APPENDIX E

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

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

While the slab and disk galvanic anodes previously described in this manual are generally preferred for civil works structures due to their inherent ruggedness and ease of installation, occasionally the elongated shape of the anodes described in this section may provide design solutions for some structures in higher resistivity environments. Their elongated shape may provide better current distribution in some structure configurations and will usually deliver higher current output for the same weight of material. On the other hand, for magnesium anodes, this higher current output will result in reduced anode life. For example, a 2 in. diameter magnesium rod anode 10 ft long installed in 1000 ohm-cm water will generate 334 milliamperes DC current output but the life of the anode will only be 3.69 years. Thus, magnesium rod anodes are normally only used in waters with resistivities in excess of 2000 ohm-cm (see Table C-3 in Appendix C).

a. Extruded Magnesium Rod Anodes

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

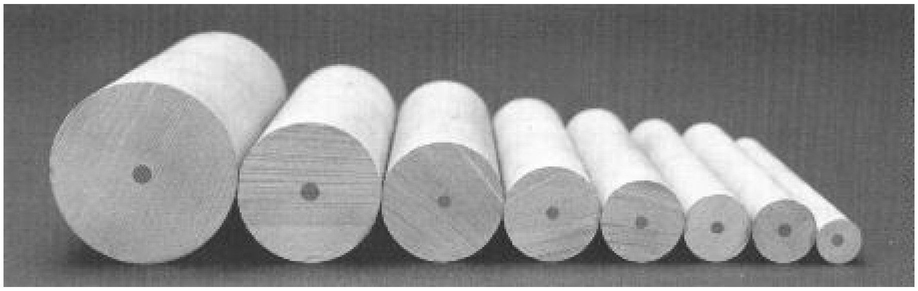

FIGURE E-1. DC-6722, DC-2375 (LEFT) AND OTHER EXTRUDED MAGNESIUM ANODE CROSS SECTIONS SHOWING GALVANIZED STEEL CORE WIRE AT CENTER

