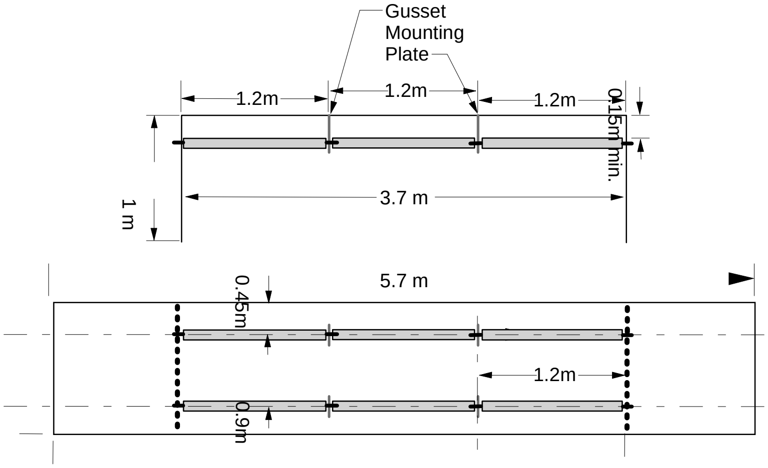


FIGURE E-7. ZINC BAR GALVANIC ANODE LOCATIONS
IN LARGEST DOWNSTREAM GATE CHAMBERS

As is the case with all galvanic anode designs on civil works structures, the intent is to deploy the anodes in a way that distributes their protective current uniformly for each similar current density surface area. 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).

APPENDIX F

DETAILED GALVANIC CATHODIC PROTECTION DESIGN EXAMPLE BASED ON LONGVIEW LAKE INTAKE TOWER EMERGENCY DRAWDOWN GATE LEAF

F-1. Design for Drawdown Gate Leafs

Figures F-1 and F-2 show a Longview Lake Emergency Drawdown Gate Leaf. This gate is approximately 2.13 m (7.0 ft) long and 2.29 m (7 ft - 6 in) high. With the lake at normal water level, portions of each gate will always be submerged and other portions may be submerged or exposed as operation changes. During times of high water, more gate surfaces will be submerged, and under conditions of flood, the entire gates may be submerged. Given these variable conditions, the cathodic protection system shall be designed to protect both sides of the gate for its full depth.

