

DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
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Engineering and Design
CATHODIC PROTECTION SYSTEM USING CERAMIC ANODES

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Engineer Technical
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1. Purpose: This letter provides criteria for the design of impressed current cathodic protection systems using ceramic anodes. The enclosure to this letter is the revised appendix E of TM 5-811-7: Electrical Design, Cathodic Protection.
2. Applicability: This letter applies to all HQUSACE/OCE elements and all Major Subordinate Commands (MSC) and District Commands (DC) having Army military design and construction responsibility.
3. Discussion: Development in ceramic anodes technology and the recent years of experience with ceramic anodes indicate that ceramic anodes can be used for general application. A wide variety of ceramic anodes are manufactured to satisfy various needs in the field of cathodic protection. The CEGS 16641 "Cathodic Protection Systems for Steel Water Tanks" and CEGS 16642 "Cathodic Protection Systems (Impressed Current)" permit the use of precious mixed metal oxide anodes but no design guidance is provided in TM 5-811-7 for the use of conductive ceramic coated titanium or mixed metal anodes. The enclosed design procedures will assist in design using these anodes.
4. Action to be taken: Where the application of an impressed cathodic protection system is required, the use of ceramic anodes should be considered. Where ceramic anode application has been the chosen type of cathodic protection, the enclosed design manual shall be used in the preparation of final design documents.
5. Implementation: This letter will have special application as defined in paragraph 6c, ER 1110-345-100.

FOR THE DIRECTOR OF MILITARY PROGRAMS:

Encl

RICHARD C. ARMSTRONG
Chief, Engineering Division
Directorate of Military Programs

**IMPRESSED CURRENT CATHODIC PROTECTION SYSTEMS
USING CERAMIC ANODES**

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CATHODIC PROTECTION DESIGN

1-1. Introduction.

Recently, ceramic coated anodes have been incorporated in cathodic protection systems. Ceramic or metal-oxide anodes have been used for cathodic protection since 1971 in Europe and since 1984 in the United States. One of the main advantage of ceramic anodes are that they are not consumed.

Ceramic anodes consist of various shapes of high purity titanium substrates with coatings of precious metal oxides tailored to the environment in which they will be used.

Unlike most other metal oxides (or ceramics), these metal oxides are conductive. Ceramic anodes are dimensionally stable. The ceramic coating is already oxidized (corroded). The current capacity is a function of constituent variables and is rated by the manufacturers. They have design life expectancies of up to 20 years at a rated current output. The life can be extended by a reduction in output current density. Their life is limited by time and current density. The end of the ceramic anode life is marked by a chemical change in the oxide form and a resultant loss in conductivity. Ceramic anodes are made in a variety of shapes for various applications. Among these are wire, rods, tubes, strips, discs, and mesh. Ceramic anodes have excellent ductility, which has eliminated the concern about mechanical damage during shipment and installation. Ceramic anodes are also a fraction of the size and weight of traditional anode materials.

Scratches or other minor physical damages to the coating result in the formation of an inert and nonconductive oxide of the substrate (titanium) when operated at less than 60 V in fresh water and underground applications. If they are installed in salt or brackish water, the DC design voltage should be limited to 12 V. The overall function of the anode is not significantly impaired.

1-2. Cathodic Protection Design Using Ceramic Anodes.

The following steps are involved in designing a cathodic protection system using ceramic anodes:

a. Collect data.

Design requirements should be established, and certain assumptions will be made.

1) History

Information from occupants in the area can indicate the severity of corrosion problems. Data on failures and failure rates of nearby structures can be invaluable and must be considered.

2) Drawings

Drawings of the structure to be protected and the area where it is or will be installed are needed to provide the physical dimensions of the structure for determining surface area to be protected, and locations of other structures in the area that may cause interference, of insulating devices, and of power sources. Information on coatings should be obtained.

3) Tests

Current requirement test and potential survey test results are needed for existing structures that will be protected. Electrolyte (soil or water) resistivity tests and evaluation of conditions that could support sulfate-reducing bacteria are needed for all cathodic protection designs. This information will indicate the size of the cathodic protection system that will be required as well as the probability of stray current problems. Soil resistivities contribute to both design calculations and location of the anode groundbed.

4) Life

The user must determine the required number of years that the structure needs to be protected, or the designer must assume a nominal life span. The structure will begin to deteriorate from corrosion at the end of the cathodic protection system's design life unless the system is rejuvenated.

5) Coatings

Cathodic protection complements the protective coating system. A good coating system substantially reduces the amount of cathodic protection current required. The coating efficiency has to be assumed.

6) Short circuits

All short circuits must be eliminated from both new and existing structures for which a cathodic protection system is being designed.

b. Calculate surface area to be protected.

The overall current requirement of a cathodic protection system is directly proportional to the surface area to be protected. This includes underground or submerged pipes, buried tanks, and wetted surfaces (up to high water(level) of watertanks (including risers)).

c. Determine current requirement.

For existing structures, a current requirement test will provide the actual current requirement at the time of the test. Allowance should be made in the design for future degradation of coatings or structure additions that will increase the current requirement.

For new structures not yet installed, the amount of current needed to provide protection as defined in National Association of Corrosion Engineers (NACE) RP-01-69 (reference 22) will be dependent on a number of variables. Table 3-1 gives guidelines for current requirements in various soil and water conditions.

The efficiency of the coating system, both when new and at the end of design life, is a determining factor in the range of current that will be required over the lifetime of the system. Total current required is given by the following equation:

$$I = (A)(I')(1.0 - C_E) \quad (\text{eq 1-1})$$

where I is the total current requirement, A is the total surface area to be protected, I' is the estimated current density, and C_E is the efficiency of the coating system. This procedure should always be followed, even when a

current requirement test has been performed, as a check on assumptions made. Current density may be estimated from information given in table 3-1.

d. Select anode type.

Ceramic anodes are made in a variety of shapes, such as, wires, rods, tubes, strips, disks, and mesh.

The 0.062-in. diameter anode wire has a 20-year life at a maximum current rating of 115 mA per linear ft in fresh water, 285 mA in salt water, and 170 mA in brackish water. Wire anodes are well suited for applications in water tanks. They are generally not used underground.

Ceramic rod anodes are manufactured bare for aqueous environments and prepackaged for installation in soil. Ceramic rod anodes are produced in diameters of 1/8 in., 1/4 in., 3/8 in. and 1/2 in. and in standard lengths of 4, 6, and 8 ft, although almost any length can be custom fabricated with self-healing screw connections for field assembly to the desired length, or with permanent, factory-molded, cable-to-anode connections. For underground applications, rods are frequently packaged in 2- or 3-in. diameter steel tubes filled with a high carbon, low resistivity coke breeze. Their small size and high current capacity make rods particularly well suited for both underground shallow and deep anode systems. For marine applications, the rod anode is often encased in a perforated PVC package that provides mechanical protection and prevents the possibility of the anode contacting the protected structure. They are used in a similar manner as high silicon cast iron and graphite anodes.

For long ceramic anode wires and rods, the voltage drop in the titanium substrate must be considered. While titanium is a relatively good metallic conductor, its resistance is approximately 33 times that of copper. The maximum length for solid titanium wire and rod anode applications to assure that uniform discharge of current is achieved in several different environments is provided below:

Maximum Anode Length From Connection Point

Solid Titanium Anodes

Anode Diameter 0.062 in. 0.125 in. 0.250 in.

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ENVIRONMENT	LENGTH (ft)		
Sea Water	3	5	9
Coke Breeze	6	10	20
Fresh Water	30	50	100

Where a specific design requires longer length anodes than provided for in the above table, the titanium wire or rod can be provided with a copper core to reduce the effective resistance. This type of construction has been in use for over 15 years and has proved to be very durable. The titanium wall thickness should be a minimum of 20 percent of the wire or rod diameter (e.g., for 0.062-in. diameter wire, the titanium wall thickness should be 0.0124 in., minimum)

The maximum allowable length for copper-core titanium wire and rod anodes is provided in the table below:

Maximum Anode Length From Connection Point

Copper Cored Titanium Anodes

Anode Diameter 0.062 in. 0.125 in. 0.250 in.

ENVIRONMENT	LENGTH (ft)		
Sea Water	7	12	24
Coke Breeze	12	24	54
Fresh Water	70	135	300

A strip anode is presently manufactured as a 3- or 7-ft bar of ceramic-coated substrate, molded into a multilayer composite of fiberglass-reinforced plastic (FRP) and polyurethane 4 or 8 ft long and 4 in. wide that provides impact resistance, mechanical support, and electrical insulation.

A mesh anode is produced using highly expanded titanium sheet metal and is used where a large area is to be protected, where area for anode placement is confined, and where future access is not practicable. Its use under a structure's base such as an on-grade tank bottom with secondary membrane containment or select reinforced concrete bridges, wharfs, etc., would be appropriate. Because of its size and the nature of its application, mesh is generally restricted to use in new facilities.

e. Calculate number of anodes (N) or length of bare anode wire (L_B).

1) For required design life

Since ceramic anodes are not consumed during their life, the quantity of ceramic material beyond that required to form a coating is not relevant. The number of anodes or length of anode wire required is determined from the total current required and the manufacturer's published current rating for a given life. For rod, strip, tube and disk anodes:

Number of anodes required =

$$\frac{\text{Total current required}}{\text{Manufacturers rated current for specific size, environment and life.}} \quad (\text{eq 1-2a})$$

2) For wire anodes:

Total footage of anode =

$$\frac{\text{Total current requirement}}{\text{Manufacturers rated current capacity per foot of wire for a given environment and life.}} \quad (\text{eq 1-2b})$$

The number calculated will determine the minimum number of anodes or anode wire length required.

f. Calculate the total circuit resistance (R_T).

The total circuit resistance (R_T) consists of the anode-to-electrolyte resistance (R_N) plus the interconnecting wire resistance (R_W) plus the structure-to-electrolyte resistance (R_C).

$$R_T = R_N + R_W + R_C \quad (\text{eq 1-3})$$

A criterion of 2-ohm maximum groundbed resistance is often used to limit the rectifier output voltage and the associated hazards of overprotection. When the total required current is low, a higher total resistance is often

acceptable. As the required current increases, the total resistance should be reduced. See table 3-10.

The total anode-to-electrolyte resistance (R_N) is calculated in different ways according to the type of anode installation. The anode-to-electrolyte resistance for a single anode is given by R_A .

For a single vertical anode:

$$R_A = \frac{(0.0052) p}{(L)} [\ln (8L/d)-1] \quad (\text{eq 1-4})$$

Where R_A is the anode-to-electrolyte resistance for a single anode, p is the electrolyte resistivity in ohm-cm, L is the length of the backfill column in feet, and d is the diameter of the backfill column in feet.

It should be noted that the anode dimensions are the overall length and diameter including backfill, if the backfill is coke breeze and is not significantly more than 2 ft longer than the anode or not significantly more than 20 ft longer than the anode column in a deep vertical groundbed configuration. For earth backfill, the backfill column dimensions should be the dimensions of the manufacturer's standard packaged anode can. Bare ceramic anodes shall not be installed in ground without coke breeze backfill. Coke breeze allows venting of gases and effectively reduces R_A .

If vertical anode dimensions are assumed to be 6 in. in diameter and 8 ft in length, the following empirical relations may be used:

$$R_A = \frac{p}{398} \quad (\text{eq 1-5})$$

If the anode dimensions are different, a different empirical relation may be used:

$$R_A = \frac{p K}{L} \quad (\text{eq 1-6})$$

where R_A is the anode-to-electrolyte resistance, p is the electrolyte resistivity in ohm-cm, L is the length of the backfill column in feet, and K is a shape function that is selected from table 3-4.

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Deep anode groundbed resistance graphs are available for deep vertical ground beds. (See figure 2-9a through 2-9c located in section 2-4.)

For a single horizontal anode:

$$R_A = \frac{(0.0052) p}{L} \left[\ln \frac{4L^2 + 4L \sqrt{(2h)^2 + L^2}}{2 d h} \right. \quad (\text{eq 1-7}) \\ \left. + \frac{2 h}{L} - \frac{\sqrt{(2 h)^2 + L^2}}{L} - 1 \right]$$

where R_A is the anode-to-electrolyte resistance in ohms, p is the electrolyte resistivity in ohm-cm, L is the length of the backfill cylinder in feet, d is the diameter of the backfill cylinder in feet, and h is the depth of the backfill cylinder in feet.

If the horizontal anode dimensions are assumed to be 6 in. in diameter, 8 ft long, and buried 6 ft below the surface, the following empirical expression may be used.

$$R_A = \frac{p}{441} \quad (\text{eq 1-8})$$

where R_A is the anode-to-electrolyte resistance in ohms and p is the electrolyte resistivity in ohm-cm.

For multiple vertical anodes:

$$R_N = \frac{(0.0052) p}{N L} [(\ln (8L/d) - 1) \\ + \frac{2 L}{C_c} \ln (.656 N)] \quad (\text{eq 1-9})$$

where R_N is the anode-to-electrolyte resistance, p is the electrolyte resistivity in ohm-cm, N is the number of anodes, L is the length of the backfill column in feet, d is the diameter of the backfill column in feet, and C_c is the center-to-center spacing of the anodes in feet. This equation assumes a linear configuration of the groundbed anodes.

If the number of anodes used does not produce a low enough anode-to-electrolyte resistance, the number of anodes will have to be increased accordingly.

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For optimum results, the length of the backfill column (L) should be less than the anode spacing (C_c).

If multiple anodes are assumed to be 6 in. in diameter and 8 ft long, the following empirical expression may be used:

$$R_N = \frac{p F_{ADJ}}{398} \quad (\text{eq 1-10})$$

where R_N is the anode-to-electrolyte resistance in ohms, p is the electrolyte resistivity in ohm-cm and F_{ADJ} is selected from table 3-9, which compensates both for the number and spacing of the anodes, which will be connected together as one groundbed.

If the anode dimensions are different, another empirical expression may be used:

$$R_N = \frac{R_A}{N} + \frac{p P_F}{C_c} \quad (\text{eq 1-11})$$

where R_N is the anode-to-electrolyte resistance, R_A is the anode-to-electrolyte resistance for a single anode, p is the soil resistivity in ohm-cm, N is the number of anodes used, P_F is a paralleling factor selected from table 3-5, and C_c is the center-to-center spacing of anodes in feet. This equation assumes a linear configuration of the groundbed anodes.

For multiple horizontal anodes:

$$R_N = \frac{p F_{ADJ}}{441} \quad (\text{eq 1-12})$$

where p is the electrolyte resistivity in ohm-cm and F_{ADJ} is an adjusting factor for groups of anodes selected from table 3-9.

For a circle of rod anodes (as in a water storage tank):

where R_N is the anode-to-electrolyte resistance, p is the electrolyte resistivity in ohm-cm, L_B is the length of each

$$R_N = \frac{0.0052 \times p \times \ln [D/2 A_R \times D_E]}{L_B} \quad (\text{eq 1-13})$$

rod anode in feet, D is the tank diameter in feet, A_R is the radius of the anode circle in feet, and D_E is an equivalent diameter factor from figure 2-17.

For wire anode circle or hoop (in a water storage tanks):

$$R_N = \frac{0.0016 p}{D_R} \left(\ln \frac{8D_R}{D_A} + \ln \frac{2 D_R}{H} \right) \quad (\text{eq 1-14})$$

where R_A is the anode-to-electrolyte resistance, p is the electrolyte resistivity, D_R is the diameter of the anode circle in feet, D_A is the diameter of the anode wire in feet, and H is the depth below the high water level in feet.

Experience has shown that the diameter of the anode wire circle (D) should be typically between 40 and 70 percent of the tank diameter.

Wire resistance (R_W) is the sum of both the rectifier-to-anode lead and the rectifier-to-protected-structure lead.

$$R_W = \frac{L_W R_{MFT}}{100 \text{ ft}} \quad (\text{eq 1-15})$$

where L_W is the length of wire in thousands of feet and R_{MFT} is the resistance of the wire in ohms per 1000 ft.

The structure-to-electrolyte resistance (R_C) is dependent primarily on the condition of the coating.

$$R_C = \frac{R_S}{A} \quad (\text{eq 1-16})$$

where R_s is the coating resistance in ohm-square feet and A is the total surface area. If the structure surface is bare, negligible resistance is assumed ($R_c = 0$).

- g. Calculate required rectifier voltage and current.

The required rectifier voltage (V_{REC}) and maximum current rating should include at least an extra 20 percent to allow for variations in calculations from actual conditions and for changes in the system over the system's life.

$$V_{REC} = (I) (R_T) (1.2) \quad (\text{eq 1-17})$$

where I is the total current required and R_T is the total circuit resistance as calculated above.

$$I_{REC} = (I) (1.2) \quad (\text{eq 1-18})$$

where I is the total current required and I_{REC} is the minimum current rating for a rectifier for this particular application.

Select a rectifier with DC voltage and current capacity of a slightly larger size (as calculated above) from the cathodic protection rectifier manufacturer's published literature.

- h. Prepare life cycle cost analysis.

The life cycle cost analysis should be prepared according to the guidelines given in TM 5-802-1 (reference 9). Another source of information on performing life cycle cost analyses is NACE RP-02-72 (reference 21). The choice of a particular anode type and configuration for design calculation is somewhat arbitrary. The economics may dictate switching to a different design configuration and repeating the applicable design steps.

- i. Prepare plans and specifications.

Prepare plans that show the protected structure, locations of anodes, rectifier, test stations, and power source, wire routing, and details of wire-to-structure connections, building or structure penetrations, wire color coding, potential survey test points in paved areas, and other pertinent information. Prepare a one-line diagram to show the entire system including wire sizes, anode type(s), power circuit, power circuit protection, and source of

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power. Prepare specifications to describe required features of the system components.

1-3. References.

The following documents describe corrosion fundamentals, traditional corrosion control techniques, and particular requirements of U.S. Department of Defense agencies:

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22. NACE RP-01-69, "Recommended Practice - Control of External Corrosion on Underground or Submerged Metallic Piping Systems" (National Association of Corrosion Engineers, Houston, 1969)

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23. NACE RP-02-85, "Recommended Practice - Control of External Corrosion on Metallic Buried, Partially Buried, or Submerged Liquid Storage Systems" (National Association of Corrosion Engineers, Houston, 1985).
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EXAMPLES OF IMPRESSED CURRENT CATHODIC PROTECTION DESIGN

2-1. Purpose.

The following examples show the use of design procedures explained in the previous section:

- 2-2 Steel fuel oil lines
- 2-3 Underground storage tanks
- 2-4 On-grade tank bottoms
- 2-5 Gas distribution systems
- 2-6 Elevated water tanks (ice is expected)
- 2-7 Elevated water tanks (no icing will occur)
- 2-8 On-grade water storage reservoir (ice is expected)

2-2. Steel Fuel Oil Lines.

Impressed current cathodic protection is desired for the 6-in. welded fuel oil line shown in figures 2-1A and 2-1B. Since this pipeline is in existence, current requirement tests have already been made. There are no other underground structures in the area, so a surface point groundbed is chosen. Figure 2-2 illustrates a surface point groundbed anode system using prepackaged ceramic rod anodes. These prepackaged ceramic rod anodes are further detailed in figures 2-3 and 2-4.

a. Design data.

- 1) Soil resistivity in area where groundbed is desired is 2000 ohm-cm.
- 2) Pipe has 6-in. diameter (outside diameter = 6.625 in.)
- 3) Pipe length is 6800 ft.
- 4) Design life for cathodic protection anodes is 15 years since the structure will no longer be needed after that time.
- 5) Design current density is 2-mA per sq ft of bare pipe.
- 6) The pipe is coated with hot-applied coal-tar enamel.
- 7) 90 percent coating efficiency based on previous experience with this type coating.

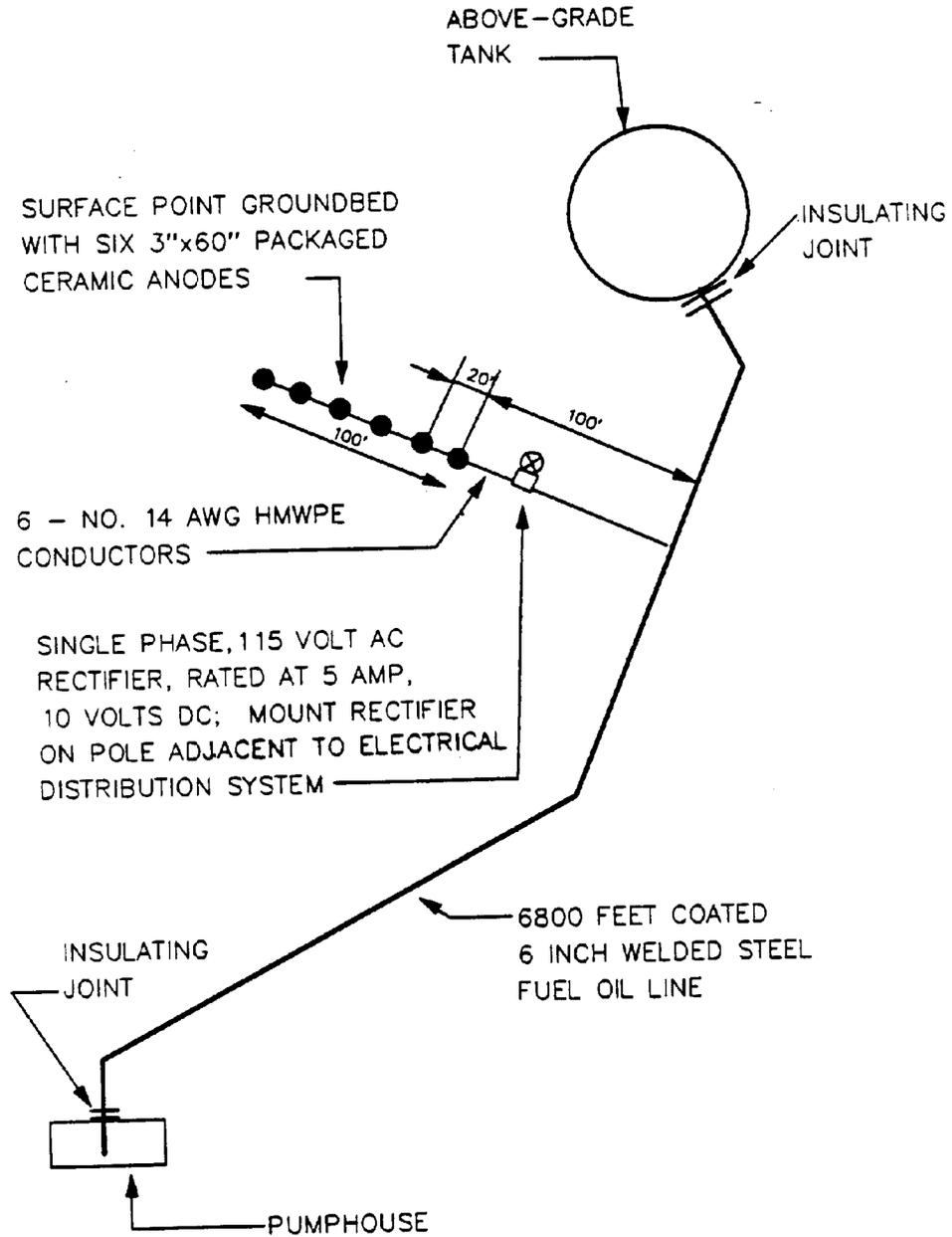


Figure 2-1A Cathodic Protection System for Fuel Oil Line With Anode Bed Extended Perpendicular From Pipeline

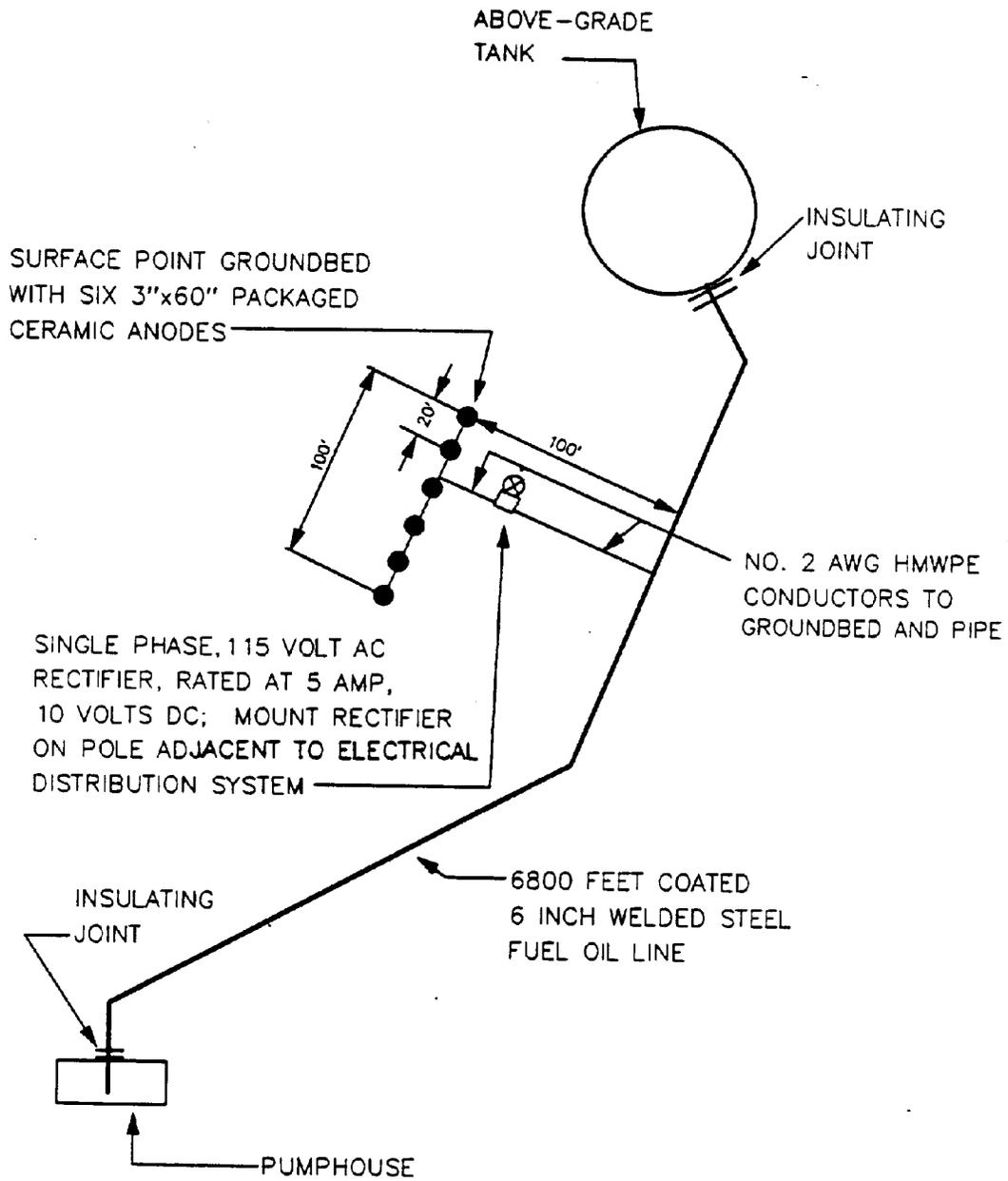


Figure 2-1B Cathodic Protection System for Fuel Oil Line With Anode Bed Installed Parallel to Pipeline

