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US Army Corps
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ENGINEERING AND DESIGN

Cathodic Protection Systems for Civil Works Structures

ENGINEER MANUAL

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Engineering and Design

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

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

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

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

FOR THE COMMANDER:

13 Appendices
(See Table of Contents)

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

Contents

Chapter 6: System Operation and Maintenance

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

Appendixes

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4. References. References are listed in Appendix A.

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

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

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Chapter 1
Introduction

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

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

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

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

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

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

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

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

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

1.3 Corrosion Prevention and Control Program and Plan.

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

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

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

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

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

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

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

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

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

1.4 Training and Available Services.

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

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

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

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

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

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

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Chapter 2
Cathodic Protection System Types

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

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

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

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

Figure 2.1. Slab Type Anode

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

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

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

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

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

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

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

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

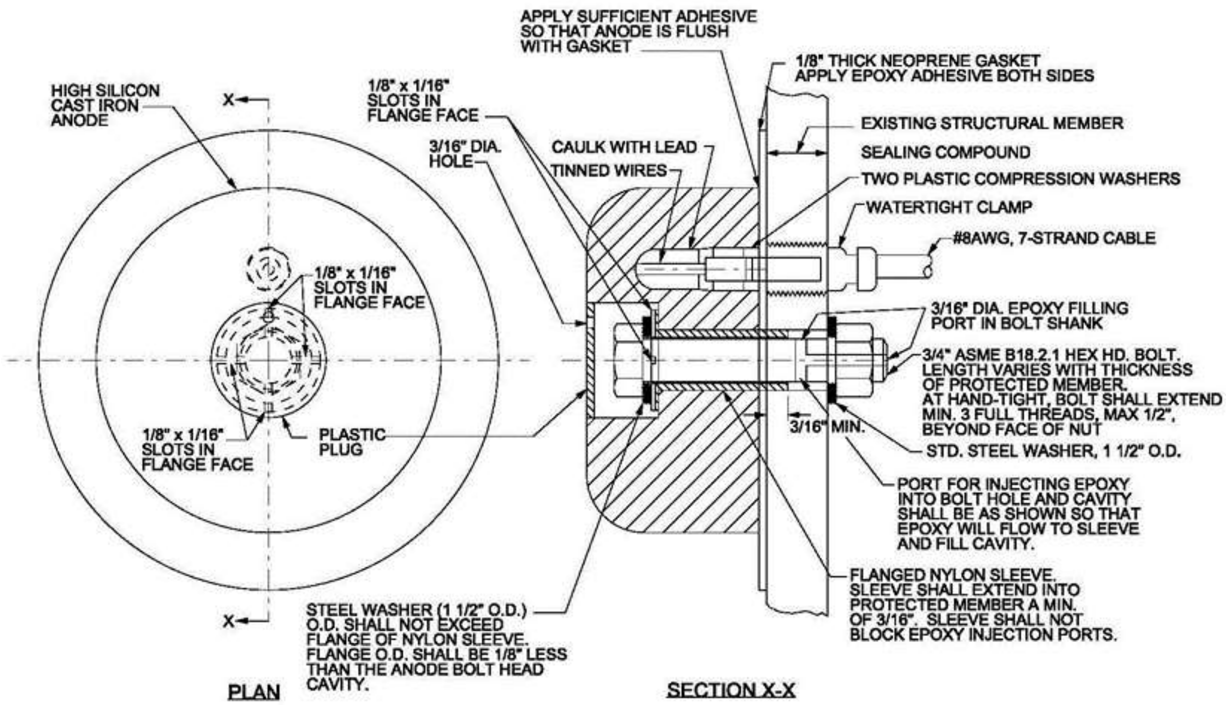

Figure 2.2. High Silicon Cast Iron (HSCI) Button Anode

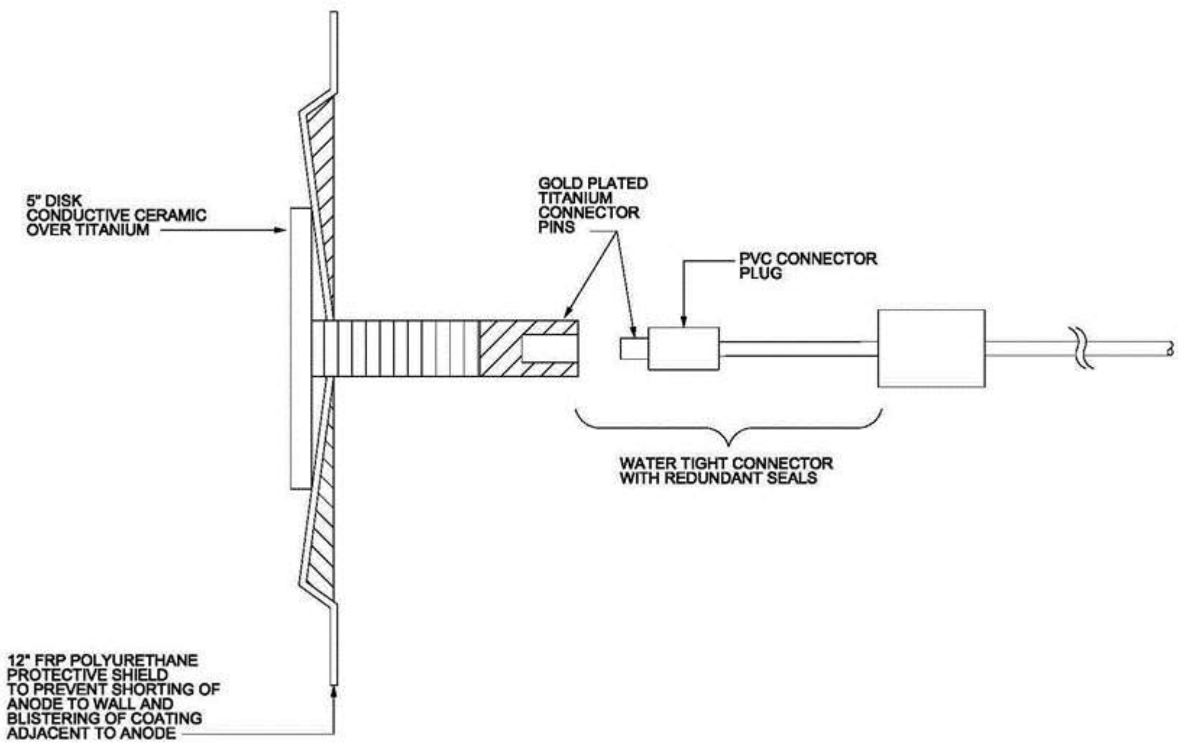

Figure 2.3. Ceramic Coated Flat Disk Anode

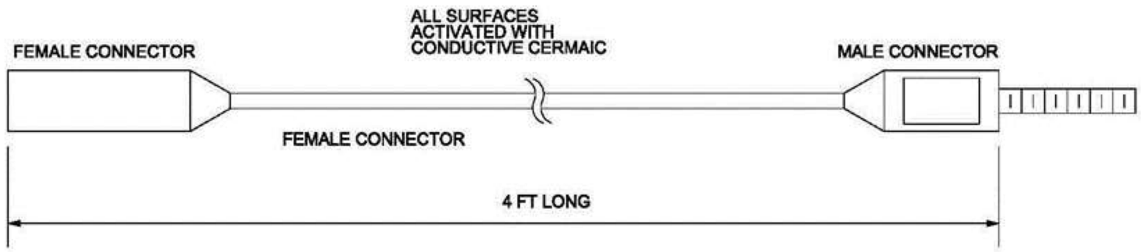

Figure 2.4. Rod Anode Segment

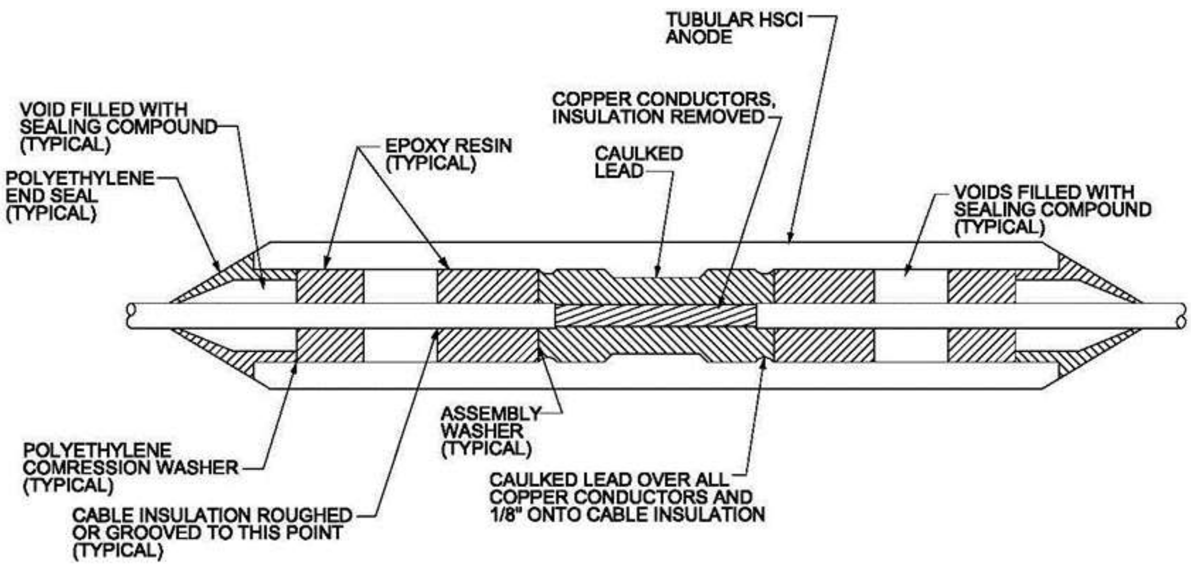

Figure 2.5. High Silicon Cast Iron Sausage or String Anode

Chapter 3
System Selection

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

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

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

c. Advantages of an Impressed Current System.

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

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

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

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

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

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

d. Disadvantages of an Impressed Current System.

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

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

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

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

e. Advantages of a Galvanic Anode System.

(1) External power source is not required.

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

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

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

f. Disadvantages of a Galvanic Anode System.

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

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

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

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

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

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

Chapter 4
Cathodic Protection System Design

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

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

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

4.2 USACE Criteria for HSS.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

4.4 Other Design Considerations.

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

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

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

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

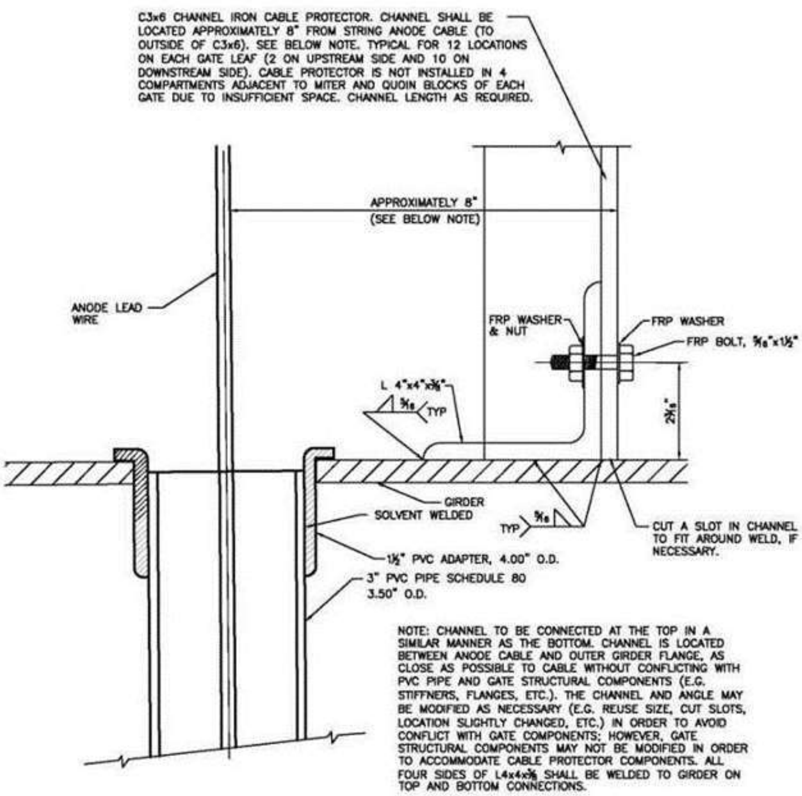

Figure 4.1. Anode Protection Pipe Upper Girder Termination

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

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

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

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

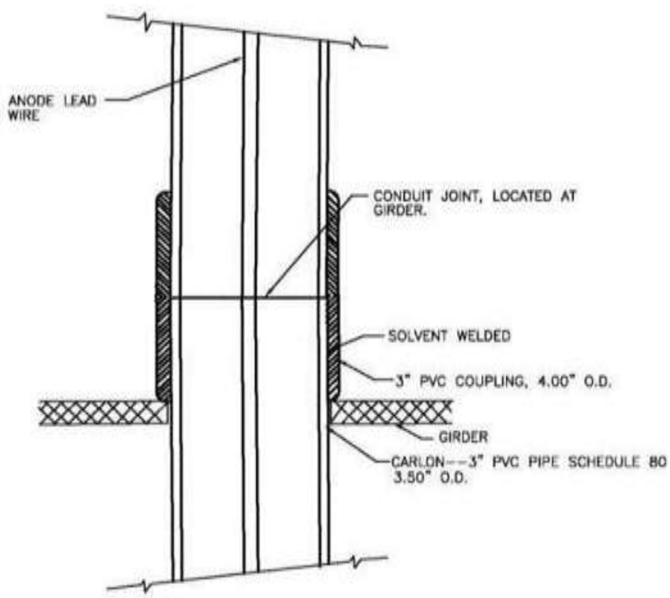

Figure 4.2. Anode Protection Pipe Girder Penetration

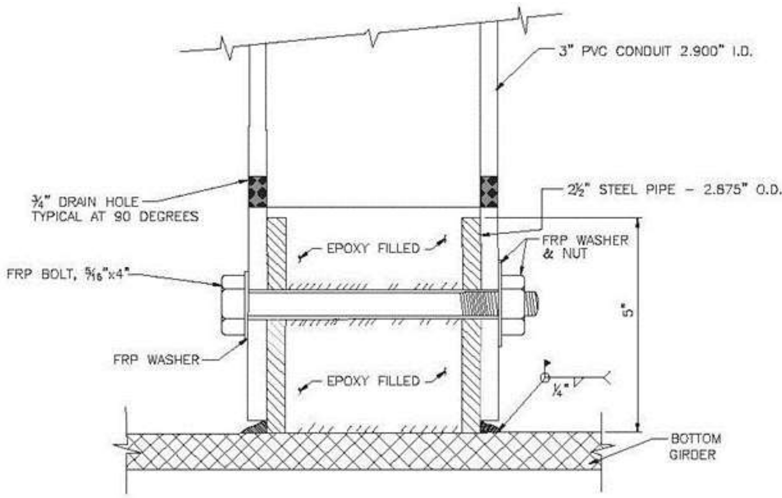

Figure 4.3. Anode Protection Pipe Bottom Girder Termination

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

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

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

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

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

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

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

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

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

b. Guide Specifications.

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

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

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

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

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

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

Chapter 5
System Testing and Optimizing

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

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

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

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

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

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

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

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

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

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

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

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

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

5.3 Galvanic (Sacrificial) CPS Criterion. The criterion of protection for use with galvanic anode CPSs in relation to submerged surfaces of HSS is as follows: a negative polarized voltage of at least 850 mV as measured between the structure and a saturated copper-copper-sulfate reference electrode contacting the electrolyte.

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

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

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

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

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

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

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

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

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

Chapter 6
System Operation and Maintenance

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

g. When available, this information is to be obtained and provided in an appendix to the CPS design analysis and must be used appropriately in the CPS design calculations. Also, notes to Appendix G of this manual discuss insufficient collection and confirmation of resistivity data. As stated above, if possible, water quality data are to be obtained for a period of several years and analyzed for use in the CPS design.

h. In general, cooler waters have more capacity for dissolved oxygen than warmer waters. Since oxygen is necessary for corrosion to occur, greater oxygen content results in greater corrosivity. That is, with respect to dissolved oxygen content, corrosivity varies inversely with temperature.

i. In addition, some periodic operation activities that occur at navigation locks on a regular basis contribute to the aeration of water, such as operation of air bubbler systems, boat propellers, and the valves to allow the lock chamber water level to be raised or lowered. Some periodic operation activities that occur at powerhouse facilities on a regular basis also contribute to the aeration of water, such as the generation of power (i.e., turning of turbines).

j. However, it is also generally true that conductivity increases with higher temperatures and corrosivity increases with higher conductivity. Consequently, with respect to conductivity, warmer waters are generally more corrosive than cooler waters. That is, generally speaking, conductivity varies directly with temperature. Hence, conductivity generally varies in opposition to the variation of dissolved oxygen content, with respect to temperature.

k. If water quality data are analyzed, one will generally conclude that higher chloride levels are consistent with higher conductivity. For example, if it were discovered that water quality data indicated the highest chloride content measured at some specific point in time was 204 mg/L, then it would also be expected that the conductivity of the water at that same point in time would be found to be much higher than the conductivity of common potable water.

l. As a guide for comparison, the chloride content of potable water is about 50 mg/L and below whereas brackish water is about 500 mg/L and higher. The conductivity of brackish water and salt water is much higher than the conductivity for common potable water.

m. For fresh water, a 204 mg/L chloride content is high. Consequently, special care should be practiced when selecting stainless steel materials, in particular, for future work in relation to HSS since some stainless steels are more affected by chlorides than others.

n. With above discussion, since conductivity is generally considered to be the more dominant variable affecting corrosion, warmer waters are generally considered more corrosive than cooler waters. With respect to dissolved oxygen content, conductivity, and temperature, one will generally find that the data obtained from water monitoring stations in the vicinity of the project will usually correspond to the generalities stated above. However, this data will also reveal any anomalies from these generalities stated above.

o. In general, pH above 4 is not a significant factor of influence on corrosivity.

p. For corrosion risk assessment purposes, it is usually desirable to estimate the overall water corrosivity. One of the simplest classifications is based on a single parameter, water resistivity.

q. Based on experience, for use in relation to HSS, the corrosivity ratings can reasonably be designated as: essentially non-corrosive (greater than 20,000 ohm-cm), mildly corrosive (10,000 to 20,000 ohm-cm), moderately corrosive (5,000 to 10,000 ohm-cm), corrosive (3,000 to 5,000 ohm-cm), highly corrosive (1,000 to 3,000 ohm-cm), and extremely corrosive (less than 1,000 ohm-cm).

r. Consequently, if the average of the conductivity (reciprocal of resistivity) measurements provided in relation to water environment for any given project was found to be 4,000 ohm-cm over a period of several years. Using the corrosivity scale defined above, the waters at this location for this period of time should be considered as "corrosive."

7.3 Special Corrosion Considerations.

a. Inability to Electrically Isolate and Bare Metal Exposure. Cathodic protection engineers and technicians have long realized that the measured impressed current CPS potentials on the submerged surfaces of lock miter gates are generally lower in areas near the lock chamber concrete walls and sills than they are at other submerged gate surfaces.

b. Various improvements in the impressed current systems have been incorporated to increase the low potentials in these areas. Much of this effect can be attributed to the inability to electrically isolate the cathodic protected miter gate structure (primarily coated) from embedded metals and the bare stainless steel or carbon steel miter and quoin blocks, and corresponding wall blocks.

c. It would be impossible to totally isolate these miter gates from the electrical grounding conductors, all the bare rebar, and other embedded metals located in the concrete lock walls and sills near the miter gates, and the miter and quoin blocks (including the quoin wall blocks). In fact, it would also pose a safety hazard to isolate the miter gates from the electrical grounding conductors.

d. Correct application of the National Electrical Code would make the gates electrically continuous with the grounding grid. (Note: The inability to electrically isolate the gates from other metals is an important reason for not using a sacrificial or galvanic anode system and/or a sacrificial coating, such as thermal sprays, on these particular structures.)

e. Gates must be effectively grounded, as defined in the National Electrical Code, including to the electrical grounding systems. This also includes all of the gate handrails, lock wall handrails, and other metallic structures that are easily accessible by personnel. These ancillary structures should be connected to a common electrical ground to ensure personnel safety.

f. Consequently, a large degree of electrical continuity between the gate structural steel and surrounding embedded metals would be expected. In addition, experience has shown that, at most locks, it is very difficult to meet NACE potential criteria in areas of the gates adjacent to lock walls, even with the adjustable impressed current systems.

g. Experience has indicated that external sacrificial systems cannot provide sufficient protective current in these areas and bare sacrificial coating systems would most likely fail. In many locations, potential measurements, taken with respect to a copper/copper-sulfate reference electrode, have been consistently low in these areas.

h. In addition to the above described problem, bare stainless steel miter blocks, quoin blocks, and quoin wall blocks have been installed on many USACE navigation lock miter gates. These blocks are attached directly to the gates and cannot be electrically isolated from the gates.

i. The wall-mounted blocks are at least in electrical contact when the gates are closed. However, since pitting corrosion has been observed even on stainless steel wall-mounted blocks at some navigation locks (e.g., Bankhead Lock), the wall blocks should always be electrically bonded to the miter gate structure to ensure that the wall blocks are protected by the impressed current CPS. Coatings cannot be applied to the block points of contact, leaving only exposed metal in these areas.

7.4 Dissimilar Metals. As mentioned in the preceding paragraph, dissimilar metal corrosion (e.g., stainless steels to carbon steels) is also a very common problem in relation to HSS. Electrical continuity between various dissimilar metals is a cause of much of the corrosion found at various HSS, including navigation lock miter gates. Material selection is very important when it comes to corrosion prevention. The section discusses corrosion caused by electrical continuity between dissimilar metals in immersion service.

a. As in an operational battery circuit, for electrochemical corrosion to occur in relation to any metallic structure operating in an electrolyte (i.e., water in this case), four electrical circuitry components must exist to allow the corrosion current to flow: (1) an anode, (2) a cathode, (3) an electrolyte, and (4) a metallic conductive path between the anode and the cathode.

b. For example, the following is assumed in this discussion: the cathode is stainless steel; the anode is carbon steel; the stainless steel and carbon steel are directly connected to each other (i.e., they are electrically continuous with each other); both metals are submerged in water; and there is no external CPS applied so as not to confuse the use of the term “anode” as used in this illustration.

c. Therefore, given these assumptions, the cathode would be the stainless-steel material that is electrically bonded to the carbon steel material (the anode in this case). Since the carbon steel and stainless steel are electrically bonded together and they are all assumed to be in contact with water, the carbon steel will act as an anode and, subsequently, will corrode (sacrifice itself) to protect the stainless steel.

d. Even though the carbon steel would be coated, the coating system will still have defects, holidays, and otherwise damaged areas that allow these areas to act as anodes so that corrosion will occur at these locations. This type corrosion is referred to as galvanic or dissimilar metal corrosion.

e. Galvanic corrosion between coated carbon steel surfaces and uncoated stainless steel surfaces is likely to occur as pitting corrosion, since small defects (holidays) in the coating system expose small areas of the carbon steel substrate, which act like small anodes trying to “protect” a large cathode (i.e., bare stainless steel) by allowing the carbon steel surface to corrode.

f. A higher corrosion rate than the rate that is generally predicted as a result of uniform corrosion will occur at these small carbon steel anodes because of their connection to a larger bare stainless-steel cathode. This corrosion will eventually result in pitting at the coating defects.

g. It is critical to recognize that the corrosion observed on miter gates is not a uniform corrosion, especially since HSS are coated structures. From a strictly corrosion control perspective, adding extra metal thickness to structural members, to serve as a “corrosion allowance” provides little benefit.

h. If corrosion is non-uniform, then attempting to predict a reasonable or expected corrosion rate for any specific location on the miter gate surface where a coating imperfection or flaw may exist is impractical (at least), if not impossible. There is no way to know precisely where coating imperfections might exist, or whether those imperfections might occur in an area of the steel substrate that might be exposed to the water.

i. An additional precautionary note should be made regarding dissimilar metal corrosion. Materials and procedures used in the welding processes should also be carefully evaluated to ensure galvanic corrosion (or dissimilar metal corrosion) does not occur at welded areas. Consequently, weld joints should be inspected by an American Welding Society Certified Welding Inspector and due diligence should be given to corrosion issues related to weld joints and adjacent areas that may be adversely affected by the welding process.

7.5 Corrosion of Carbon Steel Miter, Quoin, and Wall Blocks (Miter Gates). When carbon steel materials are used for the miter blocks, quoin blocks, and quoin wall blocks on miter gates, then an additional and different type of corrosion issue is introduced in relation to the HSS.

a. As stated earlier, the contact surfaces between the miter blocks and the gate quoin blocks and their associated wall quoin blocks cannot be coated with a conventional dielectric coating system. Consequently, these surfaces are left bare.

b. When these miter and quoin block surfaces are in mechanical contact (i.e., the miter gates are in the closed position), crevices are created between the mating surfaces. Below the water line, even a perfectly operating impressed current CPS system (much less a galvanic CPS) cannot provide protective current to the bare steel surfaces concealed within the crevices.

c. Consequently, since these mating surfaces are generally not coated (e.g., Belzona™, at times, is used to resurface damaged blocks) and CPS protective current cannot reach the surfaces to mitigate the corrosion, corrosion will occur on these surfaces. Because of the corroding blocks, gate leaks will also eventually occur.

d. As the corrosion continues and the corrosion bi-product washes away, the leaks will undoubtedly become worse. Gate leaks work against the achievement of adequate corrosion control on the miter gate surfaces affected by the leaks even if a viable CPS is installed on the gates.

e. Protective polarization is adversely affected, resulting in a higher protective current demand (to effectively prevent corrosion) in the gate areas affected by the leaks. Moreover, the difficulty encountered when taking close interval potential survey measurements makes it very hard, if not impossible, to obtain potential measurements across the submerged steel gate surfaces affected by the leaks. This, in turn, makes it more difficult to make customized adjustments in those areas, if needed.

f. This miter and quoin block corrosion process may result in structural loading imbalances because of the loss of metal in these areas resulting from corrosion. Although detailed case studies have most likely not been performed on this particular theory, some structural engineers theorize that the changing load path (from the loss of bearing) in the miter and quoin blocks may result in unanticipated structural loading and stress cracking in the pintle socket area and lower quoin area of the gate.

g. If this particular theory is correct, then it would appear that, while corrosion is not a direct cause of the gate and pintle socket cracks, it may (minimally) be at least one indirect contributing factor to the initiation of these stress cracks. (These are not necessarily corrosion fatigue cracks as discussed below, but structural stress cracks.)

h. Since a different material, other than bare carbon steel, might need to be used for miter and quoin blocks, then it appears that some additional materials research for this application may be required by the USACE laboratories such as ERDC. One common practice for repairing corrosion damaged miter and quoin blocks is the application of Belzona™, which is a dielectric material. At least some Districts seem to prefer Belzona™ although other repair methods are also available and used.

i. Therefore, research should be done regarding cladding the bare carbon steel blocks with either a durable dielectric material or possibly a different and more noble metal. Stainless steel blocks are used by some Districts to alleviate issues with corroding blocks.

j. The Tennessee-Tombigbee Waterway, Mobile District, uses many stainless-steel blocks on their navigation lock miter gates. However, these miter gates are also equipped with functional impressed current CPS, which do a good job at mitigating dissimilar metal corrosion between the coated carbon steel miter gates and the stainless-steel blocks. However, stainless steel blocks are also much more expensive than carbon steel blocks. Additional materials research is needed to resolve the issues associated with miter and quoin block corrosion.

7.6 Corrosion Allowance. For HSS, such as lock miter gates, any extra metal thickness incorporated into the structural design to meet structural life expectancy must also include an adequate corrosion control system (to include both coatings and CPS).

a. A corrosion allowance is intended to allow extra metal thickness to provide some capacity for metal loss resulting from “uniform” corrosion. Uniform corrosion means that corrosion is even across the surface of the structure. However, miter gates do not experience uniform corrosion, but, rather, primarily experience pitting corrosion since they are painted structures.

b. Without CPS, corrosion will occur where coating holidays and damage exist and the steel substrate is exposed. In painted steel areas adjacent to bare stainless steel miter and quoin blocks, the fact that stainless steel and carbon steel occupy different locations on the galvanic series combined with the fact that anodic areas will be much smaller than the cathodic area (stainless steel) results in a much higher corrosion rate at the anodic areas (i.e., gate steel) than would be anticipated for uniform corrosion.

c. These various combinations result in pitting type corrosion, not uniform corrosion. Consequently, it would be impractical, if not impossible, and costly to attempt to provide enough corrosion allowances for critical structural members in such areas instead of providing adequate CPS to supplement the coating system.

d. Since no coating system is perfect, it is also highly unlikely that any coating system acting alone will be adequate to prevent pitting corrosion from occurring in these areas and to yield the desired structure and/or coating design life. Consequently, the structural design of the miter gates is, or should be, dependent on a properly operated and maintained CPS whether specifically stated or not.

7.7 Corrosion Fatigue. Failure of a metallic structure resulting from cyclic stresses is known as fatigue failure.

a. Corrosion greatly accelerates fatigue failure of metal. Fatigue occurring in a corrosive environment is called corrosion fatigue.

b. A distinguishing feature of some corrosion fatigue is the presence of numerous cracks which could lead to structural failure. For the continued integrity of the structure, it is essential for the corrosion aspect of fatigue failure to be eliminated by maintaining the corrosion control systems including both CPS and coatings.

c. Note, however, that corrosion and existing weaknesses in the structural integrity of the gates and other components caused by corrosion cannot be repaired or undone by CPS, which can only halt any future corrosion. The more corrosion damage that is present on a structure, the more difficult it is to prevent further degradation to the structure.

7.8 Hydrogen Embrittlement. Hydrogen embrittlement is basically defined as the process by which various metals, most importantly high strength steel and some stainless steels, become brittle and crack following exposure to atomic hydrogen.

a. Although CPS could cause hydrogen embrittlement in some metals (e.g., high strength steel and some stainless steels) under certain conditions provided that the CPS were also not properly controlled, it is highly unlikely that the impressed current systems on lock miter gates could cause structural damage resulting from hydrogen embrittlement if the CPS was properly designed, installed, adjusted, operated, and maintained.

b. For hydrogen embrittlement to occur, a source to generate hydrogen has to be available. While cathodic protection could generate hydrogen at potentials more negative than –1.2 volts with reference to a $Cu/CuSO_4$ reference electrode, sources of hydrogen other than CPS also exist.

c. Because of the potential limit that should not be exceeded to avoid causing cathodic disbondment of the gate coating system, the CP potentials should be monitored and adjusted to be less negative than –1.1 volts with respect to a reference cell (which is less negative than that required for hydrogen generation by the CPS).

7.9 Corrosion from Bacteria. If bacteria activity is confirmed at any particular USACE facility where an impressed current CPS is present, the impressed current rectifiers can be adjusted to mitigate the adverse impact caused by the bacteria (i.e., increased protective potentials).

a. The impressed current system, if properly designed, installed, and maintained, will have the capacity to provide higher protective potentials, if necessary. Consequently, confirmation of such activity at any navigation lock facility should not necessitate an impressed current CPS change.

b. It is more likely that a CPS re-adjustment will suffice. However, on the other hand, if a sacrificial CPS were installed rather than the impressed current system as is required for navigation lock miter gates, then the potentials supplied by the installed sacrificial or galvanic anodes would be incapable of adjustment.

c. If most all plastisol covering had already been removed, which would necessarily be the case, anode current output could not even be increased by removing additional plastisol coating from the sacrificial or galvanic anodes. Additional protective current would be required to increase the protective potentials supplied, which can be done with the impressed current CPS.

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

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

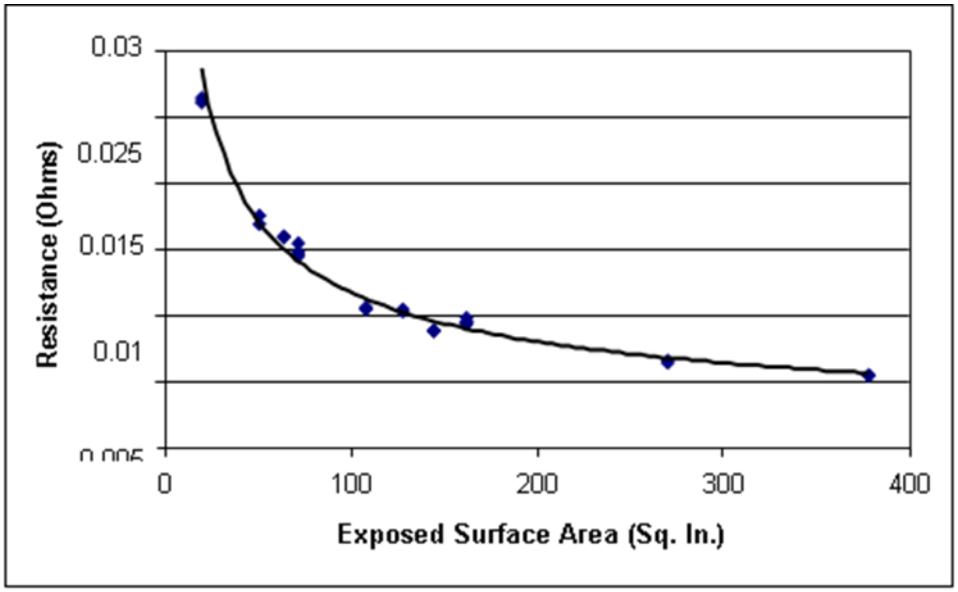


Figure B.1. Resistance vs. Anode Surface Area Normalized for 1 ohm-cm Resistivity Water

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

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

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

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

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

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

Table B.2
Approximate Anode Weight

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

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

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

Where:

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

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

P = measured resistivity of water surrounding structure to be protected

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

139,706 / 2700 = 51.74 mA

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

102,941 / 2700 = 38.13 mA

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

36,765 / 2700 = 13.62 mA

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

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

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

Where:

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

W = weight of magnesium metal in anode

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

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

I = current output of single anode in milliamperes

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

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

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

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

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

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

Where:

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

W = weight of zinc metal in anode

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

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

I = current output of single anode in milliamperes

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

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

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

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

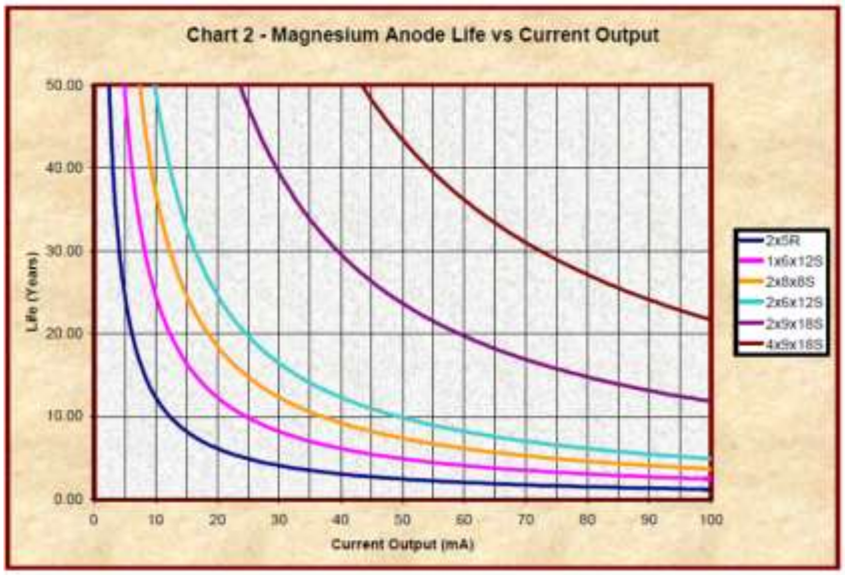


Figure B.2. Magnesium Anode Life vs. Current Output

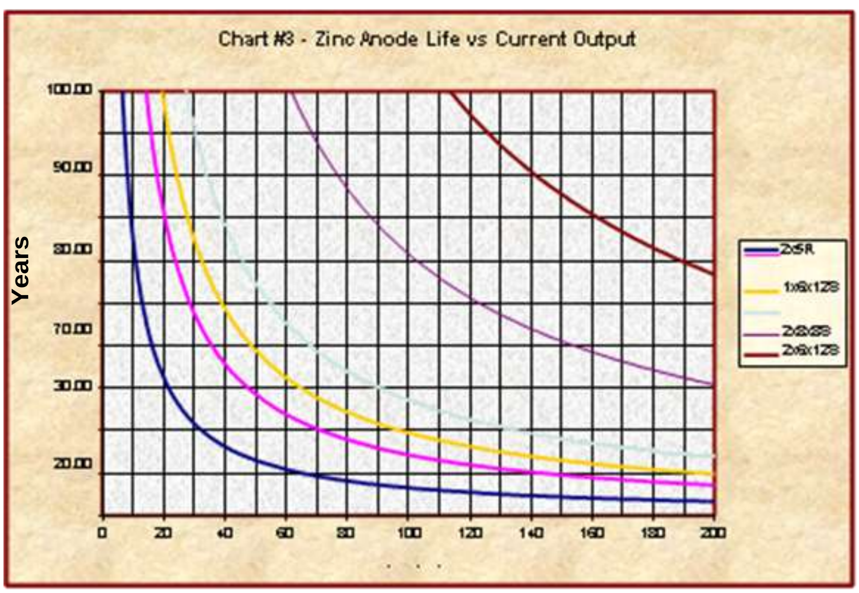


Figure B.3. Zinc Anode Life vs. Current Output

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

Table B.3
Preferred Alloys for Various Resistivity Waters

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

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

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

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

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

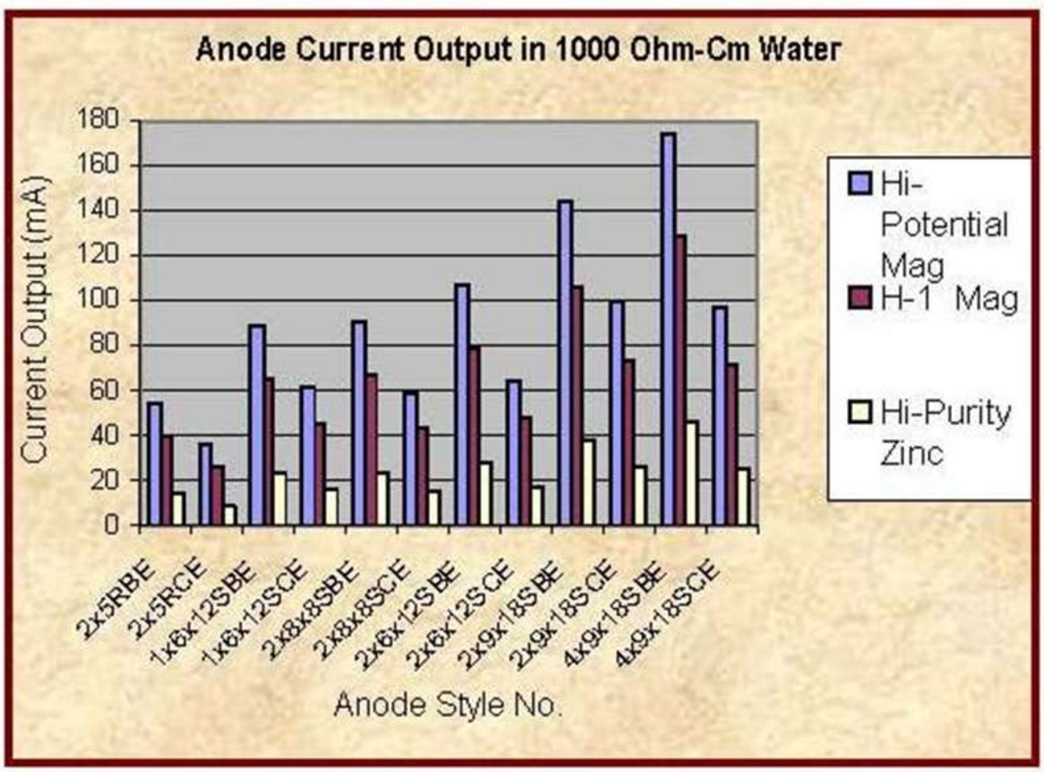


Table B.5
Anode Current Output in 1500 ohm-cm Resistivity Water

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

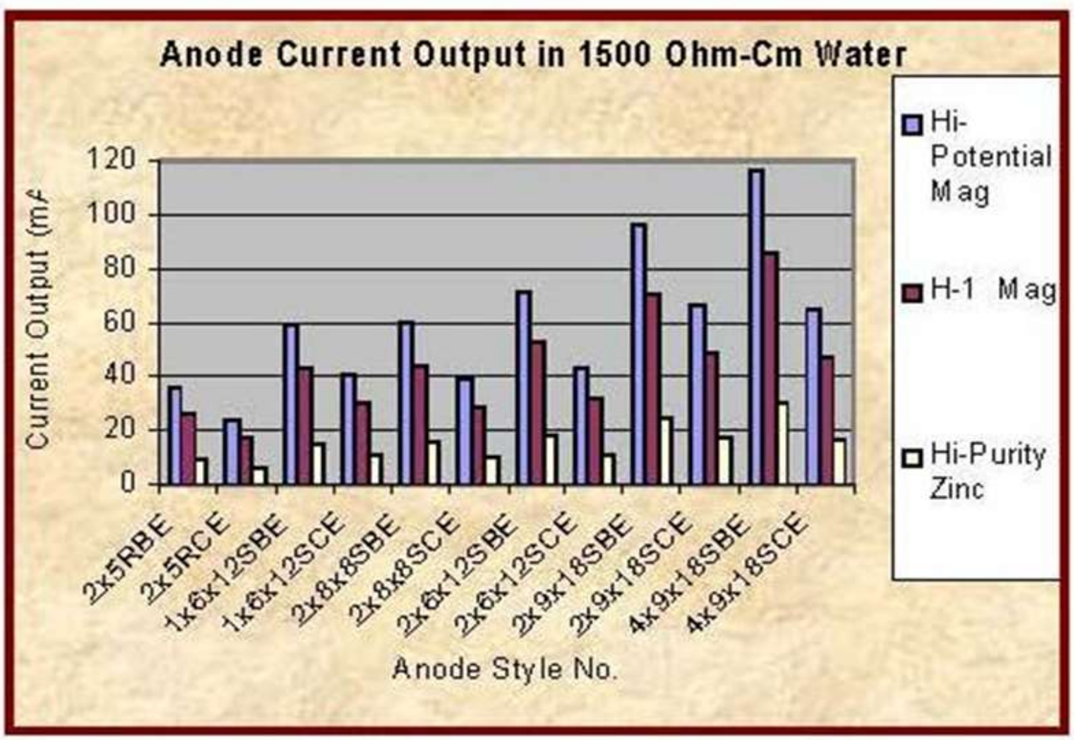
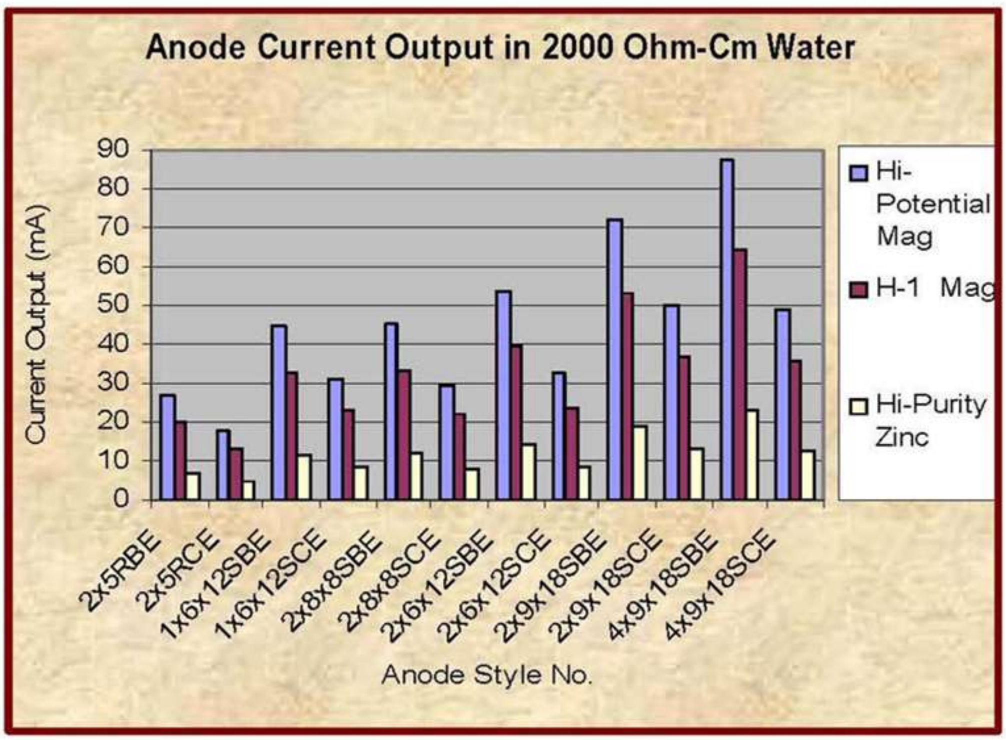


Table B.6
Anode Current Output in 2000 ohm-cm Resistivity Water

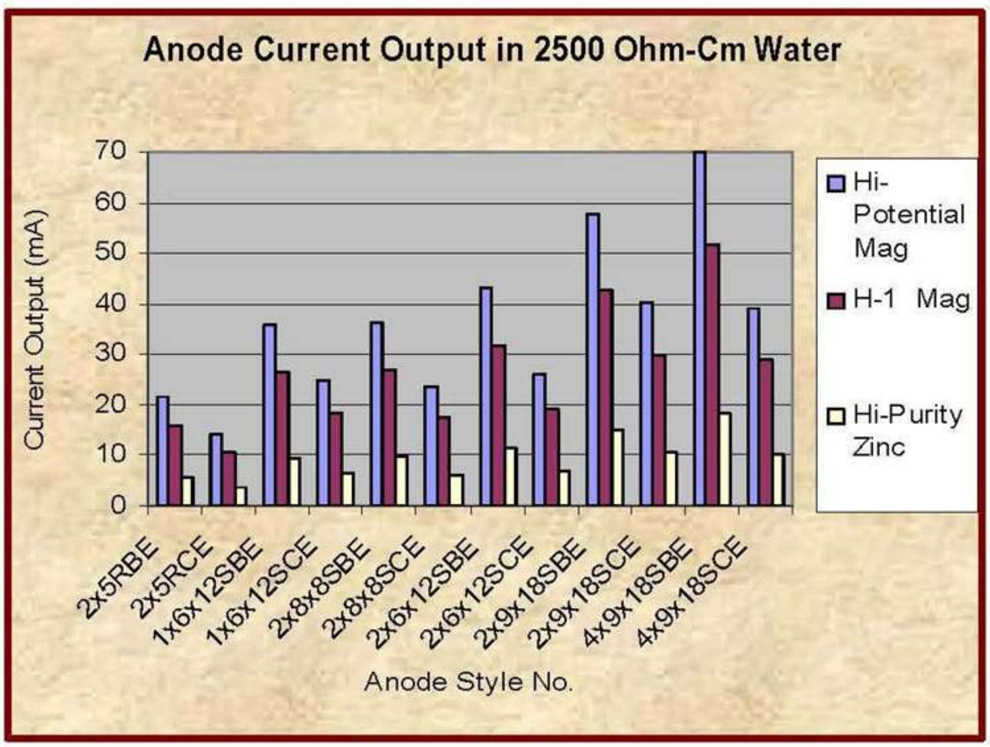
	high-potential Mag	H-1 Mag	high-purity Zinc*
2x5RBE	27.94	20.59	7.35
2x5RCE	16.55	12.20	4.36
1x6x12SBE	42.04	30.97	11.06
1x6x12SCE	33.69	24.82	8.87
2x8x8SBE	46.12	33.98	12.14
2x8x8SCE	31.67	23.33	8.33
2x6x12SBE	49.48	36.46	13.02
2x6x12SCE	33.69	24.82	8.87
2x9x18SBE	69.85	51.47	18.38
2x9x18SCE	52.78	38.89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



