PDHonline Course E291W (4 PDH)

Introduction to Cathodic Protection (Live Webinar)

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AN INTRODUCTION TO CATHODIC PROTECTION OF UNDERGROUND STRUCTURES

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This is what we will talk about today….

1. **INTRODUCTION TO CATHODIC PROTECTION**
2. **CATHODIC PROTECTION DESIGN**
3. **CURRENT REQUIREMENT TESTING**
4. **EXAMPLES OF GALVANIC CATHODIC PROTECTION DESIGN**
5. **EXAMPLES OF IMPRESSED CURRENT CATHODIC PROTECTION DESIGN**

1. INTRODUCTION TO CATHODIC PROTECTION

1.1 Purpose. This course presents introductory design guidance for cathodic protection systems. Practitioners must refer to current guidelines and practices when designing for specific projects.

1.2 Corrosion. Corrosion is an electrochemical process in which a current leaves a structure at the anode site, passes through an electrolyte, and re-enters the structure at the cathode site. For example, one small section of a pipeline may be anodic (positively charged) because it is in a soil with low resistivity compared to the rest of the line. Current would leave the pipeline at that anode site, pass through the soil, and re-enter the pipeline at a cathode (negatively charged) site. Current flows because of a potential difference between the anode and cathode. That is, the anode potential is more negative than the cathode potential, and this difference is the driving force for the corrosion current. The total system – anode, cathode, electrolyte, and metallic connection between anode and cathode is termed a *corrosion cell.*

1.3 Cathodic protection. Cathodic protection is a method to reduce corrosion by minimizing the difference in potential between anode and cathode. This is achieved by applying a current to the structure to be protected (such as a pipeline) from some outside source. When enough current is applied, the whole structure will be at one potential; thus, anode and cathode sites will not exist. Cathodic protection is commonly used on many types of structures, such as pipelines, underground storage tanks, locks, and ship hulls.

1.4 Types of cathodic protection systems. There are two main types of cathodic protection systems: galvanic and impressed current. Figure 1-1 shows these two types. Note that both types have anodes (from which current flows into the electrolyte), a continuous electrolyte from the anode to the protected structure, and an external metallic connection (wire). These items are essential for all cathodic protection systems.

INTRODUCTION TO CATHODIC PROTECTION

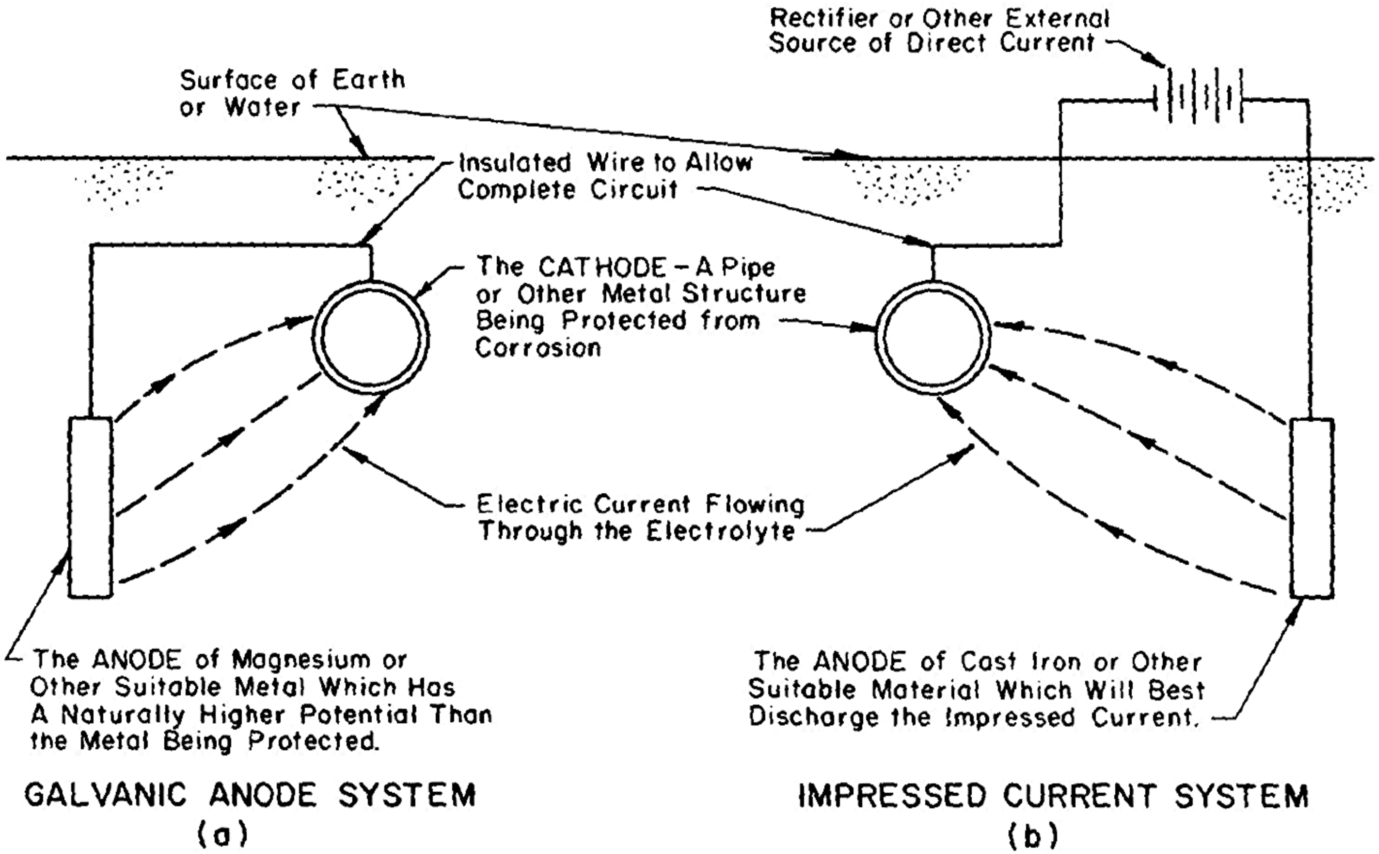

Figure 1-1
Galvanic (a) and impressed (b) current systems for cathodic protection

1.4.1 Galvanic system. A galvanic cathodic protection system makes use of the corrosive potentials for different metals. Without cathodic protection, one area of the structure exists at a more negative potential than another, and corrosion results. If, however, a much less inert object (that is, with much more negative potential, such as a magnesium anode) is placed adjacent to the structure to be protected, such as a pipeline, and a metallic connection (insulated wire) is installed between the object and the structure, the object will become the anode and the entire structure will become the cathode. That is, the new object corrodes sacrificially to protect the structure as shown in Figure 1-1(a). Thus, the galvanic cathode protection system is called a *sacrificial anode* cathodic protection system because the anode corrodes sacrificially to protect the structure. Galvanic anodes are usually made of either magnesium or zinc because of these metals' higher potential compared to steel structures.

INTRODUCTION TO CATHODIC PROTECTION

Active End

- Magnesium
- Magnesium alloys
- Zinc
- Galvanized steel
- Aluminum 1100
- Aluminum 6053
- Alclad
- Cadmium
- Aluminum 2024 (4,5 Cu 1.5 Mg, 0.6 Mn)
- Mild steel
- Wrought iron
- Cast iron
- 13% Chromium stainless steel Type 410 (active)
- 18-8 Stainless steel Type 304 (active)
- 18-12-3 Stainless steel Type 316 (active)
- Lead-tin solders
- Lead
- Tin
- Muntz metal
- Manganese bronze
- Naval brass
- Nickel (active)
- 76 Ni – 16 Cr – 7 Fe alloy (active)
- 60 Ni – 30 Mo – 6 Fe – 1 Mn
- Yellow brass
- Admiralty brass
- Aluminum brass
- Red brass
- Copper
- Silicon brass
- 70-30 Cupro nickel
- G-Bronze
- M-Bronze
- Silver solder
- Nickel (passive)
- 76 Ni-15 Cr – 7 Fe alloy (passive)
- 67-Ni-33 Cu alloy (Monel)
- 13% Chromium stainless steel Type 410 (passive)
- Titanium
- 18-8 Stainless steel Type 304 (passive)
- 18-12-3 Stainless steel Type 316 (passive)
- Silver
- Graphite
- Gold
- Platinum

Noble or Passive End

1.4.2 Impressed current systems. Impressed current cathodic protection systems use the same elements as the galvanic protection system, only the structure is protected by applying a current to it from an anode. The anode and the structure are connected by an insulated wire, as for the galvanic system. Current flows from the anode through the electrolyte onto the structure, just as in the galvanic system. The main difference between galvanic and impressed current systems is that the galvanic system relies on the difference in potential between the anode and the structure, whereas the impressed current system uses an external power source to drive the current, as shown in Figure 1-1(b). The external power source is usually a rectifier that changes input AC power to the proper DC power level. The rectifier can be adjusted so that proper output can be maintained during the system's life. Impressed current cathodic protection system anodes typically are high-silicone cast iron or graphite.

2. CATHODIC PROTECTION DESIGN

2.1 Required information. Before deciding which type, galvanic or impressed current, cathodic protection system will be used and before the system is designed, certain preliminary data must be gathered.

2.1.1 Physical dimensions of structure to be protected. One important element in designing a cathodic protection system is the structure's physical dimensions (for example, length, width, height, and diameter). These data are used to calculate the surface area to be protected.

2.1.2 Drawing of structure to be protected. The installation drawings must include sizes, shapes, material type, and locations of parts of the structure to be protected.

2.1.3 Electrical isolation. If a structure is to be protected by the cathodic system, it must be electrically connected to the anode, as Figure 1-1 shows. Sometimes parts of a structure or system are electrically isolated from each other by insulators. For example, in a gas pipeline distribution system, the inlet pipe to each building might contain an electric insulator to isolate in-house piping from the pipeline. Also, an electrical insulator might be used at a valve along the pipeline to electrically isolate one section of the system from another. Since each electrically isolated part of a structure would need its own cathodic protection, the locations of these insulators must be determined.

2.1.4 Short circuits. All short circuits must be eliminated from existing and new cathodic protection systems. A short circuit can occur when one pipe system contacts another, causing interference with the cathodic protection system. When updating existing systems, eliminating short circuits would be a necessary first step.

2.1.5 Corrosion history of structures in the area. Studying the corrosion history in the area can prove very helpful when designing a cathodic protection system. The study should reinforce predictions for corrosivity of a given structure and its environment; in addition, it may reveal abnormal conditions not otherwise suspected. Facilities personnel can be a good source of information for corrosion history.

2.1.6 Electrolyte resistivity survey. A structure's corrosion rate is proportional to the electrolyte resistivity. Without cathodic protection, as electrolyte resistivity decreases, more current is allowed to flow from the structure into the electrolyte; thus, the structure corrodes more rapidly. As electrolyte resistivity increases, the corrosion rate decreases (Table 2-1). Resistivity can be measured either in a laboratory or at the site with the proper instruments. The resistivity data will be used to calculate the sizes of anodes and rectifier required in designing the cathodic protection system.

Soil resistivity range (ohm-cm)	Corrosivity
0 to 2000	Severe
2000 to 10,000	Moderate to severe
10,000 to 30,000	Mild
Above 30,000	Not likely

Table 2-1

Corrosivity of soils on steel based on soil resistivity

2.1.7 Electrolyte pH survey. Corrosion is also inversely proportional to electrolyte pH. In general, steel's corrosion rate increases as pH decreases when soil resistivity remains constant.

2.1.8 Structure versus electrolyte potential survey. For existing structures, the potential between the structure and the electrolyte will give a direct indication of the corrosivity. According to NACE Standard No. RP-01, <u>the potential requirement for cathodic protection is a negative (cathodic) potential of at least 0.85 volt</u> as measured between the structure and a saturated copper-copper sulfate reference electrode in contact with the electrolyte. A potential which is less negative than -0.85 volt would probably be corrosive, with corrosivity increasing as the negative value decreases (becomes more positive).

2.1.9 Current requirement. A critical part of design calculations for cathodic protection systems on existing structures is the amount of current required per square foot (called *current density)* to change the structure's potential to -0.85 volt. The current density required to shift the potential indicates the structure's surface condition. A well coated structure (for example, a pipeline well coated with coal-tar epoxy) will require a very low current density (about 0.05 milliampere per square foot); an uncoated structure would require high current density (about 10 milliamperes per square foot). The average current density required for cathodic protection is 2 milliamperes per square foot of *bare* area. The amount of current required for complete cathodic protection can be determined three ways:

- An actual test on existing structures using a temporary cathodic protection setup.
- A theoretical calculation based on coating efficiency.
- An estimate of current requirements using tables based on field experience.

2.1.9.1 The second and third methods above can be used on both existing and new structures.

2.1.9.2 Current requirements can be calculated based on coating efficiency and current density (current per square foot) desired. The efficiency of the coating as supplied will have a direct effect on the total current requirement, as Equation 2-1 shows:

$$I = (A)(I')(1.0 - CE) \qquad \text{(Equation 2-1)}$$

where I is total protective current, A is total structure surface area in square feet, I' is required current density, and CE is coating efficiency. Equation 2-1 may be used when a current requirement test is not possible, as on new structures, or as a check of the current requirement test on existing structures. Coating efficiency is directly affected by the type of coating used and by quality control during coating application. The importance of coating efficiency is evident in the fact that a bare structure may require 100,000 times as much current as would the same structure if it were well coated.

2.1.9.3 Current requirements also can be estimated from Table 2-2. The table gives an estimate of current, in milliamperes per square foot, required for complete cathodic protection. That value, multiplied by the surface area of the structure to be protected (in square feet) gives the total estimated current required. Caution should be used when estimating, however, as under- or overprotection may result.

Environment		
Neutral soil	0.4	to 1.5
Well aerated neutral soil	2	to 3
Wetsoil	1	to 6
Highly acidic soil	3	to 15
Soil supporting active sulfate-reducing bacteria	6	to 42
Heated soil	3	to 25
Stationary freshwater	1	to 6
Moving freshwater containing dissolved oxygen	5	to 15
Seawater	3	to 10

Table 2-2
Typical current density requirements
for cathodic protection of uncoated steel
mA/SF

2.1.10 Coating resistance. A coating's resistance decreases greatly with age and directly affects structure-to-electrolyte resistance for design calculations. The coating manufacturers supply coating resistance values.

2.1.11 Protective current required. By knowing the physical dimensions of the structure to be protected, the surface area can be calculated. The product of the surface area multiplied by current density obtained previously in *I* above gives the total current required.

2.1.12 The need for cathodic protection. For existing structures, the current requirement survey (above) will verify the need for a cathodic protection system. For new systems, standard practice is to assume a current density of at least 2 milliamperes per square foot of bare area will be needed to protect the structure. (However, local corrosion history may demand a different current density.) In addition, cathodic protection is *mandatory* for underground gas distribution lines and for water storage tanks with a 250,000-gallon capacity or greater. Cathodic protection also is required for underground piping systems located within 10 feet of steel reinforced concrete because galvanic corrosion will occur between the steel rebar and the pipeline.

2.2 Determining type and design of cathodic protection system. When all preliminary data have been gathered and the protective current has been estimated, the design sequence can begin. The first question to ask is: which type (galvanic or impressed current) cathodic protection system is needed? Conditions at the site sometimes dictate the choice. However, when this is not clear, the criterion used most widely is based on current density required and soil resistivity. If the soil resistivity is low (less than 5000 ohm-centimeters) and the current density requirement is low (less than 1 milliampere per square foot), an impressed current system should probably be used. However, if the soil resistivity and/or current density requirement exceeds the above values, a galvanic system should probably be used. Figure 2-2 will be used in the design sequence. Design sequences for each type of cathodic protection system are given below.