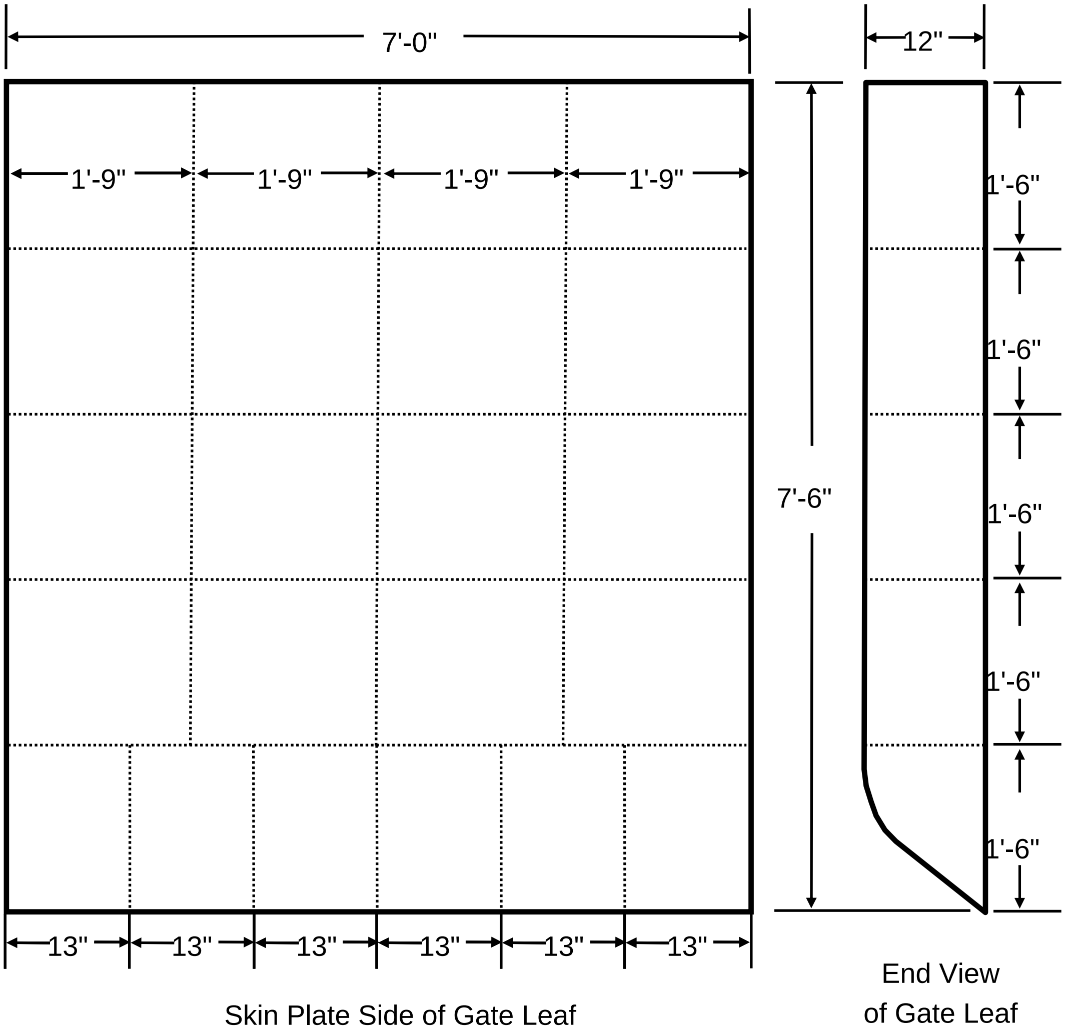


FIGURE F-1. DRAWDOWN GATE LEAF, UPSTREAM STRUCTURAL LAYOUT

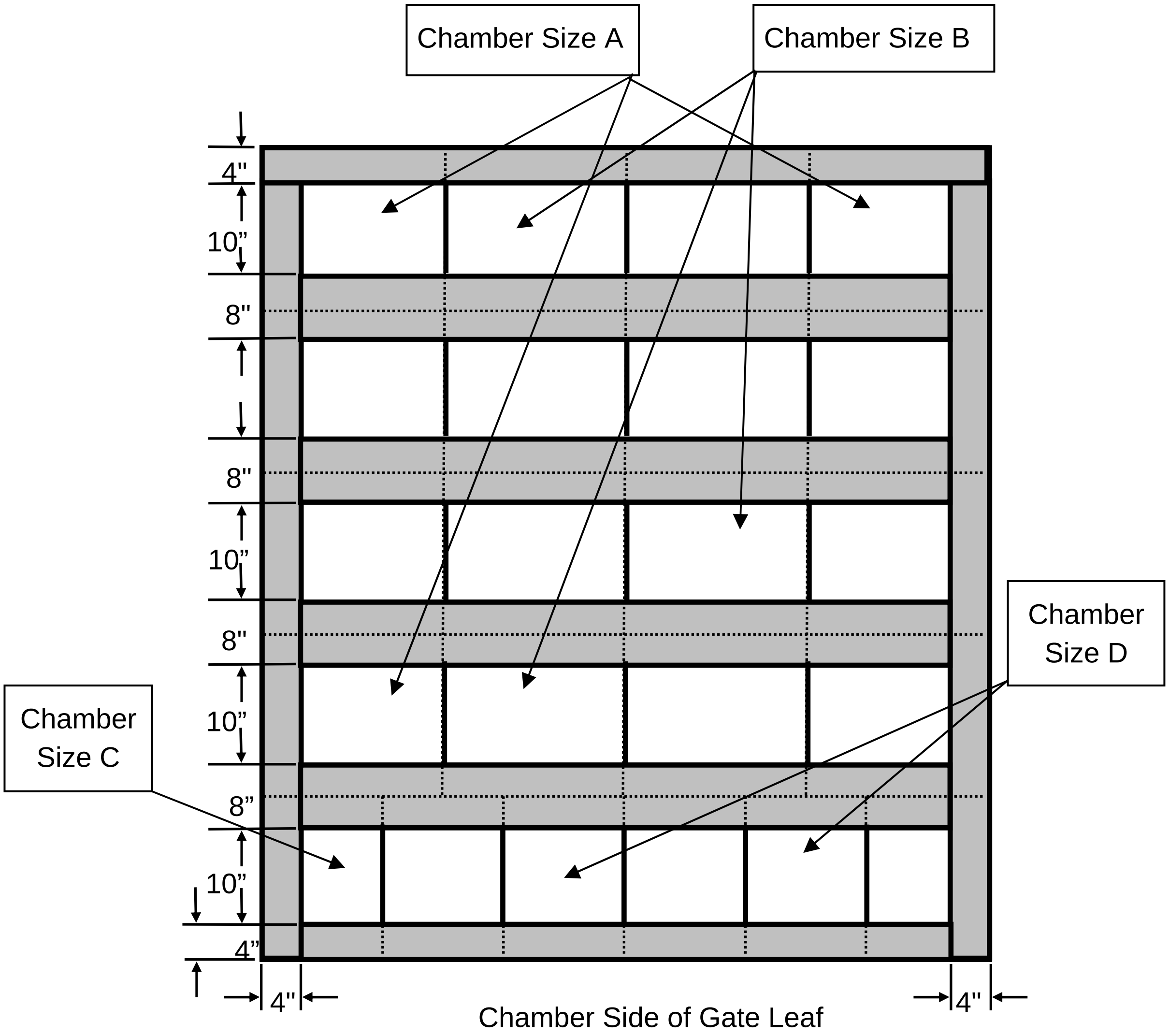


FIGURE F-2. DRAWDOWN GATE LEAF,
DOWNSTREAM STRUCTURAL LAYOUT

The leaves are constructed of welded structural steel with both horizontal and vertical framing. The downstream side of the leaf consists of a pattern of rectangular chambers closed on five faces and partially open to the water on the sixth face. The upstream face of the leaf is covered with a single skin plate measuring 213 cm (7 ft) wide by 229 cm (7 ft - 6 in.).

The main (large) chambers (chambers A and B) on the downstream face of the gate are set in four columns and are approximately 53 cm (1 ft - 9 in.) wide by 46 cm (1 ft - 6 in.) high and a depth of 30.5 cm (12 in.). The A chambers are partially faced on the top and bottom and on one side by steel plates that are 10 cm (4 in.) wide, and the B chambers are partially faced only on the top and bottom by steel plates that are also 10 cm (4 in.) wide. The six smaller bottom chambers (chambers C and D) are somewhat smaller — approximately 33 cm (13 in.) wide by 46 cm (1 ft-6 in.) high with a depth of 30.5 cm (12 in.). The two outermost D chambers are partially faced on the top and bottom and on one side by steel plates that are 10 cm (4 in.) wide, and Chamber C is partially faced only on the top and bottom by steel plates that are also 10 cm (4 in.) wide.

F-2. Design Data

The following information *must* be known to design a CP system for this example application or for any other gate leaf structure and environment:

a. The lock is located in fresh water with a resistivity of 1900 ohm-centimeters. Note that this information must be measured either onsite or from sample of water obtained onsite. The sample should be obtained when the water onsite is at it's highest resistivity, which is usually in the fall, when rainfall and run-off are at their lowest for the year).

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 percent of the area bare due to holidays in the coating.

e. The coating will deteriorate during 20 years of exposure. Based on recent experience with the coating systems presently being applied in the field, it is reasonable to assume that 15 percent of the surface area will become bare in 20 years.

f. Design for 75.35 mA/m2 (7.0 mA/ft2) (moving fresh water).

g. Design for a 20-year life.

h. Design for normally submerged surface areas.

i. For galvanic anode systems, anode specifications must be based on the maximum (final) current requirement over the design life because the current cannot be readjusted over time.

F-3. Computations

a. Find the Surface Area to be Protected

(1) Upstream Side

i. Area of Skin Plate: The gate leaf has an overall height of 2.29 m and is sometimes completely submerged. The width of the gate covered by the skin plate measures 2.13 m. Therefore, the submerged surface area of the skin plate is 2.29 m x 2.13 m = 4.88 m^2 (52.5 ft^2).