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

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

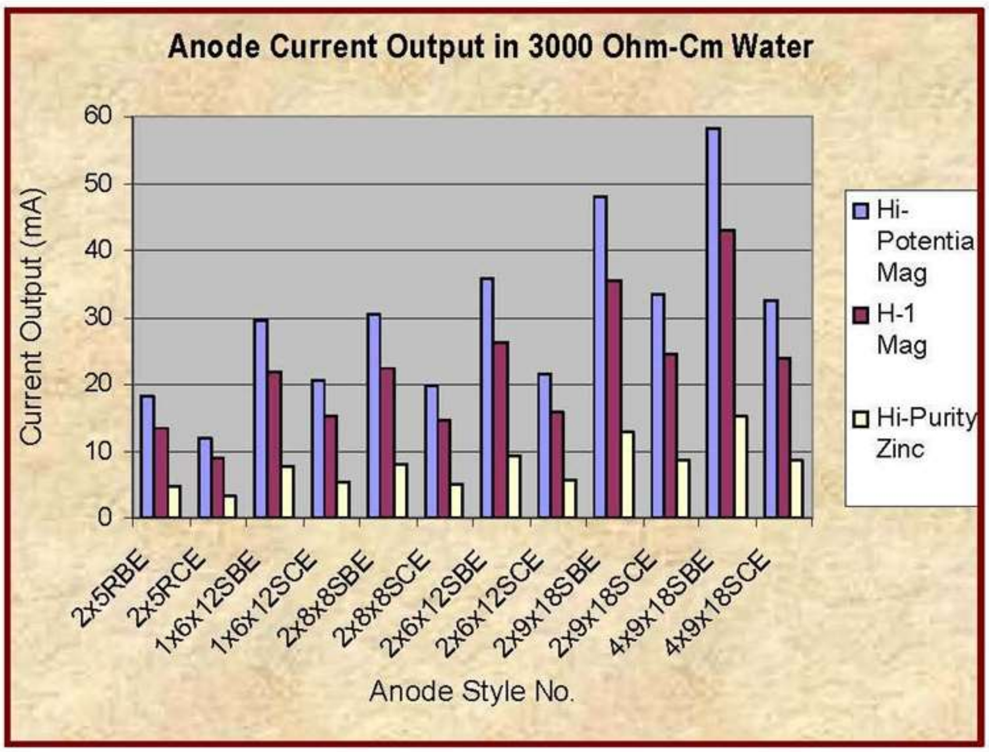
	high-potential Mag	H-1 Mag	high-purity Zinc*
2x5RBE	22.35	16.47	5.88
2x5RCE	13.24	9.76	3.48
1x6x12SBE	33.63	24.78	8.85
1x6x12SCE	26.95	19.86	7.09
2x8x8SBE	36.89	27.18	9.71
2x8x8SCE	25.33	18.67	6.67
2x6x12SBE	39.58	29.17	10.42
2x6x12SCE	26.95	19.86	7.09
2x9x18SBE	55.88	41.18	14.71
2x9x18SCE	42.22	31.11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



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

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

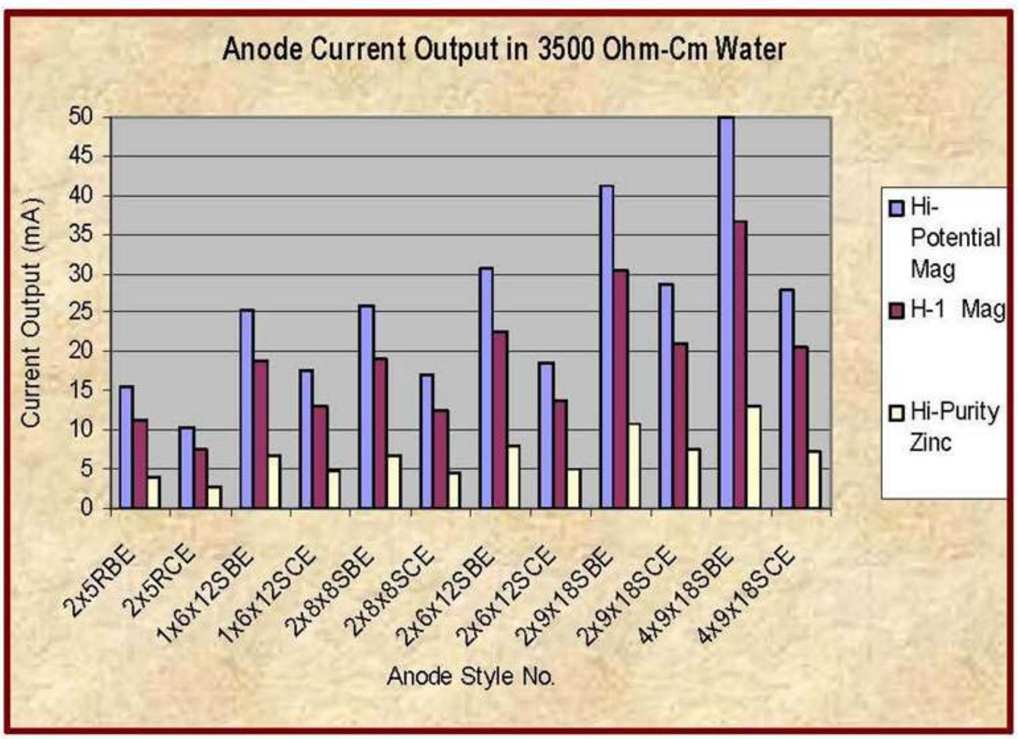
	high-potential Mag	H-1 Mag	high-purity Zinc*
2x5RBE	18.63	13.73	4.90
2x5RCE	11.03	8.13	2.90
1x6x12SBE	28.02	20.65	7.37
1x6x12SCE	22.46	16.55	5.91
2x8x8SBE	30.74	22.65	8.09
2x8x8SCE	21.11	15.56	5.56
2x6x12SBE	32.99	24.31	8.68
2x6x12SCE	22.46	16.55	5.91
2x9x18SBE	46.57	34.31	12.26
2x9x18SCE	35.19	25.93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



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

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

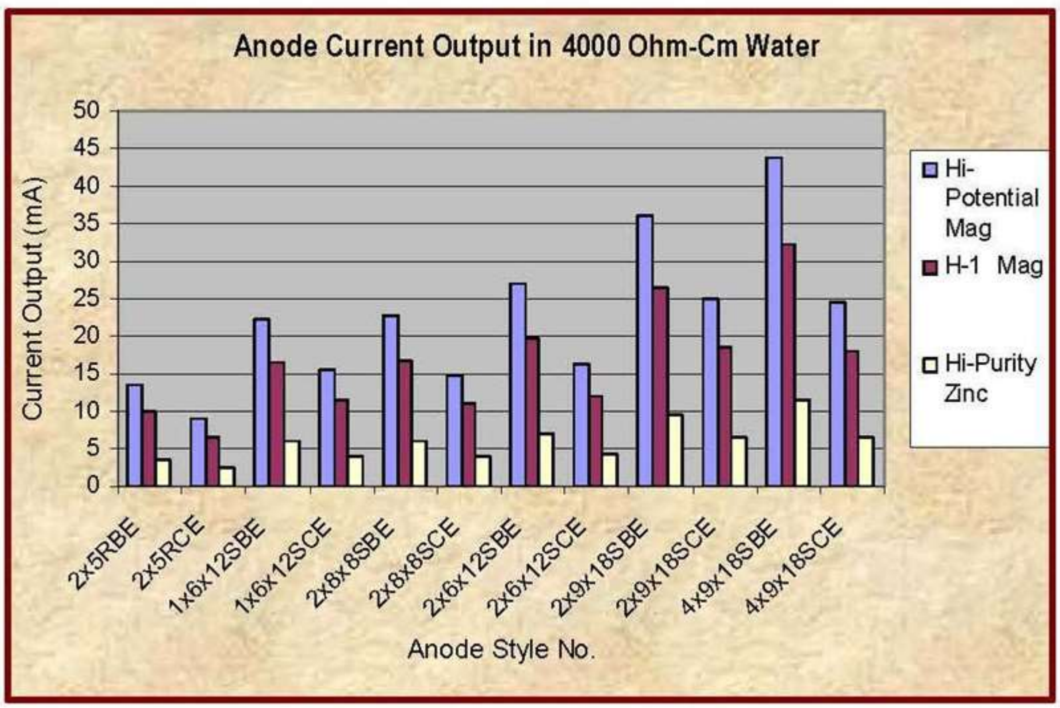
	high-potential Mag	H-1 Mag	high-purity Zinc*
2x5RBE	15.97	11.76	4.20
2x5RCE	9.46	6.97	2.49
1x6x12SBE	24.02	17.70	6.32
1x6x12SCE	19.25	14.18	5.07
2x8x8SBE	26.35	19.42	6.93
2x8x8SCE	18.10	13.33	4.76
2x6x12SBE	28.27	20.83	7.44
2x6x12SCE	19.25	14.18	5.07
2x9x18SBE	39.92	29.41	10.50
2x9x18SCE	30.16	22.22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



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

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

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



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

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

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

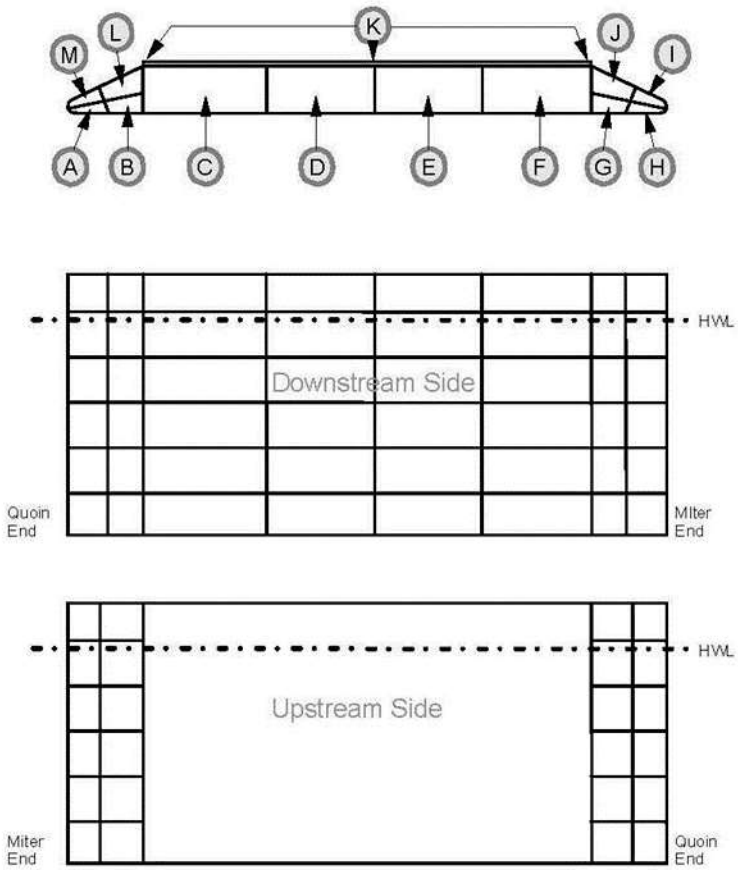

Figure C.1. Lock Gate Vertical, Downstream, and Upstream Structural Layout

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

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

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

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

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

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

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

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

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

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

g. Design for a 20-year life.

h. Design for normally submerged surface areas.

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

C.3 Computations.

a. Find the surface area to be protected.

(1) Upstream Side.

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

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

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

(2) Downstream Side.

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

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

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

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

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

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

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

Table C.1
Chamber Area Values

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

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

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

Where:

A = surface area to be protected

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

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

Example calculation only for skin plate requirement:

$$I = 133 \text{ m}^2 \text{ x } 75.35 \text{ mA/m}^2 \text{ x } (1 – 0.85) = 1503 \text{ mA}$$

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

Table C.2
Current Requirements for Each Structure Component

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

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

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

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

(1) Chambers A and H.

(a) Current required per unit = 31.4mA.

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

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

(2) Chambers B and G.

(a) Current required per unit = 49.1 mA.

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

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

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

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

(a) Current required per unit = 213.6 mA.

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

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

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

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

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

(4) Chambers I and M.

(a) Current required per unit = 41.8 mA.

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

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

(5) Chambers J and L.

(a) Current required per unit = 73.5 mA.

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

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

(6) Surface K (Skin Plate).

(a) Current required = 1503.2 mA.

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

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

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

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

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

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

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

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

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

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

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

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

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

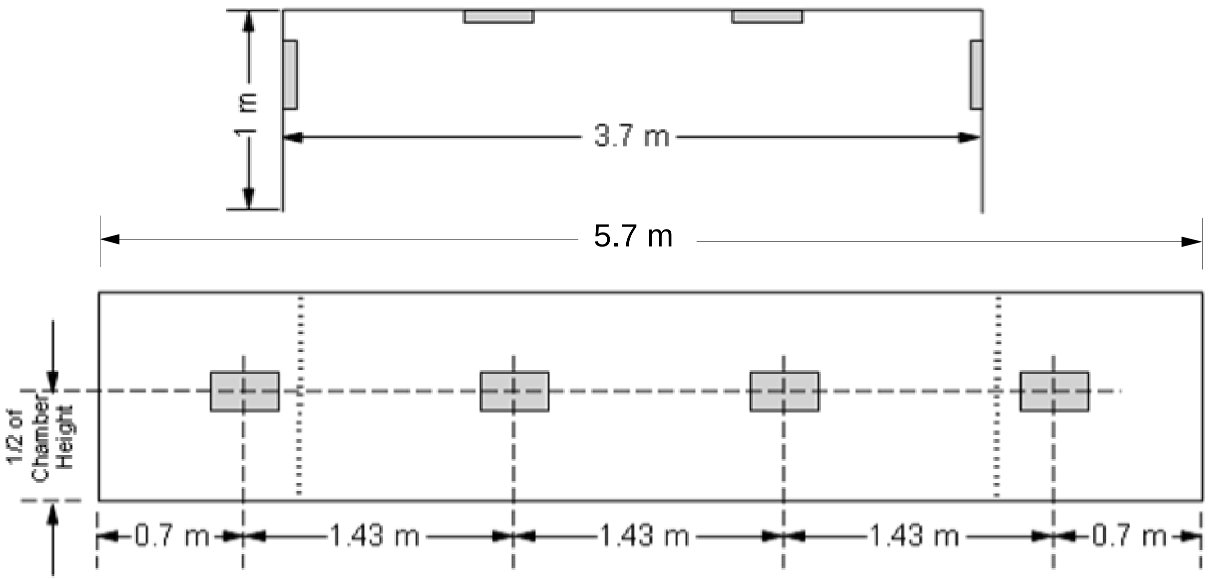

Figure C.2. Galvanic Slab Anode Locations in Largest Downstream Gate Chambers

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

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

Where:

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

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

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

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

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

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

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

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

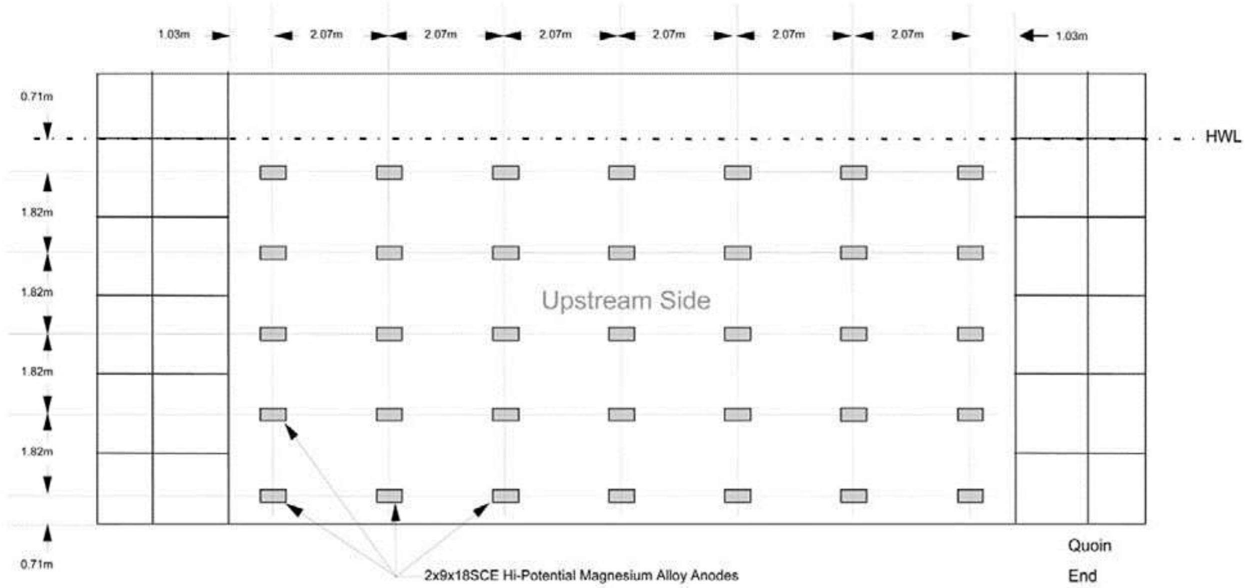

Figure C.3. Example Slab Anode Layout for Upstream Side (Skin Plate)

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

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

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

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

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

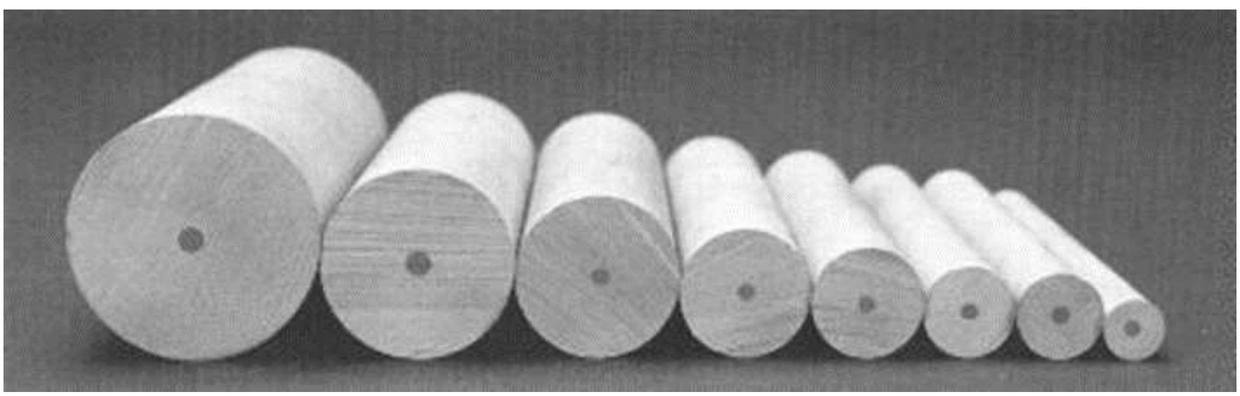

Figure D.1. DC-6722, DC-2375 (Left) and Other Extruded Magnesium Anode Cross-Sections Showing Galvanized Steel Core Wire at Center

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

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

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

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

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

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

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

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

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

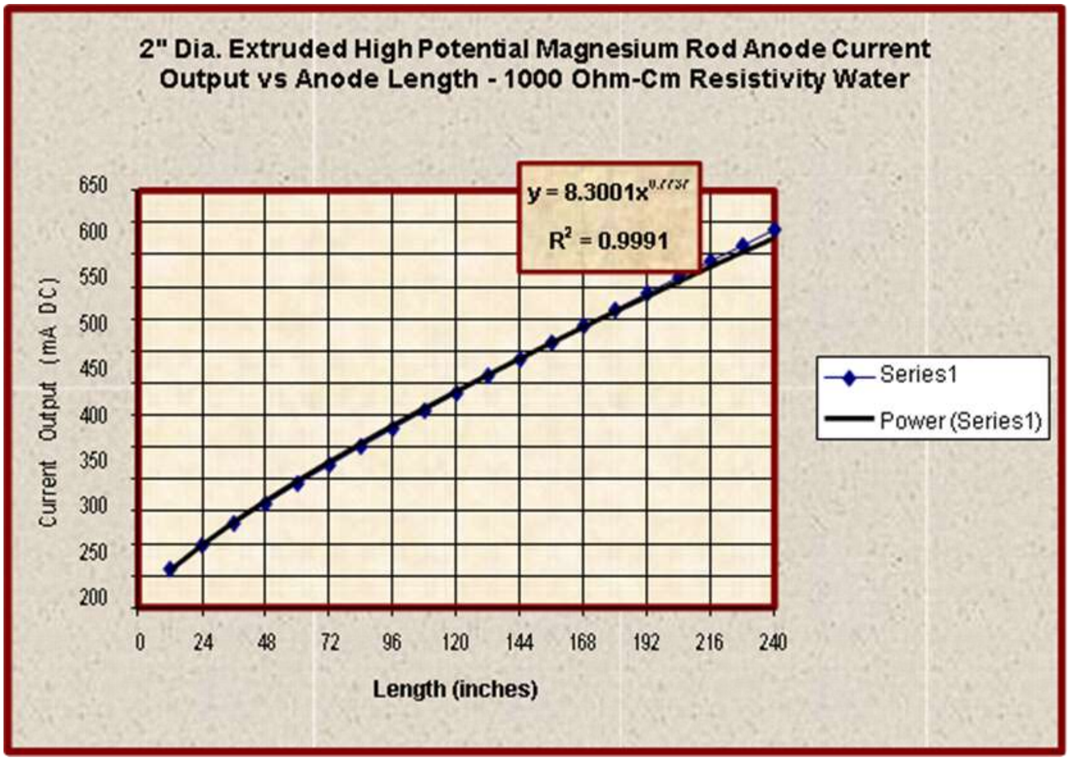

Figure D.2. Current Output vs. Anode Length for 2-Inch Diameter High-Potential Magnesium Rod Anodes

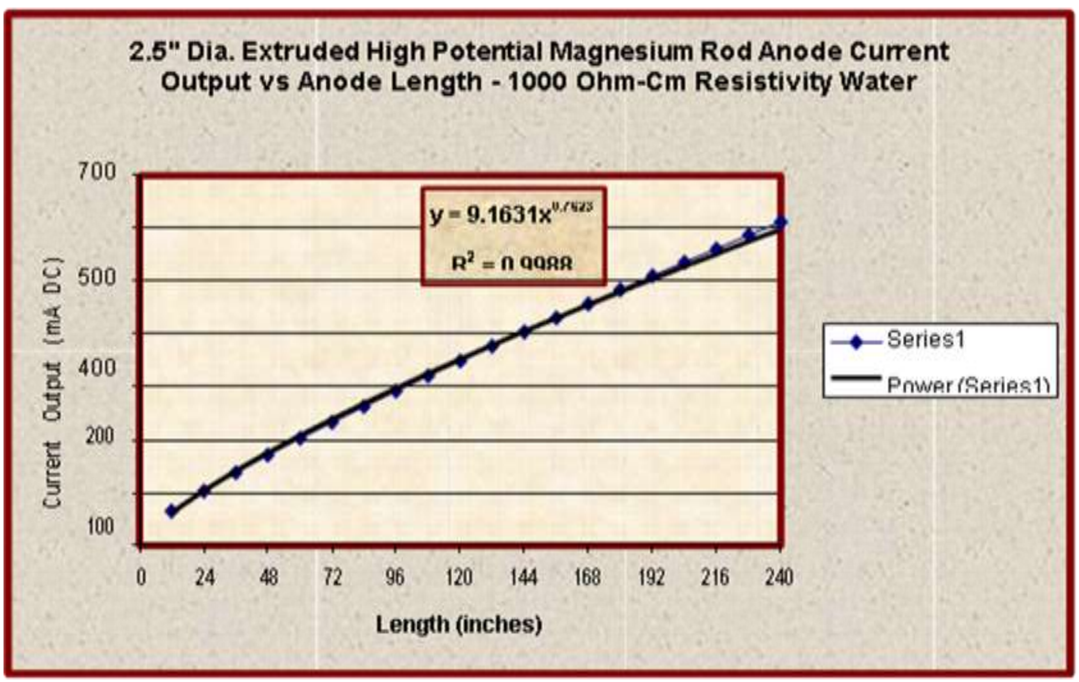

Figure D.3. Current Output vs. Anode Length for 2.5-Inch Diameter High-Potential Magnesium Rod Anodes

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

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

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

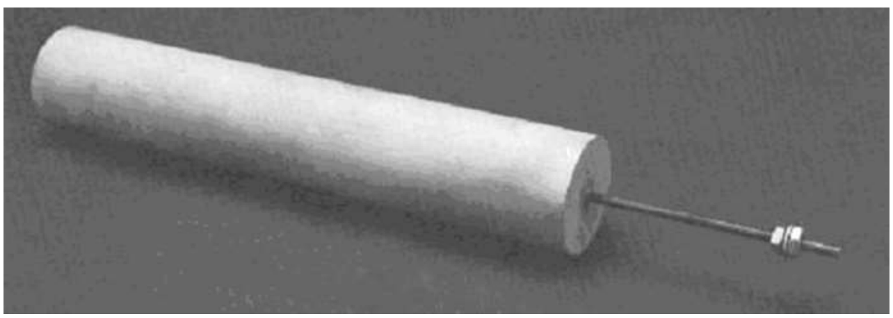

Figure D.4. Magnesium Rod Anode Showing Threaded Core Wire, Double Nuts, and Washers

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

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

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

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

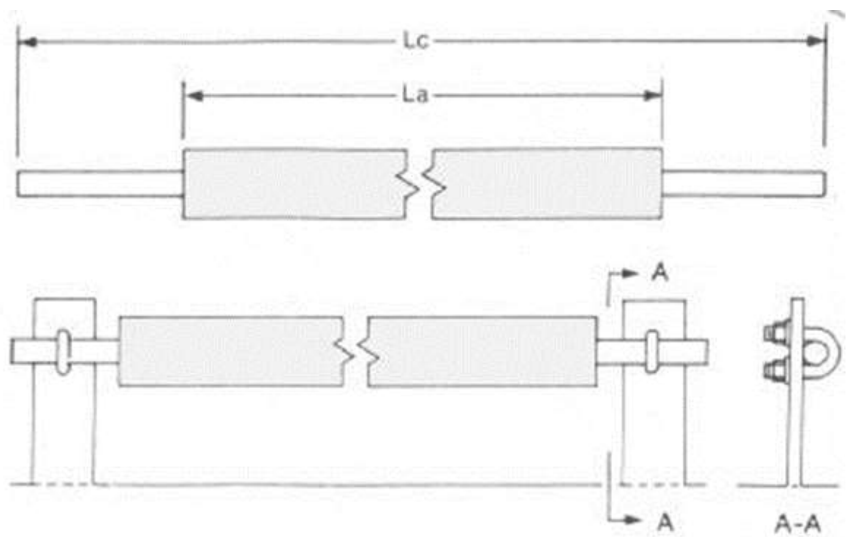

Figure D.5. Connection Schematic for High-Purity Cast Zinc Bar Anodes

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Table D.8
Current Requirements for Each Downstream Structure Component

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

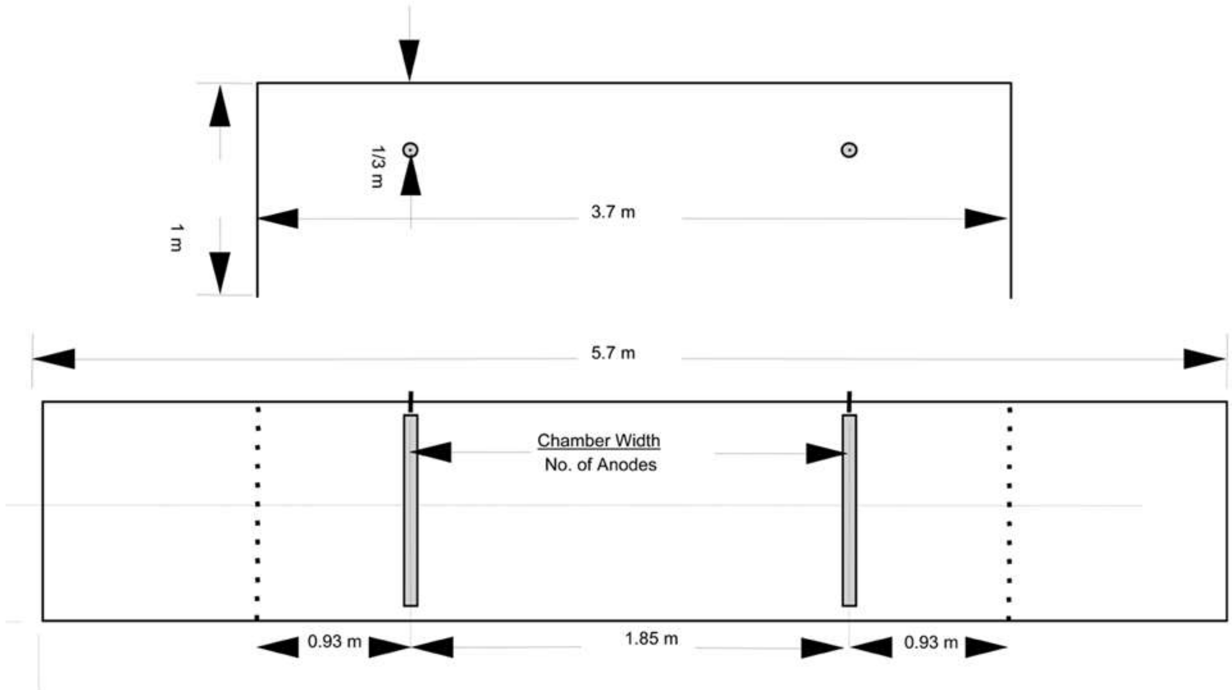

Figure D.6. Rod Galvanic Anode Locations in Largest Downstream Chambers

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

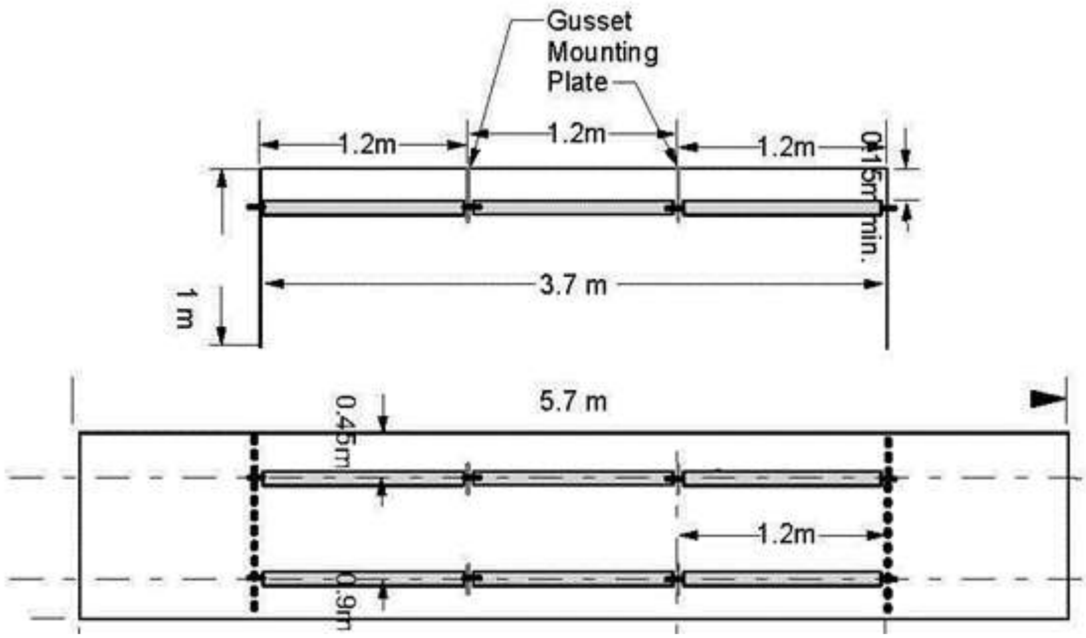

Figure D.7. Zinc Bar Galvanic Anode Locations in Largest Downstream Gate Chambers

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Appendix E
Detailed Cathodic Protection System Design Procedures for Pike Island Auxiliary Lock Gates

E.1 Designs for Lock Gates. Figure E.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).

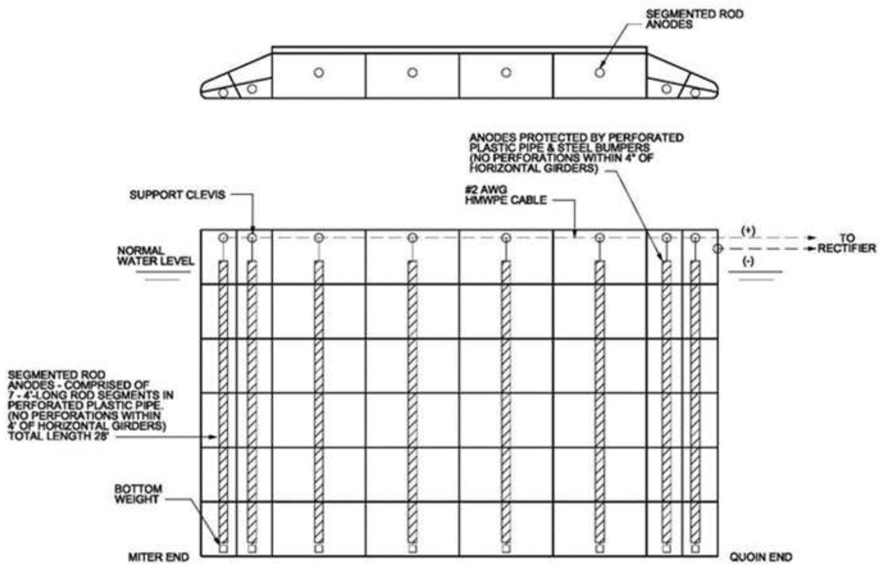

Figure E.1. Pike Island Auxiliary Lock Miter Gate

a. The gates are constructed of welded structural steel, horizontally framed, with a cast pintle. The downstream side of the gate consists of a pattern of rectangular chambers closed on five faces and open to the water on the sixth face. The upstream face of the gate 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.

b. 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.). See Table E.1. 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.

E.2 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% 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% of the area will become bare in 20 years.

f. Design for 75.35 mA/m^2 (7.0 mA/ft2) (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.

E.3 Computations.

a. Find the surface area to be protected.

(1) 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

(2) Downstream Side.

Table E.1
Lock Gate Chamber Data

Number of Chambers	Chamber Area m^2	Total Area
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)
Total number of chambers = 48 Total chamber area = 194.17 m^2 (2092 ft^2) Total area = 617.81 m^2 (6650 ft^2)		

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

$$I = A * I'(1.0 - C_E)$$

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)

(1) 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%):

$$I = 154.82\ m^2 \times 75.35\ mA/m^2 \times (1 - 0.99) = 116\ mA\ (\text{use } 120\ mA)$$

Final current requirement (C_E = 70%):

$$I = 154.82\ m^2 \times 75.35\ mA/m^2 \times (1 - 0.70) = 3498\ mA\ (\text{use } 3500 mA)$$

Average current requirement:

$$I = (120 + 3500)/2\ mA = 1810\ mA\ (\text{use Step 2A for skin plate})$$

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%):

$$I = 39.02\ m^2 \times 75.35\ mA/m^2 \times (1 - 0.99) = 29.4\ mA\ (\text{use 30 mA for 6 chambers})$$

Final current requirement (C_E = 70%):

$$I = 39.02\ m^2 \times 75.35\ mA/m^2 \times (1 - 0.70) = 882\ mA\ (\text{use 900 mA per 6 chambers})$$

Average current requirement:

$$I = (30 + 900)/2 = 465\ mA \text{ per 6 chambers (use 0.5 per 6 chambers in a vertical column)}$$

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

$$I = 0.5 \times 4 = 2.0\ A \text{ for chamber}$$

Total current requirement (I_T) for upstream side:

$$I_T = 120\ mA + (4 \times 30\ mA) = 240\ mA = 0.24 \text{ amps (initial)}$$

$$I_T = 2.0\ A + 2.0\ A = 4.0 \text{ amperes (average)}$$

$$I_T = 3500\ mA + (4 \times 900\ mA) = 7100\ mA = 7.10 \text{ amps (final)}$$

(2) Downstream Side.

Calculate I

Where A = 22.20 m^2 (239 ft^2) (from computational Step 1B).

Initial current requirement (C_E = 99%):

$$I = 22.20\ m^2 \times 75.35\ mA/m^2 \times (1 - 0.99) = 16.8\ mA \text{ per chamber}$$

Final current requirement (C_E = 70%):

$$I = 22.20\ m^2 \times 75.35\ mA/m^2 \times (1 - 0.70) = 502\ mA \text{ per chamber}$$

Average current requirement:

$$I = (16.8 + 502)/2 = 260\ mA \text{ per chamber}$$

Total current requirement for downstream side (48 chambers):

$$I_T = 16.8\ mA/chamber \times 48\ chamber = 806\ mA = 0.8\ A \text{ (initial)}$$

$$I_T = 260\ mA/chamber \times 48\ chamber = 12{,}480\ mA = 12.4\ A \text{ (average)}$$

$$I_T = 502\ mA/chamber \times 48\ chamber = 224{,}096\ mA = 24.2\ A \text{ (final)}$$

(3) 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

(4) Note: Average current requirements determine anode selection. Final current requirements determine rectifier selection.

c. Select the anode and calculate the number of anodes required (N) to meet the design life requirements. Tables E.2 through E.17 below provide design data for disk anodes and tubular anodes. Tables E.2 through E.9 are in Metric units and Tables E.10 through E.17 are in English Customary units.

(1) Disk anodes such as those shown in Figure 2.3 were selected for the skin plate on the upstream side. Either 3.2-mm- (1/8-in.-) diameter segmented rod anodes consisting of 1,219-mm (4-ft) segments, as shown in Figure 2.3 for the chambers.

(2) For this example, the design was 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:

$$N = I/I_A$$

Where:

I = total current requirement

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

(3) Upstream Side: Skin Plate – Number of Disk Anodes:

Calculate N where:

N = 0.5 / 1 = 0.5 anodes

Where I = 0.5 A (from Step 2A)

I_A = 1.0 A/1219-mm- (4-ft-) long segmented rod
(From Table E.9 (Metric)/E17(U.S. Customary))

Use 1 segmented rod anode per 6 vertical chambers.

(4) Downstream Side.

$$I = 260 \text{ mA per chamber}$$

For each set of 6 chambers in a vertical column:

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

$$I_A = 1.0 \text{ A/anode}$$

$$N = 1.56 / 1 = 1.56 \text{ anodes}$$

Use 2 segmented rod anodes per 6 vertical chambers.

d. Select number of anodes to provide adequate current distribution.

(1) Upstream Side.

(a) 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 E.2 shows a suitable configuration using a combination of 19 disk anodes.

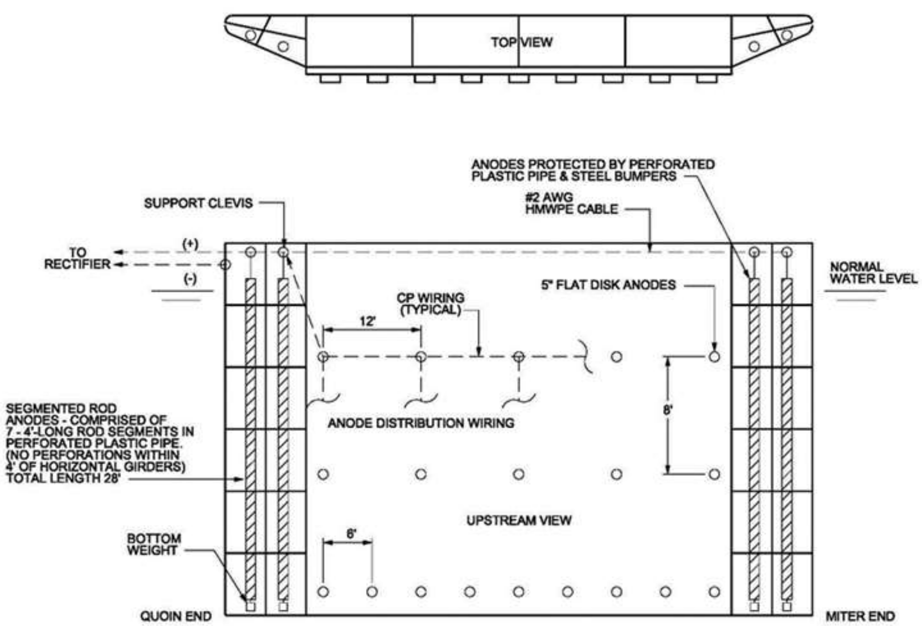

Figure E.2. Auxiliary Lock Miter Gate Design at Pike Island

Table E.2 (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).

Table E.3 (Metric)
Wire and Rod Anodes (Packaged)

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 E.4 (Metric)
Fresh and Seawater Usage Ratings 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 E.5 (Metric)
Tubular Anodes (Bare)

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

Table E.6 (Metric)
Current Density Limitations Wire and Rod Anode
Anode Life vs. 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

Table E.7
Metric Tubular Anodes
Anode Life vs. Maximum Current Density (amps per 0.0929 m^2)

Life, Years	**Fresh Water**	**Brackish Water**	**Seawater**
20	9.3	9.3	56

Table E.8 (Metric)
Fresh and Seawater Usage Expected Life – Disc Anodes

Size: 127 mm diameter (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

Table E.9 (Metric)
Fresh and Seawater Usage Expected Life Segmented Rod Anodes

Size: 1219-mm length; 3.5-mm diameter 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

Table E.10 (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).

Table E.11
Underground Usage Wire and Rod Anodes (Packaged)

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 E.12
Fresh and Seawater Usage Ratings 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 E.13
Anode Life Fresh and Seawater Usage Tubular Anodes

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

Table E.14
Current Density Limitations Wire and Rod Anode
Anode Life vs. Maximum Current Density (amps/square foot)

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

Table E.15
Tubular Anodes
Anode Life vs. Maximum Current Density (amps/square foot)

Life, Years	**Fresh Water**	**Brackish Water**	**Seawater**
20	9.3	9.3	56

Table E.16
Fresh and Seawater Usage 20-Year Expected Life Disk Anodes

Size: 5-in. diameter (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

Table E.17
Fresh and Seawater Usage 20-Year Expected Life Segmented Rod Anodes

Size: 4-ft length; 0.138-in. diameter 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		

(b) 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 E.3.

Total anodes required for the upstream side:

19 disk anodes
4 segmented rod anodes (28 individual rod segments)

(2) 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 E.3.

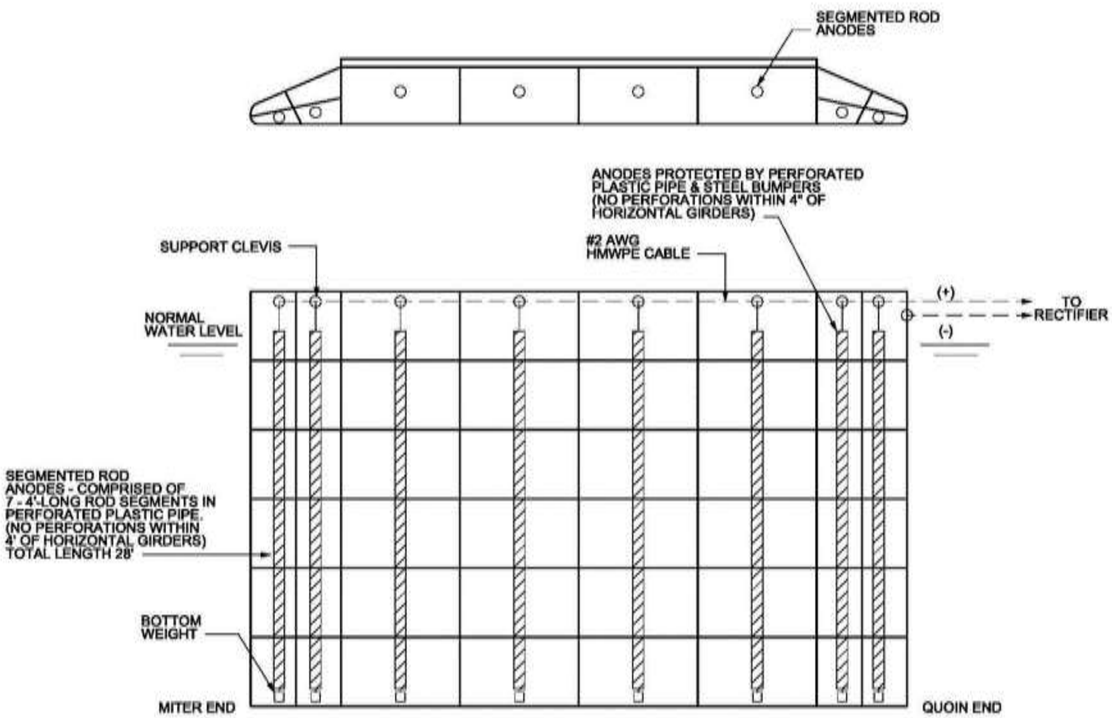

Figure E.3. Auxiliary Lock Miter Gate at Pike Island Showing Rod Anode Placement

e. Determine the anode-to-water resistance (R_A) of the individual anodes.

(1) Disk Anodes. 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.

$$R_A = p/21.5$$

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

$$R_A = 3000 / 21.5 \text{ ohms}$$

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

$$R_N = R_A/N + (p * P_F)/C_C$$

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 E.18 and E.19)

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.

$$E = I \times R$$

E = 3.5 x 7.7 = 27 volts

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

(2) Segmented Rod Anodes. The segmented rod anode-to-water resistance (R_A) 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.

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

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 = (0.158 x 3000)/853 x [ln (8 x 853 / 0.35) – 1]

= 0.557 (9.88 – 1)
= 4.95 ohms

Table E.18 (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 E.19 (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			

(3) 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.

(4) 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.

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

$$R_T = R_N + R_W + R_C$$

Where:

R_N = anode-to-water resistance

R_W = header cable/wire resistance

R_C = tank-to-water resistance

(1) Upstream Side.

(a) 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 American Wire Gage (AWG), High Molecular Weight Polyethylene (HMWPE) insulated cable is selected. The resistance of the anode distribution wiring is considered negligible. The header cable resistance is calculated from Equation 8.

$$R_W = L_W \times R_{MFT}/1000$$

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 = 30.48 x 0.159 / 304.8 ≅ 0.016 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% bare structure which would have negligible resistance.

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

$$R_T = R_N + R_W + R_C = 7.7 + 0.02 + 0.0 = 7.72 \text{ ohms}$$

(b) 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.

$$R_N = R_A / N = 4.95 / 4 = 1.24 \text{ ohms}$$

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:

$$R_W = L_W \times R_{MFT}/1000$$

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 = 24.38 x 0.159 / 304.8 = 0.01 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:

$$R_T = R_N + R_W + R_C$$

$$R_T = 1.24 + 0.01 + 0.0 = 1.25 \text{ ohms}$$

(2) 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:

$$R_T = R_N + R_W + R_C = 0.62 + 0.01 + 0.0 = 0.63 \text{ ohms}$$

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

(1) 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

(2) 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

h.   Selection of Rectifier.

(1) The largest design voltage requirement is 27 volts. Using a factor of safety of 120%, rectifier voltage is calculated:

27 volts x (120%) = 33 Volts

Total current required:

Upstream Skin Plate	=	3.5 amperes
Upstream Chambers	=	7.1 amperes
Downstream Chambers	=	24.2 amperes
		34.8 amperes

(2) 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 E.4 shows the circuitry.