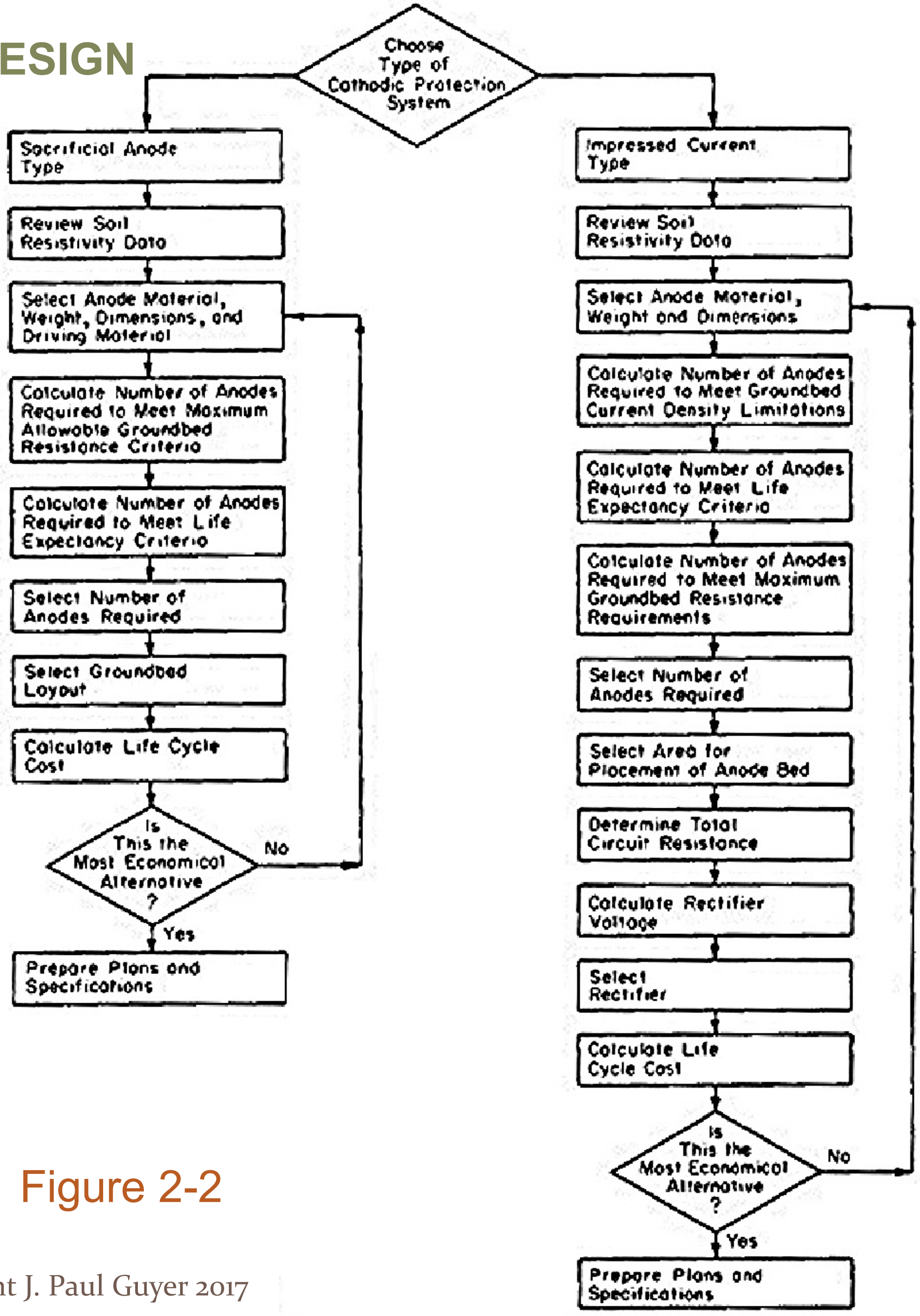
Choose Type of Cathodic Protection System
Sacrificial Anode Type
Review Soil Resistivity Data
Select Anode Material, Weight, Dimensions, and Driving Material
Calculate Number of Anodes Required to Meet Maximum Allowable Groundbed Resistance Criteria
Calculate Number of Anodes Required to Meet Life Expectancy Criteria
Select Number of Anodes Required
Select Groundbed Layout
Calculate Life Cycle Cost
Is This the Most Economical Alternative ?
No
Yes
Prepare Plans and Specifications
Impressed Current Type
Review Soil Resistivity Data
Select Anode Material, Weight and Dimensions
Calculate Number of Anodes Required to Meet Groundbed Current Density Limitations
Calculate Number of Anodes Required to Meet Life Expectancy Criteria
Calculate Number of Anodes Required to Meet Maximum Groundbed Resistance Requirements
Select Number of Anodes Required
Select Area for Placement of Anode Bed
Determine Total Circuit Resistance
Calculate Rectifier Voltage
Select Rectifier
Calculate Life Cycle Cost
Is This the Most Economical Alternative ?
No
Yes
Prepare Plans and Specifications

Figure 2-2

2.2.1 Sacrificial anode (galvanic) cathodic protection system design. The following nine steps are required when designing galvanic cathodic protection systems.

2.2.1.1 Review soil resistivity. The site of lowest resistivity will likely be used for anode location to minimize anode-to-electrolyte resistivity. In addition, if resistivity variations are not significant, the average resistivity will be used for design calculations.

2.2.1.2 Select anode. As indicated above, galvanic anodes are usually either magnesium or zinc. Data from commercially available anodes must be reviewed. Each anode specification will include anode weight, anode dimensions, and package dimensions (anode plus backfill), as Table 2-3 shows for magnesium-alloy anodes. In addition, the anode's driving potential must be considered. The choice of anode from those available is arbitrary; design calculations will be made for several available anodes, and the most economical one will be chosen.

Sacrificial anode (galvanic) cathodic protection system

Table 2-3

Weights and dimensions of selected high-potential magnesium-alloy anodes for use in soil or water

Weight (lb)	Size (in.)	Packaged wt (lb)	Packaged size (in.)
3	3.75 x 3.75 x 5	12	6 x 10
5	3.75 x 3.75 x 7.5	17	6 x 12
9	2.75 x 2.75 x 26	35	6 x 31
9	3.75 x 3.75 x 13.25	27	6 x 17
12	3.75 x 3.75 x 18	36	6 x 23
14	2.75 x 2.75 x 41	50	6 x 46
14	3.75 x 3.75 x 21	42	6.5 x 26
17	2.75 x 2.75 x 50	60	6 x 55
17	3.75 x 3.75 x 26	45	6.5 x 29
20	2.5 x 2.5 x 59.25	70	5 x 66
24	4.5 x 4.5 x 23	60	7 x 30
32	5.5 x 5.5 x 21	74	8 x 28
40	3.75 x 3.75 x 59.25	105	6.5 x 66
48	5.5 x 5.5 x 30	100	8 x 38
48	8 x 16	100	12 x 25
60	4.5 x 4.5 x 60	—	—

Note: Core material is a galvanized 20-gage perforated steel strip. Anodes longer than 24 inches have a 9-gage core. The connecting wire is a 10-foot length of solid No. 12 AWG TW insulated copper wire, silver-soldered to the core with joints sealed against moisture. Special wires or other lengths are available.

2.2.1.3 Calculate net driving potential for anodes. The open-circuit potential of standard alloy magnesium anodes is approximately -1.55 volts to a copper-copper sulfate half-cell. The open-circuit potential of high-manganese magnesium anodes is approximately -1.75 volts to a copper-copper sulfate half-cell.

2.2.1.3.1 The potential of iron in contact with soil or water usually ranges around -0.55 volt relative to copper-copper sulfate. When cathodic protection is applied using magnesium anodes, the iron potential assumes some value between -0.55 and - 1.0 volt, depending on the degree of protection provided. In highly corrosive soils or waters, the natural potential of iron may be as high as -0.82 volt relative to copper-copper sulfate. From this, it is evident that -0.55 volt should not be used to calculate the net driving potential available from magnesium anodes.

2.2.1.3.2 <u>A more practical approach is to consider iron polarized to -0.85 volt. On this basis, standard alloy magnesium anodes have a driving potential of 0.70 volt (1.55-0.85 =0.70) and high potential magnesium anodes have a driving potential of 0.90 volt (1.75-0.85 =0.90).</u> For cathodic protection design that involves magnesium anodes, these potentials, 0.70 and 0.90 volt, should be used, depending on the alloy selected.

2.2.1.4 Calculate number of anodes needed to meet groundbed resistance limitations. The total resistance (R_T) of the galvanic circuit is given by Equation 2-2:

$$R_T = R_A + R_W + R_C \qquad \text{(Equation 2-2)}$$

where R_A is the anode-to-electrolyte resistance, R_W is the anode lead wire resistance, and R_C is the structure-to-electrolyte resistance. The total resistance also can be found by using Equation 2-3:

$$R_T = \Delta E/I \qquad \text{(Equation 2-3)}$$

Sacrificial anode (galvanic) cathodic protection system

where E is the anode's driving potential discussed above and I is the current density required to achieve cathodic protection. R_C Equation 2-2 can be calculated by using Equation 2-4:

$$R_C = R/A \qquad \text{(Equation 2-4)}$$

where R is the average coating resistance, in ohms per square feet, at the end of the proposed lifetime for the system (R is specified by the supplier), and A is the structure's surface area in square feet. Assuming R_W in Equation 2-2 is negligible, that anode-to-electrolyte resistance can then be calculated from Equation 2-5:

$$R_a = R_T - R_C \qquad \text{(Equation 2-5)}$$

Which gives the maximum allowable groundbed resistance; this will dictate the minimum number of anodes required (as number of anodes decreases, groundbed resistance increases). To calculate the number of anodes required, Equation 2-6 is used:

Sacrificial anode (galvanic) cathodic protection system

$$N = \frac{(0.0052)(\rho)}{(R_a)(L)}\left[\ln\frac{8L}{d} - 1\right]$$

(Equation 2-6)

where N is the number of anodes, ρ is the soil resistivity in ohms, R_a is the maximum allowable groundbed resistance in ohms (as computed in Equation 2-5), L is the length of the backfill column in feet (specified by the supplier) and d is the diameter of the backfill column in feet (specified by the supplier).

2.2.1.5 Calculate number of anodes for system's life expectancy. Each cathodic protection system will be designed to protect a structure for a given number of years. To meet this lifetime requirement, the number of anodes (N) must be calculated using Equation 2-7:

$$N = LI/49.3W \qquad \text{(Equation 2-7)}$$

Where L is the expected lifetime in years, W is weight (in pounds) of one anode, and I is the current density required to protect the structure (in milliamperes).

2.2.1.6 Select number of anodes to be used. The greater value of Equation 2-6 or Equation 2-7 will be used as the number of anodes needed for the system.

2.2.1.7 Select groundbed layout. When the required number of anodes has been calculated, the area to be protected by each anode is calculated by Equation 2-8:

$$A = A_T/N \qquad \text{(Equation 2-8)}$$

Where A is the area to be protected by one anode, A_T is total surface area to be protected, and N is the total number of anodes to be used. For galvanic cathodic protection systems, the anodes should be spaced equally along the structure to be protected.

2.2.1.8 Calculate life-cycle cost for proposed design. NACE Standard RP-02 should be used to calculate the system's life-cycle cost. The design process should be done for several different anode choices to find the one with minimal life-cycle cost.

2.2.1.9 Prepare plans and specifications. When the design procedure has been done for several different anodes and the final anode has been chosen, plans and specifications can be completed.

2.2.2 Impressed current cathodic protection system design. Thirteen steps are required when designing impressed current cathodic protection systems.

2.2.2.1 Review soil resistivity. As with galvanic systems, this information will contribute to both design calculations and location of anode groundbed.

2.2.2.2 Review current requirement test. The required current will be used throughout the design calculations. The calculated current required to protect 1 square foot of bare pipe shall agree with the values in Table 2-2.

2.2.2.3 Select anode. As with the galvanic system, the choice of anode is arbitrary at this time; economy will determine which anode is best. Table 2-4 gives common anode sizes and specifications. The anodes used most often are made of high-silicon chromium-bearing cast-iron (HSCBCI). When impressed current-type cathodic protection systems are used to mitigate corrosion on an underground steel structure, the auxiliary anodes often are surrounded by a carbonaceous backfill. Backfill materials commonly used include coal coke breeze, calcined petroleum coke breeze, and natural graphite particles. The backfill serves three basic functions: (a) it decreases the anode-to-earth resistance by increasing the anode's effective size, (b) it extends the system's operational life by providing additional anode material, and (c) it provides a uniform environment around the anode, minimizing deleterious localized attack. The carbonaceous backfill, however, cannot be expected to increase the groundbed life expectancy unless it is well compacted around the anodes. In addition to HSCBCI anodes, the ceramic anode should be considered as a possible alternative for long-term cathodic protection of water storage tanks and underground pipes in soils with resistivities less than 5000 ohm-centimeters. The ceramic anode consumption rate is 0.0035 ounce per ampere-year compared a 1 pound per ampere-year for HSCBCI anodes.

Impressed current cathodic protection system

Anode weight (lb)	Anode dimensions (in.)	Anode surface size (in.)	Package area (sq ft)
12	1 x 60	1.4	10 x 84
44	2 x 60	2.6	10 x 84
60	2 x 60	2.8	10 x 84
110	3 x 60	4.0	10 x 84

Table 2-4
Weights and dimensions of typical selected circular high-silicon chromium-bearing cast iron anodes

2.2.2.4 Calculate number of anodes needed to satisfy manufacturer's current density limitations. Impressed current anodes are supplied with a recommended maximum current density. Higher current densities will reduce anode life. To determine the number of anodes needed to meet the current density limitations, use Equation 2-9:

$$N = I/A_1I_1 \qquad \text{(Equation 2-9)}$$

where N is number of anodes required, I is total protection current in milliamperes, A_1 is anode surface area in square feet per anode, and I_1 is recommended maximum current density output in milliamperes.

2.2.2.5 Calculate number of anodes needed to meet design life requirement. Equation 2-10 is used to find the number of anodes:

$$N = LI/1000W \qquad \text{(Equation 2-10)}$$

where N is number of anodes, L is life in years, I is the current density required to protect the structure (in milliamperes), and W is weight of one anode in pounds.

2.2.2.6 Calculate number of anodes needed to meet maximum anode groundbed resistance requirements. Equation 2-11 is used to calculate the number of anodes required:

$$R_a = \rho K/NL + \rho P/S \qquad \text{(Equation 2-11)}$$

where R_a is the anodes' resistance, ρ is soil resistivity in ohm-centimeters, K is the anode shape factor from the manufacturer's literature, N is the number of anodes, L is length of the anode backfill column in feet, P is the paralleling factor from the manufacturer's literature, and S is the center-to-center spacing between anode backfill columns in feet.

2.2.2.7 Select number of anodes to be used. The highest number calculated by Equation 2-9, 2-10, or 2-11 will be the number of anodes used.

2.2.2.8 Select area for placement of anode bed. The area with the lowest soil resistivity will be chosen to minimize anode-to-electrolyte resistance.

2.2.2.9 Determine total circuit resistance. The total circuit resistance will be used to calculate the rectifier size needed.

2.2.2.9.1 Calculate anode groundbed resistance. Use Equation 2-11.

2.2.2.9.2 Calculate groundbed header cable resistance. The cable is typically supplied with a specified resistance in ohms per 100 feet. The wire resistance then is calculated from Equation 2-12:

$$R_w = \frac{\text{ohms} \ (L)}{100 \ \text{ft}} \qquad \text{(Equation 2-12)}$$

where L is the wire's length in feet. Economics are important in choosing a cable, and may indeed be the controlling factor. To determine the total annual cable cost, Kelvin's Economic Law can be used as shown in Equation 2-13.

Impressed current cathodic protection system

$$T = \frac{(0.0876)(I^2)(R)(L)(P)}{E} = (0.15)(S)(L)$$

(Equation 2-13)

Where T is total annual cost in dollars per year, I is total protection current in amperes, R is cable resistance in ohms per 1000 feet, L is cable length in feet, P is cost of electrical energy in kilowatt-hour, E is the rectifier efficiency expressed as percent, and S is the cable's initial cost in dollars per foot.

2.2.2.9.3 Calculate structure-to-electrolyte resistance.
Using Equation 2-14:

$$R_c = \frac{R}{N} \qquad \text{(Equation 2-14)}$$

where R is the structure-to-electrolyte resistance, R_c is the coating resistance in ohms per square feet, and N is the coated pipe area in square feet.

