ELECTRICAL TECHNICAL PAPER 16
IMPRESSED CURRENT ANODE MATERIAL SELECTION AND DESIGN CONSIDERATIONS (NON-MANDATORY)

Information in this technical paper was excerpted from previous versions of DoD cathodic protection criteria manuals. The information has been updated to reflect current practices and technology.

1.0 ANODES FOR IMPRESSED CURRENT SYSTEMS.

Although any electrically conductive material can serve as an anode in an impressed current system, anode materials that have a low rate of deterioration when passing current to the environment, are mechanically durable, and are available in a form and size suitable for application in impressed current cathodic protection systems at a low cost are most economical. While “abandoned in place” steel such as pipelines and rails can, and are, used as anodes, they are consumed at a rate of approximately 20 pounds per ampere-year. The most commonly used, “purchased” materials for impressed current anodes are high silicon chromium bearing cast iron and mixed metal oxide (ceramic).

1.1 **Graphite Anodes.** Although rarely used anymore on DoD CP system installations, in the past, graphite anodes were one of the most commonly used materials for impressed current anodes in underground applications. They are made by fusing coke or carbon at high temperatures and are impregnated with linseed oil to reduce porosity and increase oxidation resistance. An insulated copper cable is attached to the anode internally for electrical connection to the rectifier. This connection must be well sealed to prevent moisture penetration into the connection and must be strong to withstand handling. A typical anode end connection and seal is shown in Figure 1. However, if graphite anodes are desired, specify center connected anodes as shown in Figure 1a to minimize failure due to “necking” and “end effect”. While more recently developed anodes such as mixed metal oxide are now more often specified, the information on graphite anodes is being provided in the event graphite anodes must be specified.

1.1.1 Specifications**.** Table 1 lists typical specifications for commercially available graphite anodes.

1.1.2 Available sizes**.** Table 1-2 provides examples of the sizes of commercially available graphite anodes. Manufacturers can provide material catalogs with detailed anode information and also provide the same information on their company internet websites. The weights indicate are for the bare graphite only and do not include the weight of the lead wire or connection, or prepackaged backfill.

Table 1 Graphite Anode Properties	
Composition	
Impregnant (Linseed Oil)	6.5 wt % max
Ash	1.5 wt % max
Moisture & Volatile Matter	0.5 wt % max
Water Soluble Matter	1.0 wt % max
Graphite	Remainder
Physical Properties	
Density	99.84 lb/cu ft max
Resistivity	0.0011 ohm-cm max
Mechanical Requirements	
Lead wire connection strength	325 lbs minimum

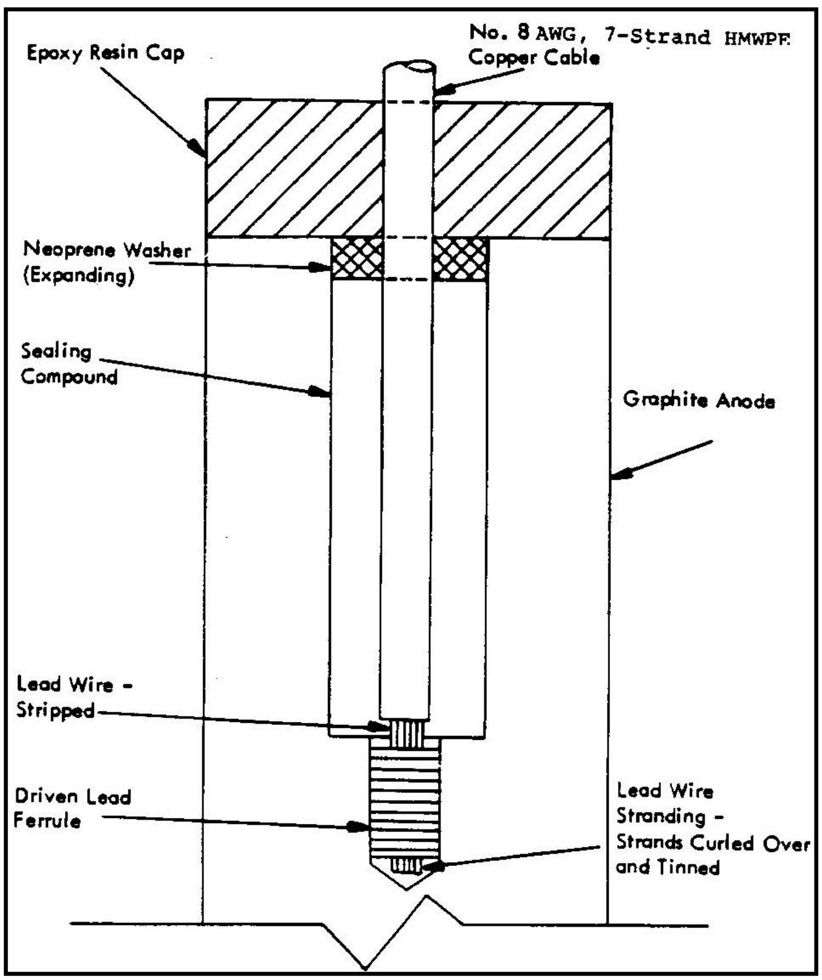

Figure 1
Typical anode end connection and seal

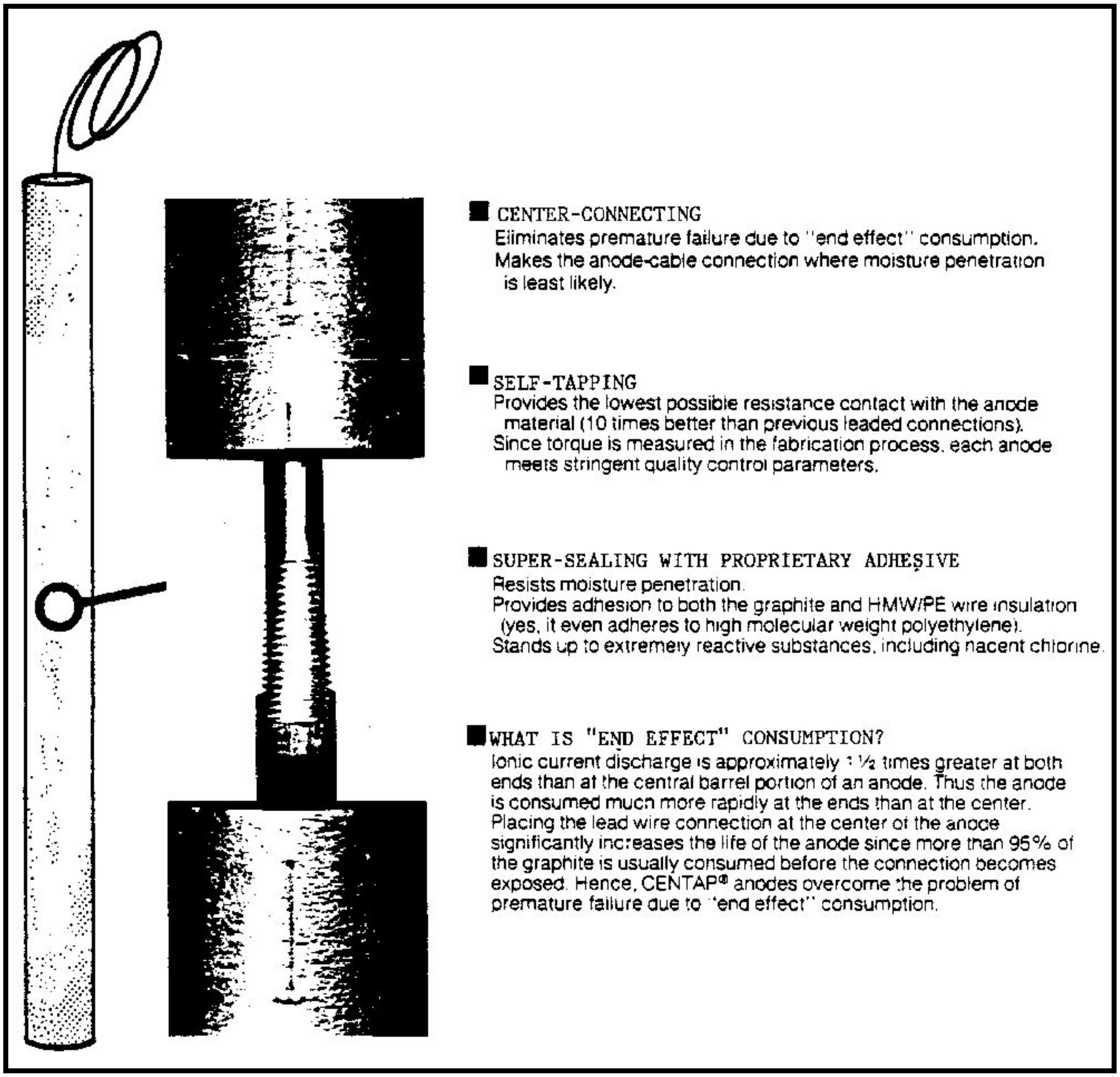

Figure 1a
Center Connected Graphite Anode

1.1.3 Characteristics. All products from the operation or deterioration of graphite anodes are gases. In fresh water or non-saline soil, the principal gases produces are carbon dioxide and oxygen. In saline soils or in seawater, chlorine is also produced and is the major gas produced in seawater applications. The gases generated, if allowed to collect around the anode, can displace moisture around the anode which results in a local increase is soil resistivity and an increase in circuit resistance.

Table 1-2. Examples of Commercially Available Graphite Anodes			
Nominal Weight* (LB) *(Kg)*	Nominal Dimensions*		
	Diameter (in.) *(mm)*	Length (in.) *(mm)*	Surface area (ft^2) *(m^2)*
13 *(5.9)*	3 *(76.2)*	30 *(762)*	2.0 ***(0.18)***
35 *(15.9)*	4 *(101.6)*	40 *(1016)*	3.5 ***(0.32)***
27 *(12.3)*	3 *(76.2)*	60 *(1524)*	3.9 ***(0.36)***
70 *(31.8)*	4 *(101.6)*	80 *(2032)*	7.0 ***(0.65)***

* Note for Table 1-2: Refer to manufacturers' brochures for more specific information. Metric sizes are soft metric conversions from U.S. standard SI units. Actual metric sizes for materials available in foreign countries may differ.

1.1.4 Operation. Graphite anodes must be installed and operated properly in order to insure optimum performance and life.

1.1.4.1 Current Densities. Do not exceed the current densities in Table 3 in order to ensure optimum anode life:

Table 3 Maximum Current Densities for Graphite Anodes		
Maximum Current Density (amp/sq ft)		
Seawater	Fresh Water	Soil
3.75	0.25	1

1.1.4.2 Operating Potentials. As the potential difference between steel and graphite is approximately 1.0 volt with the graphite being the cathode, this potential difference must be overcome before protective current will begin to flow in the impressed current cathodic protection system circuit. This 1.0 voltage difference must be added to the other voltage and IR drop requirements during the selection of proper power supply driving voltage.

1.1.4.3 Consumption Rates. Assuming uniform consumption, the rate of deterioration of graphite anodes in soil and fresh water at current densities not exceeding the values in the table above will be approximately 2.5 pounds per ampere-year. The deterioration rate for graphite anodes in seawater ranges from 1.6 pounds per ampere-year at current densities below 1 ampere per square foot to 2.5 pounds per ampere-year at current densities of 3.75 amperes per square foot.

1.1.4.4 Need for Backfill. The deterioration of any point on a graphite anode is proportional to the current density at that point. If the resistivity of the environment at any one point is lower than the resistivity at other points, the current density and resulting deterioration will be higher there. This can result in uneven consumption and premature failure of graphite anodes, particularly if the low resistivity area is near the top of the anode. In this case “necking” of the anode at the top occurs and the connection to the lower portion of the anode is severed. Use carbon (coke breeze) backfill of uniform resistivity when graphite anodes are used in soil in order to prevent uneven anode deterioration.

1.2 **High Silicon Cast Iron.** Cast iron containing 14 to 15 percent silicon and one to two percent other alloying elements such as manganese and molybdenum form a protective film of silicon dioxide when current is passed from their surface into the environment. This film is stable in many environments except in chloride rich environments. The formation of this film reduces the deterioration rate of this alloy from approximately 20 pounds per ampere-year for ordinary steel, to one pound per ampere-year for the silicon iron. While more recently developed anodes such as mixed metal oxide are now more often specified, high silicon cast iron anodes are still used.

1.3 **High Silicon Chromium Bearing Cast Iron (HSCBCI).** When using high silicon cast iron anodes, specify the chromium-bearing alloy. The chromium-bearing alloy of similar silicon and other alloy content was developed to help prevent premature deterioration of high silicon cast iron in environments containing chloride.

1.3.1 **Specifications.** The nominal composition and typical mechanical and physical properties of HSCBCI are as shown in Tables 4 and 5:

Table 4
HSCBCI Anode Composition

Element	Percent
Silicon	14.35 min
Chromium	4.5
Carbon	0.95
Manganese	0.75
Iron	Remainder

Being a metal HSCBCI has much greater mechanical strength than nonmetals such as graphite magnetite. However, due to its low elongation under load it is brittle and should be protected from both mechanical and thermal shock.

Table 5 **Physical Properties of HSCBCI Anodes**	
Tensile Strength	15,000 PSI
Compressive Strength	100,000 PSI
Hardness	520 Brinell
Specific Gravity	7
Melting Point	2,300 Degrees F
Specific Resistance	72 micro ohms/cu cm
Coefficient of Expansion per degree F	7.33 micro inches per inch

1.3.2 **Available sizes.** HSCBCI anodes are available in a wide variety of standard sizes and shapes. Tables 6 and 7 provide examples of sizes of solid rod and tubular HSCBCI anodes. Manufacturers can provide material catalogs with detailed anode information and also provide the same information on their company internet websites. The weights indicated are for the bare anodes only and do not include the weight of the lead wire or connection, or prepackaged backfill. Special configurations can be produced at extra cost and are usually practical when standard anodes have been shown to be unsatisfactory for a particular application and where a large number of special configuration anodes are required. In most case, however, commercially available sizes are specified.