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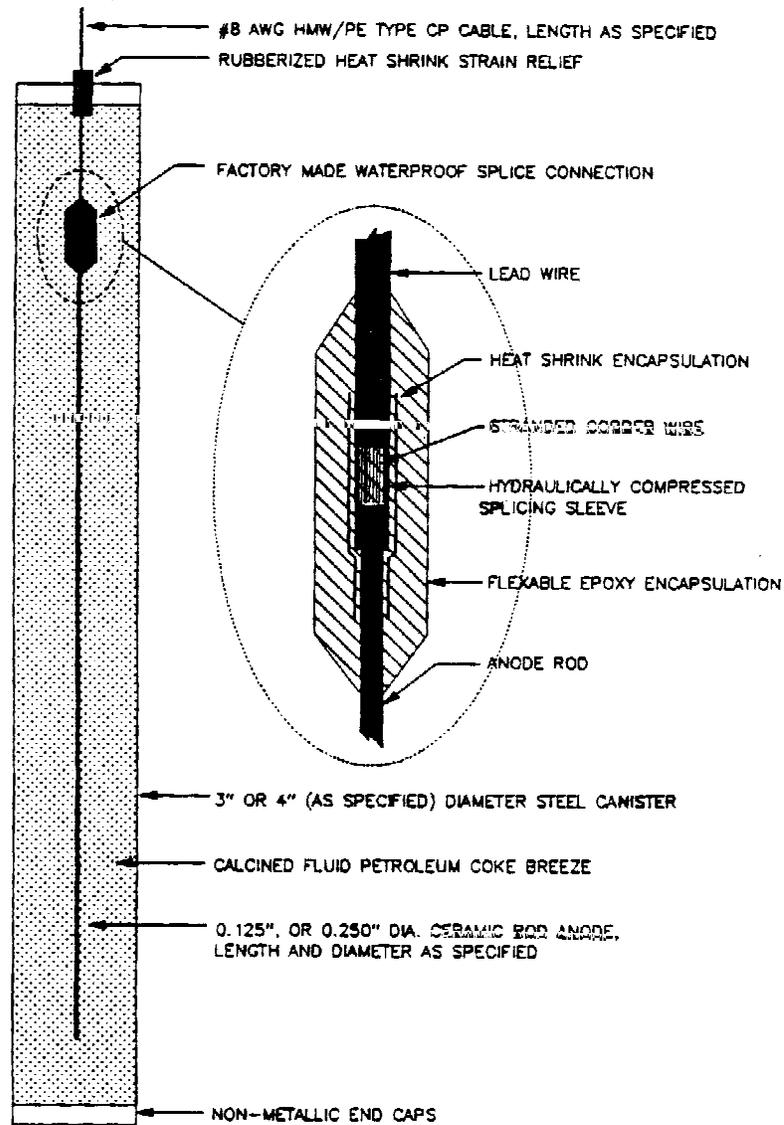


Figure 2-3 Prepackaged Ceramic Rod Anode for Underground Use

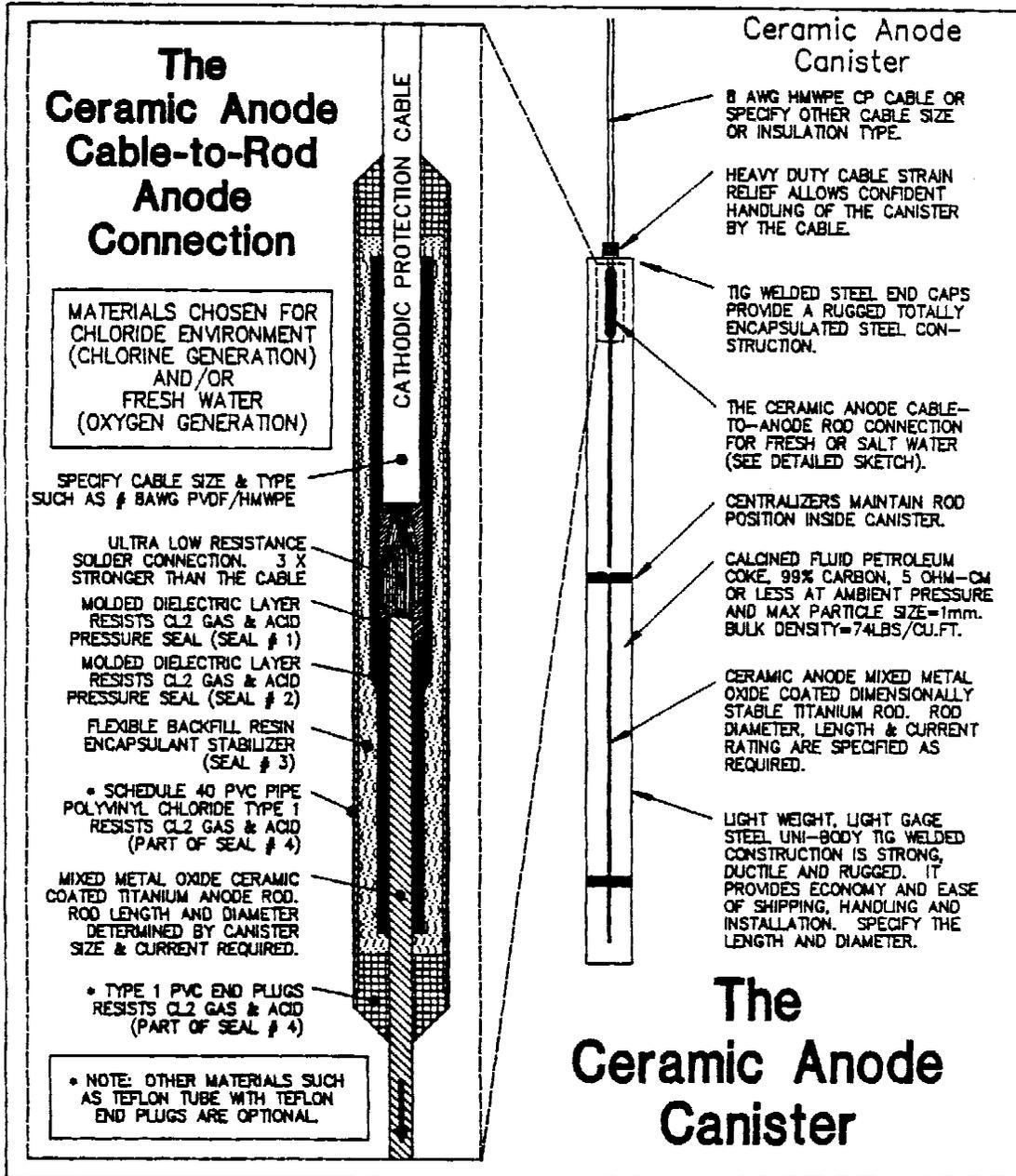


Figure 2-4 Ceramic Anode Canister Prepackaged Rod

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- 8) Effective coating resistance at 15 years is estimated at 2500 ohm-sq ft.
- 9) The pipeline is isolated from the pumphouse and tank with insulating joints.
- 10) For this example, we have decided that the cathodic protection system circuit resistance should not exceed 2.5 ohms.
- 11) Electric power is available at 120/240 V single phase AC from a nearby overhead distribution system.
- 12) Current requirement testing indicates that 2.8 amp are needed for adequate cathodic protection.

b. Computations.

- 1) Calculate the external surface area of the pipe.

Pipe diameter = 6 in.

Pipe length = 6800 ft

Pipe surface
area per lin ft = 1.734 sq ft/lin ft (from
table 3-2)

External pipe
surface area = 6800 lin ft x 1.734 sq
ft/lin ft = 11,791 sq ft

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

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

Where:

A = 11,791 sq ft - External pipe surface
area from previous calculation.

I' = 2 mA/sq ft - Required current density
from item 5 of paragraph 2-2a.

C_E = 0.90- Coating efficiency expressed in
decimal form from item 7 of paragraph
2-2a.

I = 11,791 sq ft x 2 mA/sq ft x (1.0 -
0.90)

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$$I = 2358 \text{ mA or approximately } 2.4 \text{ amp}$$

which agrees well with the current requirement test data provided in item 12 of paragraph 2-2a.

- 3) Select an anode and calculate the number of anodes required (N) to meet the design life requirements. Two sizes are selected for trial calculations using equation 1-2:

$$N = \frac{I}{I_A}$$

Where:

$$I = 2.8 \text{ amp (Current requirement from item 12 of paragraph 2-2a)}$$

$$I_A = \text{Current rating per anode, varies depending on anode size from table 3-3.}$$

Several different size anodes could be chosen. Experience has shown that for this type of groundbed, 60-in. long anode packages are desirable.

For a 3-in. by 60-in. packaged canisters with a 1/8-in. by 48-in. ceramic anode rod, $I_A = 1.2$ amp/anode (from table 3-3 for 15-year design life).

$$N = \frac{2.8}{1.2} = 2.33; \text{ use 3 anodes.}$$

For a 3-in. by 60-in. packaged canister with a 1/4-in. by 48-in. ceramic anode rod, $I_A = 2.4$ amp/anode (from table 3-3 for a 15-year design life).

$$N = \frac{2.8}{2.4} = 1.17; \text{ use 2 anodes.}$$

- 4) Calculate the resistance of a single anode-to-earth (R_A) from equation 1-6:

$$R_A = \frac{p K}{L}$$

Where:

$$p = 2000 \text{ ohm-cm (Soil resistivity in area where groundbed is desired from item 1 of paragraph 2-2a)}$$

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K = 0.0213 (Shape function, from table 3-4
[where: L/d = 60 in./3 in. = 20])

L = 5 ft (Effective anode length [canister
length])

d = 3 in. (Anode backfill diameter [canis-
ter diameter])

$$R_A = \frac{2000 \times 0.0213}{5}$$

R_A = 8.53 ohms

- 5) Calculate the number of anodes required to meet maximum anode grounded-to-earth resistance requirements from equation 1-11:

$$R_N = \frac{R_A}{N} + \frac{p P_F}{C_c}$$

Where:

R_N = Groundbed-to-earth resistance.

R_A = 8.53 ohms (Resistance of a single
anode-to-earth from the previous
calculation)

N = Assume 5 anodes (discussed below)

p = 2000 ohm-cm (Soil resistivity)

P_F = 0.00268 (Paralleling factor from table
3-5 [discussed below])

C_c = 20 ft (Center-to-center spacing of
anodes [discussed below])

To determine P_F, a figure for N must be assumed. This paralleling factor compensates for mutual interference between anodes and is dependent on spacing. From the law of parallel circuits, it appears that five anodes might give the desired circuit resistance of 2.0 ohms maximum, i.e.:

$$\frac{8.53 \text{ ohms/anode}}{5 \text{ anodes}} = 1.706 \text{ ohms}$$

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This is the approximate resistance based on the law for parallel circuits. (When equal resistance values are joined together in a parallel circuit, the total resistance value of the circuit is approximately equal to a single resistance value divided by the number of resistance values.)

To calculate the true anode resistance for five anodes, we must perform the calculation from equation 1-11.

$C_c = 20$ ft (The spacing must be chosen based on previous experience to solve the equation.) The spacing can typically be from 10 to 50 ft. For this example, we will try 20 ft:

$$R_N = \frac{8.53}{5} + \frac{2000 \times 0.00268}{20}$$

$$R_N = 1.706 + 0.268$$

$$R_N = 1.974 \text{ ohms}$$

This is within specification, but very close to exceeding maximum specified circuit resistance. Try six anodes to allow for variations in soil resistivity and to allow for wire and pipe-to-earth resistance. Repeat calculation from equation 1-11,

Where:

$$N = 6 \text{ anodes}$$

$$P_F = 0.00252, \text{ paralleling factor from table 3-5}$$

$$R_N = \frac{8.53}{6} + \frac{2000 \times 0.00252}{20}$$

$$R_N = 1.67 \text{ ohms}$$

- 6) Based on the previous selection of six anodes for the number of anodes to be used, the total circuit resistance must be determined.
- 7) Select an area for anode bed placement. Here, the selected area is 100 ft from the pipeline for improved current distribution. The anode bed location for this type design must be far enough away from the structure

to be protected to assure uniform distribution of the protective current to all structure components. The higher the soil or water resistivity, the further away the ground must be located. For this example, previous experience has shown that the nearest anode should be located a minimum of 100 ft from the structure to assure good current distribution. Since there are no other underground utilities in the area, the groundbed may be installed either perpendicular or parallel to the pipe (figures 2-1A and 2-1B).

- 8) Determine the total circuit resistance (R_T) from equation 1-3:

$$R_T = R_N + R_W + R_C$$

Where:

- R_N = Groundbed resistance-to-earth (ohms)
 R_W = Header cable and resistance (ohms)
 R_C = Pipe-to-earth resistance (ohms)

- a) Groundbed-to-earth resistance (R_N) from step 5.

$$R_N = 1.67 \text{ ohms}$$

Specify anodes with individual lead wires of sufficient length so that each anode wire can be run directly to the rectifier without splices. (This is virtually always true for anode bed designs where the individual lead wire lengths required do not exceed an average of 400 ft.)

- b) Anode lead wire resistance from equation 1-15:

c

$$R_W = \frac{L_W R_{MFT}}{1000 \text{ ft}}$$

Where:

- L_{AVG} = Total of each actual lead wire lengths/number of anodes
= (140 ft + 120 ft + 100 ft + 80 ft + 60 ft + 40 ft)/6 anodes
= 90 ft per anode
- L_W = L_{AVG}/N
= 90/6
= 15 ft

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$$= \text{Average anode lead wire length/} \\ \text{number of anodes. This is based} \\ \text{on the circuit resistance for 6} \\ \text{anode lead wires in parallel.}$$

$$R_{MFT} = 2.58 \text{ ohms} - \text{Resistance for No.} \\ \text{14 AWG cable which has been} \\ \text{selected from table A-6.}$$

$$R_W = \frac{15 \text{ ft} \times 2.58 \text{ ohms}}{1000 \text{ ft}}$$

$$R_W = 0.039 \text{ ohms}$$

c) Pipe-to-earth resistance (R_C) from equation 1-16:

$$R_C = \frac{R_S}{A}$$

Where:

$$R_S = 2500 \text{ ohm-sq ft} - \text{Effective} \\ \text{coating resistance from item 8} \\ \text{of paragraph 2-2a.}$$

$$A = 11,791 \text{ sq ft} - \text{External} \\ \text{pipe surface area calculated in} \\ \text{step 1 of paragraph 2-2b.}$$

$$R_C = \frac{2500 \text{ ohm-sq ft}}{11,791 \text{ sq ft}}$$

$$R_C = 0.212 \text{ ohm}$$

d) Calculate the total circuit resistance (R_T) from equation 1-3:

$$R_T = R_N + R_W + R_C$$

$$R_T = 1.67 + 0.039 + 0.212$$

$$R_T = 1.921 \text{ ohms}$$

e) Since the design requirements call for a maximum allowable groundbed resistance of 2.0 ohms and $R_T = 1.921$ ohms, the design using six (3-in x 5-ft) ceramic anode canisters will work.

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- 9) Calculate the rectifier voltage (V_{REC}) from equation 1-17:

$$V_{REC} = (I) (R_T) (120\%)$$

Where:

$$I = 2.8 \text{ amps (Current requirement from item 12 of paragraph 2-2a.)}$$

$$R_T = 1.92 \text{ ohms (Total circuit resistance from previous calculation.)}$$

$$120\% = \text{Rectifier voltage capacity design safety factor.}$$

$$V_{REC} = 2.8 \text{ amp} \times 1.92 \text{ ohms} \times 1.2$$

$$V_{REC} = 6.45 \text{ V}$$

- c. Select rectifier.

Based on the design requirement of 2.8 amperes and 6.45 volts, specify a 10-V, 5-amp rectifier, which is the nearest standard capacity available from commercial cathodic protection rectifier manufacturers.

2-3. Underground Storage Tanks (USTs).

The service station shown in figure 2-5 has three existing underground tanks and associated pipe. The quality of the coating is unknown and it is not feasible to install dielectric insulation to isolate the UST system. Because of the anticipated large current requirement, an impressed current protection system is chosen. To distribute the current evenly around the tanks and piping, and to minimize interference effects on other structures, a distributed anode surface bed using vertical anodes is selected. Vertical anodes can be installed with relative ease in holes cored through the paving around the UST system. Wiring can be installed several inches below the paving by cutting and hand excavating narrow slots/trenches through the paving.

a. Design data.

- 1) Soil resistivity is 4500 ohm-cm.
- 2) Pipe is 2 in., nominal size. Total length of all buried piping is 750 ft.
- 3) Tanks are 8000 gal, 96 in. diameter by 21 ft 3 in. long.
- 4) Electrical continuity of tanks and piping has been assured.
- 5) It is not feasible to install dielectric insulation; system is therefore not isolated electrically from other structures.
- 6) Design cathodic protection anodes for 20-year life.
- 7) Coating quality is unknown, assume bare.
- 8) The cathodic protection system circuit resistance should not exceed 2.5 ohms.
- 9) Electric power is available at 120 V single phase in the station building.
- 10) Current requirement test indicates that 8.2 amperes are needed for cathodic protection.

b. Computations.

- 1) Find the external surface area (A) of the storage tanks and piping.

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Area of each tank = $2 \mathbf{B} (\text{tank radius})^2 + \mathbf{B} (\text{tank diameter}) (\text{tank length})$

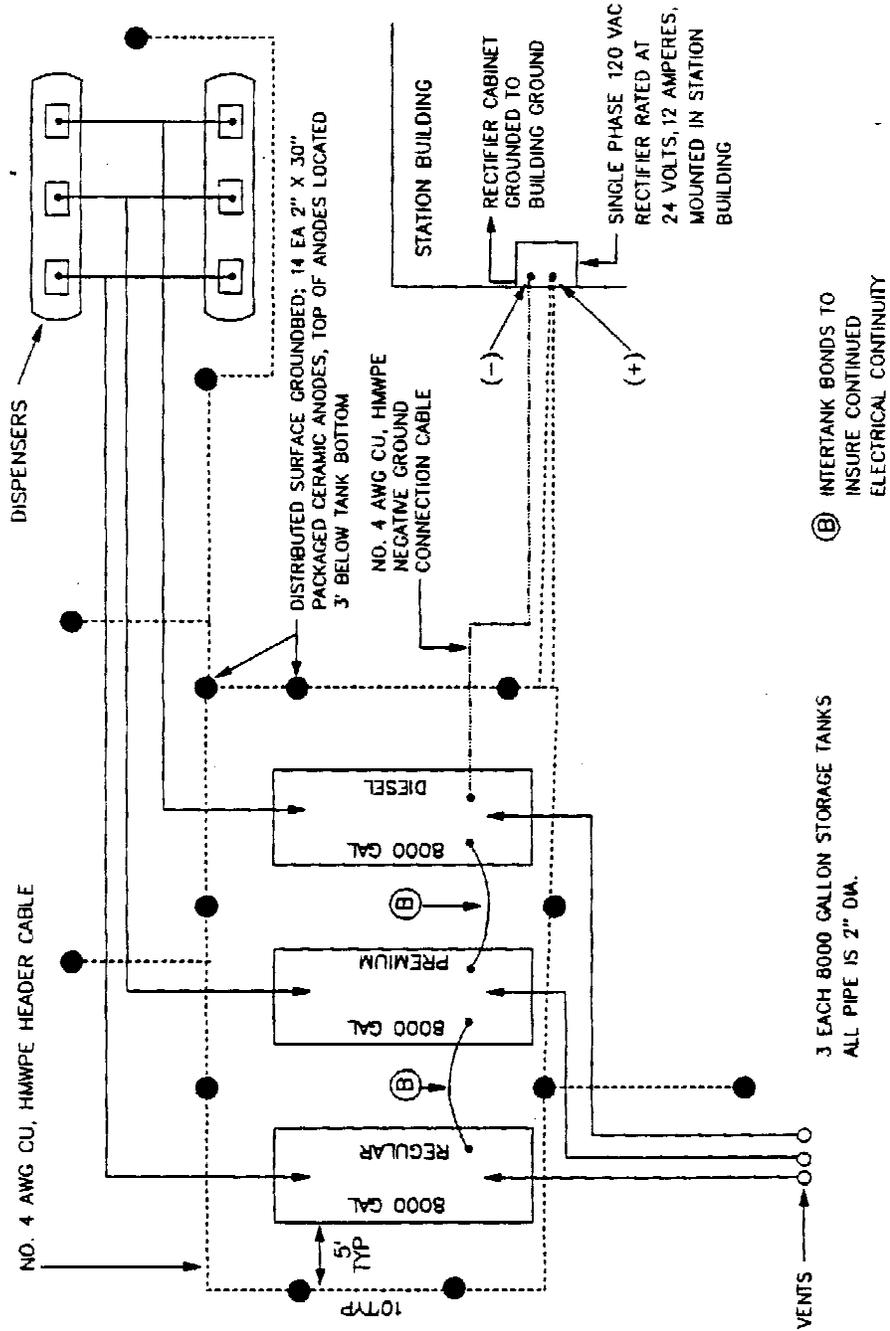


Figure 2-5 Cathodic Protection for Underground Storage Tanks and Piping

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$$\begin{aligned} \text{Area of 3 tanks} &= 3 [2 \times 3.14 \times 4^2 + 3.14 \times 8 \times 21.25] \\ &= 1905 \text{ sq ft} \end{aligned}$$

$$\text{Area per lin ft of 2-in. pipe} = 0.621 \text{ sq ft/ft (from table A-2)}$$

$$\text{Total pipe area} = 750 \text{ ft} \times 0.621 \text{ sq ft/ft} = 466 \text{ sq ft}$$

$$\text{Total area} = 1905 \text{ sq ft} + 466 \text{ sq ft} = 2371 \text{ sq ft}$$

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

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

Where:

$$A = 2371 \text{ sq ft (External tank and piping surface area from previous calculation)}$$

$$I' = 2 \text{ mA/sq ft (Required current density [assumed])}$$

$$C_E = 0.00 \text{ (Coating efficiency expressed in decimal form from item 2 of paragraph 2-3a)}$$

$$I = 2371 \text{ sq ft (2 mA/sq ft)} \times (1.0 - 0.0)$$

$$I = 4742 \text{ mA or 4.7 amp.}$$

The 4.7 amp would be reasonable for the facility if it were insulated. The actual current requirement of 8.2 amp occurs because of current loss to other underground structures and is also reasonable in relation to that calculated for an isolated facility.

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

Calculations can be run on several size anodes, but in this case 2-in. by 60-in. packaged rod anodes (rod size = 0.125 in x 4 ft long) are chosen for ease of construction. Using equation 1-2, the number of anodes required to meet the cathodic protection system design life can be calculated:

$$N = \frac{I}{I_A}$$

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Where:

$$I = 8.2 \text{ amp (Current requirement from item 10 of paragraph 2-3a)}$$

$$I_A = 1.0 \text{ amps/anode (Current rating per anode from table 3-3)}$$

$$N = \frac{8.2}{1.0} = 8.2 \text{ anodes; use nine, 2-in. by 60-in. packaged rod anodes}$$

- 4) Calculate the resistance of a single anode-to-earth (R_A) from equation 1-6:

$$R_A = \frac{p K}{L}$$

Where:

$$P = 4500 \text{ ohm-cm (Soil resistivity from item 1 of paragraph 2-3a)}$$

$$K = 0.0234 \text{ (Shape function from table A-4 [where: } L/d = 60 \text{ in./2 in.} = 30])}$$

$$L = 5 \text{ ft (60 in.) (Effective anode length).}$$

$$d = 2 \text{ in. (Anode/backfill diameter)}$$

$$R_A = \frac{4500 \times 0.0234}{5}$$

$$R_A = 21.06 \text{ ohms}$$

- 5) Calculate the number of anodes required to meet maximum anode groundbed resistance requirement. A distributed anode array does not lend itself to an exact calculation of equation 1-11 because the anodes are positioned at various locations and are not located in a straight line. Equation 1-11 assumes a straight line configuration. However, to approximate the total anode-to-earth resistance, equation 1-11 may be used.

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$$R_N = \frac{R_A}{N} + \frac{p P_F}{C_c}$$

Where:

- R_N = Groundbed-to-earth resistance
- R_A = 21.06 ohms (Resistance of a single anode-to-earth from the previous calculation)
- p = 4500 ohm-cm (Soil resistivity from item 1 of paragraph 2-3a)
- C_c = 10 ft (Estimated approximate spacing of anodes)
- P_F = 0.00212 (Paralleling factor from table 3-5; assume 9 anodes; reasoning is the same as in step 5, paragraph 2-2b)
- N = 9 anodes (Estimated number of anodes required; from step 3, paragraph 2-2b)
- R_N = $\frac{21.06}{9} + \frac{4500 \times 0.00212}{10}$
- R_N = 3.29 ohms.

Resistance is too high. Additional calculations using an increasing number of anodes (i.e., 11, 12, 13, 14, etc.) have to be made; these calculations show that fourteen anodes will yield a groundbed-to-earth resistance of 2.26 ohms.

- 6) Select the number of anodes to be used. The numbers determined are:

For life = nine anodes maximum required
For resistance = fourteen anodes maximum required

Therefore, the larger number of anodes, fourteen, is selected.

- 7) Determine the total circuit resistance (RT) from equation 1-3:

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$$R_T = R_N + R_W + R_C$$

Where:

- R_N = Groundbed resistance (ohms)
 R_W = Header cable/wire resistance (ohms)
 R_C = Structure-to-earth resistance (ohms).

- a) Groundbed resistance (R_N) from step 5.

$$R_N = 2.26 \text{ ohms}$$

- b) Header cable/wire resistance (R_W) from equation 1-15:

$$R_W = \frac{L_W R_{MFT}}{1000 \text{ ft}}$$

Where:

L_W = 150 ft (Effective cable length. The loop circuit makes calculating effective wire resistance complex. Since current is discharged from anodes spaced all along the cable, one-half the total cable length may be used to approximate the cable resistance. Total cable length = 300 ft. Effective cable length = $\frac{1}{2}$ (300 ft) = 150 ft.)

R_{MFT} = 0.254 ohm (This is the resistance per 1000 lin ft of No. 4 AWG cable, which has been selected for ease of handling.)

$$R_W = \frac{150 \text{ ft} \times 0.254 \text{ ohm}}{1000 \text{ ft}}$$

$$R_W = 0.038 \text{ ohm; use } 0.04 \text{ ohm}$$

- c) Structure-to-earth resistance.

Since the tanks and piping are essentially bare and are not electrically isolated, structure-to-earth resistance may be considered negligible. Therefore $R_C = 0$.

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- d) Calculate total circuit resistance (R_T) from equation 1-3:

$$R_T = R_N + R_W + R_C$$

$$R_T = 2.26 + 0.04 + 0 = 2.30 \text{ ohms}$$

Since the design requirements call for a maximum grounded resistance of 2.5 ohms and $R_T = 2.30$ ohms, the design using fourteen 2-in. by 60-in. packaged ceramic anodes will work.