(2) <u>Downstream Side</u>

i. Largest-Area Downstream A-Chamber Areas: Eight larger chambers adjacent to the skin plate each have the surface area of a cube on the interior less the open part of the downstream side plus the exterior 10 cm (4 in.) wide surface plate on three sides. The cube surface area is the sum of their six side areas, or [2 x (0.53m x 0.46m + 0.53m x 0.30m + 0.46m x 0.30m) = 2 x 0.541 m^2 = 1.08 m^2] minus the open area of [0.25 x 0.43 = 0.11 m^2] plus the outside surface area of the 10 cm plate perimeter on three side of [0.10 x (0.53 + 0.53m + 0.25) = 0.131 m^2] = 1.08 m^2 – 0.11 m^2 + 0.131 m^2 = 1.10 m^2.

ii. Second-Largest-Area Downstream B-Chamber Areas: Eight larger chambers adjacent to the skin plate each have the surface area of a cube on the interior minus the open part of the downstream side plus the exterior 10 cm (4 in.) wide surface plate on three sides. The cube surface area is the sum of their six side areas [2 x (0.53m x 0.46m + 0.53m x 0.30m + 0.46m x 0.30m) = 2 x 0.541 m^2 = 1.08 m^2] minus the open area of [0.25 x 0.53 = 0.13 m^2] plus the outside surface area of the 10 cm plate perimeter on two sides of [0.10 x (0.53 + 0.53m) = 0.106 m^2] = 1.08 m^2 – 0.13 m^2 + 0.106 m^2 = 1.06 m^2.

iii. Smaller-Area Downstream C-Chamber Areas: Eight of these normally submerged chambers adjacent to the skin plate each have the surface area of a cube on the interior minus the open part of the downstream side plus the exterior 10 cm (4 in.) wide surface plate on three sides. The cube surface area is the sum of their six side areas [2 x (0.33m x 0.46m + 0.33m x 0.30m + 0.46m x 0.30m) = 2 x .39 m^2 = 0.78 m^2] minus the open area of [0.23 x 0.25 = 0.06 m^2] plus the outside surface area of the 10 cm plate perimeter on three side of [0.10 x (0.33 + 0.33m + 0.25) = 0.091 m^2] = 0.78 m^2 – 0.06 m^2 + 0.091 m^2 = 0.81 m^2.

iv. Smallest-Area Downstream D-Chamber Areas: Eight larger normally submerged chambers adjacent to the skin plate each have the surface area of a cube on the interior minus the open part of the downstream side plus the exterior 10 cm (4 in.) wide surface plate on three sides. The cube surface area is the sum of their six side areas [2 x (0.33m x 0.46m + 0.33m x 0.30m + 0.46m x 0.30m) = 2 x .39 m^2 = 0.78 m^2] less the open area of [0.23 x 0.25 = 0.06 m^2] plus the outside surface area of the 10 cm plate perimeter on two side of [0.10 x (0.33 + 0.33m) = 0.066 m^2] = 0.78 m^2 – 0.06 m^2 + 0.066 m^2 = 0.79 m^2.

(3) *Create a Summary Table of Area for Each Chamber*

TABLE F-1. CHAMBER AREA VALUES

				Area Each		**Area Total**	
Chamber or Surface ID	**Side of Gate**	**Type of Area**	**Total of Each**	**m^2**	**ft^2**	**m^2**	**ft^2**
A	Downstream	Chamber	8	1.1	11.8	8.8	94.7
B	Downstream	Chamber	8	1.06	11.4	8.5	91.5
C	Downstream	Chamber	2	0.81	8.7	1.62	17.4
D	Downstream	Chamber	4	0.79	8.5	3.16	34.0
Skin	Upstream	Chamber	1	4.88	52.5	4.88	52.5
Total Submerged Area						27.0	290.2

b. Calculate the Current Required for a Single Structure Component

$$I = A \times I'(1.0 - C_E) \qquad [EQ\ 1]$$

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)

Skin plate requirement:

$I = 4.88\ m^2 \times 75.35\ mA/m^2 \times (1 - .085) = 55.2\ mA$

c. Create a Table of Current Requirements for Each Structure Component

TABLE F-2. CURRENT REQUIREMENTS FOR EACH STRUCTURE COMPONENT

Chamber or Surface ID	**Side of Gate**	**No. of this Type**	**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	Downstream	8	1.1	75.35	0.15	1	12.4	99.2
B	Downstream	8	1.06	75.35	0.15	1	12.0	96
C	Downstream	2	0.81	75.35	0.15	1	9.2	18.4
D	Downstream	4	0.79	75.35	0.15	1	8.9	35.6
Skin	Upstream	1	4.88	75.35	0.15	1	55.2	55.2
Total Current Required:								304.4

* To ensure uniform current distribution, it is normally good design practice to provide at least 1 galvanic anode per 10 m^2 structure surface to be protected.

F-4. Anode Design Based on Using Flush-Mounted Slab or Disk Anodes

a. Select Anode Alloy

Refer to Appendix C, Table C-3, for current output data associated with magnesium and zinc alloys. Because the water resistivity is approximately 1900 ohm-cm, and considering both the current output available and required anode life, it is apparent that the preferred alloy anode material is either H-1 Grade A or B magnesium alloy. Should none of the available shapes provide sufficient current, then we would re-evaluate using high-potential magnesium alloy anodes. If anode life would be too short with either magnesium alloy, then consider using high-purity zinc alloy anodes.

b. Select Anode Size

Size is based on 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 because designing the smaller components is easier and will help familiarize the designer with the process.

(1) Chamber D

i. Current Required = 8.9 mA

ii. Initial Anode Selection: Refer to Tables C-4 through C-10 and select the chart with the resistivity closest to that of the measured water resistivity. In this case, the water resistivity is 1900 ohm-cm, so consult Table C-6. That table includes a bar chart of the data it presents, and the chart makes it easy to determine which anodes may be appropriate for the D-chambers. From the chart, we could consider the use of the 1x6x12SBE in high-purity zinc (output = 12 ma), a 2x6x12SCE also in high-purity zinc (output = 9 ma), or a 2x5RCE in H-1 alloy magnesium (output = 13 ma).

iii. Anode Selection Based On Life: We want the anode to last 20 years. Figure C-2 indicates that only the 2x5RCE magnesium anode will not have enough life (20 years desired) at 13 ma output. Figure C-3 indicates that both zinc anodes have the required life at their respective outputs of 9 ma and 12 ma. Since the 2x6x12SCE has sufficient life and will provide the desired current for this chamber, we will install one 2x6x12SCE plastisol-coated high-purity zinc alloy anode for the two D-chambers. We also check Table F-2 and note that one anode per chamber is all that is required for good current distribution in these chambers.

(2) Chamber C

i. Current Required = 9.2 mA

ii. Initial Anode Selection: Refer to Tables C-4 through C-10 and select the chart with the resistivity closest to that of the measured water resistivity. Since the water resistivity is 1900 ohm-cm, consult Table C-6. That table includes a bar chart of the data it presents, and the chart makes it easier to discern which anodes may be appropriate for the C-chamber. From the chart, we could consider the use of the 1x6x12SBE in high-purity zinc (output = 12 ma) or a 2x5RCE in H-1 alloy magnesium (output = 13 ma). Because the actual water resistivity is 5% less than the chart value of 2000 ohm-cm, the anodes will put out 5% more current than Table C-6 indicates. Thus we can also consider the use of the 2x6x12SCE in high-purity zinc (output in 1900 ohm-cm = 9.5 ma).

iii. Anode Selection Based On Life: We want the anode to last 20 years. Figure C-2 indicates that only the 2x5RCE magnesium anode will not have enough life (20 years desired) at 13 ma output. Figure C-3 indicates that both zinc anodes have the required life at their respective outputs of 9.5 ma and 12 ma. Because the 2x6x12SCE has sufficient life and will provide the desired current for this chamber, we will install one 2x6x12SCE plastisol-coated high-purity zinc alloy anode for the four C-chambers. Again, we also check Table F-2 and note that one anode per chamber is all that is required for good current distribution in these chambers.