The anode sizes and shapes in Tables 6 and 7 are the most commonly used anodes in DoD applications. In addition to solid rod and tubular anode configurations, HSCBCI anodes are also available in button, bullet, and other shapes and sizes of anodes, where needed for particular applications. Refer to manufacturers' brochures for more specific information.

1.3.3 **Anode Lead Wire Connection.** The maximum acceptable resistance between the cable and the anode should be 0.01 ohms. The cable to anode connection is critical, as in the case of all impressed current anodes. Two common methods of achieving the cable to anode connection and seal are shown in Figures 2 through 4.

The solid rod anodes shown in Table 6 had been commonly used in the past. Lead wire connections at the end of the anode often resulted in a higher rate of consumption, or "necking", at that end of the anode that resulted in premature loss of lead wire connection. To help prevent the necking of the anode at the connection point, select anodes that were manufactured with an enlarged end if solid rods are to be specified. In addition, specify external epoxy encapsulation as shown in Figure 3 to help reduce the necking of the anode. The tubular anodes listed in Table 7 with the lead wire connected in the center of the anode are now preferred over solid rod anodes as these help reduce the chance of premature failure due to necking. Figures 4 and 5 are illustrative examples of tubular anodes.

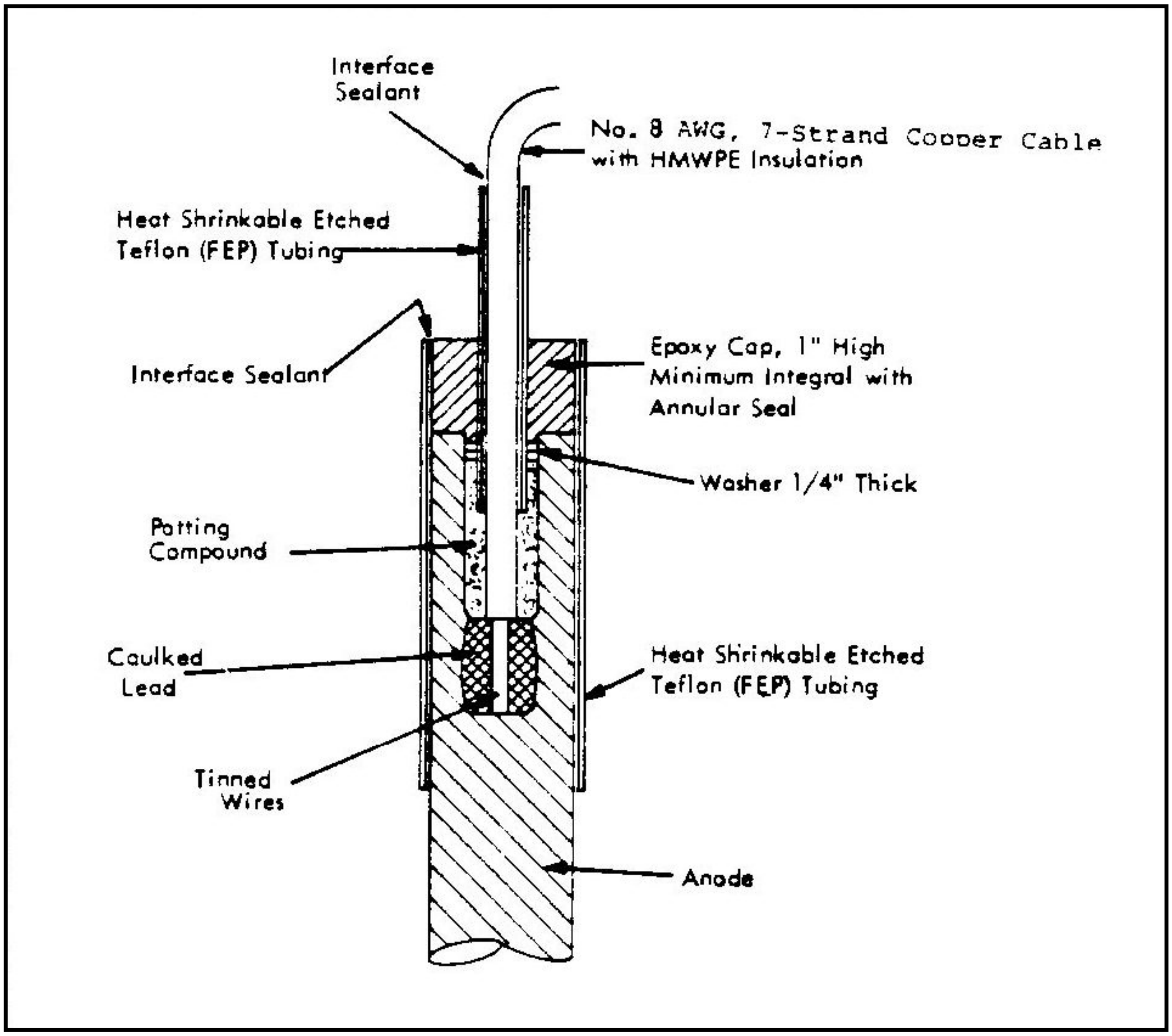

Figure 2
Anode to cable connection – Teflon seal.

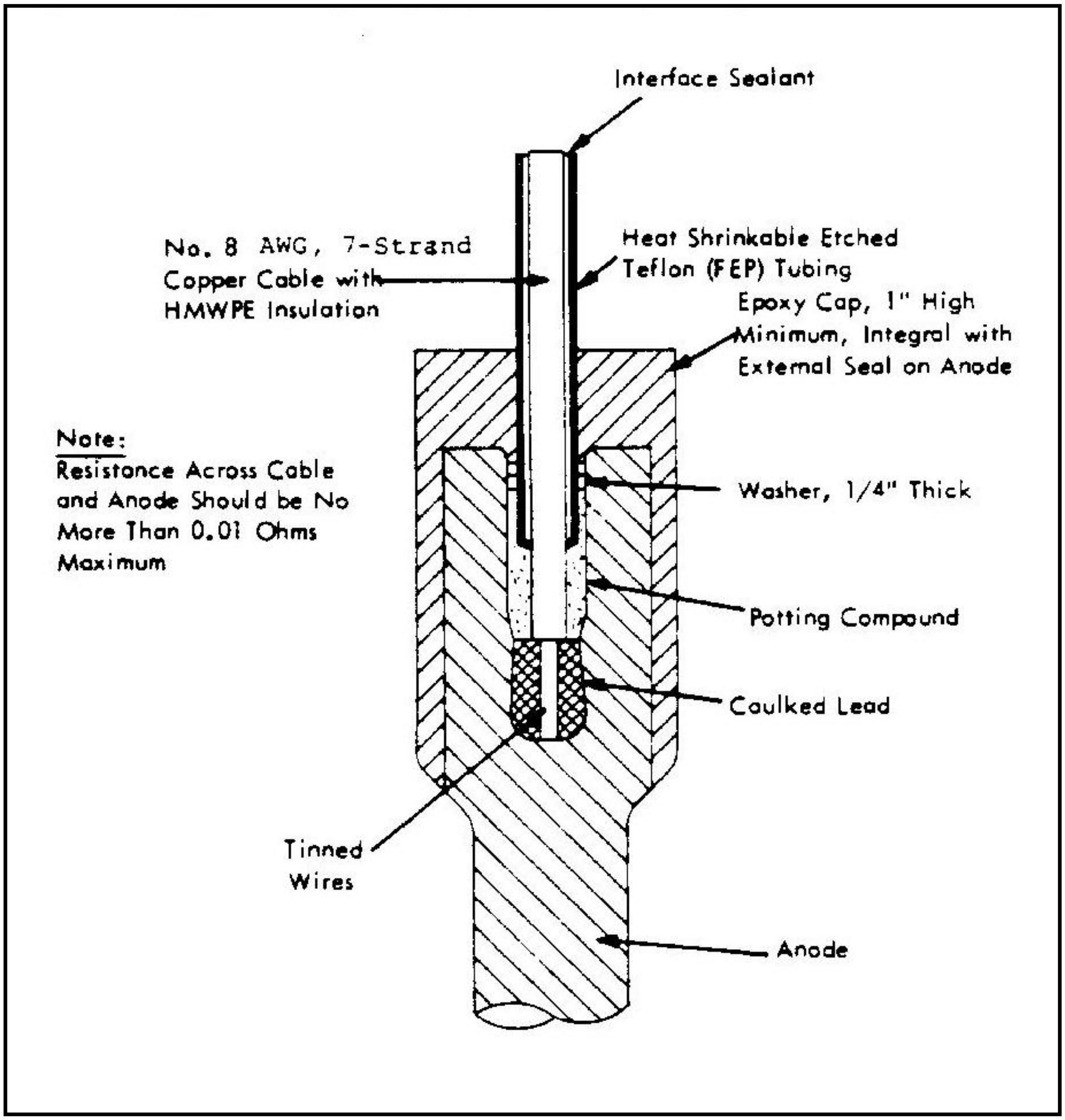

Figure 3
Anode to cable connection – Epoxy seal.

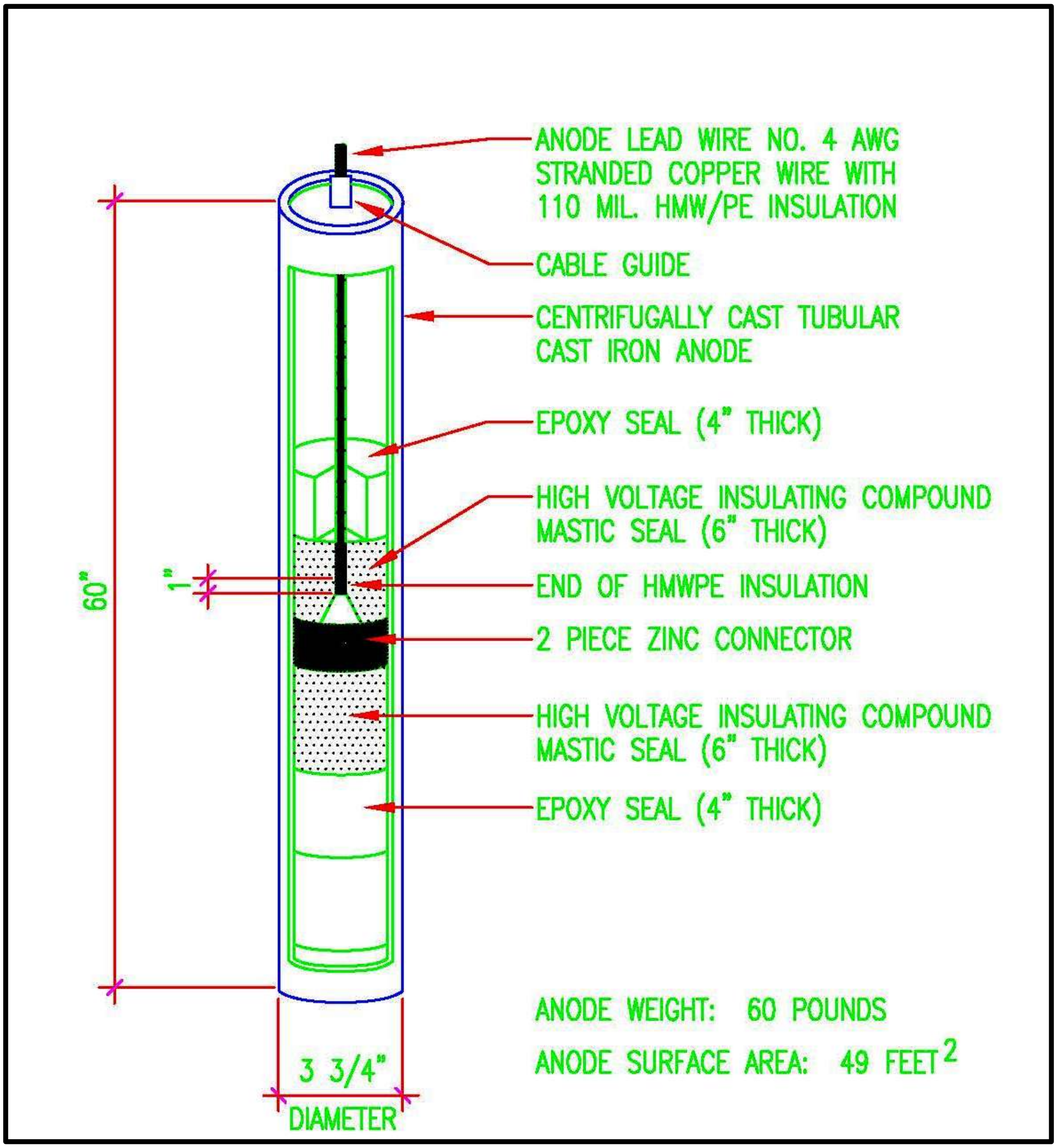

Figure 4
Anode to cable center connection

1.3.4 **Operation.** HSCBCI anodes are consumed at a rate of about one (1) pound per ampere year when used at a current not exceeding their nominal discharge rates. The potential difference between and steel HSCBCI can be neglected in the selection of impressed current rectifiers. HSCBCI anodes do not require backfill in most applications, but backfill can reduce the anode to electrolyte resistance in many cases and its use should be evaluated based upon a tradeoff between the cost of the backfill and the savings in power associated with the lower circuit resistances and required driving potentials.