- 8) Calculate the rectifier voltage (V_{REC}) from equation 1-17:

$$V_{REC} = (I) (R_T) (120\%)$$

Where:

$I = 8.2$ amp (Current requirement from step 2, paragraph 2-3b)

$R_T = 2.30$ ohms (Total circuit resistance from previous calculation)

120% = Rectifier voltage capacity design safety factor.

$$V_{REC} = 8.2 \text{ amp} \times 2.30 \text{ ohms} \times 1.2$$

$$V_{REC} = 22.6 \text{ V}$$

c. Select rectifier.

Based on the design requirement of 22.6 V and 8.2 amp, a rectifier can be chosen. A 12-amp, 24-V unit is selected because this is the nearest standard commercial size available.

2-4. On-Grade Tank Bottoms.

Four on-grade fuel oil storage tanks are to be constructed with the configuration shown on figure 2-6. This design may be prohibited if secondary containment uses a nonconductive membrane beneath the tanks. The membrane would not allow the cathodic protection current to flow from the remotely located deep anode through the nonconductive membrane to the tank bottoms. If this situation exists, a distributed anode design with the anodes located between the membrane and the tank bottoms would have to be used. All piping will be above grade. To minimize the extent of underground cable, it was decided to use a deep anode groundbed, located just outside the spill containment dikes. (Note: Some county, state, or federal agencies such as the EPA may have regulations that affect the use of deep anode beds because they can provide a conduit for the mixing of water between aquifer levels. In such cases, regulations have sometimes required cementing of the annulus between the deep anode bed casing and the augered hole to prevent this water migration. The system designer should check with the applicable agencies before committing to a deep anode design. Figures 2-7, 2-7A, 2-8, and 2-8A illustrate a typical deep anode groundbed using ceramic rod anodes. The tank bottoms will be bare. All piping will be above ground. The tanks will be dielectrically insulated from the structures. Field tests were made at the site and the subsurface geology was determined to be suitable for a deep anode groundbed (reference 25).

a. Design data.

- 1) Soil resistivity at anode depth is 1500 ohm-cm.
- 2) Tanks are 75 ft in diameter.
- 3) Design cathodic protection anodes for a 15-year life.
- 4) Design current density is 2 A per sq ft of tank bottom.
- 5) Since the tanks are electrically isolated from each other, intertank bonds will be required.
- 6) The cathodic protection system circuit resistance should not exceed 0.75 ohm.
- 7) Electric power is available at a switch rack in an unclassified (nonexplosion proof) area 125 ft from the desired groundbed location, 230 V AC, single phase.

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- 8) Since the exterior bottom of these type tanks are always bare, the coating efficiency will equal 0.00.

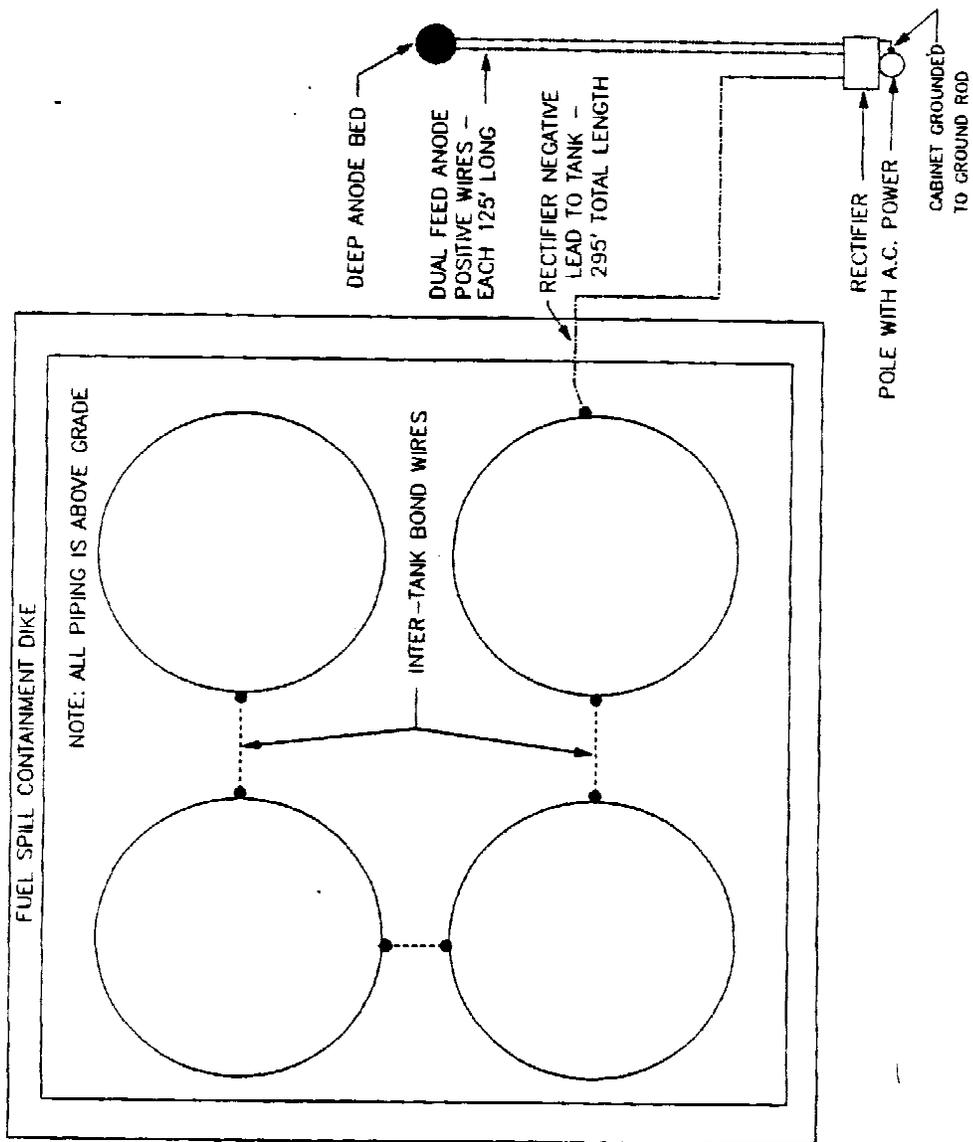


Figure 2-6 On-Grade Tank Bottoms

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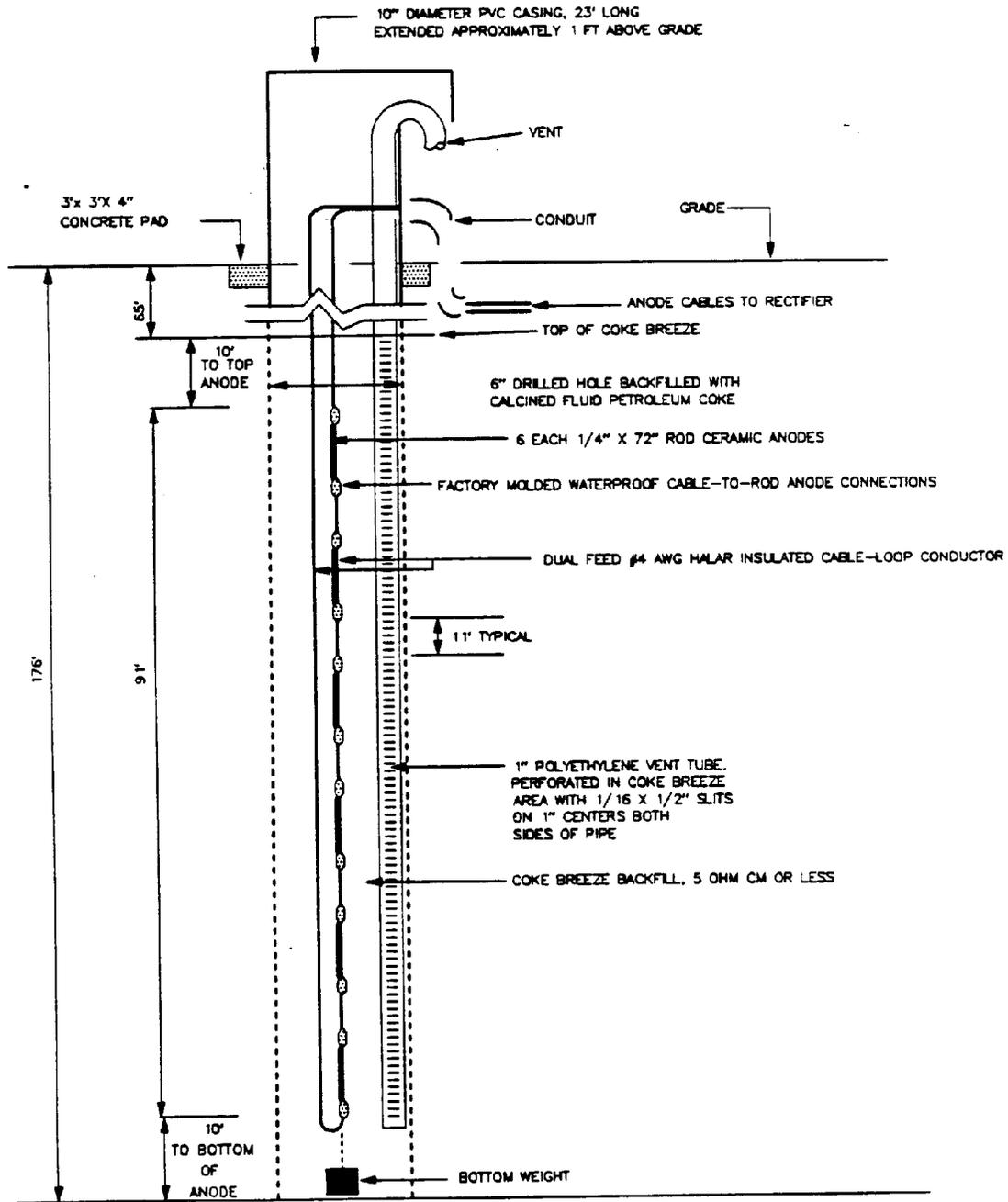


Figure 2-7 Typical Deep Anode Groundbed Using Rod Angles

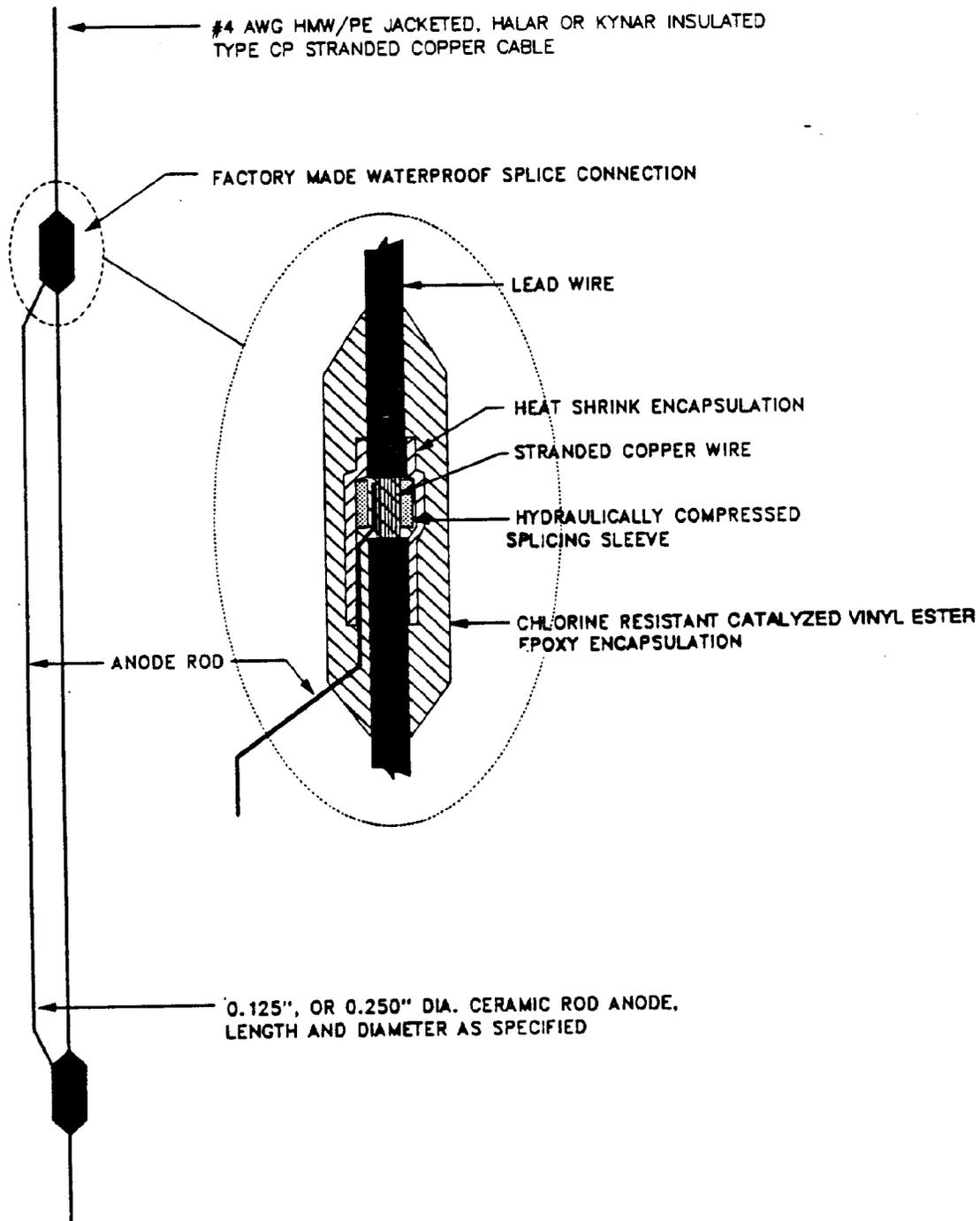


Figure 2-7A Ceramic Rod Anode for Deep Groundbed Use

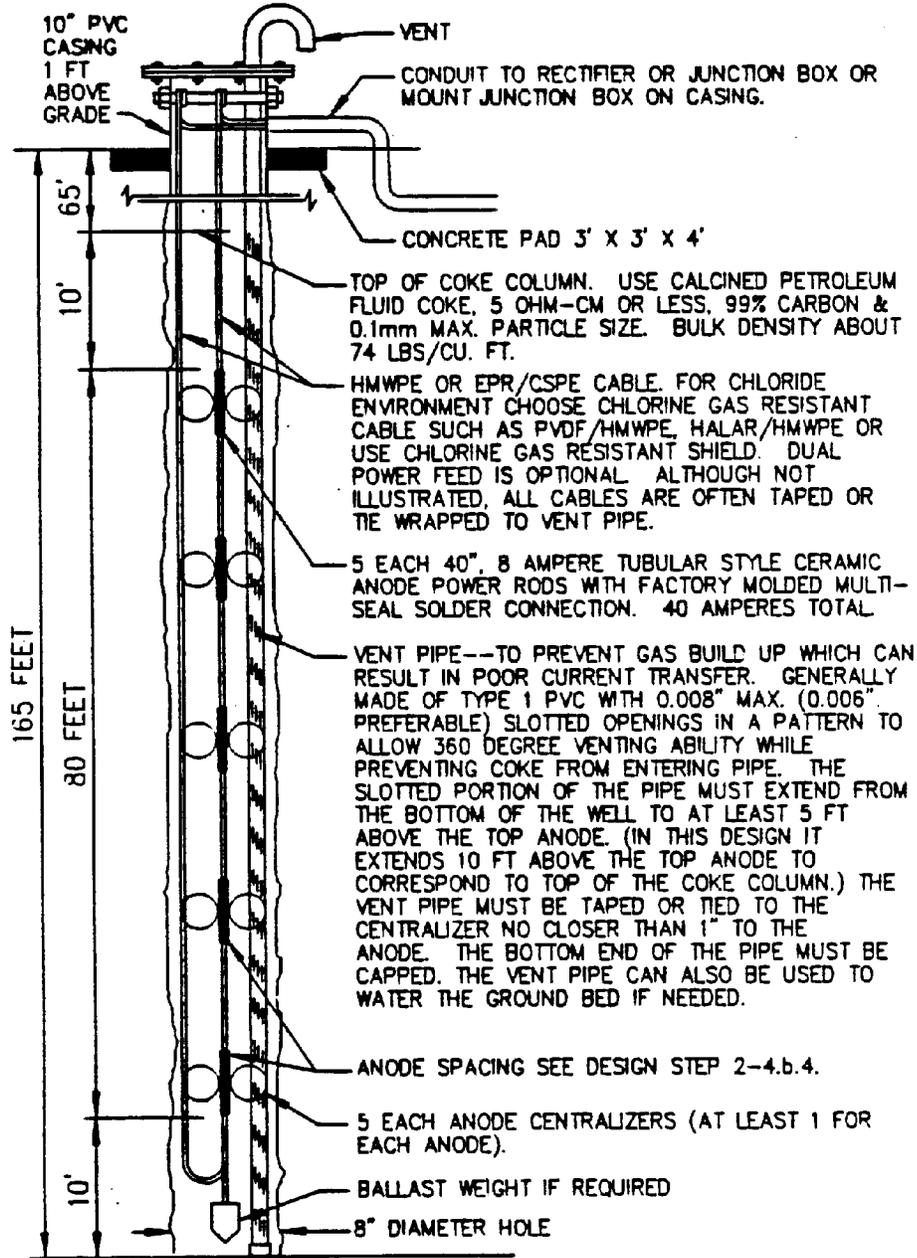


Figure 2-8 Ceramic Anode Tubular Power Rod Used in Deep Anode Bed.

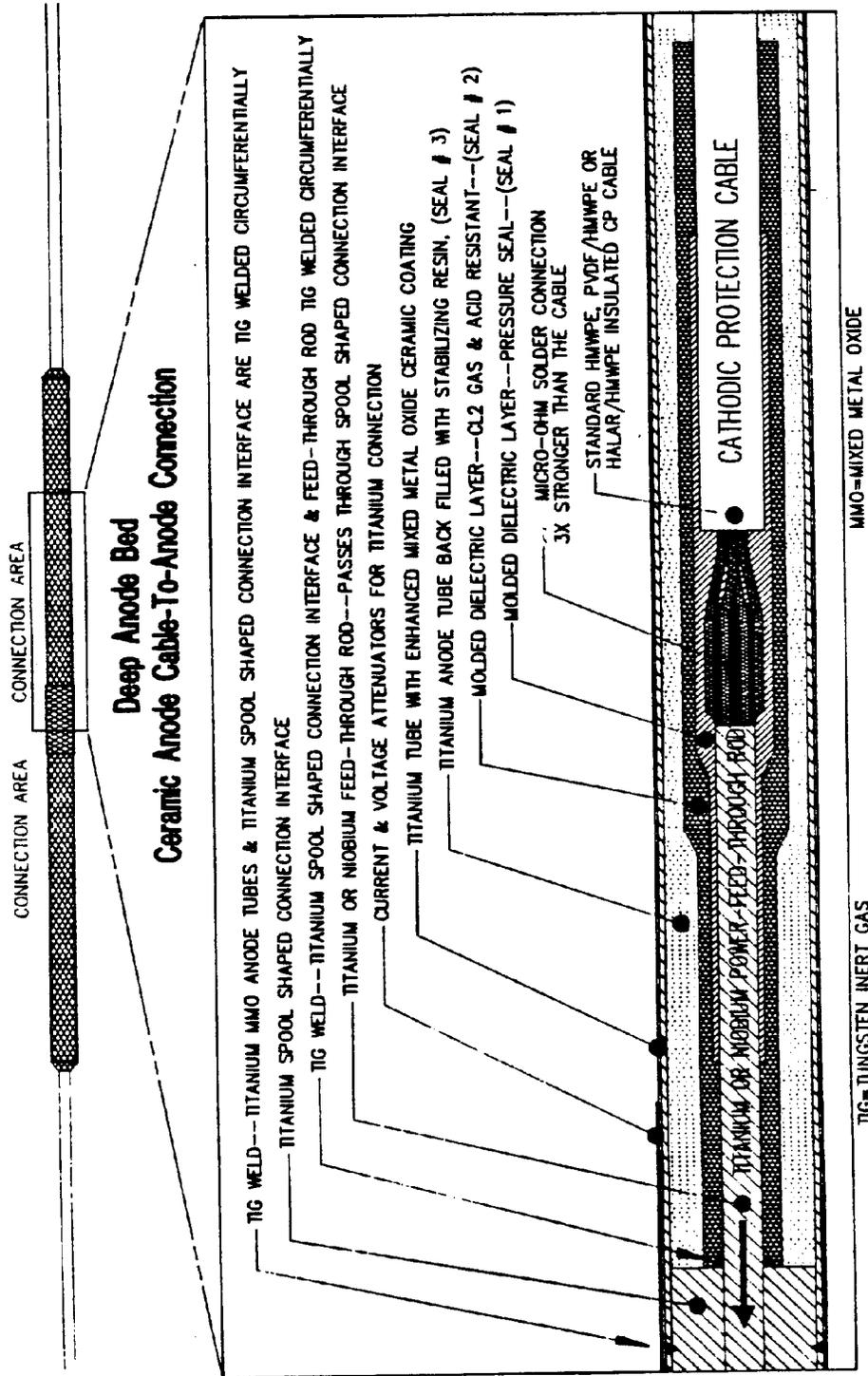


Figure 2-8A. Ductile Ceramic Anode Tubular Power Rod

b. Computations.

- 1) Find the surface area to be protected.

Area of each tank bottom = πr^2 :

$$A = \pi \times 37.5^2 = 4418 \text{ sq ft}$$

Area of the four bottoms:

$$A = 4 \times 4418 = 17,672 \text{ sq ft}$$

- 2) Determine the current requirement (I) from equation 1-1:

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

Where:

A = 17,672 sq ft (Total surface area from previous calculation)

I' = 2 mA/sq ft (Current density from item 4 of paragraph 2-4a)

C_E = 0.0 (bare) (Coating efficiency from item 8 of paragraph 2-4a)

$$I = 17,672 \text{ sq ft} \times 2 \text{ mA/sq ft} \times (1.0 - 0.0)$$

$$I = 35 \text{ amp}$$

- 3) Select an anode and calculate the number of anodes (N) required to meet the design life. The deep anode groundbed will consist of a series of rods connected to a continuous header cable. For physical strength, the 1/8-in. or 1/4-in. diameter rods are usually chosen. To ensure good transmission of current in to the backfill column, long anodes, typically 6 ft or 8 ft are used. For this example, 1/4-in. diameter by 72-in. long rods have been chosen. Using equation 1-2:

$$N = \frac{I}{I_A}$$

Where:

I = 35 amp (Current requirement from previous calculation)

I_A = 6.6 amp/anode (Current rating per heavy duty coated anode from table 3-3)

$$N = \frac{35}{6.6} = 5.3; \text{ use 6 anodes}$$

- 4) Calculate the required length of the backfill column.

Spacing between anodes depends primarily on the resistivity of both the backfill column (coke breeze). If low resistivity calcined fluid petroleum coke is used, than the spacing between rod anode (1/8-in. and 1/4-in. diameter) should not be greater than twice the individual rod length. Based on previous design experience, a spacing between anode rods of 11 ft is selected.

The minimum length of the backfill column is then calculated as follows:

6 anodes at 6 ft per anode =	36 ft
Spacing between anodes: 5 at 11 ft =	55 ft
Space above and below anode string* =	<u>20 ft</u>
Total length	111 ft

* Generally, the coke breeze column extends from 10 ft below the bottom anode to 10 ft above the top anode as shown in figures 2-7 and 2-8.

- 5) Calculate the backfill column-to-earth resistance (R_A).

This can be done from equation 1-4. Because several attempts may have to be made to obtain the required groundbed resistance, the process is facilitated by using the curves in figures 2-9A through 2-9C. Typical hole diameters are 6 or 8 in.; a 6-in. diameter hole has been selected for this groundbed. Figure 2-9C will be used for this design.

Figure 2-9C shows that, for a 111-ft long coke breeze backfill column, the resistance to earth per 1000 ohm-cm is 0.31 ohm. In 1500 ohm-cm soil, the resistance is $0.31 \times 1500/1000 = 0.47$ ohm (groundbed resistance in 1000 ohm-cm soil, times actual soil resistivity in ohm-cm per 1000). This is well below the design requirement of 0.75 ohm.

- 6) Determine total circuit resistance (R_T) from equation 1-3 :

$$R_T = R_A + R_W + R_C \text{ (Because the cathodic protection system utilizes a single deep anode groundbed } R_A = R_N)$$

DEEP ANODE GROUNDBED RESISTANCE

IN 1000 OHM-CM RESISTIVITY SOIL

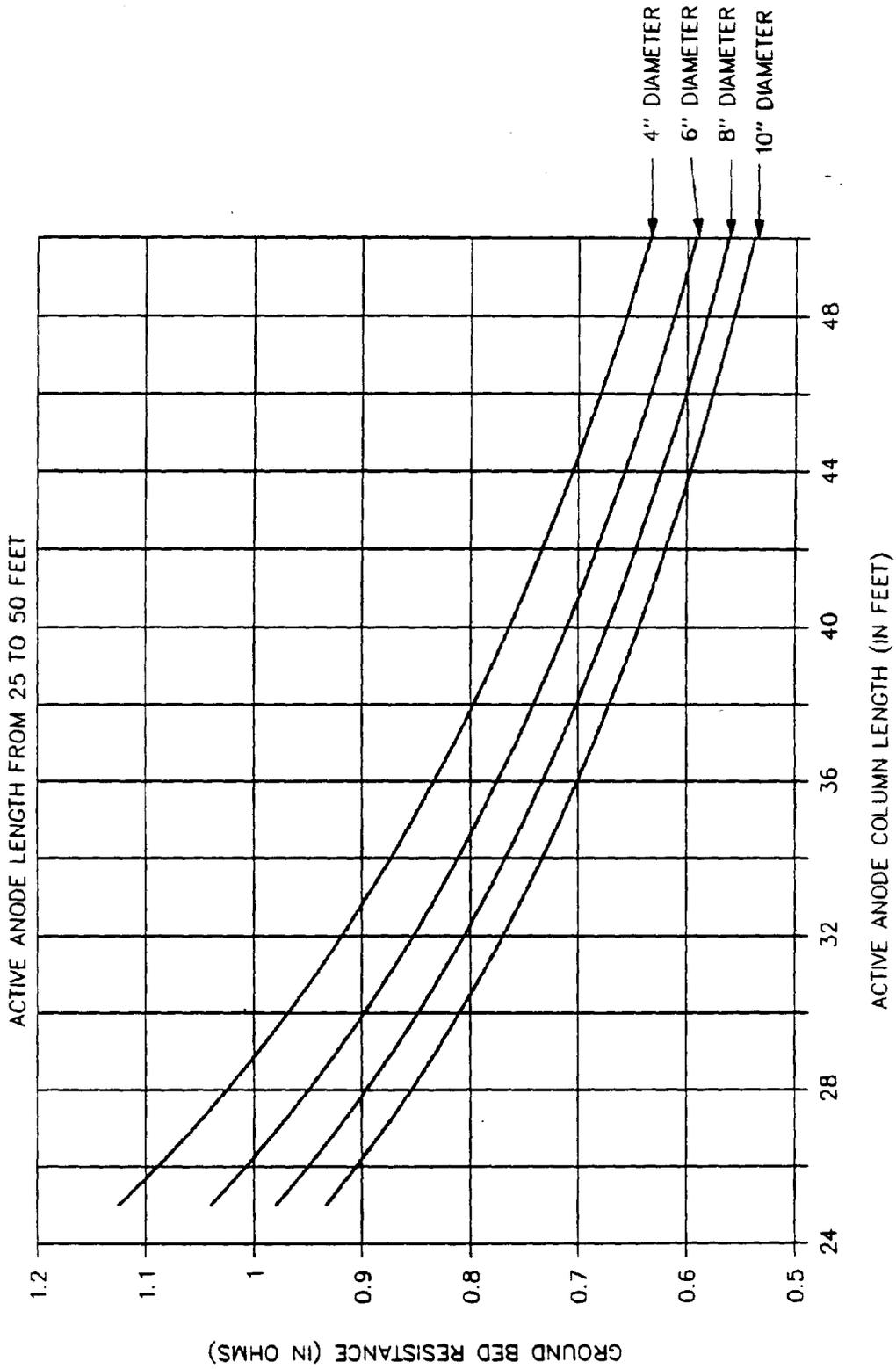


Figure 2-9A Deep Anode Groundbed Resistance 25 to 50 ft.