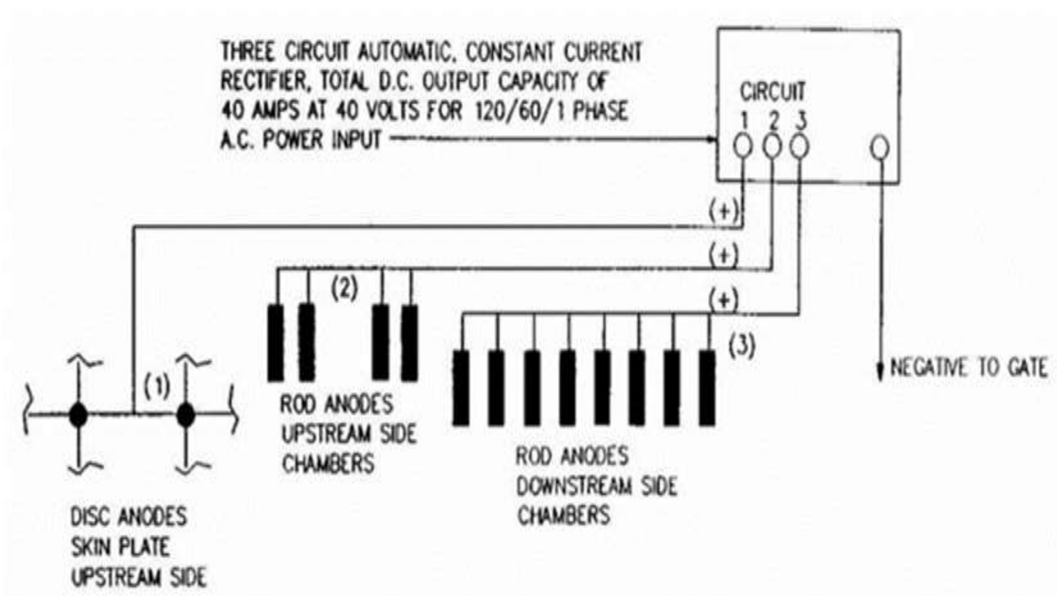

Figure E.4. Circuit Diagram for Lock Miter Gate

Appendix F
Impressed Current Cathodic Protection System Design Analysis and Calculations to Replace Lower Miter Gates at Selden Lock

F.1 Foreword. The design of the Cathodic Protection System for the Selden Lock is provided as an example of a typical impressed current CPS application for miter gates designed by the CCCP TCX.

a. Currently, this type system is used on miter gates for all 22 navigational locks operated by the Mobile District. The design uses a combination of HSCI Button Anodes installed on skin plates and HSCI String anodes installed inside girder compartments.

b. Mobile District has found that HSCI Button Anodes offer superior survivability from impacts resulting from ice and debris. The Selden Lock example is also notable because of the water corrosivity being highly corrosive.

F.2 Background. The lower gates at the Selden Lock had been in service since 1955. See Figure F.1. Because of the highly corrosive water quality in the area, by 2009 the gates had exceeded their expected life, and the decision was made to replace the gates and their respective CPS.

F.3 Corrosion Control and Cathodic Protection System.

a. Coating System. The Mobile District uses vinyl protective coating systems with zinc enriched primer as the primary corrosion control system on HSS. To provide the total CPC system for lock miter gates, the vinyl coating system is supplemented with impressed current. To avoid cathodic disbondment of vinyl paint, it is Mobile District's CP policy to provide protective potentials less negative than minus 1100 mV "instant off," with respect to a copper/copper-sulfate reference cell.

b. Cathodic Protection. Two types of CPS used are sacrificial (galvanic) systems and impressed current systems.

c. Sacrificial Cathodic Protection. Sacrificial or galvanic anode type CPS provide cathodic current by galvanic corrosion. The current is generated by metallically connecting the structure to be protected to a metal/alloy (e.g., magnesium blocks and rods) that is electrochemically more active than the material to be protected.

(1) Galvanic anodes have many desirable advantages. They require no external power supply, are relatively easy to install, require much less maintenance, and are considerably less complex than an impressed current system. However, they also have many disadvantages. Compared to the impressed current system, galvanic system has limited driving potential, limited current output, limited system and structure monitoring capability, and an inability to be adjusted to meet changing conditions.

(2) In addition, galvanic anodes are not recommended for installation on lock miter gates due the inability to electrically isolate the lock gates from the embedded metals in the lock walls and sills and the existence of bare stainless steel miter and quoin blocks. For a galvanic system to be effective, the structure must be coated with a good bonded dielectric coating and the structure must be electrically isolated from embedded metals and bare or poorly coated structures.

(3) Also, galvanic anode systems are at times impractical for protection of the miter gates because of the large number of anodes required to meet potential criteria. For this example, in addition to impressed current calculations (Section F.4), galvanic anode calculations (Section F.5) are provided for comparative purposes. For example, for the upstream skin plate (Area A), 20 HSCI Button Type anodes were required for an impressed current system whereas 65 anodes would be required for a galvanic system over the same area.

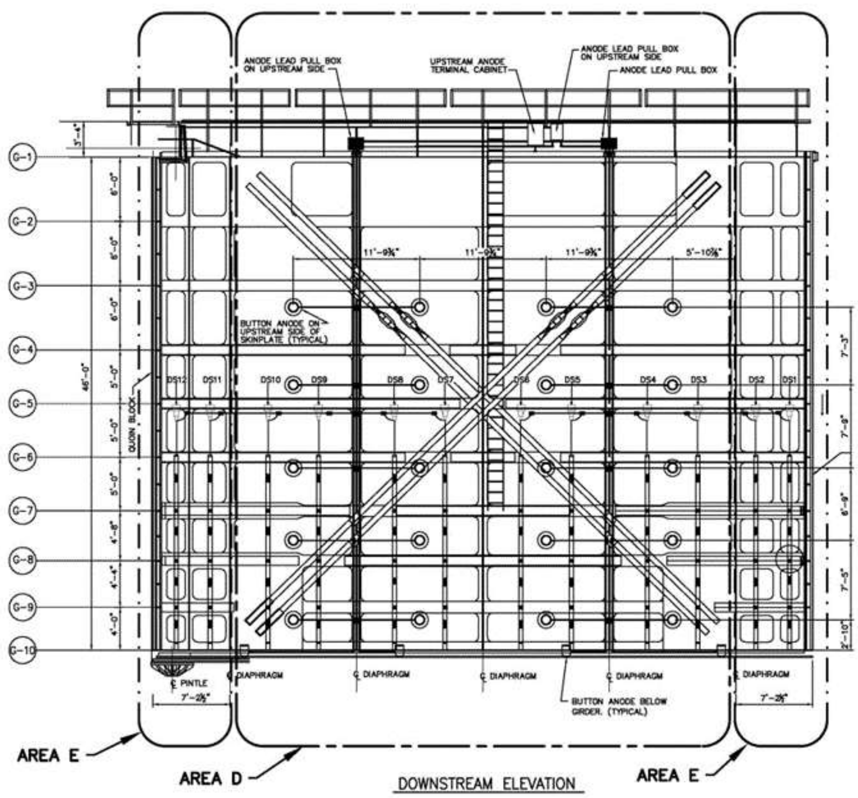

Figure F.1. Downstream Elevation of Selden Lower Lock Gate

d. Impressed Current Cathodic Protection. Impressed-current-type CPS provide cathodic current from an external power source to force current to discharge from expendable anodes through the electrolyte and onto the structure to be protected.

(1) The impressed current system designed for the Selden Lock gates used a combination of HSCI Button Anodes installed on skin plates and HSCI String anodes installed inside girder compartments with current being supplied by constant voltage rectifiers. HSCI Button Anodes

used on skin plates and other areas subject to impacts resulting from ice and debris offer superior survivability than a typical ceramic coated flat disk anode. HSCI Button Anodes can actually lose material from an impact and remain operational.

(2) Constant voltage rectifiers were selected for use with the impressed current CP system for a number of reasons. First, they have simpler circuitry and are more reliable. Second, since the voltage is constant, the rectifier current output changes with changes in water resistivity, water temperature, and water level inside the lock chamber (i.e., V=IR). With automatic potential rectifiers, each rectifier circuit is automatically controlled via use of permanent reference cells attached to the gate to maintain a constant potential at each circuit's reference cell.

(3) Automatic potential rectifiers require that a permanent reference cell be mounted on each gate for each DC circuit, which would most likely not have a very long life because of damage caused from debris. In fact, the Tenn-Tom has tried to mount permanent reference cells on miter gates and found that their life was very short. Consequently, the likely premature failure of the extra circuitry and components required to automatically adjust the potential output indicates that these rectifiers are not as reliable as the constant voltage rectifiers.

(4) Constant current rectifiers are not desired because constant current output from the rectifier is not always desired. When the lock chamber is lowered, the amount of submerged surface area inside the lock chamber is decreased, thereby resulting in less surface area to protect. Consequently, less current is required when the chamber is down. Constant current rectifiers would automatically adjust to provide the same amount of current output whether the chamber is up or down.

(5) Excessive potentials may exist when the lock chamber is down. In addition, these rectifiers are not as reliable simply because they have additional automatic circuitry and more components to contend with and to possibly fail. Constant voltage rectifiers are the best choice for this application.

e. The Selden Lock Gate CP design also incorporated many improvements and lessons learned gained from years of experience such as:

(1) The installation of a split bus and an adjustable rheostat in each upstream DC circuit.

(2) The use of Fiberglass Reinforced Plastic (FRP) caps rather than steel caps for the 6-in. button cable and cable connections' protector pipe.

(3) Electrical bonding of the wall quoin blocks to the gate structure.

(4) The provision of additional holes in the PVC string anode protector pipes to allow for better distribution of string anode current.

F.4 Water Corrosivity. For CP design and corrosion risk assessment purposes, it is necessary to estimate the overall water corrosivity. To aid in the development of the CP design for this project, water quality data were obtained from the Alabama Department of Environmental Management (ADEM) and are provided in Table F.1 of this appendix.

a. The data provided consisted of measurements taken from April through October of 2006 and 2007. The data provided by ADEM indicated that the pH measurements were all generally in the neutral range (i.e., pH around 7). In general, pH above 4 is not a significant factor of influence on corrosivity.

b. Corrosivity ratings are designated as: essentially non-corrosive (greater than 20,000 ohm-cm), mildly corrosive (10,000 to 20,000 ohm-cm), moderately corrosive (5,000 to 10,000 ohm-cm), corrosive (3,000 to 5,000 ohm-cm), highly corrosive (1,000 to 3,000 ohm-cm), and extremely corrosive (less than 1,000 ohm-cm).

c. Based on the average of the conductivity (reciprocal of resistivity) measurements ranging from 5266 and 3545 ohm-cm, and using the corrosivity scale defined above, the waters at Selden Lock would have been considered as "corrosive" in 2006, but "highly corrosive" in 2007. Consequently, the waters should be considered as "corrosive to highly corrosive."

F.5 Impressed Current Calculations. Note, in the following calculations, the normally submerged surface area (at full chamber) designations are defined as:

Upstream Side DC Circuit:

Area A is the submerged portion of Gate Skin Plate, Upstream Side (to upper pool elevation).

Area B is the area below bottom horizontal gate girder.

Area C is the Lower Gate U.S. Compartments between Miter or Quoin and Skin Plate (typical of two areas).

Downstream Side DC Circuit:

Area D is the submerged portions of Large Lower Gate Compartments behind skin plate.

Area E is the Lower Gate Downstream (DS) Compartments between Miter or Quoin and Large Compartments (typical of two areas).

A graphical representation of these areas is shown in Figures F.1, F.2, and F.3.

a. Design Data: Areas A and B.

(1) Water Resistivity is 5265.93 ohm-cm (based on minimum measured water conductivity of 189.9 micro-mhos/cm, of 142 measurements taken from April through October of 2006 and 2007).

(2) NOTE: Maximum resistivity must be used to determine rectifier requirements.

(3) Coating Efficiency (Dielectric Coating): 90% (at end of design life).

(4) Design Life: 50 years.

(5) Type of Anode Selected:

Material: HSCI Button Type
Dimensions:
Diameter: 6 in.
Length: 4.33 in. (adjusted for face area).
Weight (W): 18 lb.
Consumption Rate (C): 1 lb/ampere-yr.
Anode surface area: 0.57 ft^2.
Anode Current Density Limitation: 1000 mA/ft^2.

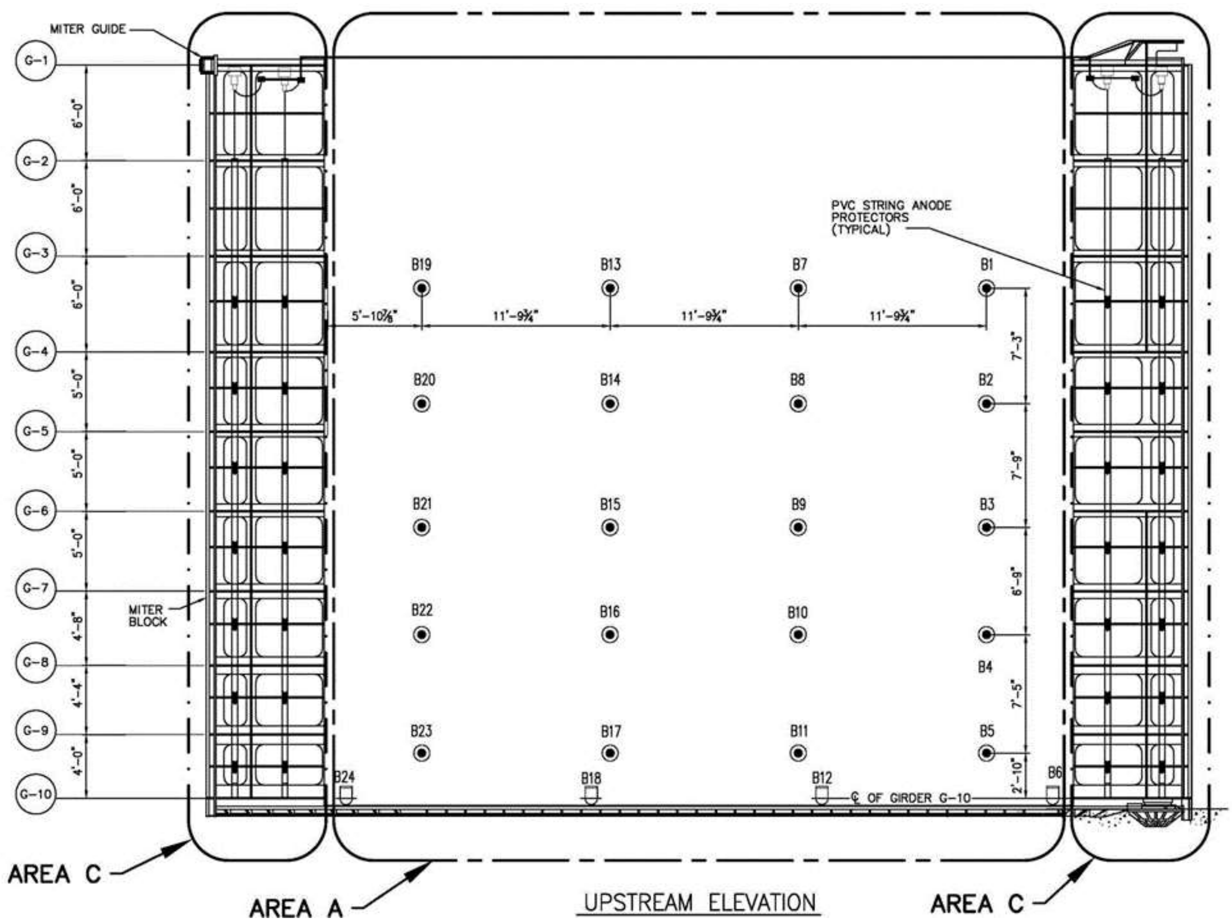

Figure F.2. Upstream Elevation of Selden Lower Lock Gate

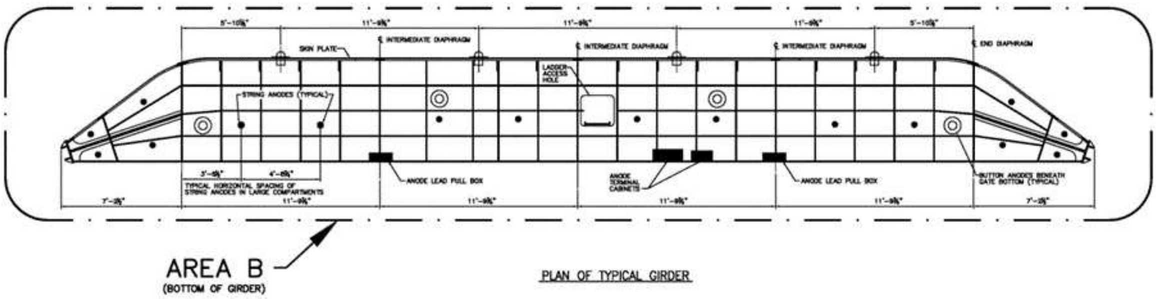

Figure F.3. Plan View of Girder for Selden Lower Lock Gate

(6) Design Current Density (I′): 7 mA/ft^2 of bare steel.

(7) Dimensions of Submerged Portion of Area A:
Upper Pool Depth (D): 35.00 ft.
Width (W): 47.25 ft.

(8) Dimensions of Bottom Side of Bottom Girder, Area B:
Depth of Gate (DG): 6.00 ft.
Quoin End Width (W G): 7.21 ft.
Skin Plate Width (W): 47.25 ft.

(9) Computations: Areas A and B.

(a) Total Surface Areas for Area A and Area B:
$Area_A = WD$.
$Area_A = 1653.75$ ft^2.
$Area_B = WD_G + D_GW_G$.
$Area_B = 326.75$ ft^2.
Total Area = $Area_A + Area_B = 1980.50$ ft.

(b) Total Current required in these areas at design current density:

$$I_{AB} = A\,I'(1 - C_E)$$

Where:

A = surface area to be protected.

I′= required current density to provide adequate protection to submerged bare steel (mA/ft^2).

C_E = coating efficiency at end of design life.

I_{AB} = 1386.35 mA.

(c) Number of anodes required in these areas to meet Supplier's Current Density Limitations:

$$N = I_{AB}/(A_a)(I_{a1})$$

Where:

N = number of anodes required to meet anode current limitations.

I_{AB} = total current required in mA, in these areas.

A_a = surface area of single anode in ft^2.

I_{a1} = current density limitation of single anode in mA/ft.

N = 2.45 or 3 (based on current limitations).

(d) Number of anodes required in these areas to meet Design Life Requirements:

$$N = (L_{design})(I_{AB})/(1000)(W_A)$$

Where:

N = total number of anodes required.

W_a = weight per bare anode in pounds.

L_{design} = design life in years.

I_{AB} = total current required in mA, in these areas.

N = 3.85 or 4 (based on design life).

(e) Number of anodes required for adequate current distribution for these surface areas: Note: To ensure uniform current distribution in a distributed impressed current system, it is normally good design practice to provide at least one button anode every 100 to 144 ft^2 of structural surface area to be protected. Additional anodes should be allowed to provide extra protection near the bottom of the skin plate. Based on an average grid spacing of 9.28 ft, the minimum number of anodes for this area is:

N = Total area to be protected / 100.

N = 19.80 or 20 (for good current distribution).

(f) Based on the above, the Number of Anodes Selected to be installed in this area is: Compare all N's calculated above and enter a number below for N, which is at least greater than or equal to the greater calculated value for N.

Use N = 24 in these areas, for symmetry and to fit specific structural layout.

(g) Calculation of Anode Groundbed Resistance. Using the Sunde equation:

$$R_a = [(0.00522)(\rho)/(N)(L)]\,[\ln(8L/d){:}\,1 + (2)(L/S)\ln(0.656N)]$$

Where:

N = number of anodes in groundbed = 24.

ρ = maximum resistivity at groundbed in ohm-cm.

R_a = calculated anode groundbed resistance in ohms.

L = total length of anode in feet.

d = diameter of anode in feet.

S = avg. anode spacing in feet. Enter value for S here, S = 9.28.

Ra = 3.174151 X [0.75325 + 0.214358278] Ra = 3.071 ohms

(h) Calculation of Header Conductor Resistance (r). For anode header conductor, choose:

Conductor size and type: 10 Cu.
Resistance per 1000 ft: 1.2900 ohms/1000 ft.
Length of Header Cable: 40 ft.

r = 0.0516 ohms

(10) Total Circuit Resistance for These Areas.

$$R_{AB} = R_a + r$$

R_{AB} = 3.1229 ohms

(11) Computation Summary for These Areas.

(a) Minimum Number of Specified Anodes Required for These Areas. 24 button anodes to be installed in Areas A and B.

(b) Calculated Current Required for These Areas. Total: 1.39 Amperes DC.

(c) Calculated Voltage Required for These Areas.

$$V_{AB} = I_{AB} R_{AB}$$

$$V_{AB} = 4.33 \text{ Volts, DC}$$

(d) 4.33 Volts, DC required for this part of circuit.

(e) NOTE: An adjustable rheostat must be installed electrically upstream of these anodes to reduce voltage since they are on the same DC circuit as string anodes. (Voltage required by string anodes is greater.)

b. Design Data: Area C.

(1) Water Resistivity is 5265.93 ohm-cm (based on minimum measured water conductivity of 189.9 micro-mhos/cm, of 142 measurements taken from April through October 2006 and 2007).

(2) NOTE: Maximum resistivity must be used to determine rectifier requirements.

(3) Coating Efficiency (Dielectric Coating): 90% (at end of design life).

(4) Design Life: 50 years.

(5) Type of Anode Selected:

Material: High Silicon Chromium Bearing Cast Iron (HSCBCI) Type G2, Durichlor, String Anode
Number of Anodes per string, submerged: 7 Anodes
Anode Dimensions:
Diameter: 2 in.
Length: 9 in.
Weight (W): 5 lb.
Consumption Rate (C): 1 lb/ampere-yr.
Anode surface area: 0.40 ft^2.
Anode Current Density Limitation: 1000 mA/ft^2.

(6) Design Current Density (I′): 7 mA/ft^2 of bare steel.

(7) Relative Dimensions for Calculation of Surface Area to be Protected:

Small Miter Compartments (Identical for small Quoin Compartments)
Number Submerged (C_p): 7
Width (W): 3.167 ft
Average Height (H): 4.857 ft
Greatest Depth (D): 1.500 ft
Girder Flange Width (F): 1.000 ft
Larger Miter Compartments, next to Skin Plate (identical for larger Quoin Compartments) Number Submerged (C_p): 7
Width (W_2): 4.500 ft
Average Height (H): 4.857 ft
Greatest Depth (D_2): 3.000 ft
Shortest Depth (D): 1.500 ft
Girder Flange Width (F): 1.000 ft

(8) Computations: Area C.

(a) Total Normally Submerged Surface of Area C:

Area = C_p [WH+HD+WD+2F (W + H)] + C_p [H (D+W_2 +D_2) +2DW_2+W_2 (D_2-D) +2F (W_2+H)]
Area = 883.00 ft^2

(b) Total Current required in this area at design current density:

$$I_C = AI'(1 - C_E)$$

Where:

A = surface area to be protected.

I′ = required current density to provide adequate protection to submerged bare steel (mA/ft^2).

C_E = coating efficiency at end of design life.

I_C = 618.10 mA, for one out of two Area C’s.

I_{CT} = 1236.20 mA, total for both Area C’s.

(c) Number of Anodes required in this area to meet Supplier’s Current Density Limitations:

$$N_a = I_C/(A_a)\,(I_{al})$$

Where:

N_a = number of anodes required to meet anode current limitations.

I_C = total current required in mA, in this area.

A_a = surface area of single anode in ft^2.

I_{al} = current density limitation of single anode in mA/ft^2.

N_a = 1.55 or 2 (based on current limitations).

(d) Number of Anodes required to meet Design Life Requirements:

$$N_a = (L_{design})(I_C)/(1000)(W_a)$$

Where:

N_a = total number of anodes required.

W_a = weight per bare anode in pounds.

L_{design} = design life in years.

I_C = total current required in mA, in this area.

N_a = 6.18 or 7 (based on design life).

(e) Number of anodes required for adequate current distribution for this surface area:
Note: To ensure uniform current distribution in a distributed impressed current system, it is normally good design practice to provide at least one anode every 100 to 144 ft2 of flat structure surface to be protected.

(f) For columns of compartments, this can many times be done by placing at least one anode unit per compartment. At least one string should be provided for each column of compartments. The minimum number of anodes for this area is:

N_a = Number of compartment submerged X number of columns in this area.

N_a = 14 (For good current distribution).

(g) Based on above, Number of Anodes selected to be installed in this area: Compare all N_a's calculated above and enter a number below for N_a, which is at least greater than or equal to the greater calculated value for N_a.

Use N_a = 14 or one anode per submerged compartment.

Select N = 2, where N is the number of anode strings, consisting of seven anodes each.

(h) Calculation of Anode Groundbed Resistance. Using the Sunde equation:

$$R_a = [(0.00522)(\rho)/(N)(L)][\ln(8L/d){:}\,1 + (2)(L/S)\ln(0.656N)]$$

Where:

N = number of anodes in groundbed = 2.

P = maximum resistivity at groundbed in ohm-cm.

R_a = calculated anode groundbed resistance in ohms.

L = total length of all anodes per string in feet, L = 5.25.

d = diameter of anode in feet.

S = anode spacing in feet, enter value for S here, S = 3.69.

R_a = 2.617919 X [4.52943 + 0.772710908] Ra = 13.881 ohms.

$R_{a,\ Total}$ = 1/ (1/R_a + 1/R_a) Two identical resistances, one in Quoin and one in Miter, separated by over 50 ft) R_{aT} = 6.940 ohms.

(i) Calculation of Header Conductor Resistance (r). For anode header conductor, choose:

Conductor size and type: 10 Cu.
Resistance per 1000 ft: 1.2900 ohms/1000 ft.
Length of Header Cable: 40 ft.
r = 0.0516 ohms.

(9) Total Circuit Resistance for this Area.

$$R_{CT} = R_{aT} + r$$

R_{CT} = 6.9919 ohms

(10) Computation Summary for this Area.

(a) Minimum Number of Specified Anodes required for these Areas. Strings consisting of seven anodes each in each of two Area C's.

(b) Calculated Total Current Required for both Area C's: 1.24 Amperes DC.

(c) Calculated Voltage Required for Combined Area C's.

$$V_{CT} = I_{CT} R_{CT}$$

V_{CT} = 8.64 Volts, DC

8.64 Volts, DC required for this part of circuit.

c. Design Data: Areas D and E.

(1) Water Resistivity is: 5265.93 ohm-cm (based on minimum measured water conductivity of 189.9 micro-mhos/cm, of 142 measurements taken from April through October of 2006 and 2007).

(2) NOTE: Maximum resistivity must be used to determine rectifier requirements.

(3) Coating Efficiency (Dielectric Coating): 90% (at end of design life).

(4) Design Life: 50 years.

(5) Type of Anode Selected:

Material: HSCBCI Type G2, Durichlor, String Anode.
Number of Anodes/string, normally submerged: 3 Anodes.
Anode Dimensions:
Diameter: 2 in.
Length: 9 in.
Weight (W): 5 lb.
Consumption Rate (C): 1 lb/ampere-yr.
Anode Surface Area: 0.40 ft^2.
Anode Current Density Limitation: 1000 mA/ft^2.

(6) Design Current Density (I′): 7 mA/ft^2 of bare steel.

(7) Relative Dimensions for Calculation of Surface Area D:

Number Submerged (C_p): 12.
Compartment Width (W L): 11.813 ft.
Avg. Comp. Height (H): 4.333 ft.

Compartment Depth (D_L): 6.000 ft.
Girder Flange Width (F): 1.000 ft

(8) Relative Dimensions for Calculation of Surface Area E:

Small Miter and Quoin Compartments.
Number Submerged (C_p): 6.
Width (W_S): 3.167 ft.
Average Height (H): 4.333 ft.
Greatest Depth (D): 1.500 ft.
Girder Flange Width (F): 1.000 ft.

Larger Miter and Quoin Compartments, next to Skin Plate:
Number Submerged (C_p): 6.
Width (W_2): 4.500 ft.
Average Height (H): 4.333 ft.
Greatest Depth (D2): 3.000 ft.
Shortest Depth (D): 1.500 ft.
Girder Flange Width (F): 1.000 ft.

(9) Computations: Areas D and E.

(a) Total Surface Area for Area D and Area E:

$Area_D = C_P [W_L H + 2W_L D_L + 2HD_L + 2F (W_L + H)]$.
$Area_D = 3326.74$ ft^2.

$Area_E$ = Cp [WSH+HD+WSD+2F (WS + H)]
+ Cp [H (D+W2 +D2) +2DW2+W2 (D2-D) +2F (W2+H)].
$Area_E = 701.31$ ft^2
Total Area = $Area_D + Area_E = 4028.05$ ft^2.

(b) Total current required in these areas at design current density:

$$I_{DE} = AI'(1 - C_E)$$

Where:

A = surface area to be protected.

I' = required current density to provide adequate protection to submerged bare steel (mA/ft^2).

C_E = coating efficiency at end of design life.

I_{DE} = 2819.64 mA.

(c) Number of anodes required in these areas to meet Supplier's Current Density Limitations:

$$N_a = I_{DE}/(A_a)(I_{al})$$

Where:

N_a = number of anodes required to meet anode current limitations.

I_{DE} = total current required in mA, in these areas.

A_a = surface area of single anode in ft^2.

I_{al} = current density limitation of single anode in mA/ft^2.

N_a = 7.05 or 8 (based on current limitations).

(d) Number of anodes required in these areas to meet Design Life Requirements:

$$N_a = \left(L_{design}\right)(I_{DE})/(1000)\,(W_a)$$

Where:

N_a = total number of anodes required.

W_a = weight per bare anode in pounds.

L_{design} = design life in years.

I_{DE} = total current required in mA, in these areas.

N_a = 28.20 or 29 (based on design life).

(e) Number of anodes required for adequate current distribution for these surface areas: Note: To ensure uniform current distribution in a distributed impressed current system, it is normally good design practice to provide at least one anode every 100 to 144 ft2 of flat structure surface to be protected.

(f) For columns of smaller compartments, this can usually be done by placing at least one anode unit per compartment. For the large compartments in this design, at least two anode units must be installed per compartment. At least one string should be provided for smaller columns and two strings per large columns of compartments. The minimum number of anodes for this area is:

N_a = 2 X Number of large submerged compartments + number of small submerged compartments.

N_a = 36 (For good current distribution)

(g) Based on above, Number of Anodes Selected to be installed in this area: Compare all N_a's calculated above and enter a number below for N_a, which is at least greater than or equal to the greater calculated value for N_a.

Use N_a = 36 or one anode per submerged compartment

(h) NOTE: Drawings show an additional 12 anodes in compartments above the minimum lower pool elevation to provide protection during frequent high water.

Select N = 12, where N is the number of anode strings, consisting of four anodes each.

(i) Calculation of Anode Groundbed Resistance. Using the Sunde equation:

$$R_a = [(0.00522)\,(\rho)/(N)(L)][\ln(8L/d) : 1 + (2)(L/S)\ln(0.656N)]$$

Where:

N = number of anodes in groundbed = 12.

ρ = maximum resistivity at groundbed in ohm-cm.

R_a = calculated anode groundbed resistance in ohms.

L = total length of all anodes per string in feet.

L = 2.25 d= diameter of anode in feet.
S = avg. anode spacing in feet, enter value for S here, S = 5.06.

R_a = 1.018080 X [3.68213 + 1.834961407] Ra = 5.617 ohms.

(j) Calculation of Header Conductor Resistance (r). For anode header conductor, choose:

Conductor size and type: 10 Cu.
Resistance per 1000 ft: 1.2900 ohms/1000 ft.
Length of Header Cable: 40 ft.

r = 0.0516 ohms.

(10) Total Circuit Resistance for these Areas.

$$R_{DE} = R_a + r$$

R_{DE} = 5.6684 ohms

(11) Computation Summary for these Areas.

(a) Minimum Number of Specified Anodes Required for these Areas. Precisely 12 strings consisting of three anodes each. 12 strings consisting of four anodes each will be used to protect above minimum lower pool elevation during frequent high-water events.

(b) Calculated Total Current Required for these Areas: 2.82 Amperes DC.

(c) Calculated Voltage Required for these Areas.

$$V_{DE} = I_{DE} R_{DE}$$

V_{DE} = 15.98 Volts, DC

15.98 Volts, DC required for this part of circuit.

d. Rectifier Selection. Rectifier must have two adjustable DC outputs: one circuit for upstream anodes and under bottom girder, and one circuit for downstream anodes. Each DC circuit must be able to provide a maximum of 15 amperes. The highest voltage required for any circuit is 16 volts. Rectifier voltage output should be 1.6 times this value (to allow for future upward adjustment) or 25.6 volts. Select a 30V rectifier with dual 15 amperes (DC) outputs.

Table F.1
Water Quality Data (April – October 2006 and 2007)

Date	FM Depth (m)	T-H_2O (C)	Cond (umhos @ 25 °C)	Resistivity (ohm-cm)	pH (su)	DO (mg/l)
4/18/2006	0.2	21.93	193	5181.35	7.44	9.79
4/18/2006	1	21.07	193.6	5165.29	7.38	9.92
4/18/2006	1.5	20.98	193.2	5175.98	7.35	9.75
4/18/2006	2	20.98	193.4	5170.63	7.36	9.68
4/18/2006	3	20.96	193.2	5175.98	7.39	9.66
4/18/2006	4	20.94	193.1	5178.66	7.4	9.63
4/18/2006	5	20.92	192.8	5186.72	7.39	9.56
4/18/2006	6	20.9	192.6	5192.11	7.39	9.56
4/18/2006	7	20.89	192.6	5192.11	7.38	9.53
4/18/2006	7.9	20.89	192.7	5189.41	7.36	9.54
5/16/2006	0.2	21.54	190.5	5249.34	7.36	8.54
5/16/2006	1	21.5	190.5	5249.34	7.32	8.48
5/16/2006	1.5	21.46	190.7	5243.84	7.32	8.41
5/16/2006	2	21.46	190.5	5249.34	7.3	8.38
5/16/2006	3	21.42	190.4	5252.10	7.29	8.37
5/16/2006	4	21.43	190.4	5252.10	7.31	8.34
5/16/2006	5	21.43	190.4	5252.10	7.31	8.32
5/16/2006	6	21.4	189.9	5265.93	7.29	8.31
5/16/2006	7	21.4	190.1	5260.39	7.27	8.29
5/16/2006	7.8	21.4	190.1	5260.39	7.29	8.26
6/20/2006	0.2	29.56	242.6	4122.01	7.53	7.57
6/20/2006	1	28.82	242.4	4125.41	7.41	7.57
6/20/2006	1.5	28.69	242.5	4123.71	7.32	7.1
6/20/2006	2	28.7	242.4	4125.41	7.28	6.73

Date	FM Depth (m)	T-H_2O (C)	Cond (umhos @ 25 °C)	Resistivity (ohm-cm)	pH (su)	DO (mg/l)
6/20/2006	3	28.65	242.5	4123.71	7.24	6.61
6/20/2006	4	28.64	242.4	4125.41	7.22	6.48
6/20/2006	5	28.55	243.1	4113.53	7.17	6.3
6/20/2006	6	28.55	242.8	4118.62	7.16	5.99
6/20/2006	7	28.37	243.2	4111.84	7.09	5.74
6/20/2006	7.9	28.32	243.8	4101.72	7.06	5.08
7/18/2006	0.3	31.63	277.1	3608.81	7.49	6.76
7/18/2006	1	31.3	277.3	3606.20	7.36	6.52
7/18/2006	1.5	31.24	276.8	3612.72	7.32	6.38
7/18/2006	2	31.17	277	3610.11	7.24	6.04
7/18/2006	3	31.14	277	3610.11	7.18	5.72
7/18/2006	3	31.14	277.1	3608.81	7.18	5.69
7/18/2006	4	31.12	277.3	3606.20	7.13	5.54
7/18/2006	5	31.06	277.1	3608.81	7.04	4.77
7/18/2006	6	31.04	276.9	3611.41	7.02	4.65
7/18/2006	7	31.03	277.1	3608.81	7	4.57
7/18/2006	8	31	277.3	3606.20	7.02	4.34
7/18/2006	8.1	31	277.4	3604.90	7.03	4.31
8/23/2006	0.2	32.24	331.2	3019.32	7.41	5.53
8/23/2006	1	31.85	331.2	3019.32	7.36	5.32
8/23/2006	1.5	31.78	331.5	3016.59	7.33	5.19
8/23/2006	2	31.76	331.9	3012.96	7.32	5.06
8/23/2006	3	31.75	331.1	3020.24	7.29	5
8/23/2006	4	31.73	331.2	3019.32	7.26	5
8/23/2006	5	31.73	331.1	3020.24	7.24	4.99
8/23/2006	6	31.73	331.3	3018.41	7.23	4.97

Date	FM Depth (m)	T-H_2O (C)	Cond (umhos @ 25 °C)	Resistivity (ohm-cm)	pH (su)	DO (mg/l)
8/23/2006	7	31.7	331.3	3018.41	7.21	4.91
8/23/2006	7.9	31.61	331	3021.15	7.14	4.42
9/19/2006	0.2	27.88	373.1	2680.25	7.35	5.63
9/19/2006	1	27.86	373.3	2678.81	7.34	5.56
9/19/2006	1.5	27.82	373.6	2676.66	7.33	5.55
9/19/2006	2	27.85	373.2	2679.53	7.32	5.53
9/19/2006	3	27.85	373	2680.97	7.31	5.45
9/19/2006	4	27.83	373.2	2679.53	7.32	5.44
9/19/2006	5	27.82	372.9	2681.68	7.3	5.44
9/19/2006	6	27.85	373	2680.97	7.3	5.4
9/19/2006	7	27.84	372.9	2681.68	7.29	5.4
9/19/2006	8	27.84	373.1	2680.25	7.26	5.02
10/18/2006	0.2	23.31	320.2	3123.05	7.52	6.84
10/18/2006	1	22.9	319.7	3127.93	7.51	6.66
10/18/2006	1.5	22.84	319.8	3126.95	7.49	6.53
10/18/2006	2	22.82	319.8	3126.95	7.5	6.49
10/18/2006	3	22.81	319.8	3126.95	7.48	6.46
10/18/2006	4	22.81	319.9	3125.98	7.47	6.41
10/18/2006	5	22.81	319.6	3128.91	7.49	6.39
10/18/2006	6	22.81	320	3125.00	7.49	6.29
10/18/2006	7	22.81	320	3125.00	7.47	6.22
10/18/2006	7.9	22.82	320.1	3124.02	7.44	6.12
Maximum Resistivity			189.9	5265.93		
Minimum Resistivity			373.6	2676.66		
Average		26.54	275.4	3630.90	7.31	6.67
Note: ADEM measurements taken from April 2006. Total of 72 readings.						

Date	FM Depth (m)	T-H_2O (C)	Cond (umhos @ 25 °C)	Resistivity (ohm-cm)	pH (su)	DO (mg/l)
4/17/2007	0.2	19.16	283.2	3531.07	7.37	9.57
4/17/2007	1	17.72	282.6	3538.57	7.78	10.45
4/17/2007	1.5	17.47	282.4	3541.08	7.96	10.52
4/17/2007	2	17.33	282.2	3543.59	7.84	10.3
4/17/2007	3	17.27	282.2	3543.59	7.75	9.94
4/17/2007	4	17.21	282.4	3541.08	7.86	9.63
4/17/2007	5	17.22	282	3546.10	7.56	9.47
4/17/2007	6	17.19	282.3	3542.33	7.59	9.47
4/17/2007	7	17.18	282.1	3544.84	7.53	9.43
4/17/2007	7.7	17.17	282.3	3542.33	7.56	9.41
5/15/2007	0.2	26.98	294.8	3392.13	7.79	8.76
5/15/2007	1	26.43	294.9	3390.98	7.56	8.35
5/15/2007	1.5	26.28	295	3389.83	7.37	7.65
5/15/2007	2	26.16	293.6	3405.99	7.23	7.06
5/15/2007	3	26.02	293.8	3403.68	7.13	6.21
5/15/2007	4	25.92	295	3389.83	7.06	5.95
5/15/2007	5	25.84	294.1	3400.20	7	5.18
5/15/2007	6	25.75	294.6	3394.43	6.98	4.9
5/15/2007	7	25.57	296.6	3371.54	6.9	4.09
5/15/2007	7.5	25.5	297	3367.00	6.88	3.73
6/19/2007	0.2	29.2	383.1	2610.28	7.28	5.91
6/19/2007	1	29.24	383.1	2610.28	7.3	5.87
6/19/2007	1.5	29.27	382.7	2613.01	7.32	5.84
6/19/2007	2	29.25	382.9	2611.65	7.33	5.85
6/19/2007	2.9	29.28	382.8	2612.33	7.35	5.75
6/19/2007	4	29.27	382.7	2613.01	7.36	5.73

Date	FM Depth (m)	T-H_2O (C)	Cond (umhos @ 25 °C)	Resistivity (ohm-cm)	pH (su)	DO (mg/l)
6/19/2007	5.1	29.27	382.6	2613.70	7.37	5.74
6/19/2007	6	29.27	382.6	2613.70	7.38	5.73
6/19/2007	7	29.27	382.4	2615.06	7.39	5.74
6/19/2007	7.7	29.25	382.5	2614.38	7.38	5.7
7/25/2007	0.2	30.11	403.4	2478.93	7.09	6.16
7/25/2007	1	29.9	402.9	2482.01	7.1	6.14
7/25/2007	1.5	29.75	403	2481.39	7.08	5.98
7/25/2007	2	29.64	402.8	2482.62	7.03	5.84
7/25/2007	3.1	29.53	403	2481.39	6.98	5.35
7/25/2007	4	29.49	402.7	2483.24	6.97	5.26
7/25/2007	5.1	29.47	402.9	2482.01	6.96	5.24
7/25/2007	6	29.46	402.6	2483.85	6.95	5.21
7/25/2007	7.1	29.43	402.4	2485.09	6.93	5.14
7/25/2007	7.6	29.4	402.7	2483.24	6.9	4.86
8/21/2007	0.2	33.56	475	2105.26	7.74	7.11
8/21/2007	1	32.77	474.8	2106.15	7.68	7.12
8/21/2007	1.5	32.61	474.9	2105.71	7.54	6.83
8/21/2007	2	32.46	475.1	2104.82	7.31	5.27
8/21/2007	3	32.41	475.3	2103.93	7.3	4.85
8/21/2007	4	32.4	475.5	2103.05	7.25	4.86
8/21/2007	5	32.35	475.6	2102.61	7.21	4.59
8/21/2007	6	32.32	475.7	2102.17	7.19	4.52
8/21/2007	7	32.25	475.8	2101.72	7.14	4.6
8/21/2007	7.7	32.1	477.2	2095.56	7.08	4.5
9/18/2007	0.2	28.85	425.3	2351.28	7.98	7.42
9/18/2007	1	28.69	424.6	2355.16	7.95	7.3

Date	FM Depth (m)	T-H_2O (C)	Cond (umhos @ 25 °C)	Resistivity (ohm-cm)	pH (su)	DO (mg/l)
9/18/2007	1.5	28.61	424.4	2356.27	7.87	6.97
9/18/2007	2.1	28.55	424.8	2354.05	7.76	6.5
9/18/2007	3.1	28.51	424.6	2355.16	7.69	6.25
9/18/2007	4	28.48	424.7	2354.60	7.68	6.24
9/18/2007	5	28.49	424.7	2354.60	7.67	6.21
9/18/2007	6	28.49	424.6	2355.16	7.65	6.16
9/18/2007	7.1	28.43	424.5	2355.71	7.64	6.13
9/18/2007	7.8	28.2	425.2	2351.83	7.52	6.19
10/23/2007	0.2	24.23	385.8	2592.02	7.52	6.46
10/23/2007	1	24.35	386	2590.67	7.53	6.41
10/23/2007	1.5	24.35	386.4	2587.99	7.57	6.41
10/23/2007	2	24.43	385.9	2591.34	7.57	6.39
10/23/2007	3.1	24.4	385.8	2592.02	7.58	6.36
10/23/2007	4	24.42	385.9	2591.34	7.58	6.36
10/23/2007	5	24.41	386	2590.67	7.58	6.36
10/23/2007	6	24.45	385.4	2594.71	7.59	6.34
10/23/2007	7	24.43	385.3	2595.38	7.58	6.34
10/23/2007	7.9	24.4	385.9	2591.34	7.6	6.19
Maximum Resistivity			282.1	3544.84		
Minimum Resistivity			477.2	2095.56		
Average		26.84	378.4	2642.55	7.41	6.52
Note: ADEM measurements taken from April-October 2007. Total of 70 readings.						

F.6 Sacrificial Cathodic Protection Calculations. Note, the following sacrificial (galvanic) anode calculations are provided for information only to illustrate why sacrificial or galvanic anode systems are impractical for application on miter gates. It should also be noted that these calculations are using anodes made of high-potential magnesium alloy, which are currently not readily available for these type specialty anodes within the United States. If the readily available H-1 alloy magnesium anodes were substituted in the calculations, using the same design parameters, and shapes and sizes of anodes, then even more anodes would be required.

a. NOTE: In the following calculations, the normally submerged surface area (with chamber full) designations are defined as:

(1) Area A is the submerged portion of Gate Skin Plate, Upstream Side.

(2) Area B is the one Lower Gate Upstream Side (US) Compartment next to Skin Plate (Typical of 14).

(3) Area C is the one Lower Gate US Compartment next to Miter or Quoin (Typical of 14).

(4) Area D is the one Large Lower Gate Compartment behind skin plate (Typical of 12).

(5) Area E is the one Lower Gate DS Compartment next to Large Compartments (Typical of 6).

(6) Area F is the one Lower Gate DS Compartment next to Miter or Quoin (Typical of 6).

(7) Area G is the area below bottom horizontal gate girder.

(8) Area H is the bottom normally submerged portion of Highest Compartment on each side (Total of 12).

b. Design Data: Area A.

(1) Water Resistivity is: 5265.93 ohm-cm (based on minimum measured water conductivity of 189.9 micro-mhos/cm, of 142 measurements taken from April through October of 2006 and 2007).

(2) NOTE: Maximum resistivity must be used since galvanic systems cannot be adjusted.

(3) Coating Efficiency (Dielectric Coating): 90% (at end of design life).

(4) Design Life: 50 years.

(5) Type of Anode Selected:

Material: High-potential Magnesium Alloy, with plastisol, face only exposed.
Dimensions:
Width: 9 in.
Length: 18 in.
Thickness: 2 in.
Weight (W): 24 lb.
Consumption Rate (C): 8.6 lb/ampere-yr.
Efficiency (E): 50%.
Utilization Factor (U): 85%.
Open Circuit Potential: -1.774 Volts to $Cu\text{-}CuS0_4$.

(6) Design Current Density (I′): 7 mA/ft^2 of bare steel.

(7) Dimensions of Submerged Portion of Area A:

Upper Pool Depth (D): 35.00 ft.
Width (W): 47.25 ft.

(8) Computations: Area A.

(a) Total Normally Submerged Surface of Area A:

Area = WD
Area = 1653.75 ft^2

(b) Total Current Required at Design Current Density:

$$I_T = AI'(1 - C_E)$$

Where:

A = surface area to be protected.

I’ = required current density to provide adequate protection to submerged bare steel (mA/ft^2).

C_E = coating efficiency at end of design life.

I_T = 1157.63 mA.

(c) Anode Current Output. Using the maximum measured water resistivity (see attached water data), the current output of a single magnesium anode can be calculated using McCoy’s formula and Ohm’s Law, as follows:

According to McCoy's formula:

$$R = 0.315\rho/\sqrt{A}$$

Where:

R = resistance of anode to water in ohms.

ρ = water resistivity 5265.93 ohm-cm.

A = total exposed anode surface in cm^2 = 1045.16.

R = 51.31 ohms.

According to Ohms Law:

$$I_A = E/R$$

Where:

I_A = current output in Amperes per anode.

R = resistance of anode to water or 51.31 ohms.

E = anode driving voltage or 0.924 volts. (Derived as follows: -0.85V: open circuit potential (in volts) of anode with respect to Cu-$CuSO_4$ reference cell).

I_A = 0.018009 amperes or 18.01 mA per anode.

(d) Number of anodes required for this surface area:

$$N = I_T/I_A$$

Where:

N = number of anodes required.

I_T = total current required in mA.

I_A = current output per anode in mA.

N = 64.28 or 65 (based on resistivity).