Table 6. Examples of Commercially Available HSCBCI Solid Rod Anodes

Nominal Weight* (LB) *(Kg)*	Nominal Dimensions*		
	Diameter (in.) *(mm)*	Length (in.) *(mm)*	Surface area (ft^2) *(m^2)*
1 *(0.5)*	1.13 *(29)*	9 *(229)*	0.2 *(0.02)*
5 *(2.3)*	2 *(51)*	9 *(229)*	0.4 *(0.04)*
25 *(11.4)*	1.5 *(38)*	60 *(1524)*	2.0 *(0.19)*
44 *(20.0)*	2 *(51)*	60 *(1524)*	2.6 *(0.24)*
63 *(28.6)*	2.25 *(57)*	60 *(1524)*	2.8 *(0.26)*
110 *(49.9)*	3 *(76)*	60 *(1524)*	4.0 *(0.37)*

* Note for Table 6: Refer to manufacturers' brochures for more specific information. Metric sizes are soft metric conversions from U.S. standard SI units. Actual metric sizes for materials available in foreign countries may differ.

Table 7. Examples of Commercially Available HSCBCI Tubular Anodes

Nominal Weight* (LB) *(Kg)*	Nominal Dimensions*		
	Diameter (in.) *(mm)*	Length (in.) *(mm)*	Surface area (ft^2) *(m^2)*
4.3 *(1.8)*	2.2 *(56)*	8 *(203)*	0.38 *(0.04)*
6.5 *(2.9)*	2.2 *(56)*	12 *(304)*	0.47 *(0.05)*
23 *(10.4)*	2.2 *(56)*	42 *(1067)*	2.0 *(0.19)*
31 *(14.1)*	2.66 *(67)*	42 *(1067)*	2.4 *(0.22)*
46 *(20.9)*	2.2 *(56)*	84 *(2133)*	4.0 *(0.37)*
63 *(28.6)*	2.66 *(67)*	84 *(2133)*	4.9 *(4.6)*
85 *(38.6)*	3.75 *(95)*	84 *(2133)*	6.9 *(0.64)*
110 *(49.9)*	4.75 *(121)*	84 *(2133)*	8.7 *(0.81)*
175 *(79.4)*	4.75 *(121)*	84 *(2133)*	8.7 *(0.81)*

* Note for Table 7: Refer to manufacturers' brochures for more specific information. Metric sizes are soft metric conversions from U.S. standard SI units. Actual metric sizes for materials available in foreign countries may differ.

Figure 5
Tubular HSCBCI Anodes

1.4 **Aluminum.** Aluminum anodes were sometimes used as impressed current CP system anodes for the protection of the interior of water storage tanks in the past because of their low cost, light weight and the lack of water contamination from the products of deterioration of the anodes. They were commonly used where seasonal icing of the tank would damage the anodes. In this case, the aluminum anodes were sized to last one year and were replaced each spring. HSCBCI and mixed metal oxide anodes are now more commonly used in water tanks.

1.5 **Lead-Silver Alloy.** Lead alloyed with silver, antimony or tin has been used in the past as anodes for impressed current cathodic protection systems in seawater. The chief advantage of these anodes was their low operating cost. The consumption rate for silverized lead is 2 to 3 pounds per ampere year initially but drops off to approximately 0.2 pounds per ampere year after 2 years, as the anode surface develops a passivating film. Alloyed lead anodes have been unreliable in many specific applications either because they failed to passivate, their consumption rate remained in the 2 to 3 pound per ampere year range and they were completely consumed, or they became so highly passivated that the anode to electrolyte resistance increased substantially. When properly operating, the current density from silverized lead anodes is typically 10 amperes per square foot. Because of the environmental concerns with lead, these anodes are no longer used.

1.6 **Platinum.** Pure platinum wire is sometimes used for impressed current cathodic protection anodes where space is limited. Platinum is essentially immune to deterioration in most applications. In seawater its consumption rate at current densities as high as 500 amperes per square foot is 0.00001 pound per ampere year. Due to the high cost of platinum, this material is more commonly used as a thin coating on other metals.

1.7 **Platinized anodes.** Platinum can be bonded or deposited on other materials for use as an impressed current cathodic protection anode. The substrate materials, namely titanium, tantalum and niobium have the special characteristic of being covered with a naturally formed stable oxide film that prevents current flow from their surfaces, even when exposed to high anodic potentials. These “platinized” anodes, although high in initial unit cost, can be used at very high current densities and have had wide application to service in tanks and other liquid handling systems as well as in seawater. Their use in soils has been primarily for deep well applications. Since the thin film of platinum material is what corrodes as current flows, the platinized anodes are known as dimensionally stable anodes since no noticeable change in the anode dimension will occur as the platinum coating corrodes. This is contrast with other bulk anodes such as graphite and HSCBCI where significant changes in anode dimensions occur as the anodes corrode during operation.

1.7.1 **Types.** Platinized anodes are available in a wide variety of sizes and shapes as shown below. Table 8 provides examples of platinized niobium wire anode configurations used for impressed current anodes in water storage and processing vessels. Manufacturers can provide material catalogs with detailed anode information and also provide the same information on their company Internet websites. An example of a platinized anode configuration is shown in Figure 6.

Table 8. Examples of Commercially Available Platinized Niobium Wire Anodes

Wire Diameter **(in.)** ***(mm)***	Length	Niobium Thickness **(in.)** ***(mm)***	Platinum Thickness **(μ-in.)** ***(μ-M)***
(0.063) *(1.6)*	As required	(0.007) *(0.18)*	(25) *(0.635)*
(0.063) *(1.6)*	As required	(0.007) *(0.18)*	(50) *(1.275)*

* Note for Table 8: Refer to manufacturers’ brochures for more specific information. Metric sizes are soft metric conversions from U.S. standard SI units. Actual metric sizes for materials available in foreign countries may differ.

Platinized niobium/titanium probe type anodes are also available for use in steel vessels such as condenser water boxes and heat exchangers where the interior is difficult to access and its space limited. Such anodes are often mounted through the vessel shell, with the anode part of the probe extending into the vessel, and wire connections made to the probe on the exterior of the vessel. Table 9 provides examples of platinized niobium wire anode configurations used for impressed current anodes in water storage and processing vessels. Manufacturers can provide material catalogs with detailed anode information and also provide the same information on their company internet websites.

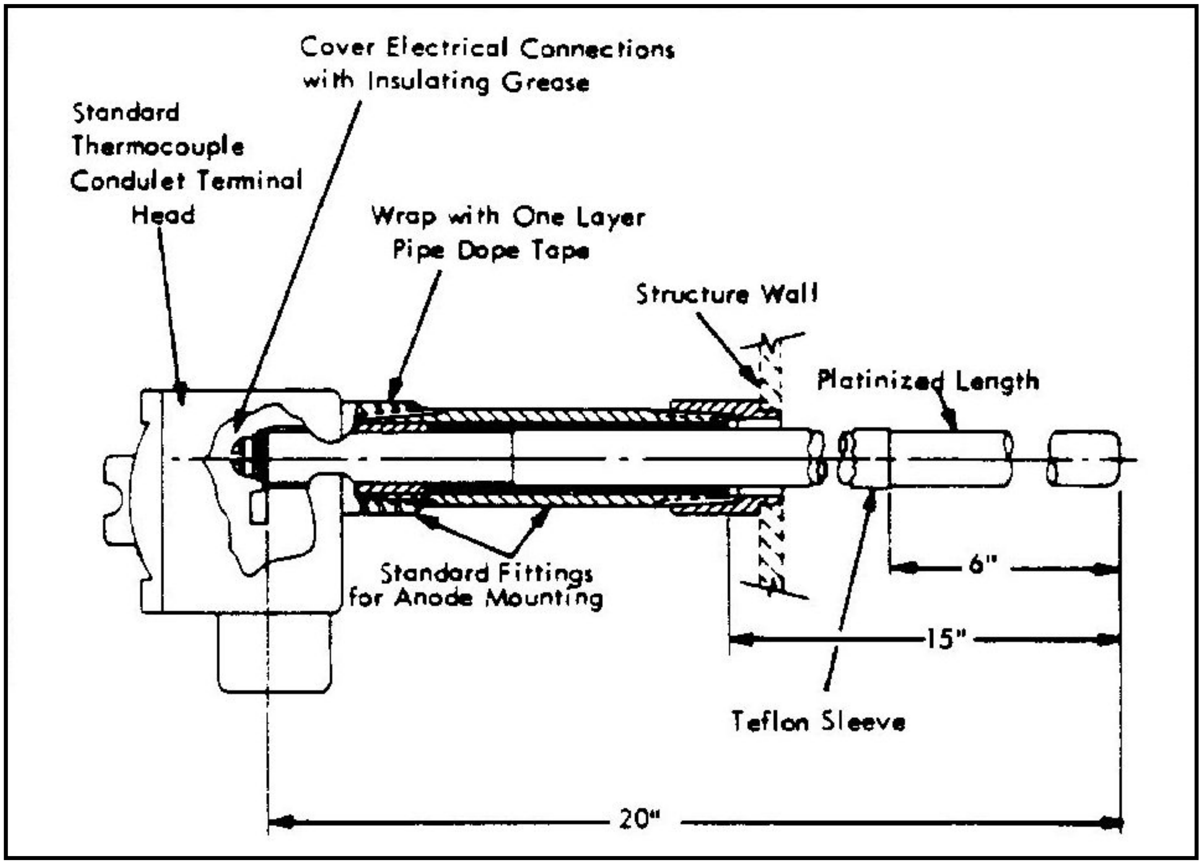

Figure 6
Example platinized anode configuration

Table 9. Examples of Commercially Available Platinized Niobium/Titanium Probe Anodes		
Anode Diameter **(in.)** ***(mm)***	Pipe Nipple NPT **(in.)** ***(mm)***	Platinum Thickness **(μ-in.)** ***(μ-M)***
(0.25) *(6.4)*	(1.0) *(25.4)*	(50 - 300) *(1.27 – 7.62)*
(0.50) *(12.7)*	(1.0) *(25.4)*	
(0.75) *(19.1)*	(1.0) *(25.4)*	

* Note for Table 9: Refer to manufacturers' brochures for more specific information. Metric sizes are soft metric conversions from U.S. standard SI units. Actual metric sizes for materials available in foreign countries may differ.

1.7.2 **Operation.** Platinized anodes can be operated at very high current densities. 100 Amperes per square foot are typical. All of the current flows from the platinum coated portion of the anode surface. However, if this coating is damaged, current may also flow from the substrate material resulting in its premature failure. The primary limitation of platinized anodes is that the oxide film on the substrate can break down if excessive anode-to-electrolyte voltages are encountered. The practical limit for platinized titanium is 12 volts. Platinized niobium can be used at potentials as high as 100 volts.

1.8 Mixed Metal Oxide and Ceramic Anodes.

1.8.1 **Types.** Mixed metal oxide (MMO) and ceramic anodes are available in a variety of substrate configurations:

- Solid rod
- Tubular substrates
- Wire
- Ribbon
- Expanded mesh
- Probe

For DOD applications, Solid rod, tubular, and wire type anodes are commonly used where bulk anodes such as HSCBCI and graphite are used. As the cost of these anodes have decreased, these anodes are now preferred in many applications over their bulk anode predecessors. Their smaller dimensions and lower weights can reduce and simplify CP system installation. There generally higher current density capacities can often result in installation of less anodes that their bulk anode counterparts. Probe anodes are used in water storage and processing vessels. Wire, ribbon, and mesh anodes are used in CP systems installed to protect the exterior bottoms of on-grade storage tanks with a secondary containment liner because of limited space between the tank bottom and the containment liner. Ribbon and mesh anodes are most often the anode configurations of choice for CP systems installed to protect the reinforcing steel in concrete.

Tables 10 through 13 provide examples of commercially available MMO/ceramic anode configurations. Manufacturers can provide material catalogs with detailed anode information and also provide the same information on their company Internet websites. Figures 7 through 9 illustrate some examples of MMO anodes.

Table 10. Examples of Commercially Available MMO Solid Rod Anodes[1]				
Nominal Dimensions[1,2]		Nominal Weight[1,2,3]		Current Rating (Amperes)[4]
Diameter **(in.)** ***(mm)***	Length **(ft.)** ***(mm)***	Bare Weight **(oz/ft)** ***(g/M)***	Packaged Wt **(LB)** ***(Kg)***	
0.125 *(3.18)*	4 *(101.6)*	0.38 *(35.6)*	22 *(10)*	7.0
0.125 *(3.18)*	8 *(203.2)*	0.38 *(35.6)*	44 *(20)*	14.0
0.25 *(6.35)*	4 *(101.6)*	1.5 *(43.4)*	22 *(10)*	15.0
0.25 *(6.35)*	8 *(203.2)*	1.5 *(43.4)*	44 *(20)*	30.0
0.50 *(12.7)*	4 *(101.6)*	6.1 *(173.8)*	23 *(10.5)*	29.0
0.50 *(12.7)*	8 *(203.2)*	6.1 *(173.8)*	46 *(21)*	58.0

Notes for Table 10.
1. Refer to manufacturers' brochures for more specific information.
2. Metric sizes are soft metric conversions from U.S. standard SI units. Actual metric sizes for materials available in foreign countries may differ.
3. Mixed metal oxide rod anodes can be ordered either bare or pre-packaged in coke backfill.
4. Current rating based on a 15 year design life in seawater.