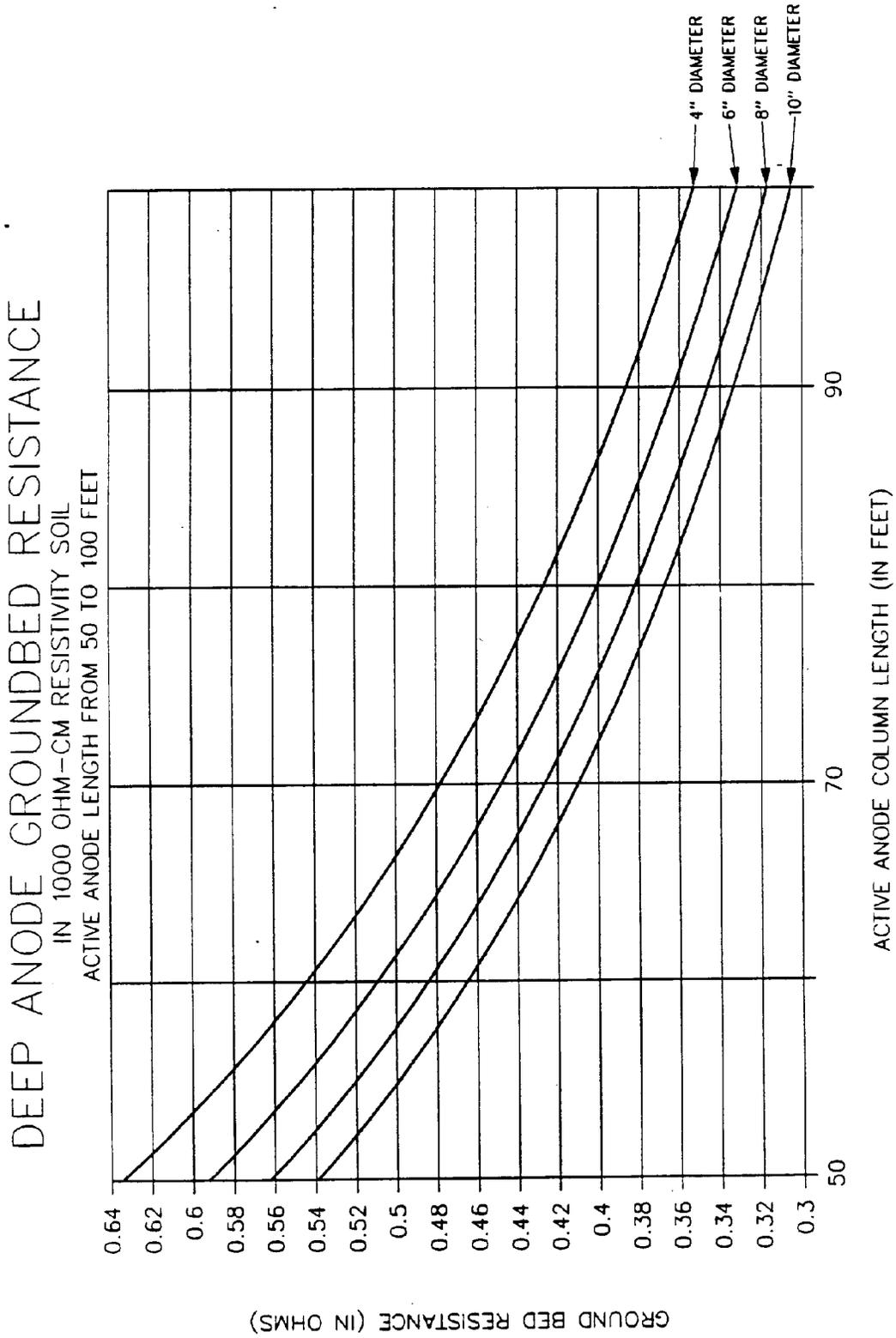
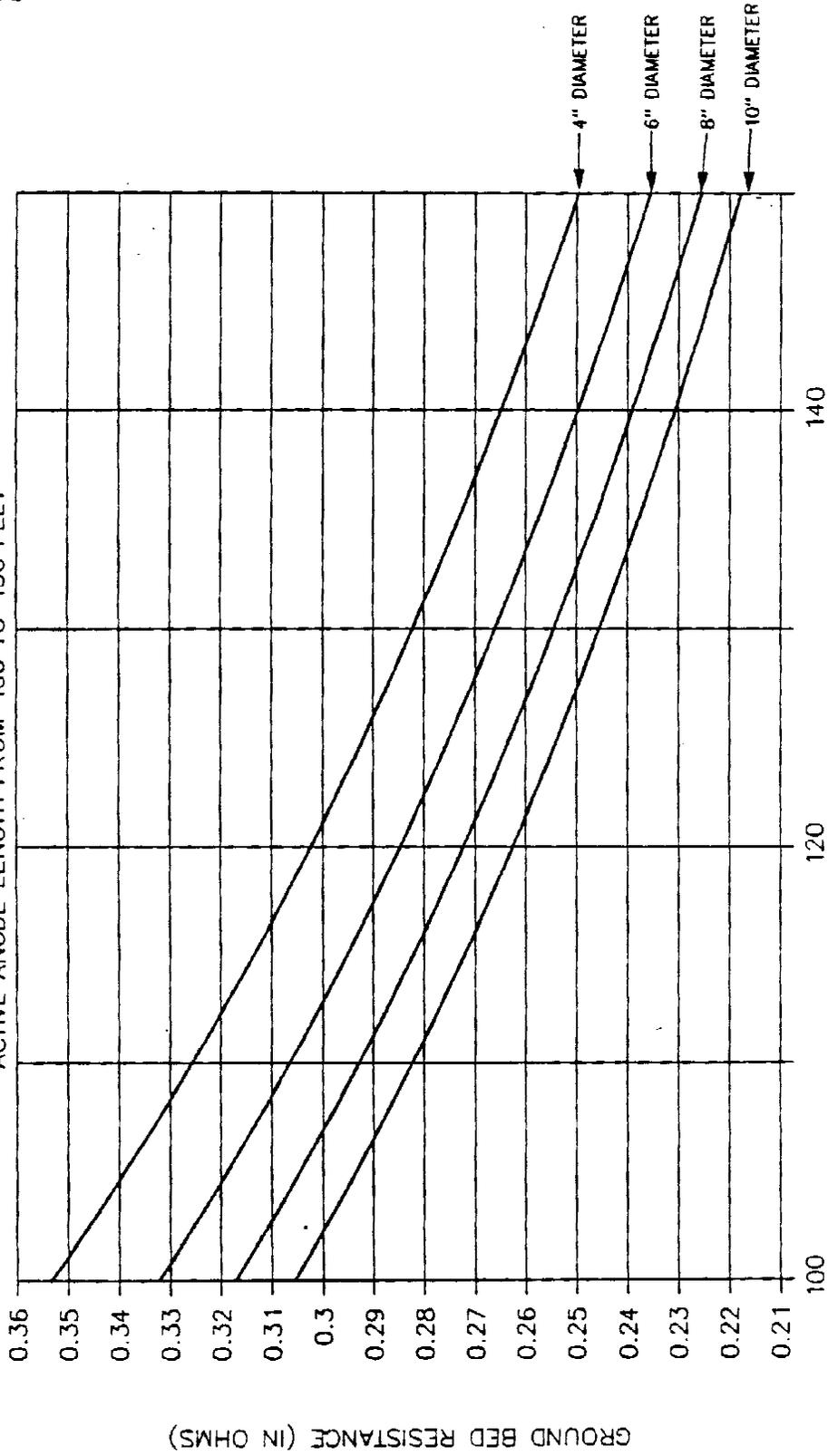


Figure 2-9B Deep Anode Groundbed Resistance 50 to 100 ft.

DEEP GROUNDBED ANODE RESISTANCE

IN 1000 OHM-CM RESISTIVITY SOIL
ACTIVE ANODE LENGTH FROM 100 TO 150 FEET



ACTIVE ANODE COLUMN LENGTH (IN FEET)

Figure 2-9C Deep Anode Groundbed Resistance 100 to 150 ft.

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Where:

R_A = Backfill column-to-earth resistance (ohms), calculated in step 5 above

R_W = Header cable/wire resistance (ohms)

R_C = Structure-to-earth resistance (ohms).

- a) Backfill column-to-earth resistance (R_A) from step 5:

$$R_A = 0.47 \text{ ohm}$$

- b) Wire resistance

A deep anode groundbed is defined as one where the top of the backfill column is at least 50 ft below the surface of the earth. Actual depth will vary, depending on subsurface geology and the distance over which the current is expected to spread. In this example, 65 ft was selected as the depth to the top of the coke breeze column. The anodes can be supplied through a single or dual feed. Dual feed is preferred to reduce both the resistance of the circuit and the chance of a failure due to a cable break.

No. 4 AWG cable has been chosen. Cable lengths have been calculated based on the following distances, illustrated in the deep groundbed example shown in figure 2-7.

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From grade to top of backfill column	65 ft
From top of backfill column to top anode	10 ft
From grade to bottom of backfill column	176 ft
From bottom anode to bottom of backfill column	10 ft
From anode hole to rectifier 2 cables at 125 ft	250 ft
From top of anode assembly to bottom of anode assembly	91 ft
Total cable length from top anode feed to rectifier 125 ft + 65 ft + 10 ft =	200 ft
Total cable length from bottom anode feed to rectifier 125 ft + 176 ft - 10 ft =	291 ft

Calculate top cable resistance (R_{WT}) from equation 1-15:

$$R_{WT} = \frac{L_{WT} R_{MFT}}{1000 \text{ ft}}$$

Where:

L_{WT} = 200 ft (Cable length from previous calculation)

R_{MFT} = 0.254 ohm (Resistance per 1000 lin ft of No. 4 AWG cable which has been selected for installation. These resistance values can be found in table 3-6).

$$R_{WT} = \frac{200 \text{ ft} \times 0.254 \text{ ohm}}{1000 \text{ ft}} = 0.051 \text{ ohm}$$

Calculate bottom cable resistance (R_{WB}) from equation 1-15:

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Where:

$$L_{WB} = 291 \text{ ft (Cable length from previous calculation)}$$

$$R_{MFT} = 0.254 \text{ ohm (Cable resistance per 1000 lin ft [same as above])}$$

$$R_{WB} = \frac{291 \text{ ft} \times 0.254 \text{ ohm}}{1000 \text{ ft}} = 0.074 \text{ ohm}$$

These two cables are in parallel, so that their wire resistance ($R_{T/B}$) is calculated from the law of parallel circuits:

$$\frac{1}{R_{T/B}} = \frac{1}{R_{WT}} + \frac{1}{R_{WB}}$$

$$\frac{1}{R_{T/B}} = \frac{1}{0.051} + \frac{1}{0.074}$$

$$\frac{1}{R_{T/B}} = 19.6 + 13.5 = 33.1$$

$$R_{T/B} = 0.030 \text{ ohm}$$

Since current is dissipating along the portion of the cable to which the anodes are connected, the resistance of this cable (R_{POS}) is taken as one half its total resistance as was done in example 2-2.

$$R_{POS} = \frac{L_W R_{MFT}}{1000 \text{ ft}} \times \frac{1}{2} = \frac{91 \text{ ft} * \times 0.254 \text{ ohm/ft}}{1000 \text{ ft}} \times \frac{1}{2}$$

*91 ft is the overall anode column length including the interconnecting wire from the top of the top anode to the bottom of the bottom anode (see item 4 from paragraph 2-4b.)

$$R_{POS} = 0.012 \text{ ohm}$$

Negative circuit wire resistance must also be calculated:

Negative cable from rectifier to closest tank = 125 ft of No. 4 AWG

Intertank bonds = 170 ft of No. 4 AWG**

**The two intertank bond circuits are in parallel and of about the same length. From the law of parallel circuits, total resistance of two parallel circuits of equal resistance is one half the resistance of each circuit.

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Therefore, one half the cable length is used in this calculation. The calculation is also conservative since not all the current flows through the complete intertank bond circuit.

Total ft of negative circuit wire = 295 ft of No. 4 AWG cable

Negative resistance if calculated from equation 1-15:

$$R_{\text{NEG}} = \frac{L_{\text{W}} R_{\text{MFT}}}{1000 \text{ ft}}$$

Where:

$$L_{\text{W}} = 295 \text{ ft (Negative cable length)}$$

$$R_{\text{MFT}} = 0.254 \text{ ohm (Negative cable resistance per 1000 un ft of No. 4 AWG cable [table A-6])}$$

$$R_{\text{NEG}} = \frac{295 \times 0.254}{1000}$$

$$R_{\text{NEG}} = 0.074$$

Total wire resistance therefore is:

$$R_{\text{W}} = R_{\text{T/B}} + R_{\text{POS}} + R_{\text{NEG}} = 0.030 + 0.012 + 0.074$$

$$R_{\text{W}} = 0.116 \text{ ohm}$$

Cable insulation is also important. High molecular weight polyethylene insulation, commonly used for cathodic protection work, tends to blister, become brittle, and then crack in deep groundbed use where chlorine gas generation can occur. This has been most prevalent in open holes containing brackish water, but may occur in coke breeze backfilled holes also. Consequently, to minimize the chances of cable failure, one of the two following types of insulation, which show good resistance to these oxidizing environments should be used:

Polyvinylidene fluoride (Kynar)¹

¹ Registered trademark of Penwalt Corp.

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Copolymer of chlor-tri-fluorethylene and ethylene (Halar)²

To protect the insulation itself and to facilitate handling, cables for deep anode groundbeds also have an outer jacket of high-molecular weight polyethylene extruded over the Kynar or Halar insulation.

- c) Structure-to-earth resistance (R_c).

Since the tank bottoms are bare, their resistance-to-earth is considered negligible, therefore, R_c is taken as zero.

- d) Calculate total circuit resistance (R_T) from equation 1-3:

$$R_T = R_N + R_W + R_C$$

$$R_T = 0.470 + 0.116 + 0.0$$

$$R_T = 0.586 \text{ ohm}$$

This is well below the design requirement and, therefore, this groundbed with 6 - 1/4 in. by 6 ft ceramic anode rods with total backfill column length of 111 ft will be used.

- 7) Calculate rectifier voltage (V_{REC}) from equation 1-17:

$$V_{REC} = (I) (R_T) (120\%)$$

Where:

$$I = 35 \text{ amp (Current requirement from step 2, paragraph 2-4b)}$$

$$R_T = 0.586 \text{ ohm (Total circuit resistance from previous calculation)}$$

$$120\% = \text{Rectifier capacity safety factor}$$

$$V_{REC} = 35 \text{ amp} \times 0.586 \text{ ohm} \times 120\%$$

$$V_{REC} = 24.6 \text{ V}$$

c. Select rectifier.

² Registered trademark of Allied Chemical Corp.

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Based on the design requirement of 24.6 V and 35 amp, a rectifier can be chosen. A 30 V, 42 ampere unit is commercially available and is selected. This rectifier can be pole mounted as illustrated in figure 2-10.

d. Installation.

Figures 2-7 and 2-8 show this deep anode design.

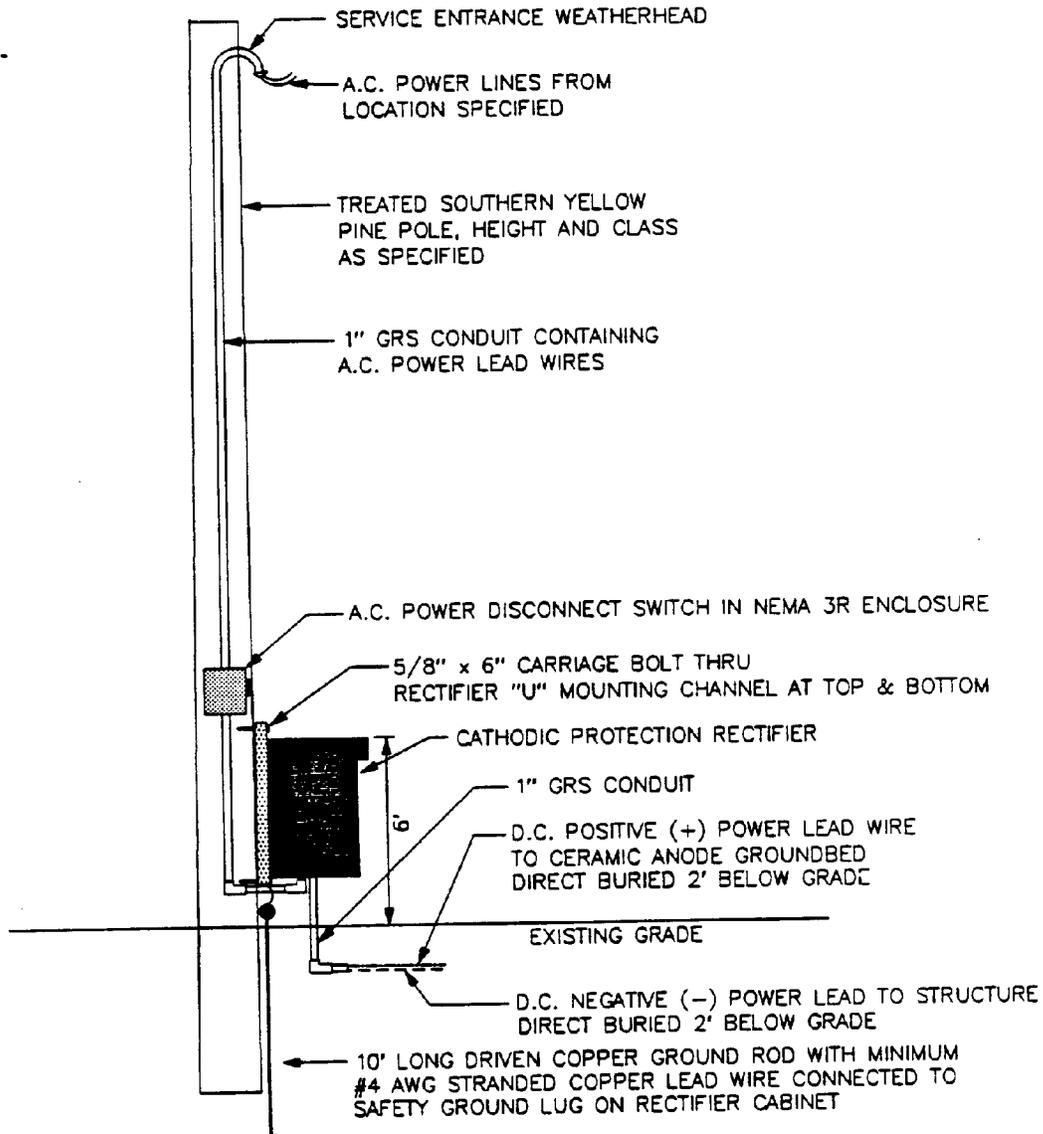


Figure 2-10 Pole-Mounted Rectifier

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2-5. Gas Distribution System.

It has been decided to install cathodic protection on the gas distribution piping in a post housing facility. Figure 2-11 shows a portion of the piping.

The water distribution system has recently been replaced with nonmetallic pipe. On this basis, it has been decided that the gas piping can be protected with impressed current from a deep anode groundbed without causing interference to the water pipe. (Note: Some county, state, and federal agencies such as the EPA may have regulations which prevent the use of deep anode beds because they can provide a conduit for mixing of waters between aquifer layers. In such cases, regulations have required cementing of the annulus between the deep anode bed casing and the augered hole to prevent this water migration. The system designer should check with the applicable agencies before committing to a deep anode design.)

a. Design data.

- 1) Experience in the area shows the subsurface resistivity at a depth of 50 and 200 ft to be 2000 ohm-cm.
- 2) Piping consists of:
 - 28,000 ft of 1 1/4-in. diameter pipe
 - 1,200 ft of 4-in. diameter pipe
 - 3,600 ft of 6-in. diameter pipe
- 3) Design cathodic protection anode for a 20-year life.
- 4) Experience with similar pipe in the same general soil type has shown that a design current density of 2 A per sq ft of bare pipe is conservative.
- 5) Piping is welded steel, poorly coated; considered to be bare for protection purposes and, therefore, the coating efficiency is 0.0 (CE = 0.0).
- 6) Piping is isolated at each house and at the tie-in to the main supply line.
- 7) The cathodic protection circuit resistance should not exceed 1 ohm.
- 8) 120/240 V AC, single phase power is available.

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- 9) Current requirement tests are not practiced in this case, so design will be based on calculations. (Note: Current requirement tests should be conducted whenever practicable.)

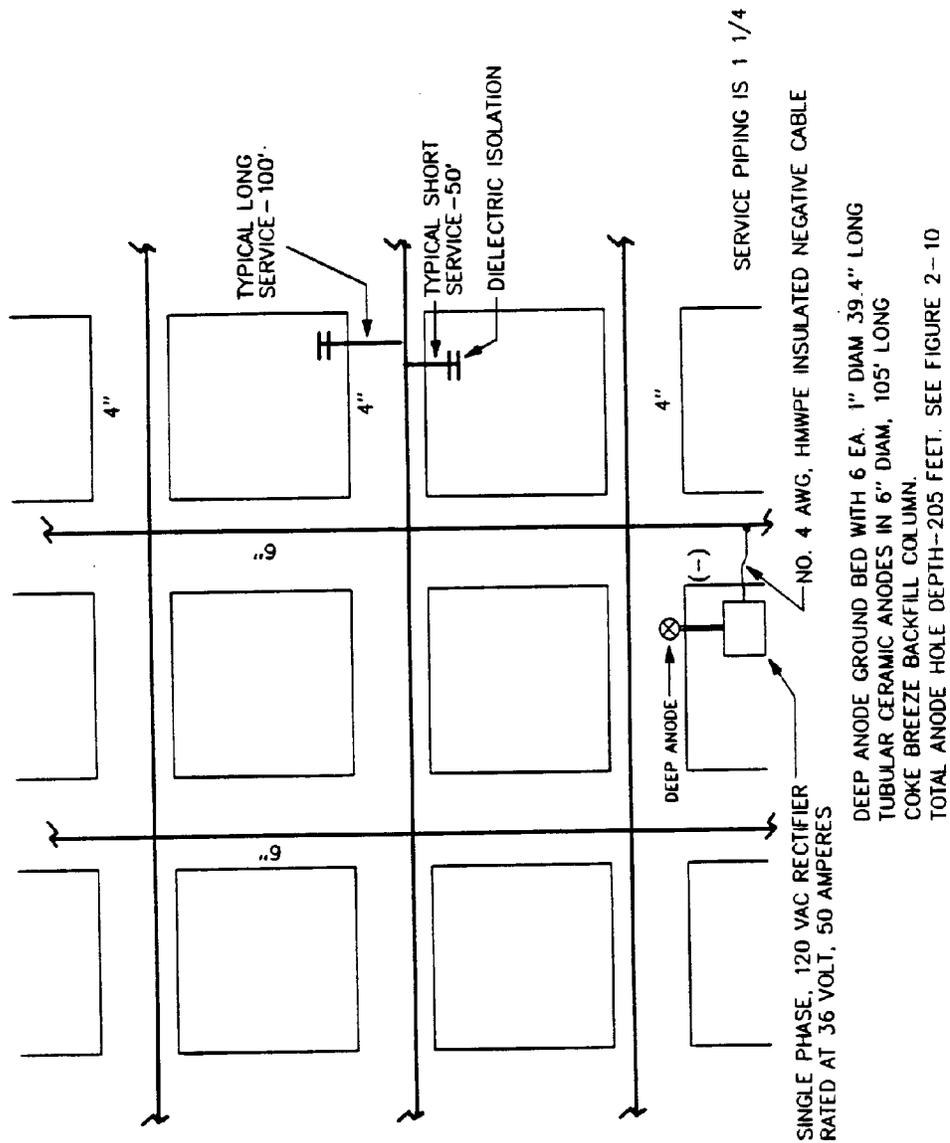


Figure 2-11 Deep Anode Cathodic Protection for Gas Distribution System

b. Computations.

- 1) Calculate the external surface area of the pipe (A) to be protected.

Pipe diameter	Length	Unit Area* (sq ft/lin ft)	Area (sq ft)
1 1/4 in.	28,000 ft	0.434	12,152
4 in.	1,200 ft	1.178	1,414
6 in.	3,600 ft	1.734	<u>6,242</u>
*from table A-2		Total	19,808

- 2) Determine current requirement (I) from equation 1-1:

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

Where:

A = 19,808 sq ft (Surface area of pipe to be protected from previous calculation)

I' = 2 mA/sq ft (Current density, from item 4, paragraph 2-5a)

C_E = 0.0 (Coating efficiency [bare pipe])

I = 19,808 sq ft x 2 mA/sq ft x (1.0 - 0.0)

I = 39,616 mA or 39.6 amp; use 40 amp

- 3) Select an anode and calculate the number of anodes required (N) to meet the design life. For this design, tubular anodes have been chosen. The groundbed will consist of a series of anodes attached to a continuous header cable. A typical size tubular ceramic anode used in deep anode beds, 1-in. diameter by 39.4 in. long, is selected. The number of anodes are determined using equation 1-2:

$$N = \frac{I}{I_A}$$

Where:

I = 40 amp (Current requirement from previous calculation)

I_A = 8.0 amp/anode (Current rating per anode from table 3-3 [in coke breeze])

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$$N = \frac{40}{8} = 5 \text{ anodes}$$

To allow a factor of safety, use 6 anodes

- 4) Calculate the required length of the backfill column.