TABLE E-1. EXTRUDED MAGNESIUM ROD ANODES
SUITABLE FOR CIVIL WORKS STRUCTURES

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

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

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

TABLE E-2. MAGNESIUM ANODE RESISTANCE – CURRENT OUTPUT AND LIFE CALCULATIONS FOR 2 IN. DIAMETER BARE ROD

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

TABLE E-3. MAGNESIUM ANODE RESISTANCE – CURRENT OUTPUT AND LIFE CALCULATIONS FOR 2.5 IN. DIAMETER BARE ROD

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

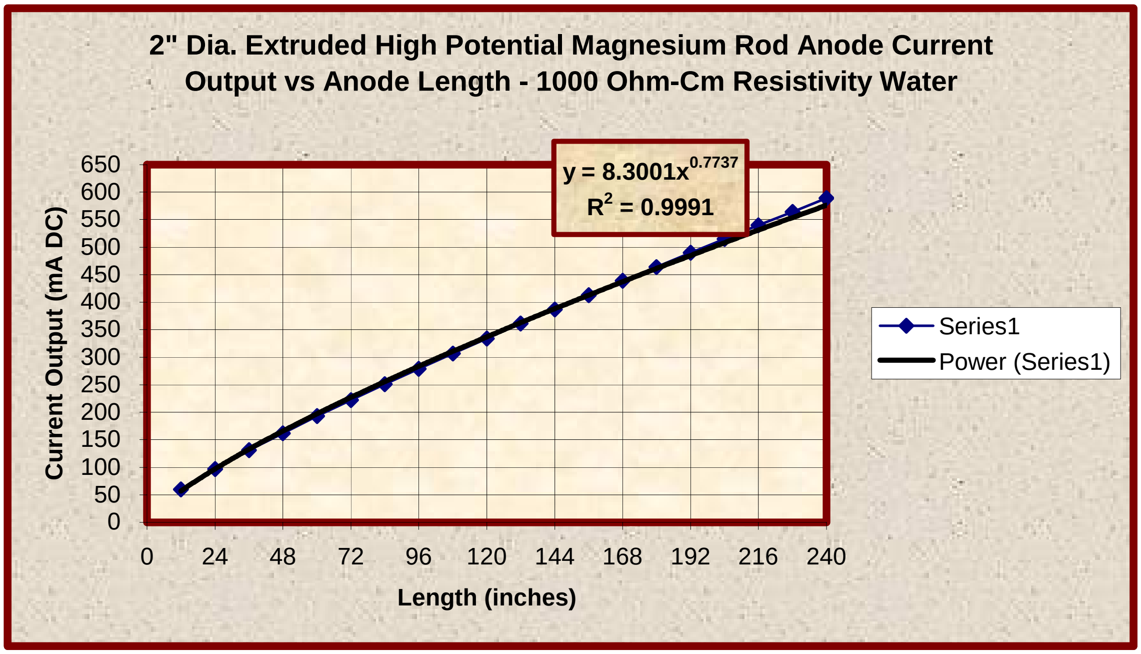

FIGURE E-2. CURRENT OUTPUT VERSUS ANODE LENGTH FOR 2 IN. DIAMETER HIGH-POTENTIAL MAGNESIUM ROD ANODES.

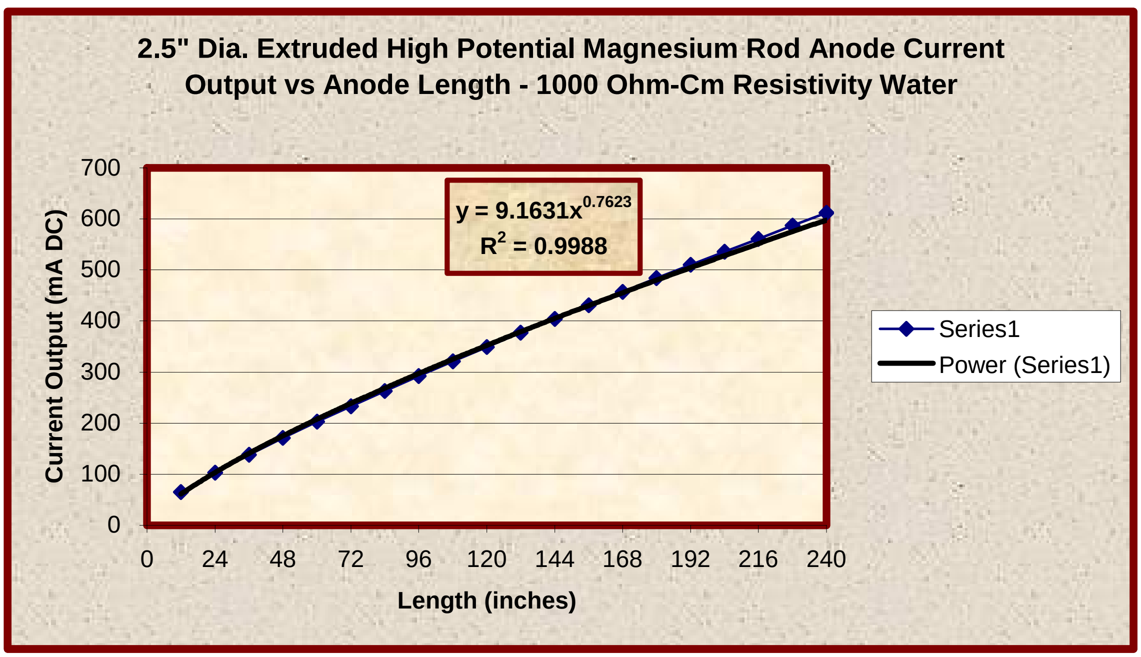

FIGURE E-3. CURRENT OUTPUT VERSUS ANODE LENGTH FOR 2.5 IN. DIAMETER HIGH-POTENTIAL MAGNESIUM ROD ANODES.