2.2.2.9.4 Calculate total circuit resistance. To calculate the total resistance, R_T , equation 2-15 is used:

$$R_T = R_a + R_w + R_c \qquad \text{(Equation 2-15)}$$

2.2.2.10 Calculate rectifier voltage. Equation 16 is used to determine voltage output (V) of the rectifier:

$$V_{rec} = (I)(R_T)(150\%) \quad \text{(Equation 2-16)}$$

where I is total protection current in amperes, R_T is total circuit resistance, and 150 percent is a factor to allow for aging of the rectifier stacks.

2.2.2.11 Select a rectifier. A rectifier must be chosen based on the results of Equation 2-16. Many rectifiers are available commercially; one that satisfies the minimum requirements of (I) and (V_{rec}) in Equation 16 should be chosen. Besides the more common rectifiers being marketed, a solar cathodic protection power supply (for d.c. power) may be considered for remote sites with no electrical power. Three factors should be considered when specifying a solar cathodic protection power supply are:

- The cost of the solar cathodic protection power supply in dollars per watt of continuous power.
- The solar cathodic protection power supply's much higher initial cost compared to selenium rectifiers operated by a.c. power.
- The additional maintenance required for a solar cathodic protection power supply, mainly to keep the solar panels free of dirt deposits.

2.2.2.12 Calculate system cost. As with the galvanic cathodic protection system, the choice of anode for design calculation is arbitrary. When several anodes have been used in the design calculations, an economic evaluation should be done as recommended in NACE Standard RP-02.

2.2.2.13 Prepare plans and specifications.

3. CURRENT REQUIREMENT TESTING

3.1 Required current.

A critical element in designing galvanic and impressed current cathodic protection systems is the current required for complete cathodic protection. Complete cathodic protection is achieved when the structure potential is -0.85 volt with respect to a copper-copper sulfate reference electrode.

3.2 Sample test.

Current requirement tests are done by actually applying a current using a temporary test setup, and adjusting the current from the power source until suitable protective potentials are obtained. Figure 3-1 shows a temporary test setup. In this setup, batteries can be used as the power supply, in series with heavy-duty adjustable resistors. The resistors can be adjusted to increase the current until the potential at the location of interest, such as point A in figure 3-1, is at -0.85 volt with respect to a copper-copper sulfate reference cell. The current supplied is the current required for cathodic protection. The effectiveness of the insulating joints shown in figure 3-1 can also be tested. The potentials at points B and C are measured, first with the current interruptor switch closed, then with it open. If there is any difference between the two readings at either point, the joint is not insulating completely.

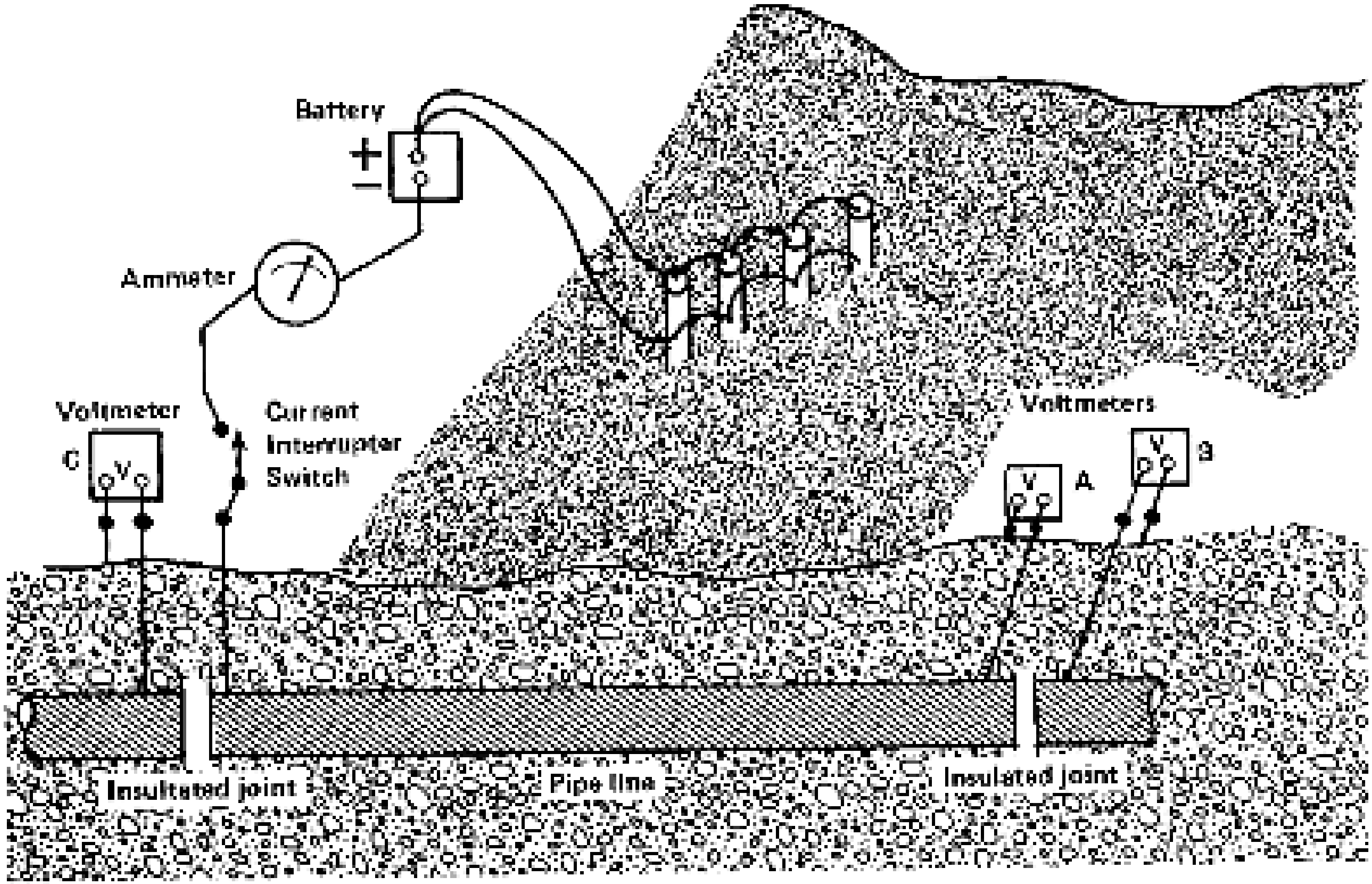

Figure 3-1
Current Requirement Test on Pipeline

4. EXAMPLES OF GALVANIC CATHODIC PROTECTION DESIGN

4.1 Underground steel storage tank.

Galvanic cathodic protection is designed for an underground steel storage tank shown in figure 4-1. The tank is already installed and current requirement tests have been made.

EXAMPLES OF GALVANIC CATHODIC PROTECTION DESIGN

Underground steel storage tank

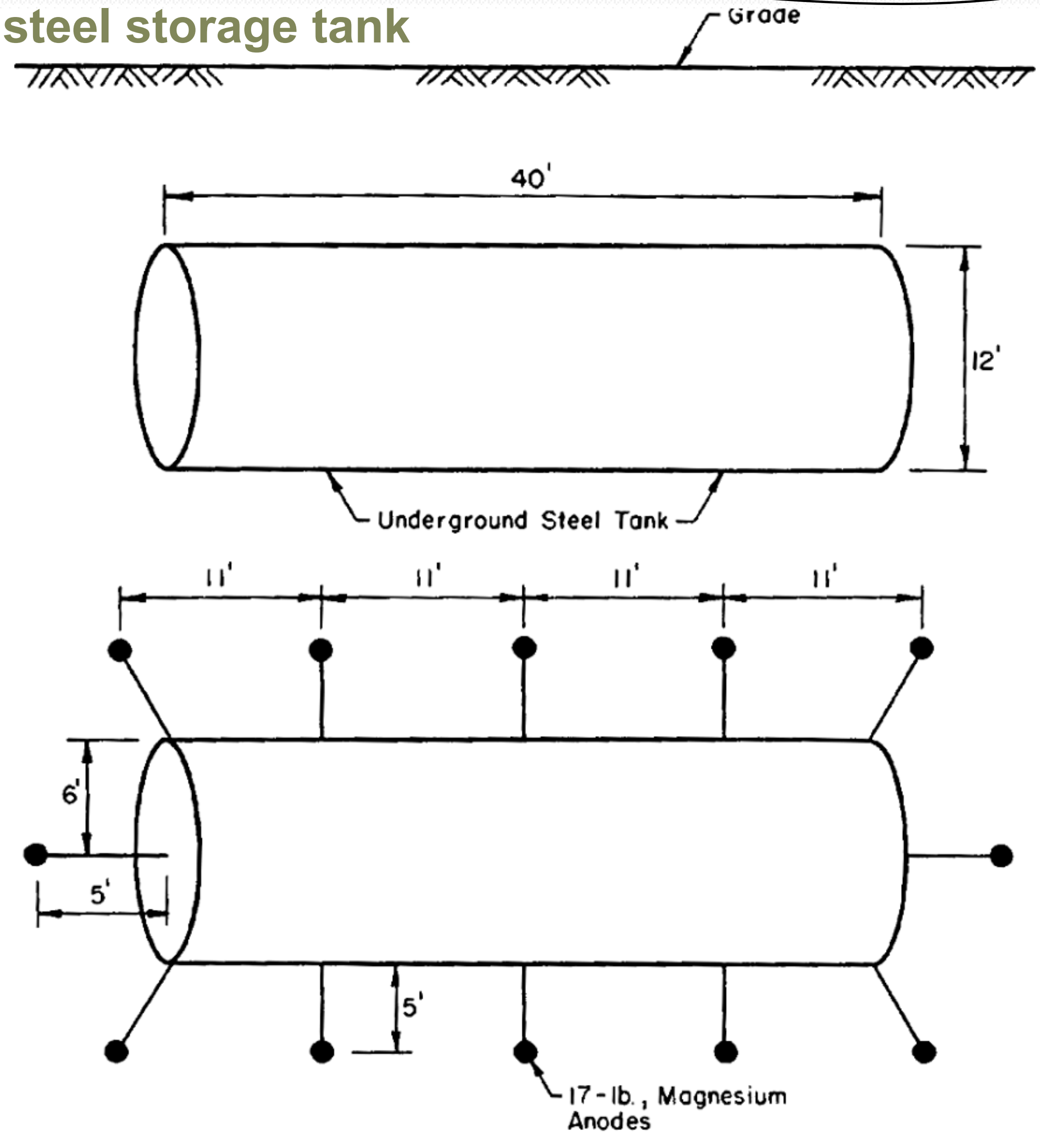

Figure 4-1

4.1.1 Design data.

(1) Tank diameter is 12 feet.
(2) Tank length is 40 feet.
(3) Design for 80 percent coating efficiency, based on experience.
(4) Design for 15-year life.
(5) Current requirement is 0.7 ampere.
(6) Packaged 17-pound standard magnesium anodes must be used.
(7) The tank is insulated well enough from foreign structures.

4.1.2 Computations.

(1) Find the minimum weight of anodes required for the tank using equation 4-I:

$$W = \frac{YSI}{E} \qquad \text{Equation 4-1}$$

where Y = 15 years, S = 8.8 pounds per ampere-year, I = 0.7 ampere, and E = 0.50 efficiency. Thus,

$$W = \frac{(15\ \text{yr})(8.8\ \text{lb/A-yr})(0.7\ \text{A})}{0.50}$$

W= 184.8 lb.

(2) Find the number of magnesium anodes (17 pounds each) required:

N =184.8/17 = 10.9 (use 12 anodes for symmetry).

4.1.3 Placement. Locate anodes as shown in figure 4-1.

4.2 Gas distribution system.

Galvanic cathodic protection is designed for a gas distribution system in a residential area as shown in figure 4-2.

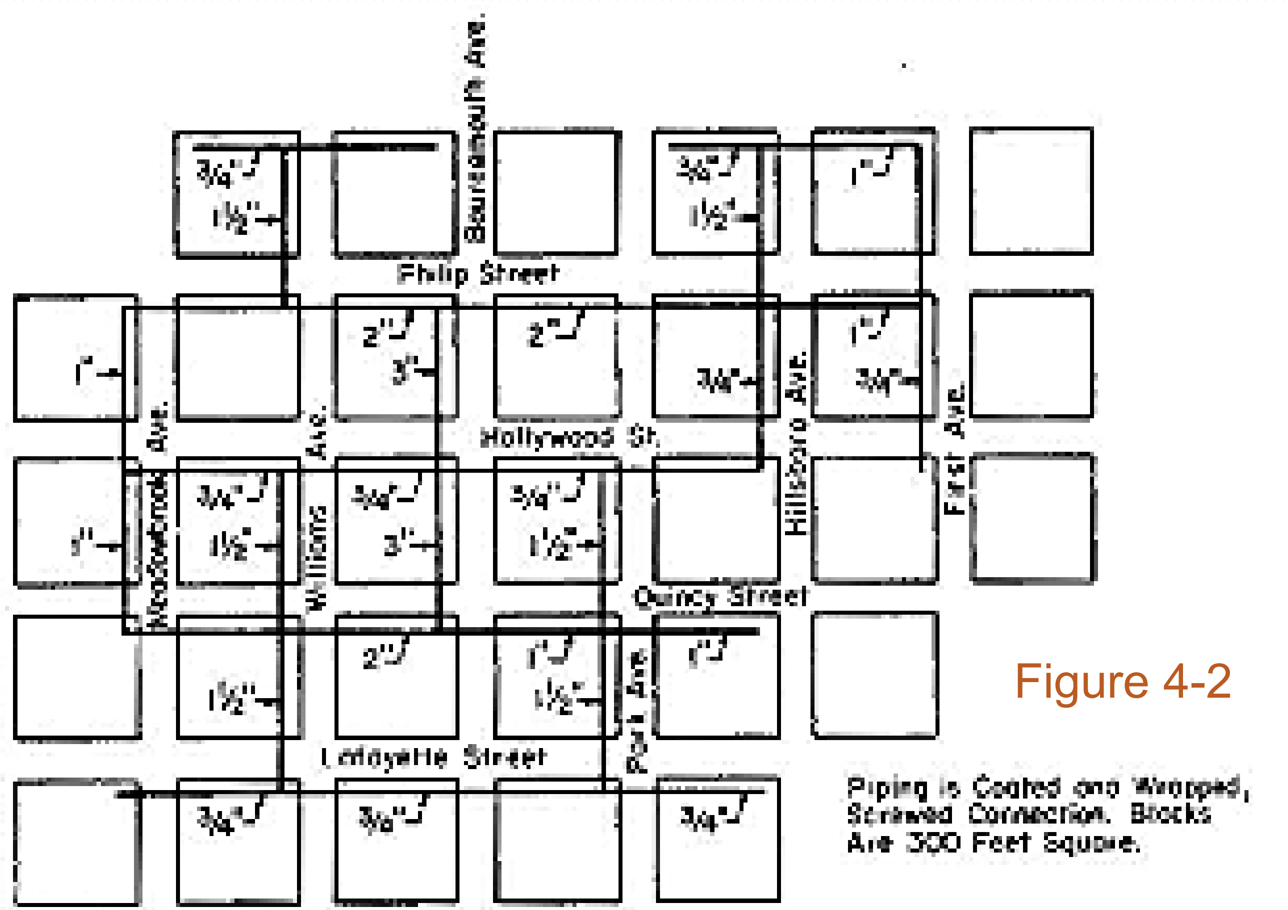

Figure 4-2

4.2.1 Design data.

(1) Average soil resistivity is 4500 ohm-centimeters.
(2) Design for 90 percent coating efficiency, based on experience.
(3) Design for 15-year life.
(4) Design for 2 milliamperes per square foot of bare pipe.
(5) Packaged-type magnesium anodes must be used.
(6) Insulating couplings are used on all service taps. Mains are electrically isolated from all other metal structures in the area.
(7) All pipe has been pre-coated at the factory and wrapped with asbestos felt. The coating has been tested over the trench for holidays and defects have been corrected. The coating is considered to be better than 99.5 percent perfect when installed.