The maximum allowable spacing between anodes depends primarily on the resistivity of the backfill column (coke breeze). For tubular anodes of ½-in. diameter or greater, maximum spacing between anodes should not exceed four times the anode tube length. For this example, we will try the maximum allowable spacing of 13 ft (39.4 in. x 4/12 = 13.1 ft).

The minimum length of the backfill column is calculated as:

6 anodes at 39.4 in. (3.3 ft) =	19.8 ft
Spacing between anode: 5 at 13 ft =	65.0 ft
Space above and below anode string*	<u>20.0 ft</u>

Total length 104.8 ft
 (use 105 ft)

* Generally, the coke breeze column extends from 10 ft below the bottom anode to 10 ft above the top anode.

- 5) Calculate the backfill column-to-earth resistance (R_A).

This can be done from equation 1-4. Because several attempts may have to be made to obtain the required resistance-to-earth, the process is facilitated by using the curve in figure 2-9C. Typical hole diameters are 6 or 8 in.; a 6-in. diameter hole has been selected for this groundbed.

From figure 2-9C for a 105 ft long coke breeze backfill column, the resistance to earth per 1000 ohm-cm is 0.325 ohm. In 2000 ohm-cm soil, the resistance is 0.325 x 2 = 0.65 ohm, which is below the design requirement defined in item 7 of paragraph 2-5a.

- 6) Determine total circuit resistance (R_T) from equation 1-3:

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$R_T = R_A + R_W + R_C$ (Because the cathodic protection system uses a single deep anode groundbed $R_A = R_N$)

Where:

R_A = Backfill column-to-earth resistance (ohms).

R_W = Wire resistance (ohms).

R_C = Structure-to-earth resistance (ohms).

- a) Backfill column-to-earth resistance (R_A) from step 5.

$$R_A = 0.65 \text{ ohm}$$

- b) Wire resistance (R_W) from general equation 1-15:

$$R_W = \frac{L_W R_{MFT}}{1000 \text{ ft}}$$

A deep anode groundbed is defined as one where the top of the backfill column is at least 50 ft below the surface of the earth. Actual depth will vary, depending on subsurface geology and the distance over which the current is expected to spread. In this example, the depth to the top of the coke breeze backfill column was determined to be 100 ft. The anodes can be supplied through a single or dual feed. Dual feed is preferred to reduce both the resistance of the circuit and the chance of a failure due to a cable break.

The assembly is made on a single length of cable, beginning at the rectifier, running down through the tubular anodes to the bottom anode and then back up adjacent to the anodes to the rectifier. Resistance calculations are made as though there were three cables as noted below. The conductor provided with some tubular ceramic anodes is designated EPR/HY50 for one-in. diameter anodes and EPR/HY16 for 0.63-in. diameter anodes. These cables have an ethylene-propylene rubber inner insulation and a chlorosulphonated polyethylene outer jacket and are suitable for deep anode use if the insulation is protected with a chlorine-resistant sheath or shield.

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EPR/HY50 cable has been chosen. The cable lengths have been calculated based on the following distances, which are illustrated in the deep groundbed examples shown in figures 2-12 and 2-13:

From grade to top of backfill column	100 ft
From top of backfill column to top anode	10 ft
From grade to bottom of backfill column	205 ft
From bottom anode to bottom of backfill column	10 ft
From anode hole to rectifier 2 cables at 10 ft	20 ft
From top of anode assembly to bottom of anode assembly	85 ft

Total cable length from top anode feed to rectifier 10 ft + 100 ft + 10 ft = 120 ft

Total cable length from bottom feed to rectifier 10 ft + 205 ft - 10 ft = 205 ft

Calculate top cable resistance (R_{WT}) from equation 1-15:

$$R_{WT} = \frac{L_{WT} R_{MFT}}{1000 \text{ ft}}$$

Where:

L_{WT} = 120 ft (Cable length from previous calculation)

R_{MFT} = 0.1183 ohm (Resistance per 1000 lin ft of EPR/HY50 [table 3-6])

R_{WT} = $\frac{120 \text{ ft} \times 0.1183 \text{ ohm}}{1000 \text{ ft}} = 0.014 \text{ ohm}$

Calculate bottom cable resistance (R_{WB}) from equation 1-15:

Where:

L_{WB} = 205 ft (Cable length from previous calculation)

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$$R_{MFT} = 0.1183 \text{ ohm (Cable resistance per 1000 lin ft [same as above])}$$

$$R_{WB} = \frac{205 \text{ ft} \times 0.1183 \text{ ohm}}{1000 \text{ ft}} = 0.024 \text{ ohm}$$

These two cables are in parallel, so that total resistance ($R_{T/B}$) is calculated from the law of parallel circuits:

$$\frac{1}{R_{T/B}} = \frac{1}{R_{WT}} + \frac{1}{R_{WB}}$$

$$\frac{1}{R_{T/B}} = \frac{1}{0.014} + \frac{1}{0.024}$$

$$\frac{1}{R_{T/B}} = 71.43 + 41.66 = 113.1$$

$$R_{T/B} = 0.009 \text{ ohm}$$

Since current dissipates along the portion of the cable to which the anodes are connected, the resistance of this cable (R_{POS}) is taken as one half its total resistance, as was done in example 2-2.

$$R_{POS} = \frac{L_W R_{MFT}}{1000 \text{ ft}} \times \frac{1}{2} = \frac{85 \times 0.1183 \text{ ohm/ft}}{1000 \text{ ft}} \times \frac{1}{2}$$

$$R_{POS} = 0.005 \text{ ohm}$$

Negative cable resistance: The rectifier is placed 25 ft from the connection to the piping, using No. 4 AWG HMWPE insulated cable. Negative resistance is calculated from equation 1-15:

$$R_{NEG} = \frac{L_W R_{MFT}}{1000 \text{ ft}}$$

Where:

$$L_W = 25 \text{ ft (Length of cable)}$$

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$$R_{MFT} = 0.254 \text{ ohm (Resistance per 1000 lin ft of No. 4 AWG HMWPE insulated cable [table A-6])}$$

$$R_{NEG} = \frac{25 \times 0.254}{1000}$$

$$R_{NEG} = 0.006 \text{ ohm}$$

Total wire resistance therefore is:

$$R_{T/B} + R_{POS} + R_W + R_{NEG} = 0.009 + 0.005 + 0.006 + 0.006 = 0.020 \text{ ohm}$$

c) Structure-to-earth resistance (R_C).

The piping is essentially bare, so structure-to-earth resistance is negligible ($R_C = 0.0$).

d) Calculate total circuit resistance (R_C) from equation 1-3:

$$R_T = R_A + R_W + R_C \text{ (Because the cathodic protection system uses a single deep anode grounded } R_A = R_N)$$

$$R_T = 0.65 + 0.020 + 0.0$$

$$R_T = 0.670 \text{ ohm}$$

7) Calculate rectifier voltage (V_{REC}) from equation 1-17:

$$V_{REC} = (I) (R_T) (120\%)$$

Where:

$$I = 40 \text{ amp (Current requirement from step 2, paragraph 2-5b)}$$

$$R_T = 0.670 \text{ ohm (Total circuit resistance from previous calculation)}$$

$$120\% = \text{Rectifier voltage capacity design safety factor}$$

$$V_{\text{REC}} = 40 \text{ amp} \times 0.670 \text{ ohm} \times 1.2$$

$$V_{\text{REC}} = 32.2 \text{ V}$$

c. Select rectifier.

Based on the design requirement of 32.2 V and 40 amp, a rectifier can be chosen. A 36-V, 50-amp unit is commercially available and is selected.

d. Installation.

Figures 2-12 and 2-13 show how the deep anode groundbed might look.

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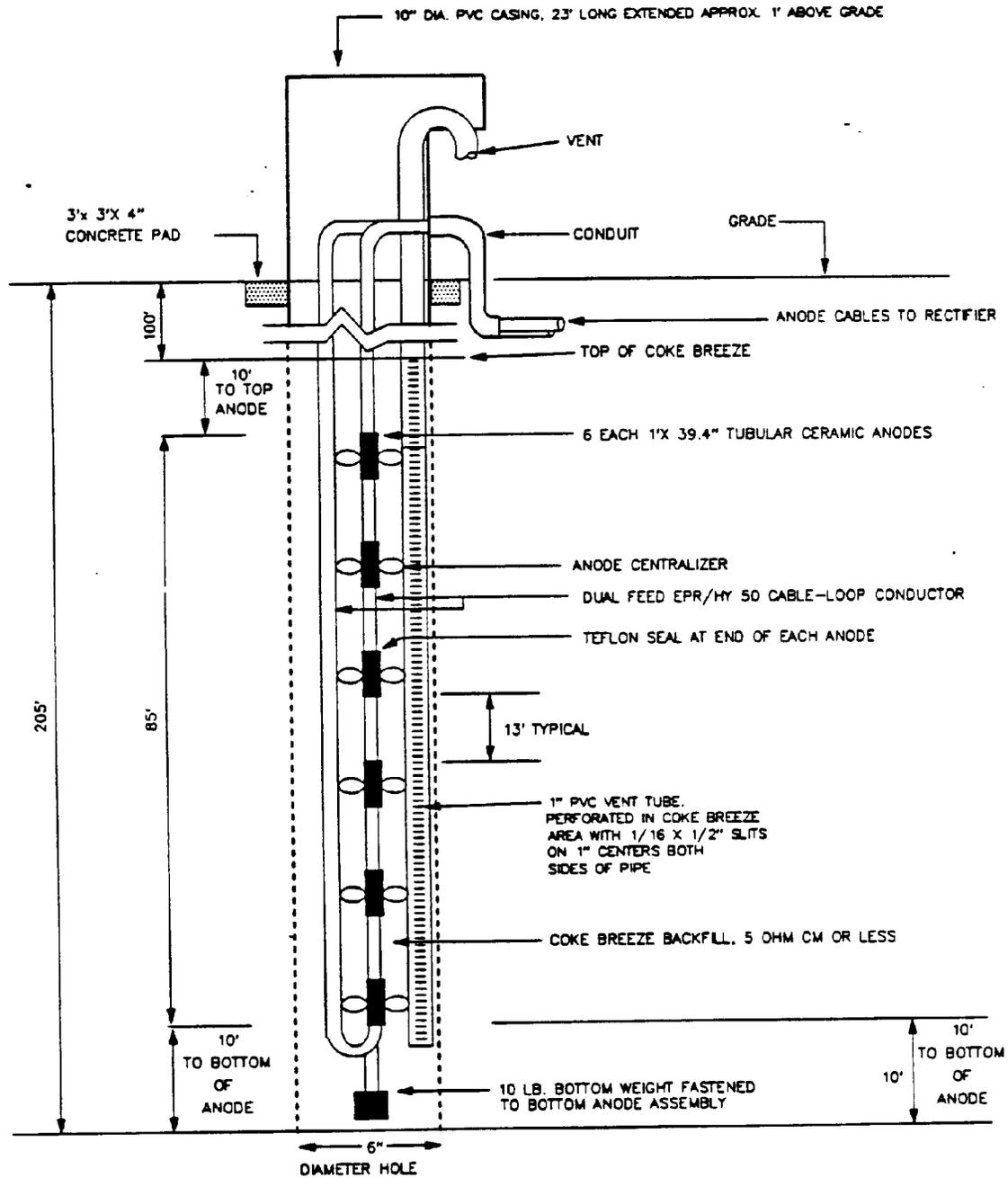


Figure 2-12 Typical Deep Anode Groundbed Using Tubular Anodes

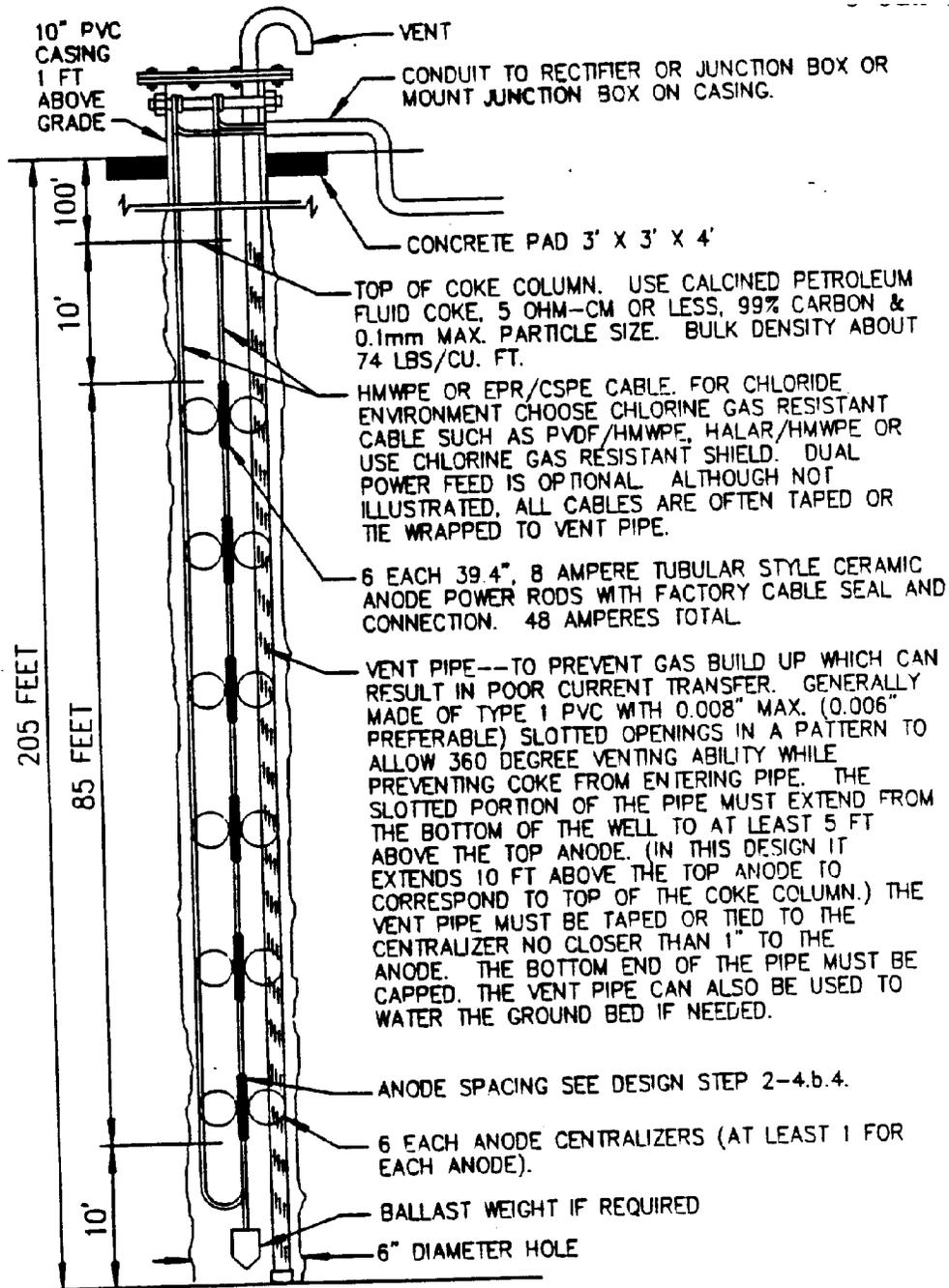


Figure 2-13 Ceramic Anode Tubular Power Rod Used in Deep Anode Bed

2-6. Elevated Water Tank (Ice Is Expected).

Impressed current cathodic protection is designed for an elevated water tank (figure 2-14). 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 ft thick) covers the water surface during winter. The anode cables could not tolerate this weight, so another type of support must be used. An internally supported hoop shaped wire anode system is selected.

a. Design data.

- 1) Tank is a pedestal supported spheroid with a 10-in. riser pipe. Only the bowl will be protected because the riser pipe is less than 30 inches in diameter. For riser pipes see section 2-7.
- 2) Tank dimensions are:
Capacity = 400,000 gal
Diameter of bowl = 51 ft 6 in.
High water depth = 35 ft
Height of bowl above ground = 100 ft
- 3) Water resistivity is 2000 ohm-cm.
- 4) Design cathodic protection anodes for a 15-year life.
- 5) Wire type ceramic anode will be used.
- 6) Wetted surfaces are uncoated.
- 7) Area above high water level is kept well coated.
- 8) Tank is subject to freezing.
- 9) The cathodic protection circuit resistance must not exceed 2 ohms.
- 10) The available electrical power is 120/240 V AC, single phase.
- 11) Based on structure current requirement testing recently performed on this tank, the current required for adequate cathodic protection is 25 amp. This high current requirement indicates that the tank internal coating is severely deteriorated.

b. Computations.

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- 1) Calculate the length of wire in ft (LB) needed for the current required from a modification of equation 1-2:

$$L_B = \frac{I}{I_A}$$

where:

I = 25 amp (Current requirement from adequate cathodic protection from item 11 of paragraph 2-6a)

I_A = Allowable amp per ft of anode wire (varies depending on desired anode life and diameter), found in table A-3.

Select 0.0625-in. diameter copper cored anode wire based on the current requirement of 25 amp, 81 ft of anode wire will be required to provide an anode life of 15 years.

	Length of Anode Ring Wire	Diameter (D_R)
For 0.0625 in. $L_B = \frac{25}{0.31} =$	81 ft	25 ft 9 in.

- 2) Calculate the desired diameter of the anode wire ring (D_B). Experience shows that the diameter of the anode wire ring should be between 40 and 70 percent of the bowl diameter. For this example, use a hoop diameter equal to 40 percent of the tank bowl diameter:

$$D_R = 51.5 \text{ ft} \times 40\% = 20.5 \text{ ft}$$

- 3) Select anode wire:

Prior to calculating the circuit resistance of the anode wire ring, it must first be checked to determine if the length is adequate for the desired anode life. For an anode ring diameter of 20.5 ft, the circumference is $20.5 \times \pi = 64.4$ ft. This length is inadequate for the 0.0625-in. wire (which requires a minimum of 81 ft to meet the desired anode life). Therefore, we will increase the hoop diameter by 10 percent to 50 percent of the tank diameter:

$$D_R = 51.5 \times 50\% = 25.75 \text{ ft}$$

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But this diameter provides an anode length that is still slightly less than that required for a 15-year mode life. Therefore, we will use a hoop diameter that is 55 percent of the bowl diameter:

$$D_E = 51.5 \times 55\% = 28.3 \text{ ft}$$

- 4) Calculate the anode-to-water resistance (R_A) for a 0.0625-in. diameter anode wire using equation 1-14:

$$R_A = \frac{0.0016 p}{D_R} \left(\ln \frac{8 D_R}{D_A} + \ln \frac{2 D_R}{H} \right)$$

Where:

- $p =$ 2000 ohm-cm (Water resistivity from item 3 of paragraph 2-6a)
- $D_R =$ 28.3 ft (Anode ring diameter from step 2 of paragraph 2-6b)
- $D_A =$ 0.00521 ft (0.0625 in) (Diameter of anode determined in step 3 of paragraph 2-6b)
- $H =$ 21 ft (Anode depth below water surface.) (Anode depth determined from the following calculations).

The anode depth below the high water line is approximately 60 percent of the distance between the high water line and the bottom of the tank. Water depth = 35 ft, cf. design data section 2-6a.

Calculate R_A :

$$R_A = \frac{0.0016 (2000)}{28.3} \left[\ln \frac{8 \times 28.3}{0.00521} + \ln \frac{2 \times 28.3}{21} \right]$$

$$R_A = 0.113 [\ln 43,455 + \ln 2.70]$$

$$R_A = 0.113 (10.68 + 0.99)$$

$$R_A = 1.32 \text{ ohms}$$

This is within the design limitation of 2.0 ohms.

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- 5) Determine the total circuit resistance (R_T), from equation 1-3:

$$R_T = R_N + R_W + R_C$$

Where:

$$\begin{aligned} R_N &= \text{Anode-to-water resistance} \\ R_W &= \text{Wire resistance} \\ R_C &= \text{Tank-to-water resistance.} \end{aligned}$$

- a) Anode-to-water resistance (R_N) = 1.32 ohms from step 4 above. ($R_N = R_A$ since R_A is equal to one continuous wire anode).
- b) Header cable/wire resistance (R_W) is solved using equation 1-15:

$$R_W = \frac{L_W R_{MFT}}{1000 \text{ ft}}$$

Where:

$$L_W = 115 \text{ ft (Effective wire length. The positive wires from the rectifier to each end of the anode circle will be approximately 115 ft long)}$$

$$R_{MFT} = 0.51 \text{ ohm (Effective wire resistance per 1000 lin ft. Since there are positive wires from the rectifier to each end of the anode circle, each wire will carry about one half of the current [12.5 amp]. The wires selected are No. 10 AWG. Because the two wires are in parallel, the effective resistance is one half the single wire resistance [1.02 ohms per 1000 lin ft/2 = 0.51 ohm])}$$

$$R_W = \frac{115 \text{ ft} \times 0.51 \text{ ohm}}{1000 \text{ ft}}$$

$$R_W = 0.06 \text{ ohm}$$

- c) Tank-to-water resistance (R_C) and negative circuit resistance.

The negative wire is connected to the tank structure near the rectifier, so its resistance

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is negligible. The tank-to-water resistance is also negligible because the coating is very deteriorated.

d) Calculate R_T :

$$R_T = 1.32 + 0.06 + 0.00$$

$$R_T = 1.38 \text{ ohms}$$

This is well below the design requirement.

6) Calculate rectifier voltage (V_{REC}) from equation 1-17:

$$V_{REC} = (I) (R_T) (120\%)$$

Where:

I = 25 amp (Current requirement from step 11, paragraph 2-6a)

R_T = 1.38 ohms (Total circuit resistance from previous calculation)

120% = Rectifier voltage capacity design safety factor

$$V_{REC} = 25 \text{ amp} \times 1.38 \text{ ohms} \times 1.2$$

$$V_{REC} = 41.4 \text{ V}$$

c. Select rectifier.

Based on the design requirements of 41.4 V and 25 amp, a commercially available 48-V, 28-amp unit is selected. To prevent over- or under-protection as the water level varies, automatic potential control is specified. The tank-to-water potential is maintained by the controller through two permanent copper-copper sulfate reference electrodes suspended beneath the anode wire circle. The reference electrodes should have a life of at least 5 years. The tank-to-water potential measured by the controller should be free of IR drop error.

d. Installation.

Figure 2-14 shows a typical installation while figure 2-14A provides a typical detail for a pressure entrance fitting for underwater power and reference cell wire penetrations.

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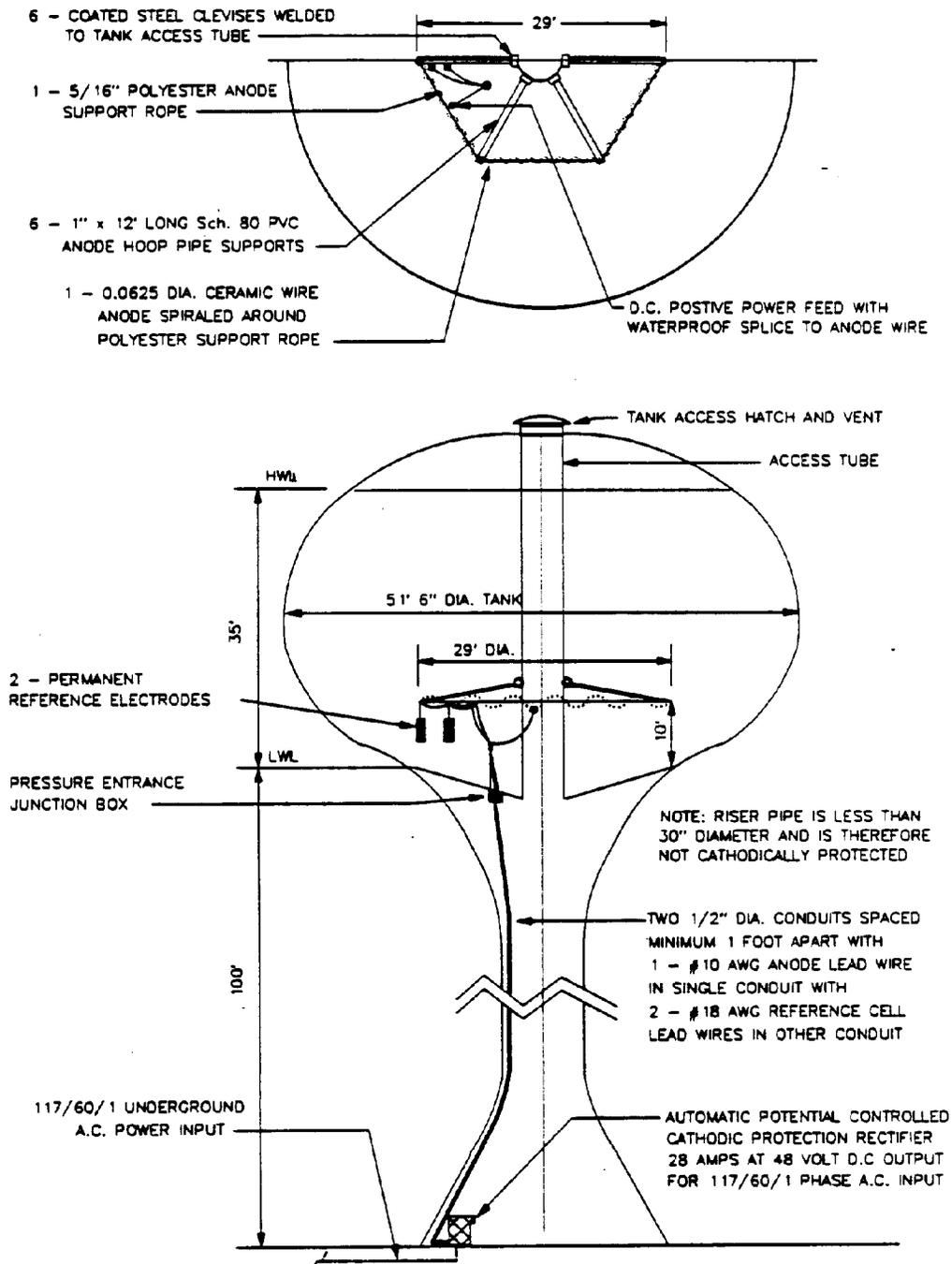


Figure 2-14 Elevated Pedestal Tank (Icing Conditions) With Hoop Ceramic Anode

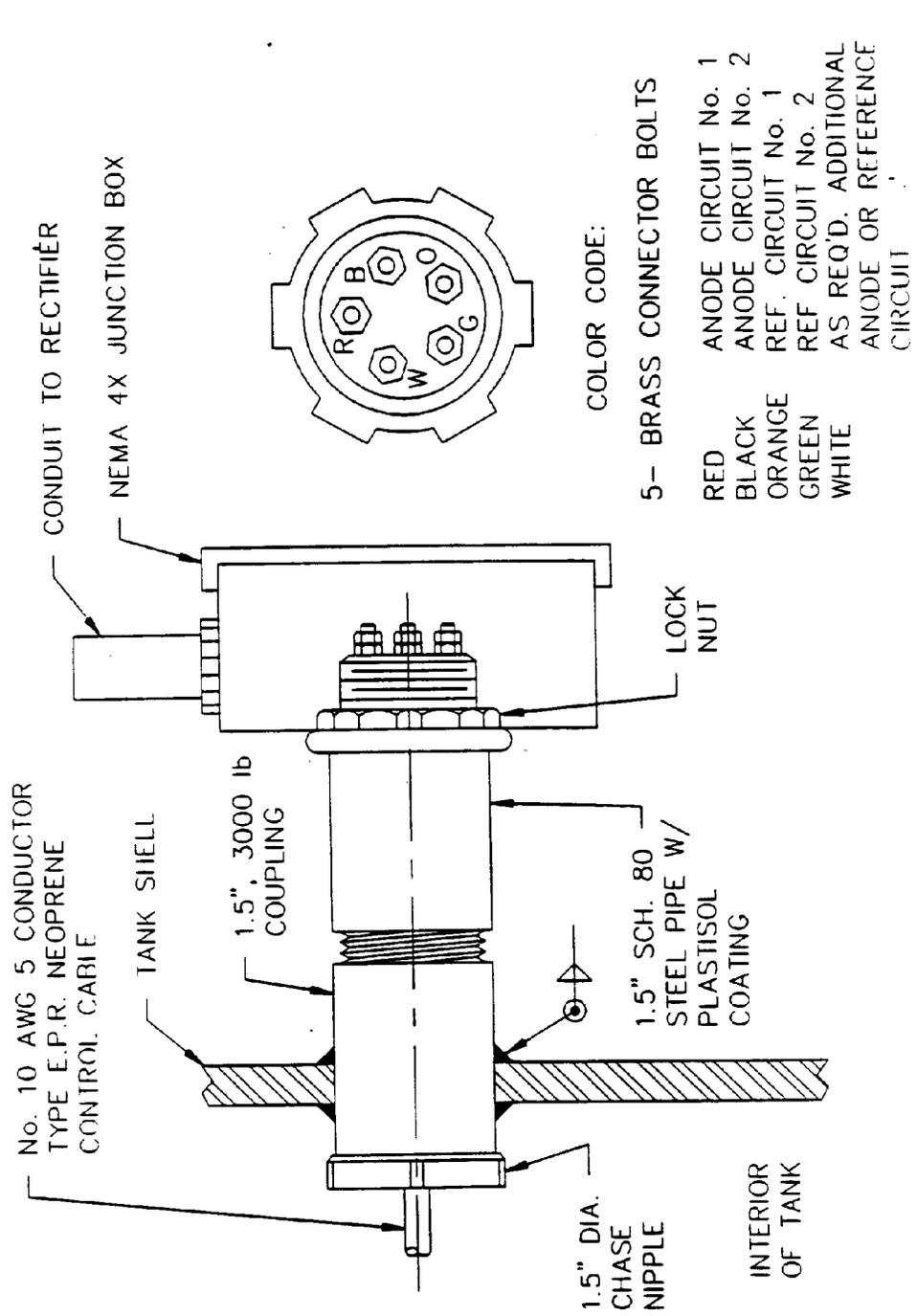


Figure 2-14A A Pressure Entrance Fitting for Underwater Power and Reference Cell Wire Penetrations in Water Storage Tanks

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2-7. Elevated Water Tank (No Icing Will Occur).