For any magnesium anode to provide protection, a positive electrical connection must be established and maintained between the anode and the structure being protected. The standard end configurations used on civil works structures are 3 – 6 in. x 1/8 in. threaded core extended one end only. This threaded rod can then be used to suspend the rod vertically from a suitable support bracket. Generally, this connection is made by threading a standard galvanized steel nut and washer on the rod (Figure E-4) and then inserting the rod up through a support bracket (minimum 1/4 in. thick) or suitable plate on the structure. The wire core should be extended at least 6 in. so the anode material is at least 5 in. from the metal mounting bracket or structure surface to assure good anode current distribution. A galvanized steel star washer followed by a standard washer and nylon insert lock nut are then used to fasten the rod in position. The star washer improves the electrical contact to the structure. The entire connection must be properly coated to prevent corrosion of the connection.

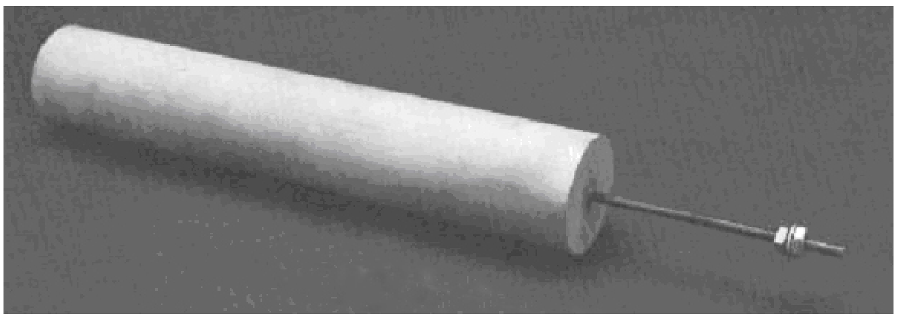

FIGURE E-4. MAGNESIUM ROD ANODE SHOWING THREADED CORE WIRE, DOUBLE NUTS, AND WASHERS

b. High-Purity Cast Zinc Rods

Zinc rod anodes suitable for use on civil works structures are cast in molds around their core rod. They are usually only practical for use in waters with resistivities from 100 to 2000 ohm-cm. Waters with higher resistivities will provide relatively low current to the protected structure although providing a theoretical service life well in excess of 100 years. In waters below 100 ohm-cm these anodes will have a service life of less than 10 years. In terms of material properties, this anode is inherently more rugged and impact-resistant than the extruded magnesium rod anode. The most commonly used shape has either a 2 in. or 2.5 in. square cross section with a standard length of either 5 ft or 6 ft.

These anodes are cast with a 1/2 in. diameter straight electro-galvanized steel core rod for direct welding or assembly to two flat attachment bars with U bolts to facilitate routine replacement, as shown in Figure E-5. The U bolts clamp the anode core in place and provide electrical continuity to the support bar and structure. These U bolts are held in place with nylon insert galvanized steel lock nuts and washers on the back side of the plate. Either connection should be thoroughly coated to prevent corrosion attack in any crevices created by the connection. The steel support plate must be welded to the structure and is typically ¼ in. thick x 2 in. wide x 8 in. long. The core is usually extended 6 in. on both ends and is fastened to the plate so that end of the anode material is at least 5 – 6 in. from the mounting plate and also 4 in. away from the structure to provide good current distribution to the structure being protected.

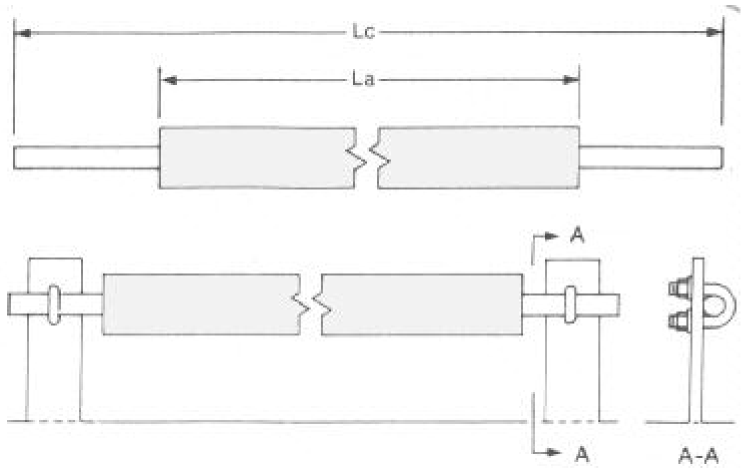

FIGURE E-5. CONNECTION SCHEMATIC FOR HIGH-PURITY CAST ZINC BAR ANODES.