4.2.2. Computations.

(1) Find the total outside area of piping (table 4-1).

(2) Find the area of bare pipe to be protected cathodically based on 90 percent coating efficiency:

$$A = 4288 \times 0.1$$

$$A = 429 \text{ sq. ft.}$$

EXAMPLES OF GALVANIC CATHODIC PROTECTION DESIGN
Gas distribution system

Pipe size (in.)	Pipe length (ft)	Pipe area (sq ft/lin ft)	Pipe area (sq ft)
3	600	0.916	550
2	1500	0.622	933
1½	1800	0.497	894
1	2400	0.344	826
	3900	0.278	1084
Total area of pipe in square feet			4288

Table 4-1

(3) Find the maximum protective current required based on 2 milliamperes per square foot of bare metal:

I = 2 mA x 429 SF

I = 858 mA or 0.858 A.

(4) Find the weight of anode material required based on maximum current requirement and 15-year life. Use equation 4-1:

W = (YSI/E) Equation 4-1

where Y = 15 years, S = 8.8 pounds per ampere-year, I = 0.858 ampere, and E = 0.50 efficiency. Thus,

W = [(15 yr)(8.8 lb/A&yr)(0.858 A)]/0.50

W = 227 lb

Note that the 227-pound value is based on an output current of 0.86 ampere for the cathodic protection system's full design life, 15 years. Strictly speaking, this is not the true condition, because current output after new installation is much less due to the high coating efficiency. The average current requirement at first may be as low as 0.03 milliampere per square foot of pipe.

(5) Find the current output to ground for a single 17-pound standard packaged magnesium anode using equation 4-2:

$$i = (Cfy)/P \qquad \text{(Equation 4-2)}$$

where C = 120,000, a constant for well coated structures using magnesium, f = 1.00, y = 1.00, P = 4500 ohm-centimeters. Values for f (galvanic anode size factor) and y (structure potential factor) have been obtained from technical literature. Thus,

$$i = (120000 \times 1.00 \times 1.00)/4500 \text{ ohm-cm} = 26.7 \text{ mA}.$$

Because the structure is well coated, anode spacing will be relatively large.

Gas distribution system

(6) Find the number of anodes (n) required from equation 4-3:

$$n = I/i \qquad \text{(Equation 4-3)}$$

where I = 858 milliamperes and i = 26.7 milliamperes.

$$n = 858/26.7 = 32.1$$

Thus, n = 32.1 (use 32 anodes).

(7) Find the anode distribution.

(a) Pipe area protected by one anode:

$$A = 4288/32 = 134 \text{ sq ft/anode}$$

(b) Find the anode division (table 4-2).

EXAMPLES OF GALVANIC CATHODIC PROTECTION DESIGN
Gas distribution system

Pipe size (in.)	Pipe area (sq ft)	Pipe length (ft)	Number of anodes	Anode spacing (ft)
3	550	600	4	150
2	933	1500	7	214
1½	895	1800	7	257
1	826	2400	6	400
¾	1084	2900	8	488
Total number of anodes			32	

Table 4-2
Dimensions for finding anode division

4.3 Aircraft multiple hydrant refueling system

Galvanic cathodic protection is designed for a standard aircraft hydrant refueling system as shown in figure 4-3. This design is for a system not yet installed.

EXAMPLES OF GALVANIC CATHODIC PROTECTION DESIGN
Aircraft multiple hydrant refueling system

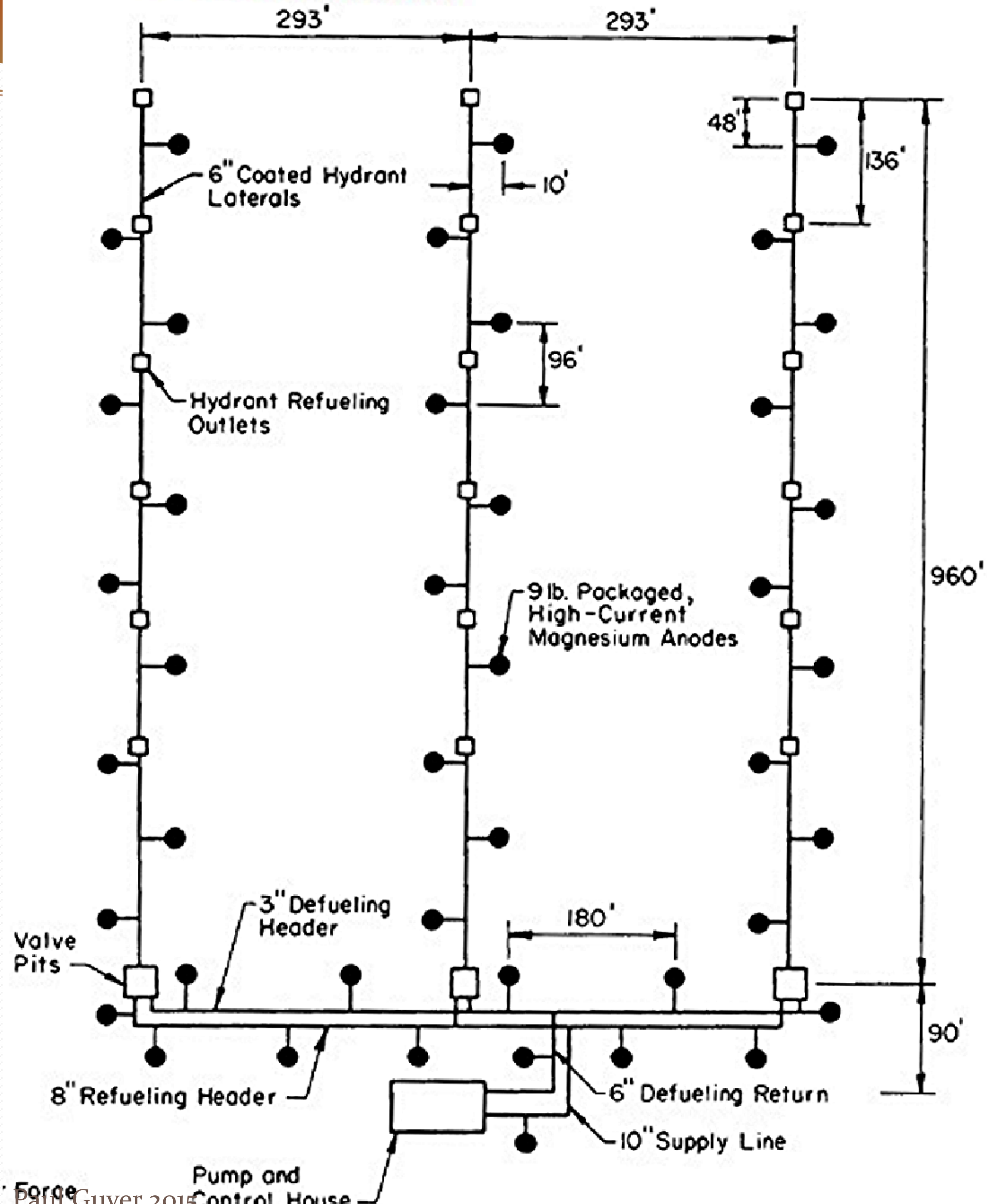

Figure 4-3

4.3.1 Design data.

(1) Average soil resistivity is 5000 ohm-centimeters.

(2) Effective coating resistance at 25 years will be 2500 ohms per square foot, as suggested by the manufacturer.

(3) Design for 80 percent coating efficiency, based on experience.

(4) Design for 25-year life.

(5) Design for 1 milliampere per square foot of bare pipe after polarization (corrosion history of area indicates this value is adequate).

(6) Magnesium packaged-type anodes must be used (soil resistivity is greater than 2000 ohm-centimeters).

(7) System is insulated well enough from foreign structures.

(8) All piping is mill-coated with hot-applied coal-tar enamel and wrapped with asbestos felt. Coating has been tested over the trench for holidays and defects have been corrected. Coating is assumed better than 99.5 percent perfect at installation.

4.3.2 Computations.

(1) Find the total outside area of liquid fuel pipes serving the hydrant refueling area from lengths and sizes of pipe = 7264 SF

(2) Some experience has shown that steel in this type soil can be cathodically protected with approximately 1 milliampere per square foot of uncoated surface. Thus, find the required current based on this value and using equation 2-1:

$$I = (A)(I')(1.0 - CE)$$
$$I = (7264 \text{ sq ft})(1.0 \text{ mA/sq ft})(1.0 - 0.8)$$
$$I = 726 \text{ mA.}$$

Aircraft multiple hydrant refueling system

(3) Calculate the number of anodes needed based on maximum groundbed resistance limitations.

(a) Select a 9-pound anode, 3.5 by 3.5 by 13 inches, from table 2-4. Driving potential as provided by the manufacturer is 0.9 volt.

(b) Calculate total circuit resistance using equation 2-3:

$R_T = \Delta E/I$
$R_T = 0.9/0.726 = 1.23$ ohms

(c) Calculate structure-to-electrolyte resistance from equation 2-4:

$R_C = R/N$
$R_C = (2500 \text{ ohms/sf })/7264 \text{ sf} = .345$ ohm

Aircraft multiple hydrant refueling system

(d) Find maximum allowable groundbed resistance using equation 2-2:

$R_T = R_a + R_w + R_c$

1.23 ohm = R_a + 0.345 ohm (assume R_w is negligible)

0.89 ohm = R_a

(e) Calculate number of anodes from equation 2-6:

$$N = \frac{(0.0052)(\rho)}{(R_a)(L)}\left[\ln\frac{8L}{d} - 1\right],$$

$$N = \frac{(0.0052)(500 \text{ ohm-cm})}{(0.89 \text{ ohm})(1.42 \text{ ft})}\left[\ln\frac{(8)(1.42 \text{ ft})}{(0.5 \text{ ft})} - 1\right]$$

N = 44 anodes.

(4) Calculate number of anodes based on system's life expectancy using equation 2-7:

$$N = \frac{(L)(I)}{49.3\ (W)},$$

$$N = \frac{(25\ \text{yr})(726\ \text{mA})}{49.3\ (9\ \text{lb/anode})},$$

$$N = 41\ \text{anodes.}$$

(5) Select number of anodes. Since 44 anodes are required to meet maximum allowable groundbed resistance (e above), that will be the number used.

Aircraft multiple hydrant refueling system

(6) Select groundbed layout. Determine the area to be covered by each anode using equation 2-8:

$$A = \frac{A_T}{N}$$

$$A = \frac{7264 \text{ sq ft}}{44 \text{ anodes}}$$

$$A = 164 \text{ sq/ft anode.}$$

(7) Space anodes by proportioning distribution of anodes based on area of pipe protected, and spacing on length of pipe:

Laterals:	30 anodes @ 96 ft spacing
Headers:	12 anodes @ 98 ft spacing
Supply and return lines:	2 anodes @ 90 ft spacing

(8) Calculate life-cycle cost as recommended above. Comparisons with other anode sizes and types will yield the most economical design.

4.3.3 Placement. Locate anodes as shown in figure 4-3.

5. EXAMPLES OF IMPRESSED CURRENT CATHODIC PROTECTION DESIGN

5.1 Steel gas main.

Impressed current cathodic protection is designed for the 6-inch welded gas main shown in figure 5-1. This pipeline is not yet constructed, so measurements cannot be taken.

EXAMPLES OF IMPRESSED CURRENT CATHODIC PROTECTION DESIGN

Steel gas main

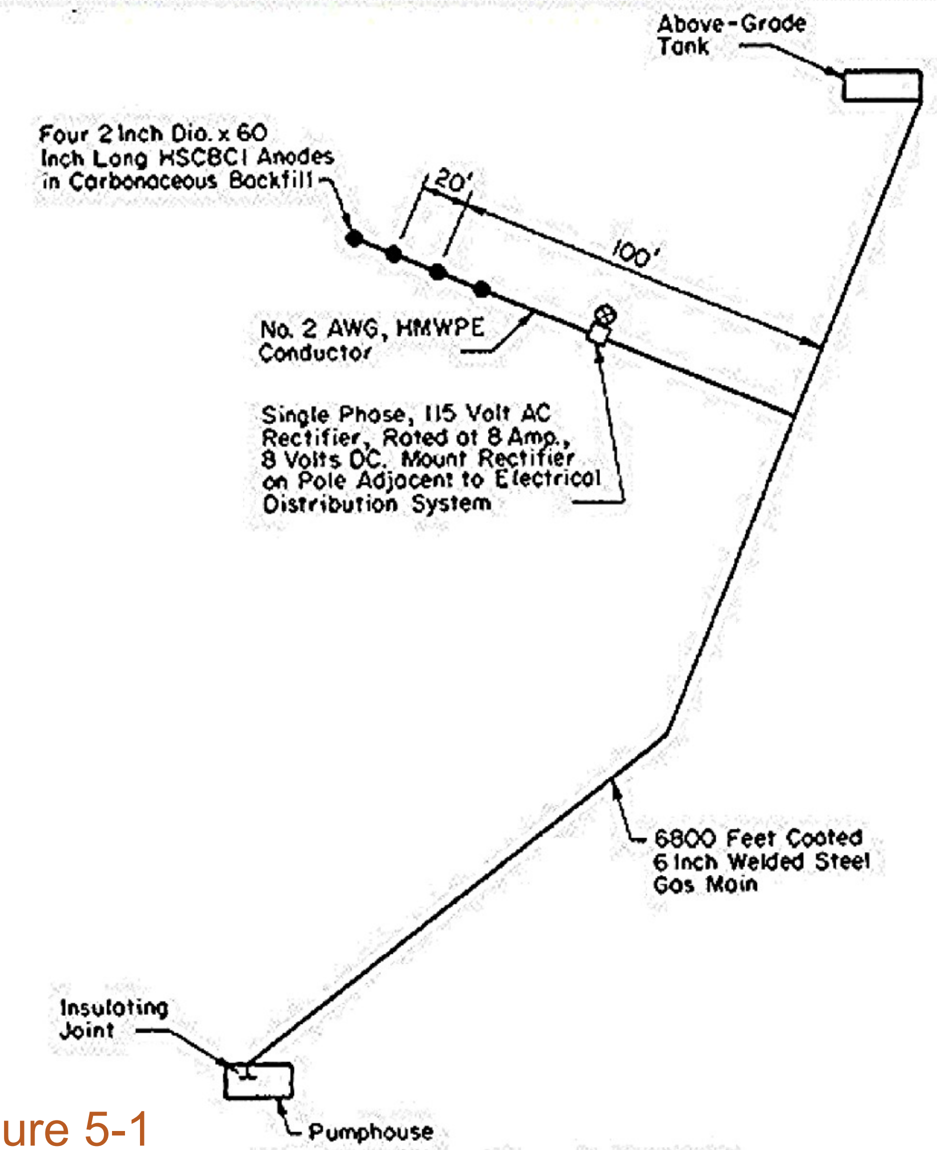

Figure 5-1

EXAMPLES OF IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Steel gas main

5.1.1 Design data.

(1) Average soil resistivity is 2000 ohm-centimeters.

(2) Effective coating resistance at 15 years is estimated at 2500 ohms per square foot.

(3) Pipe has a 6-inch outside diameter.

(4) Pipe length is 6800 feet.

(5) Design for 15-year life.

(6) Design for 2 milliamperes per square foot of bare pipe.

(7) Design for 90 percent coating efficiency based on experience.

EXAMPLES OF IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Steel gas main

(5.1.1 Design data.)

(8) The pipeline must be isolated from the pumphouse with an insulating joint on the main line inside the pumphouse.

(9) HSCBCI anodes must be used with carbonaceous backfill.

(10) The pipe will be coated with hot-applied coal-tar enamel and will be holiday-checked before installation.

(11) Anode bed must not exceed 2 ohms.

(12) Electric power is available at 120/240 volts a.c. single phase from a nearby overhead distribution system.

(13) Current requirement test indicates that 2.36 amperes are needed for adequate cathodic protection.

5.1.2 Computations.

(1) Find the gas main's outside area:

Pipe size - 6 in.
Pipe length - 6800 ft
Pipe area – (6800)([π/2](A) = (L)(π)(d) = (6800)(π)(6/12) = 10,681 sq ft.