This impressed current design is for a tank (figure 2-15) 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 will be ellipsoidal on both top and bottom.
- 2) Tank dimensions will be:
 - Capacity = 500,000 gal
 - Diameter = 56 ft
 - Tank height (from ground to bottom of bowl) = 115 ft
 - Overall tank depth = 39 ft
 - Vertical shell height = 11 ft
 - High water level = 35 ft
 - Riser pipe diameter = 5 ft
- 3) Water resistivity is 4000 ohm-cm.
- 4) Design for a 20-year life.
- 5) The tank water will not be subjected to freezing.
- 6) Segmented rod anodes will be used; 4-ft long by 0.138-in. diameter. Note: Segmented rods have an advantage in that they can be field assembled using factory-made connections. On the other hand, continuous wire (.0625-in. diameter) is also available in long lengths (typically 500 ft). These can be fabricated with factory-made wire connections but their overall length must be specified. Continuous wire will almost always be less expensive.
- 7) All wetted inner surfaces will be uncoated. Area above water will be coated.
- 8) Electric power available will be 120/240 V AC, single phase.
- 9) Design for a current requirement of 2.5 A per sq ft for the bowl and 8.0 A per sq ft for the riser. Due to the velocity of the water in the riser, the riser's current requirement is typically much higher than the bowl.

b. Computations.

- 1) Find the area of wetted surface or tank bowl (A) shown in figure 2-16 from equation 2-1:

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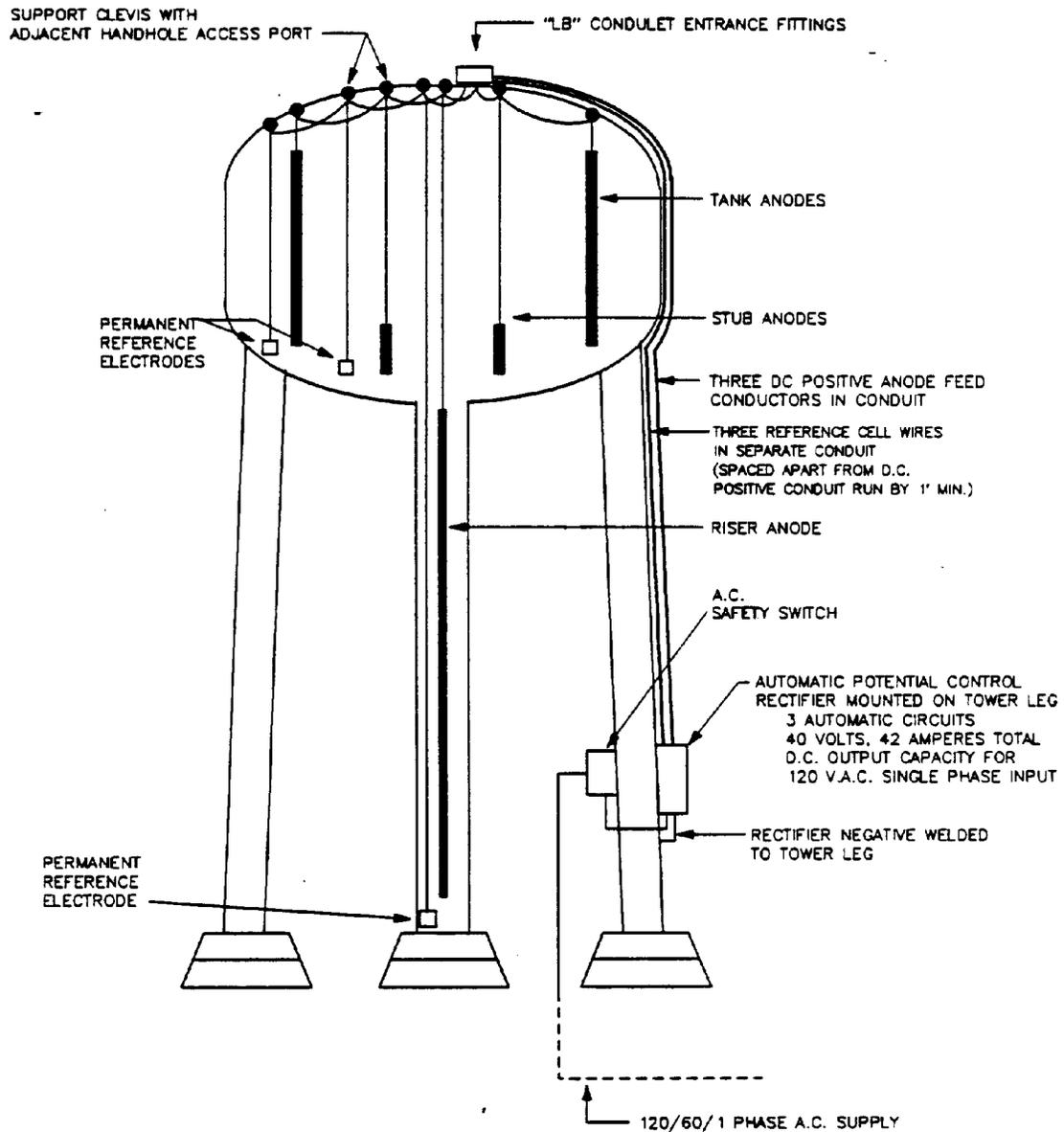


Figure 2-15 Elevated Water Tank Showing Rectifier and Anode Arrangement

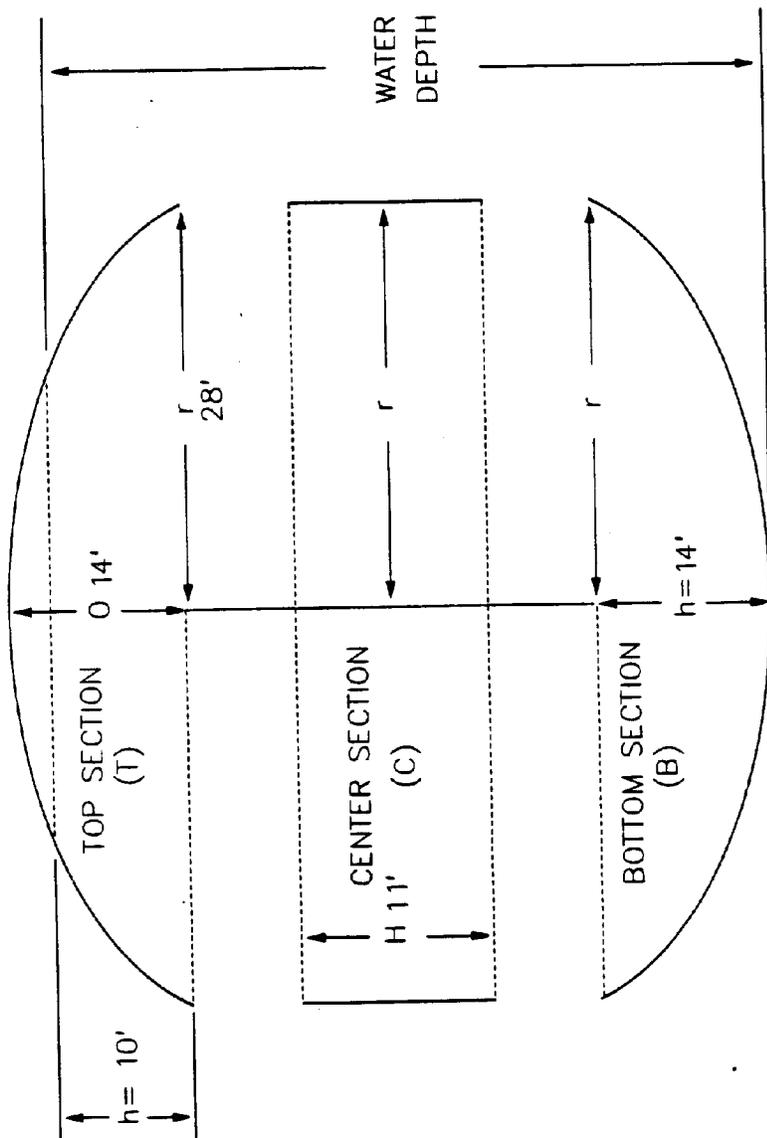


Figure 2-16 Segmented Elevated Tank for Area Calculations

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$$A = A_T + A_C + A_B \quad (\text{eq 2-1})$$

Where:

A_T = Wetted area of the top section
 A_C = Area of the center section
 A_B = Area of the bottom section.

- a) Find the appropriate wetted area of the top section (A_T) using equation 2-2:

$$A_T = 2 \mathbf{B} rh \quad (\text{eq 2-2})$$

Where:

r = 28 ft (Tank radius)
 h = 10 ft (Water height)

$$A_T = 2 \times 3.1416 \times 28 \text{ ft} \times 10 \text{ ft}$$

$$A = 1759 \text{ sq ft (approximate).}$$

- b) Find the wetted area of the center section (A_C) using equation 2-2:

$$A_C = 2 \mathbf{B} rh \quad (\text{eq 2-2})$$

r = 28 ft (Tank radius)
 h = 11 ft (Water height)

$$A_C = 2 \times 3.1416 \times 28 \text{ ft} \times 11 \text{ ft}$$

$$A = 1935 \text{ sq ft}$$

- c) Find the wetted area of the bottom section (A_B) from equation 2-3:

$$A_B = \sqrt{2} \times \mathbf{A} \times r \times \sqrt{h^2 + r^2} \quad (\text{eq 2-3})$$

Where:

r = 28 ft (Tank radius)
 h = 14 ft (Water height)

$$A_B = \sqrt{2} \times 3.1416 \times 28 \times \sqrt{(14)^2 + (28)^2}$$

$$A_B = 3894 \text{ sq ft}$$

d) Calculate (A):

$$\begin{aligned} A &= 1759 \text{ sq ft} + 1935 \text{ sq ft} + 3894 \text{ sq ft} \\ A &= 7588 \text{ sq ft} \end{aligned}$$

2) Find the riser pipe area (A_R) using equation 2-2:

$$A_R = 2 \mathbf{B} r_R h_R \quad (\text{eq 2-2})$$

Where:

$$r_R = 2.5 \text{ ft (Riser radius)}$$

$$h_R = 115 \text{ ft (Height of riser)}$$

$$A_R = 2 \times 3.1416 \times 2.5 \text{ ft} \times 115 \text{ ft}$$

$$A_R = 1806 \text{ sq ft}$$

3) Find the maximum design current for the tank bowl (I_T) using equation 1-1:

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

Where:

$$A = 7588 \text{ sq ft (Total wetted area of tankbowl from step 1 of paragraph 2-7b)}$$

$$I' = 2/5 \text{ mA/sq ft (Required current density from item 9 of paragraph 2-7a)}$$

$$C_E = 0.0 \text{ (Coating efficiency, wetted inner surfaces will be uncoated, from item 7 of paragraph 2-7a)}$$

$$I_T = 7588 \text{ sq ft} \times 2.5 \text{ mA/sq ft} \times (1.0 - 0.0).$$

$$I_T = 18,970 \text{ mA; use 19.0 amp}$$

4) Find the maximum design current for the riser (I_R), using equation 1-1:

$$I_R = (A_R) (I') (1.0 - C_E)$$

Where:

$$A_R = 1806 \text{ sq ft (Total surface area of riser pipe from step 2 of paragraph 2-7b)}$$

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$I' = 8.0 \text{ mA/sq ft}$ (Required current density for riser pipe from item 9 of paragraph 2-7a)

$C_E = 0.0$ (Coating efficiency. Inner surfaces will be uncoated, from item 7 of paragraph 2-7a)

$I_R = 1806 \text{ sq ft} \times 8.0 \text{ mA/sq ft} \times (1.0 - 0.0).$

$I_R = 14,448 \text{ mA};$ use 14.5 amp.

- 5) Select the number of anodes required for the bowl, to meet the anode system's 20-year design life using equation 1-2:

$$N = \frac{I}{I_A}$$

Where:

$I = 19 \text{ amp}$ (Current requirement determined in step 3)

$I_A = 1 \text{ amp/anode}$ (Current rating per anode from table 3-3 for 4-ft long by 0.138-in. diameter ceramic rods)

$$N = \frac{19}{1}$$

$N = 19 \text{ rod segments}$ (4-ft long segment)

- 6) Select the number of anodes required for the riser to meet the anode system's 20 year design life using equation 1-2:

$$N = \frac{I}{I_A}$$

Where:

$I = 14.5 \text{ amp}$ (Current requirement determined in step 4)

$I_A = 1 \text{ amp/anode}$ (Current rating per anode from table 3-3 for 4 ft long by 0.138-in. diameter ceramic rods)

$$N = \frac{14.5}{1}$$

$$N = 14.5; \text{ use 15 rod segments (4 ft. long)}$$

- 7) Calculate the radius of the main anode circle (AR), using equation 2-4:

$$A_R = \frac{D \times N}{2 (A + N)} \quad (\text{eq 2-4})$$

Where:

$$D = 56 \text{ ft (Tank diameter, from item 2 of paragraph 2-7a)}$$

$$N = 10 \text{ anode strings (assumed: it is necessary to assume a number of anode strings since there are two unknowns in this equation.)}$$

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

$$A_R = \frac{560 \text{ ft}}{26.28}$$

$$A_R = 21.3 \text{ ft; use 22 ft for the main anode circle radius}$$

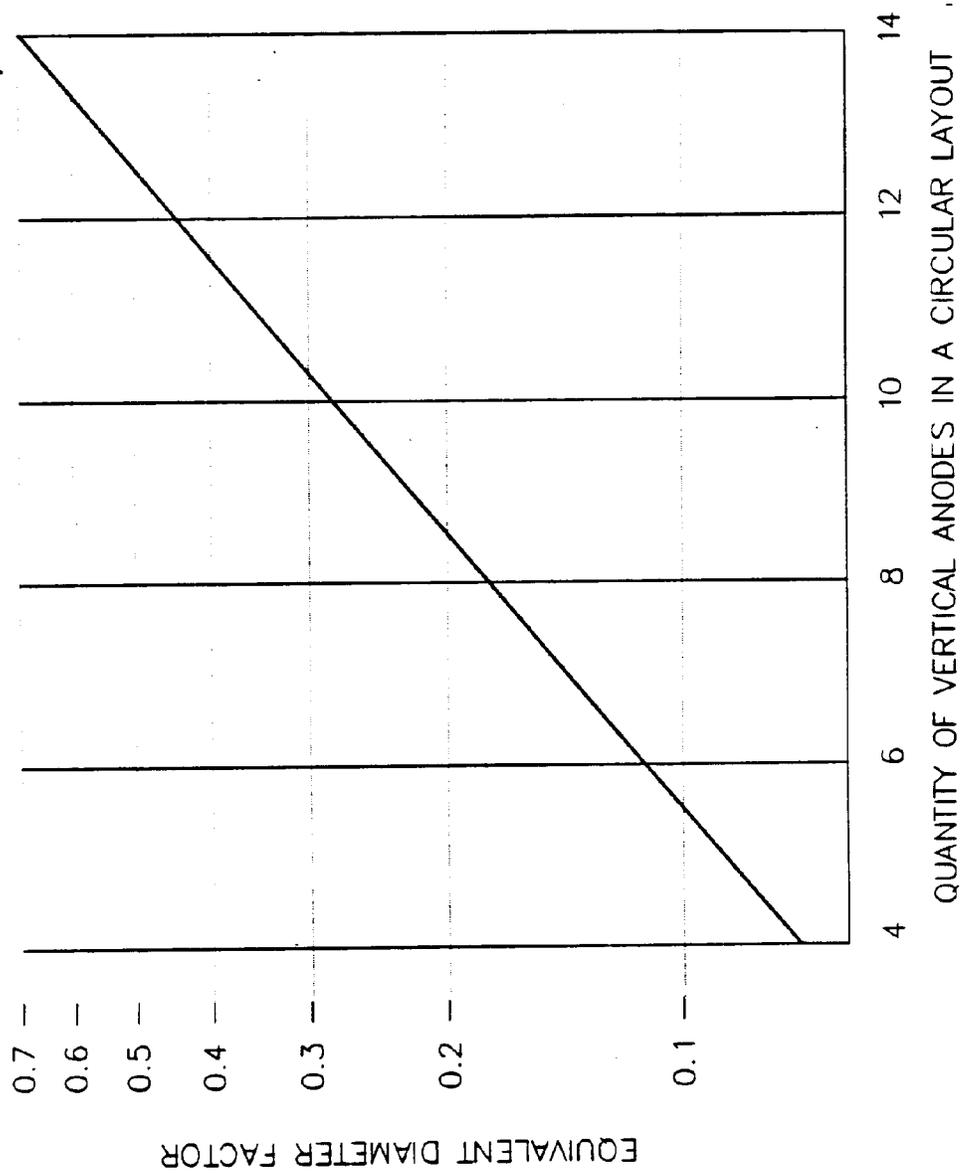
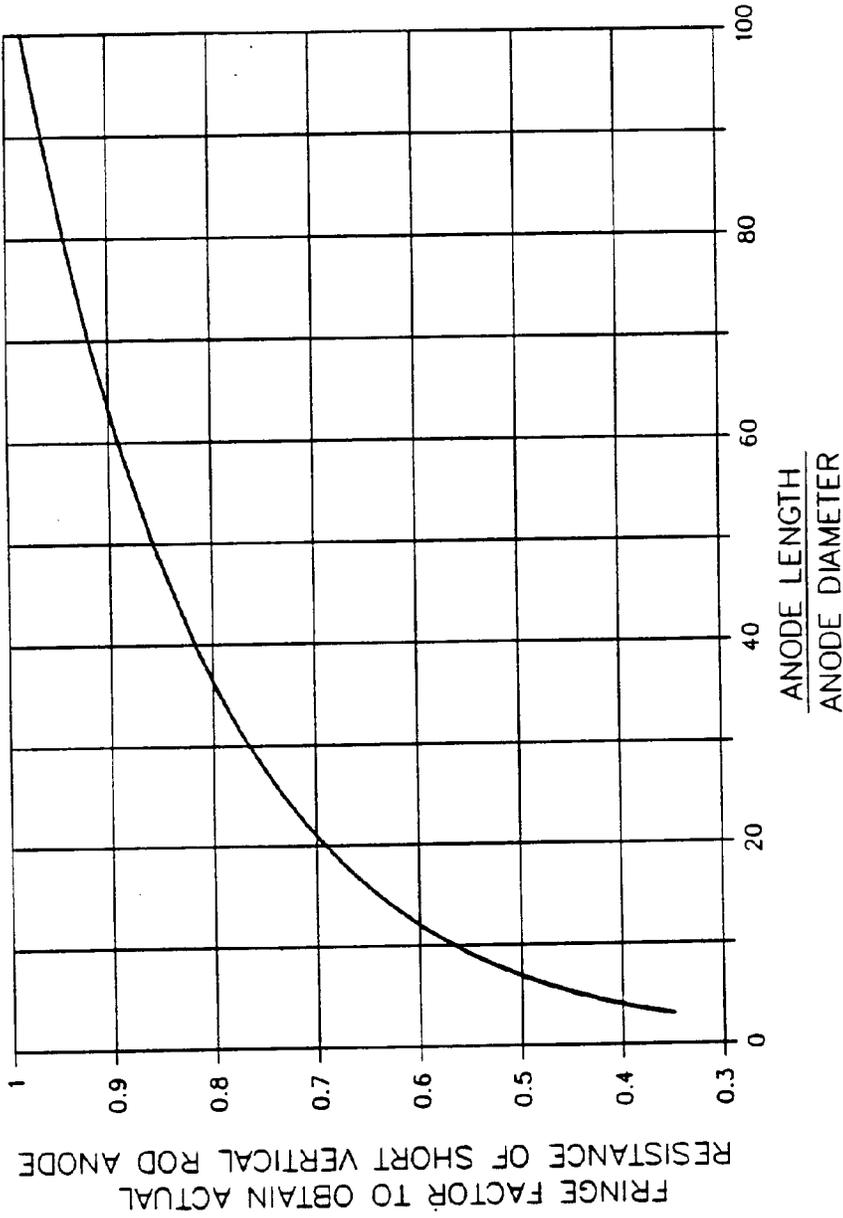


Figure 2-17 Equivalent Diameter Factor for Anodes in a Circle in a Water Tank



TO CALCULATE THE ACTUAL RESISTANCE OF A SHORT ANODE ($L/D < 100$)
MULTIPLY THE CALCULATED RESISTANCE BY THE FRINGE FACTOR
PROVIDED BY THIS CHART

Figure 2-18 Fringe Factor for Stub Anodes

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- 8) Determine the center-to-center spacing (C_c) for the main anode strings.
- a) To find circumference spacing (C_c), use equation 2-5:

$$C_c = \frac{2 A A_R}{N} \quad (\text{eq 2-5})$$

Where:

A_R = 22 ft (Radius of main anode circle from previous calculation.)

N = 10 anode strings ([Assumed] Used in previous calculation)

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

C_c = 13.8 ft; use 14 ft for center-to-center spacing between anode strings.

- b) The cord spacing is approximately the same as circumferential spacing; 14 ft will be used (figure 2-19).

- 9) Select main anode system

Number of 4-ft long rod segments needed for the current requirement (from step 5) = 19. Number of anode strings utilized (from step 7) = 10. Using two rod segments per string will provide twenty anodes, which is sufficient for the current requirement. However, for rod type anode designs, the main anode rods should extend from a distance of 4 ft above the tank bottom to within 4 ft of the HWL. Due to the curvature of the tank bottom, the total water depth at the location of the main anodes is approximately 30 ft. Therefore, the minimum rod length should be 22 ft (30 ft - 4 ft - 4 ft = 22 ft). Since these rods come in 4 ft lengths, we will use six segments per anode with a total length of 24 ft.