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

TABLE E-4. HIGH-PURITY ZINC ANODE RESISTANCE – CURRENT OUTPUT AND LIFE CALCULATIONS FOR 1.4 IN. CROSS-SECTION BARE BAR

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

TABLE E-5. HIGH-PURITY ZINC ANODE RESISTANCE – CURRENT OUTPUT AND LIFE CALCULATIONS FOR 2 IN. CROSS-SECTION BARE BAR

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

TABLE E-6. HIGH-PURITY ZINC ANODE RESISTANCE – CURRENT OUTPUT AND LIFE CALCULATIONS FOR 2.5 IN. CROSS-SECTION BARE BAR

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

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

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

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

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

E-3. <u>Computations and Current Requirements for Each Structure Component</u>

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

TABLE E-8. CURRENT REQUIREMENTS FOR
EACH DOWNSTREAM STRUCTURE COMPONENT

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

E-4. Anode Design Based on Using Magnesium Rod Anodes

a. Select Anode Alloy

The only available option is high-potential magnesium alloy.

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

(1) Chambers A and H

i. Current Required = 31.4 mA

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

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

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

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

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

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

(2) Chambers B and G

i. Current Required = 49.1 mA

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

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

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

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

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

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

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

i. Current Required = 213.6 mA

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

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

The rod anodes are designed for vertical suspension. The overall gate height is 18.85 m (35 ft) divided into 6 uniform height chambers with an internal height of approximately 1.8 m (5.83 ft). Thus, the maximum anode length in each chamber will be approximately 150cm (5ft). A quick check of Tables E-2 and E-3 reveals that a single anode of either diameter will not put out sufficient current. We calculate that a 150 cm (60 in.) anode 5 cm (2 in.) in diameter will put out 101 milliamperes DC (193x1000/1900 = 101) while the same length anode 6.4 cm (2.5 in.) in diameter will put out 107 ma (203x1000/1900 = 107). Based on the current requirement of 213.6 ma, we would need either three of the 5 cm diameter anodes per large chamber or two of the 6.4 cm diameter rods.

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

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

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

c. Develop Anode Locations for Each Structure Element

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

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

Chambers C, D, E, and F: Where more than one anode is required in each chamber, the anodes again will again all be placed at a distance 1/3 of the chamber depth from the back surface of the each chamber. In addition, the top of the anode threaded rod will be fastened so that the anode magnesium body will be approximately 10 cm (4 in.) down from the chamber top plate and at least 10 cm (4 in.) up from the chamber bottom plate (this latter distance will be a function of the anode body length but should be no less than 10 cm) to enhance current distribution. The locations for the anodes in the large chambers is shown in Figure E-6.