Table 11. Examples of Commercially Available MMO Tubular Anodes[1]				
Nominal Dimensions[1,2]		Nominal Weight[1,2,3]		Current Rating (Amperes)[4]
Diameter **(in.)** ***(mm)***	Length **(ft.)** ***(mm)***	Bare Weight **(oz/ft)** ***(g/M)***	Packaged Wt **(LB)** ***(Kg)***	
0.75 *(19.1)*	2.0 *(610)*	3.4 *(314)*	23 *(10.5)*	23
0.75 *(19.1)*	4.0 *(1219)*	3.4 *(314)*	25 *(11.4)*	45
1.0 *(25.4)*	3.3 *(1006)*	3.8 *(351)*	25 *(11.4)*	50
1.25 *(31.8)*	4.0 *(1219)*	5.8 *(538)*	27 *(12.3)*	73

Notes for Table 12.
1. Refer to manufacturers' brochures for more specific information.
2. Metric sizes are soft metric conversions from U.S. standard SI units. Actual metric sizes for materials available in foreign countries may differ.
3. Mixed metal oxide tubular anodes can be ordered either bare or pre-packaged in coke backfill.
4. Current rating based on a 15 year design life in seawater.

Table 12. Examples of Commercially Available MMO Ribbon Anode Components[1]			
Component	Nominal Dimensions[1,2]		Nominal Bare Weight **(LB/ft)** ***(Kg/M)***
	Width **(in.)** ***(mm)***	Thickness **(in.)** ***(mm)***	
Ribbon Anode	0.25 *(6.4)*	0.025 *(0.6)*	6 LB/500 ft *(2.7 Kg/152 M)*
Ribbon Anode	0.5 *(12.7)*	0.025 *(0.6)*	10 LB/500 ft *(3.0 Kg/152 M)*
Conductor Bar	0.5 *(12.7)*	0.040 *(1.0)*	4 LB/100 ft *(0.07 Kg/M)*

Notes for Table 12.

1. Refer to manufacturers' brochures for more specific information.
2. Metric sizes are soft metric conversions from U.S. standard SI units. Actual metric sizes for materials available in foreign countries may differ.

Table 13. Examples of Commercially Available MMO Ribbon Anode Components[1]				
Component	Nominal Dimensions[1,2]			Nominal Bare Weight **(LB/ft)** ***(Kg/M)***
	Width **(in.)** ***(mm)***	Profile **(in.)** ***(mm)***	Length **(in.)** ***(mm)***	
Mesh Strip	2.5 *(63.5)*	0.125 *(3.2)*	24 *(7.3)*	6 LB/500 ft *(2.7 Kg/152 M)*
Conductor Bar	0.5 *(12.7)*	0.040 *(1.0)*	250 *(76.2)*	4 LB/100 ft *(0.07 Kg/M)*

Notes for Table 13.

1. Refer to manufacturers' brochures for more specific information.
2. Metric sizes are soft metric conversions from U.S. standard SI units. Actual metric sizes for materials available in foreign countries may differ.

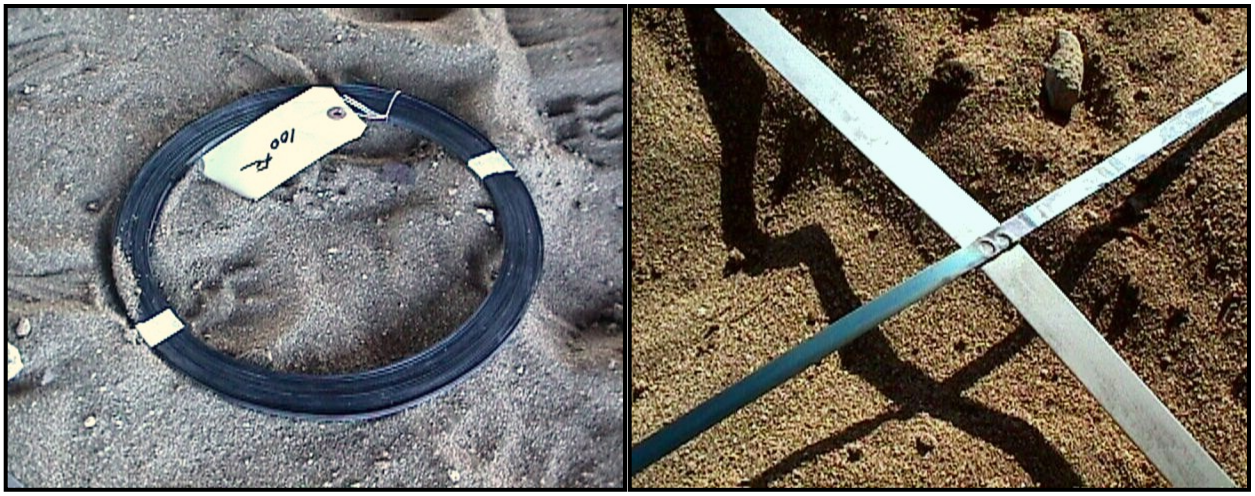

Figure 7
Roll of MMO Ribbon Anode (left). MMO Ribbon installed (right). Thinner metal strip is the MMO anode.

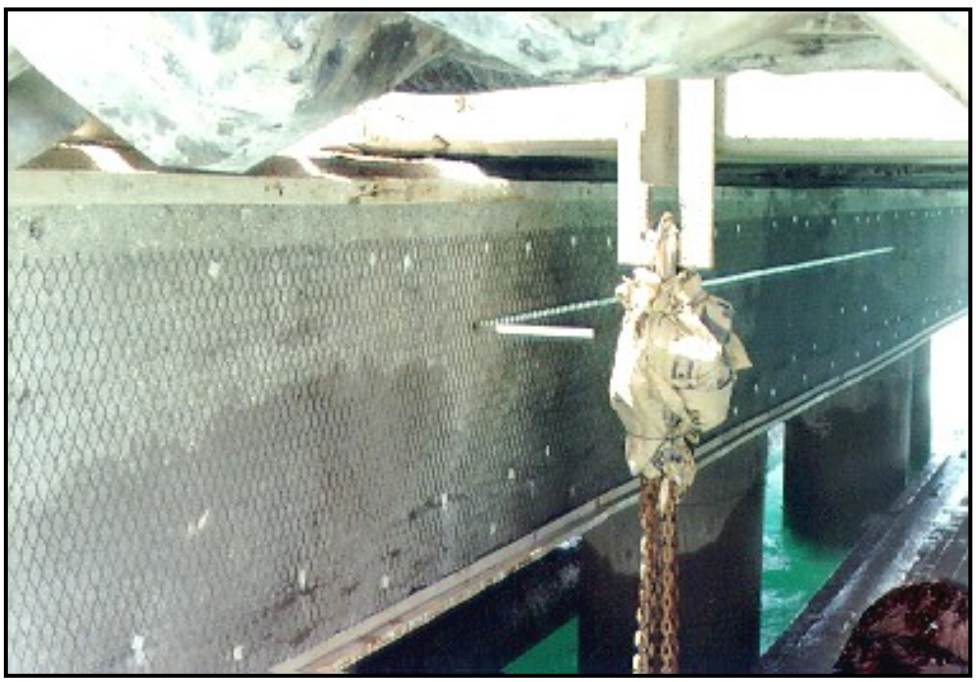

Figure 8
Mixed Metal Oxide Mesh Anode installed on a concrete beam.

Figure 9
Mixed Metal Oxide tubular anode.

1.9 **Anode Backfill.** For nearly all underground installations, a special carbon backfill, referred to in the industry as coke breeze, is provided in the anode hole or well. Some of the reasons for using this special backfill include

- Lower anode ground bed resistance, hence, resulting in lower rectifier design voltages and reduced probability of stray current interference.
- Improved current distribution along the anode since the backfill will provide a generally uniform environment. Helps avoid premature anode failure.Prolonged anode life since the carbon backfill is also consumed instead of anode.Backfill will help maintain the stability of the anode hole or well.Backfill will provide a permeable medium for migration of gases, thereby avoiding premature increase in anode bed resistance.

1.9.1 **Specifying the Type of Backfill.** Ensure that the appropriate type of backfill is specified and provided. Generally, calcined petroleum coke, or coke that has been heated to remove high resistivity petroleum by-products, should be specified. The calcined petroleum coke has a lower total bulk resistivity, and its more spherical particles aids in the compaction of the backfill (Figure 10). Also, specify backfill that has a carbon content greater than 92%, preferably greater than 99%, for greater anode system life.

Figure 10
Petroleum coke backfill

2.0 POWER SUPPLY SELECTION

2.1 **Determination of Power Supply Requirements.** The power supply requirements, namely current and voltage are determined by ohms law from the required current for protection of the structure and the calculated or measured total circuit resistance.

2.2 **Selection of Power Supply Type.** Any source of direct current of appropriate voltage and current can be used as a source of power for impressed current cathodic protection systems. The selection of the power supply depends upon local conditions at the site and should be evaluated based upon economics, availability of AC power or fuel, and the availability of maintenance.

2.2.1 **Transformer-Rectifiers.** Transformer-rectifiers, or more simply, rectifiers, are by far the most commonly used power supply type for impressed current cathodic protection systems. They are available in a wide variety of types and capacities specifically designed and constructed for use in impressed current cathodic protection systems. The most commonly used type of rectifier has an adjustable step down transformer, rectifying units (stacks), meters, circuit breakers, lightning arresters, current measuring shunts, and transformer adjusting points (taps), all in one case.

2.2.2 **Thermoelectric generators.** These power supplies convert heat directly into direct current electricity. This is accomplished through a series of thermocouples that is heated at one end by burning a fuel and cooled at the other, usually by cooling fins. Thermoelectric generators are highly reliable as they have few, if any moving parts. They are available in sizes from 5 to 500 watts. They are very expensive and should only be considered for remote locations where electrical power is not available and fuel is available. They are used as a power supply for impressed current cathodic protection on remote pipelines where the product in the pipeline can be used as a fuel.

2.2.3 **Solar Power.** For solar powered systems, solar cells convert sunlight directly into direct current electricity. Their cost per watt is high but is decreasing as solar cell technology is improved. Solar panels are used for cathodic protection power supplies at remote sites where neither electrical power nor fuel is available. In order to supply current continuously, solar cells are used in a system that both supplies power to the CP system and also recharges a set of batteries when sunlight is received (Figure 11). When sunlight is not being received, the batteries supply the required current. Security must be considered with solar power systems as many of the solar powered systems have been damaged by vandalism and theft. Environmental and safety considerations must include procurement, maintenance and disposal of battery electrolytes, usually acids.

2.2.4 **Batteries.** When current requirements are low, storage batteries can be used to supply power for impressed current cathodic protection systems at remote sites. They must be periodically recharged and maintained. Again, environmental and safety considerations must include procurement, maintenance and disposal of battery electrolytes, usually acids.

Figure 11
Solar powered CP system. Solar panels shown in picture on the left. Battery bank and control center shown in picture on the right.

2.2.5 **Generators.** Engine or wind driven generators can also be used to supply direct current power for impressed current cathodic protection systems at sites where AC power is not available.

3.0 RECTIFIER SELECTION.

Since most CP systems are powered by rectifiers, the rest of this section will concentrate on the procedures for selecting rectifiers. The rectifier selected for a specific impressed current cathodic protection application must be matched to both the electrical requirements and the environmental conditions at the site. Rectifiers are available in many electrical types and specifically designed for use in impressed current cathodic protection systems in many environments.

3.1 **Rectifier Components.** Figure 1-12 is a circuit diagram for a typical single phase full wave bridge type rectifier having the components found in most standard rectifiers of this type. The diagram also shows an external switch and circuit protection device that is recommended for all rectifier installations to conform with the requirements of the National Electrical Code.