- 10) Calculate the resistance of the main anodes to water (R_N) using equation 1-13:

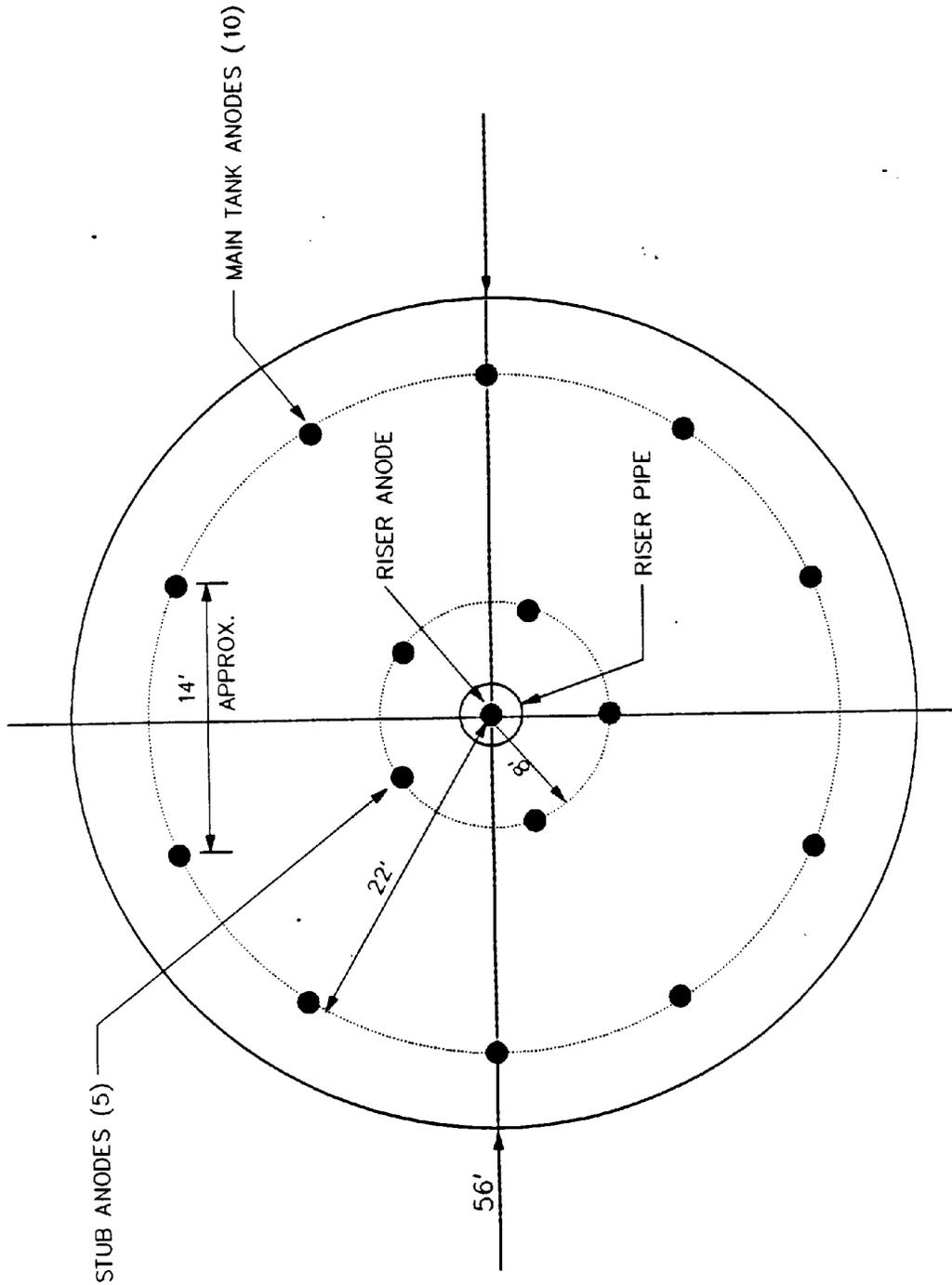


Figure 2-19 Anode Spacing for Elevated Steel Water Tanks

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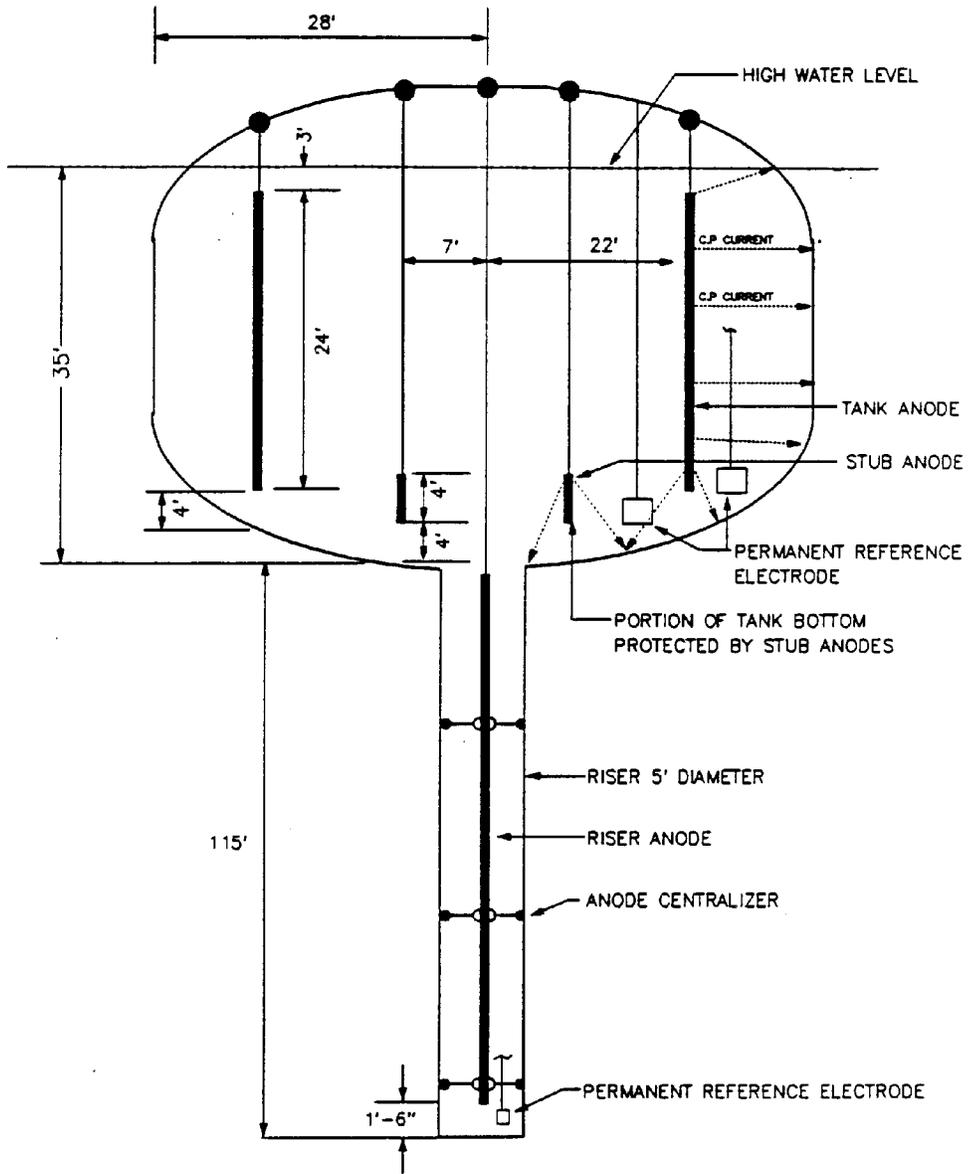


Figure 2-20 Anode Suspension Arrangement for Elevated Steel Water Tank

$$R_N = \frac{0.0052 \times p \times \ln [D / (2 A_R \times D_E)]}{L_B}$$

Where:

p = 4000 ohm-cm (Water resistivity from item 3 of paragraph 2-7a)

D = 56 ft (Tank diameter from item 2 of paragraph 2-7a)

A_R = 22 ft (Radius of main anode circle from step 7 of paragraph 2-7b)

D_E = 0.275 (Equivalent diameter factor from figure 2-17)

L_B = 24 ft (Length of each anode from step 9 of paragraph 2-7b)

R_N = $\frac{0.0052 \times 4000 \times \ln(56 / (44 \times 0.275))}{24}$

R_N = 1.33 ohms.

If the anode rod length-to-diameter ratio (L/d) is less than 100, the anode-to-water resistance needs to be adjusted by the fringe factor. (See step 12 for a discussion of fringe factor.)

In this case, $L = 24$ ft and $d = 0.0115$ ft. L/d , therefore, is $(24/0.0115) = 2086$. No fringe factor correction is required.

11) Calculate the stub anode requirement (N_s):

a) The main anode radius has been calculated to be 22 ft. The main anodes are spaced to provide approximately the same distance from the sides and the bottom of the tank. The main anode will protect a length inward along the tank bottom equal to approximately the same spacing that the anode is spaced away from the tank wall.

b) The anode suspension arrangement for the tank being considered is shown in figure 2-20. It can

be seen that stub anodes are required for this design. For a two-ring anode design (main and one-stub anode ring), which is usually sufficient for tanks up to 1 million gal storage capacity, the 4-ft long stub anodes are located on a radius one-fourth of the bowl radius, or 7 ft (28 ft x 0.25 = 7 ft). Typically, there will be about one half as many stub anodes (two ring design) as there are main anodes so we will plan for five 4-ft long stub anodes on a 7-ft radius. The outside radius of the area to be protected by the stub anodes is approximately 13 ft and the inside radius is 2.5 ft (riser radius). The stub anodes are thus located on an 7-ft radius to place them in the center of the area to be protected. (Note: For smaller diameter tanks, stub anodes may not be required.)

c) Find the current division between main and stub anodes.

(1) The area of tank bottom protected by stub anodes (A_{SB}) is found by equation 2-6 (see figure 2-20):

$$A_{SB} = B (r_2^2 - r_1^2) \quad (\text{eq 2-6})$$

Where:

$r_1 =$ 2.5 ft (Riser radius)
 $r_2 =$ 13 ft (Radius of protected segment.)
This is based on the fact that the main anode string is 6 ft from the tank wall and that the anode will protect another 9 ft (1.5 x 6 ft in toward the center on the tank bottom due to arc shape of the tank bottom). Outside radius of the area to be protected by the stub anodes is, therefore:

$$28 \text{ ft (tank radius)} - 6 \text{ ft} - 9 \text{ ft} = 13 \text{ ft}$$

$$A_{SB} = 3.1416 [(13 \text{ ft})^2 - (2.5 \text{ ft})^2]$$

$$A_{SB} = 3.1416 \times 162.75$$

$$A_{SB} = 511.3 \text{ sq ft; use 512 sq ft as the area to be protected by the stub anodes.}$$

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- (2) The current requirements for stub anodes is, therefore;

$$512 \text{ sq ft} \times 2.5 \text{ mA/sq ft} = 1280 \text{ mA or } 1.3 \text{ amp}$$

- (3) The total current requirement for the bowl is 19.0 amp (from step 3).

- (4) The current for the main anodes is, therefore;

$$19.0 \text{ amp} - 1.3 \text{ amp} = 17.7 \text{ amp}$$

- d) Select number of stub anodes (N_s).

In step 11, five stub anodes were assumed. Check the number required from equation 1-2:

$$N_s = \frac{I}{I_A}$$

Where:

$$I = 1.3 \text{ amp (Current requirement from previous calculation)}$$

$$I_A = 1 \text{ amp/anode current rating per anode from table 2-4 for 4-ft long by 0.138-in. diameter ceramic rods.}$$

$$N_s = \frac{1.3}{1}$$

$$N_s = 1.3; \text{ use } 2 - 4 \text{ ft anode rods}$$

The five anodes selected to provide proper coverage over the bottom are more than sufficient for the desired anode life.

- 12) Calculate the stub anodes-to-water resistance (R_N).

Find the stub anode resistance from equation 1-13:

$$R_N = \frac{0.0052 \times p \times \ln [D / (2 A_R \times D_E)]}{L_B}$$

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Where:

- ρ = 4000 ohm-cm (Water resistivity from item 3 of paragraph 2-7a)
- D = 56 ft (Tank diameter from item 2 of paragraph 2-7a)
- A_R = 7 ft (Radius of stub anode circle from step lib of paragraph 2-7b)
- D_E = 0.07 (Equivalent diameter factor from figure 2-17)
- L_B = 4 ft (Length of each stub anode)
- R_N = $\frac{0.0052 \times 4000 \times \ln [56 / (14 \times 0.07)]}{4}$
- R_N = 21.03 ohms.

Because the stub anodes are short, their anode-to-water resistance may have to be adjusted by the fringe factor. The fringe factor depends on the ratio of length-to-diameter (L/d). If L/d is less than 100, obtain the fringe factor from figure 2-18. Multiply the calculated stub anode-to-water resistance by the fringe factor (F) to obtain the adjusted resistance (R_{ADJ}).

$$R_{ADJ} = R_N \times F \quad (\text{eq 2-7})$$

Where:

- R_N = Stub anode-to-water resistance from step 12.
- F = Fringe factor from figure 2-18.

In this example, L/d for the stub anodes is:

$$L = 4 \text{ ft}$$

$$d = 0.0115 \text{ ft}$$

$$L/d = \frac{4}{0.0115} = 348$$

In this case L/d is greater than 100, so no fringe factor correction is required.

- 13) Determine total resistance of main and stub anodes (R_T) from equation 1-3:

$$R_T = R_N + R_W + R_C$$

Where:

$$\begin{aligned} R_N &= \text{Anode-to-water resistance.} \\ R_W &= \text{Header cable/wire resistance.} \\ R_C &= \text{Tank-to-water resistances.} \end{aligned}$$

- a) Main anode rods:

$$R_N = 1.33 \text{ ohms (from step 10)}$$

$$R_W = 0.13 \text{ ohm}$$

Header cable/wire resistance is calculated from equation 1-15:

$$R_W = \frac{L_W R_{MFT}}{1000 \text{ ft}}$$

Where:

$$L_W = 200 \text{ ft (After reviewing figure 2-20, it is estimated that 200 ft of wire will be required to connect the rectifier to the anode distribution wiring at the top of the tank)}$$

$$R_{MFT} = 0.640 \text{ ohm (Wire resistance per 1000 lin ft of No. 8 AWG HMWPE insulated wire)}$$

$$R_W = \frac{200 \text{ ft} \times 0.640 \text{ ohm}}{1000 \text{ ft}} = 0.13 \text{ ohm}$$

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$$R_C = 0.0 \text{ ohm (Resistance of the tank-to-water and negative wire is negligible)}$$

- b) Calculate the total resistance of the main anode rods circuit (R_T):

$$R_T = 1.33 + 0.13 + 0.0$$

$$R_T = 1.46 \text{ ohms for main anodes.}$$

- c) Calculate the total resistance of the stub anode rods circuit (R_T):

Where:

$$R_N = 21.03 \text{ ohms (from step 12)}$$

$$R_W = 0.13 \text{ ohm (same as main anode header)}$$

$$R_C = 0.0 \text{ ohm (negligible)}$$

$$R_T = 21.03 + 0.13 + 0.0$$

$$R_T = 21.16 \text{ ohms for stub anodes.}$$

- 14) Design riser anode.

- a) Current requirement = 14.5 amp (from step 4)
- b) Number of anode rods required from step 6 = 15 rod segments (4-ft long each)
- c) Select riser anode system.

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 $1 \frac{1}{2}$ times the spacing of the anode from the riser pipe wall plus the length of the anode. The length of riser protected by one 4-ft long anode located 2.5 ft from the riser wall is therefore:

$$(2.5 \times 1.5) + 4 = 7.75 \text{ ft}$$

Number of anode required for a 115-ft riser:

$$N = \frac{115}{7.75} = 14.8 \text{ or } 15 \text{ anodes}$$

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The number of anodes required for current distribution equals the number needed for the current requirement. To allow for a factor of safety, use twenty anodes.

- d) Determine anode spacing.

Total riser length = 115 ft
 Distance from bottom of riser to bottom of bottom anode = 1.5 ft
 Space consumed by anodes = 20 anodes x 4 ft each = 80 ft
 Total space consumed = 80 + 1.5 = 81.5 ft
 Space remaining = 115 - 81.5 = 33.5 ft

For twenty anodes, there are nineteen spaces

Spacing = $\frac{33.5}{19}$ = 1.76 ft or 1 ft 9 in.

Such an assembly is possible since anode rod segments can be connected together with wire. Since the anodes are spaced so close together, it is better to use one long anode. Such an anode has less flexibility than the disjointed cable connected string, so there is less chance of its vibrating or being damaged by water turbulence.

For one long anode made of 4-ft segments screwed together, the number of anodes required is:

115 ft - 1.5 ft (distance from bottom) = 113.5 ft

$\frac{113.5}{4}$ = 28.4 anodes

Use 28 anode segments to keep the top segment within the riser.

Total anode length = 28 anodes x 4 ft/anode = 112 ft.

Weight of the anode string will be:

2.4 oz/anode x 28 anodes = 67.2 oz = 4.2 lb

Weight is not a factor in supporting the string.

- 15) Calculate the anode-to-water resistance of a single anode rod (R_A), using equation 2-8:

$$R_A = \frac{0.0052 p \ln(D/D_A)}{L_B} \quad (\text{eq 2-8})$$

Where:

p = 4000 ohm-cm (Water resistivity from item 3 of paragraph 2-7a)

D = 5 ft (Riser diameter from item 2 of paragraph 2-7a)

D_A = 0.0115 ft (0.138 in) (Diameter of anode rod from item 6 of paragraph 2-7a)

L_B = 112 ft (Length of anode rod from previous discussion)

$$R_A = \frac{0.0052 \times 4000 \times \ln(5./0.0115)}{112}$$

$$R_A = 1.13 \text{ ohms}$$

- 16) Determine the total circuit resistance (R_T) of the riser anode, from equation 1-12:

$$R_T = R_A + R_W + R_C$$

Where:

R_A = Anode-to-water resistance of a single anode rod.

R_W = Wire resistance.

R_C = Tank-to-water resistance.

- a) Anode-to-water resistance (R_A) = 1.13 ohms from step 15 of paragraph 2-7b.
- b) Header cable/wire resistance (R_N) from equation 1-15:

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$$R_w = \frac{L_w R_{MFT}}{1000 \text{ ft}}$$

Where:

$L_w =$ 240 ft (After reviewing figure 2-20, it is estimated that 240 ft of wire will be required to connect the rectifier to the riser anode string)

$R_{MFT} =$ 0.640 ohm (Wire resistance per 1000 lin ft of No. 8 AWG HMWPE insulated wire)

$$R_w = \frac{240 \text{ ft} \times 0.640 \text{ ohm}}{1000 \text{ ft}} = 0.15 \text{ ohm}$$

Since this anode string is very long, the metal of the anode can represent a significant resistance. Since the current discharges all along the anode, one half of its length is used in the resistance calculation.

Manufacturer's data show the longitudinal resistance of a single 4-ft anode segment to be 0.053 ohm. Effective resistance of the string is:

$$\frac{0.053 \text{ ohm/anode} \times 28 \text{ anodes}}{2} = 0.74 \text{ ohm}$$

This resistance is very high compared to the anode resistance (greater than 10 percent) as a result, too much current will discharge near the top of the anode and not enough current will be discharged near the bottom of the anode. Therefore, either a double-end feed method will have to be used or copper-cored rods must be used. (Note: This is usually only a problem in fresh water applications when the anode rod length is greater than 30 ft.) In this case, we will elect to use copper cored 1/8-in. diameter rods. Manufacturer's data show the longitudinal resistance of a single 4-ft long copper-cored rod of this diameter is 0.0034 ohm. Effective resistance of this string is therefore:

$$\frac{0.0034 \text{ ohm/anode} \times 28 \text{ anodes}}{2} = 0.048 \text{ ohm}$$

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Thus, the copper cored anode longitudinal resistance is less than 10 percent of the anode-to-water resistance (0.048 ohm/1.13 ohm - 0.043 = 4.3 percent) making this an acceptable riser anode design.

- c) Tank-to-water resistance (R_C) and negative circuit resistance = 0.0 ohm.
- d) Calculate total resistance of the riser circuit (R_T):

$$R_T = 1.13 + 0.15 + 0.0$$

$$R_T = 1.28 \text{ ohms for riser anode.}$$

17) Calculate the rectifier voltage (V_{REC}) and current:

- a) First, determine the voltage requirement (E) for each circuit using Ohm's Law:

$$E = I R_T$$

Where:

I = Current requirement.

R_T = Total circuit resistance.

Main Anodes:

I = 17.7 amp (from step 11c).

R_T = 1.46 ohms (from step 13b).

$$E = 17.7 \times 1.46 = 25.8 \text{ V}$$

Stub Anodes:

I = 1.3 amp (from step 11c).

R_T = 21.16 ohms (from step 13c).

$$E = 1.3 \times 21.16 = 27.5 \text{ V}$$

Riser Anodes:

I = 14.5 amp (from step 4)

R_T = 1.28 ohms (from step 16d)

$$E = 14.5 \times 1.28 = 18.6 \text{ V}$$

- b) Summarize each circuit's resistance, current requirement and voltage requirement:

	Circuit (amp)	Current Resistance (ohm)	Voltage Required (V)
Main anodes	17.7	1.46	25.8
Stub anodes	1.3	21.16	27.5
Riser anodes	<u>14.5</u>	1.28	18.6
Total current requirement	33.5		

- c) Determine the rectifier voltage (V_{REC}) based on the largest circuit voltage requirement of 27.5 V, because voltage requirement varies for all three circuits. With a 120 percent safety factor as in equation 1-17, the rectifier voltage is calculated:

$$27.5 \times (120\%) = 33 \text{ V}$$

Total current required = 33.5 amp.

c. Select rectifier

- 1) Rectifier capacity.

A commercially available rectifier having a rated output of 40 V, 42 amp is selected.

Because of the different circuit resistances, separate control of each circuit is required. This is best handled by a rectifier having three separate output circuits.

- 2) Automatic potential control

To prevent over or under protection as the water level varies, automatic potential control is specified. The tank and riser-to-water potentials are maintained by the controller through permanent copper-copper sulfate reference electrodes suspended within the bowl and riser. The reference electrodes should have a life of at least 15 years.

The automatic controller is located in the rectifier unit. The controller must be capable of sensing the potential accurately and free of IR (voltage) drop error. The control does this by turning off the

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rectifier for a fraction of a second, during which time the tank-to-water potential is measured. The measurement is then compared with a preset standard and the output adjusted accordingly.

d. Installation details.

Figures 2-19, 2-20, and 2-21 show typical details.

e. Guidelines for number of anode rings required.

The number of rings of anodes required varies with tank diameter. Table 3-7 gives suggestions.

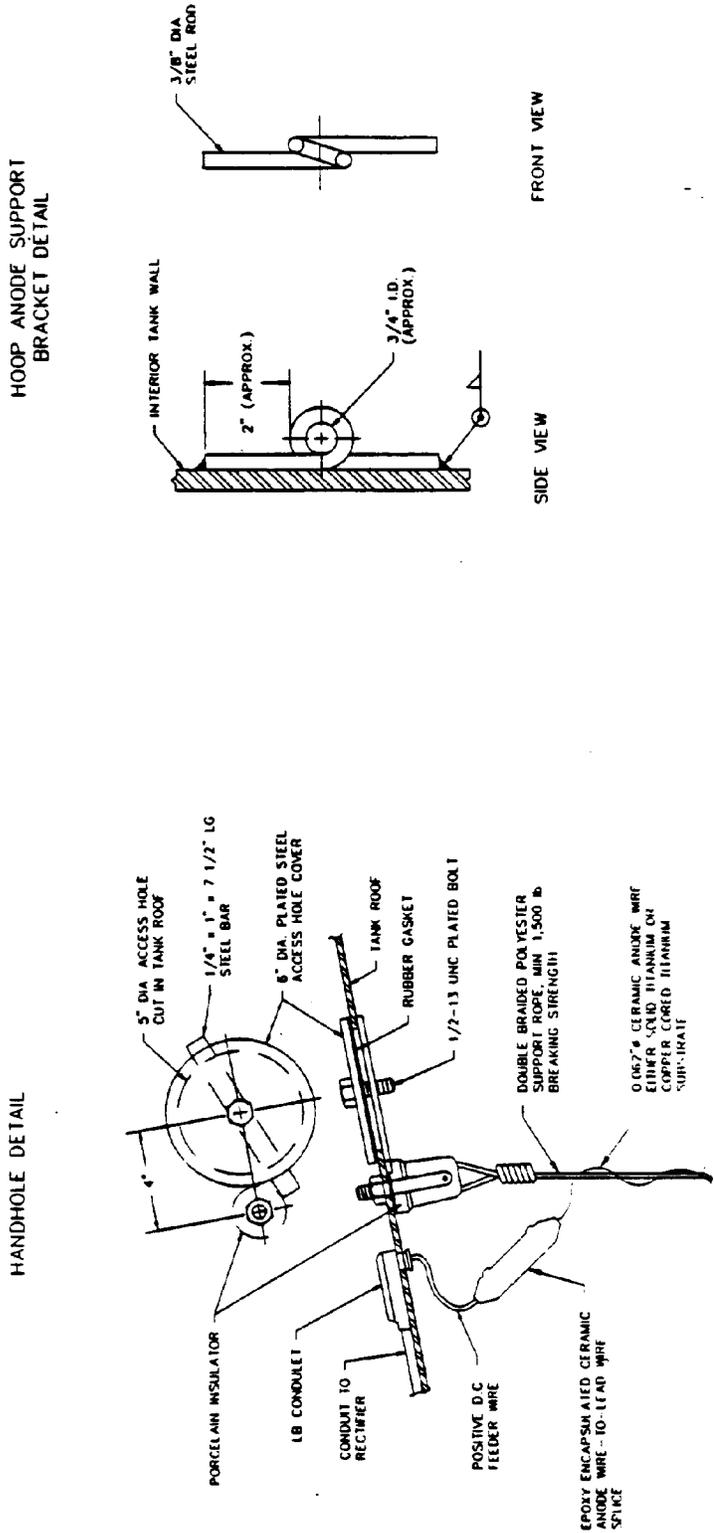


Figure 2-21 Water Tank Hand Hole Assembly for Roof-Supported Anodes and Support Bracket for Submerged Hoop Anodes

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2-8. On-Grade Water Storage Reservoir (Ice Is Expected).

Impressed current cathodic protection is to be designed for the existing ground level water reservoir shown in figure 2-22. Coating is in poor condition and expected to deteriorate in the future. As the tank is not heated, ice forms in the winter. Current requirement tests have been made.

a. Design data.

- 1) Tank is cylindrical with a flat bottom.
- 2) Water resistivity is 2000 ohm-cm.
- 3) Tank dimensions are:

Capacity = 250,000 gal
Diameter of bowl = 46 ft
High water depth = 20 ft.
- 4) Design cathodic protection anodes for a 15-year life since tank will be repainted at that time.
- 5) Wire type ceramic anode will be used.
- 6) Design current density is 2.5 A per sq ft of tank area to be protected.
- 7) Wetted surfaces are poorly coated. As coating is expected to deteriorate, design for bare tank.
- 8) Area above high water level will be kept well coated.
- 9) Tank is subject to freezing and therefore a hoop type anode support system will be used.
- 10) Electrical power available is 120 V AC, single phase.
- 11) Current requirement at present for adequate cathodic protection is 9.0 amp.

b. Computations.