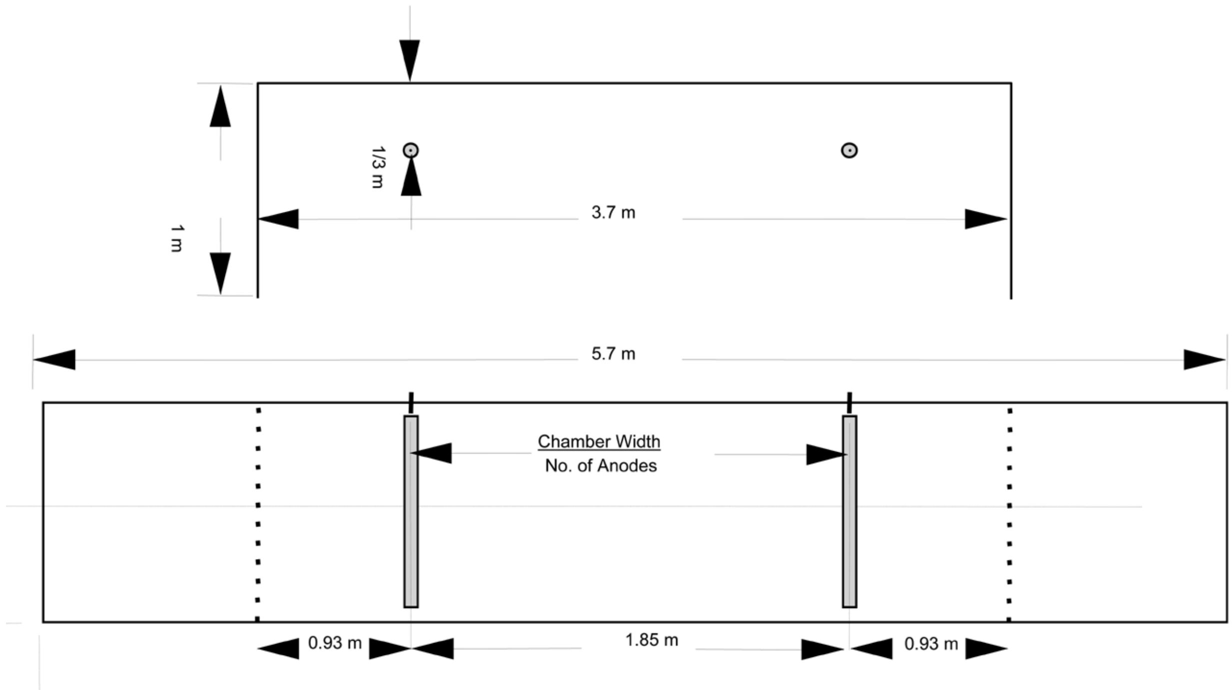

FIGURE E-6. ROD GALVANIC ANODE LOCATIONS
IN LARGEST DOWNSTREAM CHAMBERS

Multiple anodes must be evenly distributed from the side panels of the chamber to achieve more uniform current distribution. In order to assure good current flow also to the chamber end plates, the anode spacing is modified so that the center-to-center spacing between the anodes is equal to the chamber width divided by the number of anodes per chamber. In this design example, with two anodes per large chamber, the chamber width of 3.7 m is divided by 2 so that the center-to-center spacing between the two anodes would be 1.85 m and the distance between the anodes and their adjacent chamber walls is half this distance or 0.93 m.

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

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

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

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

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

a. Select Anode Alloy

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

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

(1) Chambers A and H

i. Current Required = 31.4 mA

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

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

The zinc bar anodes are designed for either vertical or horizontal suspension. Since these small chambers are less than 1 meter in width, the anodes will have to be installed vertically. The overall gate height is 18.85 m (35 ft) divided into six uniform-height chambers with an internal height of approximately 1.8 m (5.83 ft). Thus, the maximum anode length in each chamber is approximately 1.5 m (5 ft). We calculate that even the highest-output anode with zinc bar dimensions of 6.4 cm (2.5 in) square by 152 cm (60 in.) long will only put out about 30.5 milliamperes DC (58x1000/1900 = 30.5). Since this does not quite meet our minimum current requirement, we will need to use to smaller anodes. We then calculate that the smallest available zinc bar anode with zinc bar dimensions of 3.6 cm (1.4 in.) square by 91 cm (36 in.) long will put out about 17.9 milliamperes DC (34x1000/1900 = 17.9). Thus two mounted vertically and spaced laterally as far apart as possible will generate the desired current.