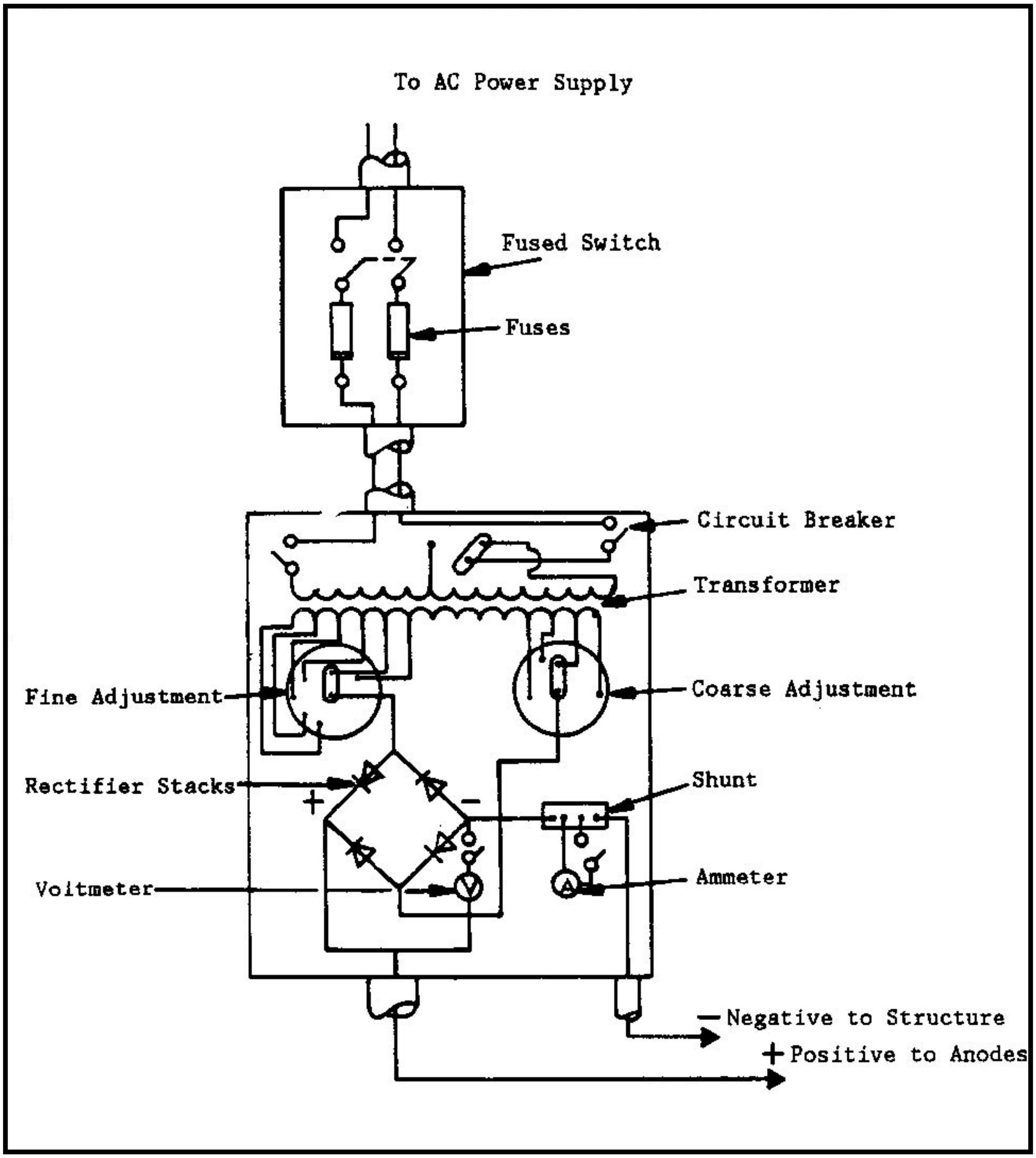

Figure 12
Single Phase, Full-Wave Bridge Rectifier

3.1.1 **Transformer Component.** The transformer reduces the incoming alternating current (AC) voltage to the alternating current voltage required for the operation of the rectifier component. The incoming alternating current is applied to one coil (primary winding) wound on an iron core. The magnetic field produced by the flow of current through the primary winding induces an alternating current voltage in a second coil (secondary winding) that is also wound on the same iron core. The ratio of voltage between the primary and secondary winding equals the ratio of turns in each coil. In most impressed current cathodic protection rectifiers, the voltage output from the secondary windings can be varied by changing the effective number of secondary windings through a system of connecting bars or "taps". Two sets of taps are normally present, one for coarse adjustments and one for fine adjustments. By manipulation of these taps, the rectifier direct current (DC) output voltage can be adjusted from zero to its maximum capacity in even steps of not more than 5 percent of the maximum output voltage.

3.1.2 **Rectifying Elements.** The alternating current (AC) from the secondary windings of the transformer element is converted to direct current (DC) by the rectifying elements or "stacks". The stack is an assembly of plates or diodes and may be in several configurations. The most common rectifying elements are selenium plate stacks and silicon diodes. Each has advantages and disadvantages as discussed below. The most common configurations of rectifying elements are the single-phase bridge, single-phase center tap, three-phase bridge and three phase wye. These arrangements are described in detail in section 3.2. The rectifying elements allow current to flow in one direction only and produce a pulsating direct current. The rectifying elements do allow a small amount of alternating current to pass. This "ripple"" is undesirable and should be held to low levels. Rectifiers are not 100% efficient in converting alternating current to direct current. This is due to the presence of alternating current and to inherent losses in the rectifying elements that result in heating of the stacks. Silicon elements are more efficient than selenium elements at high output voltages but are more susceptible to failure due to voltage overloads or surges. The efficiency of a rectifying element is calculated by the following equation:

$$\text{Efficiency (\%)} = \frac{\text{DC output power X 100}}{\text{AC input power}}$$

Typical efficiencies of single phase rectifying elements are in the order of 60 to 75 % but can be increased by filtering the output or by using a three-phase circuit. Selection of appropriate circuit type is discussed in section 3.3. Selection of silicon versus selenium rectifying elements is discussed in detail in section 3.3.8.

3.1.3 **Overload Protection.** Overload protection in the form of circuit breakers, fuses, or both should be used on all impressed current rectifiers. In addition to protecting the circuits from overloads, circuit breakers provide a convenient power switch for the unit. Circuit breakers are most commonly used on the alternating current input to the rectifiers and fuses are most commonly used on the direct current outputs. In addition to circuit breakers and fuses, the rectifier should be furnished with lightning arresters on both the input and output in order to prevent damage from lighting strikes or other short duration power surges. Due to their susceptibility to damage from voltage surges, rectifiers using silicon elements should always be furnished with lightning arresters.

3.1.4 **Meters.** In order to conveniently measure the output current and potential, the rectifier should be furnished with meters for reading these values. The meter should not be continuously operating but should be switched into the circuit as required. This not only protects the meter from electrical damage from surges but, when the meter is read, its movements from zero to a value on the meter can be used to help detect defective meters. Often, one meter and a two-position switch are used to measure both potential and current. Current is usually measured using a millivolt meter connected to an external current shunt. Output voltage and current can also be conveniently measured by the use of portable meters used across the rectifier output and the current shunt.

3.2 Standard Rectifier Types.

3.2.1 **Single Phase - Bridge.** The circuit for this type of rectifier is shown in Figure 12. This type of rectifier is the most commonly used type of rectifier up to an output power of about 1,000 watts. Above 1,000 watts, the extra cost of three phase types is often justified by the increased electrical efficiency of the three phase units. The rectifying unit consists of four elements. If any one of the rectifying elements fails or changes resistance, the other elements usually also fail. Current passes through pairs of the rectifying elements through the external load (structure and anode circuit). The active pair of elements alternates as the polarity of the alternating current reverses while the other pair blocks the flow of current. The result is full wave rectified current as shown in Figure 13.

3.2.2 **Single Phase - Center Tap.** The circuit of a single-phase center tap rectifier is shown in Figure 14. This type of rectifier has only two rectifying elements but produces full wave rectified output. However, as only one-half of the transformer output is applied to the load, the transformer required is considerably heavier and more costly than in single-phase bridge type units. This type of unit is also less sensitive to adjustment than the single-phase bridge type, however it is electrically more efficient.

3.2.3 **Three Phase - Bridge.** The circuit for a three-phase bridge rectifier is shown in Figure 15. The circuit operates like three combined single-phase bridge circuits that share a pair of diodes with one of the other three bridges. There are three secondary windings in the transformer that produce out of phase alternating current that is supplied to each pair of rectifying elements. This out of phase relationship produces a direct current output with less alternating current “ripple” than the single-phase type, typically, only 4.5%. Due to the reduction in alternating current ripple, three-phase bridge rectifiers are more electrically efficient than the single-phase types, and the extra initial cost of the unit is often justified by savings in supplied power, particularly for units of over 1000 watts capacity.

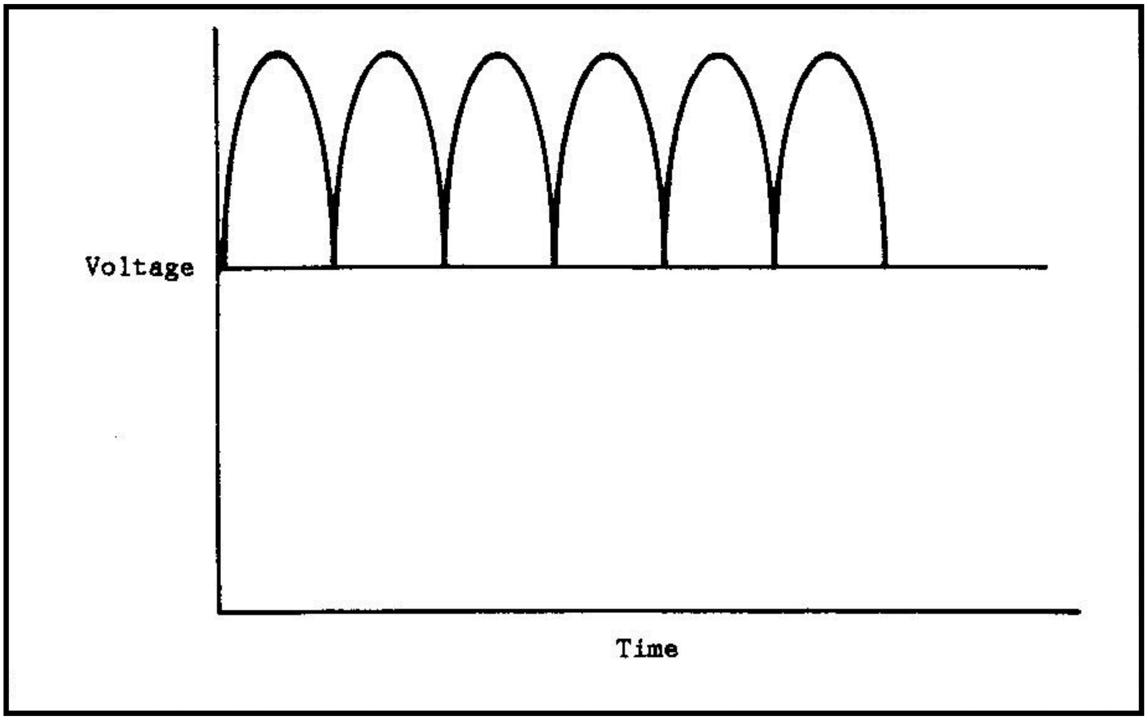

Figure 13
Full-Wave Rectified Current

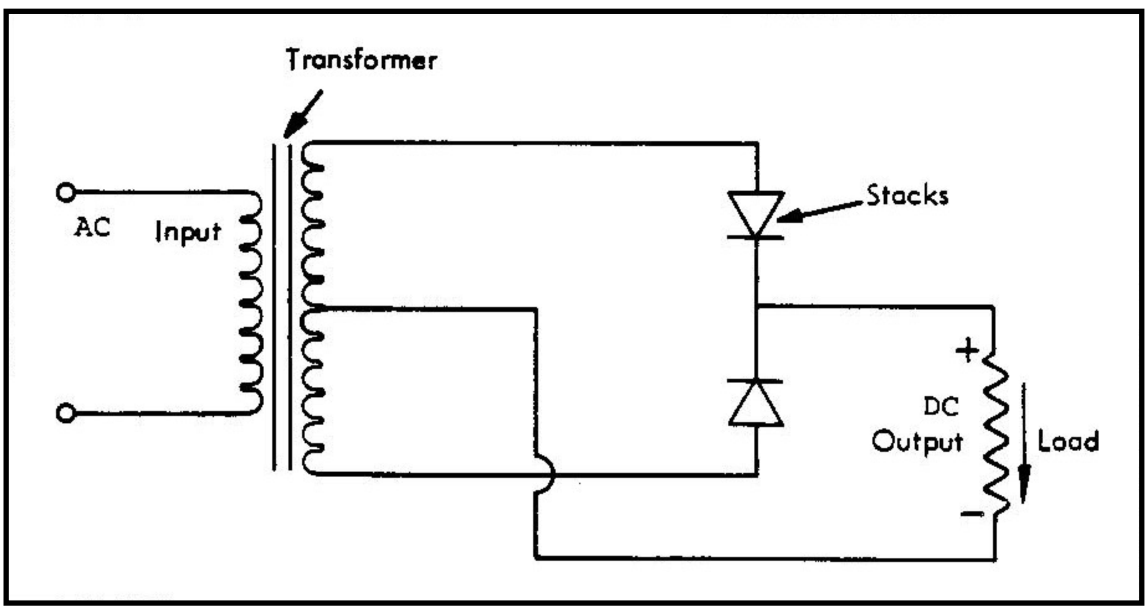

Figure 14
Single-Phase Center-Tap Circuit

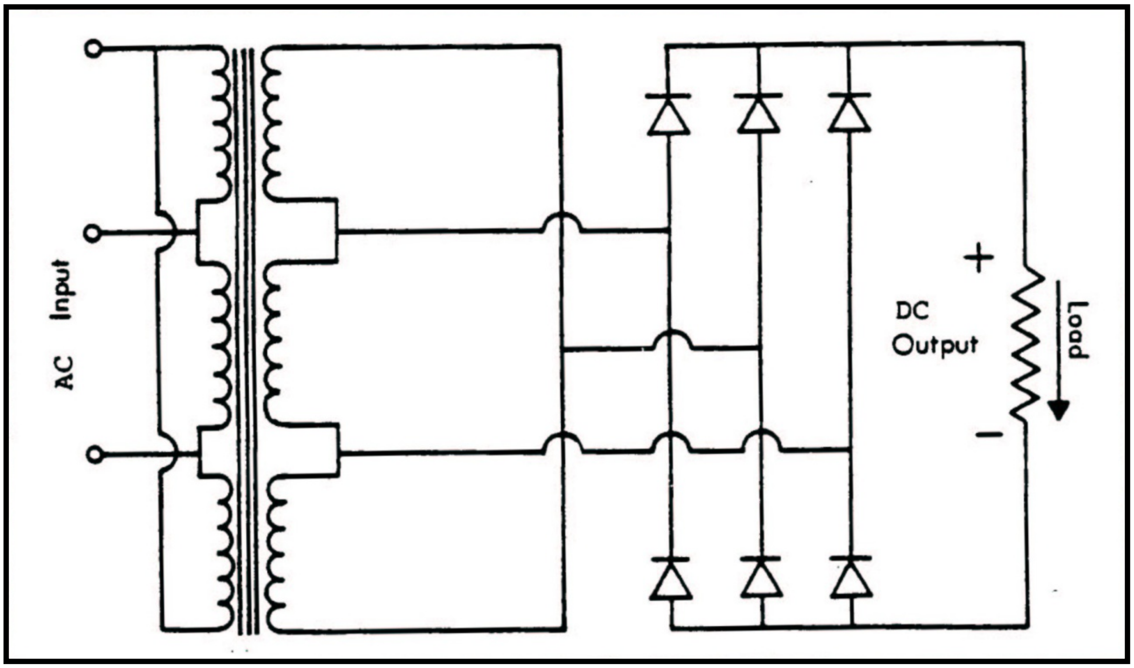

Figure 15
Three-Phase Bridge Circuit

3.2.4 **Three Phase - Wye.** The circuit for a three-phase wye rectifier is shown in Figure 16. This type of rectifier supplies half-wave rectified current as shown in Figure 17. The power to the rectifier unit is supplied by three separate windings on a transformer but only three rectifying elements, each in series with the output, are provided. This type of rectifier unit is practical only for systems requiring low output voltages.