- 1) Find the area of the tank to be protected (A).

$$A = 2 B r h + B r^2$$

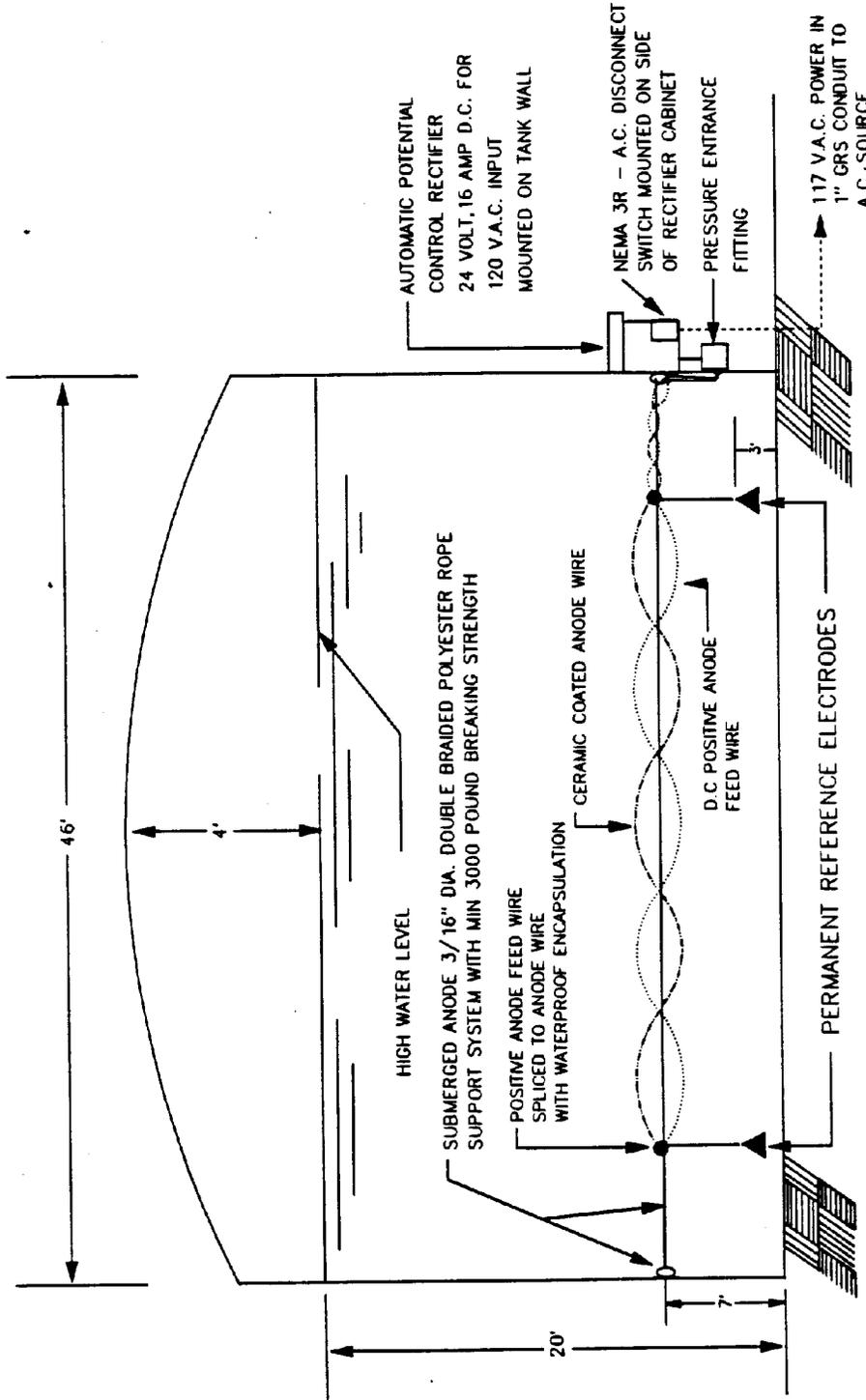


Figure 2-22 Submerged Cathodic Protection System for Ground-Level Water Storage Reservoir

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Where:

$r = 23 \text{ ft}$ (Tank radius from item 3 of paragraph 2-8a)

$h = 20 \text{ ft}$ (High water depth from item 3 of paragraph 2-8a)

$A = 2 \text{ it} \times 23 \times 20 + \text{it} \times 232$

$A = 2890 + 1662$

$A = 4552 \text{ sq ft}$

- 2) Compute the current requirement (I) using equation 1-11:

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

Where:

$A = 4552 \text{ sq ft}$ (Area of tank to be protected from previous calculation)

$I' = 2.5 \text{ mA/sq ft}$ (Required current density from item 6 paragraph 2-8b)

$C_E = 0.0$ (Coating efficiency, assuming tank will eventually be essentially bare)

Current required:

$$I = 2.5 \text{ IDA/sq ft} \times 4552 \text{ sq ft}$$

$$I = 11,380 \text{ IDA; use 12 amp}$$

Since the computed 12 amp is larger than the tested requirement of 9 amp, use the 12 amp as the required current.

- 3) Calculate the length of anode wire in ft (L_B) needed for the current required, using a modification of equation 1-2:

$$L_B = \frac{I}{I_A}$$

Where:

$I = 12 \text{ amp}$ (Current requirement from previous calculation)

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I_A = Allowable amp per ft of anode wire (varies depending on desired anode life and diameter), found in table A-3.

Based on selecting a wire anode of 0.0625-in. diameter, the minimum wire length and hoop diameter can be calculated:

$$\begin{aligned} \text{For } 0.0625 \text{ in. } L_B &= \frac{12 \text{ amp}}{0.31 \text{ amp/ft}} \\ &= 38.7 \text{ ft} && 12 \text{ ft } 4 \text{ in} \\ &&& \text{(Length of} && \text{(Minimum} \\ &&& \text{Wire for} && \text{Diameter of} \\ &&& \text{15-Year Life)} && \text{Wire Circle)} \end{aligned}$$

- 4) Calculate the desired diameter of the anode wire circle (D_R). Experience shows that the diameter of the anode wire circle should be between 40 and 70 percent of the tank diameter for a cylindrical tank. In this case, we will try a hoop shape with a diameter equal to 60 percent of the bowl diameter:

$$D_R = 60\% \times 46 \text{ ft} = 27.6 \text{ ft}; \text{ use } 27 \text{ ft } 6 \text{ in}$$

- 5) Calculate the anode anode-to-water resistance (R_A) from equation 1-14:

$$R_A = \frac{0.0016 p}{D_R} \left(\ln \frac{8 D_R}{D_A} + \ln \frac{2 D_R}{H} \right)$$

Where:

- p = 2000 ohm-cm (Water resistivity from item 2 of paragraph 2-8a)
- D_R = 27.5 ft (Anode ring diameter from previous calculation)
- D_A = Assume 0.0052 ft (0.0625 in) (Diameter of anode wire from step 3 of paragraph 2-8b)

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H = 12 ft (Anode depth below water surface) Anode depth has been determined from the following calculations:

The distance from the bottom of the tank to the anode wire circle should be about 40 percent of the water depth.

Water depth = 20 ft from item 3 of paragraph 2-8a.

20 ft x 40% = 8 ft

Anode depth below water surface (H):

H = 20 ft - 8 ft = 12 ft

Calculate R_A :

$$R_A = \frac{0.0016 \times 2000}{27.5} \left[\ln \frac{8 \times 27.5}{0.0052} + \ln \frac{2 \times 27.5}{12} \right]$$

$$R_A = 0.1164 [\ln 42,307.7 + \ln 4.6]$$

$$R_A = 0.1164 [10.65 + 1.531]$$

$$R_A = 1.42 \text{ ohm}$$

At a current requirement of 12 amp, voltage required for this resistance, from Ohm's Law is:

$$E = I \times R_A$$

$$E = 12 \times 1.42 = 17.2 \text{ V}$$

This is a reasonable voltage, so the resistance of 1.42 ohms is acceptable.

- 6) Determine the total circuit resistance (R_T), from equation 1-3:

$$R_T = R_N + R_W + R_C$$

Where:

R_N = R_A = Anode-to-water resistance.

R_W = Header cable/wire resistance.

R_C = Tank-to-water resistance.

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- a) Anode-to-water resistance = 1.42 ohms from step 5.
- b) Header cable/wire resistance (R_W) from equation 1-15:

$$R_W = \frac{L_W R_{MFT}}{1000 \text{ ft}}$$

Where:

L_W = The positive wire from the rectifier to the first splice is 15 ft long. The power feed then continues on around the hoop to the opposite side. The length of this run is about 43.2 ft but since only half the current is passing through this portion, its effective length is $43.2/2 = 21.6$ ft.

R_{MFT} = 1.02 ohms (From table 3-6, based on selecting No. 10 AWG cables)

$$R_W = \frac{(15 \text{ ft} + 21.6 \text{ ft}) \times 1.02 \text{ ohms}}{1000 \text{ ft}}$$

$$R_W = 0.037 \text{ ohm}$$

- c) Negative circuit and tank-to-water resistance (R_C).

The negative wire is connected to the tank structure near the rectifier, so its resistance is negligible. Tank-to-water resistance is also negligible.

- d) Calculate R_T :

$$R_T = 1.42 + 0.037 + 0.00$$

$$R_T = 1.457 \text{ ohms; use } 1.5 \text{ ohms}$$

This is well below the design requirement.

- 7) Calculate the rectifier voltage (V_{REC}) from equation 1-17:

$$V_{\text{REC}} = (I) (R_{\text{T}}) (120\%)$$

Where:

I	=	12 amp (Current requirement from step 3)
R _T	=	1.5 ohms (Total circuit resistance from previous calculation)
120%	=	Rectifier voltage capacity design safety factor.
V _{REC}	=	12 amp x 1.5 ohms x 1.2
V _{REC}	=	21.6 V

c. Select rectifier.

Based on the design requirements of 21.6 V and 12 amp, a commercially available 24-V 16-amp unit is selected.

d. Automatic potential control.

To prevent over- or under-protection as the water level varies, automatic potential control is specified. The tank and riser to water potential is maintained by the controller through permanent copper-copper sulfate reference electrodes suspended with the bowl and riser. The reference electrodes should have a design life of at least 15 years.

The automatic controller is located in the rectifier unit. The controller must be capable of sensing the potential accurately and must be free of IR (voltage) drop error. The controller does this by turning off the rectifier for a fraction of a second, during which time the tank-to-water potential is measured. The measurement is then compared with a present standard and the output adjusted accordingly.

e. Installation details.

Figures 2-22 and 2-23 show typical details.

f. Loop anode attachment guidelines.

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The wire circle, or loop anode is supported from the sides of the tank by polyester rope as shown in figure 2-22. The number of supports varies with the tank diameter as recommended in table 3-8.

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2-9. Horizontal Anodes. (Underground Applications)

There are times when it is advantageous to install anode horizontally as shown in figure 2-24. For further information, see paragraphs 10.91 through 10.93 of TM 5-811-7 (reference 10). This configuration is particularly helpful when using packaged ceramic anodes (figure 2-24) since earth backfill can be solidly tamped around them. The anodes can be laid on the bottom of a trench or excavation with compacted backfill. This often achieves better compaction than when tamping in vertical holes. The design is undertaken in the same manner as described in Section 2-2 and 2-3. The single anode-to-earth resistance is calculated by using equation 2-11:

(eq 2-11)

Where:

- RA = Anode-to-electrolyte resistance in ohms.
- p = Electrolyte resistivity in ohm-cm.
- L = Length of anode in ft.
- d = Diameter of anode in ft.
- h = Depth of anode in ft.

This equation is used to calculate the resistance of a single anode-to-earth.

For multiple anode installations, equation 1-11 may be used to approximate total resistance:

$$R_N = \frac{R_A}{N} + \frac{p P_F}{C_C}$$

Where:

R_N = Resistance-to-electrolyte of "N" number of anodes

R_A = Resistance-to-electrolyte of a single horizontal anode

N = Number of anodes

p = Electrolyte resistivity in ohm-cm

P_F = Paralleling factor (table 3-5)

C_C = Spacing between anodes in ft. (The spacing between anodes is taken as the center-to-center distance between horizontal anode.)

As before, when equation 1-11 is applied to horizontal anodes, it yields approximate results. This is because the equation is based on vertical anodes. However, the results are sufficiently accurate for cathodic protection design.

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2-10. Backfilling Packaged Anodes With Coke Breeze.

Although the calculations shown in Sections 2-2 and 2-3 assume that the packaged ceramic anodes will be buried directly in the earth, the accepted fail-safe design practice is to bury the packaged anode canister in a coke breeze backfill.

Backfilling the packaged anodes in coke breeze offers three advantages. First, it reduces anode-to-ground resistance. A typical example would be to backfill a 3-in. by 60-in. anode in a 8-in. diameter by 84-in. long coke breeze column. These dimensions, $d = 0.66$ ft and $L = 7.0$ ft, are then used in equation 2-8 or 2-10 to calculate resistance-to-earth.

The second advantage of using coke breeze backfill around packaged anodes is that coke breeze often results in better compaction than does soil. This also reduces anode-to-ground resistance and improves anode performance.

The most important reason, however, for backfilling these (as well as any other) prepackaged anode is that gas-blocking of the anodes will not occur. Gases (primarily oxygen) are released at the anode package surface. These can be entrapped by the soil at the anode package surface which can prevent further current discharge by the anode. The coke breeze provides a porous media through which these gases can migrate and dissipate preventing the possibility of gas blocking.

SECTION 3

TABLES

Table 3-1. Range of current density requirements for cathodic protection of uncoated steel.

Environment	Current density (mA/sq ft of bare steel)		
	APM 88-9 ^a	Gerrard ^b	Others ^c
Neutral soil	0.4 to 1.5	0.4 to 1.5	0.5 to 1.5
Well-aerated neutral soil	2 to 3	2 to 3	1.5 to 3
Wet soil	1 to 6	2.5 to 6	1 to 3
Highly acidic soil	3 to 15	5 to 15	3 to 15
Soil-supporting active sulfate-reducing bacteria	6 to 42	Up to 42	-----
Heated soil	3 to 25	5 to 25	3 or more
Stationary freshwater	1 to 6	Up to 5	1.5 to 3
Moving freshwater	-----	-----	3 to 8
Moving freshwater containing dissolved oxygen	5 to 15	5 to 15	-----
Seawater (depending on velocity, temperature & oxygen content)	3 to 10	5 to 25	5 to 50

^aCorrosion Control, Air Force Manual (AFM) 88-9 (Headquarters, U.S. Air Force, August, 1962), ch. 4, p. 203.

^bJ.S. Gerrard, "Practical Applications of Cathodic Protection," *Corrosion*, (Newnes-Butterworths, London, 1976), vol. 2, p 11:65. Used with permission.

^cData based on the experience of other Professional Cathodic Protection engineers.

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Table 3-2. Typical Surface Area Per Linear Foot of Common Size Pipe.

Nominal Pipe Size	Outside Diameter (in.)	Sq Ft/Lin Ft
½	0.840	0.220
¾	1.050	0.275
1	1.315	0.344
1 ¼	1.660	0.434
1 ½	1.900	0.497
2	2.375	0.621
2 ½	2.875	0.752
3	3.500	0.916
3 ½	4.000	1.047
4	4.500	1.178
5	5.563	1.456
6	6.625	1.734
8	8.625	2.258
10	10.750	2.814
12	12.750	3.338
14	14.000	3.665
16	16.000	4.189
18	18.000	4.712
20	20.000	5.236
22	22.000	5.760
24	24.000	6.283

NOTE: Data on anodes shapes and sizes as well as recommended operating limits were obtained from the following manufacturers:

APS-Materials Inc.
153 Walbrook
Dayton, OH 45405
(513) 278-6547
FAX: (513) 278-4352

Oronzio De Nora S.A.
P.O. Box 3387
Houston, TX 77253-3387
(713) 978-3925
FAX: (713) 978-3930

Materials Protection Company
P.O. Box 31354
Houston, TX 77231-1354
(713) 270-0952
FAX: (713) 988-0673

As their specifications change from time to time, it is recommended that the designer contact the companies prior to specifying a particular anode to determine what is currently available.

Table 3-3. Dimensions and ratings of ceramic anodes.
Underground Usage

Wire and Rod Anodes (Packaged)

Anode Element Dimension	Package Size	Weight	<u>Current Rating - Amperes</u>					
			10-Year		15-Year		20-Year	
			<u>Design Life</u> HDC*	<u>Design Life</u> SC**	<u>Design Life</u> HDC*	<u>Design Life</u> SC**	<u>Design Life</u> HDC*	<u>Design Life</u> SC**
1/8" x 2'	2" x 30"	6 lbs.	1.3 amps	0.6 amps	1.10 amps	0.6 amps	0.9 amps	0.5 amps
1/16" x 5'	2" x 72"	14 lbs.	1.5 amps	0.7 amps	1.25 amps	0.7 amps	1.0 amps	0.6 amps
1/16" x 5'	3" x 72"	26 lbs.	1.5 amps	0.7 amps	1.25 amps	0.7 amps	1.0 amps	0.6 amps
1/8" x 4'	2" x 60"	12 lbs.	2.7 amps	1.2 amps	2.2 amps	1.2 amps	1.8 amps	1.0 amps
1/8" x 4'	3" x 60"	22 lbs.	2.7 amps	1.2 amps	2.2 amps	1.2 amps	1.8 amps	1.0 amps
1/4" x 4'	3" x 60"	22 lbs.	5.5 amps	2.4 amps	4.4 amps	2.4 amps	3.5 amps	2.0 amps
1/8" x 6'	3" x 96"	35 lbs.	4.0 amps	1.8 amps	3.3 amps	1.8 amps	2.7 amps	1.5 amps
3/8" x 4'	3" x 60"	22 lbs.	7.5 amps	3.6 amps	6.0 amps	3.6 amps	5.1 amps	3.0 amps
1/2" x 4'	3" x 60"	23 lbs.	10.0 amps	4.8 amps	8.0 amps	4.8 amps	6.8 amps	4.0 amps
3/4" x 4'	3" x 60"	24 lbs.	15.0 amps	7.2 amps	12.0 amps	7.2 amps	10.0 amps	6.0 amps
1/8" x 6'	3" x 96"	35 lbs.	4.0 amps	1.8 amps	3.3 amps	1.8 amps	2.7 amps	1.5 amps
1/4" x 6'	3" x 96"	35 lbs.	8.2 amps	3.6 amps	6.6 amps	3.6 amps	5.3 amps	3.0 amps
1/8" x 8'	3" x 120"	44 lbs.	5.4 amps	2.4 amps	4.4 amps	2.4 amps	3.6 amps	2.0 amps
1/4" x 8'	3" x 120"	44 lbs.	11.0 amps	4.8 amps	8.8 amps	4.8 amps	7.0 amps	4.0 amps

*Heavy Duty Coating Tubular Anodes (in Coke Breeze)

**Standard Coating Tubular Anodes (in Coke Breeze)

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Table 3-3. (Cont*d)

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

Table 3-3 (Cont*d). Fresh and Seawater Usage
Wire and Rod Anodes (Bare)

Life (years)	Fresh Water	Brackish Water	Seawater
Maximum Current/1-ft Length for 20-Year Design Life of .0625 in. Dia. Wire			
10	0.39	0.51	0.85
15	0.31	0.44	0.74
20	0.26	0.39	0.67
Maximum Current/1-ft Length for 20-Year Design Life of .125 in. Dia. Rod or Wire			
10	0.79	1.02	1.70
15	0.62	0.88	1.47
20	0.52	0.79	1.33
Maximum Current/1-ft Length for 20-Year Design Life of .25 in. Dia. Rod			
10	1.58	2.04	3.41
15	1.24	1.76	2.95
20	1.04	1.58	2.66
Maximum Current/1-ft Length for 20-Year Design Life of .325 in. Dia. Rod			
10	2.37	3.06	5.11
15	1.85	2.63	4.42
20	1.56	2.37	3.99
Maximum Current/1-ft Length for 20-Year Design Life of .5 in. Dia. Rod			
10	3.16	4.08	6.81
15	2.47	3.51	5.90
20	2.08	3.16	5.33
Maximum Current/1-ft Length for 20-Year Design Life of .625 in. Dia. Rod			
10	3.95	5.10	8.52
15	3.09	4.39	7.37
20	2.60	3.95	6.66
Maximum Current Per 1-ft Length for 20-Year Design Life of .75 in. Dia. Rod			
10	4.74	6.12	10.22
15	3.71	5.27	8.85
20	3.12	4.74	7.99

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Tubular Anodes (Bare)

<u>Seawater</u> - Current in amp per anode (15-Year Design Life)	
1 in. x 19.7 in.	25 amp
1 in. x 39.4 in.	50 amp
0.63 in. x 19.7 in.	15 amp
0.63 in. x 39.4 in.	30 amp
<u>Sea Mud</u> - Current in amp per anode (20-Year Design Life)	
1 in. x 19.7 in.	6 amp
1 in. x 39.4 in.	12 amp
<u>Fresh Water</u> - Current in amp per anode (20-Year Design Life)	
1 in. x 19.7 in.	4.00 amp
1 in. x 39.4 in.	8.00 amp
0.63 in. x 19.7 in.	2.50 amp
0.63 in. x 39.4 in.	5.00 amp

Current Density Limitations

Wire and Rod Anode
 Anode Life Versus Maximum Current Density (ampere/sq ft)

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

* Anode packaged in coke breeze

Tubular Anodes
Anode Life Versus Maximum Current Density (ampere/sq ft)

Life (years)	Coke	Fresh Water	Brackish Water	Seawater
20	9.3	9.3	9.3	56 **

*Anode packaged in coke breeze
**15-Year Design Life

Disc Anodes (see figure 2-28)

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 (amp/anode)	0.84	5.0
Operating voltage - 20-year life (V)	20.0	10.0

Segmented Rod Anodes (see figure 2-2 9)

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 (amp/anode)*	1.00	2.5
Operating voltage - 20-year life (V)	50.0	10.0

*Standard Coating

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Table 3-4. Shape functions (K) for impressed current cathodic protection anodes where L is effective anode/backfill length and d is anode/backfill diameter.

L/d	K	L/d	K
5	0.0140	20	0.0213
6	0.0150	25	0.0224
7	0.0158	30	0.0234
8	0.0165	35	0.0242
9	0.0171	40	0.0249
10	0.0177	45	0.0255
12	0.0186	50	0.0261
14	0.0194	55	0.0266
16	0.0201	60	0.0270
18	0.0207		

Table 3-5. Anode paralleling factors (P) for various numbers of anodes (N) 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		

Table 3-6. Resistance and other parameters for stranded copper conductors.

Size ** AWG	Overall Diameter Not Incl. Insulation (in.)	Approximate Weight Not Incl. Insulation (lb/M ft)	Maximum Breaking Strength (lb)	Maximum DC Resistance at 20 °C (ohms/M ft)	Maximum Allowable DC Current Capacity (ampere)
14	0.0726	12.68	130	2.5800	15
12	0.0915	20.16	207	1.6200	20
10	0.1160	32.06	329	1.0200	30
8	0.1460	50.97	525	0.6400	45
6	0.1840	81.05	832	0.4030	65
4	0.2320	128.90	1320	0.2540	85
3	0.2600	162.50	1670	0.2010	100
2	0.2920	204.90	2110	0.1590	115
1	0.3320	258.40	2660	0.1260	130
1/0	0.3730	325.80	3350	0.1000	150
2/0	0.4190	410.90	4230	0.0795	175
3/0	0.4700	518.10	5320	0.0631	200
4/0	0.5280	653.30	6453	0.0500	230
250 MCM	0.5750	771.90	7930	0.0423	255
EPR/HY-50*	0.3730 ⁽¹⁾	75.0 ⁽¹⁾	1896	0.1183	150
EPR/HY-16*	0.1840 ⁽²⁾	87.0 ⁽²⁾	628	0.3658	50

⁽¹⁾ With insulation: Overall diameter = 0.88 in.; weight - 610 lb/1000 ft.

⁽²⁾ With insulation: Overall diameter = 0.51 in.; weight - 200 lb/1000 ft.

* Data from Dow Chemical

** Data from Rome Cable Company

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Table 3-7. suggested number of anode rings for various size tanks.

Tank Diameter (ft)	Number of rings of anodes	
	Coated	Bare
24	1	1
30	1	1
36	1	1
42	1	1
48	1	2
54	1	2
60	2	2
66	2	2
72	2	2
78	2	3
84	2	3

Table 3-8. Recommended number of support points for loop anode systems.

Tank Diameter (ft)	Number of Support Points
24	6
30	6
36	6
42	6
48	6
54	8
60	8
66	8
72	10
78	10
84	10

Table 3-9. Adjusting factors for parallel anodes.

No. of Anodes in Parallel	Adjusting Factors			- Anode Spacing in Feet		
	5 ft	10 ft	15 ft	20 ft	25 ft	
2	0.652	0.576	0.551	0.538	0.530	
3	0.586	0.460	0.418	0.397	0.384	
4	0.520	0.385	0.340	0.318	0.304	
5	0.466	0.333	0.289	0.267	0.253	
6	0.423	0.295	0.252	0.231	0.218	
7	0.387	0.265	0.224	0.204	0.192	
8	0.361	0.243	0.204	0.184	0.172	
9	0.332	0.222	0.185	0.166	0.155	
10	0.311	0.205	0.170	0.153	0.142	
11	0.292	0.192	0.158	0.141	0.131	
12	0.276	0.180	0.143	0.132	0.122	
13	0.262	0.169	0.139	0.123	0.114	
14	0.249	0.160	0.131	0.116	0.107	
15	0.238	0.152	0.124	0.109	0.101	
16	0.226	0.144	0.117	0.103	0.095	
17	0.218	0.138	0.112	0.099	0.091	
18	0.209	0.132	0.107	0.094	0.086	
19	0.202	0.127	0.102	0.090	0.082	
20	0.194	0.122	0.098	0.086	0.079	
22	0.182	0.114	0.091	0.079	0.073	
24	0.171	0.106	0.085	0.074	0.067	
26	0.161	0.100	0.079	0.069	0.063	
28	0.152	0.094	0.075	0.065	0.059	
30	0.145	0.089	0.070	0.061	0.056	

Table 3-10. Cathodic Protection System Recommended Allowable Circuit Resistance

System Current (I) (amp)	<u>Resistance (RT) in ohm</u>	
	Maximum	Typical
5	10	5
10	6	3
20	3	2
30	2	1.3
40	1.5	1.0
60	1.0	0.6
80	0.75	0.4

SECTION 4

IDENTIFICATION OF VARIABLES

- A = Total surface area to be protected.
- A_R = Radius of anode circle (rod system).
- A_S = Area protected by a single anode.
- A_{SB} = Area protected by stub anodes.
- C_C = Center-to-center spacing of anodes.
- C_E = Coating efficiency in decimal form (0 to 0.99)
- d = Anode backfill diameter.
- D = Tank diameter.
- D_A = Diameter of anode wire or rod.
- D_E = Equivalent diameter factor for anodes in a circle (for submerged applications).
- D_R = Diameter of anode ring (wire anode system).
- E = Rectifier efficiency expressed in decimal form.
- F = Fringe factor (for submerged rod anodes).
- F_{ADJ} = Adjusting factor for parallel anodes.
- H = Anode depth below water surface.
- I = Total current requirement based on field test or assumed current density per square foot of bare steel.
- I' = Required current density.
- I_A = Maximum current per anode for the anode's desired life.
- K = Shape function.
- L = Effective anode length.

- L_{AVG} = Average lead wire length of anodes with individual lead wires run in parallel.
- L_B = Bare anode length (used in submerged applications).
- L_F = Expected anode life.
- \ln = Natural or Napierian logarithm.
- L_W = Header cable/wire length.
- M = Anode depth below water surface in centimeters.
- N = Number of anodes required to meet the desired life of a cathodic protection system.
- N_S = Number of stub anodes required.
- π** = Greek letter pi, or 3.14159.
- P_F = Paralleling factor.
- ρ = Greek letter rho, or Electrolyte resistivity in ohm-centimeters.
- R = Average coating resistance in ohm-square feet.
- R_A = Single anode-to-electrolyte resistance.
- R_{ADJ} = Adjusted resistance.
- R_C = Structure-to-electrolyte resistance.
- R_H = Single horizontal anode-to-electrolyte resistance.
- R_L = Single anode wire hoop-to-electrolyte resistance.
- R_{MFT} = Resistance per 1000 linear feet of cable/wire.
- R_N = Multiple anodes to electrolyte resistance.
- R_{NEG} = Resistance of the rectifier-to-structure negative (ground) cable.
- R_S = Effective coating resistance.
- R_T = Total circuit resistance.

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R_N = Header cable/wire resistance.

V_{REC} = Rectifier voltage.