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

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

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

(2) <u>Chambers B and G</u>

i. Current Required = 49.1 mA

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

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

The zinc bar anodes are designed for either vertical or horizontal suspension. Again, since these relatively small chambers are less than 1.2 meter in width, the anodes, the shortest of which is slightly more than 1.2 meters, will have to be installed vertically. The overall gate height is 18.85m (35 ft) divided into six uniform height chambers with an internal height of approximately 1.8 m (5.83 ft). Thus, the maximum anode length in each chamber is approximately 1.5 m (5 ft). We calculate that even the highest-output anode with zinc bar dimensions of 6.4 cm (2.5 in.) square by 152 cm (60 in.) long will only put out about 30.5 milliamperes DC (58x1000/1900 = 30.5). Since this does not nearly meet our minimum current requirement for chambers B and G, we will need to use two anodes. We then calculate that the smallest available zinc bar anode with zinc bar dimensions of 3.6 cm (1.4 in.) square by 91 cm (36 in.) long will put out about 17.9 milliamperes DC (34x1000/1900 = 17.9). Thus, even two mounted vertically and spaced laterally as far apart as possible will not generate the desired current. We then re-calculate based on the next largest available zinc bar anode with zinc bar dimensions of 5.0 cm (2 in.) square by 122 cm (48 in.) long will put out about 24.2 milliamperes DC (46x1000/1900 = 24.2). Thus, even two of these next size anodes will not generate the desired current (48.4 ma versus a minimum requirement of 49.1 ma). By selecting the next size up zinc bar anode with dimensions of 5.0 cm (2 in.) square by 152 cm (60 in.) long will put out about 28.2 milliamperes DC

(46x1000/1900 = 28.9). Thus, two 5.0 cm (2 in.) square by 152 cm (60 in.) long zinc bar anodes mounted vertically and spaced laterally as far apart as possible will generate the desired current.

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

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

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

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

i. Current Required = 213.6 mA

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

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

The zinc bar anodes are designed for either vertical or horizontal suspension. Since these are much larger chambers with a width of 3.7 meters (12.1 ft) and a height of 1.8 meters (5.83 ft), the anodes could either be installed horizontally or vertically. The overall gate height is 18.85m (35 ft) divided into six uniform-height chambers with an internal height of approximately 1.8 m (5.83 ft). For vertical placement, the maximum anode length in each chamber is approximately 1.5 m (5 ft). For horizontal placement, not only is there no limit in anode length based on those commercially available, but up to three of the 91 cm (36 in.) anodes could be placed end-to-end inside each chamber. We then calculate that the smallest available zinc bar anode with dimensions of 3.6 cm (1.4 in.) square by 91 cm (36 in.) long will put out about 17.9 milliamperes DC (34x1000/1900 = 17.9). The total number of this size anode required per chamber can be calculated by dividing the total current per chamber of 213.6 ma by the current per anode of 17.9 which equals 11.9 anodes. Thus, our design will utilize 12 anodes mounted horizontally in four rows of three each mounted end-to-end with one row mounted on the chamber bottom, two rows on the chamber back wall, and the final row on the underside of the chamber top.

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

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

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

c. Develop Anode Locations for Each Structure Element

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

Chambers A and H: Where more than one anode is required in each chamber, the anodes will be mounted to the back surface of the each chamber held off the surface approximately 15 cm (6 in.) by mounting brackets. Multiple anodes must be evenly distributed from the side panels of the chamber to achieve more uniform current distribution. In order to also assure good current flow to the chamber end plates, the anode spacing is modified so that the center-to-center spacing is equal to the chamber width divided by the number of anodes per chamber. In this design example, with two anodes per small chamber, the chamber width of 1 m is divided by 2 so that the center-to-center spacing between the two anodes would be 0.5 m and the distance between the anodes and their adjacent chamber walls is half this distance, or 0.25 m.

Note that if three anodes were required in this same size chamber, the center-to-center spacing would be 0.33 m (1/3 = 0.33) and the outermost anodes to adjacent chamber walls would be half this spacing, or 0.17 m (0.33/2 = 0..17). Note that this spacing from the end walls should never be less than 0.15 m (6 in.) to ensure that current distribution will relatively uniform.

