APPENDIX D
EXAMPLES OF IMPRESSED CURRENT CATHODIC PROTECTION DESIGN

D-1. Purpose.

The example in paragraph D-2 below shows how to use the design procedure explained in paragraphs 2-1 and 2-2. Examples in paragraphs D-3 through D-6 are for alternative calculation methods.

D-2. Steel gas main.

Impressed current cathodic protection is designed for the 6-inch welded gas main shown in figure D-1. This pipeline is not yet constructed, so measurements cannot be taken.

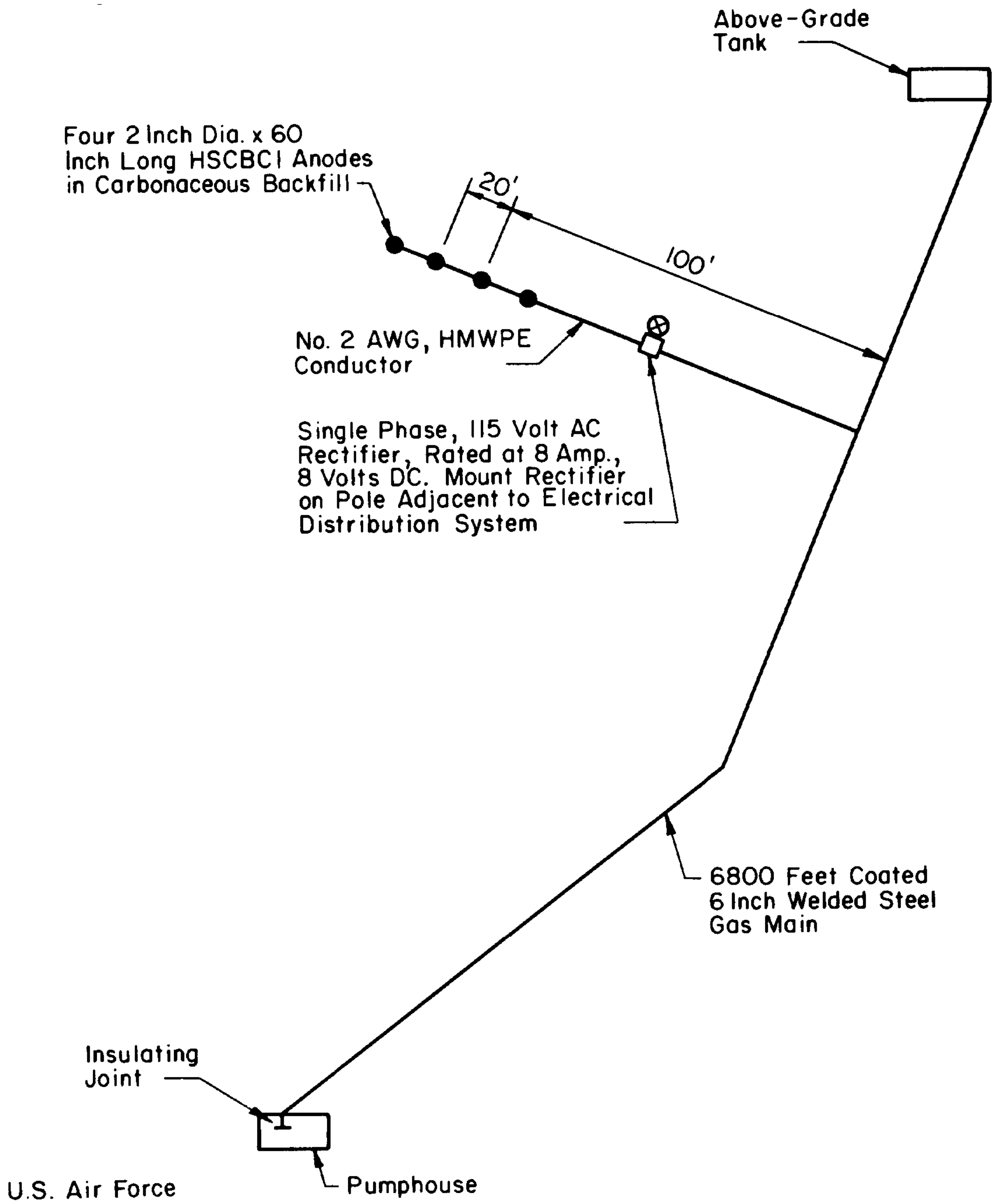

Figure D-1. Cathodic protection system for gas main.

a. Design data.

(1) Average soil resistivity is 2000 ohm-centimeters.
(2) Effective coating resistance at 15 years is estimated at 2500 ohms per square foot.
(3) Pipe has a 6-inch outside diameter.
(4) Pipe length is 6800 feet.
(5) Design for 15-year life.
(6) Design for 2 milliamperes per square foot of bare pipe.
(7) Design for 90 percent coating efficiency based on experience.
(8) The pipeline must be isolated from the pumphouse with an insulating joint on the main line inside the pumphouse.
(9) HSCBCI anodes must be used with carbonaceous backfill.
(10) The pipe will be coated with hot-applied coal-tar enamel and will be holiday-checked before installation.
(11) Anode bed must not exceed 2 ohms.
(12) Electric power is available at 120/240 volts a.c. single phase from a nearby overhead distribution system.
(13) Current requirement test indicates that 2.36 amperes are needed for adequate cathodic protection.

b. Computations.

(1) Find the gas main's outside area:
Pipe size - 6 in.
Pipe length - 6800 ft
Pipe area - 6800 x $\frac{\pi}{2}$ $A = L \pi d = 6800 \pi \frac{6}{12} = 10{,}681$ sq ft.

(2) Check the current requirement using equation 2-1:

$$I = (A)(I')(1.0 - CE)$$

$$I = 10681 \text{ sq ft } (2 \text{ mA/sq ft})(1.0 - 0.9)$$

$$I = 2136 \text{ mA},$$

which agrees with the current requirement test in *13* above.

(3) Select an anode. From table 2-4, choose the 60-pound anode with a 2.8-square-foot surface area (arbitrary selection).

(4) Calculate the number of anodes needed to meet the anode supplier's current density limitations; use equation 2-9:

$$N = \frac{I}{(A_1)(I_1)}$$

$$N = \frac{2360 \text{ mA}}{(28 \text{ sq ft/anode})(1000 \text{ mA/sq ft})},$$

(Recommended maximum current density output for high-silicon chromium-bearing cast-iron anodes is 1000 mA/sq ft.)

$$N = 0.84 \text{ anode}$$

(5) Calculate the number of anodes required to meet the design life requirements from equation 2-10:

$$N = \frac{(L)(I)}{(1000)(W)}$$

$$N = \frac{(15 \text{ years})(2360\text{mA})}{(1000)(60 \text{ lb/anode})} = 0.59 \text{ anode}$$

(6) Calculate the number of anodes required to meet maximum anode groundbed resistance requirements from equation 2-11:

$$R_a = \frac{(\rho\ K)}{LN} + \frac{\rho\ P}{S}$$

$$N = \frac{\rho\ K}{L\ (R_a - \frac{\rho}{S}\ P}$$

$$N = \frac{2000\ ohm-cm\ (0.016S)}{7\ ft\ (20\ ohm - \frac{(2000\ ohm/cm\ (0.}{20\ ft}}$$

(Values for K and P from tables 2-6 and 2-7, respectively.)

$N = 2.75 \approx 3$ anodes.

(7) Select the number of anodes to be used. Since the last calculation resulted in the largest number of anodes, it will be used. The groundbed resistance, Ra, using three anodes, would equal 1.86 ohms; to insure compliance with the manufacturer's limitations, four anodes will be used.

(8) Select an area for anode bed placement. The area of lowest resistivity will be used, which is 100 feet from the pipeline.

(9) Determine the total circuit resistance.

(a) Calculate the anode groundbed resistance using equation 2-11:

$$R_a = \frac{(\rho\ K)}{LN} + \frac{\rho\ P}{S}$$

$$R_a = \frac{2000\ ohm-cm\ (0.0165)}{(4\ anodes)(7\ ft)} + \frac{(2000}{}$$

(Values for K and P are from tables 2-6 and 2-7, respectively.)

$R_a = 1.46$ ohm.

(b) Calculate the groundbed resistance for a 50-foot header cable using equation 2-12. The resistance specified by the manufacturer is 0.0159 ohm per 100 ft of No.2 AWG cable:

$R_w = (ohms/ft)(L)$

$R_w = (0.0159\ ohm/100\ ft)(500\ ft) = 0.0795$ ohm.

(c) Calculate the structure-to-electrolyte resistance from equation 2-14:

$$R_c = \frac{R}{N}$$

$$R_c = \frac{2500\ ohm/sq\ ft}{11,800\ sq\ ft}$$

$= 0.212$ ohm

(d) Calculate the total resistance (eq 2-15):

$R_T = R_a + R_w + R_c$

R_T = 1.46 ohm + 0.0795 ohm + 0.212 ohm

R_T = 1.75 ohms.

(10) Calculate the rectifier voltage from equation 2-16:

$v(_{rec}) = (I)(R_T)(150\%)$

$v(_{rec})$ = (2.36 A)(1.75 ohms)(150%)

$v(_{rec})$ = 6.2 V.

c. Select rectifier. Based on the design requirement of 6.2 volts and 2.36 amperes, a rectifier can be chosen from those marketed. After a rectifier has been chosen, the system's cost can be calculated in accordance with paragraph 2-2. A comparison with other anode sizes and types will yield the most economical design.