(e) Note: To ensure uniform current distribution, it is normally good design practice to provide at least one galvanic anode per 108 ft^2 (10 m^2) structure surface to be protected. Based on this, the minimum number of anodes for this area is:

N = Total area to be protected / 108
N = 15.31 or 16 (For good current distribution)

(f) Theoretical Anode Life:

$$Y = (W)(E)(U)/(I_A)(C)$$

Where:

Y = anode life in years.

W = weight of single anode in pounds.

E = anode efficiency.

U = anode utilization factor.

I_A = current output in Amperes per anode.

C = anode consumption rate in pounds/Ampere-year.

Y = 65.86 years.

(9) Computation Summary for this Area.

(a) Minimum number of specified anodes required for this area: 65 Anodes (greater number calculated above).

(b) Calculated Life: 65.86 Years.

c. Design Data: Area B. Note, the calculations for this area are omitted from the galvanic calculations.

d. Design Data: Area C.

(1) Water Resistivity is: 5265.93 ohm-cm (based on minimum measured water conductivity of 189.9 micro-mhos/cm, of 142 measurements taken from April through October of 2006 and 2007).

(2) NOTE: Maximum resistivity must be used since galvanic systems cannot be adjusted.

(3) Coating Efficiency (Dielectric Coating): 90% (at end of design life). NOTE: Anodes mounted next to bare exposed steel or stainless steel will consume faster because of 0% coating efficiency.

(4) Design Life: 50 years.

(5) Type of Anode Selected:

Material: High-potential Magnesium Alloy, with plastisol, face only exposed.
Dimensions:
Width: 9 in.
Length: 18 in.
Thickness: 2 in.
Weight (W): 24 lb.
Total Anode Face Only Area: 1045.16 cm^2.
Exposed Anode Surface Area (Removed Plastisol) 1045.16 cm^2 (face only exposed).
Consumption Rate (C): 8.6 lb/ampere-yr.
Efficiency (E): 50%.
Utilization Factor (U): 85%.
Open Circuit Potential: -1.774 Volts to Cu-$CuS0_4$.

(6) Design Current Density (I′): 7 mA/ft^2 of bare steel.

(7) Relative Dimensions for Calculation of Surface Area to be Protected:

Compartment Width (W): 2.500 ft.
Compartment Height (H): 6.000 ft.
Greatest Depth (D): 1.500 ft.
Girder Flange Width (F): 1.000 ft.

(8) Computations: Area C.

(a) Total Surface Area for this Area:

$$\text{Area} = WH + WD + HD + 2F(W + H) \quad \text{Area} = 44.75\ ft^2$$

(b) Total Current required at design current density:

$$I_T = AI'(1 - C_E)$$

Where:

A = surface area to be protected.

I' = required current density to provide adequate protection to submerged bare steel (mA/ft^2).

C_E = coating efficiency at end of design life.

I_T = 31.33 mA.

(c) Anode Current Output. Using the measured water resistivity, the current output of a single magnesium anode can be calculated using McCoy's formula and Ohm's Law, as follows:

According to McCoy's formula:

$$R = 0.351\rho/\sqrt{A}$$

Where:

R = resistance of anode to water in ohms.

ρ = water resistivity 5265.93 ohm-cm.

A = total exposed anode surface in cm^2 = 1045.16.

R = 51.31 ohms.

According to Ohms Law:

$$I_A = E/R$$

Where:

I_A = current output in Amperes per anode.

R = resistance of anode to water or 51.31 ohms.

E = anode driving voltage or 0.924 volts. (Derived as follows: -0.85V: open circuit potential (in volts) of anode with respect to Cu-$CuSO_4$ reference cell).

I_A = 0.018009 amperes or 18.01 mA per anode.

(d) Number of anodes required for this surface area:

$$N = I_T/I_A$$

Where:

N = number of anodes required.

I_T = total current required in mA.

I_A = current output per anode in mA.

N = 1.74 or 2 (based on resistivity) .

(e) Note: To ensure uniform current distribution, it is normally good design practice to provide at least one galvanic anode per 108 ft^2 (10 m^2) structure surface to be protected. Based on this, the minimum number of anodes for this area is:

N = Total area to be protected / 108
N = 0.41 or 1 (For good current distribution)

(f) Theoretical Anode Life:

$$Y = (W)(E)(U)/(I_A)(C)$$

Where:

Y = anode life in years.

W = weight of single anode in pounds.

E = anode efficiency.

U = anode utilization factor.

I_A = current output in Amperes per anode.

C = anode consumption rate in pounds/Ampere-year.

Y = 65.86 years.

(9) Computation Summary for this Area.

(a) Minimum number of specified anodes required for this area: 2 Anodes (greater number calculated above).

(b) Calculated Life: 65.86 Years.

e. Design Data: Area D.

(1) Water Resistivity is: 5265.93 ohm-cm (based on minimum measured water conductivity of 189.9 micro-mhos/cm, of 142 measurements taken from April through October of 2006 and 2007).

(2) NOTE: Maximum resistivity must be used since galvanic systems cannot be adjusted.

(3) Coating Efficiency (Dielectric Coating): 90% (at end of design life).

(4) Design Life: 50 years.

(5) Type of Anode Selected:

Material: High-potential Magnesium Alloy, with plastisol, face only exposed.
Dimensions:
Width: 9 in.
Length: 18 in.
Thickness: 2 in.
Weight (W): 24 lb.
Total Anode Face Only Area: 1045.16 cm^2.
Exposed Anode Surface Area (Removed Plastisol) 1045.16 cm^2 (face only exposed).
Consumption Rate (C): 8.6 lbs. /ampere-yr.
Efficiency (E): 50%.
Utilization Factor (U): 85%.
Open Circuit Potential: -1.774 Volts to Cu-$CuS0_4$.

(6) Design Current Density (I′): 7 mA/ft^2 of bare steel.

(7) Relative Dimensions for Calculation of Surface Area to be Protected:

Compartment Width (W): 11.813 ft.
Compartment Height (H): 4.667 ft.
Compartment Depth (D): 6.000 ft.
Girder Flange Width (F): 1.000 ft.

(8) Computations: Area D.

(a) Total Surface Area for this Area:

Area = WH + 2WD + 2HD + 2F (W + H) Area = 285.83 ft^2

(b) Total Current required at design current density:

$$I_T = AI'(1 - C_E)$$

Where:

A = surface area to be protected.

I′ = required current density to provide adequate protection to submerged bare steel (mA/ft^2).

C_E = coating efficiency at end of design life.

I_T = 200.08 mA.

(c) Anode Current Output. Using the measured water resistivity, the current output of a single magnesium anode can be calculated using McCoy's formula and Ohm's Law, as follows:

According to McCoy's formula:

$$R = 0.351\rho/\sqrt{A}$$

Where:

R = resistance of anode to water in ohms.

ρ = water resistivity 5265.93 ohm-cm.

A = total exposed anode surface in cm^2 = 1045.16.

R = 51.31 ohms.

According to Ohms Law:

$$I_A = E/R$$

Where:

I_A = current output in Amperes per anode.

R = resistance of anode to water or 51.31 ohms.

E = anode driving voltage or 0.924 volts. (Derived as follows: –0.85V: open circuit potential (in volts) of anode with respect to Cu-$CuSO_4$ reference cell).

I_A = 0.018009 amperes or 18.01 mA per anode.

(d) Number of anodes required for this surface area:

$$N = I_T / I_A$$

Where:

N = number of anodes required.

I_T = total current required in mA.

I_A = current output per anode in mA.

N = 11.11 or 12 (based on resistivity) .

Note: To ensure uniform current distribution, it is normally good design practice to provide at least one galvanic anode per 108 ft^2 (10 m^2) structure surface to be protected. Based on this, the minimum number of anodes for this area is:

N = Total area to be protected / 108
N = 2.65 or 3 (For good current distribution)

(e) Theoretical Anode Life:

$$Y = (W)(E)(U)/(I_A)(C)$$

Where:

Y = anode life in years.

W = weight of single anode in pounds.

E = anode efficiency.

U = anode utilization factor.

I_A = current output in Amperes per anode.

C = anode consumption rate in pounds/Ampere-year.

Y = 65.86 years.

(9) Computation Summary for this Area.

(a) Minimum number of specified anodes required for this area: 12 Anodes (greater number calculated above).

(b) Calculated Life: 65.86 Years.

f. Design Data: Areas E, F, G, and H. Note, the calculations for these areas are omitted from the galvanic calculations.

F.7 Performance of Lower Miter Gate Cathodic Protection System. The impressed current CPS design for the Selden Lock lower miter gate replacement project was based on the Bankhead Lock lower miter gate CPS design.

a. The Bankhead Lock is the third lock north of Selden Lock and located in the same river. Therefore, the performance of the new Selden Lock systems is expected to be very similar. A complete cathodic protection potential survey and evaluation was conducted of all miter gate CPSs at the Bankhead Lock in June 2014.

b. A subsequent report was provided to document the results of this annual test and evaluation. Although both the upper and lower miter gate CPSs at Bankhead were evaluated, this appendix will only discuss the CPS of the lower miter gates at the Bankhead Lock project.

c. Survey Summary. The annual CP system potential survey and evaluation, as required by EM 1110-2-2704, was conducted at the Bankhead Lock and Dam project in June 2014. All four lock miter gate CPSs, both upper and lower gates, and the steel surfaces of these miter gates were found to be in generally very good condition. However, as stated above, this appendix will discuss and analyze only the condition and performance of the lower gate CPSs.

d. The lower miter gates, installed in 2004, were about 10 years old and found to be in excellent condition from a CP and corrosion control perspective. Nearly all test points were found to be within the acceptable CP range. There were a very few exceptions, but the rectifiers did not have to be adjusted at that time. The fact that low rectifier current is providing this excellent protection indicated that the coating below the water line was in excellent condition.

e. The combination of good, properly applied dielectric coatings supplemented with properly designed and well maintained CPS is recognized by NACE and by corrosion engineers worldwide as the most practical and economical method of corrosion control for submerged steel structures.

f. Any costs to install and maintain these corrosion control systems at this lock, or any lock, will be more than offset by reduced future costs to repair/replace the structure. If only one dewatering over the life of the lock is eliminated, the cost of all recommended corrosion control measures over the life of the lock will be well justified.

F.8 Bankhead Lock General Background. The Bankhead Lock and Dam project is located on the Black Warrior River and is the last lock upstream on this river. The existing project provides for a concrete non-overflow section on the right bank, a gated spillway in the river channel, and a single lift lock in the left bank, and a concrete, rock, and earth dam extending from the river wall of the new lock across the old lock chambers to the existing spillway.

a. The gated spillway has 20 40-ft vertical lift gates and two 21.25-ft vertical lift gates. The new single lift lock, which replaced an outdated double-lift lock, has chamber dimensions of 110 x 600 ft, a lift of 68 ft and a depth of 14 ft over the miter sills. The lake created by this dam has a normal pool elevation of 255.0. Alabama Power Company operates a small hydropower generation plant on the downstream side of the non-overflow section on the right bank.

b. Construction of the new lock was authorized on 19 September 1966 and it was opened to navigation in June 1975. The present lock has steel double-leafed miter gates at each end of the lock chamber. Unfortunately, shortly after opening the lock to navigation (circa 1975), the lower miter gates failed to properly miter. Consequently, with a tow in the lock chamber, the lower gates failed while the lock chamber was being filled.

c. Although they were repaired and reinstalled, this accident at least contributed to a reduction in the expected service life of the lower miter gates at this project. The lower miter gates were replaced in 2004. Large parts of these gates are submerged all or part of the time. Therefore, good coatings and CPS are required to mitigate corrosion on these large critical structures.

F.9 Existing CPS at Bankhead Lock.

a. General. The first line of corrosion prevention for these metallic structures is a high performance vinyl coating system. Impressed current CPS are also installed as a critical part of the overall corrosion mitigation system. These CPS mitigate metallic corrosion in uncoated and poorly coated areas and in areas where the coating has been damaged by boats or floating debris.

b. NACE Criteria. According to NACE criteria, if the “instant off” protective potential is –850 mV, full protection has been achieved. Very little additional protection is achieved above this level. Depending on circumstances, at polarization potentials of –1100 mV or greater, cathodic blistering of the coating can occur. The –850 mV level is specified by NACE to include the most corrosive type steel known.

(1) An alternate NACE criteria states that a potential shift of 100 mV more negative than the native potentials (i.e., the potentials of the steel before any CP being applied) of a given type of steel would also provide adequate protection. While native potentials for the upper gate on this lock are not available, native potentials have been measured on the new lower gates (installed 2004) at Bankhead Lock and at Demopolis Lock, both of which use similar steel.

(2) These data indicate maximum native potentials of approximately –650 mV with the typical level being more in the range of –550mV or less. Therefore, potentials more negative than approximately –750 mV could be considered as providing “good” protection, and potentials between –850 mV to –1100 mV could be considered as providing “excellent” protection for this particular type of steel. Evaluation of potential charts use the following ranges: Too high, over –1100 mV; Excellent, –850 to -1099 mV; Good, –750 to –849 mV; Marginal, –650 to –749 mV; Low, less than –650 mV.

c. Lower Gates. The lower gate leafs at this lock were replaced with entirely new gate leafs in 2004. The replacements included new CPS. The CPS have string anodes in each miter and quoin compartment on the upstream sides of the gates and in each downstream side compartment. Button anodes are used to protect the skin plate side (i.e., the upstream side) of each gate leaf. New dual DC output rectifiers were provided for these new systems. These rectifiers are Corrpro Model VAYSE 30 (2) AVZ Options, Type-Variac, with 24 Volt, 30 Amp DC per output (Figure F.4).

(1) All adjustments for each of the two outputs are made using a single, continuously variable control knob with markings from 1 to 100% with marks at each 2% that enable adjustments to 1%. Voltages applied to upstream and downstream circuits can be adjusted separately. Voltage variations between string anodes and button anodes on the upstream side of the gates can also be adjusted by means of an adjustable resistor located in the anode terminal boxes.

(2) All anodes on the lower gates are connected to the respective rectifier outputs through large terminal boxes located beneath the gratings on the miter gate walkway (see Figure F.4). Upstream anodes and downstream anodes are in separate terminal boxes. Within the upstream anode terminal box, string anodes and button anodes are also on separate busses.

Figure F.4. Bankhead Lock Lower Left Gate Rectifier (Typical)

(3) This allows for good flexibility in adjusting the voltages applied to different gate areas and even to the different anodes if required. In addition, each anode has a 0.01-ohm shunt (resistance wire) installed in series with the anode. The current flowing through each anode can thus be easily measured without disconnecting the anode connections. The original design called for 0.1-ohm shunts, which would have provided greater accuracy and repeatability of current readings, but the contractor installed 0.01-ohm shunts, which still are useful in accessing system performance, but which are limited in that regard.

(4) The CPS were put into service and contract acceptance tests were performed by the contractor and witnessed by the Government representative in March 2005.

d. Observations and Findings during 2014 Inspection. Complete CP potential measurements were made for both the upper and lower gates. This appendix will discuss only the lower miter gates and their CPSs. Consequently, in relation to the lower miter gates only, potential graphs, along with tables coordinating the measurement position number with its specific location on the gate surface, are included at the end of this appendix.

Lower Gate (LG). A complete close interval survey of protective potentials on the lower gate was done. The charts at the end of this appendix graphically show data taken on the performance of the CPS. Only one point on the left leaf, US of the gate are in the “marginal” range and there are no points in the “too high” or “low” range. The average “instant off” potential on the US of the LG is –0.910 mV, as compared to an average of –0.873 mV in 2013.

(1) In 2013, the rectifier settings on the US of the LG were increased slightly to increase potentials at a few points that were marginal. This goal was accomplished so no adjustment to the upstream side settings was necessary in 2014. No adjustment was required because 100% of points tested on the downstream side of the gate were in the “good” or “excellent” range. This was also the case in 2013. Only one point was in the “marginal” range.

(2) Lower Gate (LG). A complete close interval survey of protective potentials on the lower gate was done. The charts at the end of this appendix graphically show data taken on the performance of the CPS. Only one point on the left leaf, US of the gate are in the “marginal” range and there are no points in the “too high” or “low” range. The average “instant off” potential on the US of the LG is –0.910 mV, as compared to an average of –0.873 mV in 2013.

(3) Individual button anode and string anode currents were taken for CPS on the LGs using the 0.01-ohm shunts included in the anode terminal boxes. These data can be seen in tables at the end of this appendix. As mentioned above, the construction plans and specifications called for these shunts to be 0.1 ohm. It was found, however, that 0.01-ohm shunts were actually provided. These shunts can still be used to measure anode currents, but the measurements are less accurate and consistent as compared to what would have been provided using the specified shunts.

(4) It can also be seen that a few anodes showed “0” current, but the close interval potential survey, discussed in the previous paragraph, does not show any gaps or low potentials at any point on the gate. Thus, either all anodes are apparently working and do not actually have “0” current, or the other anodes are providing sufficient current to make up for the few anodes that are not working. Faulty shunts have been found at some locks so it is possible that it is the shunts that are broken, not the anodes.

(5) There are two string anodes on the DS left leaf and one string anode on the DS right leaf that are showing 0 amps. One anode on the DS right leaf is showing only 10 mA as

compared to 30 or 40 mA for the other strings. In 2013, two of these strings, one on the left and one on the right leafs were also showing no current flow. These should indicate measurable current flow in spite of the 0.01 ohm shunts, so these strings are likely not working or the shunt could be faulty.

(6) However, looking at the protective potential data and looking at the design drawings, the compartments with the “non-working” anode strings also have another string in the same compartment. Therefore, there apparently is sufficient current from other anodes such that there are still very good protective potentials in all areas of the gate.

(7) Because the LG is only about 10 years old, the condition of the coating, upstream and downstream, above and below the water line, is apparently still excellent. This excellent condition can, and should, be continued by frequent visual inspection of all surfaces by lock and maintenance personnel, and any signs of corrosion or coating failure above the water line should be repaired as soon as possible to keep corrosion under control.

(8) The settings and values listed in Table F.2 are those measured after potential tests were taken in this inspection. There were no adjustments made, or necessary, during this inspection. The tap readings for the lower rectifiers vary somewhat from those recorded in 2013, but the measured voltages were almost exactly the same as last year, which indicates that the settings were read differently by a different person and really have not changed since 2013.

(9) Operators and other personnel not trained in CP should not change settings except as directed by the District CP Specialist. The currents were somewhat higher indicating that water resistivity was slightly lower this year vs. last year. The fact that excellent potentials are being achieved and that the rectifier current needed to achieve this good performance, especially on the LG, is very low indicate that the coating below the water line is very good.

(10) To ensure the best possible corrosion control, it is essential that the systems on these gates remain in operation at all times. The lock operators at Bankhead Lock have been doing an excellent job of reporting rectifier readings and rectifier outages to the CP Specialist in Mobile for many years. The continuation of this practice will keep rectifiers operating and will thus provide the needed protective potentials on the gates at all times. The reading, recording, and reporting of each rectifier voltage and current output must be done weekly, at least.

Table F.2
Rectifier Data at End of 2014 Survey

Location	Unit #	Coarse Tap	Fine Tap	Voltage (Volts)	Current (Amps)	Serial Number
Upper Gate Left Leaf	N/A	3	8	10.33	3.6	810301
Upper Gate Right Leaf	N/A	High-A	1	13.75	2.96	749
LG Left Leaf Upstream	1	12%	N/A	5.80	2.32	C-043083
LG Left Leaf Downstream	2	9.2%	N/A	3.33	0.52	
LG Right Leaf Upstream	1	12%	N/A	5.51	2.16	C-043082
LG Right Leaf Downstream	2	9.2%	N/A	3.30	0.56	

e. Conclusions. Based on the above described condition and on the performance of similar CPSs at Bankhead Lock, some conclusions regarding the designed, but not yet installed, CPSs for the LGs at Selden Lock can be made.

(1) As evident from the excellent performance of the CPS on the lock gates at the Bankhead Lock, the new CPS on the new lock gates at Selden Lock should provide the same excellent performance, provided that the CPS are installed correctly and are properly operated and maintained after their installation.

(2) The weekly reading, recording, and reporting of each rectifier voltage and current output by the lock operators should begin immediately after the completion of the installation of the Selden CPSs. In addition, monitoring of the CPS protective potentials on the new lock miter gates should be done on an annual basis after installation of the new CPS at Selden Lock. Initially, potential tests should be taken more often than annually, i.e., until the systems stabilize.

(3) These annual inspections have proven to be very helpful in ensuring CPS provide adequate corrosion control. Inspections also provide information on the condition of gate surfaces below the water line.

f. Protective Potential Charts. Figures F.5 and F.6 show Protective Potential Charts for Bankhead 2014—Lower, upstream, and downstream sides, respectively. Figure F.7 shows a schematic drawing of the Upper and Lower Gate Leaf. Table F.3 and Table F.4 shows the data positions on upstream and downstream gates.

g. Individual LG Anode Currents. Note that total currents listed here do not necessarily match total currents shown in the rectifier table because of instrument inaccuracies and rounding errors in individual readings. Numeric “0” entries are not true “zero,” but a value less than 1 mV or 10mA. Data are primarily for comparison of current among individual anodes/strings. Strings showing “0” are not working. Tables F.5 and F.6 show the current readings for the lower left and right gates.

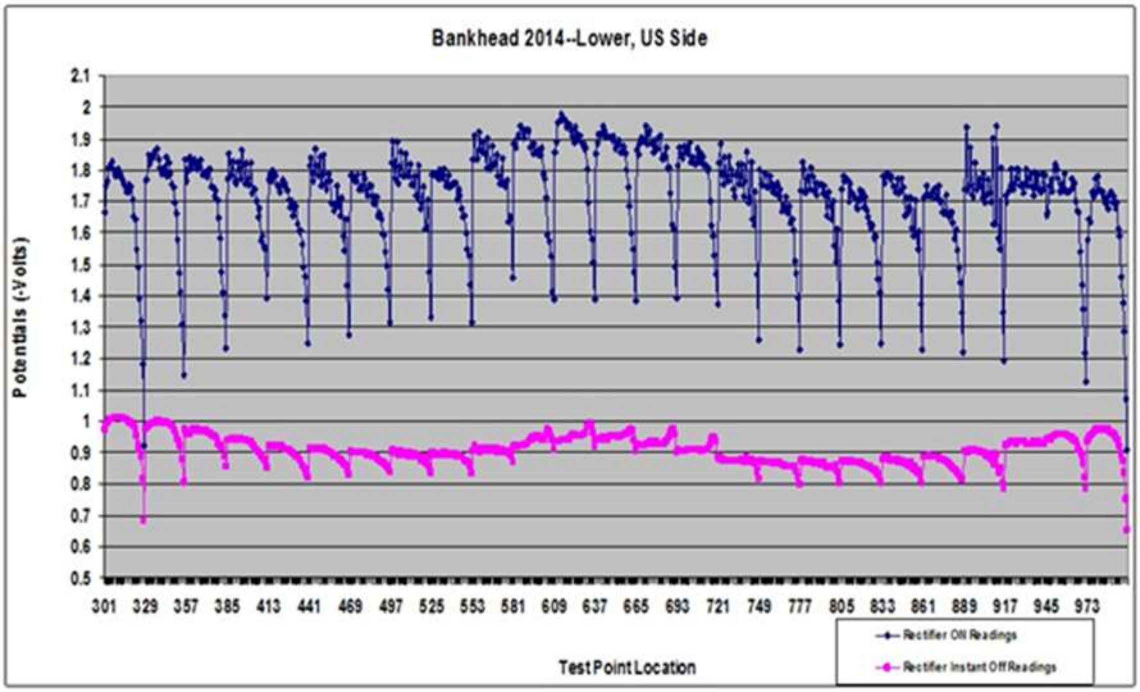

Figure F.5. Bankhead 2014—Lower, US Side

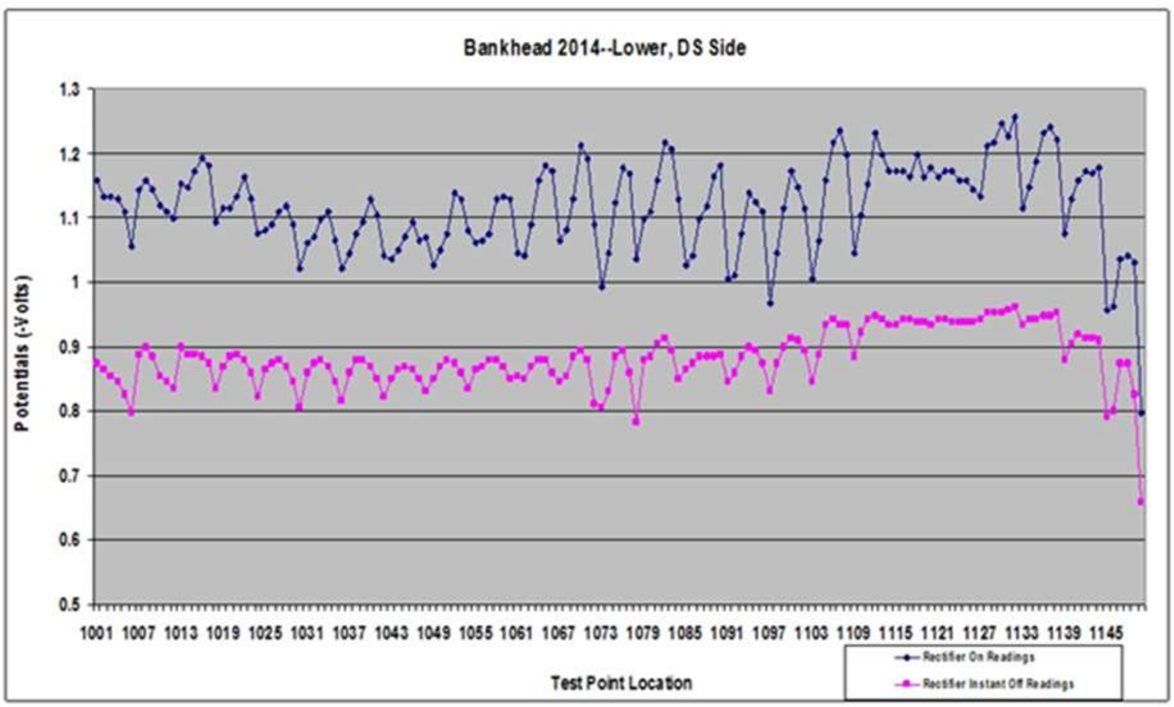

Figure F.6. Bankhead 2014—Lower, DS Side

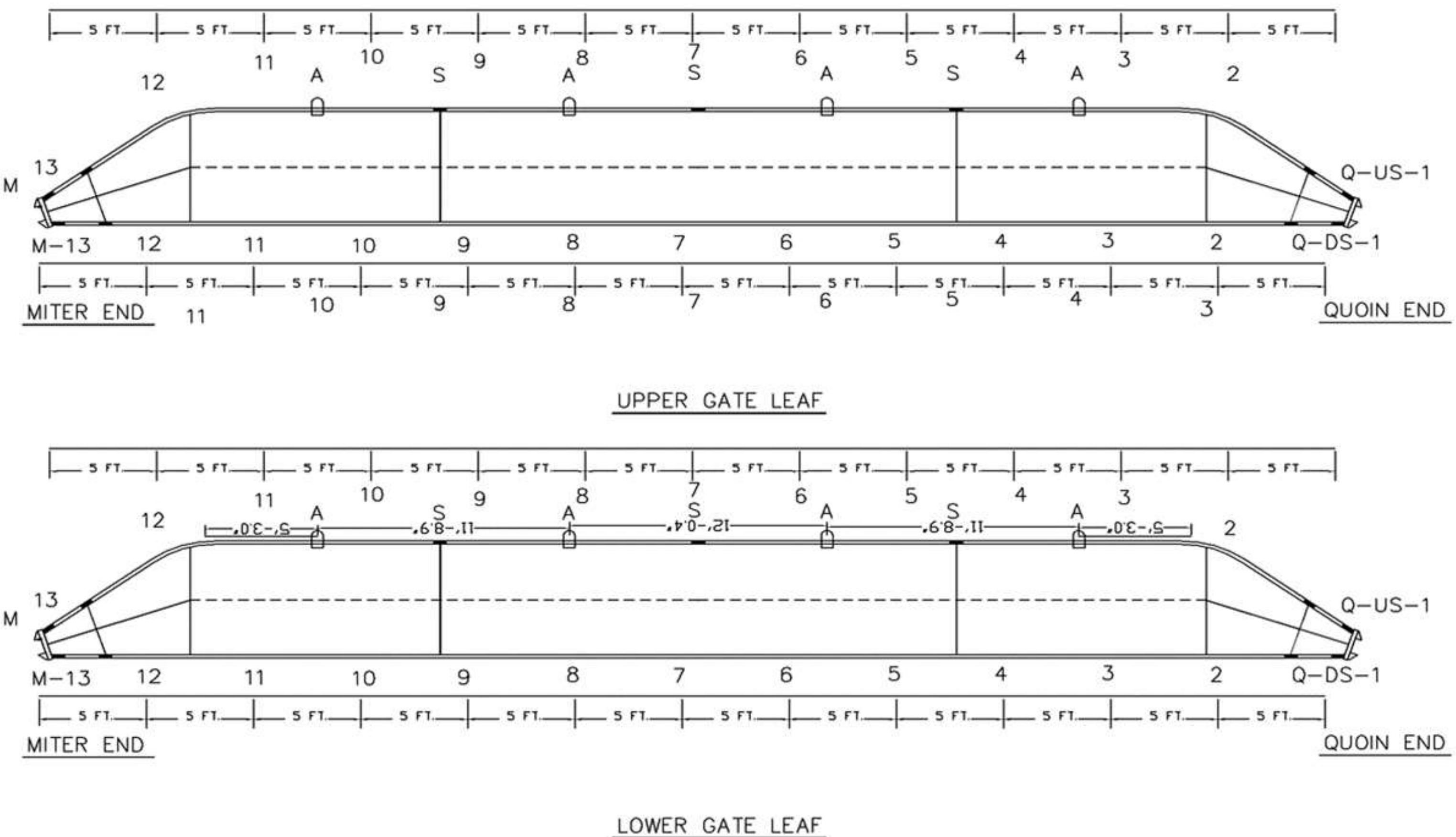

Figure F.7. Upper and Lower Gate Leafs

Table F.3
Data Position Tables, LGs, Upstream Side

POSITIONS—LG, LEFT LEAF, UPSTREAM SIDE															POSITIONS—-LG, RIGHT LEAF, UPSTREAM SIDE											
HEIGHT	1	2	3	4	5	6	7	8	9	10	11	12	13	12	11	10	9	8	7	6	5	4	3	2	1	HEIGHT
(FT)	QUOIN	55	50	45	40	35	30	25	20	15	10	5	MITER	5	10	15	20	25	30	35	40	45	50	55	QUOIN	(FT)
TOP (82)	351	379	407	435	463	491	519	547	575	603	631	659	687	715	743	771	799	827	855	883	911	939	967	995	1023	TOP (82)
78	352	380	408	436	464	492	520	548	576	604	632	660	688	716	744	772	800	828	856	884	912	940	968	996	1024	78
75	353	381	409	437	465	493	521	549	577	605	633	661	689	717	745	773	801	829	857	885	913	941	969	997	1025	75
72	354	382	410	438	466	494	522	550	578	606	634	662	690	718	746	774	802	830	858	886	914	942	970	998	1026	72
69	355	383	411	439	467	495	523	551	579	607	635	663	691	719	747	775	803	831	859	887	915	943	971	999	1027	69
66	356	384	412	440	468	496	524	552	580	608	636	664	692	720	748	776	804	832	860	888	916	944	972	1000	1028	66
63	357	385	413	441	469	497	525	553	581	609	637	665	693	721	749	777	805	833	861	889	917	945	973	1001	1029	63
60	358	386	414	442	470	498	526	554	582	610	638	666	694	722	750	778	806	834	862	890	918	946	974	1002	1030	60
57	359	387	415	443	471	499	527	555	583	611	639	667	695	723	751	779	807	835	863	891	919	947	975	1003	1031	57
54	360	388	416	444	472	500	528	556	584	612	640	668	696	724	752	780	808	836	864	892	920	948	976	1004	1032	54
51	361	389	417	445	473	501	529	557	585	613	641	669	697	725	753	781	809	837	865	893	921	949	977	1005	1033	51
48	362	390	418	446	474	502	530	558	586	614	642	670	698	726	754	782	810	838	866	894	922	950	978	1006	1034	48
45	363	391	419	447	475	503	531	559	587	615	643	671	699	727	755	783	811	839	867	895	923	951	979	1007	1035	45
42	364	392	420	448	476	504	532	560	588	616	644	672	700	728	756	784	812	840	868	896	924	952	980	1008	1036	42
39	365	393	421	449	477	505	533	561	589	617	645	673	701	729	757	785	813	841	869	897	925	953	981	1009	1037	39
36	366	394	422	450	478	506	534	562	590	618	646	674	702	730	758	786	814	842	870	898	926	954	982	1010	1038	36
33	367	395	423	451	479	507	535	563	591	619	647	675	703	731	759	787	815	843	871	899	927	955	983	1011	1039	33
30	368	396	424	452	480	508	536	564	592	620	648	676	704	732	760	788	816	844	872	900	928	956	984	1012	1040	30
27	369	397	425	453	481	509	537	565	593	621	649	677	705	733	761	789	817	845	873	901	929	957	985	1013	1041	27
24	370	398	426	454	482	510	538	566	594	622	650	678	706	734	762	790	818	846	874	902	930	958	986	1014	1042	24
21	371	399	427	455	483	511	539	567	595	623	651	679	707	735	763	791	819	847	875	903	931	959	987	1015	1043	21
18	372	400	428	456	484	512	540	568	596	624	652	680	708	736	764	792	820	848	876	904	932	960	988	1016	1044	18
15	373	401	429	457	485	513	541	569	597	625	653	681	709	737	765	793	821	849	877	905	933	961	989	1017	1045	15
12	374	402	430	458	486	514	542	570	598	626	654	682	710	738	766	794	822	850	878	906	934	962	990	1018	1046	12
9	375	403	431	459	487	515	543	571	599	627	655	683	711	739	767	795	823	851	879	907	935	963	991	1019	1047	9
6	376	404	432	460	488	516	544	572	600	628	656	684	712	740	768	796	824	852	880	908	936	964	992	1020	1048	6
3	377	405	433	461	489	517	545	573	601	629	657	685	713	741	769	797	825	853	881	909	937	965	993	1021	1049	3
BOTTOM	378	406	434	462	490	518	546	574	602	630	658	686	714	742	770	798	826	854	882	910	938	966	994	1022	1050	BOTTOM

Table F.4
Data Position Tables, LGs, Downstream Side

POSITIONS—-LG, LEFT LEAF, DOWNSTREAM SIDE																POSITIONS—-LG, RIGHT LEAF, DOWNSTREAM SIDE										
HEIGHT	1	2	3	4	5	6	7	8	9	10	11	12	13	12	11	10	9	8	7	6	5	4	3	2	1	HEIGHT
(FT)	QUOIN	55	50	45	40	35	30	25	20	15	10	5	MITER	5	10	15	20	25	30	35	40	45	50	55	QUOIN	(FT)
TOP(13)	1051	1057	1063	1069	1075	1081	1087	1093	1099	1105	1111	1117	1123	1129	1135	1141	1147	1153	1159	1165	1171	1177	1183	1189	1195	TOP(13)
12	1052	1058	1064	1070	1076	1082	1088	1094	1100	1106	1112	1118	1124	1130	1136	1142	1148	1154	1160	1166	1172	1178	1184	1190	1196	12
9	1053	1059	1065	1071	1077	1083	1089	1095	1101	1107	1113	1119	1125	1131	1137	1143	1149	1155	1161	1167	1173	1179	1185	1191	1197	9
6	1054	1060	1066	1072	1078	1084	1090	1096	1102	1108	1114	1120	1126	1132	1138	1144	1150	1156	1162	1168	1174	1180	1186	1192	1198	6
3	1055	1061	1067	1073	1079	1085	1091	1097	1103	1109	1115	1121	1127	1133	1139	1145	1151	1157	1163	1169	1175	1181	1187	1193	1199	3
BOTTOM	1056	1062	1068	1074	1080	1086	1092	1098	1104	1110	1116	1122	1128	1134	1140	1146	1152	1158	1164	1170	1176	1182	1188	1194	1200	BOTTOM

Table F.5
Anode Readings Lower Left Gate Leaf

Lower Left Gate Leaf

Anode Term.#	Bus Voltage	V Drop Across 0.01 Ohm Shunt	Anode Current	Anode Term.#	Bus Voltage	V Drop Across 0.01 Ohm Shunt	Anode Current
		Buttons (Upstream)				**Strings**	
	(Volts)	**(Mv)**	**(Ma)**		**(Volts)**	**(Mv)**	**(Ma)**
1	3.72	0.2	20	**Upstream**			
2		0.2	20				
3		0.2	20	1	5.54	6.4	640
4		0.2	20	2		6.7	670
5		0.2	20	3		5.7	570
6		0.2	20	4		6.1	610
7		0.2	20		**Subtotal:**	**24.9**	**2490**
8		0.3	30	**Downstream**			
9		0.3	30				
10		0.3	30	1	3.12	0.9	90
11		0.2	20	2		0.9	90
12		0.2	20	3		0.8	80
13		0.2	20	4		0.9	90
14		0.2	20	5		1.0	100
15		0.2	20	6		0.0	0
16		0	0	7		1.0	100
17		0.2	20	8		0.0	0
18		0.2	20	9		1.0	100
19		0.3	30	10		0.1	10
20		0.3	30	11		1.1	110
21		0	0	12		0.9	90
22		0.2	20		**Subtotal**	**8.6**	**860**
23		0.2	20				
24		0.2	20				
25		0.2	20			**All Upstream:**	3360
26		0.2	20				
27		0.2	20				
28		0.3	30			**All Downstream:**	860
29		0.3	30				
30		0.3	30				
31		0.2	20				
32		0.2	20				
33		0.2	20				
34		0.2	20				
35		0.2	20				
36		0.2	20				
37		0.3	30				
38		0.2	20				
39		0.2	20				
40		0.4	40				
	Subtotal	**8.7**	**870**				

Table F.6
Anode Readings Lower Right Gate Leaf

Lower Right Gate Leaf

Buttons (Upstream)

Anode Term #	Bus Voltage	V Drop Across 0.01 Ohm Shunt	Anode Current
	(Volts)	(Mv)	(Ma)
1	3.88	0.2	20
2		0.2	20
3		0.2	20
4		0.2	20
5		0.2	20
6		0.3	30
7		0.2	20
8		0.3	30
9		0.4	40
10		0.4	40
11		0.2	20
12		0.2	20
13		0.2	20
14		0.2	20
15		0.3	30
16		0.2	20
17		0.2	20
18		0.3	30
19		0.4	40
20		0.4	40
21		0.2	20
22		0.2	20
23		0.2	20
24		0.2	20
25		0.2	20
26		0.2	20
27		0.3	30
28		0.3	30
29		0.4	40
30		0.4	40
31		0.3	30
32		0.2	20
33		0.3	30
34		0.2	20
35		0.2	20
36		0.3	30
37		0.3	30
38		0.3	30
39		0.4	40
40		0.5	50
	Subtotal:	**10.8**	**1080**

Strings

Anode Term #	Bus Voltage	V Drop Across 0.01 Ohm Shunt	Anode Current
	(Volts)	(Mv)	(Ma)
Upstream			
1	5.2	5.7	570
2		5.5	550
3		5.3	530
4		4.6	460
	Subtotal:	**21.1**	**2110**
Downstream			
1	3.08	0.9	90
2		0.9	90
3		0.7	70
4		0.7	70
5		0.9	90
6		0.3	30
7		0.8	80
8		0.9	90
9		0.9	90
10		0.0	0
11		0.9	90
12		0.8	80
	Subtotal:	**8.7**	**870**

All Upstream:	**3190**
All Downstream:	**870**

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Appendix G
Impressed Current Cathodic Protection System Design Analysis and Calculations to Replace Lower Miter Gates at Selden Lock

G.1 Foreword. The design of the Colorado River Lock Cathodic Protection System is provided as an example of an impressed current CPS application for a sector gate in highly corrosive brackish water. This design would also be comparable to tainter and spillway gates although in these applications, anodes might not be located on the forward skin plate because of possible interference with seals.

G.2 Background. As shown in Figure G.1, the Galveston District Colorado River Locks are located in the GIWW at its intersection with the Colorado River near Matagorda, TX. The navigational locks, comprised of two sets of sector gates, exists on each side of the Colorado River have been in operation for over 50 years.

a. Figure G.2 provides an enlarged view of one set of Sector Gates in the recessed position. The sector gates are constructed of riveted steel. Normally these gates remain in the recessed (open) position but are closed and used for locking GIWW vessel traffic during periods of high river levels and swift currents.

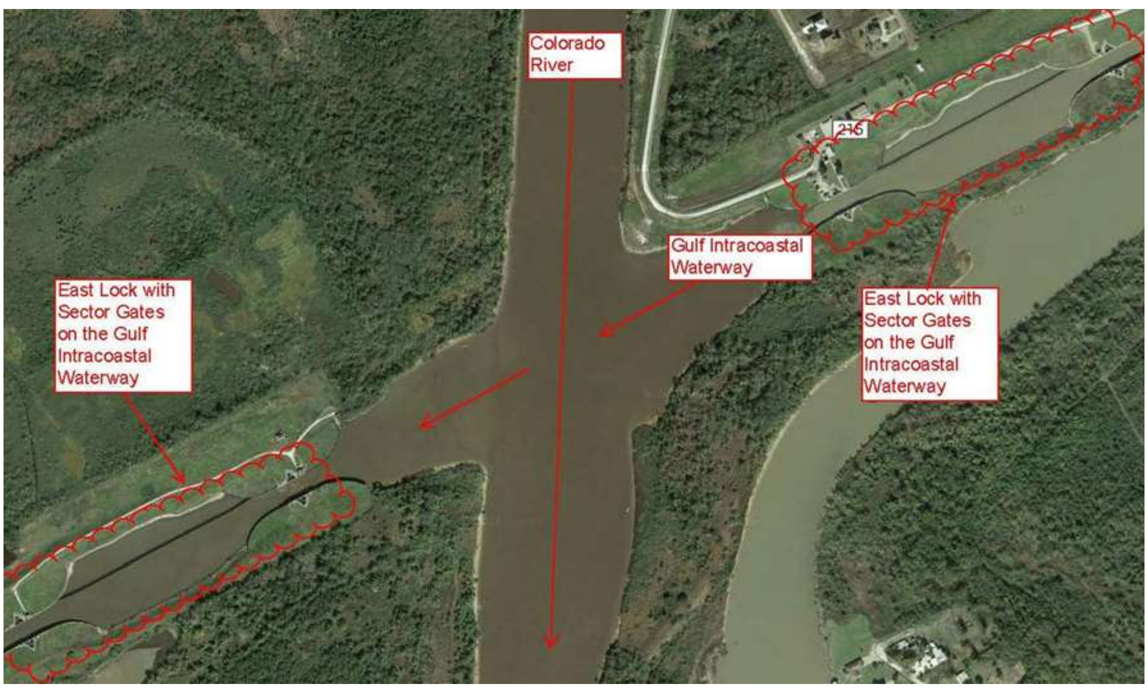

Figure G.1. Colorado River Locks Located in the GIWW at Intersection with Colorado River

Figure G.2. Enlarged View of Colorado River Lock Sector Gate (Typical of Four)

b. The sector gates are removed for inspection and rehabilitation, as necessary, approximately once every 8 to 10 years. Rehabilitation efforts include cleaning, inspecting, repairing, repainting, and repair/replacement of the CPS, as necessary.

c. In addition, diver inspections are done periodically between scheduled maintenance activities to discover and report any significant problems that may have become evident since the last rehabilitation efforts. During the 2009–2010 gate rehabilitation, severe pitting corrosion was observed in some areas on the sector gates, which indicated that the previous impressed current CPS were not operating properly.

d. Consequently, the Galveston District requested that the CCCP TCX perform an analysis to determine the causes for the CPS' premature failure and, additionally, to provide recommendations for remedial actions. Therefore, a new, more robust and reliable impressed current CP system was designed to replace the failed magnesium anode CP system.

G.3 Corrosion Control and Cathodic Protection System.

a. Impressed Current Cathodic Protection. A very similar CP system was installed on the Brazos River floodgates and, consequently, many features of the impressed current CPS for the Brazos River Project were duplicated in this project. Figure G.3 shows two of the rectifiers currently installed at the Brazos River Project.

b. Figure G.4 shows the interiors of the above rectifiers. These two rectifiers were for the west gate: one for the north sector of the west gate and the other for the south sector. Each rectifier had two DC circuits: one for the river side anodes of the sector and the other for the canal side anodes of the sector. The Colorado River Project had a total of eight dual circuit rectifiers located at the same relative locations at each control booth.

Figure G.3. Electrical Setup and Location for Two Rectifiers

Figure G.4. Typical Interior View of One Rectifier

c. Constant voltage rectifiers were selected for use with this impressed current CP system for a number of reasons. First, they have simpler circuitry and are more reliable. Second, since the voltage is constant, the rectifier current output changes with changes in water resistivity, water temperature, and water level (i.e., V=IR).

d. In addition, a constant current impressed current system, in which the rectifier supply current is automatically held constant, and an automatic potential impressed current system, which automatically holds potential at a gate-mounted reference electrode constant, had already been used on these gates in the past.

e. Both of these systems had failed prematurely. Rectifiers operating in an automatic potential mode require that a permanent reference cell be mounted on each gate. At this location, these cells do not typically experience very long lives because of damage caused from floating logs and other debris and possibly other reasons.

f. Consequently, because of the likely premature failure of the extra circuitry and/or components required to automatically adjust the rectifier voltage or current outputs, these rectifiers appear to generally not be as reliable for use on USACE HSS as the constant voltage rectifiers have already proven to be for these types of applications.

g. Moreover, constant current type rectifiers are not desired for this application for additional reasons provided herein. Constant current rectifiers would automatically adjust to provide the same amount of current output regardless of the amount of rod anode material surfaces or the amount of structural surfaces submerged at any given time. Consequently, if not carefully adjusted by experienced personnel, excessive potentials could be applied during periods of low water and/or low tides.

h. In addition, these rectifiers are not as reliable simply because they have additional control circuitry and more components to contend with and to possibly fail. Again, constant voltage rectifiers are the best choice for this application.

i. Figure G.5 shows a view of one of the anode terminal cabinets currently installed at the Brazos River Project. These anode terminal cabinets are for the west gates. One terminal cabinet was installed on the north sector of the west gate and another installed on the south sector. Each terminal cabinet had two busses: one where the river side anodes were terminated and the other where the canal side anodes were terminated.

j. A total of eight anode terminal cabinets were installed at the Colorado River Project. Figure G.6 shows an interior view of the above anode terminal cabinet. There were two tubular rod anode assemblies on the river side of each sector at the Colorado River Project. In addition, two parallel No. 6 cables with Type PVDF/HMWPE (polyvinylidene difluoride/high molecular weight polyethylene) insulation were extended from each anode assembly and will terminate in each respective terminal cabinet.

k. The anode design consisted of high silicon cast iron tubular rod anodes, with diameters of 2.2 in, of 5- and 7-ft lengths, installed in fiberglass reinforced plastic (FRP) lined MC8X22.8 steel channels. These anode assemblies were completely fabricated in a shop and subsequently installed on the gates by divers.

l. The steel channels were appropriately sized angle irons welded to the channels, which were used for attachment of each assembly onto the gate frames on the canal side of each gate. The anode assemblies for the river side of each gate were bolted to the skin plate. Figures G.7 and G.8 show two typical cross-sectional views of the anode assemblies.