(2) Check the current requirement:

I = (A)(I')(1.0 - CE)
I = 10681 sq ft (2 mA/sq ft)(1.0 - 0.9)
I = 2136 mA,

which agrees with the current requirement test indicated in (13) above.

EXAMPLES OF IMPRESSED CURRENT CATHODIC PROTECTION DESIGN

Steel gas main

(3) Select an anode from manufacturer's literature (high-silicon chromium-bearing cast-iron anodes). Choose a 60-pound anode with a 2.8-square-foot surface area (arbitrary selection).

(4) Calculate the number of anodes needed to meet the anode supplier's current density limitations:

$$N = I/(A_1)(I_1) = 2360 \text{ mA}/(28 \text{ sf/anode})(1000 \text{ mA/sf}) = 0.84 \text{ anode}$$

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

EXAMPLES OF IMPRESSED CURRENT CATHODIC PROTECTION DESIGN

Steel gas main

(5) Calculate the number of anodes required to meet the design life requirements:

N = (L)(I)/(1000)(W) = (15 yrs)(2360 mA)/(1000)(60 lb/anode) = 0.59 anode

(6) Calculate the number of anodes required to meet maximum anode groundbed resistance requirements:

$R_a = (\rho K/LN) + (\rho P/S)$

$N = \rho K/(L(R_a - (\rho P/S))) = 2.75 = 3$ anodes

Steel gas main

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

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

(9) Determine the total circuit resistance.

(a) Calculate the anode groundbed resistance:

$R_a = (\rho K/LN) + (\rho P/S) = 1.46$ ohms

EXAMPLES OF IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Steel gas main

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

R_w = (ohms/ft)(L)

R_w = (0.0159 ohm/100 ft)(500 ft) = 0.0795 ohm

(c) Calculate the structure-to-electrolyte resistance:

R_c = R/N = 2500 ohms/sf/11,800 sf = 0.212 ohm

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

$R_T = R_a + R_w + R_c = 1.46 \text{ ohm} + 0.0795 \text{ ohm} + 0.212 \text{ ohm} = 1.75 \text{ ohms}$

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

$v_{rec} = (I)(R_T)(150\%) = (2.36 \text{ A})(1.75 \text{ ohms})(150\%) = 6.2 \, V_{rec}$

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

5.2 Heating distribution system.

Impressed current cathodic protection is designed for a well coated, buried heating distribution system as shown in figure 5-2. The distribution system has not yet been installed, so measurements cannot be made. Rectifier size need not be calculated, because it is sized in the field after anode installation.

EXAMPLES OF IMPRESSED CURRENT CATHODIC PROTECTION DESIGN

Heating distribution system

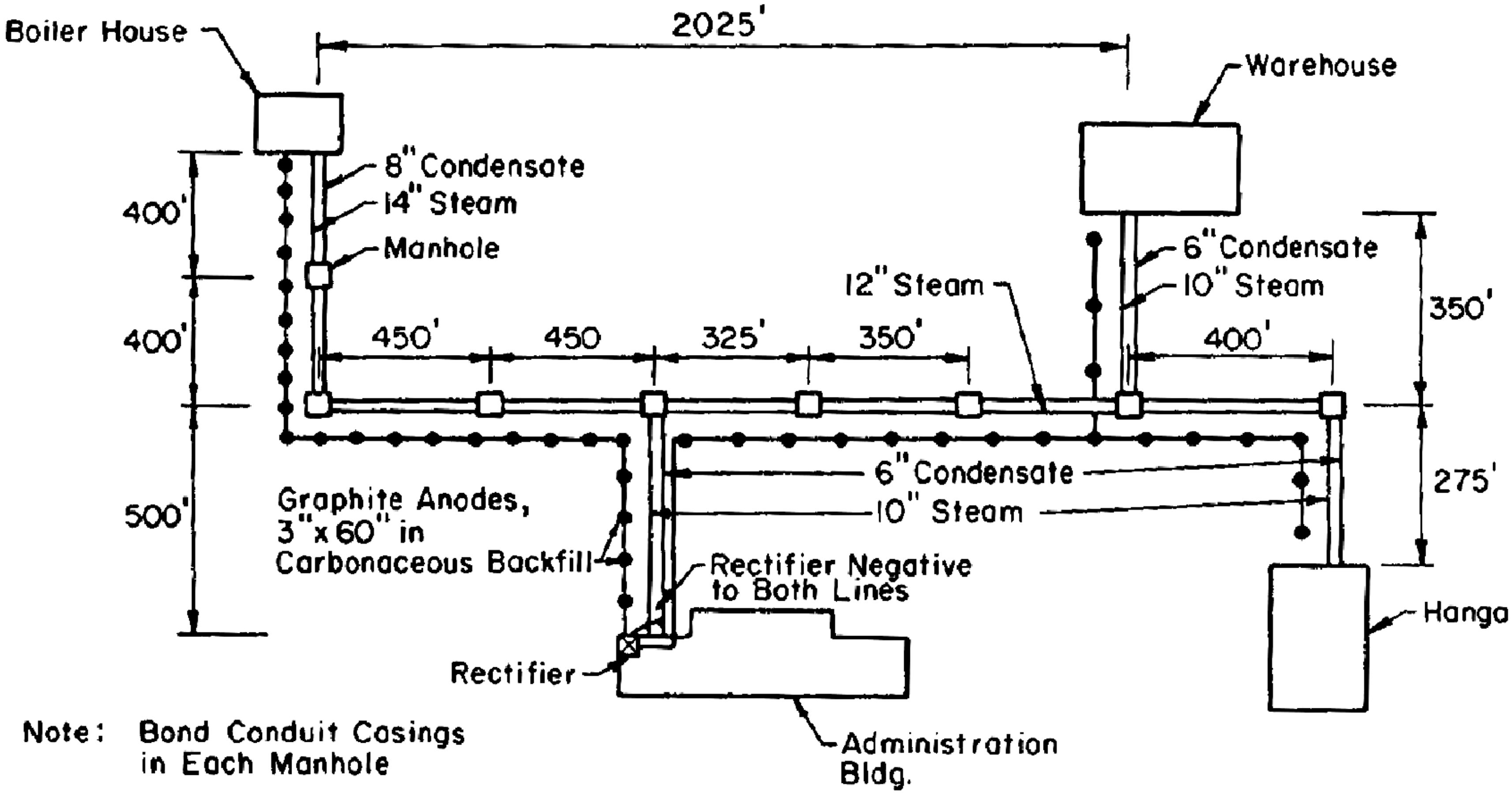

Figure 5-2

5.2.1 Design data.

(1) Average soil resistivity is 1000 ohm-centimeters.

(2) Design for 80 percent coating efficiency based on experience.

(3) Design for 4 milliamperes per square foot of bare metal heating conduits.

(4) Groundbed resistance must not exceed 1.5 ohms.

(5) Graphite anodes must be installed with carbonaceous backfill.

(6) Design for a 15-year life.

EXAMPLES OF IMPRESSED CURRENT CATHODIC PROTECTION DESIGN

Heating distribution system

(7) Insulating joints must be provided on both steam and condensate lines at the first flange connection inside all buildings.

(8) All conduit must be metal-bonded together in each manhole.

(9) All conduit will be pre-coated at the factory and will not have been holiday-checked.

(10) Single-phase electrical power is available at 120/240 volts a.c. from the administration building.

5.2.2 Computations.

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

(a) Steam conduit area must be calculated (table 5-1).

EXAMPLES OF IMPRESSED CURRENT CATHODIC PROTECTION DESIGN

Heating distribution system

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

Table 5-1
Dimensions for finding steam conduit area: heat distribution system

Heating distribution system

(b) Condensate return conduit area must be calculated (table 5-2).

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

Table 5-2
Dimensions for finding condensate return conduit area: heat distribution system

EXAMPLES OF IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Heating distribution system

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

$A=21,481 \times 0.2$
$A = 4296$ sq ft.

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

$I = 4296 \times 4$
$I = 17,184$ mA or 17.2 A.

(4) Compute the maximum weight of anode material needed for 15 years' life.

(a) Graphite anodes are used.
(b) Average deterioration rate for graphite is 2.0 pounds per ampere-year.

EXAMPLES OF IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Heating distribution system

(c) Find the maximum weight of anode material required:

$$W = YSI/E$$

Where Y = 15 years, S = 2.0 lb/ampere-year, I = 17.2 amperes, and E = 0.50 efficiency. Thus:

$$W = (15)(2.0)(17.2)/(0.50) = 1032 \text{ lb}$$

5.2.3 Groundbed Design

(1) Anode size is 3” x 60” (backfilled (10” x 84”) and weight is 25 lb per anode unit.

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

$$R_v = PK/L$$

Where P = 1000 ohm-cm, L = 7.0 ft (backfilled size) and K = 0.0167, L/d = 8.4 (manufacturer’s data). Thus:

$$R_v = (1000)(0.0167)/(7.0) = 2.39 \text{ ohms}$$

EXAMPLES OF IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Heating distribution system

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

N = 1032/25 = 41.3 or 41 anodes.

These are arranged in a distributed groundbed as shown in figure 5-2 based on the following estimates.

(4) Anode distribution:

(a) Conduit area in sections 1 through 6 of figure 5-2 are given in table 5-3.

EXAMPLES OF IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Heating distribution system

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

Table 5-3
Conduit area: heat distribution system

EXAMPLES OF IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Heating distribution system

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

A = 21,481/41
A = 524 sq ft/anode.

(c) Anodes will be divided as shown in table 5-4.

EXAMPLES OF IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Heating distribution system

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

Table 5-4
Anode division: heat distribution system

EXAMPLES OF IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Heating distribution system

(d) Rectifier location. Locate the rectifier in front of the administration building as figure 5-2 shows. The rectifier will be sized after anodes are installed.

5.3 Black iron hot water storage tank.

Impressed current cathodic protection is designed for the interior of a black iron hot water storage tank as shown in figure 5-3.

EXAMPLES OF
IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Black iron hot water storage tank

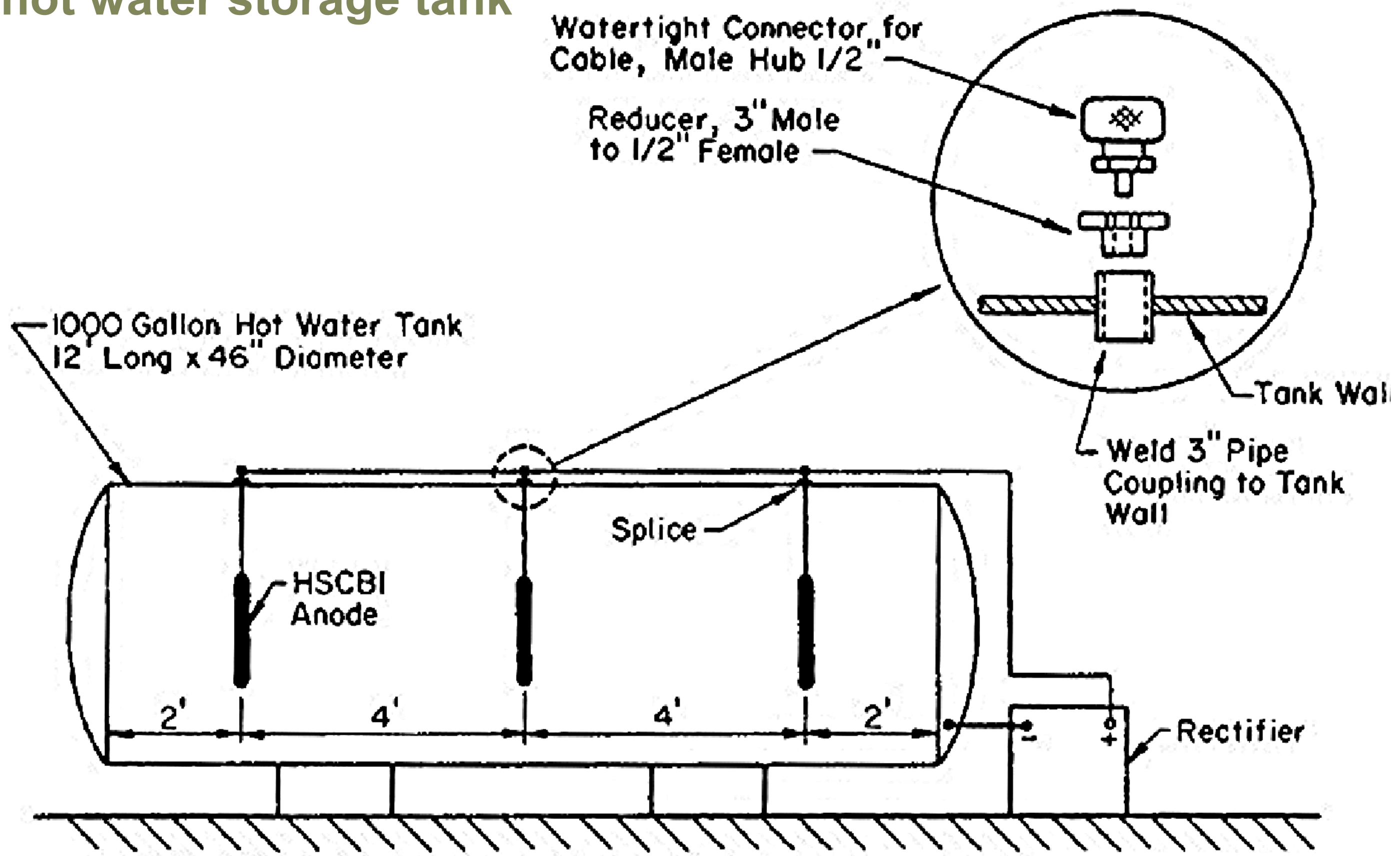

Figure 5-3
Cathodic protection for
black iron hot water storage tank

EXAMPLES OF
IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Black iron hot water storage tank

5.3.1 Design data.

(1) Tank capacity is 1000 gallons.

(2) Tank dimensions are 46 inches in diameter by 12 feet long.

(3) The tank is mounted horizontally.

(4) Water resistivity is 8600 ohm-centimeters with a pH of 8.7.

(5) The tank's inside surface is bare and water temperature is maintained at 180 degrees Fahrenheit.

(6) Design for a maximum current density of 5 milliamperes per square foot.

(7) Design for a 5-year life.

(8) Use HSCBCI anodes.

(9) Electrical current is available at 115 volts a.c., single phase.

5.3.2 Computations.

(1) Find the tank's interior area:

$A_T = 2\pi r^2 + \pi dL$, where

R = 1.92 ft, d = 3.83 ft, L = 12 ft., thus

$A_T = [2 \times 3.1416 \times (1.92)^2] + [3.1416 \times 3.38 \times 12] = 167.5$ sf

(2) Find the maximum protective current required:

$I = A_T \times 5$ ma/sf = 1675.5 x 5 = 838 ma = 0.84 A

EXAMPLES OF IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Black iron hot water storage tank

(3) Find the minimum weight of anode material needed for a 5-year life:

W = YSI/E where

Y = 5 yr, S = 1.0 lb/A-yr, I = 0.84 A, E = 0.50, thus

W = [(5)(1.0)(0.84)]/0.50 = 8.4 lb

(4) Compute the number of anodes required. An anode 1.5 inches in diameter by 9 inches long weighing 4 pounds is chosen as the most suitable size. For proper current distribution, three anodes are required.