D-3. Heating distribution system.

Impressed current cathodic protection is designed for a well coated, buried heating distribution system as shown in figure D-2. The distribution system has not yet been installed, so measurements cannot be made. Rectifier size need not be calculated, because it is sized in the field after anode installation.

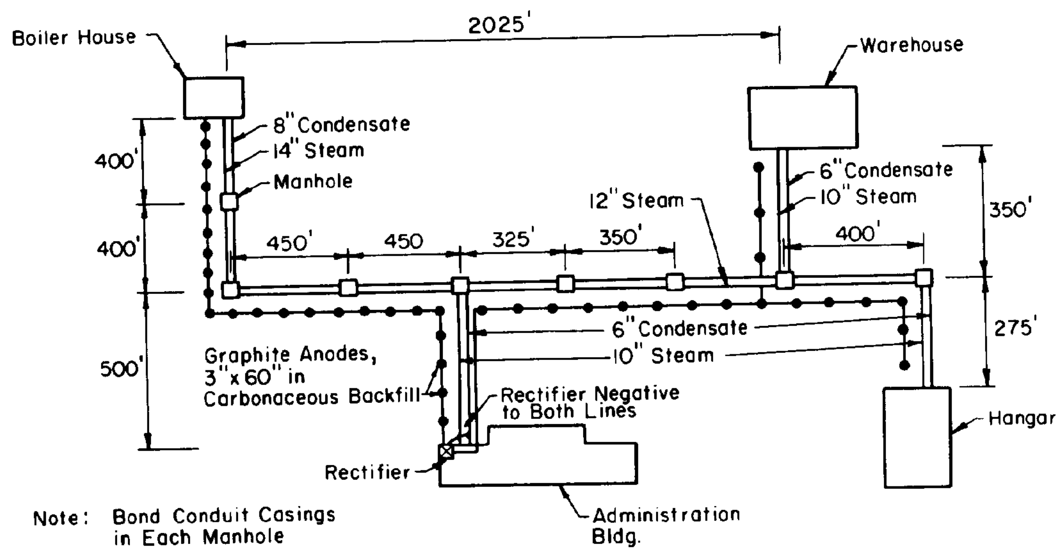

Figure D-2. Impressed current cathodic protection for heating conduit system.

a. Design data.

(1) Average soil resistivity is 1000 ohm-centimeters.
(2) Design for 80 percent coating efficiency based on experience.
(3) Design for 4 milliamperes per square foot of bare metal heating conduits.
(4) Groundbed resistance must not exceed 1.5 ohms.
(5) Graphite anodes must be installed with carbonaceous backfill.
(6) Design for a 15-year life.

(7) Insulating joints must be provided on both steam and condensate lines at the first flange connection inside all buildings.
(8) All conduit must be metal-bonded together in each manhole.
(9) All conduit will be precoated at the factory and will not have been holiday-checked.
(10) Single-phase electrical power is available at 120/240 volts a.c. from the administration building.

b. Computations.

(1) Find the conduit's total outside area. Because the gage of the metal from which the conduit is made ranges between 14 and 16, the pipe's outside diameter is considered the same as the inside diameter.
(a) Steam conduit area must be calculated (table D-1).

Table D-1. Dimensions for finding steam conduit area: heat distribution system

Conduit size (in.)	Conduit length (ft)	Conduit area (sq ft/ (lin ft)	Conduit area (sq ft)
14	1700	3.67	6239
12	1125	3.14	3533
10	1525	2.62	3996
Total area of steam conduit		13,768	

U.S. Air Force

(b) Condensate return conduit area must be calculated (table D-2).

Table D-2. Dimensions for finding condensate return conduit area: heat distribution system

Conduit size (in.)	Conduit length (ft)	Conduit area (sq ft/ (lin ft)	Conduit area (sq ft)
8	1700	2.09	3553
6	2650	1.57	4161
Total area of condensate return conduit			7713
Total outside area of all conduit			21481

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(2) Find the area of bare pipe to be cathodically protected based on 80 percent coating efficiency:

A=21,481 x 0.2

A = 4296 sq ft.

(3) Find the maximum protective current required based on 4 milliamperes per square foot of bare metal:

I = 4296 x 4

I = 17,184 mA or 17.2 A.

(4) Compute the maximum weight of anode material needed for 15 years' life.
(a) Graphite anodes are used.
(b) Average deterioration rate for graphite is 2.0 pounds per ampere-year.

(c) Find the maximum weight of anode material required (use eq C-1 from appendix C):

$$W = \frac{YSI}{E},$$

where Y = 15 years, S = 2.0 pounds per ampere-year, I = 17.2 amperes, and E = 0.50 efficiency. Thus,

$$W = \frac{(15\ \text{yr})(2.0\ \text{lb/A-yr})(17.2\text{A})}{0.50},$$

W = 1032 lb.

c. Groundbed design.

(1) Anode size is 3-inch by 60-inch (backfilled 10-inch by 84-inch) and weight is 25 pounds per anode unit.

(2) Find the resistance to earth of a single anode:

$$R_v = \frac{PK}{L}, \qquad \text{(eq D-1)}$$

where P = 1000 ohm-centimeters, L = 7.0 feet (backfilled size), and K = 0.0167, L/d = 8.4 (table 2-6). Thus,

$$R_v = \frac{(1000\ \text{ohm-cm})(0.0167)}{7.0\ \text{feet}},$$

R_v = 2.39 ohms

(3) Compute the number of anodes required. The low resistance (2.39 ohms) of a single anode and the heavy weight of anode material required (1032 pounds) for a 15-year life indicate that the controlling factor is the amount of anode material, not groundbed resistance. The minimum number of anodes (N) required is

N = 1032/25 = 41.3 or 41 anodes.

These are arranged in a distributed groundbed as shown in figure D-2 based on the following estimates.

(4) Anode distribution:

(a) Conduit area in sections 1 through 6 of figure D-2 are given in table D-3.

Table D-3. Conduit area: heat distribution system

Section	Length (ft)	Surface area (sq ft)
1	1700	3553 + 6239 = 9792
2	500	785 x 1310 = 2095
3	1125	1766 x 3533 = 5299
4	350	550+ 917=1467
5	400	628 + 1048 = 1676
6	275	432 + 721=1153

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(b) The area of conduit protected by one anode is —

A = 21,481/41

A = 524 sq ft/anode.

(c) Anodes will be divided as shown in table I)-4.

Table D-4. Anode division: heat distribution system

Section	Surface area/ anode protective area	Number of anodes
1	9792/524 =	19
2	2095/524 =	4
3	5299/524 =	10
4	1467/524 =	3
5	1676/524 =	3
6	1153/524=	2

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d. Rectifier location. Locate the rectifier in front of the administration building as figure D-2 shows. The rectifier will be sized after anodes are installed.

D-4. Black iron hot water storage tank.

Impressed current cathodic protection is designed for the interior of a black iron hot water storage tank as shown in figure D-3.

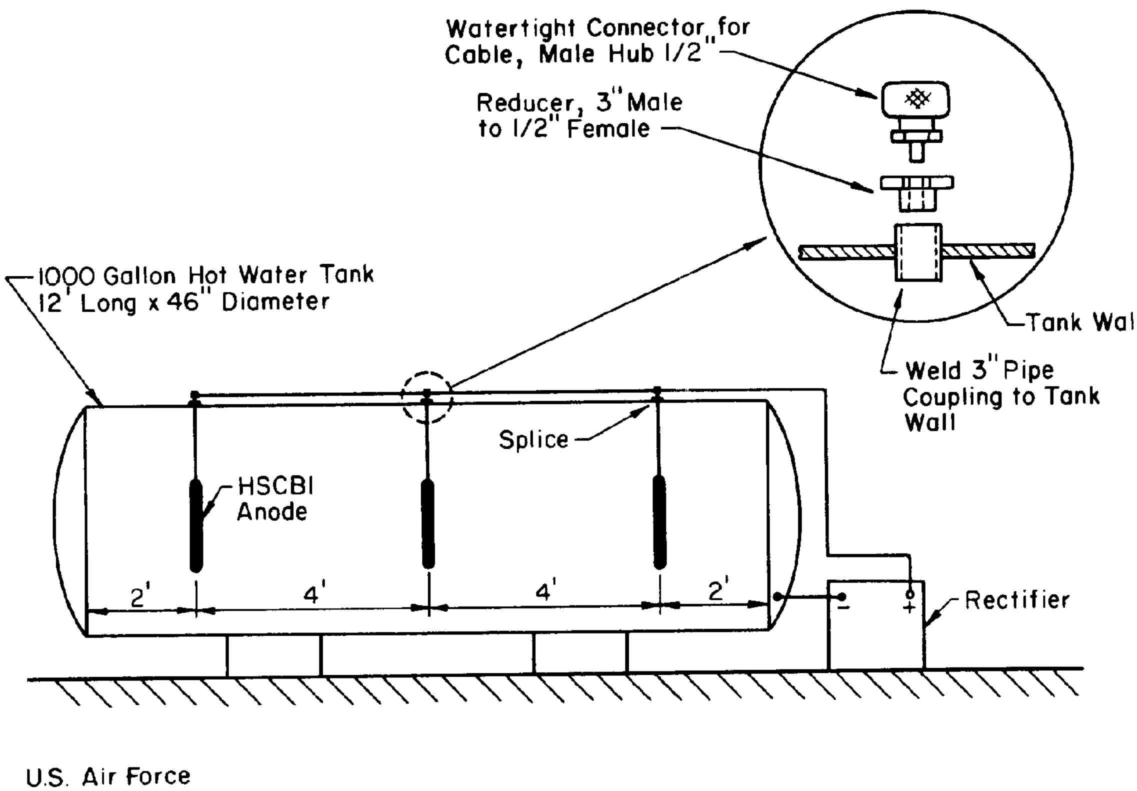

Figure D-3. Cathodic protection for black iron hot water storage tank.

a. Design data.