Figure G.5. Anode Terminal Cabinet Location

Figure G.6. Interior View of One Anode Terminal Cabinet

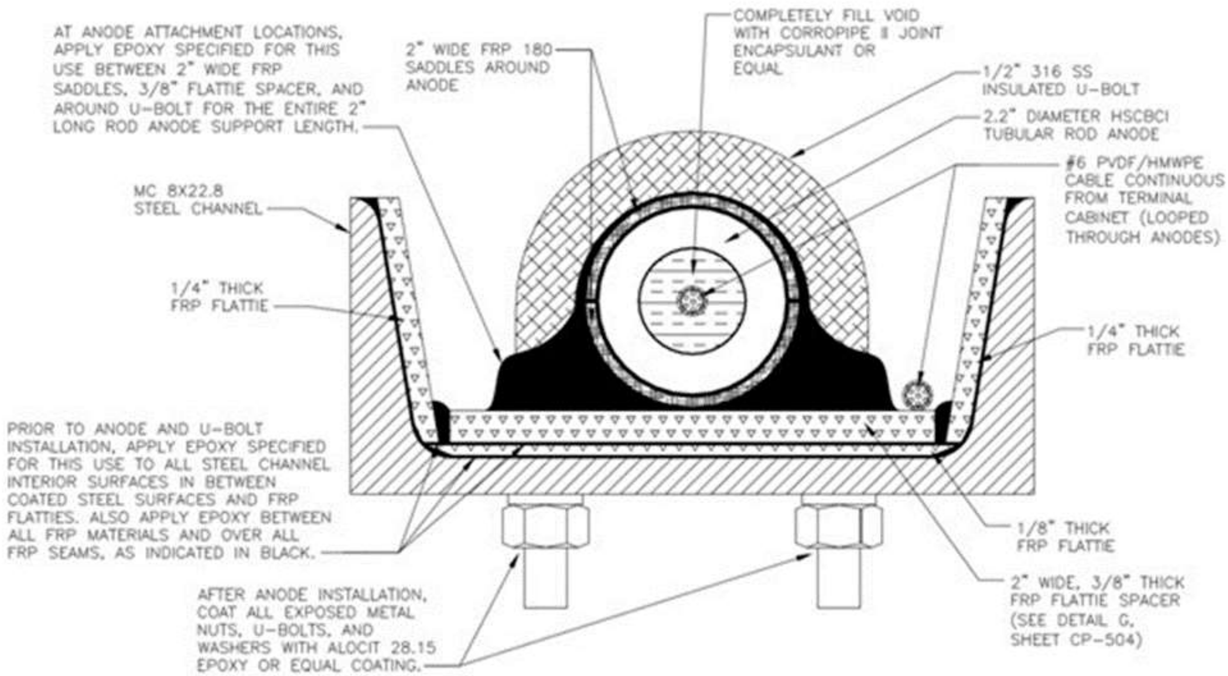

Figure G.7. Cross-Sectional View of Anode Assembly

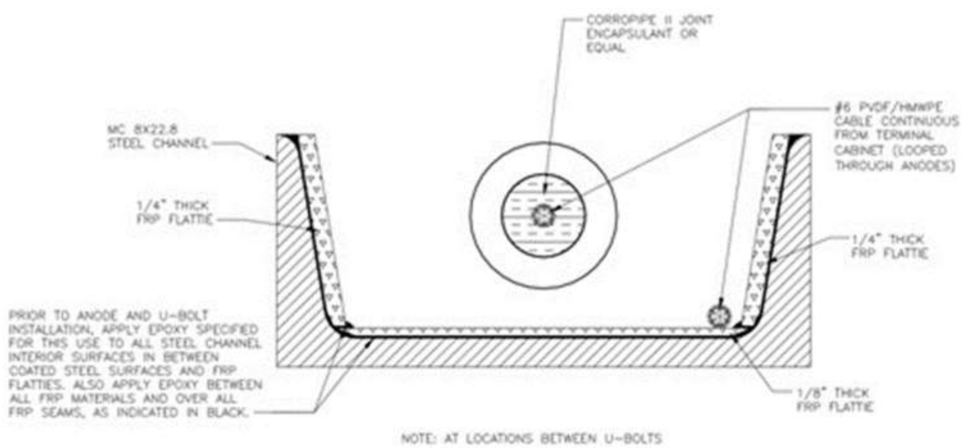

Figure G.8. Cross-Sectional View of Anode Assembly (Locations between U-Bolts)

m. In addition to the calculations provided below, this CP design was based primarily on knowledge and data obtained over many years from experience with existing impressed current systems, and from data and lessons learned from the Brazos River impressed current systems. Observations made during numerous inspections combined with an analysis of much data best define the correct design approach.

n. This design incorporated many improvements that were incorporated into the impressed current systems over many years. For example, complete anode assemblies were shop fabricated so they could then be delivered to the project site and installed on the gates by divers.

This eliminated the need to remove the gates from the water saving considerable construction time and cost. Additional design considerations included:

(1) Use of FRP lined MC8X22.8 channels for the mounting of longer, more robust tubular rod anodes, which provide more protection from logs and other floating debris.

(2) Rod anodes of longer lengths and slightly larger diameters that provide more current capacity from fewer anode mounting locations without sacrificing uniform current distribution in this particular application (current can be distributed easier in the much lower resistivity salt water).

(3) The requirement to electrically bond each set of sectors.

G.4 Coating System. The coating and CPS work in conjunction with each other to form the complete corrosion control system. Consequently, if the coating is poor, the CP system provided may not be able to achieve its desired performance.

a. However, if the CP system is installed as designed, it will serve to prevent corrosion in areas where the coating may be damaged or where holidays may exist, thereby extending the life of both the structure and the coating system.

b. All steel surfaces of the sector gates at the Colorado River Project were recently recoated with a well bonded, high quality dielectric coating. In addition, a suitable coating system, was applied to all new metallic components included in the CPS (except the anode material). To avoid cathodic disbondment of the paint, protective potentials less negative than minus 1100 mV “instant off,” with respect to a copper/copper-sulfate reference electrode were specified.

G.5 Water Corrosivity. Prior to performing design calculations, data regarding the water corrosivity must be determined. There are many variables involved in determining the corrosivity of any electrolyte environment such as temperature, pH, dissolved oxygen content, and conductivity.

a. Since this project was located very near to the Gulf of Mexico, the very high chloride content of the water was a critical consideration for the CPS design. The presence of chlorides and other dissolved salts drastically increases the conductivity of the water.

b. This lack of consideration for the influence of chlorides on the water conductivity was the primary cause for the premature failure of the magnesium anode CPS originally installed at this project. The CP subcontractor used a much higher resistivity value in CPS calculations than the value used in this design example, which resulted in a much shorter CPS life than was indicated in design calculations.

c. With the assistance of Colorado River Locks' personnel, the Lower Colorado River Authority (LCRA) provided water quality data, over a several year period, from four nearby water quality stations. These data included pH, dissolved oxygen content, salinity, conductivity, and water temperature.

d. This data indicated that the average water salinity from August 2005 to June 2011 was 14.4 ppt, which is considered brackish water. It was interesting to note that the marine growth that always existed on the sector gates serves to corroborate the LCRA salinity data. However, since the conductivity data was the most important parameter to consider for this CPS design, only the water conductivity data is provided in this example.

e. Resistivity was the critical variable in this case for ensuring a CPS anode system capable of providing a long service life. Conductivity measurements from January 2009 through June 2011 were selected from the provided LCRA data for analysis in this design.

f. Table G.1 below summarizes the maximum, average, and minimum values over a specified period of time. Resistivity is the reciprocal of conductivity. The average resistivity of 30 ohm-com was used in the CPS calculations below to ensure that an adequate number (and correct weight) of anodes, are installed to provide a 20-year system life.

Table G.1
Water Conductivity Summary

Time Period	Specific Conductivity (µS/cm)		Resistivity (ohm-cm)	
Jan 09 – Jun 11	55683	Maximum	17.96	Minimum
	33476.04	Average	29.87	Average
	224	Minimum	4464.29	Maximum
	1317	No. of Readings	1317	No. of Readings

g. In general, cooler waters have more capacity for dissolved oxygen than warmer waters. Since oxygen is necessary for corrosion to occur, greater oxygen content results in greater corrosivity. That is, with respect to dissolved oxygen content, corrosivity varies inversely with temperature. However, it is also generally true that conductivity increases with higher temperatures and corrosivity increases with higher conductivity.

h. Consequently, with respect to conductivity, warmer waters are generally more corrosive than cooler waters. Generally speaking, conductivity varies directly with temperature. Hence, conductivity generally varies in opposition to the variation of dissolved oxygen content, with respect to temperature.

i. That being said, since conductivity is generally considered to be the more dominant variable affecting corrosion, warmer waters are generally considered more corrosive than cooler waters. With respect to dissolved oxygen content, conductivity and temperature, the data provided by the LCRA appear to correspond to the generalities stated above.

j. The data provided by the LCRA indicate that the pH measurements were all generally in the neutral range (i.e., pH around 7). In general, pH above 4 is not a significant factor of influence on corrosivity.

k. For CPS design and corrosion risk assessment purposes, it is usually desirable to estimate the overall water corrosivity. One of the simplest classifications is based on a single parameter, water resistivity. For this design, the corrosivity ratings are designated as: essentially non-corrosive (greater than 20,000 ohm-cm), mildly corrosive (10,000 to 20,000 ohm-cm), moderately corrosive (5,000 to 10,000 ohm-cm), corrosive (3,000 to 5,000 ohm-cm), highly corrosive (1,000 to 3,000 ohm-cm), and extremely corrosive (less than 1,000 ohm-cm).

l. Based on the average of the conductivity (reciprocal of resistivity) measurements provided and using the corrosivity scale defined above, the waters at the Colorado River Locks were considered as "extremely corrosive."

G.6 Calculations. Install Impressed Current CPS at Colorado River Locks, Intracoastal Waterway, TX.

a. Design Calculations: Impressed Current Cathodic Protection of One Sector (Typical for eight Sectors, which form four Gates). NOTE: In the following calculations, the typically submerged surface area (at mean high tide elevation) designations are defined as:

(1) River Side or Skin Plate Side DC Circuit: Area A is the submerged portion of Gate Skin Plate Side (To Typical High Tide Elevation).

(2) Sector Gate Framework or Canal Side DC Circuit: Area B is the submerged portions of Structural Framework, including backside of Skin Plate & Gate Compartments behind Skin Plate (also includes bottom side of bottom gate girder).

b. Design Data: Area A or River Side Circuit.

(1) Water Resistivity Used: 30.00 ohm-cm (based on Average Resistivity at Colorado River Project using LCRA Water Quality Data). NOTE: Maximum expected resistivity must be used to determine rectifier requirements.

(2) Coating Efficiency (Dielectric Coating): 85% (at end of design life).

(3) Design Life: 20 years.

(4) Type of Anodes and Anode Assembly Selected:

Material: HSCBCI 1 Type 2260 Z and one Type 2284 Z, Anotec Chilled Cast, per Anode Assembly.
Types & Number of Anodes above make up: 1 Anode Assembly.

Total Anode Dimensions—Diameter: 2.2 in.
Length: 11.17 ft (total usable length, i.e., minus clamps).
Weight (W): 86 lb.
Consumption Rate (C): 1 lb/ampere-yr.
Anode Surface Area: 6.42 ft^2 (total usable anode area per assembly).
Anode Current Density Limitation: 1000 mA/ft^2.

(5) Design Current Density (I′): 7 mA/ft^2 of bare steel.

(6) Dimensions of Submerged Portion of Area A:

High-Water Depth (D): 18.00 ft.
Width (W): 47.124 ft.

c. Computations: Area A or River Side Circuit.

(1) Total Surface Area for Area A:

$Area_A$ = WD
$Area_A$ = 848.23 ft^2

(2) Total Current required in these areas at design current density:

$$I_A = AI'(1 - C_E)$$

Where:

A = surface area to be protected.

I′ = required current density to provide adequate protection to submerged bare steel (mA/ft^2).

C_E = coating efficiency at end of design life.

I_A = 890.64 mA.

(3) Number of Anode Assemblies required in this area to meet Supplier’s Current Density Limitations:

$$N_a = I_A/(A_a)(I_{a1})$$

Where:

N_a = number of anode assemblies required to meet anode current limitations.

I_A = total current required in mA, in this area.

A_a = surface area of single anode assembly in ft^2.

I_{al} = current density limitation of single anode in mA/ft.

N_a = 0.14 or 1 (based on current limitations).

(4) Number of Anode Assemblies required in this area to meet Design Life Requirements:

$$N_a = (L_{design})(I_A)/(1000)(W_a)$$

Where:

N_a = total number of anode assemblies required.

W_a = total weight per bare anode in pounds.

L_{design} = design life in years.

I_A = total current required in mA, in this area.

N_a = 0.21 or 1 (based on design life).

(5) Number of anode assemblies required for adequate current distribution for these surface areas:

(6) Note: To ensure uniform current distribution in a distributed impressed current system, it is necessary to provide additional anode assemblies to accomplish more uniform anode spacing along the structure. For this design, based on experience and data from the Brazos CPS project, the minimum number of anode assemblies for this area is:

N_a = 2 (For good current distribution)

(7) Based on above, Number of Anode Assemblies selected to be installed in this area: Compare all N_a's indicated above and enter a number below for N_a, which is at least greater than or equal to the greater value for N_a.

Use N_a = 2 Anode Assemblies

Select N= 1, where N is the number of anode assemblies used for each anode in calculations.

(8) Calculation of Anode Groundbed Resistance: Using the Sunde equation:

$$R_a = [0.00522)(\rho)/(N)(L)]\,[\ln(8L/d){:}\,1 + (2)(L/S)\ln(0.656N)]$$

Where:

N = number of anodes in groundbed = 2.

ρ = maximum resistivity at groundbed in ohm-cm.

R_a = calculated anode groundbed resistance in ohms.

L = total length of rod anode per assembly in L = 11.17.

d = diameter of anode in feet.

S = avg. anode spacing in feet, enter value for S here, S = 23.50.

R_a = 0.007010 X [5.18912 + 0.258148388].

R_a = 0.038 ohms.

(9) Calculation of Positive & Negative Conductor Resistance (r). For rectifier positive and negative DC conductors, choose:

Conductor size and type: 4 copper with PVDF/HMWPE insulation.
Resistance per 1000 ft: 0.2580 ohms/1000 ft.
Length of Header Cable: 800 ft.
r = 0.2064 ohms.

(10) NOTE: The individual anode lead cable (2#6 in parallel) resistance is negligible and, consequently, is ignored in these calculations.

d. Total Circuit Resistance for this Area.

$$R_A = R_a + r$$

R_A = 0.2446 ohms

e. Computation Summary for this Area.

(1) Minimum number of specified anode assemblies required for this area: 2 anode assemblies.

(2) Calculated total current required for this area: 0.89 Amperes DC.

(3) Calculated voltage required for this area:

$V_A = (I_A R_B + 2V) \text{ X } 125\%.$
$V_A = 2.77$ Volts, DC.

2.77 Volts, DC required for this circuit.

f. Design Data: Area B (Canal Side Circuit).

(1) Water Resistivity Used: 30.00 ohm-cm (based on Average Resistivity at Colorado River Project using LCRA Water Quality Data). NOTE: Maximum expected resistivity must be used to determine rectifier requirements.

(2) Coating Efficiency (Dielectric Coating): 85% (at end of design life).

(3) Design Life: 20 years.

(4) Type of Anodes and Anode Assembly Selected:

Material: HSCBCI 1 Type 2260 Z and one Type 2284 Z, Anotec Chilled Cast, per Anode Assembly.
Types & Number of Anodes above make up: 1 Anode Assembly.
Total Anode Dimensions:
Diameter: 2.2 in.
Length: 11.17 ft (total usable length, i.e., minus clamps).
Weight (W): 86 lb.
Consumption Rate (C): 1 lb/ampere-yr.
Anode Surface Area: 6.42 ft^2 (total usable anode area per assembly).
Anode Current Density Limitation: 1000 mA/ft^2.

(5) Design Current Density (I′): 7 mA/ft^2 of bare steel.

g. Computations: Areas B.

(1) Total Estimated Surface Area for Area B:

Total Estimated Submerged Area = 7654.40 ft.

(2) Total Current required in this area at design current density:

$$I_B = AI'(1 - C_E)$$

Where:

A = surface area to be protected.

I' = required current density to provide adequate protection to submerged bare steel (mA/ft^2).

C_E = coating efficiency at end of design life.

I_B = 8037.12 mA.

(3) Number of Anode Assemblies required in this area to meet Supplier's Current Density Limitations:

$$N_a = I_A/(A_a)(I_{a1})$$

Where:

N_a = number of anode assemblies required to meet anode current limitations.

I_A = total current required in mA, in this area.

A_a = surface area of single anode assembly in ft^2.

I_{al} = current density limitation of single anode in mA/ft.

N_a = 1.25 or 2 (based on current limitations).

(4) Number of Anode Assemblies required in this area to meet Design Life Requirements:

$$N_a = (L_{design})(I_A)/(1000)(W_a)$$

Where:

N_a = total number of anode assemblies required.

W_a = total weight per bare anode in pounds.

L_{design} = design life in years.

I_A = total current required in mA, in this area.

N_a = 1.87 or 2 (based on design life).

(5) Number of anode assemblies required for adequate current distribution for these surface areas:

(6) Note: To ensure uniform current distribution in a distributed impressed current system, it is necessary to provide additional anode assemblies to accomplish more uniform anode spacing along the structure. For this design, based on experience and data from the Brazos project, the minimum number of anode assemblies for this area is:

N_a = 4 (For good current distribution)

(7) Based on above, Number of Anode Assemblies selected to be installed in this area: Compare all N_a's indicated above and enter a number below for N_a, which is at least greater than or equal to the greater value for N_a.

Use N_a = 4 Anode Assemblies

Select N= 1, where N is the number of anode assemblies used for each anode in calculations.

(8) Calculation of Anode Groundbed Resistance: Using the Sunde equation:

$$R_a = [0.00522)(\rho)/(N)(L)]\,[\ln(8L/d){:}\,1 + (2)(L/S)\ln(0.656N)]$$

Where:

N = number of anodes in groundbed = 4.

ρ = maximum resistivity at groundbed in ohm-cm.

R_a = calculated anode groundbed resistance in ohms.

L = total length of rod anode per assembly in L = 11.17.

d = diameter of anode in feet.

S = avg. anode spacing in feet, enter value for S here, S = 13.14.

R_a = 0.003505 X [5.18912 + 1.640136615].

R_a = 0.024 ohms.

(9) Calculation of Positive & Negative Conductor Resistance (r). For rectifier positive and negative DC conductors, choose:

Conductor size and type: 4 copper with PVDF/HMWPE insulation.
Resistance per 1000 ft: 0.2580 ohms/1000 ft.
Length of Header Cable: 800 ft.
r = 0.2064 ohms.

(10) NOTE: The individual anode lead cable (2#6 in parallel) resistance is negligible and, consequently, is ignored in these calculations.

h. Total Circuit Resistance for this Area.

$$R_B = R_a + r$$

R_B = 0.2303 ohms

i. Computation Summary for this Area.

(1) Minimum number of specified anode assemblies required for this area: 4 anode assemblies.

(2) Calculated total current required for this area: 8.04 Amperes DC.

(3) Calculated voltage required for this area:

$V_{DE} = (I_{DE}R_B + 2V)$ X 125%.
V_B = 4.81 Volts, DC.
4.81 Volts, DC required for this circuit.

j. Rectifier Selection. The rectifier must have two adjustable DC outputs: one circuit for river side anodes and one circuit for canal side anodes. Each DC circuit must be able to provide a maximum of 20 amperes. The largest voltage required for any circuit is 4.81 volts. The specified rectifier voltage output must be 24 volts. Select a 24V rectifier with dual 20 amperes (DC) outputs.

G.7 Final Report and Commissioning Data. This section provides a portion of the Contractor's Final Report to illustrate the actual performance of the installed CPS.

Impressed Current Cathodic Protection Systems
USACE Colorado River Locks Matagorda, Texas
Prepared for:
United States Army Corps of Engineers
Prepared by:
Inland Construction & Engineering, Inc. and Corrpro
DATE: 25 September 2014

TABLE OF CONTENTS

Survey Notes

Final adjustments were made to the rectifiers at East Lock, West Gate (ELWG), West Lock, East Gate (WLEG), and West Lock, West Gate (WLWG) on 9/1 and 9/2/2014. No adjustments were made to the rectifiers at East Lock, East Gate (ELEG). No further adjustments were made after 9/2/2014. These adjustments are recorded in the Rectifier Operating Records. Random potentials measured after the adjustments were completed indicated that “instant off” potentials were being maintained between –850 mV and –1100 mV. Final Acceptance Survey was scheduled to begin in the afternoon of 9/8/2014. Figures G.9 and G.10 show the skin plate circuit only of both ELWG gate sectors, in which there are two circuits per sector.

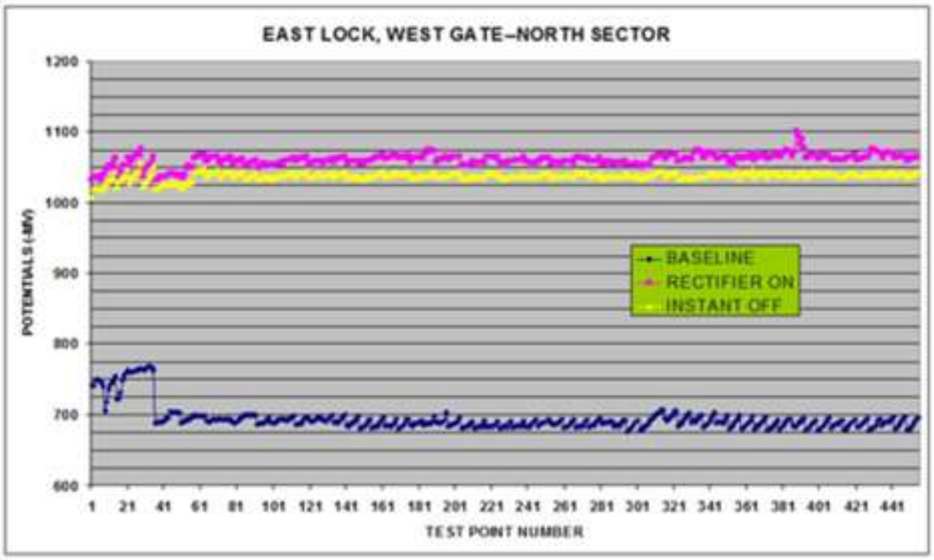

Figure G.9. Potential ELWG Data—North Sector

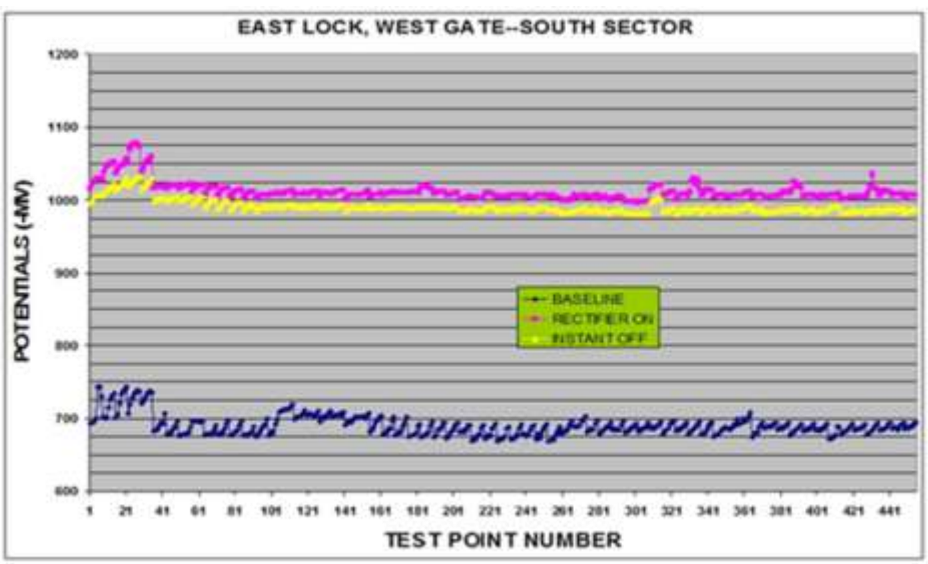

Figure G.10. Potential ELWG Data—South Sector

Survey Procedure

Water resistivities were measured and recorded on the river side (Test Point 3) and canal side (Test Point 37) of each sector gate before starting the survey. Figures G.11 and G.12 show potential test point locations. Tables G.2 and G.3 shows rectifier operating record. Water and air temperatures were also recorded. Tables G.3 through G.10 provide the survey data for north and south gates.

The silver/silver chloride reference cell was calibrated to a copper/copper-sulfate reference cell at the start and finish of the survey on each sector gate. The calibration was completed by lowering the silver chloride and copper-sulfate cells in the water (taped together side-by-side) at Test Points 3 and 37. The potential difference was measured and recorded. The average of the start and finish calibrations would be used to convert silver chloride readings to copper-sulfate readings. The current interrupter (Nilsson Model 825) was installed at the interrupter junction box.

The interrupter was set for 12 seconds “on” and 4 seconds “off.” Potentials were measured at five locations (seven readings per location) on the river side of each sector gate and 60 locations (seven readings per location) on the canal side of each sector gate. Potentials were measured in a grid pattern: 3-ft vertical intervals and 5-ft horizontal intervals. River Side = 35 readings and canal side = 420 readings. The criteria for protection will be “instant off” potentials between –850 mV and –1100 mV over 90% of the river side and 90% of the canal side of each sector gate.

9/8/2014: The Training Course for Operators and Engineering personnel was conducted and completed before noon. The Final Acceptance Survey began after lunch with ELWG-North.

The survey of ELWG-North began as described above. At Test Point 8 the 20-amp breaker inside the Control Building began to trip off. When it was reset and the survey continued, the breaker continued to trip off. After some discussions with the USACE CPS Specialist, it was decided to install a 30-amp breaker in place of the 20 amp. In addition, the interruption cycle was adjusted to 8 seconds “on” and 2 seconds “off.” The 4:1 ration between “on” and “off” was still maintained.

After these changes were completed, the survey of ELWG-North was completed. No further problems were encountered. All survey data were recorded in the Survey Data Tables. All data met the required specifications 100% for both the River Side and Canal Side of ELWG-North.

9/9/2014: The survey of ELWG-South was conducted in the same manner as described above. All survey data were recorded in the Survey Data Tables. No problems were encountered and the survey was completed with all potentials meeting the required specifications 100% for both the River Side and Canal Side of ELWG-South.

9/9/2014: The survey of WLWG-South was conducted in the same manner as described above. All survey data were recorded in the Survey Data Tables. No problems were encountered and the survey was completed with all potentials meeting the required specifications 100% for both the River Side and Canal Side of WLWG-South.

9/9/2014: The survey of WLWG-North was conducted in the same manner as described above. All survey data were recorded in the Survey Data Tables. No problems were encountered and the survey was completed with all potentials meeting the required specifications 100% for both the River Side and Canal Side of WLWG-North.

9/10/2014: The survey of WLEG-South was conducted in the same manner as described above. All survey data were recorded in the Survey Data Tables. At Test Point 65, the lead wire connection in the submersible adapter on the silver/silver chloride cell broke. The adapter was replaced with a spare. The survey was completed with all potentials meeting the required specifications 100% for both the River Side and Canal Side of WLEG-South.

9/10/2014: The original submersible adapter on the silver/silver chloride was repaired and placed back in service. The survey of WLEG-North was conducted in the same manner as described above. All survey data were recorded in the Survey Data Tables. No problems were encountered and the survey was completed with all potentials meeting the required specifications 100% for both the River Side and Canal Side of WLEG-North.

9/11/2014: The survey of ELEG-South was completed in the same manner as described above. All survey data were recorded in the Survey Data Tables on G.5, G.6, G.9, and G.10. All potentials on the river side met the required specifications 100%. There were 10 potentials on the canal side that did not meet the required specifications. These were at Test Points 30, 31, 37, and 41. These potentials are indicated as “failed” in the far-right column of the Survey Data Tables. All other potentials met the required specifications. This means there was a 97.6% pass for the ELEG-South, canal side. This meets the specification requirement.

9/11/2014: The survey of ELEG-North was conducted in the same manner as described above. All survey data were recorded in the Survey Data Tables on G.3, G.4, G.7 and G.8. No problems were encountered and the survey was completed with all potentials meeting the required specifications 100% for both the River Side and Canal Side of ELEG-North.

Final Comments and Recommendations:

Overall, the Final Acceptance Survey met all required specifications. As noted, ELEG-South had a 97.6% pass rating. As water resistivities increase, the rectifier current output will decrease because of increased circuit resistance. This will probably mean that minor rectifier adjustments will be required.

Even though WLWG-North and South met the required specifications, the potentials here will more than likely decrease with higher water resistivities, resulting in rectifier adjustments being required.

Monitor all rectifier outputs on a daily basis and record them weekly, following the instructions in the Operating and Maintenance Manual. These systems should be surveyed on an annual basis by a qualified CPS Specialist to ensure their continued and effective operation.

Table G.2
Rectifier Operating Record Serial Number 135517

COLORADO RIVER LOCKS				
Rectifier Operating Record				
Rectifier Location: East Lock/West Gate/North Sector: Unit #1 River Side				
Serial No.: 135517				
Model No.: ASAI				
Rectifier DC Output Rating: 24 volts, 20 amps				
Name of Tester: G. Rivera / J. Howard				
Date	Tap Setting	Rectifier Meters	Portable Meter	Comments
	C: F	Volts/Amps	Volts/Amps	
5/12/2014	F: 3	25.6 / 24.6	25.38 / 25.55	Test with one ohm “dummy load”
5/20/2014	B: 1	5.1 / 3.9	5.09 / 3.4	Commissioning
6/18/2014	B: 1	5.1 / 3.2	5.11 / 3.25	Adjustment survey
9/2/2014	A: 5	3.6 / 1.4	3.64 / 1.4	adjusted rectifier
9/9/2014	A: 5	3.6 / 1.4	3.59 / 1.45	Final Acceptance Survey

Table G.3
Rectifier Operating Record Serial Number 135521

COLORADO RIVER LOCKS				
Rectifier Operating Record				
Rectifier Location: East Lock/West Gate/South Sector: Unit #1 River Side				
Serial No.: 135521				
Model No.: ASAI				
Rectifier DC Output Rating: 24 volts, 20 amps				
Name of Tester: G. Rivera / J. Howard				
Date	Tap Setting	Rectifier Meters	Portable Meter	Comments
	C: F	Volts/Amps	Volts/Amps	
5/12/2014	F: 3	25.5 / 24.6	25.09 / 25.05	Test with one ohm "dummy load"
5/20/2014	B: 1	4.9 / 3.3	4.79 / 2.8	Commissioning
6/18/2014	B: 1	4.6 / 2.6	4.60 / 2.5	Adjustment survey
9/2/2014	B: 1	4.7 / 2.1	4.69 / 2.0	adjusted resistor R-1
9/9/2014	B: 1	4.7 / 2.2	4.68 / 2.1	Final Acceptance Survey

Table G.4
Anode Current Outputs North Sector

Gate: ELWG (ELEG, ELWG, WLEG, WLWG) Sector: North (North, South)

Tester: Trent Munson / Jim Howard Date: 9/9/14

Readings at Anode Terminal Box			
Anode Location	**Amperes (shunt)**	**Volts (at Anode)**	**Volts (at Header Connection)**
R1	0.730	2.450	
R2	0.680	2.430	
C1	0.860	2.490	
C2	0.890	2.470	
C3	0.960	2.500	
C4	0.940	2.500	
River Anodes Positive Terminal *			3.125
Canal Anodes Positive Terminal *			3.401
Read volts between positive and negative in terminal box			

Table G.5
Readings at Rectifier North Sector

Readings at Rectifier						
	Rectifier Meters		**Portable Meters**		**Tap Setting**	
Unit	**Volts**	**Amps**	**Volts**	**Amps**	**Coarse**	**Fine**
1	3.60	1.40	3.59	1.45	A	5
2	4.20	3.70	4.20	3.62	A	6

Table G.6
Anode Current Outputs South Sector

Gate: ELWG (ELEG, ELWG, WLEG, WLWG) Sector: South (North, South)

Tester: Trent Munson / Jim Howard Date: 9/9/14

Readings at Anode Terminal Box			
Anode Location	Amperes (shunt)	Volts (at Anode)	Volts (at Header Connection)
R1	0.650	2.360	
R2	1.450	2.570	
C1	0.940	2.440	
C2	0.730	2.380	
C3	0.710	2.400	
C4	0.760	2.380	
River Anodes Positive Terminal *			3.840
Canal Anodes Positive Terminal *			3.200
Read volts between positive and negative in terminal box.			

Table G.7
Rectifier Readings South Sector

Readings at Rectifier						
	Rectifier Meters		Portable Meters		Tap Setting	
Unit	Volts	Amps	Volts	Amps	Coarse	Fine
1	4.70	2.20	4.68	2.10	B	1
2	4.20	3.20	4.24	3.20	A	6

Table G.8

Survey Type: Structure to Structure Electrolyte Potential Measurements North Sector

Gate: ELWG (ELEG, ELWG, WLEG, WLWG) Sector: North (North, South)

Survey Type	Date	Name of Tester	Reference Cell Differential Ag/AgCl to $Cu/CuSO_4$ (mV)			Note 1 Water Resistivity (ohm-cm)	Water / Air Temperature (°F)
			Start	End	Average		
Native	5/15/2014	G. Rivera / J. Howard	19.9	13.5	17.0	3. 168.2 37.	78.2 / 81.0 /
"On"	9/8/2014	T. Munson / J. Howard	3. 73.1 37. 74.3	3. 61.6 37. 69.8	3. 67 37. 72	3. 24.0 37. 24.5	88.3 / 89.8 87.0 / 88.0
"I-Off"	9/8/2014	T. Munson / J. Howard	3. 73.1 37. 74.3	3. 61.6 37. 69.8	3. 67 37. 72	3. 24.0 37. 24.5	88.3 / 89.8 87.0 / 88.0

NOTES:

1. See test point location sketch for water resistivity test locations (3 & 37).
2. See test point location sketch for potential test locations (1 through 65).
3. Instant Off potential criterion is minimum –850 mV and maximum –1100 mV per USACE specifications.
4. River Side test locations (1 through 5).
5. Channel Side test locations (6 through 65).

Table G.9
Final Potential Measurements: Structure to Electrolyte Potential Measurements

Test Location (per Dwg.)	Note 2 Depth (ft)	Baseline Potential (mV)		"On" Potential (mV)		"I-Off" Potential (mV)		Criteria Failed *
		Ag/AgCl Measured	$Cu/CuSO_4$ Converted	Ag/AgCl Measured	$Cu/CuSO_4$ Converted	Ag/AgCl Measured	$Cu/CuSO_4$ Converted	
1	Bottom	725	742	966	1033	941	1008	
	+3 ft	725	742	968	1035	953	1020	
	+6 ft	732	749	971	1038	955	1022	
	+9 ft	733	750	970	1037	955	1022	
	+12 ft	732	749	968	1035	953	1020	
	+15 ft	729	746	966	1033	951	1018	
	+18 ft Water Line	723	740	972	1039	957	1024	
2	Bottom	689	706	974	1041	956	1023	
	+3 ft	701	718	980	1047	960	1027	
	+6 ft	718	735	984	1051	964	1031	
	+9 ft	726	743	985	1052	966	1033	
	+12 ft	728	745	982	1049	964	1031	
	+15 ft	732	749	989	1056	969	1036	
	+18 ft Water Line	738	755	997	1064	977	1044	
3	Bottom	705	722	970	1037	956	1023	
	+3 ft	706	723	977	1044	963	1030	
	+6 ft	715	732	977	1044	964	1031	
	+9 ft	732	749	985	1052	969	1036	
	+12 ft	739	756	986	1053	969	1036	
	+15 ft	742	759	986	1053	970	1037	
	+18 ft Water Line	747	764	996	1063	881	948	
4	Bottom	744	761	978	1045	962	1029	
	+3 ft	743	760	992	1059	968	1035	
	+6 ft	744	761	998	1065	971	1038	
	+9 ft	747	764	999	1066	975	1042	
	+12 ft	745	762	1000	1067	975	1042	
	+15 ft	748	765	1002	1069	977	1044	
	+18 ft Water Line	748	765	1010	1077	990	1057	
5	Bottom	746	763	970	1037	955	1022	
	+3 ft	747	764	979	1046	962	1029	
	+6 ft	749	766	984	1051	965	1032	
	+9 ft	751	768	986	1053	969	1036	
	+12 ft	751	768	987	1054	971	1038	
	+15 ft	749	766	992	1059	974	1041	
	+18 ft Water Line	745	762	999	1066	986	1053	
6	Bottom	671	688	960	1032	947	1019	

Table G.10

Survey Type: Structure to Electrolyte Potential Measurements South Sector

Gate: ELWG (ELEG, ELWG, WLEG, WLWG) Sector: South (North, South)

Survey Type	Date	Name of Tester	Reference Cell Differential Ag/AgCl to $Cu/CuSO_4$ (mV) Start	End	Average	Note 1 Water Resistivity (ohm-cm)	Water / Air Temperature (°F)
Native	5/15/2014	G. Rivera / J. Howard	29.7	13.5	22.0	3. 175.7 37.	76.4 / 64.2 /
"On"	9/9/2014	T. Munson / J. Howard	3. 70.5 37. 64.5	3. 71.9 37. 73.1	3. 71 37. 69	3. 21.5 37. 20.0	86.6 / 90.0 86.1 / 88.9
I-Off"	9/9/2014	T. Munson / J. Howard	3. 70.5 37. 64.5	3. 71.9 37. 73.1	3. 71 37. 69	3. 21.5 37. 20.0	86.6 / 90.0 86.1 / 88.9

Notes:

1. See test point location sketch for water resistivity test locations (3 & 37)
2. See test point location sketch for potential test locations (1 through 65)
3. Instant Off potential criteria is minimum –850 mV and maximum –1100 mV per ACOE specifications
4. River Side test locations (1 through 5)
5. Channel Side test locations (6 through 65)

Table G.11
Final Potential Measurements: Structure to Electrolyte Potential Measurements South Sector

Test Location	Note 2 Depth (ft)	Baseline Potential (mV)		"On" Potential (mV)		"I-Off" Potential (mV)		Criteria Failed *
		Ag/AgCl Measured	$Cu/CuSO_4$ Converted	Ag/AgCl Measured	$Cu/CuSO_4$ Converted	Ag/AgCl Measured	$Cu/CuSO_4$ Converted	
1	Bottom	671	693	944	1015	925	996	
	+3 ft	673	695	951	1022	930	1001	
	+6 ft	674	696	954	1025	933	1004	
	+9 ft	678	700	957	1028	934	1005	
	+12 ft	722	744	958	1029	936	1007	
	+15 ft	722	744	957	1028	935	1006	
	+18 ft Water Line	709	731	959	1030	938	1009	
2	Bottom	681	703	957	1028	933	1004	
	+3 ft	679	701	967	1038	940	1011	
	+6 ft	679	701	975	1046	942	1013	
	+9 ft	693	715	977	1048	945	1016	
	+12 ft	704	726	979	1050	947	1018	
	+15 ft	709	731	980	1051	948	1019	
	+18 ft Water Line	712	734	981	1052	952	1023	
3	Bottom	679	701	966	1037	943	1014	
	+3 ft	684	706	971	1042	946	1017	
	+6 ft	699	721	975	1046	949	1020	
	+9 ft	711	733	977	1048	951	1022	
	+12 ft	716	738	978	1049	952	1023	
	+15 ft	719	741	981	1052	954	1025	
	+18 ft Water Line	721	743	985	1056	960	1031	
4	Bottom	685	707	980	1051	949	1020	
	+3 ft	697	719	999	1070	953	1024	
	+6 ft	705	727	1004	1075	955	1026	
	+9 ft	711	733	1006	1077	957	1028	
	+12 ft	715	737	1007	1078	959	1030	
	+15 ft	717	739	1005	1076	960	1031	
	+18 ft Water Line	716	738	1003	1074	963	1034	
5	Bottom	699	721	967	1038	942	1013	
	+3 ft	702	724	972	1043	948	1019	
	+6 ft	707	729	979	1050	951	1022	
	+9 ft	712	734	982	1053	953	1024	
	+12 ft	714	736	983	1054	954	1025	
	+15 ft	716	738	985	1056	956	1027	
	+18 ft Water Line	713	735	989	1060	960	1031	
6	Bottom	661	683	947	1016	930	999	

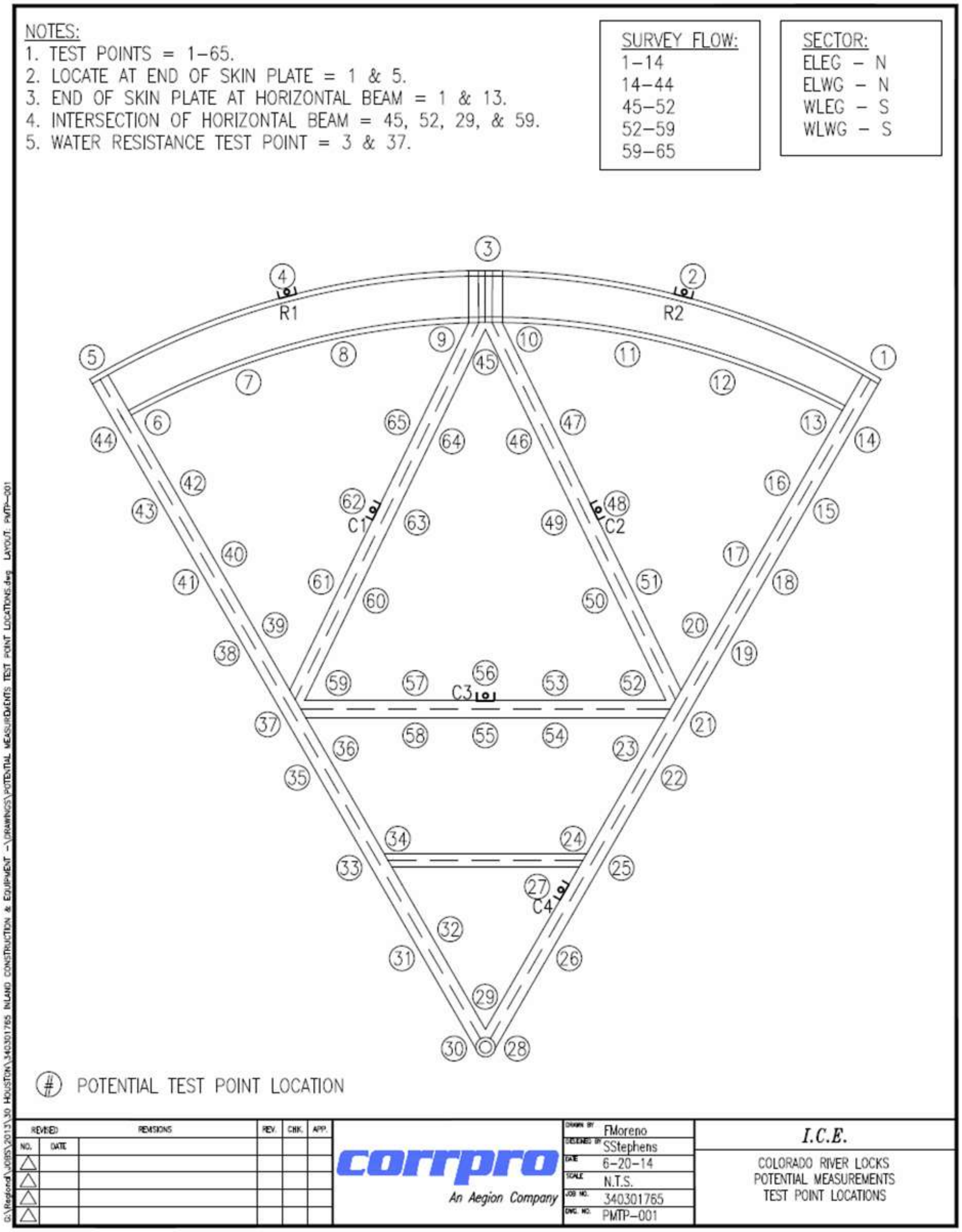

Figure G.11. Potential Test Point Locations, Drawing 1

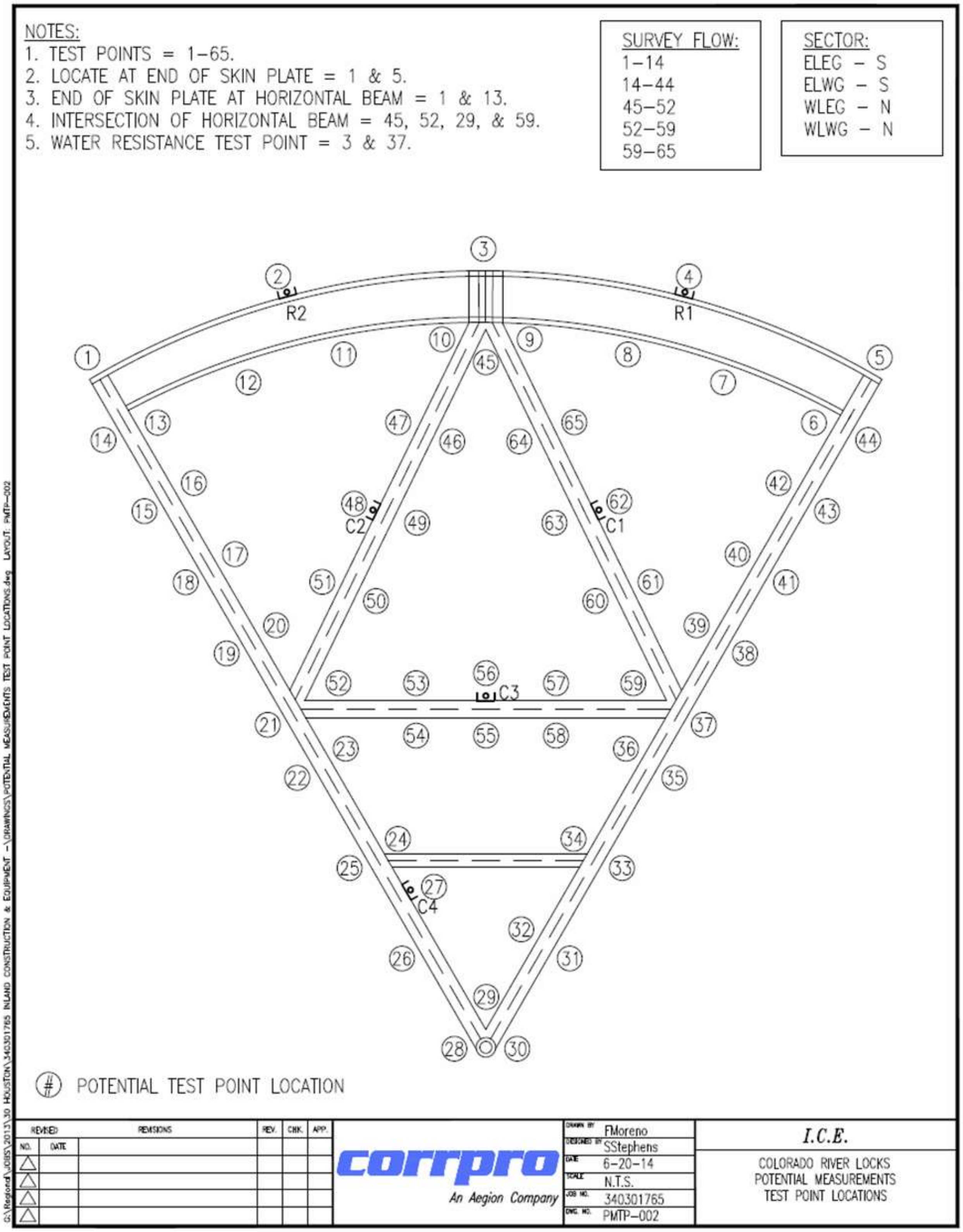

Figure G.12. Potential Test Point Locations, Drawing 2

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Appendix H
Sample Corrosion Mitigation Plan

CESAM-EN-DE

TO: Chief, Engineering Division

SUBJECT: Corrosion Mitigation Plan for Lock B Miter Gates, Tennessee -Tombigbee 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 CPS.

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 as described in UFGS-09965A, Painting; Hydraulic Structures and Appurtenant Works.

(2) Ferrous surfaces of the gate structure should be cleaned to a grade approaching white metal grade as described in UFGS-09965A. The surface anchor pattern should be consistent with the recommendations of the coating manufacturer. Quality control should be as required in 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. The attached table provides details on typical reference cell data.