3.2.5 **Special Rectifier Types.** Several special types of rectifiers, specifically designed for use in cathodic protection systems have been developed for special applications. Some special rectifiers provide automatic control of current to maintain a constant structure to electrolyte potential, others provide a constant current over varying external circuit resistances, or other features desirable in specific circumstances.

3.2.5.1 **Constant Current Type.** A block diagram of one type of constant current rectifier is shown in Figure 18. A DC input signal to the power amplifier is supplied from an adjustable resistor in the output circuit. The power amplifier uses this “feedback” signal to adjust the voltage supplied to the stack so that a constant input signal and therefore a constant output current are supplied. The power amplifier may either be of an electronic (silicon controlled rectifier) or saturable reactor type.

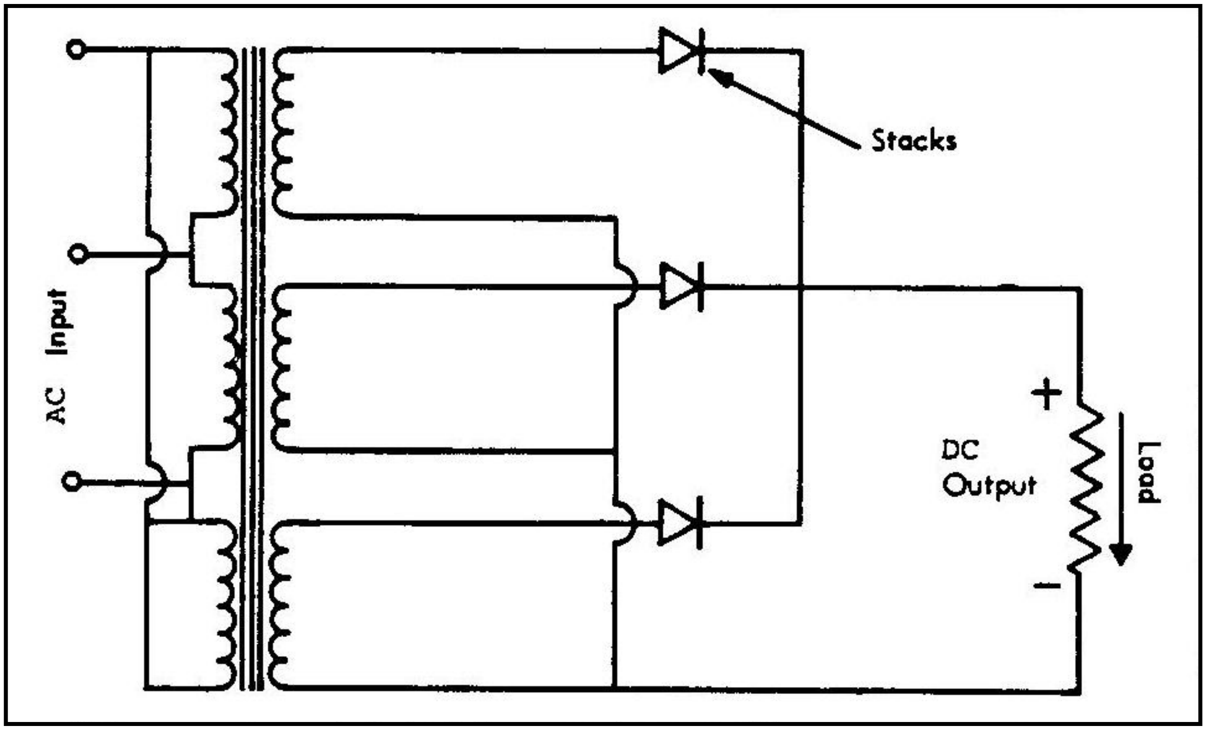

Figure 16
Three-Phase Wye Circuit Schematic

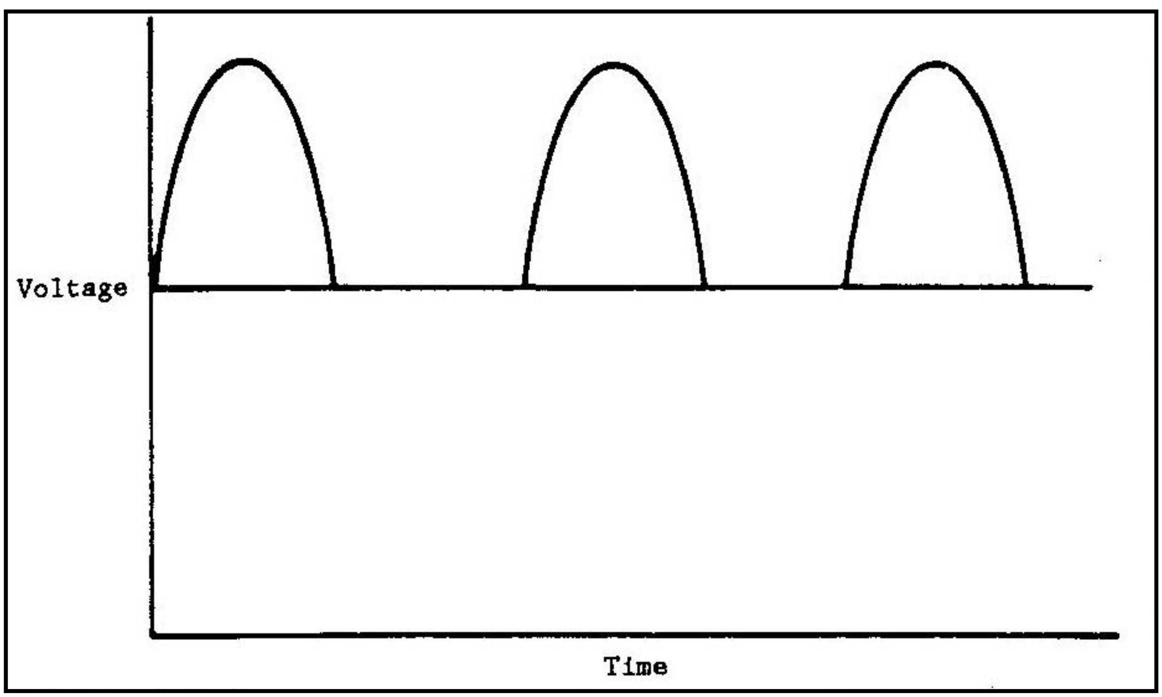

Figure 17
Half-wave rectifier output

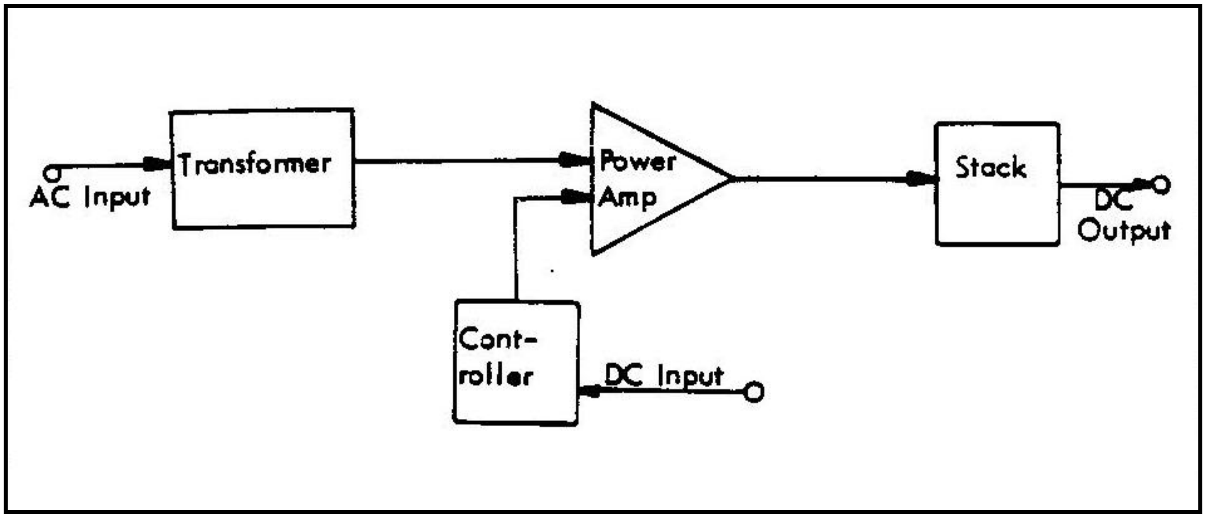

Figure 18
Constant Current Rectifier Block Diagram

3.2.5.2 **Automatic Potential Control Type.** A block diagram for an automatic potential control rectifier is shown in 19. This type of unit uses the potential between the structure and a reference electrode to control the output current of the unit. As in the constant current type of rectifier, the power amplifier can be of the electronic or saturable reactor type. This type of rectifiers are commonly used where the current requirement or circuit resistance varies greatly with time such as in the case of structure in an area with high periodic tidal currents or a water storage tank where the water level changes considerably.

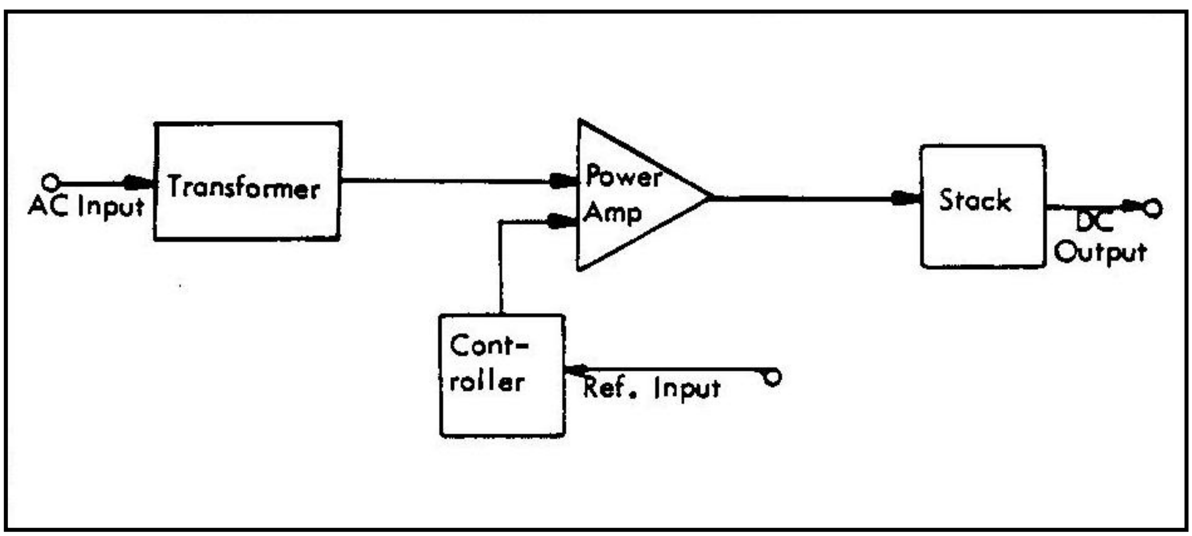

Figure 19
Constant Potential Rectifier Block Diagram

3.2.5.3 **Other Special Types.** Several standardized rectifiers have been developed for commercial applications such as natural gas and electrical distribution system protection. The use of a standardized unit allows for economy of production and reduction in overall cost of the unit as well as the installation and maintenance of the unit. Where a large number of similar capacity units are to be used, consider the selection of a standardized type of rectifier.

3.3 **Rectifier Selection And Specifications.** Rectifiers can either be selected from “stock” units or can be custom manufactured to meet specific electrical and site related requirements. Many features are available either as optional “add ons” to stock units or in custom units.

3.3.1 **Available Features.** Features now available on most units include:

- Constant Potential, Voltage or Current output (automatic)
- Remote Control (adjustment and/or interruption)
- Remote Monitoring
- GPS Syncronizeable interrupter
- Pulse Generator (for wave form analyzer potential surveys)
- Multiple circuits in the same enclosure
- Air cooled or oil immersed
- Any commercial input voltage
- Three Phase or Single Phase
- Center tap or bridge
- Wide range of output currents and voltages
- Efficiency filters to reduce AC ripple
- Interference noise filters
- Explosion proof enclosures
- Small arms proof enclosures
- Lightning protection on both AC input and DC output
- Surge protection on both AC input and DC output
- Silicon diodes or Selenium stacks
- Stainless Steel, Painted or galvanized cases
- Various mounting legs or brackets for floor, wall or pole mounting
- Units designed for direct burial
- External "on - off" indicators
- Variety of Price, Quality and Warranty

Factors that should be considered in selecting appropriate features for a specific application are given below.

3.3.2 **Air Cooled vs. Oil Immersed.** Rectifiers can be supplied as either entirely air-cooled, entirely oil-immersed or with the stacks only oil-immersed (Figures 20 through 22). Air-cooled units are lowest in cost and easiest to install and repair. However, specify oil-cooled units in marine environments, where corrosive or dirty atmospheric conditions are encountered, or where explosive gasses may be present. Air cooled units require more frequent maintenance to clean the air screens and other components and are also susceptible to damage by insects and other pests. Older oil-cooled units were supplied with oils containing Poly-Chlorinated Bisphenyls (PCBs) which have been determined to be carcinogenic and are no longer supplied with new units. Treat units containing PCB's according to current policy regarding PCB's.

Figure 20
Typical Air-cooled Rectifier.