(1) Tank capacity is 1000 gallons.
(2) Tank dimensions are 46 inches in diameter by 12 feet long.
(3) The tank is mounted horizontally.
(4) Water resistivity is 8600 ohm-centimeters with a pH of 8.7.
(5) The tank's inside surface is bare and water temperature is maintained at 180 degrees Fahrenheit.

(6) Design for a maximum current density of 5 milliamperes per square foot.
(7) Design for a 5-year life.
(8) Use HSCBCI anodes.
(9) Electrical current is available at 115 volts a.c., single phase.

b. Computations.

(1) Find the tank's interior area using equation D-2:

$$A_T = 2 \quad r^2 + \quad dL,$$

where r=1.92 feet, d=3.83 feet, and L = 12 feet. Thus,

$$A_T = 2 \times 3.1416 \times (1.92)^2 + 3.1416 \times 3.38 \times 12$$

$$A_T = 167.5 \text{ sq ft.}$$

(2) Find the maximum protective current required:

$$I = 167.5 \times 5$$

$$I = 838 \text{ mA or } 0.84 \text{ A.}$$

(3) Find the minimum weight of anode material needed for a 5-year life (eq C-I from appendix C):

$$W = \frac{YSI}{E},$$

where Y = 5 years, S = 1.0 pound per ampere-year, I = 0.84 ampere, and E = 0.50. Thus,

$$W = \frac{(5\ \text{yr})(1.0\ \text{lb/A}-\text{yr})(0.84\ \text{A})}{0.50}$$

$$W = 8.4 \text{ lb.}$$

(4) Compute the number of anodes required. An anode 1½ inches in diameter by 9 inches long weighing 4 pounds is chosen as the most suitable size. For proper current distribution, three anodes are required.

(5) Find the resistance of a single anode using equation D-3:

$$R = \frac{0.012P\ \log\ (d/D)}{L} \qquad \text{(eq D-3)}$$

where P =8600 ohm-centimeters, D = 3.83 feet (tank diameter), d = 1½ inches or 0.125 foot (anode diameter), L = 9 inches or 0.75 foot (anode length). Thus,

$$R = \frac{0.012 \times (8600\ \text{ohm}-\text{cm})\ \log\ (3.83\ \text{ft}/0.125\ \text{ft})}{0.75\ \text{ft}}$$

$$R = \frac{103.2 \times \log\ 30.64}{0.75}$$

$$R = 204.5 \text{ ohms}$$

This resistance must be corrected by the fringe factor because the anodes are short. The fringe factor is 0.48 from the curve in figure D-4 for an L/d = 9/1.5 = 6:

$$R = 204.5 \times 0.48$$

$$R = 98.2 \text{ ohms.}$$

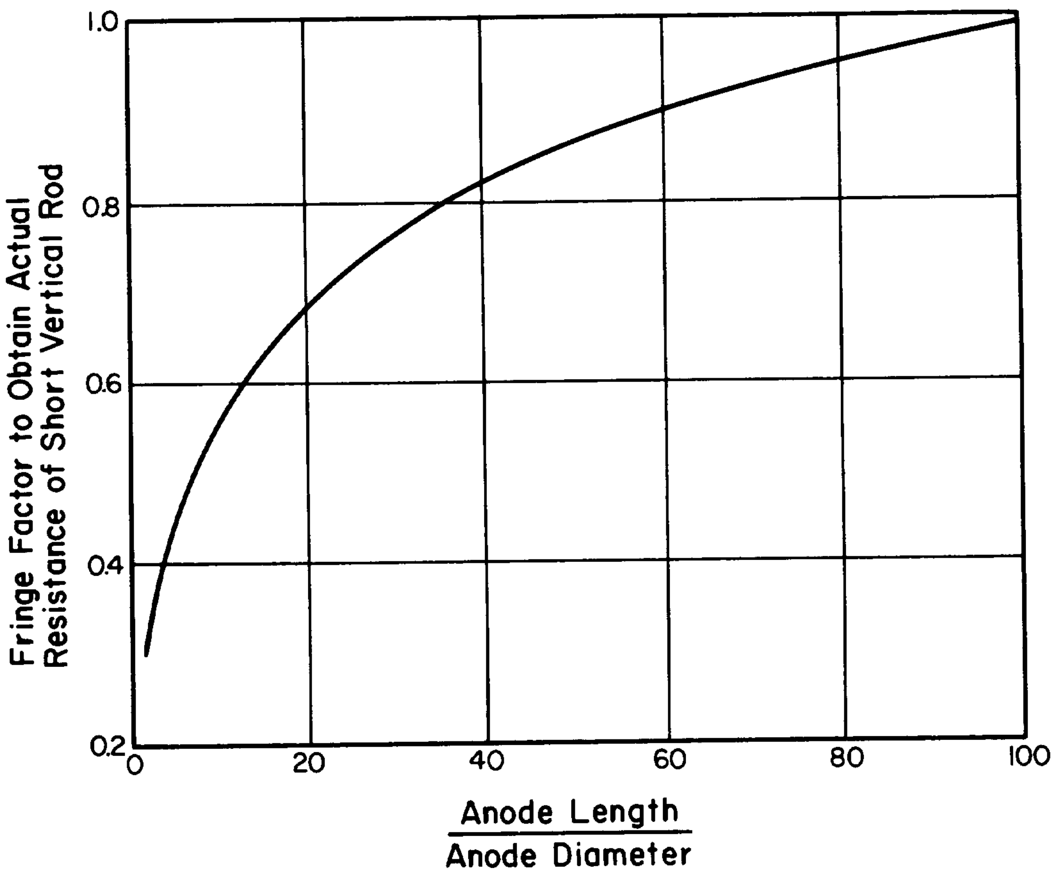

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Figure D-4. Fringe factor for stub anodes.

(6) Find the resistance of a three-anode group using an equation based on equation 2-11:

$$R_n = \frac{1}{N} R_v + \frac{\rho \cdot P}{S},$$

where R_n = the total anode-to-electrolyte resistance, N = number of anodes, R_v = resistance-to-electrolyte of a single anode, P = electrolyte resistivity, P = paralleling factor from table 2-7, and S = spacing between anodes (feet). Thus,

$$R_n = \frac{1}{3}\, 98.2 + \frac{8600 \times 0.00289}{4}$$

R_n = 38.94 ohms

(7) Find the rectifier rating:

E = IR,

where I = 0.84 ampere and R = 38.94 ohms. Thus,

E = 0.84 x 38.94

E = 32.7 V.

(a) To allow rectifier aging and film formation, it is considered good practice to use 1.5 as a multiplying factor:

E = 1.5 x 32.7 = 49.1 V.

(b) The rectifier chosen should produce a d.c. voltage that meets the size requirements of 60-volt, 4-ampere, single-phase.

(8) Locate the rectifier adjacent to tank for the following reasons:

(a) Usually cheaper to install.

(b) Easier to maintain.

(c) Keeps d.c. voltage drop to a minimum.

(9) The d.c. circuit conductors should be installed as follows:

(a) Outside tank — use No.2 AWG high molecular weight polyethylene extruded (HMWPE) conductor.

(b) Inside tank — use No.8 AWG HMWPE conductor.

(10) The cable should not be stressed or bent.

D-5. Elevated water tank (ice is expected).

Impressed current cathodic protection is designed for an elevated water tank as shown in figure D-5. The tank is already built and current requirement tests have been done. Anodes must not be suspended from the tank roof because heavy ice (up to 2 feet thick) covers the water surface during winter. The anode cables could not tolerate this weight, so another type of support must be used. Button anodes must be mounted on the tank's floor and lightweight platinized titanium anodes must be suspended in the riser from the tank bottom.

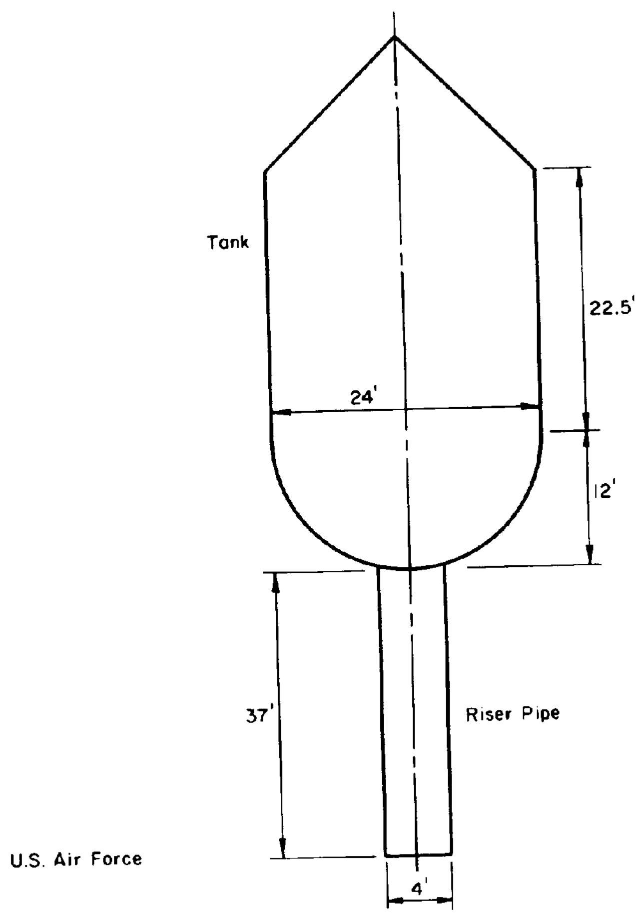

Figure D-5. Dimensions for an elevated steel water tank.

a. Design data.