(Name)
(Position)
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

*All potential measurements are expressed in units of DC volts with respect to a copper/copper sulfate half-cell.

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Appendix I
Sample Annual CPS Report

Cathodic Protection Inspection of Oliver Lock, Northport, AL

CESAM-EN-DE 18 August 2007
MEMORANDUM THROUGH CESAM-EN
FOR: CESAM-OP-BA and CESAM-EN-GG
SUBJECT: Trip Report, Cathodic Protection Inspection of Oliver Lock, Northport, AL
DATE OF INSPECTION: 2-3 May 2007

1. PURPOSE: To conduct the annually required test and evaluation of the performance of CPS on the lock miter gates.

2. NARRATIVE: This report covers impressed current CPS on the lock miter gates located at Oliver Lock. Oliver Lock was completed and put into operation in the early 1990s. The CPS equipment (anodes and rectifiers) and the coatings on the miter gates are all original equipment and materials.

The CPS on the upper and LGs consist of button anodes mounted on the skin plate (upstream side) and string anodes mounted in perforated PVC protection pipes (downstream side). Compartments on the upstream sides of the gates, in the areas of the quoins and miters, also have string anodes. Button anodes are installed along the bottom of the gates on the downstream sides to provide additional CPS to the sill area. All anodes are made of High Silicone Chromium Bearing Cast Iron (HSCBI). The dual-output rectifiers, which provide the low voltage DC to the anodes, are manufactured by Universal Rectifiers, Inc., Model SPL-2 (Figure I.5) Each DC output has coarse (A through G) and fine (1-7) tap settings. Each rectifier output circuit has a 50 mV, 5 Amp shunt (shunt factor, 0.1 A/mV) to allow easier and more accurate measurement of output currents. A Fluke digital multi-meter was used to measure the currents and voltages recorded herein.

Table I.1 lists rectifier settings and readings at the end of the inspection. Voltage, current, and coarse and fine tap settings at which data were taken are recorded on the data sheets. The rectifier settings shown below were those left at the end of the testing and adjustment procedure. The + and – numbers in the parentheses show how much the final settings were adjusted up or down from the initial settings. Protective potential data were last taken at this location (Oliver Lock) in June 2004.

A full set of potential measurements were also taken during this year's inspection. The "instant off" protective voltages were fairly uniform over the entire gate area and were primarily in the acceptable range, as can be observed in the potential graphs included at the end of this report (Figures I.1 through I.4). Also included in this report (immediately after the potential graphs) are the data position numbers as they correspond with their locations on the gate surfaces (Tables I.2 through I.5). Table I.6 provides the weekly rectifier record.

According to NACE criteria, if the “instant off” protective potential is –850 mV, full protection has been achieved. Very little additional protection is achieved above this level. Depending on circumstances, if approximately -1100 mV is reached, cathodic blistering of the coating can occur. During the test and evaluation this year, it was found that the protective potentials on the upstream side of the lower right gates were slightly lower than desirable (see protective potential graphs).

Consequently, the rectifier settings for the upstream anodes of the lower right gate were slightly adjusted, as indicated in the table above. As a precautionary note, personnel not familiar with CPS should not attempt to adjust rectifiers unless the Mobile District CP Specialist is consulted. Frequent adjustment of rectifiers should not be necessary.

Table I.1
Rectifier Settings and Readings at the End of the Inspection

1. LOCATION	UNIT #	2. COARSE TAP	3. FINE TAP	4. VOLTAGE (VOLTS)	5. CURRENT (AMPS)
Upper Gate Left Leaf Upstream	1	B	1	5.32	0.79
Upper Gate Left Leaf Downstream	2	A	7	4.92	0.92
Upper Gate Right Leaf Upstream	1	B	1	5.35	0.69
Upper Gate Right Leaf Downstream	2	B	1	5.29	0.99
Lower Gate Left Leaf Upstream	1	B	1	4.83	0.91
Lower Gate Left Leaf Downstream	2	A	6	4.02	0.86
Lower Gate Right Leaf Upstream	1	B(+1)	1(-6)	4.95	1.03
Lower Gate Right Leaf Downstream	2	A	6	4.09	0.80

The anode terminal cabinets at this facility are not equipped with individual current shunts for each anode lead conductor, which would allow fast and easy measurement of each anode lead current. Rather than shunts, jumpers were installed in the anode terminal cabinets for each anode lead (which appear to be No. 12 copper, type TW insulation as specified on original contract drawings). (See Figure I.9.)

Consequently, individual anode lead current would have to be measured by disconnecting each lead conductor and measuring its current. Time did not allow these measurements to be done during this evaluation in this manner. However, most, if not all, anodes appear to be operating well since the protective potentials across all gate surfaces appeared to be fairly uniform. If any significant number of anodes were inoperable, it would be expected that protective potentials would be uneven in value. Any anodes that might be inoperable do not seem to be adversely affecting the overall effectiveness of the corrosion control systems.

CP in conjunction with good coatings is a proven and widely accepted way of controlling corrosion on submerged metal structures, but it is essential that CPS be kept operating and properly adjusted to realize the maximum benefit. All rectifiers at Oliver were found to be operating. Most rectifier failures are caused by blown fuses from power surges or lightning strikes and, as such, are easily fixed. The simple procedure of observing, on a routine basis, that the rectifiers are operating goes a long way toward the goal of keeping the overall CPS working.

Oliver Lock personnel have consistently taken rectifier readings (using the analog meters provided in each rectifier) and emailed them to the District CP Specialist in Mobile[2]. They are to be commended for their efforts. Weekly reading of the rectifiers as shown in Table I.6 should continue since they greatly contribute to the continuity of operation of the corrosion control systems, thus making for overall good corrosion control.

Since blown fuses are the most common cause of inoperable rectifiers, at least two spare fuses should be provided in each rectifier cabinet to expedite replacement if needed. It was observed that spare fuses were available in the rectifier cabinets at Oliver. One note of caution regarding periodic rectifier readings' procedures should be added. It was discovered during this inspection that the toggle selector switch that selects either Unit 1 or Unit 2 for the rectifier voltmeter and ammeter was sometimes faulty. That is, the rectifier meters did not always agree with the Fluke meter readings, especially with regards to the rectifier ammeter (at times the rectifier ammeter indicated 0 amperes when the actual current was not 0). Lock operators should be aware of this problem and keep it in mind when taking these readings.

While the coating and CPS are providing very good corrosion control on the parts of the miter gates that are below the water line. The onset of corrosion was noted in various lock areas above the water line, e.g., downstream side of the lower right gate, on diaphragm near quoin, several feet above the water line.

Figure I.8 shows the upstream side of the lower left gate to be generally in very good condition. Some areas also may not be draining properly, which will aid in the corrosion process. If corrosion is allowed to continue to develop in any part of the gates, the structure of the gates could eventually be weakened. The only real protection against corrosion above the water line is to keep moisture off the surface as much as possible and to ensure good coatings. Poorly applied coatings provide only a cosmetic treatment for corrosion, which only allows the corrosion to proceed more rapidly and unnoticed until serious damage has occurred. Therefore, corroded

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[2] The operators at Oliver Lock consistently (on a weekly basis) read, record, and email the associated and updated rectifier operating record to the district CPC Coordinator (Mobile District CP Specialist). A recent Oliver weekly rectifier record is included in Appendix G-A of this manual as an example; as can be seen in this record, each rectifier circuit's current and voltage output value is recorded on a weekly basis. Reading, recording, and reporting to the CPC Coordinator each rectifier voltage and current outputs for each DC circuit is a requirement of EM 1110-2-2704.

areas or areas where the coating is showing signs of weakness or failure should be treated properly with adequate surface preparation and with the proper coating.

Although some debris and vegetation was observed on the gates, they appeared to be generally free of debris and vegetation at the time of this year's inspection (Figures I.6 and I.7). Because of occasional high water that occurs at this lock, there is sometimes considerable debris and mud/sand in the compartments above the water line. These items hold moisture to the gate surface.

In the presence of moisture, corrosion will proceed much more rapidly than if the coating is dry. In addition, if surfaces are covered with debris and/or mud, the gate surfaces cannot be visually inspected for signs of corrosion and no one will know recoating is needed. It is realized that all above-water compartments cannot always be kept clean and dry because of varying pool levels. However, all compartments should be cleared of mud, sand, and debris as frequently as possible, certainly at least once or twice per year.

During the 2004 inspection, it was discovered that at least two of the rectifiers (the two on the right side of the lock) had alternating current (AC) power that was not properly connected, causing a potential safety hazard. The neutral conductor, which, per the National Electrical Code, is required to be color coded white or to have white insulation, is supposed to be at about the same potential as the safety ground (i.e., the green wire). Also, the wire with black insulation is supposed to be the "hot" wire.

The black and white wires were reversed at these two rectifiers, resulting in the "white" or "neutral" actually being at line voltage while the "black" wire was essentially at the same voltage as the safety ground. During the 2004 inspection, the other two rectifiers were not tested so their condition is not known, but it is likely that they too are reversed. During this year's inspection, this wiring was not tested for this condition, so it is not known if this prior condition has been corrected.

Consequently, it is again recommended that the next time the electrician is in the vicinity of Oliver Lock, he check this wring in all rectifiers and make any necessary corrections. It was noted during this year's testing, that the upper right rectifier breaker tripped when it was attempted to take potential readings with the radio frequency (RF) switch connected to this rectifier. Since this condition persisted, it was necessary to use the RF switch only on the upper left rectifier and to connect the upper right rectifier to the upper left rectifier receptacle by using extension cords extending across the gate. This was necessary to allow simultaneous shut off of both rectifiers to obtain "instant off" readings. This method of connection for testing purposes will most likely have to be continued in future inspections when using this equipment.

This project has a fixed-crest spillway and does not have any metallic spillway gates that need inspection.

3. RECOMMENDATIONS: The following actions are recommended as a result of the annual test and evaluation inspection:

a. Lock operators should continue to take rectifier readings each week and to email data to the Mobile District CP Specialist for his/her evaluation. Data should only be taken when the lock is full. Any inoperable rectifier found should be indicated in the report and should be reported to the maintenance contractor for repair as soon as possible.

b. Monitoring of the protective potentials on the lock miter gates should be performed at least on an annual basis and more often if funds and/or opportunity allow.

c. Only qualified personnel should make adjustments to rectifiers. If adjustments are deemed necessary, the Mobile District CP Specialist should be contacted for instructions.

d. The coarse and fine adjustment switches should be periodically cleaned and coated with a corrosion prevention silicon spray to prevent any possible erratic behavior. The toggle selector switch for selecting either Unit 1 or Unit 2 for the rectifier voltmeter and ammeter on the upper right rectifier should be repaired or replaced to prevent obtaining faulty readings while using those meters.

e. Any areas above the water line showing signs of corrosion should be properly prepared and coated to halt corrosion before it gets out of control.

f. Debris and mud/sand should be removed from gate compartments to reduce corrosion potential and to increase the visibility of any corrosion that does occur. A regular program of debris and mud removal should be instituted. This will greatly increase the longevity of the gates.

4. CONCLUSION: The above findings notwithstanding, the condition of the lock miter gates, the coating on the gates, and the CPS are all in generally good condition and working well at this time. Excellent protective potentials are present in all miter gate areas below the water line. If the recommendations are followed and the noted conditions are addressed by proper maintenance procedures, this project should continue to be relatively corrosion free.

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[Name of District CPC Coordinator], P.E.
Senior Electronics Engineer
NACE Cathodic Protection Specialist

I-1. Potential Data Graphs.

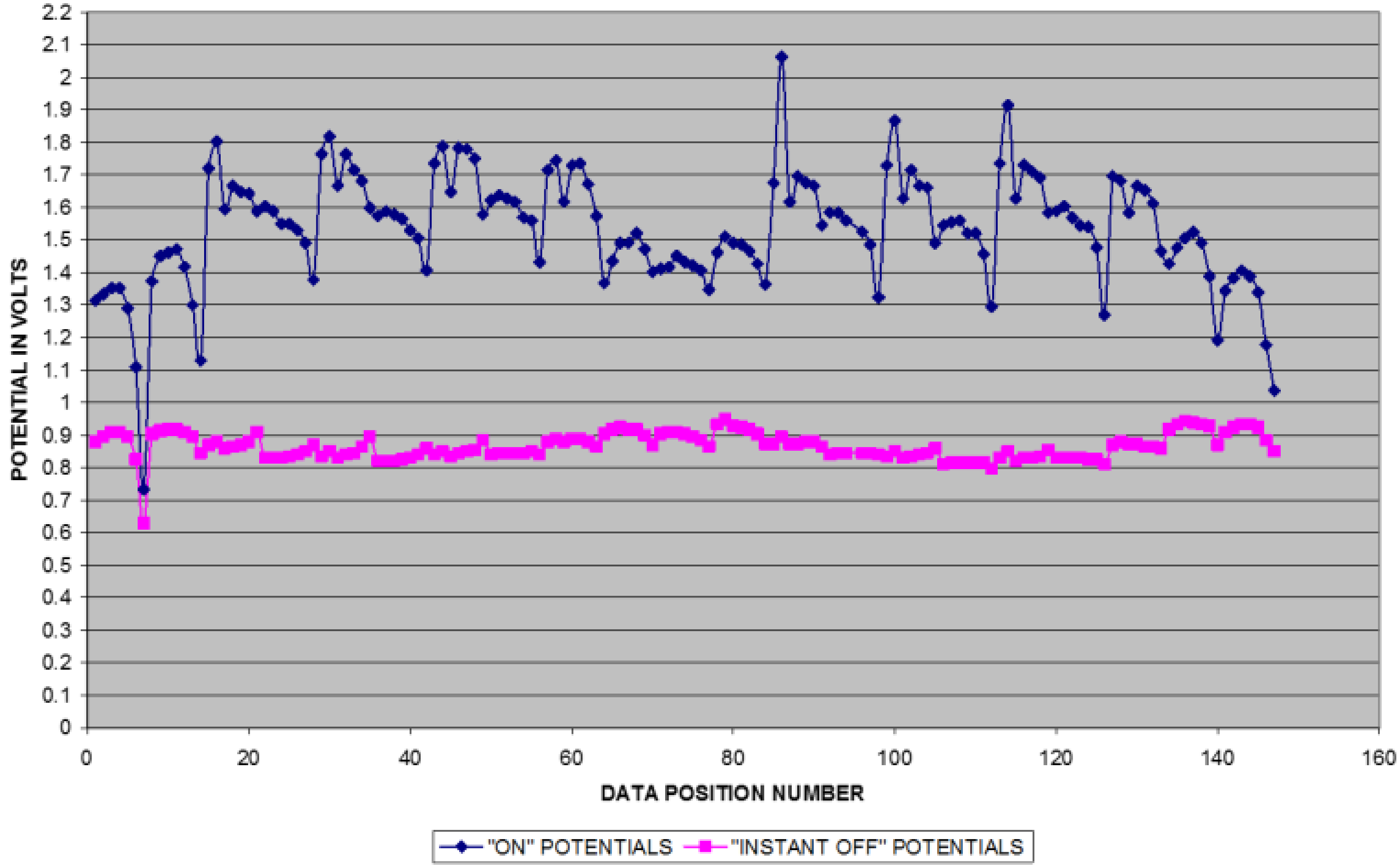

Figure I.1. Oliver Lock Upper Gates Upstream Side, 2007 Data

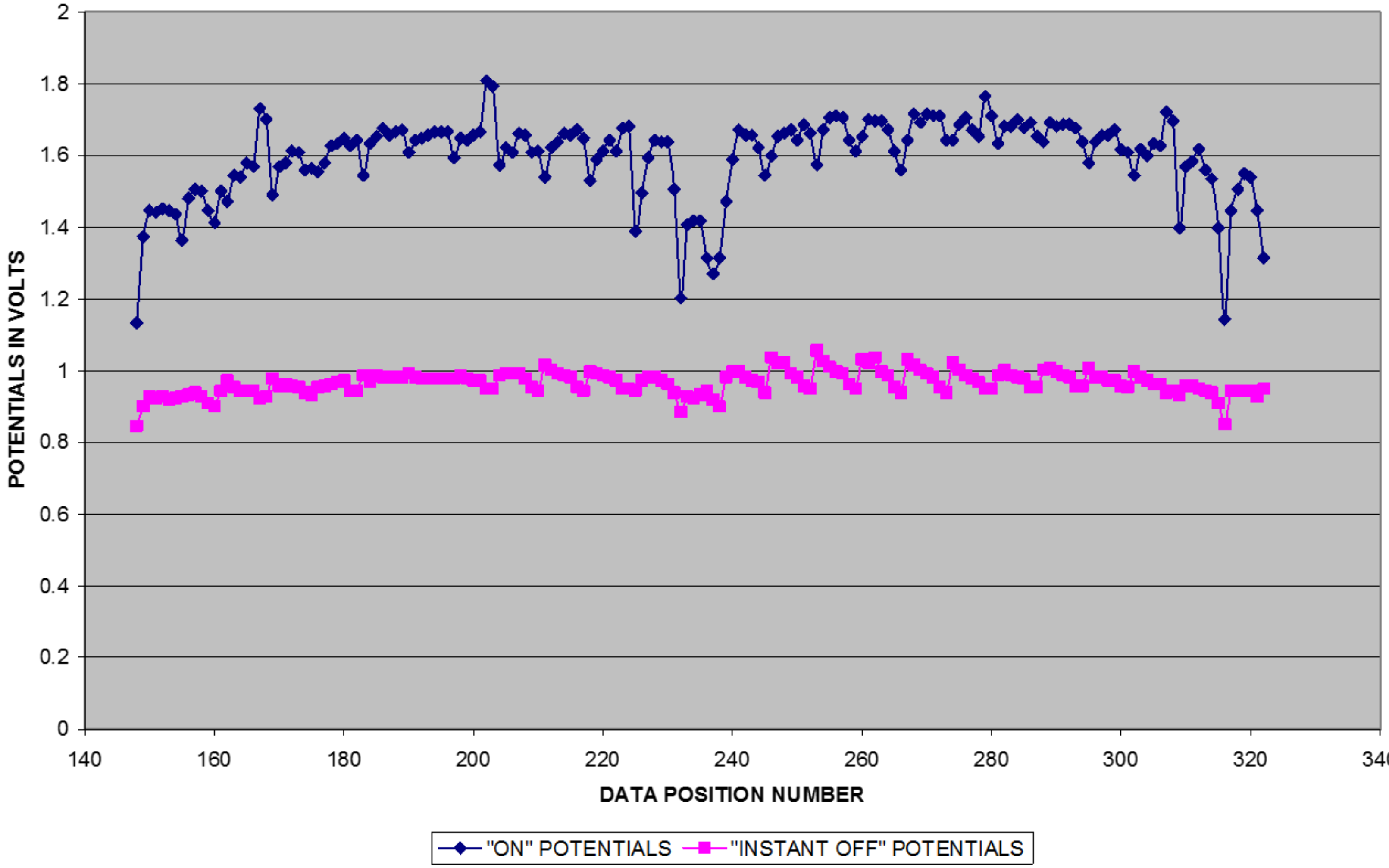

Figure I.2. Oliver Lock Upper Gates Downstream Side, 2007 Data

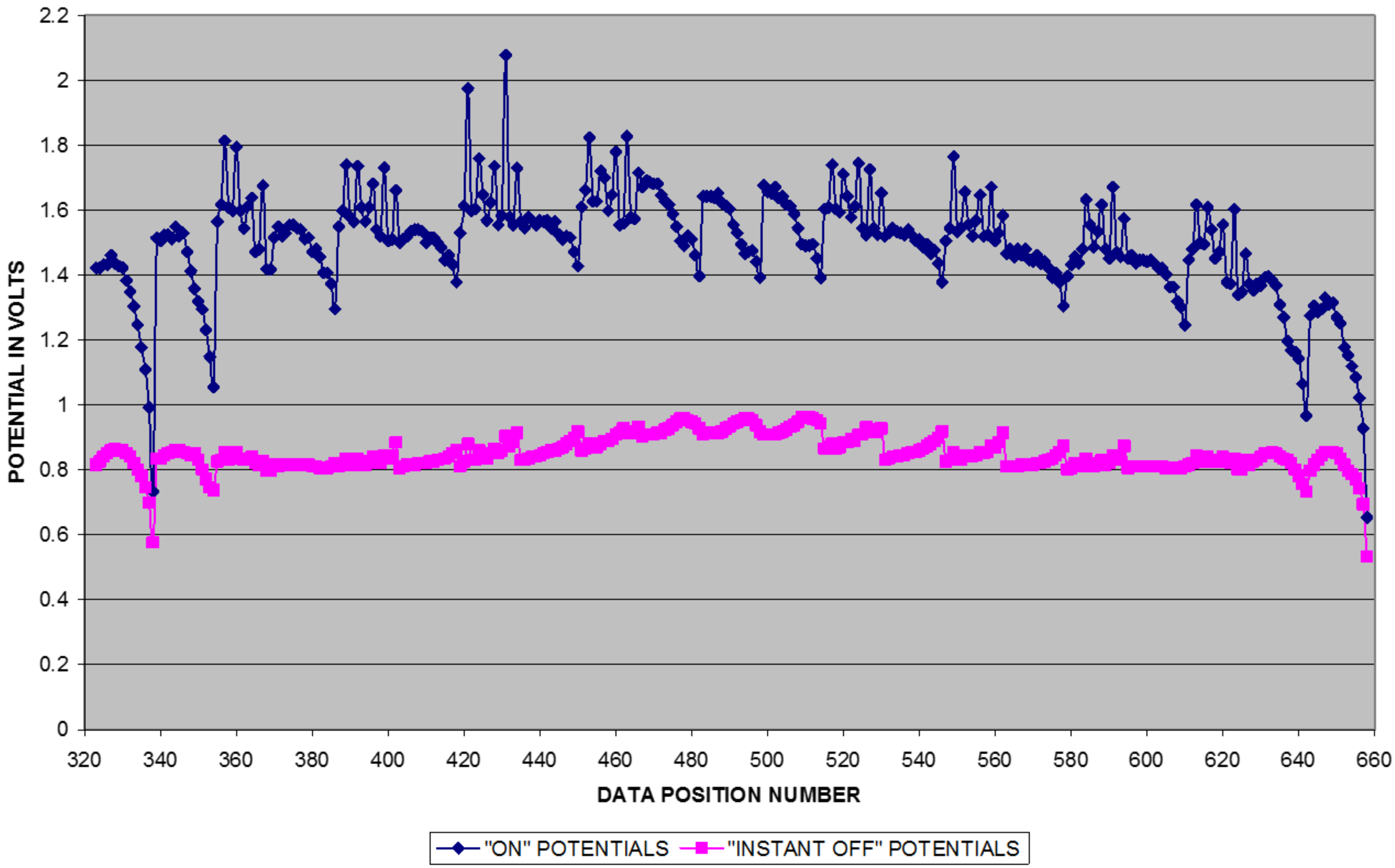

Figure I.3. Oliver Lock LGs Upstream Side, 2007 Data

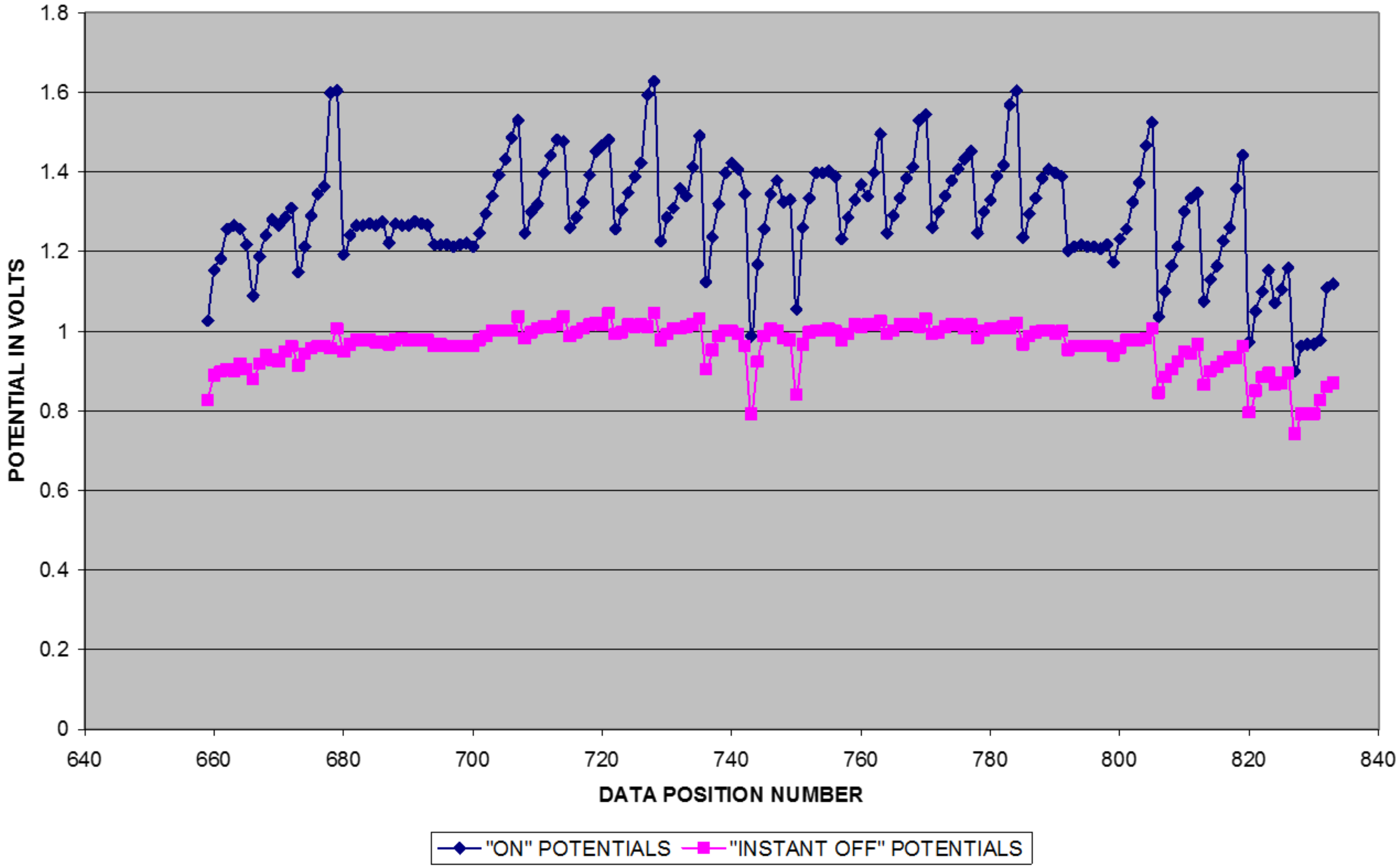

Figure I.4. Oliver Lock LGs Downstream Side, 2007 Data

I-2. Data Position Numbers.

Table I.2
Data Position Numbers Correlated with Location on Gate Surface; Upper Gate, Left Leaf, Upstream Side

POSITIONS--UPPER GATE, LEFT LEAF, UPSTREAM SIDE

HEIGHT	1	2	3	4	5	6	7	8	9	10	11	10	9	8	7	6	5	4	3	2	1	HEIGHT
(FT)	QUOIN	STRING	BUTTON	SPACE	BUTTON	SPACE	BUTTON	SPACE	BUTTON	STRING	MITER	STRING	BUTTON	SPACE	BUTTON	SPACE	BUTTON	SPACE	BUTTON	STRING	QUOIN	(FT)
TOP	1	8	15	22	29	36	43	50	57	64	71	78	85	92	99	106	113	120	127	134	141	TOP
15	2	9	16	23	30	37	44	51	58	65	72	79	86	93	100	107	114	121	128	135	142	15
12	3	10	17	24	31	38	45	52	59	66	73	80	87	94	101	108	115	122	129	136	143	12
9	4	11	18	25	32	39	46	53	60	67	74	81	88	95	102	109	116	123	130	137	144	9
6	5	12	19	26	33	40	47	54	61	68	75	82	89	96	103	110	117	124	131	138	145	6
3	6	13	20	27	34	41	48	55	62	69	76	83	90	97	104	111	118	125	132	139	146	3
BOTTOM	7	14	21	28	35	42	49	56	63	70	77	84	91	98	105	112	119	126	133	140	147	BOTTOM

Table I.3
Data Position Numbers Correlated with Location on Gate Surface; Upper Gate, Left Leaf, Downstream Side

POSITION--UPPER GATE, LEFT LEAF, DOWNSTREAM SIDE

Current reading taken measuring mV drop across 5A, 50mV shunt (shunt factor = 0.1).

HEIGHT	1	2	3	4	5	6	7	8	9	10	11	12	13	12	11	10	9	8	7	6	5	4	3	2	1	HEIGHT
(FT)	QUOIN	55	50	45	40	35	30	25	20	15	10	5	MITER	5	10	15	20	25	30	35	40	45	50	55	QUOIN	(FT)
TOP	148	155	162	169	176	183	190	197	204	211	218	225	232	239	246	253	260	267	274	281	288	295	302	309	316	TOP
15	149	156	163	170	177	184	191	198	205	212	219	226	233	240	247	254	261	268	275	282	289	296	303	310	317	15
12	150	157	164	171	178	185	192	199	206	213	220	227	234	241	248	255	262	269	276	283	290	297	304	311	318	12
9	151	158	165	172	179	186	193	200	207	214	221	228	235	242	249	256	263	270	277	284	291	298	305	312	319	9
6	152	159	166	173	180	187	194	201	208	215	222	229	236	243	250	257	264	271	278	285	292	299	306	313	320	6
3	153	160	167	174	181	188	195	202	209	216	223	230	237	244	251	258	265	272	279	286	293	300	307	314	321	3
BOTTOM	154	161	168	175	182	189	196	203	210	217	224	231	238	245	252	259	266	273	280	287	294	301	308	315	322	BOTTOM

Table I.4

Data Position Numbers Correlated with Location on Gate Surface; Positions—LG, Left Leaf, Upstream Side

POSITIONS--LOWER GATE, LEFT LEAF, UPSTREAM SIDE | POSITIONS--LOWER GATE, RIGHT LEAF, UPSTREAM SIDE

HEIGHT	1	2	3	4	5	6	7	8	9	10	11	10	9	8	7	6	5	4	3	2	1	HEIGHT
(FT)	QUOIN	STRING	BUTTON	SPACE	BUTTON	SPACE	BUTTON	SPACE	BUTTON	STRING	MITER	STRING	BUTTON	SPACE	BUTTON	SPACE	BUTTON	SPACE	BUTTON	STRING	QUOIN	(FT)
TOP	323	339	355	371	387	403	419	435	451	467	483	499	515	531	547	563	579	595	611	627	643	TOP
42	324	340	356	372	388	404	420	436	452	468	484	500	516	532	548	564	580	596	612	628	644	42
39	325	341	357	373	389	405	421	437	453	469	485	501	517	533	549	565	581	597	613	629	645	39
36	326	342	358	374	390	406	422	438	454	470	486	502	518	534	550	566	582	598	614	630	646	36
33	327	343	359	375	391	407	423	439	455	471	487	503	519	535	551	567	583	599	615	631	647	33
30	328	344	360	376	392	408	424	440	456	472	488	504	520	536	552	568	584	600	616	632	648	30
27	329	345	361	377	393	409	425	441	457	473	489	505	521	537	553	569	585	601	617	633	649	27
24	330	346	362	378	394	410	426	442	458	474	490	506	522	538	554	570	586	602	618	634	650	24
21	331	347	363	379	395	411	427	443	459	475	491	507	523	539	555	571	587	603	619	635	651	21
18	332	348	364	380	396	412	428	444	460	476	492	508	524	540	556	572	588	604	620	636	652	18
15	333	349	365	381	397	413	429	445	461	477	493	509	525	541	557	573	589	605	621	637	653	15
12	334	350	366	382	398	414	430	446	462	478	494	510	526	542	558	574	590	606	622	638	654	12
9	335	351	367	383	399	415	431	447	463	479	495	511	527	543	559	575	591	607	623	639	655	9
6	336	352	368	384	400	416	432	448	464	480	496	512	528	544	560	576	592	608	624	640	656	6
3	337	353	369	385	401	417	433	449	465	481	497	513	529	545	561	577	593	609	625	641	657	3
BOTTOM	338	354	370	386	402	418	434	450	466	482	498	514	530	546	562	578	594	610	626	642	658	BOTTOM

Table I.5

Data Position Numbers Correlated with Location on Gate Surface; Positions—LG, Left Leaf, Downstream Side

POSITIONS--LOWER GATE, LEFT LEAF, DOWNSTREAM SIDE | POSITIONS--LOWER GATE, RIGHT LEAF, DOWNSTREAM SIDE

HEIGHT	1	2	3	4	5	6	7	8	9	10	11	12	13	12	11	10	9	8	7	6	5	4	3	2	1	HEIGHT
(FT)	QUOIN	55	50	45	40	35	30	25	20	15	10	5	MITER	5	10	15	20	25	30	35	40	45	50	55	QUOIN	(FT)
TOP	659	666	673	680	687	694	701	708	715	722	729	736	743	750	757	764	771	778	785	792	799	806	813	820	827	TOP
15	660	667	674	681	688	695	702	709	716	723	730	737	744	751	758	765	772	779	786	793	800	807	814	821	828	15
12	661	668	675	682	689	696	703	710	717	724	731	738	745	752	759	766	773	780	787	794	801	808	815	822	829	12
9	662	669	676	683	690	697	704	711	718	725	732	739	746	753	760	767	774	781	788	795	802	809	816	823	830	9
6	663	670	677	684	691	698	705	712	719	726	733	740	747	754	761	768	775	782	789	796	803	810	817	824	831	6
3	664	671	678	685	692	699	706	713	720	727	734	741	748	755	762	769	776	783	790	797	804	811	818	825	832	3
BOTTOM	665	672	679	686	693	700	707	714	721	728	735	742	749	756	763	770	777	784	791	798	805	812	819	826	833	BOTTOM

I-3. Photographs.

Figure I.5. Typical Rectifier at Oliver Lock

Figure I.6. LGs, Downstream Side

Figure I.7. Upper Gates, Downstream Side

Figure I.8. Lower Left Gate, Upstream Side

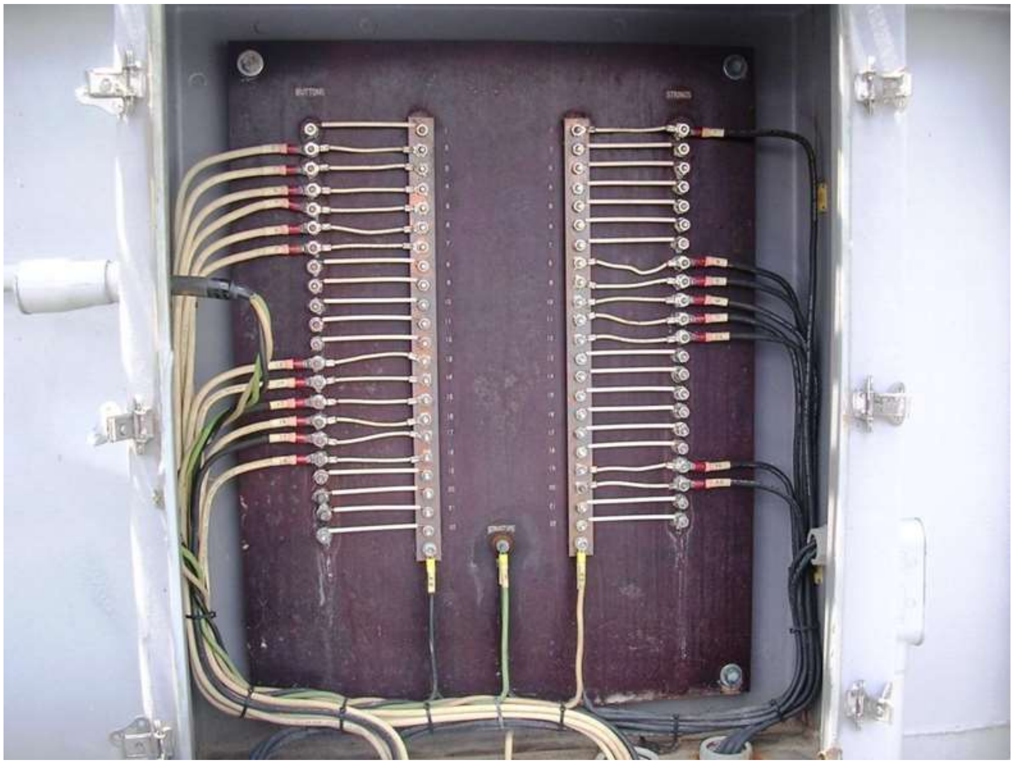
Figure I.9. Typical Inside View of Anode Terminal Cabinet

I-4. Weekly Rectifier Record.

Table I.6
Weekly Rectifier Record

Chamber Must Be Full	Date	9/1/2014	9/8/2014	9/15/2014	9/22/2014	9/29/2014
Upper Gate- Land Leaf- Upstream Unit No. 1	Gage	18.1	18.3	18.9	18.9	18.0
	Volts	6.1	6.0	6.0	6.0	6.0
	AMPS	1.1	1.1	1.1	1.1	1.1
Upper Gate- Land Leaf- Downstream Unit No. 2	Gage	18.1	18.3	18.9	18.9	18.0
	Volts	4.3	4.2	4.2	4.2	4.4
	Amps	0.7	0.7	0.7	0.7	0.7
Upper Gate-River Leaf Upstream Unit No. 1	Gage	18.1	18.3	18.9	18.9	18.0
	Volts	6.1	6.0	6.0	6.0	6.0
	Amps	1.1	1.1	1.2	1.2	1.1
Upper Gate-River Leaf Downstream Unit No. 2	Gage	18.1	18.3	18.9	18.9	18.0
	Volts	4.7	4.6	4.6	4.6	4.6
	Amps	0.9	0.8	0.8	0.8	0.8
Lower Gate-Land Leaf Upstream Unit No. 1	Gage	46.1	46.3	46.9	46.9	46.0
	Volts	5.0	4.8	5.2	5.2	5.2
	Amps	1.9	1.8	2.2	2.2	2.1
Lower Gate-Land Leaf Downstream Unit No. 2	Gage	18.7	19.0	19.1	18.8	18.6
	Volts	4.4	4.2	4.2	4.2	4.3
	Amps	0.9	0.8	0.8	0.8	0.8
Lower Gate-River Leaf Upstream Unit No. 1	Gage	46.1	46.3	46.9	46.9	46.0
	Volts	4.5	4.4	4.4	4.4	4.5
	Amps	0.9	1.0	0.9	0.9	0.9
Lower Gate-River Leaf Downstream Unit No. 2	Gage	18.7	19.0	19.1	18.8	18.6
	Volts	4.1	4.0	4.0	4.0	4.1
	Amps	1.0	1.0	1.0	1.0	0.9
Operators: Lock Chamber Must Be Full When Taking Readings.						

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Appendix J
Sample Survey Report

Demopolis Lock Miter Gate Cathodic Protection
24–25 September 2014

Prepared for the USACE Mobile District

J.1 Executive Summary.

a. The CPS on the upper gate (UG) at Demopolis Lock were found to be in good condition. Potentials were somewhat low in the quoin and miter areas, particularly on the DS side. The additional anodes previously recommended were not installed during the recent closure. Additional anodes are needed in the quoin areas of all gates to correct this problem and are again recommended. A minor upward adjustment was made on the US right leaf rectifier to better balance potential levels to match those on the left leaf.

b. Nearly all areas of the LG have potentials above the required 100 MV shift above native readings. However, many points on the US of the gate, left and right leafs, and many points on the DS left leaf did not achieve –750 MV. Therefore, adjustments were made to increase rectifier current output to provide better potentials.

c. The connector for AC power on the lower right leaf rectifier broke during plugging/unplugging to connect test equipment. This connector was replaced by the maintenance contractor’s electrician who was on site doing other work.

d. Lock operators have asked for digital meters to be added to rectifiers so that the voltage and current values reported will be easier to read and will be more accurate and consistent.

e. The maintenance contractor was on site making adjustments on the UG during the inspection, so it was necessary to schedule the CP tests around their work. This was successfully done without excessive delays or interferences.

f. The combination of good, properly applied dielectric coatings supplemented with properly designed and maintained CPS is recognized by NACE and by corrosion engineers worldwide as the most practical and economical method of corrosion control for submerged steel structures.

g. Any costs to install and maintain these corrosion control systems at this lock, or any lock, as recommended, will be more than offset by reduced future costs to repair/replace the structure. If only one dewatering over the life of the lock is eliminated, the cost of all recommended corrosion control measures over the life of the lock will be more than justified.

h. Mr. Chad Pierce of the Mobile District Office, Engineering Division, was present during this inspection and assisted in all data acquisition and testing.

J.2 Purpose. The purpose of this report is to document the results of the required annual survey of the CPS installed on the miter gates at Demopolis Lock and Dam located near Demopolis, AL. These tests are in support of the PICES Program.

a. Observations and Findings during this Inspection.

(1) Demopolis Lock underwent a 30-day closure in late July through early August of this year. During the closure all gate areas of both upper and LGs were thoroughly cleaned and recoated. As a result, this year all areas above and below the water line were in excellent condition. See Figure J.1 for coating beneath walkway.

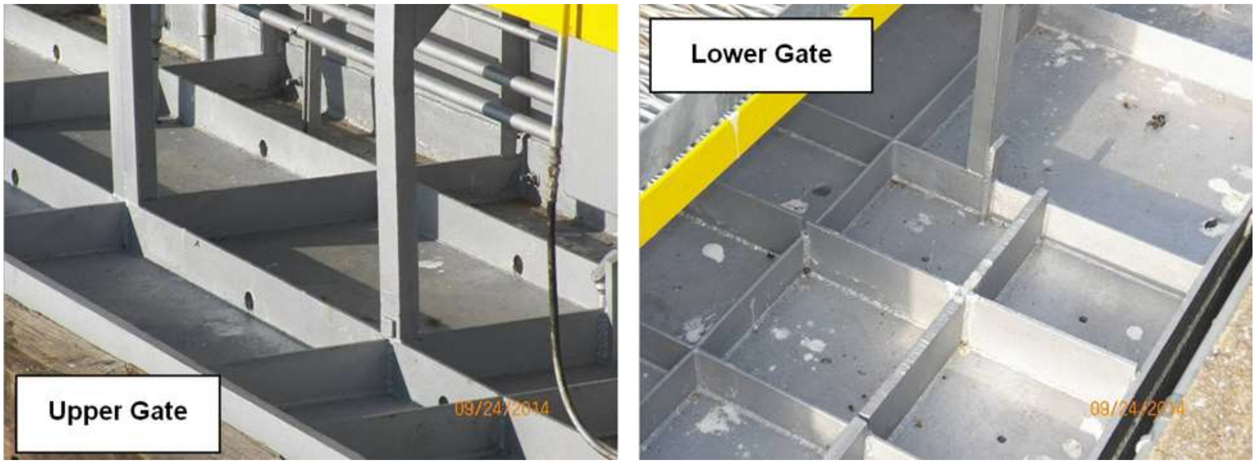

Figure J.1. Demopolis 2014—Coating Beneath Gate Walkway in Excellent Condition

(2) Areas of the lock miter gates below the water line when the lock chamber is full, but above the water when the chamber is lowered, were observed to be in excellent condition in all visible areas as shown in Figures J.2 and J.3. All visible anodes appeared to be undamaged. To confirm this observation, individual anode current data for all anodes was taken during this inspection, and is included in anode current tables at the end of this report.

(3) These data indicate that all anodes on the UG are operating properly. Last year, and in previous inspections, one anode on the UG was not working. This anode (Anode #18 on the right leaf) was apparently repaired or replaced during the closure. All LG anodes were operating properly except Anodes #50 and #51 on the left leaf, which are button anodes on the US of the gate. Twelve other anodes were showing 0 current, but all of these anodes are on the DS side of the LG, probably on the top row.

(4) Because of a somewhat low tail water level, they are likely out of the water. Hence, they are probably not inoperable from damage, but because they are not in the water. In previous years, several anodes were operating erratically or not working at all. This was likely caused by bad shunts and not by bad anodes. Apparently, these were repaired or replaced during the closure so that only the two anodes mentioned above, which did not have shunts in the circuit, were inoperable. These can probably be made operable by adding shunts to these two anode circuits.

Figure J.2. Upper Gate, Downstream—Demopolis 2014

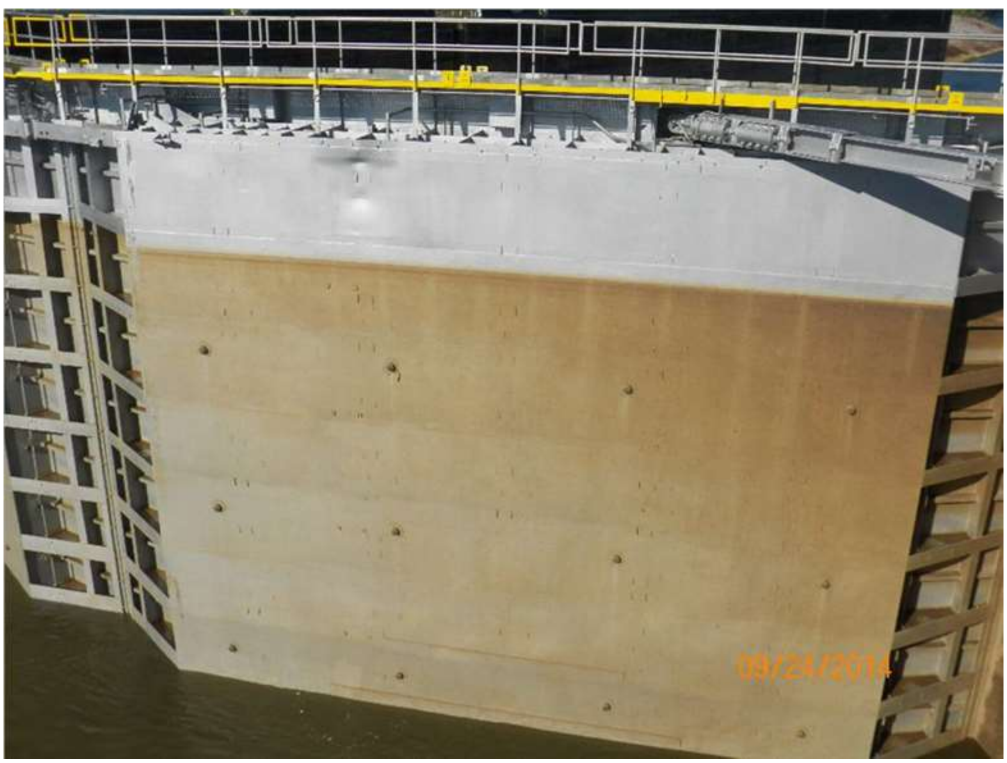

Figure J.3. Lower Gate, Upstream—Demopolis 2014

(5) In taking individual anode current measurements in the terminal cabinets beneath the miter gate walkway, it was found that the negative wire from the upper gate, right leaf rectifier, was not connected to the negative bus terminal in the cabinet nearest the quoin end of the right leaf. This is the first connection point from the rectifier, and this wire goes through to provide the negative connection in the middle and miter cabinets on this leaf.

(6) Therefore, with this connection missing in the first cabinet in the series connection, there was no current flowing to any of the anodes on this leaf, upstream or downstream. It is unknown how long this condition had existed, but it was likely done during the recent closure, which means this leaf was without CP for about a month. The connection was made and the anodes were put back into operation.

(7) It was observed that many of the shunts did not have the red plastic insulators, onto which the shunts are mounted. These insulators were seen in previous surveys and are installed in some places now. It is not known if the insulators were broken off the shunts or if this is a new type of shunt that did not come with such an insulator as shown in Figure J.4. Whichever the case, these shunts seem to be working. The layout of bus bars and anode connections were apparently changed in the terminal boxes during the closure. Connections inside the anode terminal cabinets were sprayed with a corrosion inhibitor, as had been previously recommended.