Chambers B and G: Where more than one anode is required in each chamber, the anodes will be mounted to the back surface of each chamber held off the surface approximately 15 cm (6 in.) by mounting brackets. Multiple anodes must be evenly distributed from the side panels of the chamber to achieve more uniform current distribution. In order to also assure good current flow to the chamber end plates, the anode spacing is modified so that the center-to-center spacing is equal to the chamber width divided by the number of anodes per chamber. In this design example, with two anodes per small chamber, the chamber width of 1.1 m is divided by 2 so that the center-to-center spacing would be 0.55 m and the distance between the anodes and their adjacent chamber walls is half that distance, or 0.23 m.

Note if three anodes were required in this same size chamber, the center-to-center spacing would be 0.37 m (1.1/3 = 0.37) and the outermost anodes to adjacent chamber walls would be half that spacing, or 0.19 m (0.37/2 = 0.19). Note that this spacing from the end walls should never be less than 0.15 m (6 in.) to ensure that current distribution will relatively uniform.

Chambers C, D, E, and F: In this design, zinc bar anodes are to be mounted horizontally in two parallel rows of three anodes each installed end-to-end. Each chamber is approximately 1 m (3.3 ft) deep by 1.8 m (5.8 ft) by 3.7 m (12.2 ft). Since each anode is 1.2 m (4 ft) long, the anodes will barely fit end-to-end in a horizontal row. To fit the three anodes into this chamber, a mounting hole will be drilled into each chamber end plate to receive one end of the nearest anode. The other threaded end of the anode will be held in place by a mounting plate placed 1.21 m from each end plate. The mounting plate must have a slot into which this 2nd end of the anode support rod can be fitted to be held in place by a nut and bolt. The center anode in each chamber will also have to mount into these same chamber support plates either by mounting them into the same support slots or by cutting an additional slot immediately adjacent to the support slot for the end anode rods. The two rows of anodes would be spaced equally away from the top and bottom of each chamber.

In this design example, with two horizontal rows of anodes per large chamber, the chamber height of 1.8 m is divided by 2 so that the center-to-center spacing between the two rows of anodes would be 0.9 m and the distance between the anodes and their adjacent chamber top and bottom walls is half that distance, or 0.45 m. If three anodes were required in this same size chamber, the center-to-center spacing would be 0.6 m (1.8/3 = 0.6) and the outermost anodes to adjacent chamber walls would be half that spacing, or 0.3 m (0.6/2 = 0.3). Note that this spacing from the end walls should never be less than 0.15 m (6 in.) to ensure that current distribution will relatively uniform. The locations for the anodes in the large chambers is shown In Figure E-7.

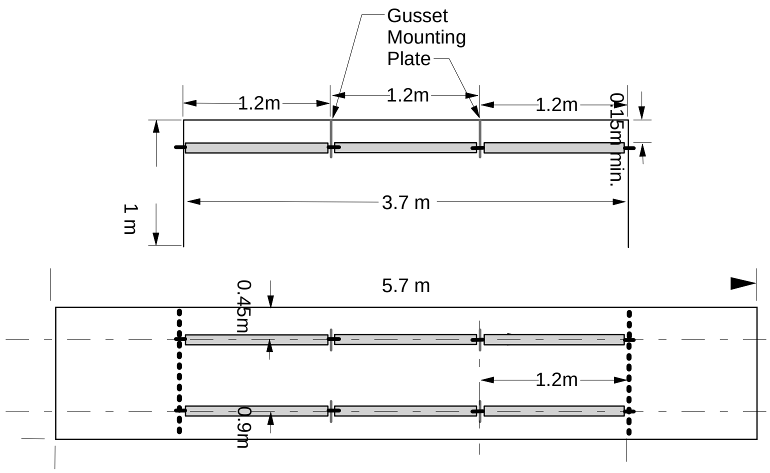

FIGURE E-7. ZINC BAR GALVANIC ANODE LOCATIONS
IN LARGEST DOWNSTREAM GATE CHAMBERS

As is the case with all galvanic anode designs on civil works structures, the intent is to deploy the anodes in a way that distributes their protective current uniformly for each similar current density surface area. For a structure where significantly different densities were required for protection, however, more anodes would be concentrated in the high-current density areas with fewer distributed uniformly in the lower current density areas (proportionate to the relative current densities required).