(1) Tank height (from ground to bottom of bowl) is 37 feet.
(2) Tank diameter is 24 feet.
(3) High water level in the tank is 34.5 feet.
(4) Overall tank depth is 34.5 feet.
(5) Vertical shell height is 22.5 feet.
(6) Riser pipe diameter is 4 feet.
(7) The tank has a semicircular bottom.
(8) All inner surfaces are uncoated.
(9) Current required for protection — bowl, 7.0 amperes, rise, 1.0 ampere.
(10) Electrical power available is 120/240-volt a.c., single phase.
(11) Tank is subject to freezing.
(12) Design for a 15-year life.
(13) Water resistivity is 4000 ohm-centimeters.
(14) Button-type HSCBCI anodes are used for the tank.
(15) Riser anodes are platinized titanium wire.

b. Computations.

(1) Find the minimum weight of button anode material required for the tank (eq C-1 from appendix C):

$$W = \frac{YSI}{E},$$

where Y = 15 years, S = 1.0 pound per ampere-year, I = 7.0 amperes, and E = 0.50. Thus,

$$W = \frac{(15\ \text{yr})(1.0\ \text{lb/A-yr})(7.0\ \text{A})}{0.50},$$

W = 210 lb.

(2) Compute the number of tank anodes needed (button anodes weigh 55 pounds):

$$N = \frac{210}{55} = 3.82\ \text{(use 4 anodes)}.$$

(3) Find the minimum weight of riser anode material required for the riser (eq C-I from appendix C):

$$W = \frac{YSI}{E},$$

where Y = 15 years, S = 1.32 x 10^{-5} pound per ampere-year, I = 1.0 ampere, and 0 = 0.50. Thus,

$$W = \frac{(15\ \text{yr})(1.32 \times 10^{-5}\text{lb/A-yr})(1.0\ \text{A}}{0.50}$$

W = 3.96 x 10^{-4} lb.

(4) Find the number of riser anodes needed. Platinized titanium wire, 0.1-inch in diameter, 3 feet long, with .001-inch-think platinum over titanium will be used for each anode. The weight of platinum on each anode is 8.8 x 10^{-5} pound. Thus,

$$N = \frac{3.96 \times 10^{-4}}{8.8 \times 10^{-5}} = 4.5\ \text{(use 5 anodes)}.$$

(5) locate anodes as shown in figure D-6.

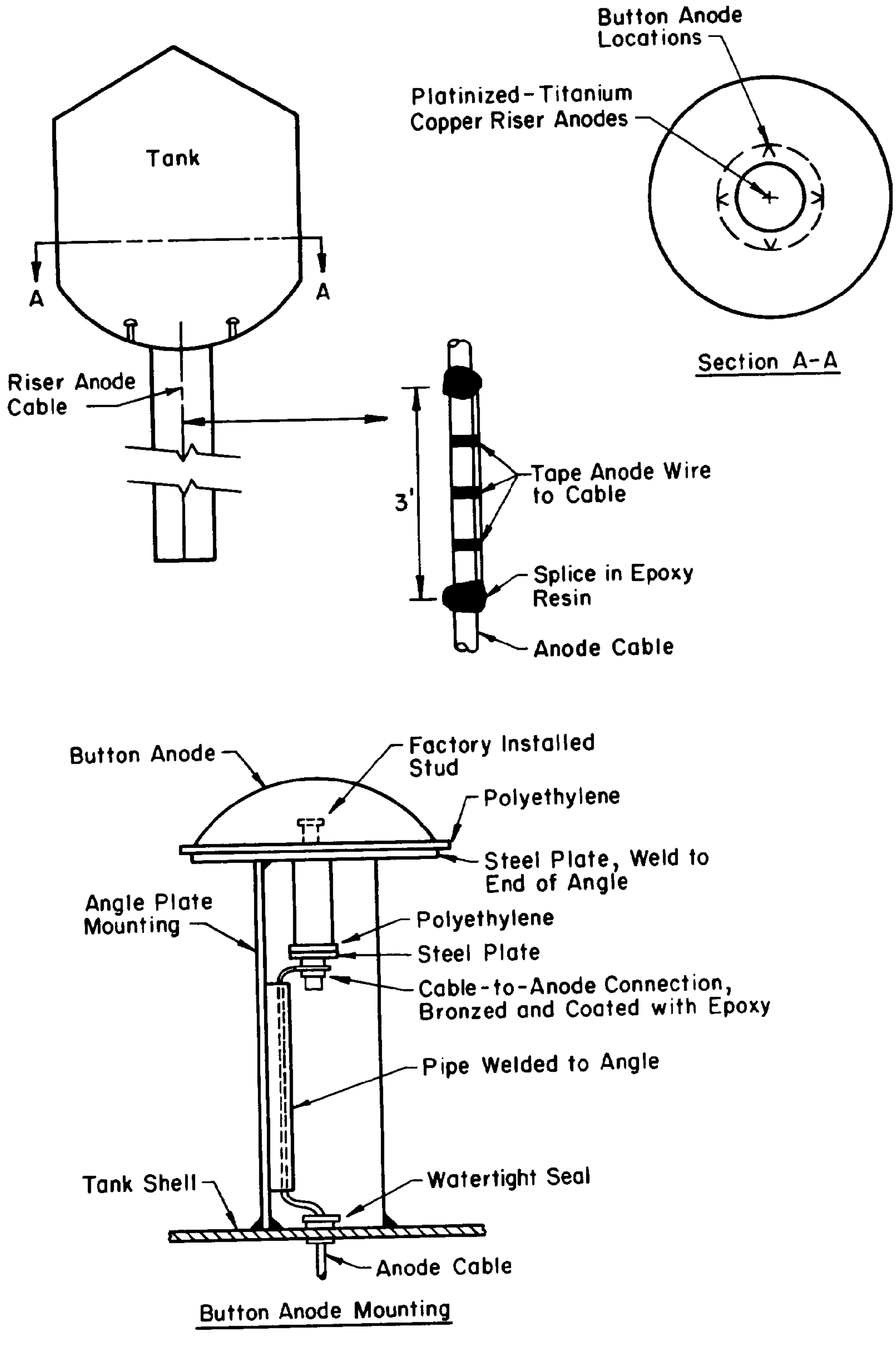

Figure D-6. Cathodic protection for tanks using rigid-mounted, button-type anodes and platinized titanium wire.

(a) Button anodes are mounted on the tank bases at a distance of one-fourth the tank diameter (??? feet) from the center. They are mounted on metal angles and plates that are welded to the tank bottom; polyethylene insulation is required to separate the anode from the metal mounting. Riser anodes are suspended in the center of the riser pipe and are spliced to a No.4 AWG cable. The top anode is placed 1 foot from the tank base. The remaining four anodes are spaced at 4-foot intervals.

(b) Each button anode has its own No.8 AWG 7-strand copper cable (HMWPE) run in conduit to a resistor box mounted at eye level on a tank leg. The riser anode's one No.4 AWG 7-strand cable is run in conduit to the resistor box. If required to get proper current output, a resistor must be installed in the riser anode circuit at the time of rectifier sizing. The rectifier must be sized after the anodes are installed and must be mounted at eye level adjacent to the resistor box.

D-6. Elevated steel water tank.

This impressed current design is for a tank that has not been built; thus, it is not possible to measure current requirements and other factors. Calculated estimates are used.

a. Design data.

(1) Tank capacity will be 500,000 gallons.
(2) Tank height (from ground to bottom of bowl) will be 115 feet.
(3) Tank diameter will be 56 feet.
(4) The tank's high water level will be 35 feet.
(5) Overall tank depth will be 39 feet.
(6) Vertical shell height will be 11 feet.
(7) Riser pipe diameter will be 5 feet.
(8) Tank will be ellipsoidal on both top and bottom.
(9) All inner surfaces will be uncoated.
(10) Design for a maximum current density of 2 milliamperes per square foot.
(11) Electric power available will be 120/240-volt a.c., single phase.
(12) String-type HSCBCI anodes will be used.
(13) Design for a 10-year life.
(14) Water resistivity is 4000 ohm-centimeters.
(15) The tank water must not be subjected to freezing.
(16) An assumed deterioration rate is 1.0 pound per ampere-year.
(17) Anode efficiency (assumed) is 50 percent.

b. Computations.

(1) Find the area of wetted surface or tank bowl (figure D-7).