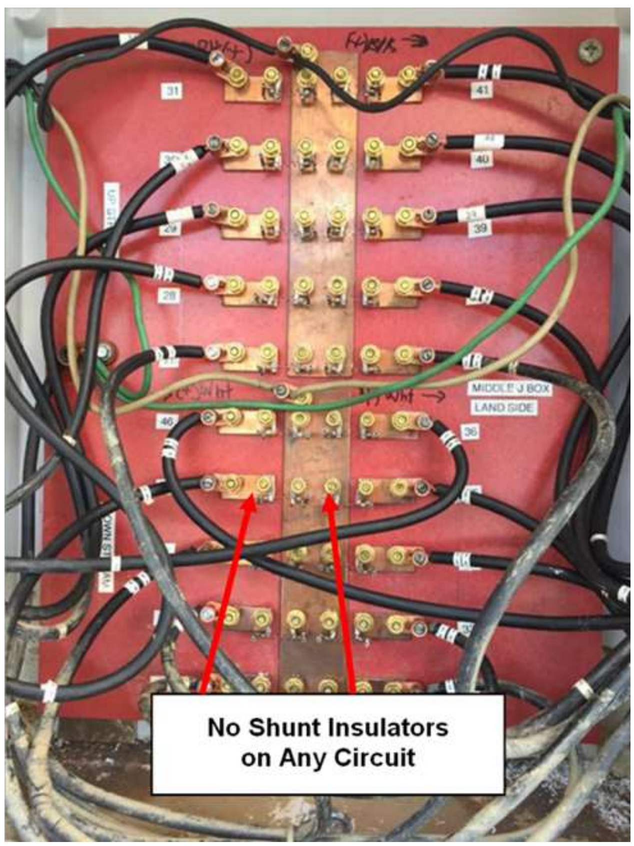

Figure J.4. Upper Gate, Anode Terminal Box, Shunts with No Insulators

(8) It is again noted in this report, as it was in previous reports, that Engineering Division does not have diagrams showing the anode layout of each gate leaf with identifying numbers adjacent to each anode correlated to the numbering in the anode terminal cabinets. Consequently, it is not readily apparent exactly where on the gate each open, partially shorted, or erratic anode is located.

(9) It is hoped that the maintenance contractor, who installed the systems, has such a diagram. Therefore, it is again recommended in this report, as it was previously recommended, that if such a diagram exists, a copy (preferably in a digital format) be provided to Engineering Division.

(10) If such correlating information does not exist, it is recommended that field work be done to obtain this information. This information will assist in correlating potential data with anodes that are not producing proper current. Anodes found to be not working can be documented for replacement as opportunities allow. Anode layout and anode numbering diagrams have been provided for the lower gate.

(11) Complete CP potential measurements were made on all gate surfaces during this inspection. Potential graphs, along with spreadsheets coordinating the measurement position number with its specific location on the gate surface, are included at the end of this report. See Figures J.6 through J.10 and Tables J.1 through J.5. Tables J.1 to J.5 provide the rectifier readings.

(12) Based on data taken, protective potentials measured on the UG, both US and DS areas, were receiving either good or excellent potentials at about 98% of the points. Only a few of the "instant off" measurements taken were less than –850 mV, and these, with few exceptions, are well in excess of 100 mV more negative than the associated native potential readings. Many of the lower potentials, which were not outside NACE criteria, were measured at the bottom of the gate where somewhat lower potentials are typical.

(13) The only areas of concern on the UG were in the quoin areas, primarily on the downstream sides of the gate. Additional anodes are needed in these areas to increase protective currents. It had previously been recommended that additional anodes be added at the next closure, but no anodes were added in the recent closure.

(14) Increasing rectifier output with the present configuration will help little in quoin areas and will drive potentials too high in other gate areas that already have good protection. Potentials on the US of the right leaf were somewhat low as compared with those on the left leaf. While these lower potentials were providing good CP, it was decided to increase the output by one fine setting to make left and right potentials more balanced. No other adjustment of UG rectifiers was made.

(15) Potential measurements made on the US of the LG this year had "instant off" readings averaging less than approximately –700 mV. The majority of all points were better than

the –100 mV shift criteria, but since about 72% of all points were less than –750 mV, it was decided to increase the current output of both left and right rectifiers by two fine settings, as indicated in the rectifier Table J.1 below.

(16) Last year, the DS side of the LG leaf had protective potentials lower than desired, although most of them were higher than the minimum NACE 100 mV negative shift criteria. Output current was increased last year to correct this. Protective potentials on the right leaf were well within criteria so no adjustments were necessary. This year over 98% of potentials on the left leaf and over 94% of the potentials on the right leaf, DS side, were in either the good or excellent ranges. The average protective potentials went from –756 mV last year to –856 mV this year.

Table J.1
Demopolis Rectifier Readings, 2014

LOCATION	UNIT #	COARSE TAP	FINE TAP	VOLTAGE (VOLTS)	CURRENT (AMPS)	SERIAL NO.
UG, Left Leaf, Upstream	2*	2	5	6.52	1.46	023609
UG, Left Leaf, Downstream	1*	2	5	6.39	1.54	
UG, Right Leaf, Upstream	1	2	6 (+1)	6.71 (6.32)	1.52 (1.44)	023607
UG, Right Leaf, Downstream	2	2	4	5.77	1.34	
LG, Left Leaf, Upstream	1	2	6 (+2)	7.0 (5.87)	2.5 (1.90)	023608
LG, Left Leaf, Downstream	2	4	2	13.08	4.44	
LG, Right Leaf, Upstream	1	2	6 (+2)	6.87 (5.81)	2.62 (2.0)	023606
LG, Right Leaf, Downstream	2	3	5	10.59	3.38	

*Note that Unit 2 on the UG, left leaf rectifier powers upstream anodes and Unit 1 powers downstream anodes. At all other rectifier's Unit 1 powers upstream anodes and Unit 2 powers downstream anodes.

(17) Operators have reported that the analog meters on these rectifiers are sometimes hard to read. Digital meters would give more accurate and easier-to-read displays. If time and resources allow, it is recommended that the analog meters in all rectifiers be changed to digital readouts.

(18) The settings and values listed in Table J.1 include information on the rectifiers at Demopolis after potential tests were taken and rectifier adjustments made. The + and – numbers in the "coarse and fine tap" columns show how much the final fine tap settings were adjusted up or down from the initial settings. Voltages and currents shown in parentheses are those

measured before making adjustments. Adjustments were made to rectifiers based on protective potential measurements, as discussed above.

(19) For a CPS to be an effective corrosion protection agent, the system must be kept operating. Since the activation of the UG CPS, the lock operators at this lock have been providing rectifier voltage and current readings to the Mobile District Cathodic Protection Specialist each week. This procedure has been of great value in keeping the CPS at Demopolis operating continuously and effectively, thus providing continuous corrosion control to the miter gates below the water line. Rectifier readings taken after the lock closure were not available so it is not known if the disconnected negative lead on the UG, right leaf, discussed above, was reflected in those readings.

(20) In the process of connecting/disconnecting equipment for the potential tests, it is necessary to disconnect the rectifiers from AC power. In so doing it was noticed last year that there was corrosion on the male connector for the lower right leaf rectifier. This corrosion had weakened the blades, and one of the male blades was bent as shown on Figure J.5.

(21) This blade was bent back into place and the rectifier was successfully plugged back in and the rectifier worked. It was recommended that this connector be replaced, but apparently it was not replaced during the closure. This year, when re-plugging this connector, the blade that was bent last year broke. Luckily there was an electrician on site doing other work who was able to put on a new plug to get the rectifier working.

(22) This plug was not waterproof like the plug removed, but it allowed the tests to continue. This temporary male plug should be replaced with a more waterproof type. The inside of plug should also be coated with corrosion inhibiting agents.

(23) Since this lock underwent a closure in 2014 and all surfaces were cleaned and recoated, all areas above the water line are completely free of mud and debris. Considerable corrosion reported previously has been eliminated and all metal surfaces are in excellent condition. This survey report should serve as a reminder, however, that, on a periodic basis, maintenance personnel should remove accumulated mud, sand, vegetation, and debris from areas of the miter gates above the water line.

(24) This should be a routine maintenance activity and should not wait until the next closure. Mud, sand, and other debris in the compartments hold moisture to the coating and can cause corrosion to start above the water line. The practice of cleaning and recoating any areas showing the first signs of corrosion is recommended.

(25) Properly designed and adjusted CPS will provide corrosion control for metal surfaces below the water line, but it cannot protect metal surfaces above the water line. Clean, dry, and well-coated surfaces will provide corrosion control above the water line. It is realized that on a river, particularly at this location where high waters are fairly frequent, it is difficult to keep all mud and sand out of compartments and other above-water areas, but this is a

maintenance item that should not be neglected since it can ultimately cause gate life to be significantly reduced leading to costly repairs or replacement.

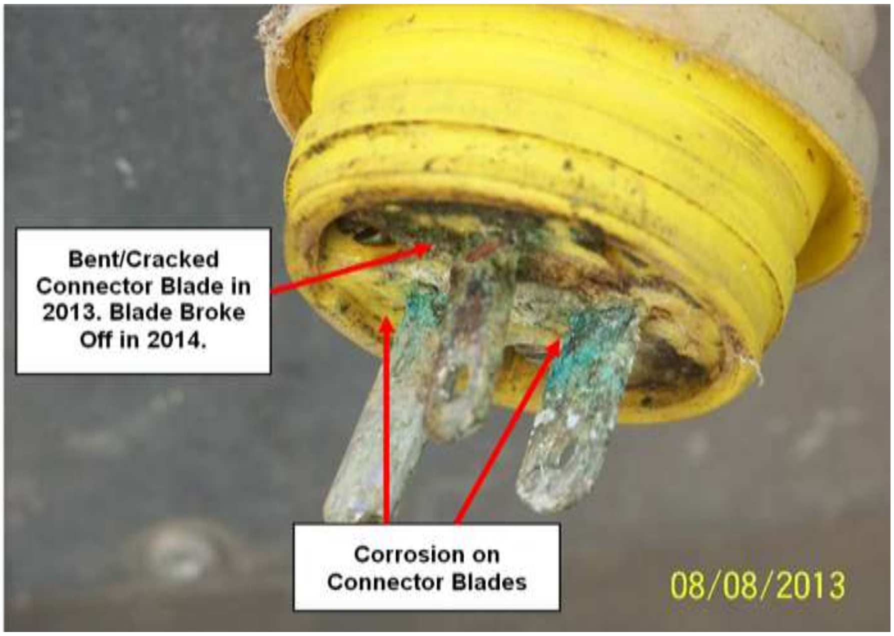

Figure J.5. Lower Gate, Right Leaf Rectifier AC Power Connector

(26) Tables J.2 to J.5 list 2014 Anode Current Readings, for the Upper Left Gate, Upper Right Gate, Lower Left Gate, and Lower Right Gate, respectively.

b. Recommendations. As a result of this year's annual test and evaluation inspection, the following recommendations are provided:

(1) If not already done, replace male part of connector providing AC to the LG right leaf rectifier with a waterproof type as soon as possible to keep rectifier working safely. Spray inside of AC connectors with corrosion inhibiting agent.

(2) Provide shunts in the two inoperable anode circuits on the LG (Anodes #50 and #51 on the left leaf).

(3) If detailed drawings exist for the CPS on the miter gates, the maintenance contractor should provide the District CP Specialist with diagrams or drawings in digital form showing the location of each numbered anode to allow for more effective correlation of anode current data and protective potential data. If such drawings do not exist, the contractor should create such drawings.

(4) Lock operators should continue to take rectifier voltage and current readings, with the lock chamber full, each week. Data should be documented on the Excel spreadsheet form presently being used and emailed to the Mobile District CP Specialist for his/her evaluation.

Any inoperable rectifier either no DC voltage or no DC current should be indicated in the report and should be reported to the local maintenance contractor electrician for repair as soon as possible.

(5) Replace analog meters in all rectifiers with digital readouts.

(6) Periodically spray all connections inside anode terminal cabinets and anywhere else they are subject to high humidity, with a high-quality liquid sealant (such as a silicone spray) that will inhibit oxidation and will seal out moisture. CorrosionX™ HD is a good product for this purpose (see website at corrosionx.com). It was noticed that newly terminated anodes and shunts had been sprayed during the closure.

(7) At least on an annual basis (and more frequently if possible), it is recommended that, after the last seasonal high-water event, debris, mud, and sand should be cleaned from gate compartments and any corroded areas recoated.

(8) Funds should continue to be made available for monitoring the protective potentials on the lock miter gates. Inspections by a fully qualified CP Specialist should continue at least on an annual basis and more often if funds and/or opportunity allow.

Table J.2
2014 Anode Current Readings, Upper Left Gate

		Anode #	Bus Voltage (Volts)	V Drop Across 0.1 ohm Shunt (MV)	Current (MA)*				Anode #	Bus Voltage (Volts)	V Drop Across 0.1 ohm Shunt (MV)	Current (MA)				Anode #	Bus Voltage (Volts)	V Drop Across 0.1 ohm Shunt (MV)	Current (MA)
		1	6.11	3.6	36			U	10	6.06	6.6	66				16	6.05	7	70
	U	2		6.9	69			P	11		6.5	65			U	17		6.7	67
	P	3		7.4	74			S	12		6.2	62			P	18		6.3	63
	S	4		6.6	66			T	13		6.8	68			S	19		6.8	68
	T	5		6.7	67			R.	14		7	70			T	20		6.9	69
	R	6		6.7	67				15		6.3	63			R	21		8	80
	E	7		6.7	67						SUBTOTAL:	394			E	22		6.3	63
Q	A	8		6.6	66		M		9	6.2	6.3	63			A	23		7	70
U	M	9		6.2	62		I		10		6.9	69		M	M	24		5.7	57
O				SUBTOTAL	574		D	D	11		5.8	58		I				SUBTOTAL	607
I	D	17	6.25	6.8	68		D	O	12		6	60		T	D	1	6.19	5.6	56
N	O	18		6.4	64		L	W	13		6.1	61		E	O	2		8.9	89
	W	19		8	80		E	N	14		6.3	63		R	W	3		5.8	58
	N	20		6.4	64			S	15		5.9	59			N	4		6.1	61
	S	21		5.4	54			T	16		7	70			S	5		5.9	59
	T	22		6.2	62			R							T	6		6.6	66
	R	23		6.1	61										R	7		7.8	78
		24		5.8	58						SUBTOTAL	503				8		6.5	65
				SUBTOTAL	511													SUBTOTAL	532
															TOTAL US	1575		TOTAL DS	1546

*Total anode current may not exactly equal rectifier output because of inaccuracies of individual measurements.

Table J.3
2014 Anode Current Readings, Upper Right Gate

		Anode #	**Bus Voltage (Volts)**	**V Drop Across 0.1 Ohm Shunt (MV)**	**Current (MA)***				**Anode #**	**Bus Voltage (Volts)**	**V Drop Across 0.1 ohm Shunt (MV)**	**Current (MA)**				**Anode #**	**Bus Voltage (VOLTS)**	**V Drop Across 0.1 ohm Shunt (MV)**	**Current (MA)**
		1	5.46	5	50			U	10	5.95	7.3	73				16	5.95	7.4	74
	U	2		5.4	54			P	11		7.4	74			U	17		7	70
	P	3		5.9	59			S	12		5.8	58			P	18		7.3	73
	S	4		6.1	61			T	13		7.4	74			S	19		7.2	72
	T	5		6.7	67		M	R.	14		7.2	72			T	20		7.1	71
	R	6		6.9	69		I		15		7.1	71			R	21		7	70
	E	7		6.5	65		D				SUBTOTAL	422			E	22		6.1	61
Q	A	8		6.6	66		D		9	5.47	5.5	55		M	A	23		6.1	61
U	M	9		6.4	64		L		10		6	60		I	M	24		6.2	62
O				SUBTOTAL	555		E	D	11		5.9	59		T				SUBTOTAL	614
I	D	?	5.97	9.2				O	12		6.2	62		E	D	1	5.47	5.8	58
N	O	17		0	0			W	13		5.9	59		R	O	2		6	60
	W	18		0	0			N	14		6.6	66			W	3		5.6	56
	N	19		7.3	73			S	15		5.8	58			N	4		5.9	59
	S	20		6.6	66			T	16		6.7	67			S	5		6.1	61
	T	21		7.4	74			R							T	6		7.5	75
	R	22		6.7	67										R			SUBTOTAL	369
		23		7.7	77						SUBTOTAL	486							
		24		6.9	69										TOTAL US	1591		TOTAL DS	1281
		?		No Conn															
				SUBTOTAL	426														

*Total Anode Current May Not Exactly Equal Rectifier Output Because of Inaccuracies of Individual Measurements.

Table J.4
2014 Anode Current Readings, Lower Left Gate

	Quoin Box	Anode #	Bus Voltage (VOLTS)	V Drop Across 0.1 ohm Shunt (MV)	Current (MA)[*]		Mid. Box	Anode #	Bus Voltage (VOLTS)	V Drop Across 0.1 ohm Shunt (MV)	Current (MA)		Miter Box	Anode #	Bus Voltage (VOLTS)	V Drop Across 0.1 ohm Shunt (MV)	Current (MA)
		1	4.9	4.6	46			1	4.87	4.2	42			1	4.84	4.5	39
		2		4.2	42			2		4.3	43			2		3.9	39
	US	3		4.2	42		US	3		3.6	36		US	3		3.9	39
		4		4	40			4		3.5	35			4		No Shunt	0
		5		3.6	36			5		3.6	36			5		No Shunt	0
		6		3.7	37			6	12.49	18.3	183			6	12.41	18.9	189
		7		3.8	38			7		13.1	131			7		20.2	202
		8		3.4	34		DS	8		17.2	172		DS	8		22.6	226
		9		3.6	36			9		18.4	184			9		19.5	195
		10		3.5	35			10		0	0			10		0	0
		11		3.7	37			11	4.87	4.6	46			11	4.84	4.1	41
		12	12.6	18.3	183			12		3.9	39			12		4.5	45
		13		19.5	195		US	13		3.7	37			13		4.2	42
	DS	14		17.8	178			14		4.6	46			14		4.3	43
		15		16.4	164			15		3.2	32			15		3.8	38
		16		0	0			16	12.49	15	150		US	16		3.5	35
		17	4.9	4.6	46		DS	17		19.2	192			17		3.4	34
		18		3.8	38			18		17.6	176			18		3.5	35
	US	19		3.7	37			19		18.2	182			19		3.4	34
		20		3.9	39			20		0	0			20		3.4	34
		21		9.4	94									21		3.3	33
		22	12.6	15.3	153									22	12.41	15	150
		23		17.8	178									23		20.2	202
	DS	24		18.5	185								DS	24		18.6	186
		25		19.3	193		TOT US	1600						25		18.4	184
		26		0	0		TOT DS	4333						26		0	0

[*]Total anode current may not exactly equal rectifier output because of inaccuracies of individual measurements.

Table J.5
2014 Anode Current Readings, Lower Right Gate

	Quoin Box	Anode #	Bus Voltage (Volts)	V Drop Across 0.1 ohm Shunt (MV)	Current (MA)*		Mid. Box	Anode #	Bus Voltage (Volts)	V Drop Across 0.1 ohm Shunt (MV)	Current (MA)		Miter Box	Anode #	Bus Voltage (Volts)	V Drop Across 0.1 ohm Shunt (MV)	Current (MA)
		1	5.46	5.3	53			1	5.42	8.4	84			1	5.37	4.4	44
		2		5.3	53			2		5.3	53			2		4.8	48
	US	3		6.2	62		US	3		4.3	43		US	3		4.2	42
		4		5	50			4		4.2	42			4		4.2	42
		5		4.4	44			5		4.4	44			5		4.4	44
		6		4.6	46			6	10.04	12.5	125			6	9.96	12.4	124
		7		4.6	46			7		15	150			7		13.8	138
		8		4.5	45		DS	8		15.2	152		DS	8		14.4	144
		9		4.5	45			9		13.4	134			9		14.4	144
		10		4.7	47			10		0	0			10		0	0
		11		4.7	47			11	5.42	4.9	49			11	5.37	5.4	54
		12	10.1	12.9	129			12		4.6	46			12		5.4	54
		13		17.9	179		US	13		4.3	43			13		5.5	55
	DS	14		13.7	137			14		4.4	44			14		5.3	53
		15		13.5	135			15		4.2	42			15		4.5	45
		16		0	0			16	10.04	13.2	132		US	16		4.2	42
		17		5.1	51		DS	17		15.2	152			17		5.3	53
		18		4.5	45			18		18.7	187			18		4	40
	US	19		4.5	45			19		13.4	134			19		4.5	45
		20		4.3	43			20		0	0			20		4.5	45
		21		4.6	46									21		4.3	43
		22		16.3	163									22	9.96	14.3	143
		23		12.9	129									23		15.9	159
	DS	24		13.8	138								DS	24		13.5	135
		25		17	170		TOT US	2007						25		14.7	147
		26		0	0		TOT DS	3480						26		0	0

*Total anode current may not exactly equal rectifier output because of inaccuracies of individual measurements.

J.3 Potential Data Graphs. Figures J.6 to J.9 provide the potential voltage data graphs for the lock gates. Figure J.10 shows location of anodes.

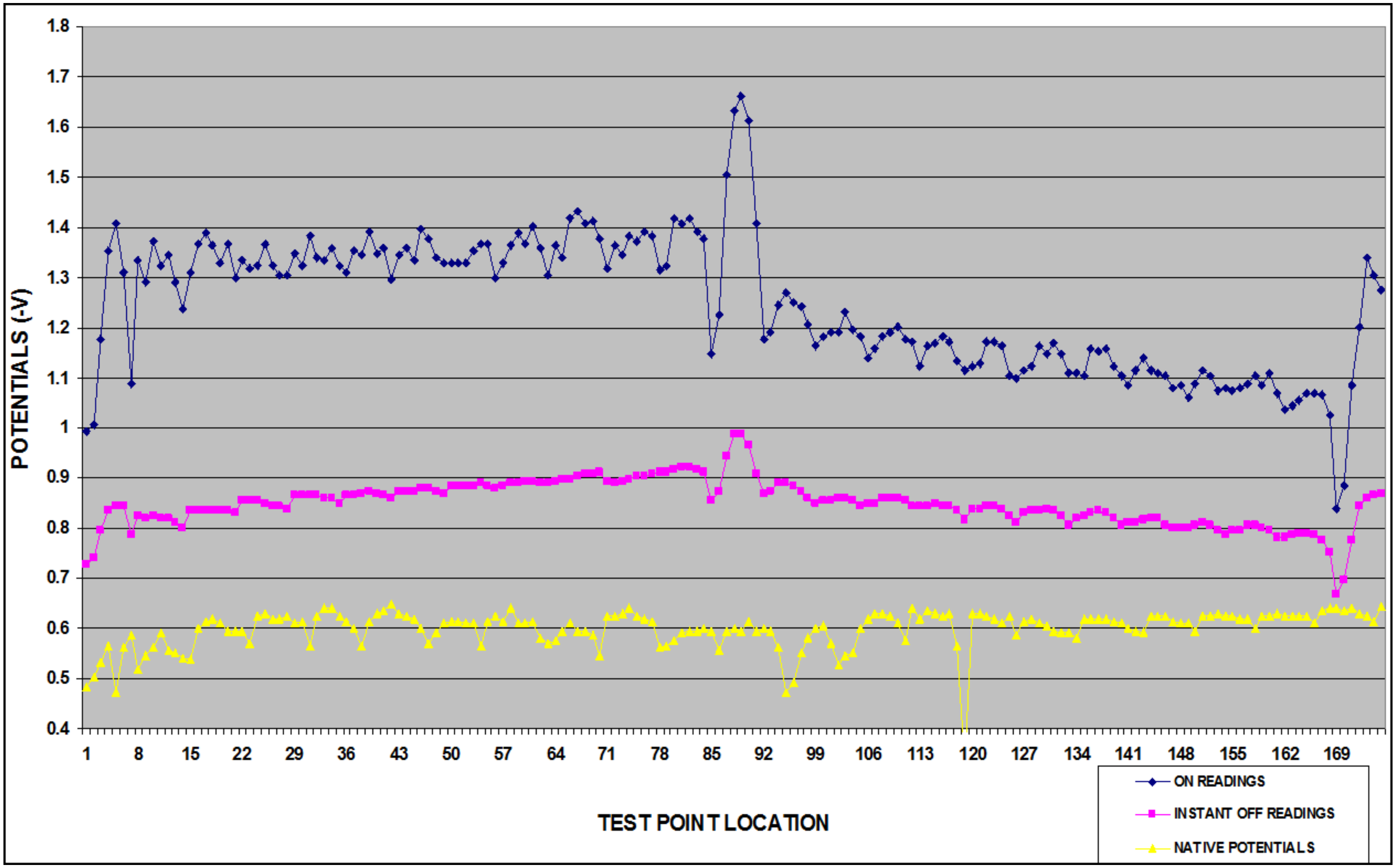

Figure J.6. Data for Demopolis Lock Upper Gates, Upstream Side, 2014

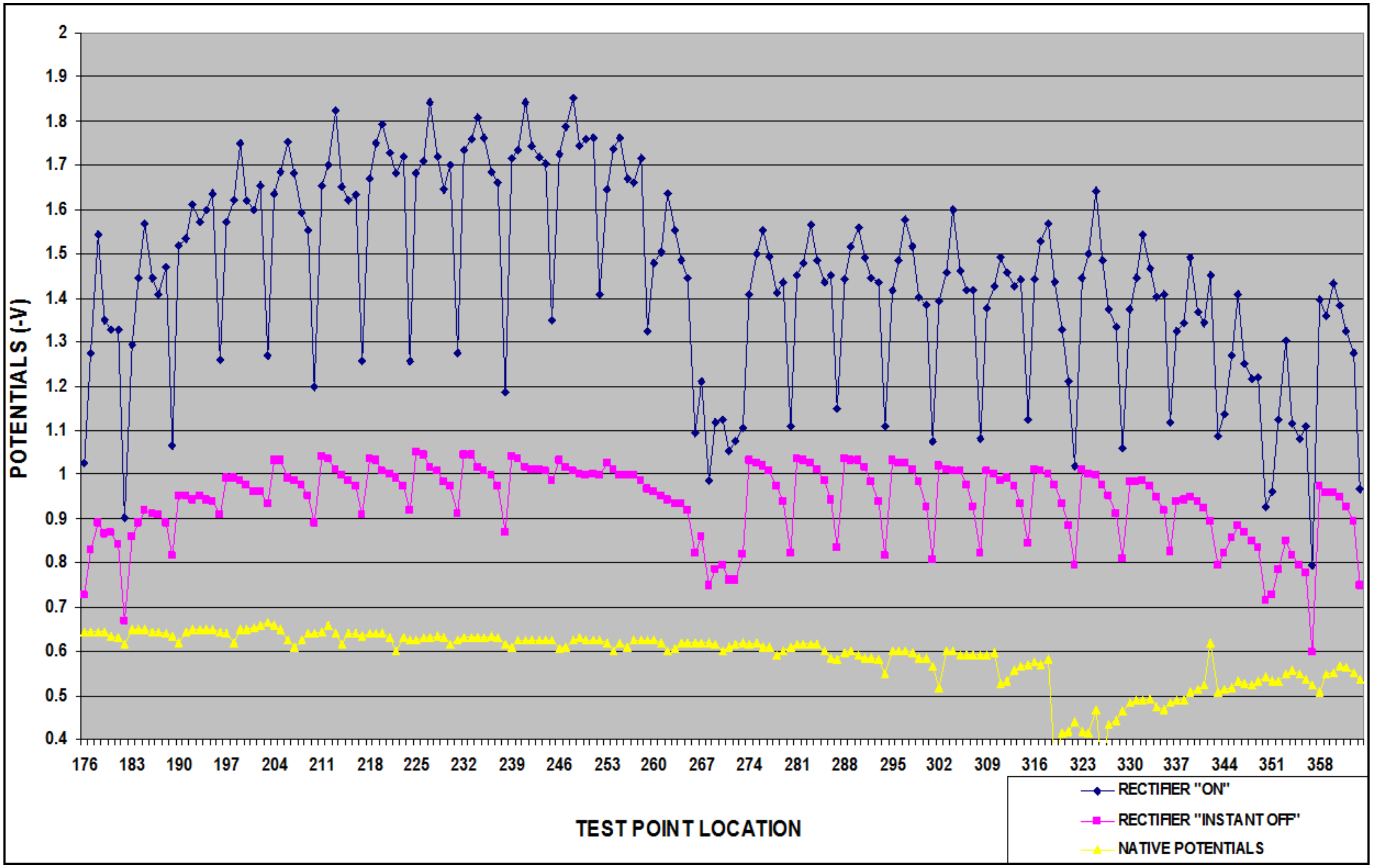

Figure J.7. Data for Demopolis Lock Upper Gates, Downstream Side, 2014

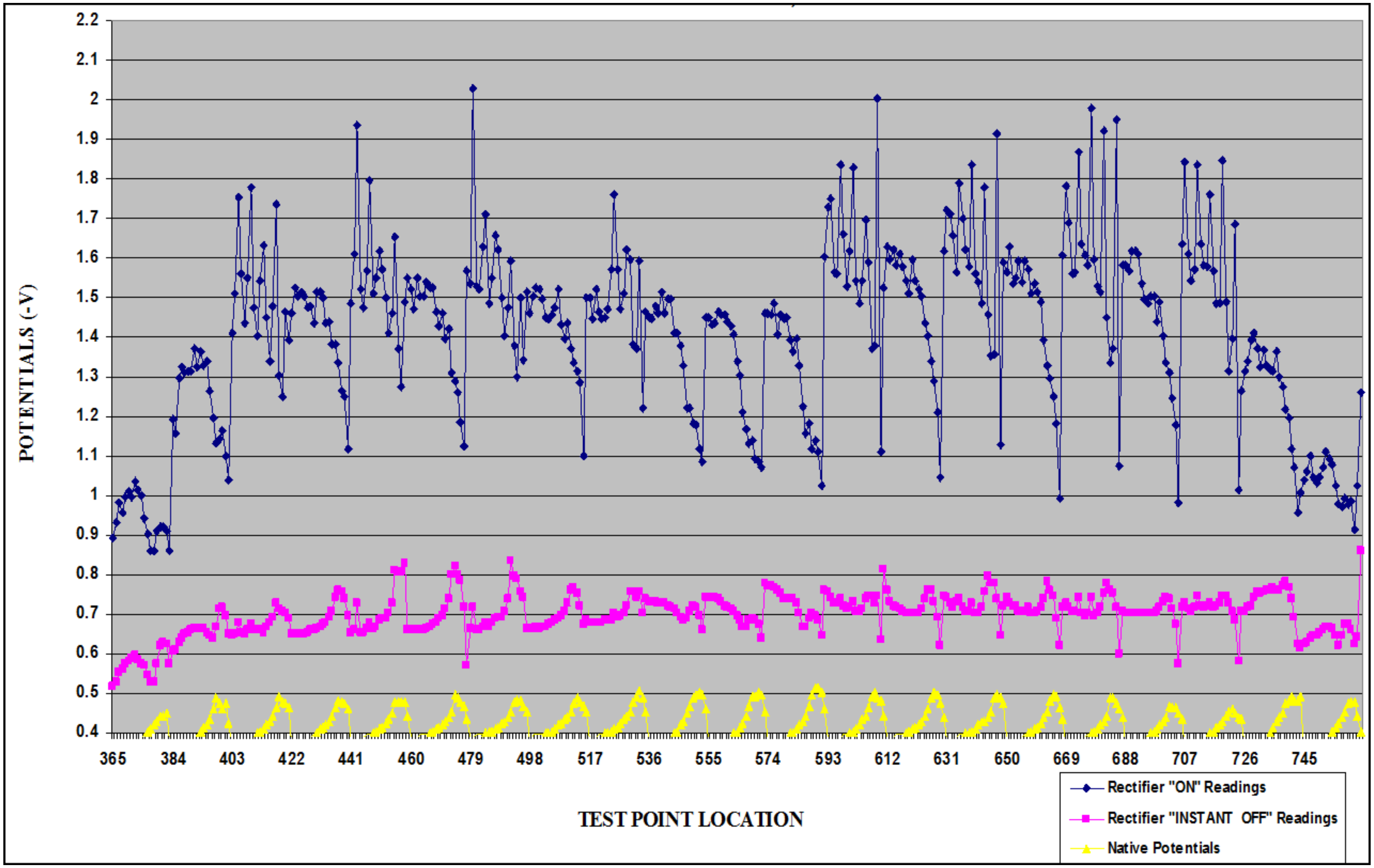

Figure J.8. Data for Demopolis Lock Lower Gates, Upstream Side, 2014

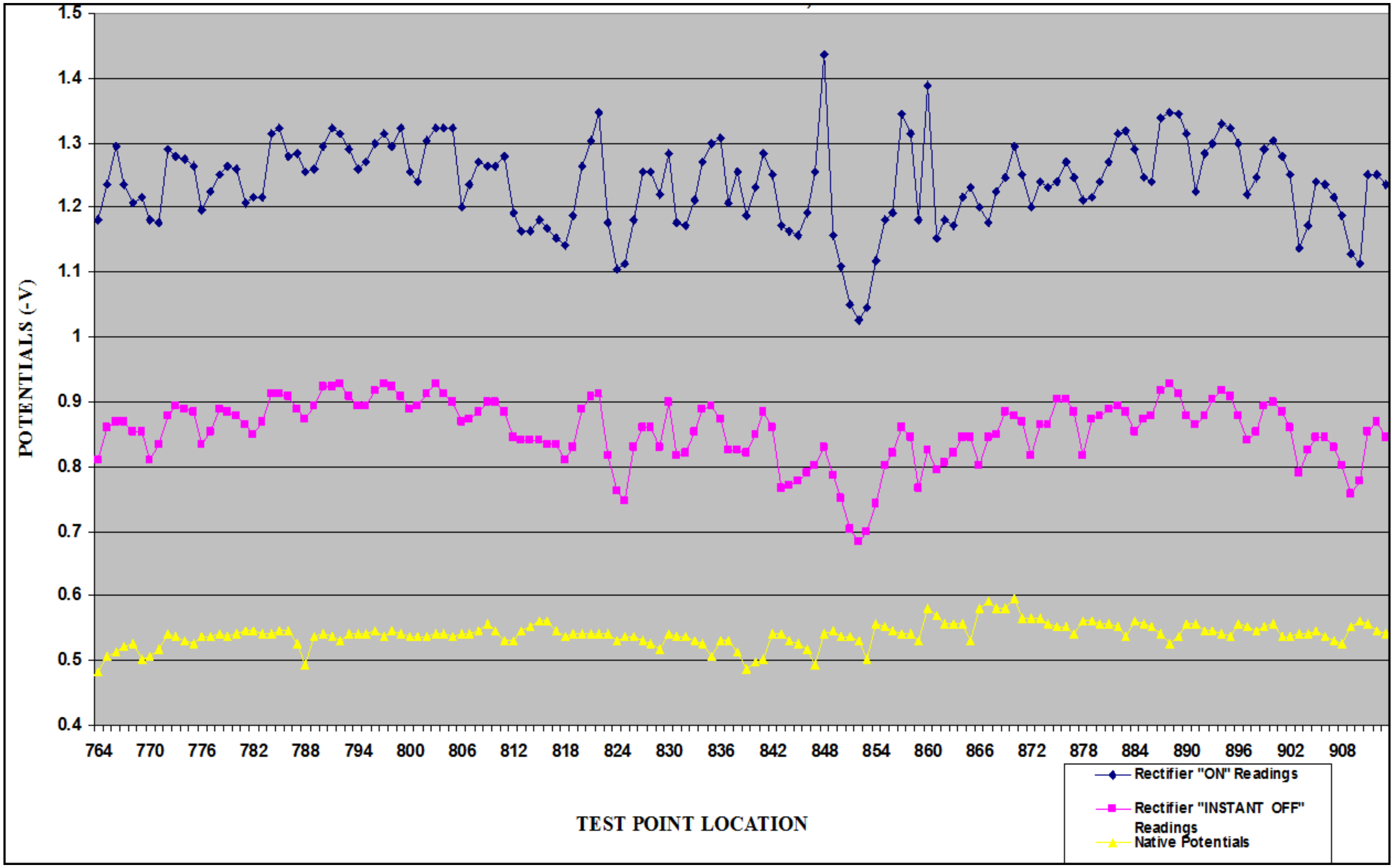

Figure J.9. Data for Demopolis Lock Lower Gates, Downstream Side, 2014

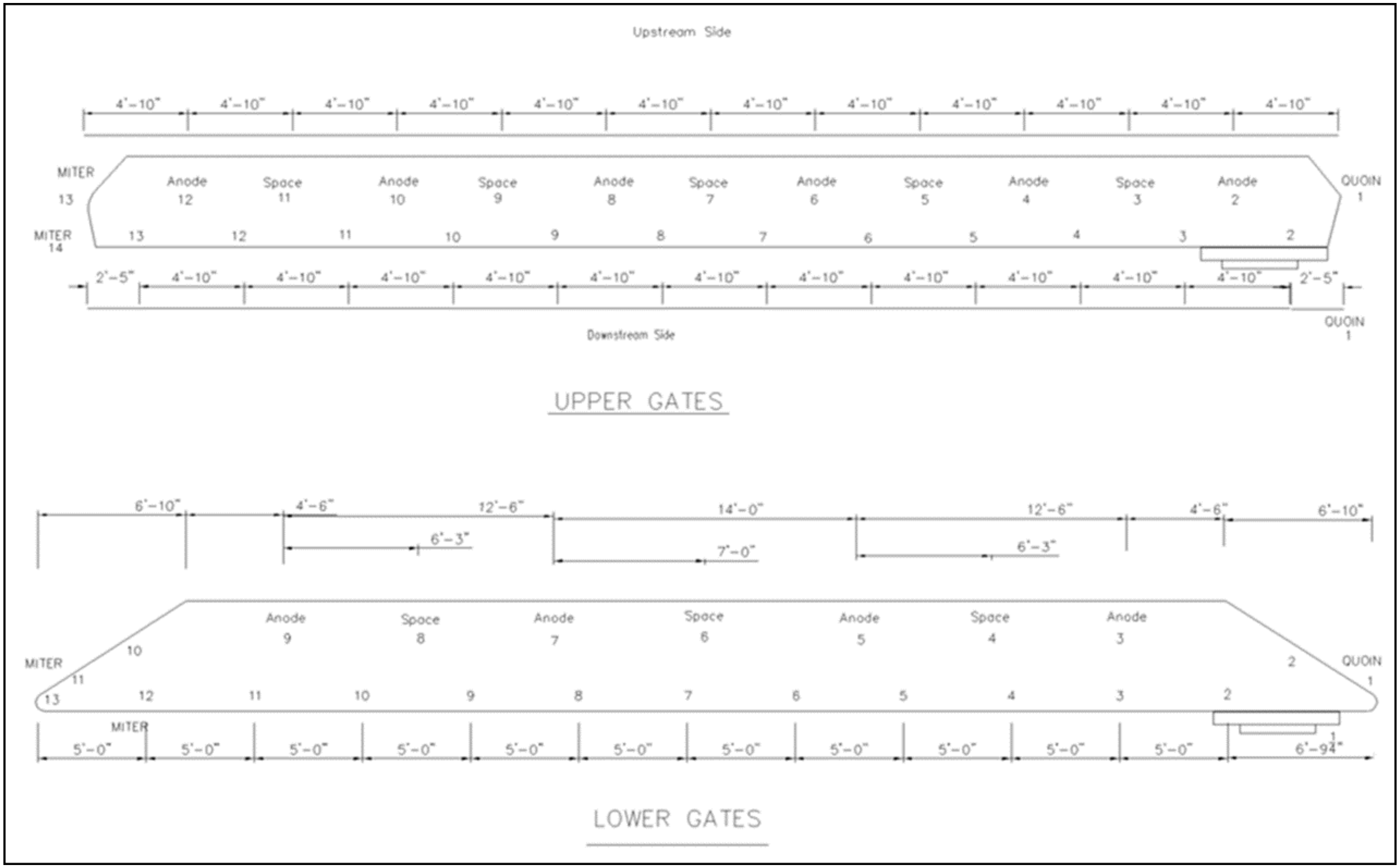

Figure J.10. Schematic View of Demopolis Lock Upper and Lower Gates

J.4 Data Position Number Correlated with Location on Gate Surface. Tables J.6 to J.9 provide the position location on each of the gate surfaces.

Table J.6
Data Position Numbers Correlated with Location on Gate Surface: Upper Gate, Upstream Side

POSITIONS—UG, LEFT LEAF, UPSTREAM SIDE															POSITIONS—UG, RIGHT LEAF, UPSTREAM SIDE											
HEIGHT	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**MITER**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**HEIGHT**
(FT)	1	2	3	4	5	6	7	8	9	10	11	12	13	12	11	10	9	8	7	6	5	4	3	2	1	(FT)
TOP (18 ft)	1	8	15	22	29	36	43	50	57	64	71	78	85	92	99	106	113	120	127	134	141	148	155	162	169	TOP (18 ft)
15	2	9	16	23	30	37	44	51	58	65	72	79	86	93	100	107	114	121	128	135	142	149	156	163	170	15
12	3	10	17	24	31	38	45	52	59	66	73	80	87	94	101	108	115	122	129	136	143	150	157	164	171	12
9	4	11	18	25	32	39	46	53	60	67	74	81	88	95	102	109	116	123	130	137	144	151	158	165	172	9
6	5	12	19	26	33	40	47	54	61	68	75	82	89	96	103	110	117	124	131	138	145	152	159	166	173	6
3	6	13	20	27	34	41	48	55	62	69	76	83	90	97	104	111	118	125	132	139	146	153	160	167	174	3
BOTTOM	7	14	21	28	35	42	49	56	63	70	77	84	91	98	105	112	119	126	133	140	147	154	161	168	175	BOTTOM

Table J.7
Data Position Numbers Correlated with Location on Gate Surface: Upper Gate, Downstream Side

POSITION—UG, LEFT LEAF, DOWNSTREAM SIDE															POSITION—UG, RIGHT LEAF, DOWNSTREAM SIDE												
HEIGHT	**QUOIN**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**MITER**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**4 ft10”**	**QUOIN**
(FT)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	13	12	11	10	9	8	7	6	5	4	3	2	1
TOP (18 ft)	176	183	190	197	204	211	218	225	232	239	246	253	260	267	274	281	288	295	302	309	316	323	330	337	344	351	358
15	177	184	191	198	205	212	219	226	233	240	247	254	261	268	275	282	289	296	303	310	317	324	331	338	345	352	359
12	178	185	192	199	206	213	220	227	234	241	248	255	262	269	276	283	290	297	304	311	318	325	332	339	346	353	360
9	179	186	193	200	207	214	221	228	235	242	249	256	263	270	277	284	291	298	305	312	319	326	333	340	347	354	361
6	180	187	194	201	208	215	222	229	236	243	250	257	264	271	278	285	292	299	306	313	320	327	334	341	348	355	362
3	181	188	195	202	209	216	223	230	237	244	251	258	265	272	279	286	293	300	307	314	321	328	335	342	349	356	363
BOTTOM	182	189	196	203	210	217	224	231	238	245	252	259	266	273	280	287	294	301	308	315	322	329	336	343	350	357	364

Table J.8
Data Position Numbers Correlated with Location on Gate Surface: Lower Gate, Upstream Side

POSITIONS—LG, LEFT LEAF, UPSTREAM SIDE												**POSITIONS—LG, RIGHT LEAF, UPSTREAM SIDE**									
HEIGHT	**1**	**2**	**3–4.5 ft from edge of SP**	**4–12.5 ft wide**	**5**	**6–14 ft wide**	**7**	**8–12.5 ft wide**	**9–4.5 ft from edge of SP**	**10**	**11**	**10**	**9–4.5 ft from edge of SP**	**8–2.5 ft wide**	**7**	**6–14 ft wide**	**5**	**4–12.5 ft wide**	**3–4.5 ft from edge of SP**	**2**	**1**
(FT)	Quoin	Comp.	Button	Space	Button	Space	Button	Space	Button	Comp.	Miter	Comp.	Button	Space	Button	Space	Button	Space	Button	Comp.	Quoin
TOP (54 ft)	365	384	403	422	441	460	479	498	517	536	555	574	593	612	631	650	669	688	707	726	745
51	366	385	404	423	442	461	480	499	518	537	556	575	594	613	632	651	670	689	708	727	746
48	367	386	405	424	443	462	481	500	519	538	557	576	595	614	633	652	671	690	709	728	747
45	368	387	406	425	444	463	482	501	520	539	558	577	596	615	634	653	672	691	710	729	748
42	369	388	407	426	445	464	483	502	521	540	559	578	597	616	635	654	673	692	711	730	749
39	370	389	408	427	446	465	484	503	522	541	560	579	598	617	636	655	674	693	712	731	750
36	371	390	409	428	447	466	485	504	523	542	561	580	599	618	637	656	675	694	713	732	751
33	372	391	410	429	448	467	486	505	524	543	562	581	600	619	638	657	676	695	714	733	752
30	373	392	411	430	449	468	487	506	525	544	563	582	601	620	639	658	677	696	715	734	753
27	374	393	412	431	450	469	488	507	526	545	564	583	602	621	640	659	678	697	716	735	754
24	375	394	413	432	451	470	489	508	527	546	565	584	603	622	641	660	679	698	717	736	755
21	376	395	414	433	452	471	490	509	528	547	566	585	604	623	642	661	680	699	718	737	756
18	377	396	415	434	453	472	491	510	529	548	567	586	605	624	643	662	681	700	719	738	757
15	378	397	416	435	454	473	492	511	530	549	568	587	606	625	644	663	682	701	720	739	758
12	379	398	417	436	455	474	493	512	531	550	569	588	607	626	645	664	683	702	721	740	759
9	380	399	418	437	456	475	494	513	532	551	570	589	608	627	646	665	684	703	722	741	760
6	381	400	419	438	457	476	495	514	533	552	571	590	609	628	647	666	685	704	723	742	761
3	382	401	420	439	458	477	496	515	534	553	572	591	610	629	648	667	686	705	724	743	762
BOTTOM	383	402	421	440	459	478	497	516	535	554	573	592	611	630	649	668	687	706	725	744	763

Table J.9
Data Position Numbers Correlated with Location on Gate Surface: Lower Gate, Downstream Side

POSITIONS—LG, LEFT LEAF, DOWNSTREAM SIDE																POSITIONS—LG, RIGHT LEAF, DOWNSTREAM SIDE									
HEIGHT	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**12**	**11**	**10**	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**
(FT)	QUOIN	5	10	15	20	25	30	35	40	45	50	55	MITER	55	50	45	40	35	30	25	20	15	10	5	QUOIN
TOP(14 ft)	754	760	766	772	778	784	790	796	802	808	814	820	826	832	838	844	850	856	862	868	874	880	886	892	898
12	755	761	767	773	779	785	791	797	803	809	815	821	827	833	839	845	851	857	863	869	875	881	887	893	899
9	756	762	768	774	780	786	792	798	804	810	816	822	828	834	840	846	852	858	864	870	876	882	888	894	900
6	757	763	769	775	781	787	793	799	805	811	817	823	829	835	841	847	853	859	865	871	877	883	889	895	901
3	758	764	770	776	782	788	794	800	806	812	818	824	830	836	842	848	854	860	866	872	878	884	890	896	902
BOTTOM	759	765	771	777	783	789	795	801	807	813	819	825	831	837	843	849	855	861	867	873	879	885	891	897	903

J.5 General Background. The existing Demopolis Lock and Dam Project is located at navigation mile 213.2 above the Bankhead Tunnel, Mobile, AL. There is a 1,485-ft long open fixed-crest spillway across the river channel, a lock and lock mound on the left bank, and an earth dike across the left bank to high ground. There is no gated spillway at this project. The lock has chamber dimensions of 110 x 600 ft, a lift of 40 ft, and a depth of 18 ft over the upper miter sill and 13.0 ft over the lower miter sill.