(3) *Chamber B*

i. Current Required = 12 mA

ii. Initial Anode Selection: Refer to Tables C-4 through C-10 and select the chart with the resistivity closest to that of the measured water resistivity. Since the water resistivity is 1900 ohm-cm, consult Table C-6. That table includes a bar chart of the data it presents, and the chart makes it easier to discern which anodes may be appropriate for the B-chambers. We will not consider the 5 in. round magnesium anode since we already know its life will not be sufficient. Thus, from the chart, we see that the only anode we should consider in magnesium is the 1x6x12SCE in H-1 alloy (output = 23 ma) or the 2x6x12SBE in zinc alloy (output also = 12 ma).

iii. Anode Selection Based On Life: We want the anode to last 20 years. Figure C-2 indicates that the 1x6x12SCE in H-1 alloy magnesium will not have enough life (20 years desired) at 23 ma output. Figure C-3 indicates that the 2x6x12SBE in zinc alloy (output also = 12 ma) will have the required life. Because the 2x6x12SCE has sufficient life and will provide the desired current for this chamber, we will install one 2x6x12SBE plastisol-coated high-purity zinc alloy anode for the eight B-chambers. Also, since we are using zinc with a maximum driving potential of 1100 mV versus a Cu-$CuSO_4$ reference electrode, we do not have to worry about cathodic debonding of the coating adjacent to the anode. Therefore, no additional dielectric shielding is needed behind the anode other than the plastisol coating that will be left in place on the back side of the anodes and on the core extensions (except around the mounting bolts where the plastisol must be removed to provide electrical contact between the bolt, core, anode, and lift gate). Again, we also check Table F-2 and note that one anode per chamber is all that is required for good current distribution in these chambers.

(4) Chamber A

i. Current Required = 12.4 mA

ii. Initial Anode Selection: Refer to Tables C-4 through C-10 and select the chart with the resistivity closest to that of the measured water resistivity. Again, the water resistivity is 1900 ohm-cm, so consult Table C-6. That table includes a bar chart of the data it presents, and the chart makes it easier to discern which anodes may be appropriate for the A-chambers. We will not consider the 5 in. round magnesium anode since we already know its life will not be sufficient. Thus, Table C-6 indicates that the only anode we should consider in magnesium is the 2x6x12SBE in zinc alloy (output = 12.6 ma in 1900 ohm-cm water = 5% greater than the chart value of 12 ma in 2000 ohm-cm water).

iii. Anode Selection Based On Life: We want the anode to last 20 years. Figure C-2 indicates that the 1x6x12SCE in H-1 alloy magnesium anode will not have enough life (20 years desired) at 23 ma output. Figure C-3 indicates that the 2x6x12SBE in zinc alloy (output also = 12 ma) will have the required life. Since the 2x6x12SCE has sufficient life and will provide the desired current for this chamber, we will install one 2x6x12SBE plastisol-coated high-purity zinc alloy anode for the eight A-chambers. Again, since we are using zinc with a maximum driving potential of 1100 mV versus a Cu-CuSO$_4$ reference electrode, we do not have to worry about cathodic debonding of the coating adjacent to the anode. Therefore, no additional dielectric shielding is needed behind the anode other than the plastisol coating that will be left in place on the back side of the anodes and on the core extensions (except around the mounting bolts where the plastisol must be removed to provide electrical contact between the bolt, core, anode and lift gate). Note we also check Table F-2 to see that one anode per chamber is all that is required for good current distribution in these chambers.

(5) Skin Plate

i. Current Required = 55.2 mA

ii. Initial Anode Selection: Refer to Tables C-4 through C-10 and select the chart with the resistivity closest to that of the measured water resistivity. Since the water resistivity is 1900 ohm-cm, consult Table C-6. That table includes a bar chart of the data it presents, and the chart makes it easier to discern which anodes may be appropriate for the skin plate. We note that the only single H-1 alloy anode with sufficient capacity to protect the entire skin plate of the gate leaf is the 4x9x18SBE anode. However, this bare-edge magnesium anode would require the use of a supplementary dielectric shield as discussed in the next paragraph. Because such use is not recommended, we will consider the use of two anodes instead with each having an output of at least 28ma. The 2x8x8SCE high-potential magnesium alloy anode (30 ma output), the 2x6x12SCE high-potential magnesium alloy anode (32 ma output), and the 2x9x18SCE H-1 alloy magnesium anode (37) could be used. Any one of these three anodes could be used based on their current output.