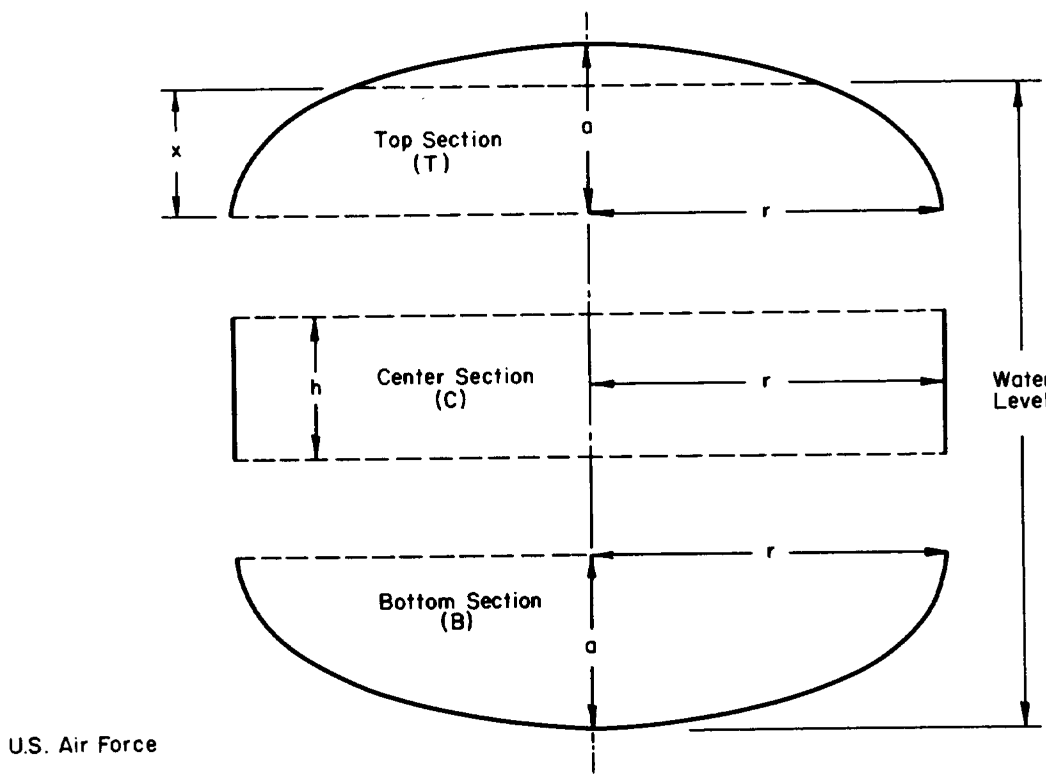

Figure D-7. Segmented elevated tank for area calculations.

(a) For the top section (T)—

$A_T = 2\ \pi$ rx (approximately),

where r == 28 feet (tank radius), x = 10 feet. Thus,

A_T =2 x 3.1416 x 28 ft x 10 ft

A= 1759 sq ft.

(b) For the center section (C)—

$A_c = 2\ \pi$ rh, (eq D-5)

where r = 28 feet (tank radius) and h = 11 feet. Thus,

` A_c = 2 x 3.1415 x 28 ft x 11 ft

A_c = 1935 sq ft.

(c) For the bottom section (b)—

$$A_B = \sqrt{2}\ \sqrt{r\ a^2 + r^2}, \qquad \text{(eq D-6)}$$

where r = 28 feet (tank radius) and a 14 feet. Thus,

$$A_B = \sqrt{2} \times 3.1416 \times 28\ \text{ft} \times \sqrt{14\ \text{ft}^2 + 28\ \text{ft}^2},$$

A_B = 3894 sq ft.

(d) Therefore, the total wetted area of the tank bowl is—

$A_T + A_C + A_B$ or 7588 sq ft.

(2) Find the riser pipe's area using equation D-7:

$A_r = 2\ \pi\ r_R h_R$, (eq D-7)

where r_R = 2.5 feet (riser radius) and h_R = 115 feet (riser height). Thus,

A_R = 2 x 3.1416 x 2.5 ft x 115 ft

A_R = 1806 sq ft

(3) Find the maximum design current for the tank:

I_T = 2.0 mA/sq ft x 7588 sq ft

I_T = 15,176 mA or 15.2 A.

(4) Find the maximum design current for the riser:

I_R = 2.0 mA/sq ft x 1806 sq ft

I_r 3612 mA or 3.62 A.

(5) Find the minimum weight of tank anode material needed (eq C-1 from appendix C):

$$W = \frac{YSI}{E},$$

where Y = 10 years, S = 1.0 pound per ampere-year, E = 0.50, and I = 15.2 amperes. Thus,

$$W = \frac{(10\ \text{yr})(1.0\ \text{lb/A}-\text{yr})(15.2\text{A})}{0.50},$$

W = 304 lb.

(6) Compute the minimum weight of riser anode material needed (eq C-1):

$$W = \frac{YSI}{E},$$

where Y = 10 years, S = 1.0 pound per ampere-year, I = 3.62 amperes, and E = 0.50.

$$W = \frac{(10\ \text{yr})(1.0\ \text{lb/A-yr})(3.62\text{A})}{0.50},$$

W = 72.4 lb.

(7) Find the main anode circle's radius using equation D-8:

$$r = (DN)/2(\pi + N) \qquad \text{(eq D-8)}$$

where D = 56 feet and N = 10 (assumed number of anodes). Thus,

$$r = \frac{56\ \text{ft} \times 10}{2(3.1416 + 10)}$$

r = 560/26.28

r = 21.3 ft, use 22 ft.

(8) Determine the spacing for the main anodes. Generally, the distance from the anode to the tank wall and tank bottom is about equal; this distance should be about one-half the circumference between anodes.

(a) To find circumferential spacing, use equation D-9:

$$C = (2\pi r) / N \qquad \text{(eq D-9)}$$

where r = 22 feet (anode circle radius) and N = 10 (assumed number of anodes). Thus,

$$C = \frac{2 \times 3.1416 \times 22\ \text{ft}}{10}$$

C = 13.8 ft, use 14 ft.

(b) The cord spacing is approximately the same as circumferential spacing; 14 feet will be used (fig D-8).

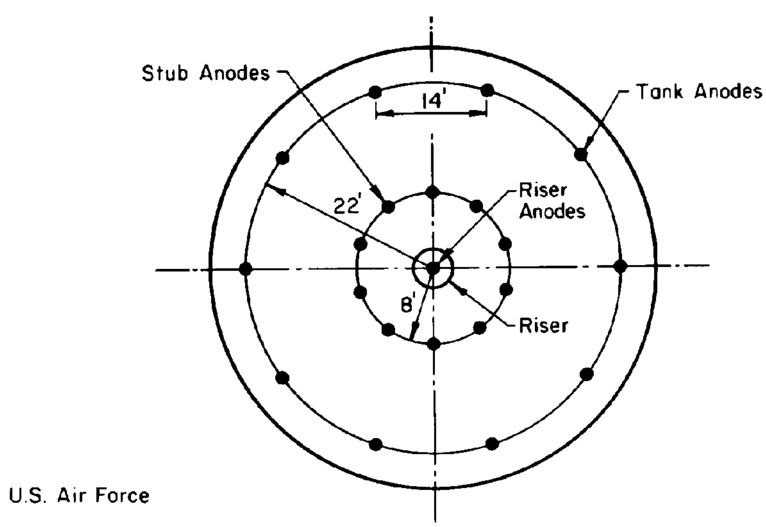

Figure D-8. Anode spacing for elevated steel water tank.

(9) Select the main anodes.

(a) The anode unit size chosen is 1c-inch outside diameter, ¾-inch inside diameter, and 9 inches long. This is a standard sausage-type anode that weighs 1 pound and has a surface area of 0.25 square foot.

(b) The minimum number of anode units per anode string (N), based on a required weight of 304 pounds and 10 anode strings, is computed as follows:

N = 304/(10 x 1)

N = 30.4, use 31 units per string.

(c) Because the inside tank surfaces are uncoated, a maximum structure-to-electrolyte voltage is not a limiting factor. However, because it is desired to hold the anode current at or below the manufacturer's recommended discharge rate of 0.025 ampere per anode for this type anode, the minimum number of anodes will be—

$$\frac{15.2\ A}{10 \times 0.025\ A} = 60.8 \text{ (use 61 anodes per string.}$$

This number is not practical for the bowl since the distance between the anode hanger and tank bottom is only 28 feet. Table D-5 shows the maximum recommended current discharge per anode for various types of anodes to insure a 10-year minimum life. Using a type B anode, three anodes per string are required. The manufacturer does not recommend more than two type B anodes per string assembly because the strings are fragile. Therefore, the best choice of anode for the main anode strings is type C or CDD. Type CDD is recommended because the lead wire connection is protected longer by the thicker wall of the enlarged ends. Two type CDD anodes per string provide a current capacity of 2 amperes 10 strings = 20 amperes. These anodes are spaced as shown in figure D-9.