EXAMPLES OF
IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Black iron hot water storage tank

(5) Find the resistance of a single anode:

R = (0.012P log (d/D))/L, where

P = 8600 ohm-cm, D = tank diameter = 3.83 ft, d = anode diameter = 1.5 in = 0.125 ft, L = anode length = 9 in = 0.75 ft, thus

R = (0.012 x 8600 x log (3.83/0.125))/0.75 =

= (103.2 x log 30.64)/0.75 = 204.5 ohms

This resistance must be corrected by the fringe factor because the anodes are short. The fringe factor is 0.48 from the curve in Figure 5-4 for a L/d = 9/1.5 = 6:

R = 204.5 x 0.48 = 98.2 ohms

Black iron hot water storage tank

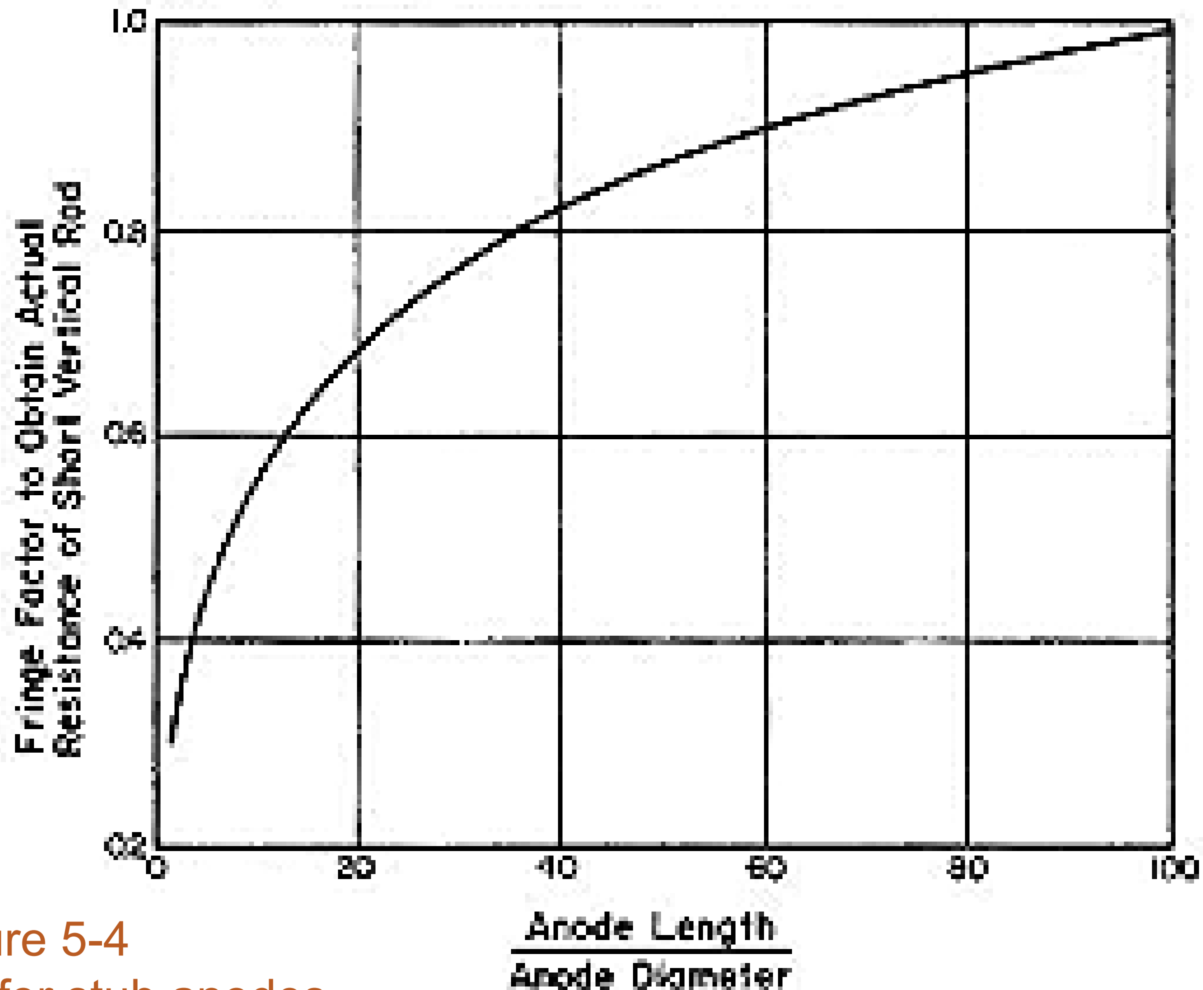

Figure 5-4
Fringe factor for stub anodes

EXAMPLES OF
IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Black iron hot water storage tank

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

$R_n = (1/N)R_v + \rho P/S$, where

R_n = total anode-to-electrolyte resistance, N = number of anodes, R_v = anode-to-electrolyte resistance of a single anode, P = electrolyte resistivity, P paralleling factor from manufacturer's data, and S = spacing between anodes (feet). Thus,

$R_n = (1/3)(98.2) + ((8600)(0.00289))/4 = 38.94$ ohms

EXAMPLES OF
IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Black iron hot water storage tank

(7) Find the rectifier rating:

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

E = 0.84 x 38.94 = 32.7 V

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

E = 1.5 x 32.7 = 49.1 V.

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

EXAMPLES OF
IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Black iron hot water storage tank

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

- Usually cheaper to install.
- Easier to maintain.
- Keeps d.c. voltage drop to a minimum.

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

- Outside tank — use No.2 AWG high molecular weight polyethylene extruded (HMWPE) conductor.
- Inside tank — use No.8 AWG HMWPE conductor.

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

5.4 Elevated water tank (ice is expected).

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

EXAMPLES OF
IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Elevated water tank (ice is expected)

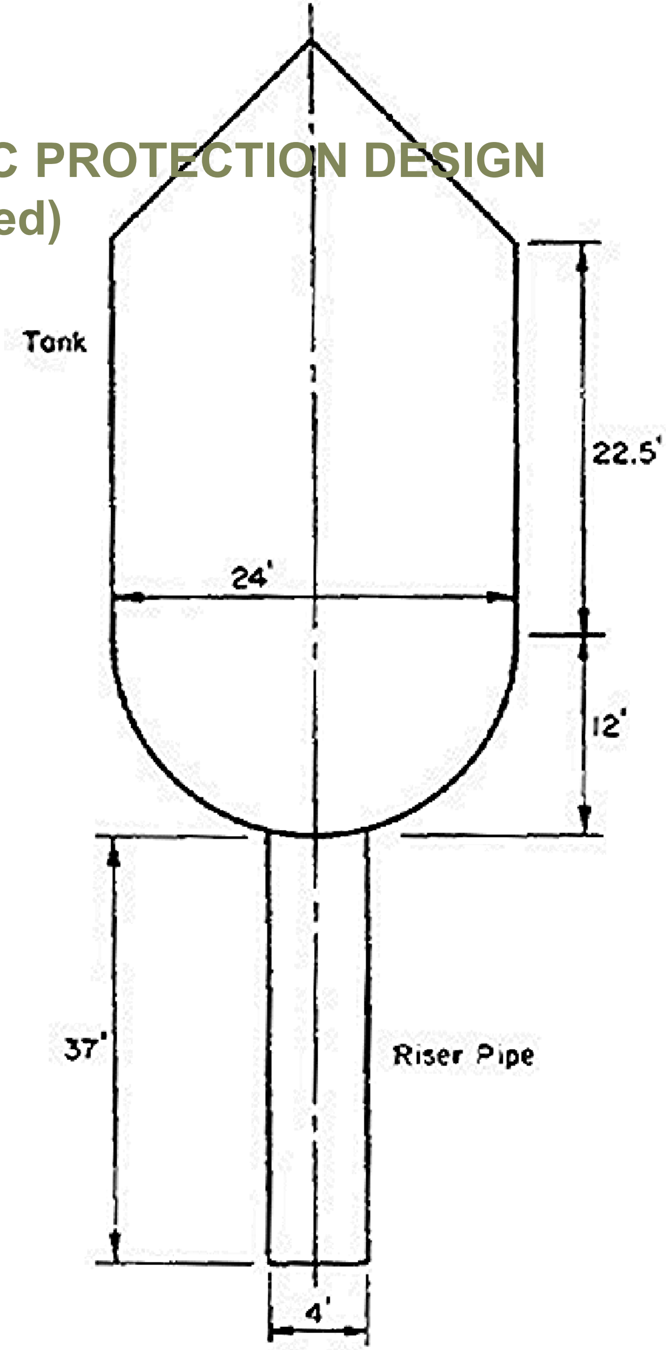

Figure 5-5
Dimensions for an
elevated steel water tank

EXAMPLES OF
IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Elevated water tank (ice is expected)

5.4.1 Design data.

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

EXAMPLES OF
IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Elevated water tank (ice is expected)

5.4.2 Computations.

(1) Find the minimum weight of button anode material required for the tank:

W = YSI/E, where

Y = 15 yr, S = 1.0 lb/ampere-yr, I = 7.0 amperes and E = 0.50, thus

W = ((15)(1.0)(7.0))/0.50 = 210 lb

(2) Compute the number of tank anodes needed (button anodes weight 55 lb):

N = 210/55 = 3.82 (use 4 anodes)

EXAMPLES OF
IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Elevated water tank (ice is expected)

(3) Find the minimum weight of riser anode material required for the riser:

W = YSI/E, where

Y = 15 yr, S = 1.32X10^{-5} lb/ampere-yr, I = 1.0 ampere, and

E = 0.50

W = ((15)(1.32X10$^{-5)}$(1.0))/0.50 3.96 x 10^{-4} lb

(4) Find the number of riser anodes needed. Platinized titanium wire, 0.1-in diameter, 3-ft long, with 0.001-in thick platinum over titanium will be used for each anode. The weight of platinum on each anode is 8.8 x 10^{-5} pound. Thus,

N = (3.96)(10^{-4})/(8.8)(10^{-5}) = 4.5 (use 5 anodes)

(5) Locate anodes as shown in figure 5-6.

EXAMPLES OF IMPRESSED CURRENT CATHODIC PROTECTION DESIGN

Elevated water tank (ice is expected)

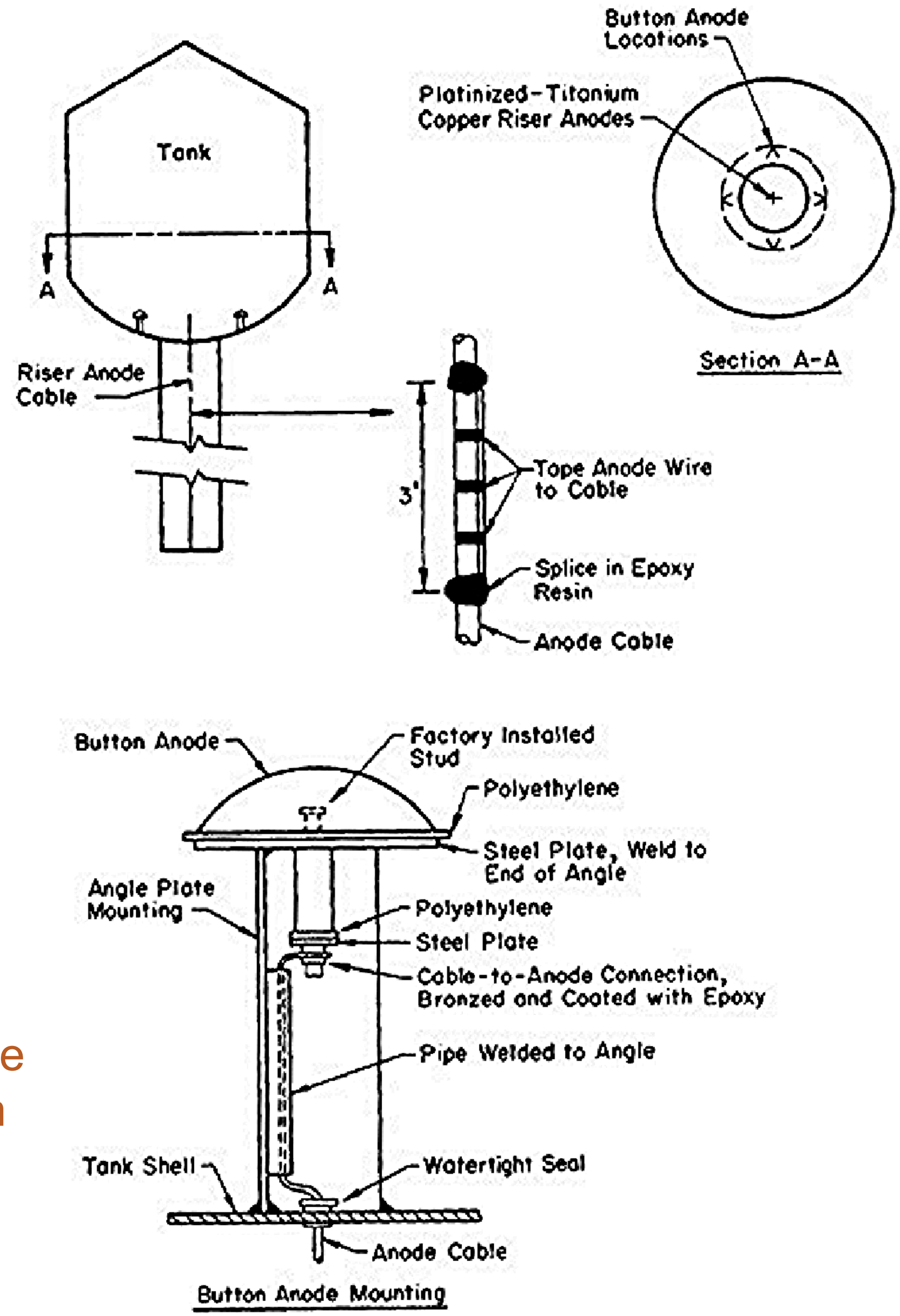

Figure 5-6
Cathodic protection for tanks using rigid-mounted, button-type anodes and platinized titanium wire

EXAMPLES OF IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Elevated water tank (ice is expected)

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

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

5.5 Elevated Steel Water Tank

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

5.5.1 Design data.

(1) Tank capacity will be 500,000 gallons.

(2) Tank height (from ground to bottom of bowl) will be 115 feet.

(3) Tank diameter will be 56 feet.

(4) The tank's high water level will be 35 feet.

(5) Overall tank depth will be 39 feet.

(6) Vertical shell height will be 11 feet.

(7) Riser pipe diameter will be 5 feet.

EXAMPLES OF IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Elevated Steel Water Tank

(8) Tank will be ellipsoidal on both top and bottom.

(9) All inner surfaces will be uncoated.

(10) Design for a maximum current density of 2 milliamperes per square foot.

(11) Electric power available will be 120/240-volt a.c., single phase.

(12) String-type HSCBCI anodes will be used.

(13) Design for a 10-year life.

(14) Water resistivity is 4000 ohm-centimeters.

(15) The tank water must not be subjected to freezing.

(16) An assumed deterioration rate is 1.0 pound per ampere-year.

(17) Anode efficiency (assumed) is 50 percent.

5.5.2 Computations.

(1) Find the area of wetted surface or tank bowl (figure 5-7).

(a) For the top section (T) —

$A = 2\pi rx$ (approximately), T
where r = 28 feet (tank radius), x = 10 feet. Thus,
A =2 x 3.1416 x 28 ft x 10 ft T
A= 1759 sq ft.

(b) For the center section (C) —

$A = 2\pi rh$
where r = 28 feet (tank radius) and h = 11 feet. Thus,
A = 2 x 3.1415 x 28 ft x 11 ft c
A = 1935 sq ft.