J.6 NACE Criteria. According to one NACE criteria, if the “instant off” protective potential is minus 850mV, full protection has been achieved, but little additional protection is achieved above this value.

a. Depending on circumstances, if approximately minus 1100 mV is reached, damage to the coating can occur. Experience has shown that good, tightly adhering coatings will not be damaged up to this potential level. Alternate NACE criteria for corrosion protection state that a potential shift of 100 mV below the native potentials (i.e., the potentials of the steel before any CP being applied) of a particular type of steel would also provide adequate protection.

b. Native potentials for this lock are available and are shown on the potential charts at the end of this report. These charts show that no native potentials are higher than –650 mV with the vast majority of native potentials around –550 mV or lower, especially on the LG. Potentials, then, in excess of approximately –750 mV could be considered as providing adequate protection, and potentials of –850 mV could be considered as providing very good protection under this criteria. Where native potentials are only -500 mV, -600mV is adequate protection per NACE criteria.

J.7 Existing CPS at Demopolis Lock.

a. Both the UG and LG at Demopolis Lock were repaired and recoated in the summer of 2002. The CPS for the UG at this lock were activated with initial adjustments in the summer of 2003. The CPS for the LG were installed during the dewatering of September 2008.

b. Activation of the systems was attempted soon thereafter, but the systems were not effective because problems were found with the shunts installed in the terminal cabinets. The LG systems, therefore, were not actually activated and adjusted properly until the summer of 2009. Hence about 7 years passed after the recoating before the LG started receiving the benefits of CPS. It is believed that the underwater coating deteriorated significantly during this time, and this accounts for why there is a much larger CPS current requirement in this gate area compared to the requirements for the UG and for the gates on other locks.

c. Miter gate CPS at this facility use only button anodes. Other than anodes mounted on the LG skin plates, beneath the bottom girders, and to diaphragms for protection of quoin and miter areas, the button anodes are primarily mounted on 5-inch high standoff plates, which are welded to the gate.

d. The UG contain 12 button anodes on the upstream side of each leaf (two horizontal rows, each with six anodes) and 24 button anodes on the downstream side of each leaf (two horizontal rows, each with 12 anodes). In addition, there are six button anodes mounted on the underside of the bottom girder plus three button anodes mounted on the end of each leaf along the miter area and three mounted on the end of each leaf along the quoin area.

e. Each leaf of the LG has 20 button anodes, four vertical columns by five horizontal rows, on the skin plate, upstream side. There is one button anode in each miter and quoin compartment on the upstream side, i.e., 11 anodes in the quoin and 11 anodes in the miter.

f. On the downstream side, there is one anode in each compartment, i.e., four compartments wide by two compartments high. There is also one anode in each miter and quoin compartment, i.e., four anodes in the quoin end and four anodes in the miter end of the leaf. In addition, there are six anodes approximately equally spaced along the bottom girder to protect the bottom seal area. Anodes on the LG are not installed on standoff brackets.

g. Each anode is mounted on a ¼-in. thick by 12-in. diameter fiberglass shield. The standoff brackets and the fiberglass shields minimize the risk of damage to the coating on the gate structure that could be caused by excessive CP potentials. Anodes and fiberglass shield assemblies are attached by

FRP nuts and bolts. Figure J.11 shows typical anodes mounted on the downstream side of the UG and the upstream side of the LG.

h. Anode terminal cabinets on both upper and LGs were designed and installed similar to the following description. At this lock, each gate leaf has three anode terminal cabinets associated with the anodes on each leaf. Figure J.12 shows an inside view of typical terminal cabinets on the upper and LGs. Each cabinet contains two bus bars, one for the upstream anodes and one for the downstream anodes.

i. Anodes on the bottom of the gate and anodes in the upstream miter and quoin areas are attached to the upstream bus bar. Each anode lead is numbered and attached to the bus bar through a 0.1-ohm shunt, which allows the current passing through each anode to be measured without having to disconnect the anode lead from the circuit. This feature is important because it allows the easy and quick determination of whether an anode is shorted, open, or working properly.

j. DC rectifiers provide the required voltages and currents to the anodes. Each gate leaf has a separate rectifier associated with it, and each rectifier at this facility has a separate output unit for the anodes on the upstream side of the gate and for those on the downstream side of the gate. Each output has both coarse and fine voltage adjustments. Course adjustments on each output unit are 1-7 and fine adjustments are 1-7.

k. The settings for the adjustment controls and the resulting voltages and currents for each rectifier output are provided later in this report. The UG rectifiers are ALCO CP Rectifiers, Model ASAI. (Figure J.13 shows one of these rectifiers.) These are actually manufactured by Universal Rectifiers, Inc., and sold through Allied Corrosion Industries, Inc. of Marietta, GA. The maximum voltage output per circuit is 24 volts DC and maximum current output is 15 Amps DC. Each rectifier output is equipped with a 10 Amp per 50 mV shunt (i.e., shunt factor is 0.2 A/mV), which can be used to measure the DC current output.

l. The UG, left leaf rectifier has Unit 2 as the output for the upstream anodes and Unit 1 provides power for the downstream anodes. In all other cases, Unit 1 powers upstream anodes and Unit 2 powers downstream anodes.

Figure J.11. Typical Button Anodes on Miter Gates

Figure J.12. Inside View of Typical Anode Terminal Cabinet, Upper and Lower Gates


Figure J.13. Typical DC Rectifier, Demopolis Lock

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Appendix K
Sample Corrosion Prevention and Control Lock Dewatering Report

Date of this Record: 4 October 2010.
Date of Inspection: 15 July 2010.
Location: Oliver Lock, Northport, AL.
Purpose: Corrosion and CP inspection during lock dewatering.

Notes.

1. Lock was dewatered to accomplish inspections and any necessary repairs (Figures K.1 and K.2). Repair work included repairs of structural welds and cracks and recoating of miter gates. Before and during dewaterings, the CPS are also routinely inspected and necessary repair work identified and done as necessary. However, it was reported that no damaged or inoperable anodes were found and, consequently, none were replaced. All of the miter gates and culvert valves were being cleaned and repainted. The existing paint was in fairly good shape except the top coat peeled off in some areas when the gates were washed (Figure K.3). The CPS were also in good shape.

2. A very detailed structural report relating to Oliver Lock, dated 14 July 2010, titled "HSS Inspections of Lock Miter Gates during FY10 Lock Dewaterings, Structural" was prepared by Allen Davis. This report contains detailed information on observed structural cracks, corrosion, and other information. In addition, many photographs are provided. A review of this report should be included in any subsequent reviews related to corrosion at this facility.

3. During this inspection, it was observed that a few structural cracks (painted orange) existed on the downstream side of the lower left gate near the quoin (Figure K.4). It was reported that a few stress cracks were found and repaired on both the upper gates and the LGs.

4. A 1998 CP inspection report of this lock stated that the impressed current CPS were commissioned in 1991. Since this lock was constructed in the late 1980s and/or early 1990s, the gates have been submerged for about 19 years. Consequently, the impressed current systems and the coating systems are original. This lock is the next lock upstream of Selden Lock. Very little damage caused by corrosion was found at Oliver Lock after 19 years of immersion service whereas Selden Lock miter gates had significant damage caused by corrosion. Although the gates were exposed to the same water environment, same operating conditions, the corrosion control systems at Oliver Lock were well maintained and the CPS were kept operable. This was not the case at Selden Lock.

5. Carbon steel miter and quoin blocks are used on the upper gates at his/her lock. Stainless steel miter and quoin blocks are used on the LGs. The upper gate blocks were being reconditioned with Belzona. These blocks were observed to be heavily corroded. However, the mild steel areas adjacent to these blocks were not pitting unlike the LGs (i.e., some pitting existed adjacent to the stainless-steel blocks on the LGs). Other than the bare mild steel miter and quoin blocks

being corroded (thus requiring Belzona), the gates looked very good with very little signs of pitting or general corrosion. Although not severe, some corrosion was observed on the upstream side, quoin areas near the bottom on both gates.

6. The impressed current CPS on these gates have been well monitored, adjusted as necessary, and maintained.

7. At this lock, the bottom chambers of each set of gates (downstream side) were enclosed. However, when these were opened, they were found to be full of water. CP button anodes were mounted inside and outside of these chambers. String anodes were in the open chambers above. Some of these chamber interiors looked very good (i.e., the paint was intact and not peeling, no corrosion) whereas some paint was observed to be peeling in others. However, the interior metal of these chambers where the coating was peeling was observed to look very good with no corrosion evident.

8. The tainter valves at this lock do not have CP. However, in relation to corrosion, they looked good. A few tubercles were noted on the lower valves, near the bottom, during the inspection. OP stated that pitting near the grease lines was noticed more after these lines were changed from copper to stainless steel.

9. Although the rectifiers were de-energized, it was noted that they had not been removed from the site.

10. On the upper-right gate, upstream side, just below the upper-pool elevation, the topcoat of paint peeled when the gate was washed. At the time of the inspection, the upstream sides of the upper gates had not all been washed. However, there did not appear to be any paint blistering around the skin plate button anodes.

11. String anodes are protected against debris by both PVC and angle irons.

[Name of CCCP TCX Technical Proponent], P.E.
Senior Electronics Engineer
NACE Cathodic Protection Specialist
Corrosion Control & CCP TCX
U.S. Army Corps of Engineers, Mobile, AL 36602

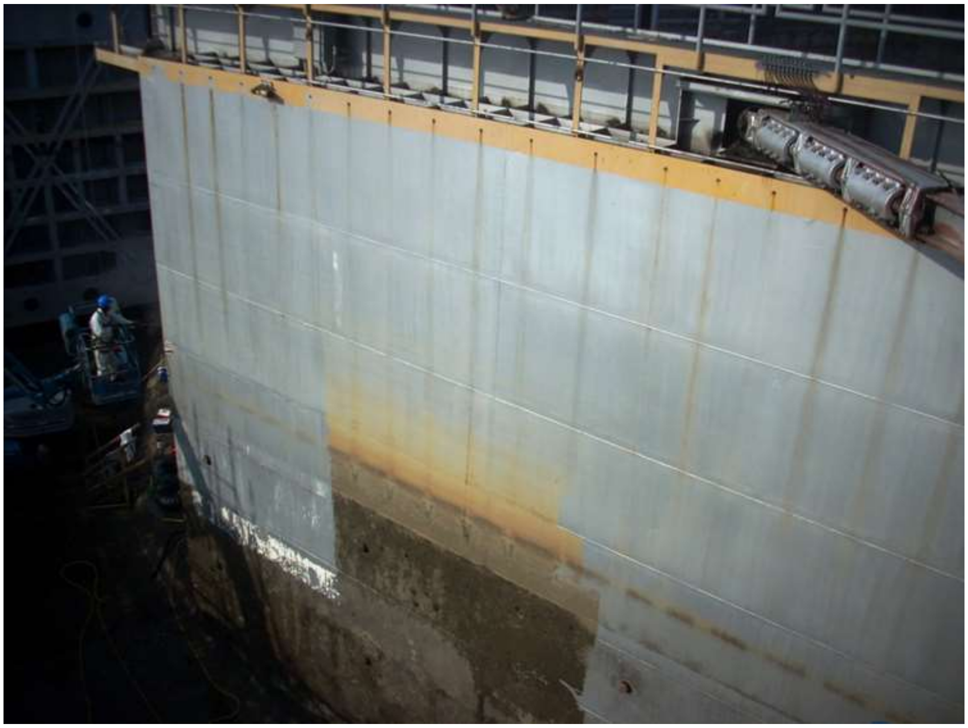
Figure K.1. Dewatered Lock, Viewed from Above


Figure K.2. Dewatered Lock, Viewed from Below

Figure K.3. View of Gates Showing Good Condition of Existing Paint

Figure K.4. Structural Cracks on the Downstream Side of the Lower Left Gate near the Quoin

Appendix L
Sample Scope of Work for Cathodic Protection Services

L.1 Purpose. This SOW establishes the parameters of the Architect/Engineering (A/E)'s Cathodic Protection Services, which include the testing, inspecting, evaluation, and subsequent engineering reports and/or submittal of the relative gathered field data, notes of observed conditions, findings, photographs, and corrective action recommendations of the various facilities described herein.

a. The requirements described in EM 1110-2-2704 for inspecting, testing, evaluating, and documenting (via reports) of impressed current CPS, similar to the procedures described in Paragraph 3 below, are to be done annually. However, although adequate funds may have been properly requested via the budgeting process, adequate funds may not always be provided to accomplish complete testing requirements conforming to guidance presented in EM 1110-2-2704.

b. Therefore, since funds at any particular project may be limited in any particular year, this SOW contains a description of work that is to be done in a "Limited Cathodic Protection Survey and Report" in addition to the description for a "Complete Cathodic Protection Survey and Report."

L.2 General Requirements.

a. Responsibilities. Except where otherwise noted, the A/E must furnish all materials, equipment, labor, and supervisory personnel to ensure the expeditious accomplishment of the work within the scope and methods described herein. Contractors must be responsible for providing their own testing assistant(s) for each survey done as described in this SOW. The contractors must schedule their trips after any applicable lock dewaterings.

b. In addition, contractor(s) must schedule their trips, in advance, to coincide with applicable lock operator schedules. Some locks are only open for operation during daytime hours from Friday through Monday. In addition, some locks may not normally have personnel on site even during the weekend or summer operating schedule (e.g., Henry Lock) thereby requiring scheduling ahead of time (as is required for all surveys) to ensure that government personnel will be on site during the accomplishment of the CP surveys.

c. Coordination. In performance of the work, the A/E must fully coordinate work and schedules at all project sites with the district CPC Coordinator and the specific USACE field office or project site to be visited to ensure complete cathodic protection testing, inspecting, evaluating services and all other specified work are coordinated with the field operating schedules and reflect all the contract requirements. All submittals must be coordinated with the CPC Coordinator.

d. Supervision and Certification Requirements. The A/E Services provider, who is contracted to perform the work described in this SOW, must have a registered professional engineer, as part of its staff, who will be responsible for supervising, as appropriate, and for approving (before submission to the Government for approval) all work done by the A/E's Corrosion Expert, who must have the following qualifications and experience in cathodic protection work such as is described in this SOW.

(1) Work described herein must be performed by a Corrosion Expert. A Corrosion Expert is a person who, by reason of thorough knowledge of the physical sciences and the principles of engineering and mathematics acquired by a professional education and related practical experience, is qualified to engage in the practice of corrosion control of submerged metallic surfaces of navigation lock miter gates.

(2) Such a person must be certified by NACE International as a NACE-certified Corrosion Specialist or a NACE-certified CP Specialist or be a registered professional corrosion engineer who has licensing that includes education and experience in corrosion control of submerged metallic surfaces of lock miter gates.

(3) The Corrosion Expert testing, inspecting, and evaluating the performance of the CPS of these structures must have a minimum of 5 years' experience in the design of these type systems, and, subsequently, in the testing, inspecting, and evaluating of these CPS. The design experience with these type systems is necessary so that the Corrosion Expert can note findings and suggest recommendations in his/her report based on his/her design experience and evaluation of the systems.

(4) The required design experience and testing/inspecting experience must be type specific. For this contract, the experience must be in the design and testing/inspecting of navigation lock miter gates equipped with impressed current CPS.

L.3 Miter Gate Cathodic Protection Testing and Inspection Procedure.

a. Complete CP Survey and Report. The lock miter gate CPS are impressed current systems. For performing the following described testing procedures, the lock chamber must be at the normal level of the upper pool for proper operation of the CP system. For CP testing at project sites identified in this SOW as requiring adherence to the "Complete Cathodic Protection Survey and Report" procedures, the Corrosion Expert must use the following procedures for all lock miter gate CP system testing:

(1) Rectifier Settings. Rectifier settings have a direct effect on the performance of the CP system. Monitoring of the current is necessary since excessive current on a structure can cause coating deterioration and damage to structure. Incorrect rectifier settings can cause excessive current and/or loss of optimization of performance of the CP system. Optimization of a CP system is achieved when the system is set for best corrosion prevention and yet will not damage paint or the gate.

(2) The rectifier's coarse and fine tap settings (or other voltage setting mechanisms) are adjusted by using the potential test at the gates. Rectifier voltage is adjusted until the potential readings on the associated gate leaf face are within the voltage ranges as required in Paragraph 3.

(3) Method of Testing Performance (Performance Tests). The primary reason for checking the cathodic protection systems is to determine if the systems are adequately protecting the structure against corrosion. The contractor must provide data sheets in his/her required submitted report or, if a report is not required, he must submit the data sheets (including electronic files of potential measurements in Excel spreadsheets) along with all other information that he obtains while on the site.

(4) Potential test results must also be provided in the form of Excel spreadsheet graphical representations to supplement tabular forms containing all of the data at each specified measuring location. This report must include the recorded structure-to-electrolyte potentials and other information required to be provided or obtained.

(5) The report must be as described herein. If a formal report is not specifically required for a particular project, then all of the gathered field information required by the Government to write the report must be submitted as if the A/E was doing the report (i.e., for these specified projects, the Government must prepare the report based on field information obtained by the A/E).

(6) If repairs are necessary, they should be detailed in the report (or in field notes where reports are not required) that is submitted to the CPC Coordinator for approval. In addition, all rectifier adjustments made by the A/E to obtain potential measurements in the acceptable range should be fully described.

(7) Structure-to-electrolyte potential measurements must be taken in the water adjacent to the face of each gate leaf (total of eight miter gate surfaces, unless noted otherwise herein). This will ensure that the CP potentials are providing proper protection and the rectifiers are set properly.

(8) This test must be done with a copper/copper-sulfate test cell, cabling, and the government-furnished data logging equipment and must be performed by the Corrosion Expert as defined in Paragraph 2.d. In the event it becomes necessary and if prior approval is obtained from the Government, a sensitive voltmeter (over 200,000 ohms per volt) may be used in lieu of the data logging equipment.

(9) The reference cell measurements must be taken in the manner described (i.e., using the detailed procedures and methods) and taken at the locations indicated. Additional measurements must be made, if required, to determine protection of the gate.

(10) The following materials are required and will be provided by the Government, as and if necessary, to the contractor, for use during testing:

(a) Copper/copper-sulfate test cell.

(b) Voltmeter and data logging equipment as described above.

(c) Flexible cable with waterproof jacket attached to cell.

(d) Flexible cable to connect test equipment to negative terminal of rectifier (or structure).

(11) On completion of all testing as defined by this SOW, the contractor must return all Government-furnished equipment to the CPC Coordinator.

(12) In miter gate tests, the reference cell will be placed in the water at intervals described herein.

b. Measuring Structure-To-Electrolyte Potential. The Government-furnished data logging equipment (or, in the alternative, a high resistance voltmeter 200,000 ohms per volt or greater) and other government-approved test equipment must be used. The equipment must be suitable for field use and accurate when in and out of level position.

(1) Connect test equipment with the negative (or structure) terminal to the structure and the positive (or probe) terminal to the reference electrode. Each of the two radio receivers, which were provided as part of the government-furnished data logging equipment, and are responsible for switching both rectifiers (two per set of gates) “off” and “on” simultaneously, must be connected in series with the phase conductor (i.e., AC hotleg) supplying each rectifier.

(2) If government-furnished data logging equipment is not used, then the contractor must accomplish simultaneous switching of both rectifiers by two current interrupters, temporary hard wiring arrangement, or by some other suitable means, as approved by the CPC Coordinator.

(3) If necessary, structure connections (-) should be scraped clean so that good contact is made. However, where possible, connections to structure should be made at the rectifier negative (or structure) terminal.

(4) Place reference electrode immediately adjacent to the structure under test at various locations and depths, as described herein. At each of these locations, both an “instant off” and an “on” (or “native” if specified herein) measurement must be conducted, recorded, and furnished in the subsequent report and/or submitted field information.

(5) Record all measurements and indicate location where measurement was obtained.

(6) Record name and number of the instrument used. If possible, use the same voltmeter or equipment each time tests are performed.

(7) Maintain reference electrode in good condition. Change solution after extended testing to ensure that it does not become contaminated. In addition to the copper-sulfate crystals, use only distilled water in the reference electrode.

(8) Maintain all test conditions as constant as possible.

c. Criteria of Protection. The standard acceptable criteria of protection must be maintained to ensure protection of the submerged metal. Since the potential performance of the cathodic protection systems must be measured to ensure that sufficient benefits are obtained, the following criteria of protection is used.

(1) If the measured potentials do not comply with the criteria below, the A/E must adjust the rectifiers, if possible, to obtain the specified potentials to the extent possible given the present condition of the existing CP system. Criteria for determining the adequacy of protection on submerged metallic

structures are defined in the NACE International Publication SP-0169. In essence, the requirements are as follows for steel structures.

(2) A negative voltage of at least minus 0.85 volts as measured between the structure surface and a saturated copper copper-sulfate reference electrode contacting the electrolyte directly adjacent to the structure. Determination of this voltage must be made with the CP system in operation. Voltage drops must be considered for valid interpretation of this voltage measurement. A minimum of minus 850 mV "instant off" potential between the structure being tested and the reference cell must be achieved over 95% of the submerged area of the structure.

(3) These "instant off" measurements must be obtained by interrupting the rectifier protective currents via use of the government-furnished data logging equipment or other approved government equipment. Alternatively, if a voltmeter is used, then the Corrosion Expert will set up and use some other acceptable means to interrupt the rectifier supplied currents to obtain the "instant off" measurements, such as the use of synchronized current interrupters or hard-wired connections with switching capability to enable the simultaneous "on" and "off" operation of both rectifiers.

(4) If the Corrosion Expert uses a voltmeter for these measurements, then the "instant off" reading will be defined as the second reading displayed on the voltmeter screen immediately after interrupting the rectifiers (i.e., immediately after turning the rectifiers off). An adequate number of measurements must be obtained over the entire structure (locations of measurements as described in Paragraph 3.a. (5) to verify and record achievement of minus 850 mV "instant off."

(5) This potential must be obtained over 95% of the total submerged metallic area without the "instant off" potential being more negative than negative 1100 mV. If necessary, the rectifiers must be adjusted to obtain these potentials.

(6) Before using the testing procedure or method described in this paragraph for any specific location, the A/E must first submit a request and obtain approval from the Government to use the method instead of the above described method. The request must contain the reasons and rationale for using this method in lieu of the method described in Paragraph 3.a.(4). With that said, this testing procedure is as follows.

(7) A minimum polarization voltage shift of 100 mV is measured between the structure and a saturated copper-copper-sulfate reference electrode contacting the electrolyte near the structure. This polarization voltage shift must be determined by interrupting the protective current and measuring the polarization decay. When the protective current is interrupted, an immediate voltage shift will occur.

(8) The voltage reading, after the immediate shift, must be used as the base reading from which to measure polarization decay. (This reading must be defined herein as being the same reading as the "instant off" reading described in the paragraph immediately above this paragraph and this term will be used below.) Measurements achieving 100 mV decay must be made over 95% of the submerged metallic surface.

(9) Alternatively, the "instant off" measurements can be compared to the native readings taken before energizing of the CP system and in the exact same locations, if these data are available. For comparison of "instant off" to native readings, the same number of measurements in corresponding locations must be taken. If the "instant off" reading is compared to the corresponding native reading in the same location, it must be a minimum of 100 mV more negative with respect to the copper/copper-sulfate reference cell than the native reading.

(10) The Corrosion Expert must ensure that a complete set of native readings are available and can be obtained (using the same locations as the "on" and "instant off" measurements required in this SOW) before using this method. This is a mandatory requirement to use this specific measurement procedure.

d. Locations of Measurements on Miter Gates. The reference cell must be located in the water, 0.5 to 3 in. from the gate structures wherever possible. Where this distance cannot be achieved, locate the reference cell as near as possible to the structure (typically locations within 3 ft of the structure or closer can be achieved even on compartmentalized sides of gate structures). The reference cell connected to a conductor on a reel must be lowered to depths in the water as indicated below.

(1) The reference cell conductor must be connected to the "probe" terminal of the government-furnished data logging equipment (or positive terminal of the digital voltmeter) or connected as required to other government-approved equipment. A second conductor must be connected from the rectifier negative terminal to the "structure" terminal of the government-furnished data logging equipment (or from the gate structure to the voltmeter negative terminal) or connected as required to other government-approved equipment.

(2) The voltage must be measured with both rectifiers "on" (i.e., two rectifiers are located at each set of miter gates and both must be "on"). A second potential measurement must be made at this location with the rectifiers turned "off." (Note that each miter gate consists of two gate leafs and a rectifier is provided for gate leaf. Both rectifiers must be "off.") This is the "instant off" potential and must be measured instantly when the rectifier currents are interrupted.

(3) The digital logging equipment (or voltmeter) will search when the rectifiers are instantaneously interrupted. For this reason, if the voltmeter is used, the second instantaneous reading is usually a more accurate "off" potential reading and must be the recorded measurement. If the data logging equipment is used, then the "instant off" reading will be automatically recorded and all data can be downloaded to a computer after completion of the testing. This procedure must be repeated for each measurement location.

(4) With the lock chamber filled to normal upper pool elevations, measurements must be made every 3 ft vertically (minimum) from normal pool elevation to the bottom of the gate. These same measurements must be made at a minimum of 5 ft horizontal intervals across the width of each gate and for both the upstream and downstream face of each gate leaf.

(5) Alternatively, on the upstream side of each gate leaf, the horizontal measurement sets may be taken at each expected minimum and each expected maximum potential location (i.e., a set at the quoin, a set at each anode column location, a set at each horizontal midpoint between each anode column, and a set at the miter). One measurement must be made at each quoin end and one at the miter end on each side of each set of gates.

(6) A sketch of each gate leaf, or an 8 ½ X 11-in. reduced construction drawing, indicating the locations of the test data correlated with the data sheets, must also be provided with the submitted data to the CPC Coordinator. Where and if "native" readings are required by this SOW, the locations of these readings must be the same as those specified for the "on" and "instant off" readings in this paragraph.

e. Inspection and Evaluation.

(1) A visual inspection must be made with the lock chamber either filled or at the lower pool elevation, as necessary, to achieve the described task. The following must be checked:

(a) Loose connections inside the terminal cabinets.

(b) Structure deterioration (chamber at lower pool elevation).

(c) Broken or disconnected conductors.

(d) Physical condition of anodes (i.e., anodes visible above lower pool elevation). Inspect anode strings accessible above lower pool elevation.

(e) Check for signs of paint blistering around anodes (above lower pool elevation).

(f) Check anode leads (inside terminal box) for proper identification.

(g) Check to see if system is properly grounded.

(h) Check connections to rectifier to ensure proper positive and negative connections.

(2) Check continuity from anode to rectifier. Confirm that low resistance electrical connections exist from the rectifier terminals to terminal cabinet terminals (including connections in the DC wall receptacle and DC cable plug). Confirm low resistance electrical connections for each terminal in the terminal cabinets and across each shunt and its connections.

(3) With the lock chamber filled to the normal upper pool elevation, perform reference cell potential measurements (performance testing) on each gate leaf, upstream and downstream sides. Adjust rectifiers as necessary to obtain optimal potentials.

(4) As a minimum, with the lock chamber filled to the upper pool elevation, at terminal cabinets where current shunts have been installed, measure and record the current of each string anode and each button anode. In addition, measure and record all buss voltages at each anode terminal cabinet for these same locations.

(5) Present these data in a tabular format within the report or in the submitted field information if a report is not required. These data must also be provided as an electronic file in an Excel spreadsheet table regardless of whether a report or just field notes are being submitted.

(6) Take a minimum of 25 photographs illustrating the condition of the miter gates and associated CP system. Photographs must also be taken with the lock chamber at the lower pool elevation. This number of photographs must be required as a minimum at each lock facility inspected. At least five of these photographs must be included in the submitted report. All photographs taken must also be submitted to the Government, regardless of whether they are included in the report, in an electronic format.

f. Evaluation Report. The report of testing and visual inspection must be submitted to the Government (CPC Coordinator). At some locations specified below, the Government may retain the responsibility of report preparation. However, for these locations, the A/E must submit all field gathered data and information necessary, in both printed and electronic formats, and as described herein, to enable the Government to create the completed report. For each gate leaf CP system and each DC circuit, the following information must be included in the report: all test measurements taken at the described locations, initial and final rectifier coarse and fine tap settings, rectifier ammeter reading, and rectifier voltmeter reading.

(1) The report must also include all photographs (as defined above) and state all findings and recommendations for repair and improvement of the systems. Data sheets must be made and the results tabulated with vertical depths noted on the left margin of the table and horizontal measurements on the top margin of the table.

(2) In addition to the required tabulated data, which includes all data at each specified measuring location, potential measurements must also be displayed in a graphical format using an Excel spreadsheet to better illustrate the results within the report. The submitted data sheets must show all data locations. The data sheets must include “on” measurements and “instant off” measurements for each required measurement location. If specified elsewhere in this SOW, “native” readings must also be included at specified location.

(3) Where taken, all individual anode currents and terminal cabinet buss voltages must be submitted in a tabular format in the report and also in electronic format (i.e., Excel spreadsheet). The data sheets must also identify the project name, test date, gate leaf tested (also identifying whether upstream side or downstream side), and rectifier number.

(4) A sketch of each gate leaf, or an 8 ½ X 11-in. reduced construction drawing, indicating the locations of the test data correlated with the data sheets must also be provided in the report or separately

if a complete report is not required from the A/E. These data sheets describe the CP system performance. The circuit “instant off” test results should vary between minus 850 mV and minus 1100 mV for optimum conditions of corrosion control.

L.4 Project Specific Requirements.

a. Specific Work to be Performed. The A/E must use the Testing and Inspection Procedures above (i.e., either in Paragraph 3.a. or 3.b., as specified for each project) for conductance of testing and inspection of cathodic protection systems listed in this section.

(1) The projects below are generally listed in their order of priority. Consequently, the listing order can be used as a general scheduling guide. However, the A/E must coordinate trips with the CPC Coordinator in advance of the Corrosion Expert’s trip. Some projects, as indicated below, are only open for operation (i.e., government staff on duty) from Friday through Monday during the contract execution period.

(2) At least one project has no government staff on duty meaning that the Government will have to be contacted ahead of the inspection trip so that an operator can be sent to the site for the duration of the CP testing and inspection activities. Two projects will be dewatered this summer and the CP inspections are required to be conducted after the locks are watered up again (i.e., after the lock closures). Because of these various operating schedules, it is critical that the A/E’s Corrosion Expert coordinate with the CPC Coordinator to ensure that the inspection is scheduled for a time that will not conflict with lock operating schedules and ongoing maintenance activities.

(3) In addition, for the reasons cited above, the A/E must coordinate all site visits, via the CPC Coordinator, with the appropriate project point of contact at least 1 week before site visit. (Points of contact at each project site will be provided by the CPC Coordinator.) However, if the CPC Coordinator also plans to attend the site visit, then he will contact the appropriate USACE personnel to notify them of the scheduled site visit.

(4) The CPC Coordinator may be present during any, or all, inspecting and testing. To reduce contractor travel expenses to the various project sites for CP inspections, the A/E’s Corrosion Expert must schedule and accomplish, to the maximum extent possible, at least two separate CP inspections at two different project sites during the same week.

(5) Experience has indicated that two Mobile District lock project sites (e.g., Demopolis and Selden, Holt and Bankhead, Claiborne and Millers Ferry) can easily be visited and CP testing with inspections done back-to-back within 4 or 5 days (8-hr days) by using the government-furnished test equipment and proper coordination with weather forecasts.

(6) For example, if Holt and Bankhead CP testing and inspecting are done during the same week, then one trip can be made to Tuscaloosa, AL and local trips from there to each project site can be made during that same week, resulting in a significant reduction in overall travel costs as compared to two

separate trips from Mobile, AL, to each of these project sites. Similarly, Holt and Oliver or Selden and Demopolis could be scheduled and done in the same week.

(7) Also, subsequent to the inspections, both draft (for review by the CPC Coordinator) and final Evaluation Reports (for projects specified) must be prepared and submitted as presented in the guidance above. For projects indicating that the Government will accomplish the report, the A/E must submit all field data and all other field gathered information as presented in the guidance above to enable report preparation by the Government.

(8) Unless otherwise noted, each project is identified for adherence to either Paragraph 3.a.or 3.b above, but not both. That is to say, each project where testing is to be done will require either a complete CP survey and report (i.e., Paragraph 3.a.) or a limited CP survey and report (i.e., Paragraph 3.b.).

b. Specific Scopes of Work.

(1) Millers Ferry Lock:

(a) Perform all testing, inspection, and evaluation services, as described in this SOW, on all lock miter gate CPS as described above.

(b) A minimum of one site visit must be conducted. All site work by A/E must be completed at this facility within 120 days from date of the notice to proceed of this contract. The completed report (draft version for CPC Coordinator review), containing all gathered data, photographs, as required by this SOW, must be submitted to the CPC Coordinator within 45 days from completion date of the site visit.

(c) Prepare and submit an evaluation report as described in this SOW. The report must include findings and recommendations on all miter gates at this location. The report must make specific recommendations on the necessary repair work that should be performed on the lock CPS during the next lock dewatering. If necessary, the Contractor must obtain CPS prints from the CPC Coordinator and use them in the field to make notes and mark required corrective actions.

(d) Identify the type, if any, of CP system used on the spillway gates. Describe the system and its general condition in the submitted report.

(2) Claiborne Lock:

(a) Perform all testing, inspection, and evaluation services, as described in this SOW, on all lock miter gate CPS as described above. The lock operators are on duty from 6 a.m.–4 p.m., Friday through Monday, until the end of September.

(b) A minimum of one site visit must be conducted. All site work by A/E must be completed at this facility within 120 days from date of the notice to proceed of this contract. The completed report (draft version for CPC Coordinator review), containing all gathered data, photographs, as required by this SOW, must be submitted to the CPC Coordinator within 45 days from completion date of the site visit.

(c) Prepare and submit an evaluation report as described in this SOW. The report must include findings and recommendations on all miter gates at this location. The report must make specific recommendations on the necessary repair work that should be performed on the lock CPS during the next lock dewatering. If necessary, the Contractor must obtain CPS prints from the CPC Coordinator and use them in the field to make notes and mark required corrective actions.

(d) Identify the type, if any, of CP system used on the spillway gates. Describe the system and its general condition in the submitted report.

(3) Robert F. Henry Lock:

(a) Perform all testing, inspection, and evaluation services, as described in this SOW, on all lock miter gate CPS as described above. Consequently, the CP inspection will need to be scheduled for accomplishment during these days and hours and arrangements will need to be made for a Millers Ferry operator to be on site during the CP survey activities.

(b) A minimum of one site visit must be conducted. All site work by A/E must be completed at this facility within 120 days from date of the notice to proceed of this contract. The completed report (draft version for CPC Coordinator review), containing all gathered data, photographs, as required by this SOW, must be submitted to the CPC Coordinator within 45 days from completion date of the site visit.

(c) Prepare and submit an evaluation report as described in this SOW. The report must include findings and recommendations on all miter gates at this location. The report must make specific recommendations on the necessary repair work that should be performed on the lock CPS during the next lock dewatering. If necessary, the Contractor must obtain CPS prints from the CPC Coordinator and use them in the field to make notes and mark required corrective actions.

(d) Identify the type, if any, of CP system used on the spillway gates. Describe the system and its general condition in the submitted report.

(4) Selden Lock:

(a) Perform all testing, inspection, and evaluation services, as described in this SOW, on the upper lock miter gates' CPS (i.e., only the upper gates). Current plans are to replace the lower miter gates with new miter gates by the end of next year. New impressed current CPS will be installed at that time. The existing impressed current systems for the lower miter gates are inoperable and have been mostly, if not completely removed. Consequently, this CP inspection will be limited to the upper lock miter gates. In addition, the upper miter gates were completely recoated during the 2009 dewatering and new impressed current CPS were installed on the gates (existing rectifiers were retained).

(b) A minimum of one site visit must be conducted. All site work by A/E must be completed at this facility within 120 days from date of the notice to proceed of this contract. The completed report (draft version for CPC Coordinator review), containing all gathered data, photographs, as required by this SOW, must be submitted to the CPC Coordinator within 45 days from completion date of the site visit.

(c) Prepare and submit an evaluation report as described in this SOW. The report must include findings and recommendations on the upper miter gates at this location. The report must make specific recommendations on the necessary repair work that should be performed on the upper gates' CPS during the next lock dewatering. If necessary, the Contractor must obtain CPS prints from the CPC Coordinator and use them in the field to make notes and mark required corrective actions.

(d) Identify the type of CP system used on the spillway gates. Describe the system and its general condition in the submitted report.

(5) Demopolis Lock:[3]

(a) Perform all testing, inspection, and evaluation services, as described in this SOW, on all lock miter gate CPS. Since there may be some recoating and also possibly some repairs to the existing CPS, the CP testing and inspection cannot be done until after this closure and the lock is completely watered back up. This will allow rectifier adjustments to be made after CP system repairs have been done.

(b) A minimum of one site visit must be conducted. All site work by A/E must be completed at this facility within 120 days from date of the notice to proceed of this contract. The completed report (draft version for CPC Coordinator review), containing all gathered data, photographs, as required by this SOW, must be submitted to the CPC Coordinator within 45 days from completion date of the site visit.

(c) Prepare and submit an evaluation report as described in this SOW. The report must include findings and recommendations on all miter gates at this location. The report must make specific recommendations on any necessary repair work that should be performed on the lock CPS during the next lock dewatering or before that time, if possible. If necessary, the Contractor must obtain CPS prints from the CPC Coordinator and use them in the field to make notes and mark required corrective actions.

L.5 Submittal Requirements. The evaluation report with associated data, findings, and recommendations must be submitted by the date indicated. The reports must include information as defined above for the specific structure tested. One additional copy of the evaluation report with data, findings, and recommendations must also be submitted.

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[3]An example Cathodic Protection Survey Report pertaining to Demopolis Lock is included under Appendix J of this manual. The example report provided under Appendix J was prepared by a Cathodic Protection Specialist tasked to perform work on a SOW very similar to this example SOW.

a. For the sites not requiring a complete report, if any and as specified above, all field notes and annotations, associated data, findings, and recommendations must be submitted. The field gathered data and notes must include information as defined above for the specific structure tested. In addition to printed sheets, electronic files of all field data must be provided. All potential data and anode current data must be provided in Excel spreadsheets.

b. Presentation of Data. All CP evaluation reports must be presented on 8 ½ X 11-in. sheets and must be neatly bound. The report narrative must be typed in Microsoft Word format. Data must be typewritten in tabular format as described above and it must be on 8 ½ X 11-in. sheets. Data must also be presented in an Excel spreadsheet format.

c. Sketches or drawings indicating test locations must be on (or reduced to) 8 ½ X 11-in. sheets. All photographs must be provided in a digital format in addition to the printed photos included in the report. All data and information provided in the printed and bound reports must also be provided in electronic files on CDs or DVDs.

d. Document Review and Coordination. Documents must be reviewed and coordinated with the CPC Coordinator. All review comments are to be annotated and when required, incorporated into the report.

e. Site Visits. The A/E will conduct a minimum of one trip to each identified project site for the obtaining of the necessary test data and information. To the maximum extent possible, two project sites must be visited in the same week to reduce overall contractor travel expenses and to reduce contract costs. All resulting data and information must be included in the evaluation report and/or submitted to the Government as specified herein.

f. Evaluation Reports. The contractor must prepare and submit Evaluation Reports as described above by the date specified. For locations not requiring reports by the A/E, if any and as specified above, all field gathered notes and annotations, data, photographs, must be submitted. All field gathered notes and annotations, data, and photographs not included in the report must also be submitted to the Government on CDs or DVDs.

L.6 Antiterrorism/Operations Security Requirements.

a. The contractor is required to comply with latest USACE security requirements provided as attachments. These requirements were checked on the Antiterrorism/Operations Security Review Cover Sheet, which accompanies and forms a part of these contract documents. The numbers used below are the same as on the referenced cover sheet and the contract clauses are as worded on the on the antiterrorism/operations security checklist.

b. Access and General Protection/Security Policy and Procedures. All contractor and all associated sub-contractor employees must comply with applicable installation, facility, and area commander installation/facility access and local security policies and procedures (provided by government representative). The contractor must also provide all information required for background checks to meet installation access requirements of the installation Provost Marshal Office, Director of Emergency Services or Security Office. The contractor workforce must comply with all personal identity verification requirements as directed by DoD, Headquarters Department of the Army, and/or local policy.

Appendix M
Lessons Learned

M.1 Introduction. This appendix contains some CPS lessons learned over many years of USACE experience with their design, installation, operation, and maintenance.

M.2 Impressed Current CPSs.

a. Do not use steel mounting bolts, washers, and nuts for mounting HSCBCI anodes, but, instead, use FRP bots and nuts. In the early days of the installation of impressed current CPS on HSS, button anodes were mounted with steel mounting hardware that had to be carefully isolated from the anode.

b. This mounting technique was complex and resulted, many times, in the anodes electrically shorting, or partially shoring, to the HSS. The FRP mounting components eliminate this problem and have been successfully used for many years. However, do not use neoprene mounting bolts. These were tried, but were not mechanically strong enough.

c. In the early years of impressed current CPS on HSS, 8-in. diameter neoprene anode shields were used to electrically isolate silicon iron button anodes from the HSS surface. A better choice and one that has been used successfully for many years is a 12-in. diameter FRP shield. The 12-in. FRP shields are more durable and enable better current distribution from the CPS. Also, the risk of blistering the coating in the vicinity of the button anode caused from excessive protective currents is significantly reduced.

d. For impressed current lead cables used in fresh water applications, use only HMWPE insulation on the conductors. For salt or brackish water applications, use a dual insulation/jacket on the anode lead conductors, such as a combination consisting of PVDF and HMWPE.

e. Do not use header cables for connection/termination of anode lead cables. More specifically, do not splice anode lead cables to a header cable, which then extends to a junction box or directly to the rectifier. When header cables are used, if one anode shorts to the structure, an easy method to disconnect the shorted anode is not available leaving the entire circuit unable to deliver protective current to the structure.

f. Each separate anode or anode assembly (e.g., string anodes) must extend, un-spliced, from the anode to a terminal cabinet where it is terminated. Best practices is to use lead cables looped through each anode assembly such that two cable ends from each anode assembly are terminated in the terminal cabinet at one terminal for each anode string or assembly.

g. Provide one (or one per separate gate area) anode terminal cabinet for each separate HSS gate, sector, or other component (e.g., each miter gate leaf, each sector of a sector gate). Each terminal cabinet is to consist of a separate bus for each separate area of the gate, and/or for each separate anode bed configuration, and/or for each different anode type and/or configuration.

h. For example, button anodes would terminate on one bus, each separate area of string or rod anodes would terminate on its own bus. Adjustable resistors are to be installed between the busses, as necessary, to enable the proper adjustment of the CPS. Each anode string, anode assembly, or separate anode (e.g., button or disk anode) is to have its own individual 0.1 ohm shunt installed at its respective anode terminal cabinet point of termination.

i. Each separate HSS miter gate, sector gate, or other HSS, is to have its own rectifier with each having at least a dual DC output. Cables are to extend from each DC output directly to its associated terminal cabinet, which is to be mounted on the structure to be cathodic protected. The rectifiers are to be constant voltage type rectifiers.

j. Automatically controlled rectifiers, such as constant current or auto-potential rectifiers are not to be used with USACE CW' HSS. It has been documented in at least one case that both constant current and auto-potential CPS have failed prematurely and within a short period of time. These type systems are not the best technical choice for HSS because of the harsh environment and operating conditions in which the CPS will be required to perform.

k. If mixed metal oxide anodes are desired for a salt water application, ensure that the correct oxide layer is used. Some of the original mixed metal oxide technologies have been known to fail prematurely in HSS salt water applications, under certain conditions. However, newer mixed metal oxide technologies are much more robust and have been used without issues. The anode supplier can assist with the correct selection of mixed metal oxide anodes for specific applications.

l. For brackish and salt water applications, if oyster or other marine growth accumulation on the structure is a known or potential issue, ensure that the CPS is energized as soon as practical after the anodes are submerged. Oyster accumulation on the anode surfaces before energizing the system may compromise the system.

m. Although it is not known if specific research on the topic of how oyster accumulation may affect the performance of a CPS, as long as the anodes remain energized, some experience seems to indicate that oysters do not appear to attach themselves to the energized anode surfaces. However, oyster and other marine growth accumulation should be considered during the design and installation of anode debris protection devices.

n. Debris protection devices should be designed and installed in such a manner as to reduce the risk of possible disruption of the protective current distribution from the anodes (e.g., anodes remain as "open" as possible, but yet protected from debris).

M.3 Galvanic (Sacrificial) Anode CPS.

a. Sacrificial anodes have been known to have very short lives on HSS operating in brackish or salt water immersion service. One known USACE CW HSS has both zinc anodes and magnesium anodes installed on the structure in such operating conditions. It is known that this project replaces the magnesium anodes every year and the zinc anodes every 2 years.

b. A contractor of another USACE district installed magnesium anodes on a HSS after the magnesium anode CPS design calculations had indicated that the CPS would provide a life of over 20 years. These anodes were consumed in less than a year. These short lives are unacceptable and do not meet the life parameter requirement of 20 years or more.

c. It is difficult to mount enough sacrificial anode weight on a HSS operating in a brackish or salt water environment to enable a distributed sacrificial anode CPS to be practical. Consequently, sacrificial anode CPS are not to be installed in these applications unless they can be shown to meet the criterion of protection, the life requirements, and the other design parameter and selection criteria defined and described in this manual.

d. In high resistivity fresh water applications, experience has shown that, at times, an excessive and unreasonable number of sacrificial anodes were installed on HSS to avoid the design and installation of an impressed current CPS, which would have been the better choice and the one, in those cases, required by this manual. If the guidance and requirements of this manual are followed correctly, then this type of installation can be avoided in future applications.

e. Do not install sacrificial anodes within new or existing impress current CPS of HSS. Impressed current CPS are to have potential testing done once per year using current interruption of the rectifiers. If sacrificial anodes are present, they could interfere with the “instant off” potential measurements of the impressed current CPS.

f. In addition, experience has shown that, if an impressed current CPS is required on an HSS to meet the criterion of protection as defined in this manual, then the project site conditions are most likely such that the sacrificial anodes may not be providing sufficient current to be of any benefit. Test data have indicated that sacrificial anodes, where included as part of the impressed current CPS, appear to indicate very little, if any, additional protective current to the structure.

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Glossary

Term	Definition
A/E	Architect/Engineer
AC	Alternating Current
ACOE	Army Corps of Engineers
AMS	Ambient Monitoring Station
AWS	American Welding Society
BS	Bachelor of Science
CCCP TCX	Cathodic Protection Systems Technical Center of Expertise
CECW	Directorate of Civil Works, U.S. Army Corps of Engineers
COE	Corps of Engineers
CP	Cathodic Protection
CPS	Cathodic Protection Systems
CPC	Corrosion Prevention and Control
DoD	U.S. Department of Defense
DS	Downstream
EM	Engineer Manual
ER	Engineer Regulation
ERDC-CERL	Engineer Research and Development Center, Construction Engineering Research Laboratory
FRP	Fiberglass Reinforced Plastic
FY	Fiscal Year
GIWW	Gulf Intracoastal Waterway
HDC	(USACE) Hydroelectric Design Center
HMWPE	High Molecular Weight Polyethylene

Term	Definition
HQUSACE	Headquarters, U.S. Army Corps of Engineers
HSCBCI	High Silicon Chromium Bearing Cast Iron
HSCI	High Silicon Cast Iron
HSS	Hydraulic Steel Structures
INDC	Inland Navigation Design Center
LCRA	Lower Colorado River Authority
MCX	(USACE) Mandatory Center of Expertise
NACE	National Association of Corrosion Engineers
NEC	National Electric Code
NEMA	National Electrical Manufacturers Association
NFPA	National Fire Protection Association
NISPOM	National Industrial Security Program Operating Manual
O&M	Operations and Maintenance
P.E.	Professional Engineer
PICES	Periodic Inspection and Continuing Evaluation of Completed Civil Works Structures
PROSPECT	Proponent Sponsored Engineer Corps Training
PVDF	Polyvinylidene Difluoride
RFP	Request for Proposal
SES	Senior Executive Service
SOW	Statement of Work
SS	Stainless Steel
TW	Thermoplastic Insulation
UFC	Unified Facilities Criteria
UFGS	Unified Facilities Guide Specification

Term	Definition
URL	Universal Resource Locator
US	Upstream Side
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
ZMR	Zebra Mussel Research