Table D-.5. Technical data—commonly used HSCBCI anodes

Anode type	Size (in.)	Weight (1b)	Anode max discharge (A)	Area (sq ft)	Max current density (A/sq ft)
FW[a]	1c OD x 9	1	0.025	0.2	0.1
FC[b]	1½ x 9	4	0.075	0.3	0.25
G-2	2 OD x 9	5	0.100	0.4	0.25
G-2½	2½ x 9	9	0.20	0.5	0.40
B[c,d]	1 x 60	12	0.50	1.4	0.36
C	1½ x 60	25	1.00	2.0	0.50
CDD[c]	1½ x 60	26	1.00	2.0	0.50
M[c]	2 x 60	60	2.5	2.8	0.9
SM	4½ x 60	20	10.0	5.5	1.8
K-6	6 x 2½	16	0.225	0.5	0.45
K-12	12 x 3 $^{7}/_{16}$	53	0.80	1.0	0.80
B-30	1 x 30	7	0.25	0.7	0.36
TA-2	2 $^{1}/_{16}$ x 84	46	6.4	4.0	1.6

[a]For elevated freshwater tank.
[b]For distributed system in ground trench.
[c]Each end enlarged with cored opening for wire.
[d]Not more than two anodes per assembly.
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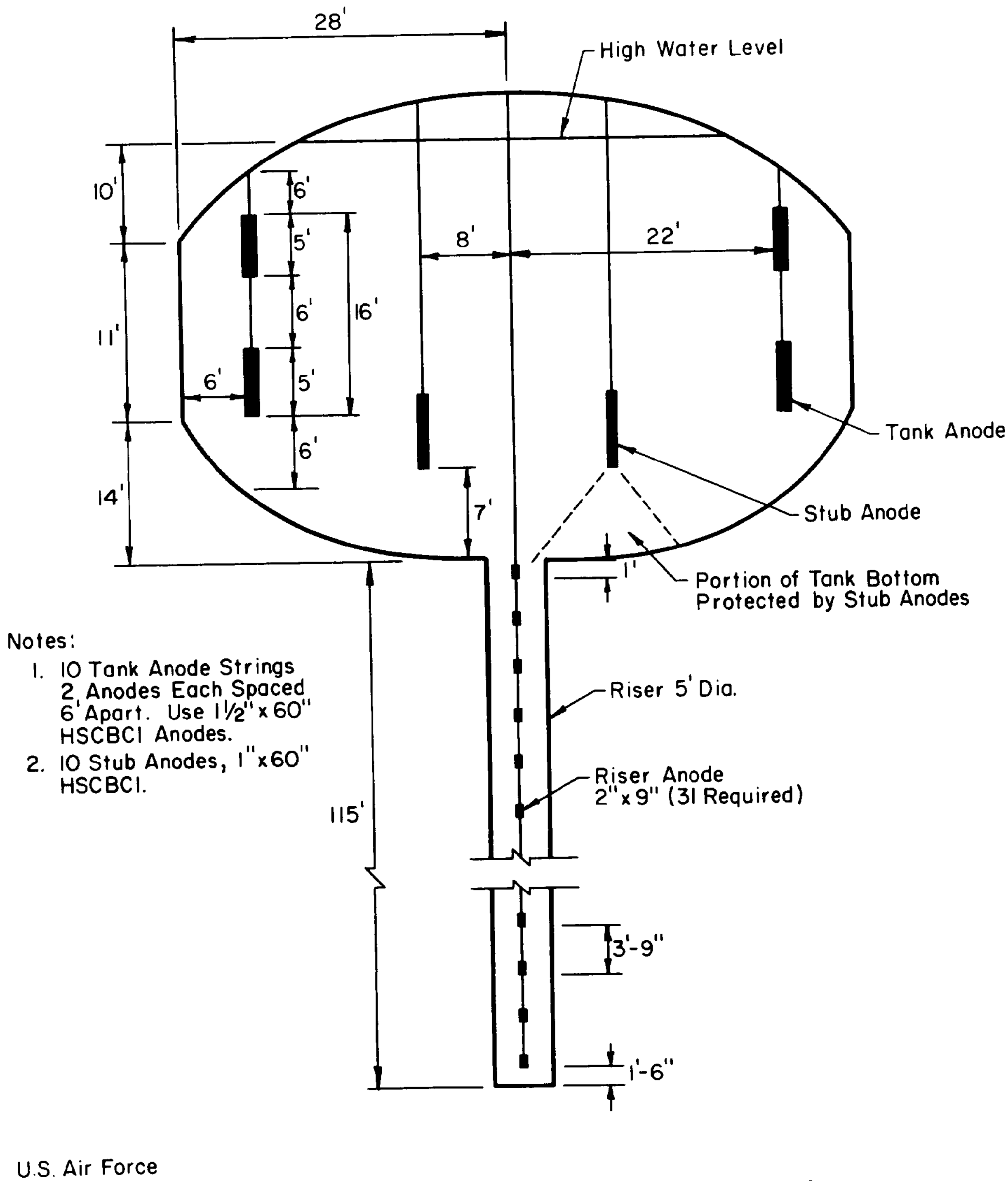

Figure D-9. Anode suspension arrangement for elevated steel water tank.

(d) Anode current density is computed as follows:

$$\text{Output} = \frac{15.2}{2 \times 10 \times 2}$$

$$= 0.38 \text{ A/sq. ft.}$$

(10) Find the main anodes’ resistance (substituting a for d in eq D-3):

$$R = \frac{0.012P \ \log \ (D/a)}{L},$$

where P = 4000 ohm-centimeters, D = 56 feet, L = 2 x 5 feet = 10 feet, and a = 44 x 0.275 = 12.1 feet (0.275 = equivalent diameter factor from curve, fig. D-10). Thus,

$$R = \frac{(0.102)(4000 \ \text{ohm-centimeters}) \ \log \ (56 \ \text{ft}/12.1 \ \text{ft})}{10 \ \text{ft}}$$

$$R = \frac{48 \ \log \ 4.628}{10}$$

R = 3/19 ohms

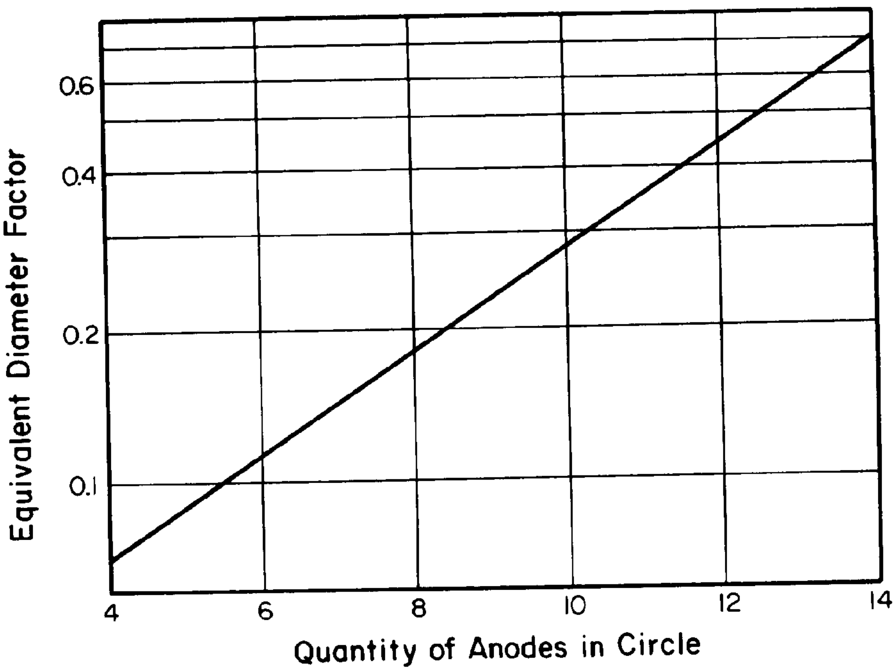

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Figure D-10. Equivalent diameter factor for anodes in a circle in water tank.

(a) However, the L/d ratio of two 1½ inch diameter, 60-inch long anodes in tandem is less than 100, so the fringe factor must be used:

L/d = (2 x 60)/1.5

L/d=80 < 100.

(b) The fringe factor from figure D-4 corresponding to this L/d ratio is 0.95. Thus,

R (adjusted) = 3.19 x 0.95

R = 3.03 ohms.

(11) In designing an elevated water tank, the need for stub anodes must be justified.

(a) The main anode radius has been calculated to be 22 feet. The main anodes are spaced to provide approximately the same distance from the sides and the bottom of the tank. The main anodes will protect a length along the tank bottom equal to 1½ times the spacing of the anode from the bottom.

(b) The anode suspension arrangement for the tank being considered is shown in figure D-9. It can be seen that stub anodes are required for this design. Ten stub anodes are spaced equally on a circumference with a radius of 8 feet in a way shown in figure D-8. For smaller diameter tanks, stub anodes may not be required.

(12) Find the current division between main and stub anodes.

(a) The area of tank bottom protected by stub anodes is found by equation D-10 (fig D-9):

$$A_s = \pi (r_2^2 - r_1^2), \qquad \text{(eq D-10)}$$

where r^2 = 13 feet (protected segment radius) and r^1 = 2.5 feet (riser radius). Thus,

A_s = 3.1416 (132 sq ft - 2.52 sq ft)

A_s = 3.1416 x 162.75

A_s = 511.3 sq ft.

(b) The maximum current for stub anodes is therefore—

I_s = 2.0 x 511.3

I_s = 1022.6 milliamperes or 1.02 amperes.

(c) The maximum current for the tank bowl is 15.2 amperes.

(d) The maximum current for main anodes is—

I_m = 15.2A - 1.02A

I_m = 14.2A.

(13) Find the rectifier voltage rating.