EXAMPLES OF
IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Elevated Steel Water Tank

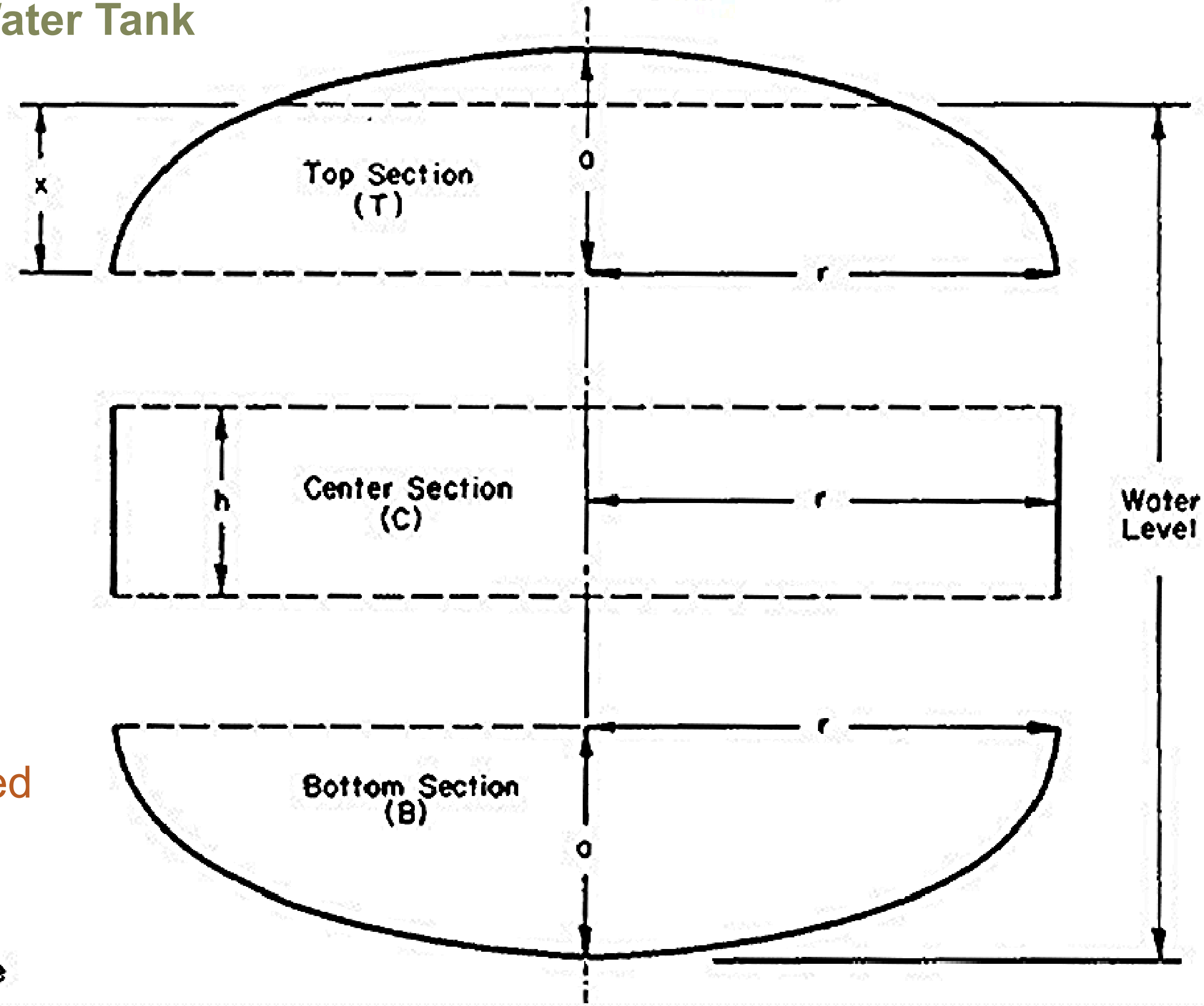

Figure 5-7
Segmented elevated tank for area calculations

(c) For the bottom section (B) –

$A_B = (2)^{½} \times r\,(a^2 + r^2)^{½}$ where

r = tank radius = 28 ft, a = 14 ft. Thus

$A_B = 1.414 \times 28 \times (14^2 + 28^2)^{½} = 3894$ sf

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

$A_T + A_C + A_B = 7588$ sf

(2) Find the riser pipe's area:

$A_r = 2\pi r_R h_R$, where r_R =riser radius = 2.5 ft, h_R = riser height = 115 ft.

Thus A_r = 2 x 3.1416 x 2.5 x 115 = 1806 sf

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

I_T = 2.0 mA/sf x 7588 sf = 15,176 mA = 15.2 A

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

I_R = 2.0 mA/sf x 1806 sf = 3612 mA = 3.62 A

EXAMPLES OF
IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Elevated Steel Water Tank

(5) Find the minimum weight of tank anode material needed:

W = YSI/E, where

Y = 10 yr, S 1.0 lb/A-yr, E = 0.50, and I = 15.2 A. Thus

W = ((10)(1.0)(15.2))/0.50 = 304 lb

(6) Compute the minimum weight of riser anode material needed:

W = YSI/E, where

Y = 10 yr, S = 1.0 lb/A-yr, E = 0.50, I = 3.62 A. Thus

W = ((10)(1.0)(3.62))/0.50 = 72.4 lb

Elevated Steel Water Tank

(7) Find the main anode circle's radius:

R = (DN)/2(π + N), where

D = 56 ft and N = 10 (assumed number of anodes). Thus

R = (56)(10)/(2(π + 10) = 560/26.28 = 21.3 ft, use 22 ft

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

(a) To find circumferential spacing:

C = (2πr)/N where

R = anode circle radius = 22 ft and N = 10 (assumed number of anodes).

Thus C = (2)(3.1416)(22)/10 = 13.8 ft, use 14 ft

Elevated Steel Water Tank

(b) The cord spacing is approximately the same as circumferential spacing, so 14 ft will be used. See figure 5-8.

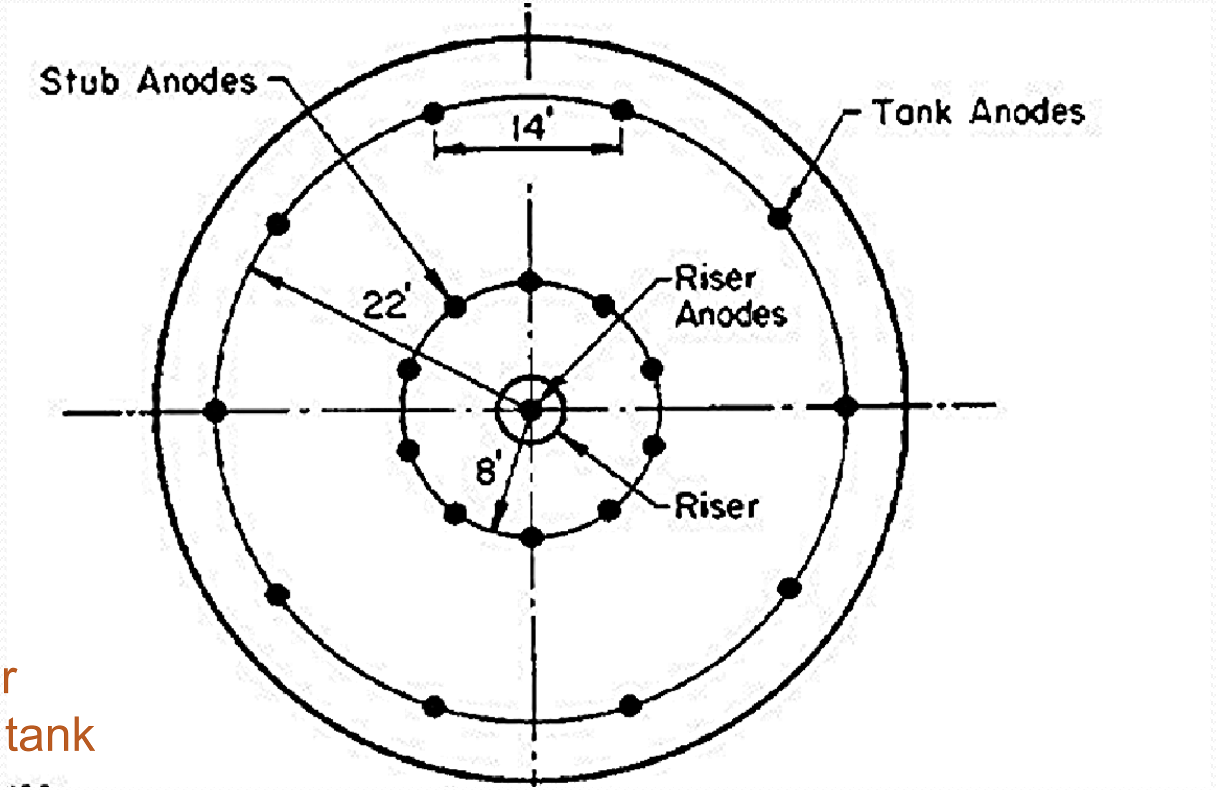

Figure 5-8
Anode spacing for
elevated steel water tank

(9) Select the main anodes.

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

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

$N = 304/(10 \times 1)$
$N = 30.4$, use 31 units per string.

(9) Select the main anodes.

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

15.2 A/(10 x 0.025 A) = 60.8 (use 61 anodes per string)

EXAMPLES OF
IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Elevated Steel Water Tank

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

EXAMPLES OF
IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Elevated Steel Water Tank

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

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

Table 5-5
Commonly Used HSCBCI anodes

EXAMPLES OF IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Elevated Steel Water Tank

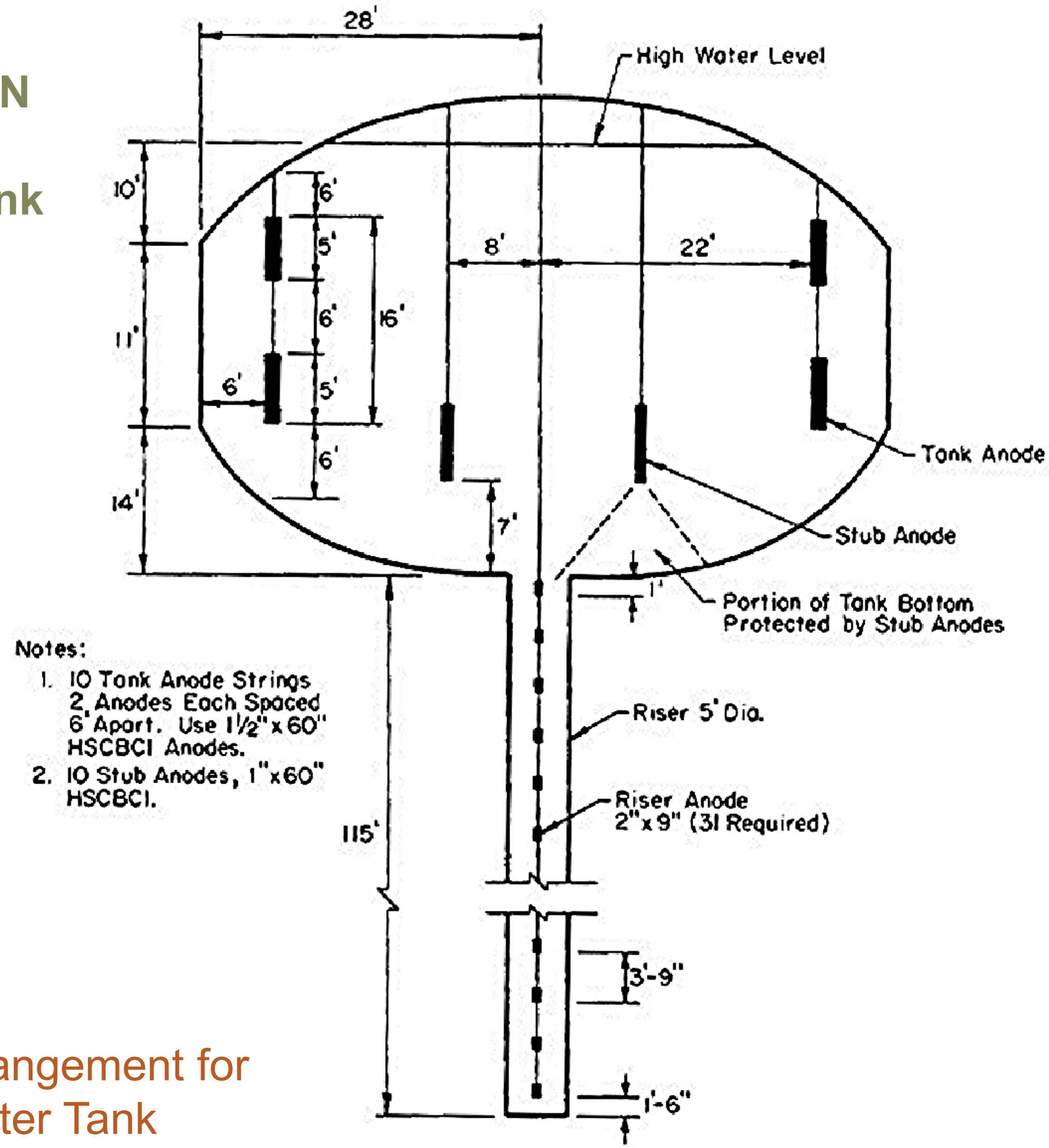

Figure 5-9
Anode Suspension Arrangement for Elevated Steel Water Tank

EXAMPLES OF
IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Elevated Steel Water Tank

(10) Find the main anodes' resistance:

R = (0.012)(P)(log (D/a))/L where

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

R = ((0.102)(4000)(log (56/12.1))/10 = (48)(log 4.628)/10 = 3/19 ohm

EXAMPLES OF
IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Elevated Steel Water Tank

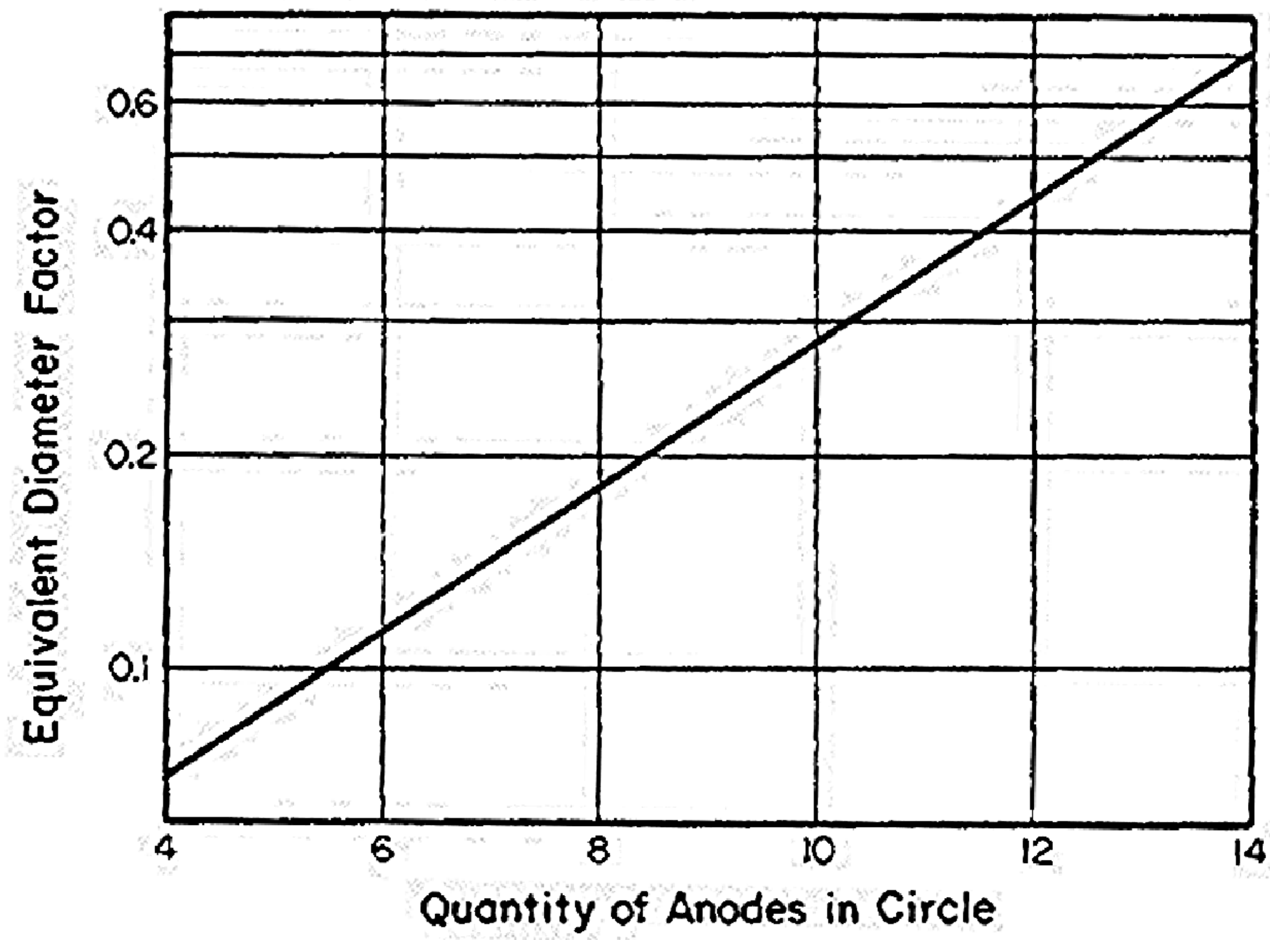

Figure 5-10
Equivalent Diameter Factor for Anodes in a Circle in Water Tank

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

$$L/d = (2 \times 60)/1.5$$

$$L/d = 80 < 100.$$

(b) The fringe factor from figure 5-4 corresponding to this L/d ratio is 0.95. Thus,

$$R\ (\text{adjusted}) = 3.19 \times 0.95$$

$$R = 3.03\ \text{ohms}.$$

EXAMPLES OF IMPRESSED CURRENT CATHODIC PROTECTION DESIGN

Elevated Steel Water Tank

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

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

(b) The anode suspension arrangement for the tank being considered is shown in figure 5-9. It can be seen that stub anodes are required for this design. Ten stub anodes are spaced equally on a circumference with a radius of 8 feet in a way shown in figure 5-8. For smaller diameter tanks, stub anodes may not be required.