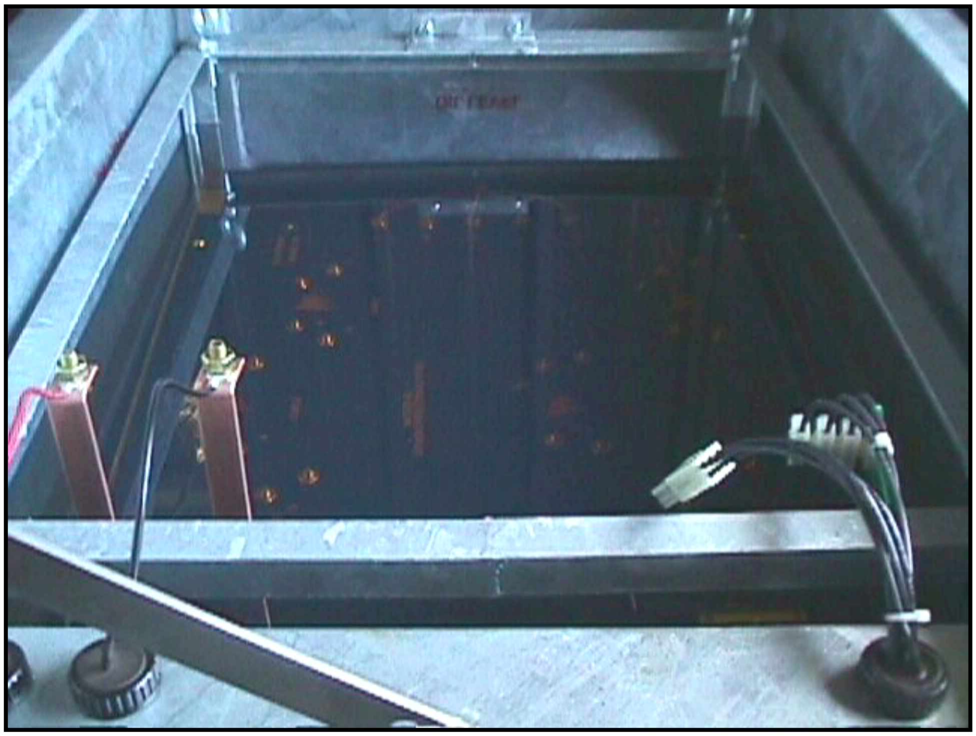

Figure 21
Typical entirely immersed oil-cooled rectifier.

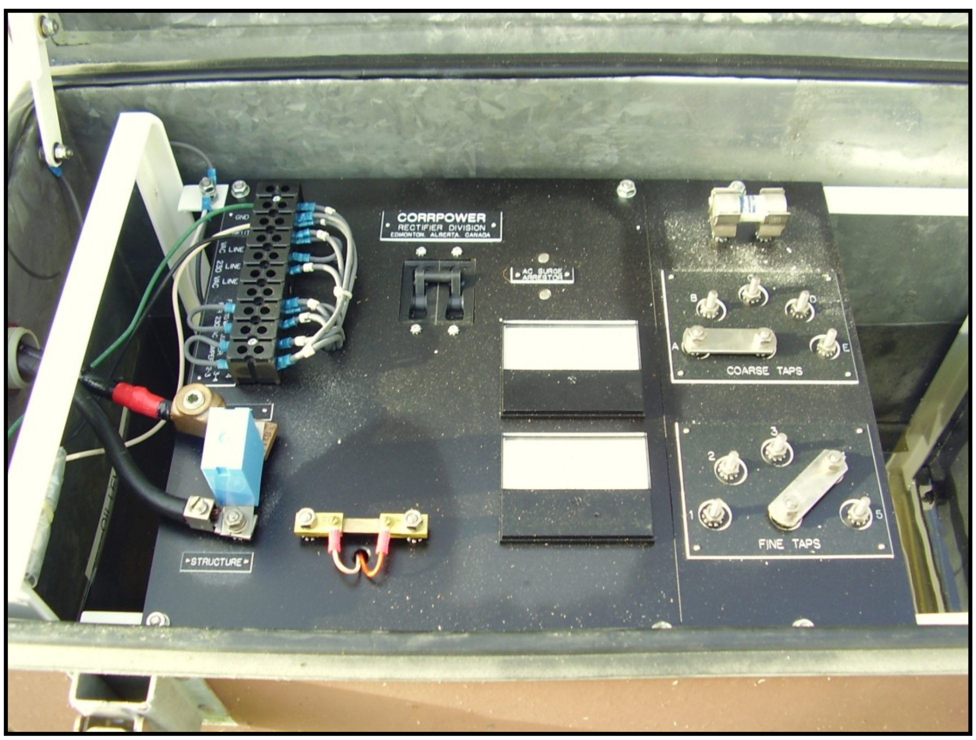

Figure 22
Typical oil-cooled rectifier with only the stacks and transformer immersed.

3.3.3 **Selecting A. C. Voltage.** Alternating current voltages of almost any commercial power supply voltage. Units with 115 volts, 230 volt or 440 volt single phase or 208, 230 or 440 volt three phase inputs are the most common. Some units are supplied with dual input voltage selected by wiring arrangements during installation. Choice between single phase and three phase units should be based upon a balance between first cost and efficiency. The following Table 14 can be used to select the combinations of rectifier capacity and input voltages that are commonly most economical if a selection of supply voltages is available:

Table 14. Rectifier Capacity and Input Voltages

Rectifier DC Rating (Watts)	Single Phase Voltage	Three Phase Voltage
Up to 2,700	115	208
2,700 to 5,400	230	230
5,400 to 7,500	440	230
Over 7,500	440	440

3.3.4 **DC Voltage And Current Output.** Direct current voltage outputs from 8 to 120 volts and current outputs from 4 amperes to 200 amperes are common in any combination. Almost any current can be provided but it is generally best to select a standard size of rectifier unit and use multiple units if very large amounts of current are required.

3.3.5 **Filters.** Electrical filters are used to both increase the efficiency of the rectifier by reducing alternating current ripple and to reduce interference with communications equipment. Efficiency filters can increase the efficiency of single-phase bridge type rectifiers by from 10 to 14 percent and their use should be based upon a first cost versus operating (power) cost basis. Efficiency filters are not commonly used with three-phase rectifiers, as the alternating current ripple in these types of units is inherently low. Use noise interference filters when a large unit is to be installed in the vicinity of communications lines or can be retrofitted when noise problems are encountered and are significantly affected by turning the unit on and off.

3.3.6 **Explosion Proof Rectifiers.** Rectifiers and other system components such as switches and circuit breakers are available in explosion proof enclosures conforming to National Electrical Code (NEC) Safety Standards for Class I, Group D hazardous conditions such as may be encountered in fuel or natural gas storage or distribution systems. Specify such enclosures where required by the NEC or whenever explosive hazards may exist.

3.3.7 **Lightning Arresters.** Lightning arresters should almost always be used on both the AC input and DC output sides of rectifiers using silicon rectifying elements. Their use on units using selenium elements is recommended in areas where lightning strikes are frequent.

3.3.8 **Selenium vs. Silicon Stacks.** While some old installations used copper oxide rectifying elements, modern units use only either silicon or selenium rectifying elements. In general, silicon units are used for larger units where their higher efficiency is more important than their lower reliability.

3.3.8.1 **Selenium Stacks.** Ordinary selenium stacks deteriorate with time. This “aging” can be reduced by variations in plate composition, and “non-aging” stacks are available. Aging rates are determined by operating temperatures that are a function of current flow; thus the selection of a unit using selenium rectifying elements which has a somewhat greater capacity than required will increase stack life. The efficiency of selenium rectifying elements is a function of operating voltage versus rated voltage as shown in Figure 23.

3.3.8.2 **Silicon Diodes.** Silicon diodes are mounted in metal cases that are mounted on either aluminum or copper plates to dissipate the heat generated during operation. Silicon diodes do not age as do selenium stacks and, as shown in Figure 24, is more efficient than selenium elements, particularly at higher voltage ratings. Silicon rectifying elements are more subject to failure from voltage surges that would only cause increased aging of selenium stacks. Surge protection should always be used on both the AC input and DC output of rectifiers using silicon diode rectifying elements.

3.3.9 **Other Options.** Select other available features such as listed in Section 3.3.1 as appropriate. In remote off-base areas, small arms proof enclosures may be required based upon local experience.

3.3.10 **Rectifier Alternating Current Rating.** Determine the AC current requirement for a rectifier based upon rectifier output and efficiency using the following formulae:

3.3.10.1 **Single Phase Rectifiers.**

$$I_{ac} = \frac{E_{dc} \times I_{dc}}{F \times E_{ac}}$$

where:

I_{ac} = Alternating Current Requirement (Amps)
E_{dc} = Direct Current Output Voltage
I_{dc} = Direct Current Output Amperage
F = Rectifier Efficiency %
E_{ac} = Alternating Current Voltage (per phase to ground)

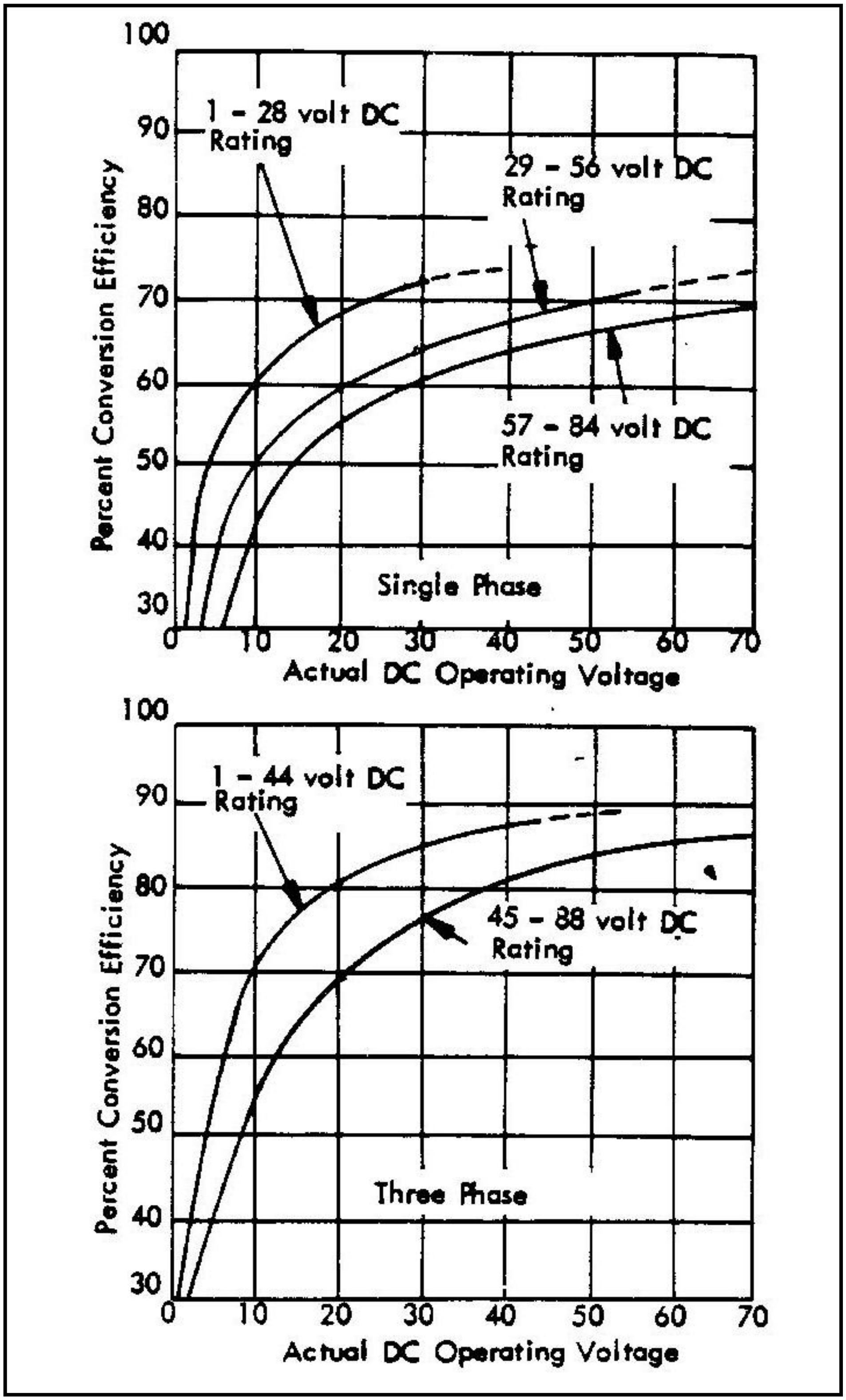

Figure 23
Efficiency versus voltage for selenium stacks

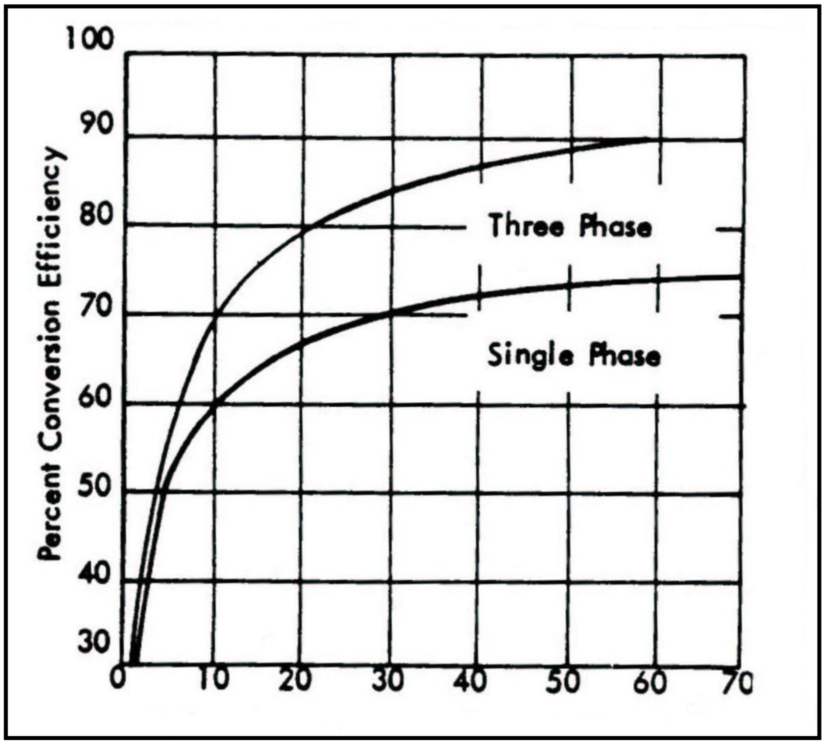

Figure 24
Efficiency versus voltage for silicon stacks

3.3.10.2 **Three Phase Rectifiers.**

$$I_{ac} = \frac{E_{dc} \times I_{dc}}{3 \times F \times E_{ac}}$$

where:

I_{ac} = Alternating Current Requirement (Amps)
E_{dc} = Direct Current Output Voltage
I_{dc} = Direct Current Output Amperage
F = Rectifier Efficiency %
E_{ac} = Alternating Current Voltage (per phase to ground)

4.0 EXAMPLES OF IMPRESSED CURRENT CP INSTALLATIONS.

4.1 **Illustrative Examples of Impressed Current CP Installations.** Figures 25 through 39, illustrate typical impressed current cathodic protection system installations. **Please note that these are NOT standard designs**. Rather, features of these designs may be applicable to the design of similar systems for similar applications but the design for each specific application must be made based upon actual specific conditions and requirements. Section 5.0 gives examples of the design of sample cathodic protection systems.