(a) The electrical conductor to the main anode is wire size No.2 AWG, rated at 0.159 ohm per 1000 feet, and has an estimated length of 200 feet. Thus, the resistance of the wire, R, is:

$$R = \frac{200 \text{ ft}}{1000 \text{ ft}} \times 0.159 \text{ ohm} = 0.032 \text{ ohm.}$$

(b) For the voltage drop in the main anode feeder—

E = IR,

where I = 14.2 amperes and R = 0.032 ohm. Thus,

E = 14.2 A x 0.032 ohm

E = 0.45 V.

(c) For the voltage drop through the main anodes—

E = IR,

where I = 14.2 amperes and R = 3.03 ohms. Thus,

E = 14.2 A x 3.03 ohms.

E = 43.0 V.

(d) The total voltage drop in main anode circuit is thus—

E_T = 0.45 + 43.0

E_T = 43.45 or 45 V.

Use a multiplying factor (safety factor) of 1.5 to get 67.5 volts.

(14) Select the stub anodes. Because it is desirable to use as small an anode as possible without exceeding the manufacturers' recommended rate, try using type FC, HSCBCI anode that measures 1½-inches by 9 inches. Use one anode per string as shown in figure D-9. Anode current density is computed as follows:

Output = 1.02/(10 x 0.03) = 0.34 A/sq ft.

Because this exceeds the recommended maximum anode current density shown in table D-1, the type B anode is the best choice.

(15) Find the stub anodes' resistance (from eq D-3):

$$R = \frac{0.012P \log (D/a)}{L},$$

where P = 4000 ohm-centimeter, D = 56 feet, L = 5 feet, and a = 16 0.275 = 4.4 feet (factor from fig D-10)

$$R = \frac{(0.012)(4000 \text{ ohm-centimeters}) \log (56 \text{ ft}/4.4 \text{ ft})}{5 \text{ ft}}$$

$$R = \frac{48 \log 12.73}{5}$$

$$R = \frac{48 \times 1.105}{5}$$

R = 10.6 ohms.

L/d = 60/1 = 60 < 100

Using the fringe factor from curve figure D-4, 0.90—

R (adjusted) = 10.6 x 0.90 = 9.54 ohms.

(16) Find the voltage drop in the stub anode circuit.

(a) The electrical conductor to the stub anodes is wire size No.2 AWG, rated at 0.159 ohm/1000 feet, and has an estimated length of 200 feet. Thus,

R = (200 ft/1000 ft) x 0.159 ohm/1000 ft = 0.032 ohm.

(b) To find the voltage drop in the stub anode feeder—

E = IR

where I = 1.02 amperes and R = 0.032 ohm. Thus,

E = 1.02 A x 0.032 ohm

E = 0.033 V.

(c) Find the voltage drop in anode suspension conductors. First, compute the resistance (R) for an estimated 50-foot-long, No.2 AWG wire rated at 0.159 ohm per 1000 feet:

R = (50/1000) x 0.159 = 0.008 ohm.

E = IR,

where I = 1.02/10 = 0.102 ampere and R = 0.008 ohm. Thus,

E = 1.02 A x 0.008 ohm

E = negligible.

(d) Find the voltage drop through the stub anodes given that the rectifier output is 80 volts, the anode current (I) is 1.02 amperes, and the resistance (R) is 9.54 ohms:

E = IR

E = 1.02 A x 9.54 ohms

E = 9.73 V.

(e) Find the total voltage drop in the stub anode circuit.

$E_T = 0.033 + 9.73$

$E_T = 9.76$ V.

(f) Since the stub anode voltage is below the 45 volts calculated for the main tank anode circuit, the necessary current adjustment can be made through a variable resistor in the stub anode circuit.

(17) Choose a stub anode circuit variable resistor.

(a) The resistor should be able to carry the maximum anode circuit current and have enough resistance to reduce the anode current by one-half when full rectifier voltage is applied to the anode circuit.

(b) Stub anode circuit data are: rectifier output = 80 volts, anode current = 1.02 amperes, and anode resistance = 9.54 ohms.

(c) The variable resistor rating is found by–

R = E/I,

where E = 80 volts and I = 1.02/2 or 0.51 ampere. Thus,

R=80/0.51

R = 156.9 ohms

Resistor's ohmic value = 156.9-9.54

= 147.4 ohms.

To find the resistor's wattage rating —

$P = I^2R$ (eq D-11)

$P = (1.02)^2 \times 147.4$

P = 153.4 W.

The commercially available resistor that nearest meets the above requirements is a 175-watt, 200-ohm, 1-ampere size.

(18) Find the riser anodes' resistance. To get the maximum desired current in the riser (3.62 amperes), the resistance limit is calculated as follows:

R = E/1,

where E = 43.45 volts and I = 3.62 amperes. Thus,

R = 43.5 V/3.62 A

R = 12.0 ohms

(19) Design the riser anode.

(a) Type FW (1-**C**-inch by 9-inch) string-type anodes cannot be used in the riser because the maximum anode current discharge of 0.025 ampere per anode would be exceeded. The number of type FW anodes required would be 145, placed continuously throughout the riser. This number is too high. The best choice of anode for a flexible riser string is type G-2 (2-inch by 9-inch) high-silicon cast-iron anode.

(b) The number of units required is found from equation D-3:

$$R = \frac{0.012P \log (D/d)}{L},$$

or

$$L = \frac{0.012P \text{ lob } (D/d)}{R},$$

where P = 4000 ohm-centimeters, D = 5 feet, d = 2 inches or 0.166 foot, and R = 12 ohms. Thus,

$$L = \frac{(0.012)(4000 \text{ ohm-cm}) \log (5 \text{ ft}/0.166 \text{ ft})}{12 \text{ ohms}}$$

$$L = \frac{48 \times \log 30.1}{12}$$

$$L = \frac{48 \times 1.479}{12}$$

L = 5.92 ft.

The nubmer of units is thus —

5.92/0.75 = 7.9 or 8 units.

For proper current distribution in the riser pipe, the anode units should not be placed too far apart. It is generally considered that each anode unit protects a length along the riser pipe equal to 1½ times the spacing of the anode from the riser pipe wall. Therefore, for a riser height of 115 feet, spacing (center of anode to tank wall) should be 2.5 feet. The riser length protected by one anode is 1.5 x 2.5 = 3.75 feet, so the number of units required is 115/3.75=30.7 or 31 units. To satisfy the maximum anode discharge current for a G-2 anode–

$$\frac{3.62 \text{ A}}{0.1 \text{ A}} = 36.$$

Therefore, 36 anodes are needed instead of 31 or 8.

(c) To find the anode resistance using 36 anode units, use equation D-3:

$$R = \frac{0.012P \log (D/d)}{L},$$

where P = 4000 ohm-centimeters, D =5 feet, d = 2 inches or 0.166 foot, and L =36 x 9 inches =324 inches or 27 feet. Thus,

$$R = \frac{(0.012)(4000 \text{ ohm-cm}) \log (5 \text{ ft}/0.166 \text{ ft})}{27 \text{ ft}}$$

$$R = \frac{48 \times \log 30.1}{27}$$

R = 2.63 ohms

The L/d ratio for the riser anode string is 324/2 or 162; thus, no fringe factor correction is used.

(20) Find the voltage drop in the riser anode circuit.

(a) Electrical conductor to riser anodes. For a wire size No.2 AWG, 0.159 ohm per 1000 feet, and estimated length 200 feet, the resistance (R) is–

$$R = \frac{200 \text{ ft}}{1000 \text{ ft}} \times \frac{0.159 \text{ ohm}}{1000 \text{ ft}}$$

R = 0.032 ohm.

(b) Find the voltage drop in riser anode feeder by–

E = IR,

where I = 3.62 amperes and R = 0.032 ohm. Thus,

E = 3.62 A 0.032 ohm

E = 0.116 V.

(c) Find the voltage drop in the riser anode suspension cables for wire size No.2 AWG, 0.159 ohm per 1000 feet rating, and estimated length 130 feet;

$$R = \frac{130\ \text{ft}}{1000\ \text{ft}} \times \frac{0.159\ \text{ohm}}{1000\ \text{ft}}$$

R = 0.02 ohm.

E = IR

where 1=3.62/2=1.81 amperes average (single current does not flow the full length of the anode string) and R = 0.02 ohm. Thus,

E = 1.81 A x 0.02 ohm

E = 0.04 V.

(d) Find the voltage drop through riser anodes:

E = IR,

where I = 3.62 amperes and R = 2.63 ohms. Thus,

E = 3.62 A x 2.63 ohms

E = 9.52 V.

(e) Find the total voltage drop in the riser anode circuit:

E_T = 0.116V + 0.04V + 9.52V

E_T = 9.68 volts.

(21) Select the riser anode circuit variable resistor.

(a) Criteria for the variable resistor are the same as given for the stub anode resistor.

(b) Riser anode circuit data — rectifier output = 80 volts, anode current = 3.62 amperes, anode resistance = 2.63 + 0.032+0.02 = 2.68 ohms.

(c) Variable resistor rating (resistor should reduce anode current by one-half when full rectifier voltage is applied)–

r = E/I,

where E = 80 volts and I = 3.62/2 = 1.81 amperes. Thus,

R = 80 V - l.18 A

R = 44.2 ohms.

Resistor ohmic value = 44.2 ohms -2.68 ohms = 41.5 ohms.

Resistor wattage rating = $(3.62\ A)^2$ x 41.5 ohms = 543.8 W.