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

(a) The area of tank bottom protected by stub anodes is found by (see fig 5-9):

$A_S = \pi(r_2^2 - r_1^2)$, where r_2 = 13 feet (protected segment radius) and r_1 = 2.5 feet (riser radius). Thus,

A_S = 3.1416 (132 sf - 2.5^2 sf) = 3.1416 x 162.75 = 511.3 sf

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

I_s = 2.0 x 511.3
I_s = 1022.6 milliamperes or 1.02 amperes.

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

(d) The maximum current for main anodes is—

I_m = 15.2A - 1.02A = 14.2 A

(13) Find the rectifier voltage rating.

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

R = (200 ft/1000 ft) x .0159 ohm = 0.032 ohm

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

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

E = 14.2 A x 0.032 ohm = 0.45 V.

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

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

E = 14.2 A x 3.03 ohms = 43.0 V.

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

E = 0.45 + 43.0 = 43.45 or 45 V. Use a multiplying factor (safety factor) of 1.5 to get 67.5 volts.

(14) Select the stub anodes. Because it is desirable to use as small an anode as possible without exceeding the manufacturers' recommended rate, try using type FC, HSCBCI anode that measures 1½-inches by 9 inches. Use one anode per string as shown in figure 5-9. Anode current density is computed as follows:

$$\text{Output} = 1.02/(10 \times 0.03) = 0.34 \text{ A/sq ft.}$$

Because this exceeds the recommended maximum anode current density shown in table 5-5, the type B anode is the best choice.

(15) Find the stub anodes' resistance:

R = (0.012P x log (D/a))/L, where

P = 4000 ohm-centimeters, D = 56 ft, L = 5 ft, and a = 16 x 0.275 = 4.4 ft (factor from figure 5-10)

R =((0.012)(4000)(log (56/4.4))/5 = 48(log 12.73)/5 =10.6 ohms

L/d = 60/1 = 60 < 100

Using the fringe factor from figure 5-4, 0.90 –

R (adjusted) = 10.6 x 0.90 = 9.54 ohms

EXAMPLES OF
IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Elevated Steel Water Tank

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

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

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

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

E = IR, where I = 1.02 A and R = 0.032 ohm, thus

E = 1.02 A x 0.032 ohm = 0.033 V

EXAMPLES OF
IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Elevated Steel Water Tank

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

$$R = (50/1000) \times 0.159 = 0.008 \text{ ohm}$$

E = IR, where I = 1.02/10 = 0.102 A and R = 0.008 ohm, thus –

$$E = 1.02 \text{ A} \times 0.008 \text{ ohm} = \text{negligible}$$

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

$$E = IR$$
$$E = 1.02 \text{ A} \times 9.54 \text{ ohms}$$
$$E = 9.73 \text{ V.}$$

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

$$E_T = 0.033 + 9.73$$
$$E_T = 9.76 \text{ V.}$$

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

(17) Choose a stub anode circuit variable resistor.

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

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

(c) The variable resistor rating is found by–

R = E/I, where E = 80 volts and I = 1.02/2 or 0.51 ampere.
Thus, R=80/0.51 =156.9 ohms

Resistor's ohmic value = 156.9 - 9.54 = 147.4 ohms.

To find the resistor's wattage rating —

$P = I^2R$
$P = (1.02)^2 \times 147.4 = 153.4$ W.

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

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

$R = E/1$, where $E = 43.45$ volts and $I = 3.62$ amperes.
Thus,
$R = 43.5\ V/3.62\ A = 12.0$ ohms

(19) Design the riser anode.

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

(b) The number of units required is:

$$R = (0.012P)(\log (D/d))/L$$

$$L = (0.012P)(\log(D/d))/R$$

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

L = (0.012)(4000)(log(5/0.166))/12 = 5.92 ft

The number of units is thus –

5.92/0.75 = 7.9, say 8 units

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

3.62 A/0.1 A = 36.

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

(c) To find the anode resistance using 36 anode units:

R = ((0.012)xP x log (D/d))/L, where –

P = 4000 ohm-centimeters, D = 5 ft, d = 2 in or 0.166 ft, and L = 36 x 9 in = 324 in or 27 ft, thus –

R = (0.012)(4000)(log (5/0.166))/27 = 2.63 ohm

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

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

(a) Electrical conductor to riser anodes. For a wire size No. 2 AWG, 0.159 ohm/1000 ft, and estimated length = 200 ft, the resistance ® is –

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

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

E = IR,

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

E = 3.62 A x 0.032 ohm = 0.116 V.

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

R = (130/1000)(0.159/1000) = 0.02 ohm

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

E = (1.81 x 0.02 = 0.04 V.

(d) Find the voltage drop through riser anodes:

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

$$E = 3.62\text{ A} \times 2.63\text{ ohms} = 9.52\text{ V}$$

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

$$E_T = 0.116\text{V} + 0.04\text{V} + 9.92\text{V} = 9.68\text{ V}$$

(21) Select the riser anode circuit variable resistor.

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

(b) Riser anode circuit data: rectifier output = 80 V, anode current = 3.62 A, anode resistance = 2.63 +0.032+0.02 = 2,68 ohm

EXAMPLES OF IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Elevated Steel Water Tank

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

r = E/I, where E = 80 V, I = 3.62/2 = 1.81 A. Thus –
R = 80 V /1.81 A = 44.2 ohms
Resistor ohmic value = 44.2 ohms – 2.68 ohms = 41.5 ohms
Resistor wattage rating = $(3.62\ A)^2$ x 41.5 ohms = 543.8 W

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

EXAMPLES OF
IMPRESSED CURRENT CATHODIC PROTECTION DESIGN
Elevated Steel Water Tank

(22) Size the rectifier for the riser.

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

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

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

(24) Determine wire sizes and types. All positive feeder and suspension cables (rectifier to anodes) must be No.2 AWG HMWPE insulated copper cable. To avoid complication, the negative rectifier cable (rectifier to structure) must be the same size and type (fig 5-11).

Elevated Steel Water Tank

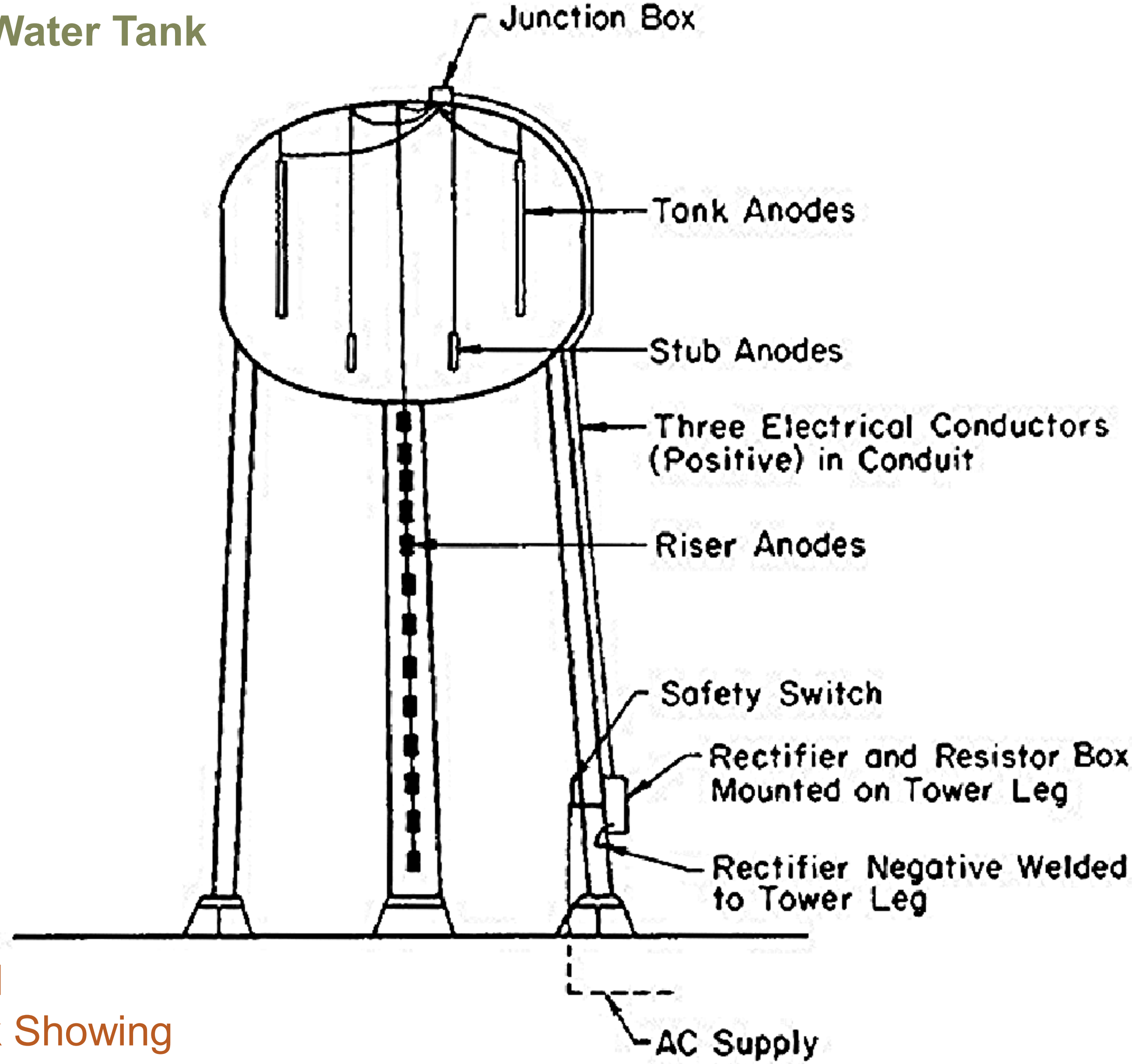

Figure 5-11
Elevated Steel Tank Showing
Rectifier and Anode Arrangement

(25) Discussion of design.

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

And now….

THE QUIZ

The Quiz….

1. The combination of an anode, cathode, electrolyte and metallic connection is called a _________________:

   a. potentiometer
   b. catalyst
   c. corrosimeter
   d. corrosion cell

2. A galvanic cathode protection system is called a _____________:

   a. sacrificial anode system
   b. impressed current system
   c. express potential system
   d. two-cell system

The Quiz….

3. The main difference between galvanic and impressed current systems is the:

   a. galvanic system relies on alternating current (a.c.) power
   b. impressed current system uses an external power source
   c. galvanic system requires a protective coating system for the protected structure
   d. impressed current systems uses a potentiometer

4. The soil resistivity range for “mild” corrosivity is:

   a. 0 – 2000 ohm-cm
   b. 2000 – 10000 ohm-cm
   c. 10000 – 30000 ohm-cm
   d. above 30000 ohm-cm

5. The typical range of current density (in mA/sq ft) required for cathodic protection of an uncoated steel tank in well aerated neutral soil is:

   a. 0.4 to 1.5
   b. 2 to 3
   c. 1 to 6
   d. 3 to 15

6. In the design of a cathodic protection system for a new underground steel pipeline, standard practice is to assume a current density of at least ____________ milliamperes per square foot of bare pipe area will be needed for its protection.

   a. 0.25
   b. 0.5
   c. 1
   d. 2

7. If soil resistivity is less than 5000 ohm-centimeters and current density is less than 1 milliampere per square foot, which of the following is the most likely cathodic protection system to be warranted?

   a. impressed current
   b. sacrificial anode
   c. cathode-anode couple
   d. any of the above

8. There are __________ steps in designing a sacrificial anode cathodic protection system.

   a. 6
   b. 7
   c. 8
   d. 9

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9. There are __________ steps in designing an impressed current cathodic protection system.

   a. 10
   b. 11
   c. 12
   d. 13

10. The open-circuit potential of standard alloy magnesium anodes to a copper-copper sulfate half-cell is approximately:

    a. – 1.45 volts
    b. – 1.55 volts
    c. – 1.65 volts
    d. – 1.75 volts

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11. The open-circuit potential of high-manganese magnesium anodes to a copper-copper sulfate half-cell is approximately:

    a. – 1.45 volts
    b. – 1.55 volts
    c. – 1.65 volts
    d. – 1.75 volts

12. Which of the following is not a step in the design of a sacrificial anode cathodic protection system?

    a. Select number of anodes
    b. Select rectifier
    c. Select number of cathodes
    d. Select groundbed layout

13. In a sacrificial anode cathodic protection system, galvanic anodes usually are either:

    a. copper or zinc
    b. zinc or magnesium
    c. magnesium or copper
    d. any of the above

14. In an impressed current cathodic protection system, cast iron anodes are usually used in soil with soil resistivity (ohm-cm) in the range of:

    a. 0 to 5,000
    b. 5,000 to 10,000
    c. 10,000 to 30,000
    d. 30,000 to 100,000

15. A protective coating's resistance to corrosion of a buried steel tank can be expected to:

    a. remain constant long-term (> 30 years)
    b. decrease greatly with age
    c. decrease slightly with age
    d. impossible to project

16. Corrosion is an electrochemical process in which a current leaves a structure at the anode site, passes through an electrolyte, and re-enters the structure at the ______ .

    a. cathode
    b. ground rod
    c. button anode
    d. rectifier

17. Impressed current cathodic protection systems use the same elements as the galvanic protection system, only the structure is protected by applying a current to it from a/an ____________.

    a. cathode
    b. rectifier
    c. electrolyte
    d. ground wire

18. All _________must be eliminated from existing and new cathodic protection systems.

    a. rectifiers
    b. electrolytes
    c. short circuits
    d. galvanic cells

19. A structure's corrosion rate is inversely proportional to the ____________ resistivity.

   a. coating
   b. cathode
   c. anode
   d. electrolyte

20. Studying the corrosion history in the area can prove very ________ when designing a cathodic protection system.

   a. helpful
   b. misleading
   c. difficult
   d. easy

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21. In general, steel's corrosion rate increases as __________ decreases when soil resistivity remains constant.

    a. current
    b. voltage
    c. pH
    d. AIC

22. Galvanic anodes are usually either ____________ or zinc.

    a. iron
    b. carbon
    c. magnesium
    d. manganese

23. A cathodic protection system will be designed to protect a structure ______________________.

    a. permanently
    b. for 5 years
    c. for 25 years
    d. for a given number of years

24. A critical part of design calculations for cathodic protection systems on existing structures is the amount of current required per square foot (called *current density)* to change the structure's potential to ______________volt.

    a. -0.85
    b. +0.85
    c. -1.85
    d. +1.85

25. The anodes used most often in impressed current cathodic protection systems are made of __________________.

    a. high-sodium carbon-bearing cast-iron (HSCBCI)
    b. high-silicon chromium-bearing cast-iron (HSCBCI)
    c. high-silicon carbon-bearing cast-iron (HSCBCI)
    d. high-sodium chromium-bearing cast-iron (HSCBCI)

That's all folks!