iii. Use of Plastisol Coatings: Plastisol restricts the current flow to the anode face, but after the coating is cut away from the face it improves current distribution (for magnesium anodes only on coated structure and for both zinc and magnesium on bare structures) because current from the sides of the anode cannot flow to the steel immediately adjacent to the anode. With bare-edge magnesium anodes, it is necessary to place a neoprene rubber shield behind the anode which is extended beyond the anode perimeter at least 2 in. This shield must be glued in place, typically using 100% silicon caulk. Unfortunately, this shielding material can be damaged by the ice and debris floating down the river and impacting primarily on the exposed skin plate anodes. Thus, it is normally recommended that the skin plate anodes be entirely coated with plastisol, with a window cut from the coating on the anode face to expose the operating surface. Therefore, we will not consider the use of bare-edge magnesium anodes for any upstream gate or leaf surface. Bare-edge zinc anodes may be used on coated skin plates since the coating will function as the dielectric shield without being damaged by the anode current output over the system design life.

iv. Anode Selection Based On Life: We want the anode to last 20 years. Using Figure C-2, we see that the 2x8x8 anode will only last about 15 years at 30 ma and therefore is not suitable for this project. The 2x6x12 also falls slightly short of the desired life at 32 ma output. Only the 2x9x18SCE H-1 alloy anode will work, providing over 30 years life at 37 ma current output. Thus, we will install two 2x9x18SCE H-1 magnesium alloy anodes with plastisol-coated back and sides to protect the skin plate. It should be noted that the use of two anodes exceeds the minimum number of one anode required for good current distribution, as shown in Table F-2.

c. 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, B, C, and D

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 both vertically and horizontally on the back surface of the each chamber to receive a single anode.

(2) Skin Plate

Since the skin plate will usually require two anodes that will be distributed uniformly both vertically and horizontally , the design procedure is somewhat simpler than that for the larger structures designed earlier in this document. Geometrically, the two anodes can either be distributed vertically along the vertical bisector of the leaf or horizontally along the horizontal bisector. Since the leaf is taller than it is wide, we choose the former vertical layout. The topmost anode is simply located one-quarter the way down from the top of the leaf (2.29 m x

0.25 = 0.57 m) and the bottom anode is located one-quarter the way up from the bottom of the leaf (also 0.57 m).

The layout for these anodes on the skin plate is shown below in Figure F-3.

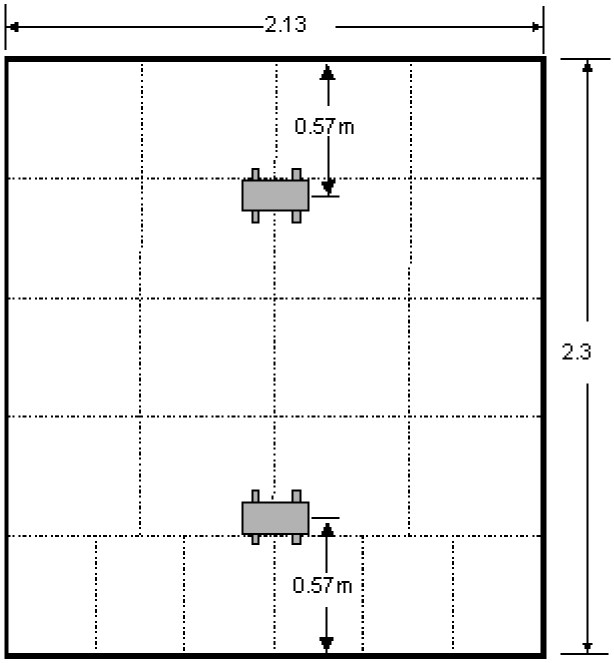


FIGURE F-3. ANODE CONFIGURATION ON UPSTREAM SKIN PLATE SIDE OF GATE.