(d) The commercially available resistor that nearest meets the size requirements is a 750-watt, 50-ohm, 3.87-ampere model. This rheostat is 10 inches in diameter and 3 inches deep and is fairly expensive. It will not fit into most rectifier cases. In addition, the rheostat consumes large amounts of power. This power generates heat that can damage components inside the rectifier case unless good ventilation is provided. The problems found with using a large rheostat can be overcome by using a separate rectifier for the riser anodes. Although initial cost may be slightly high, power savings will be substantial and heat damage will be avoided.

(22) Size the rectifier for the riser.

(a) Requirements—d.c. output = 3.62 amperes, anode circuit resistance = 2.68 ohms, d.c. voltage required = IR = 3.62 x 2.68 = 9.70 volts.

(b) Rectifier rating—standard ratings for a rectifier in this size class is 18 volts, 4 amperes.

(23) Find the rectifier d.c. rating for the bowl. Voltage output has been determined to be 80 volts. Current rating is 15.2 amperes. The commercially available rectifier that nearest meets the above requirements is 80 volts, 16 amperes.

(24) Determine wire sizes and types. All positive feeder and suspension cables (rectifier to anodes) must be No.2 AWG HMWPE insulated copper cable. To avoid complication, the negative rectifier cable (rectifier to structure) must be the same size and type (fig D-11).

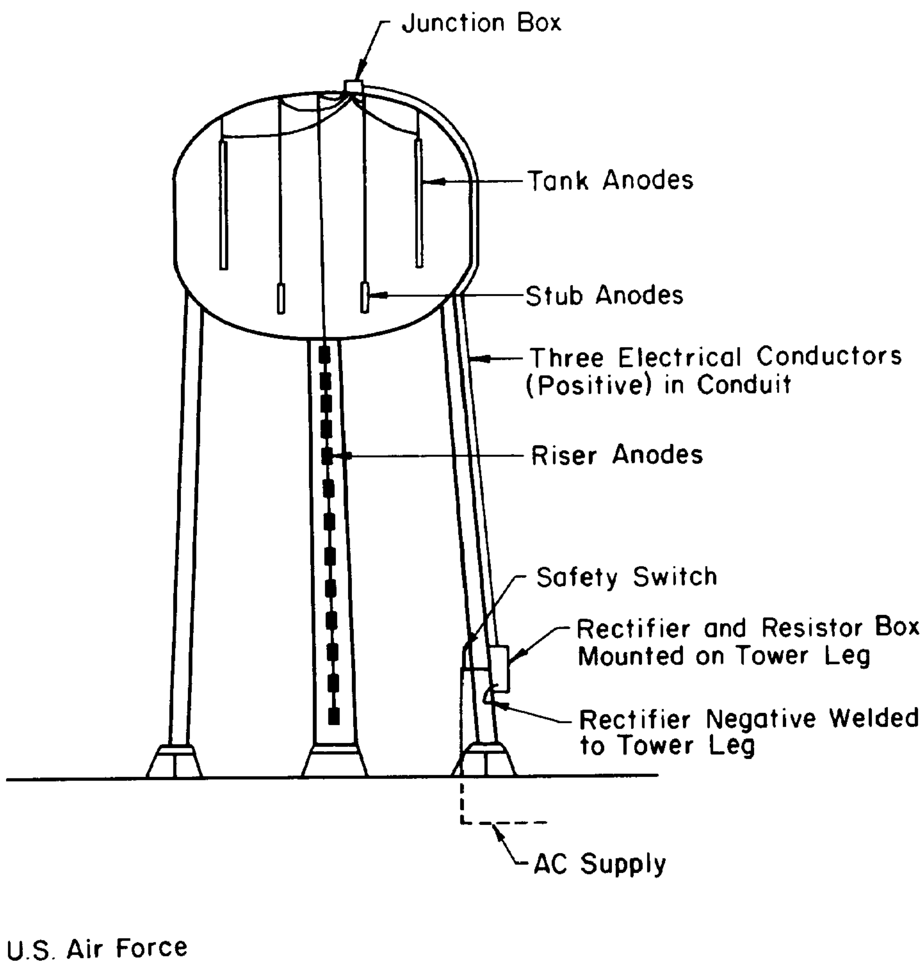

Figure D-11. Elevated steel water tank showing rectifier and anode arrangement.

(25) Discussion of design.

(a) The design points out the drawbacks of controlling corrosion through cathodic protection without the aid of a protective coating. For example, when the inside of a tank is coated, the current requirement is reduced 60 to 80 percent. On large tanks without coating, larger and more costly anodes, wire, and rectifier units must be used. In addition, the uncoated tank consumes far more power. These costs usually exceed the cost of a quality coating system over a 10-year period. Corrosion above the water line of a water storage tank is usually severe because condensation is corrosive. For this reason, protective coatings must be used above the water line on both large and small water storage tanks to slow corrosion.

(b) Figures D-11 through D-13 give more guidance in designing cathodic protection systems for elevated cold water storage tanks.

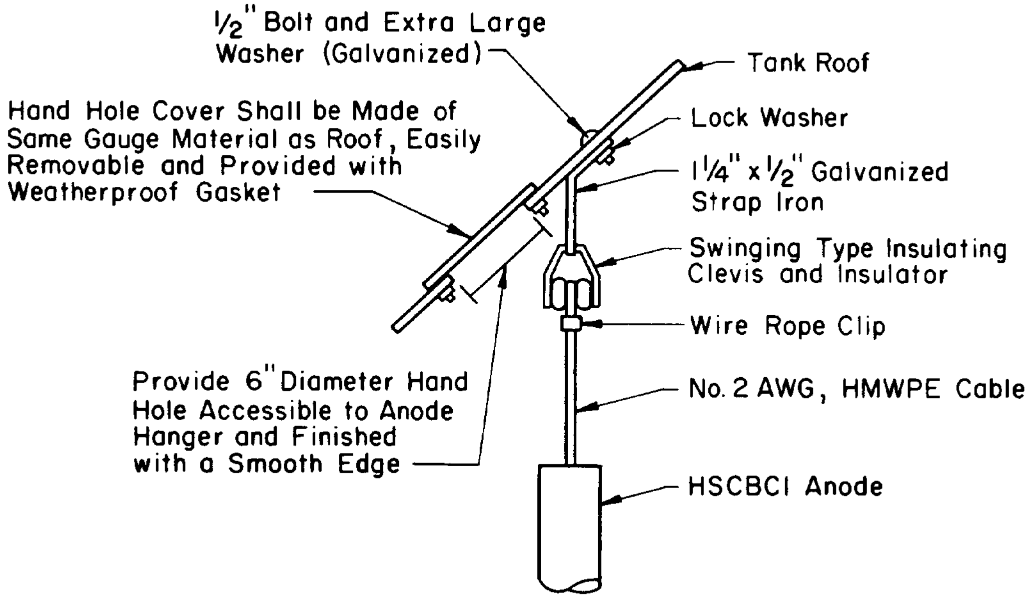

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Figure D-12. Hand hole and anode suspension detail for elevated water tank.

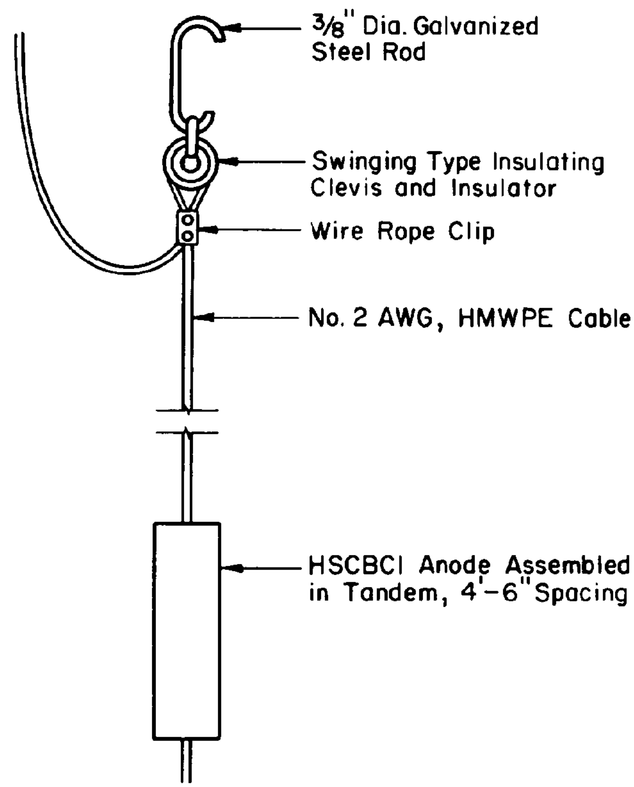

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Figure D-13. Riser anode suspension detail for elevated water tank.

(c) HSCBCI was chosen for this design purely as an example. It does not mean this material is better than other anode types. Other acceptable anode materials include aluminum and platinized titanium or niobium.

(d) For this design, silicon cells should be specified for the rectifier that protects the bowl, and selenium cells should be specified for the rectifier that protects the riser. Silicon cells operate more efficiently at high d.c. output voltages than selenium cells, but require elaborate surge and overload protection. This protection is not economical in the low power consuming units. A guide for choosing rectifying cells is as follows: use silicon cells for single-phase rectifiers operated above 72 volts d.c. or for three-phase rectifiers operated above 90 volts d.c.; use newer, nonaging selenium for single-phase rectifiers operated below 72 volts d.c. or three-phase rectifiers operated below 90 volts d.c.