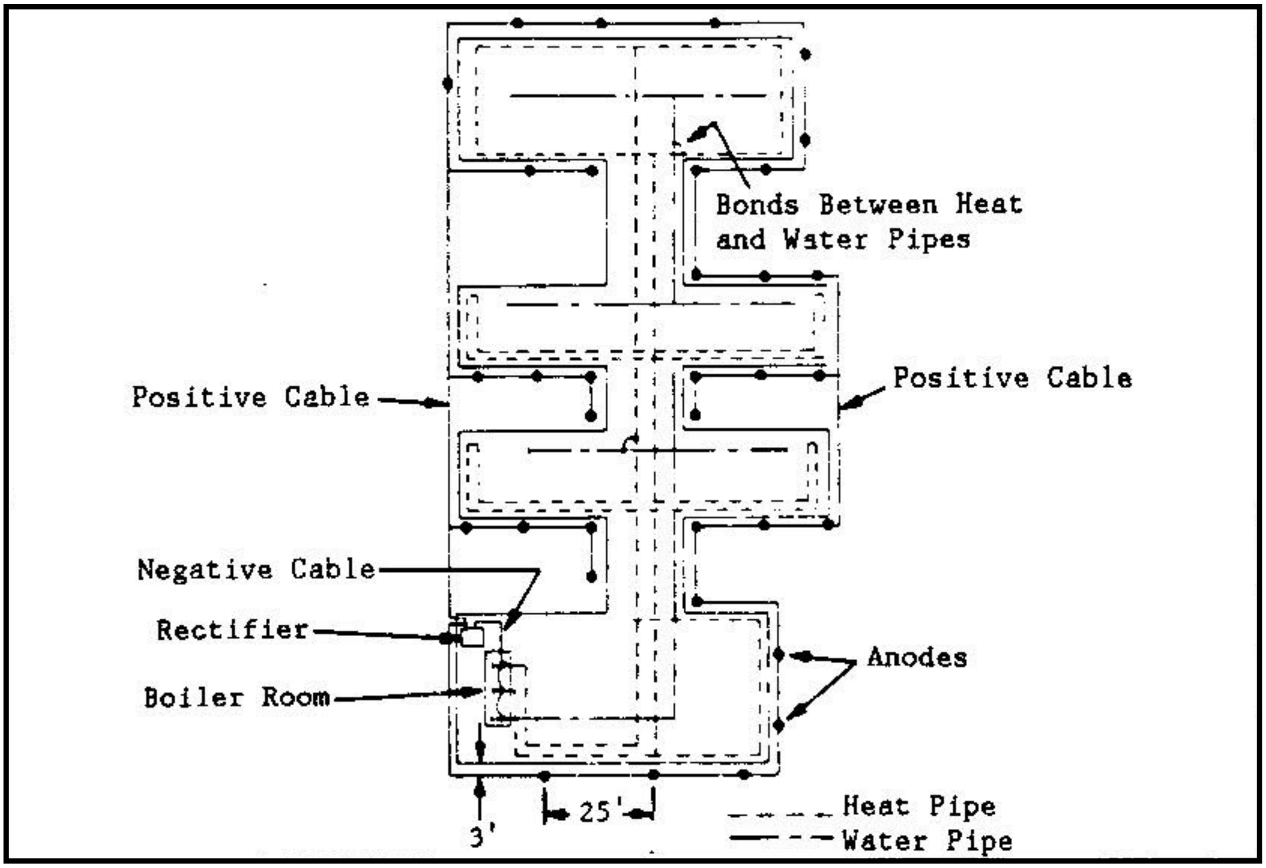

Figure 25
CP for Building Underground Heat and Water Lines

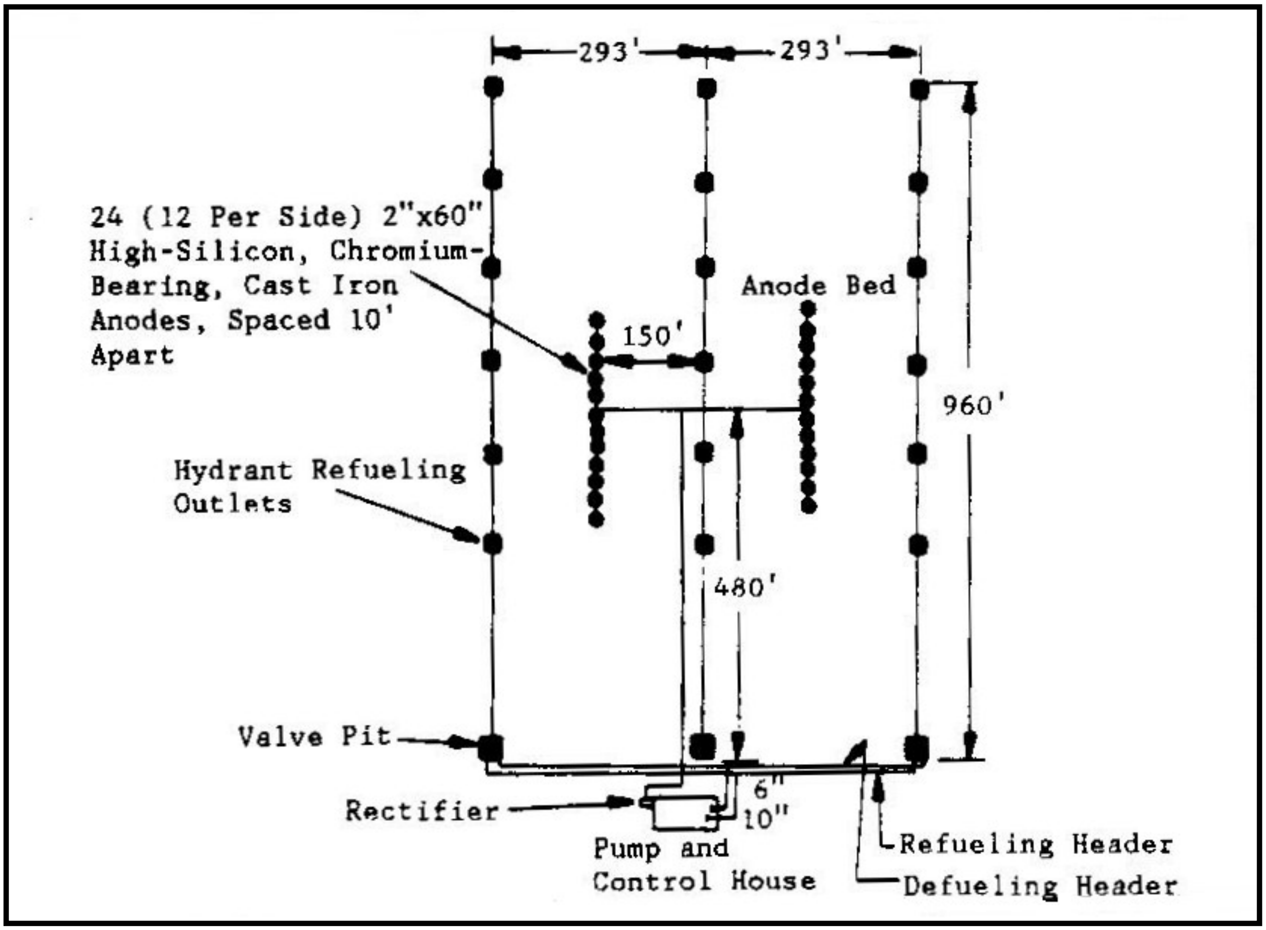

Figure 26
Impressed Current Type CP System for Aircraft Hydrant Refueling System

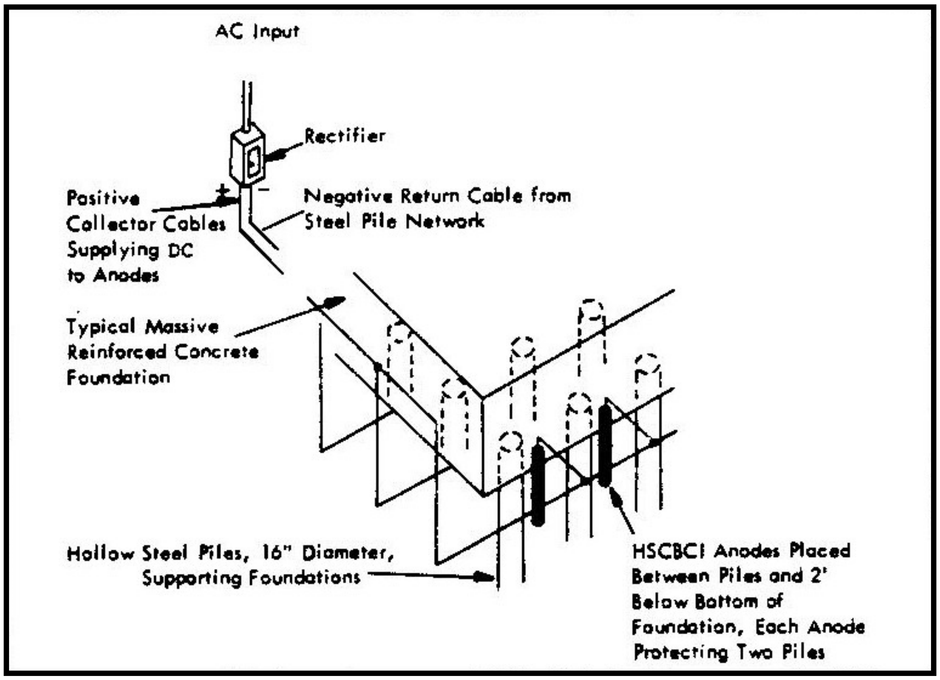

Figure 27
Cathodic Protection of Foundation Piles

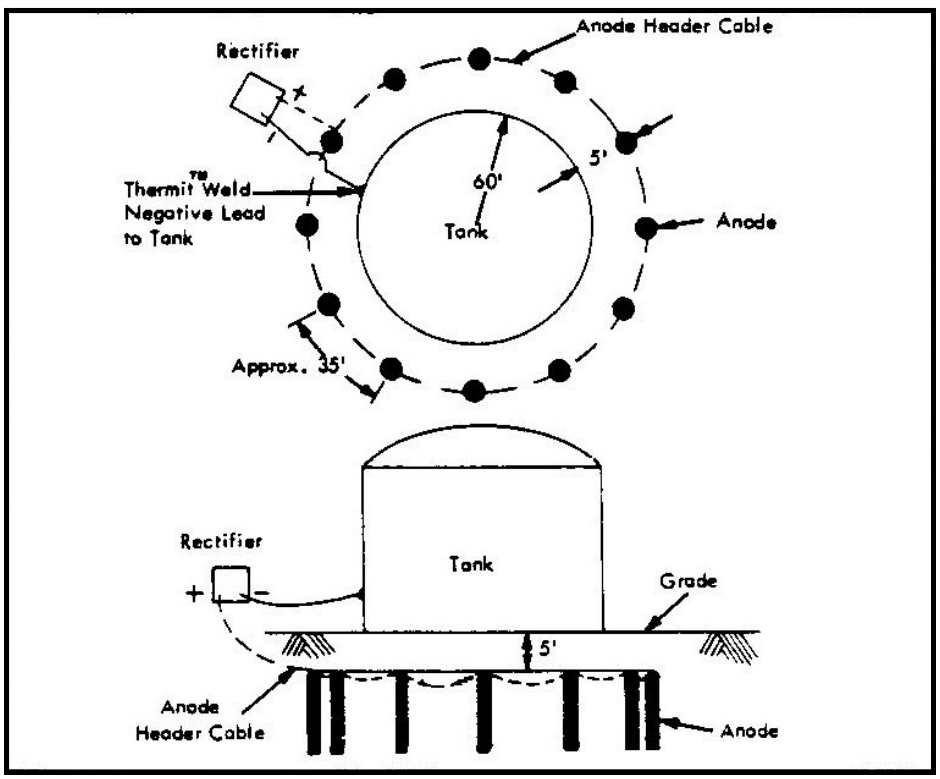

Figure 28
Impressed Current CP for Existing On-Grade Storage Tank

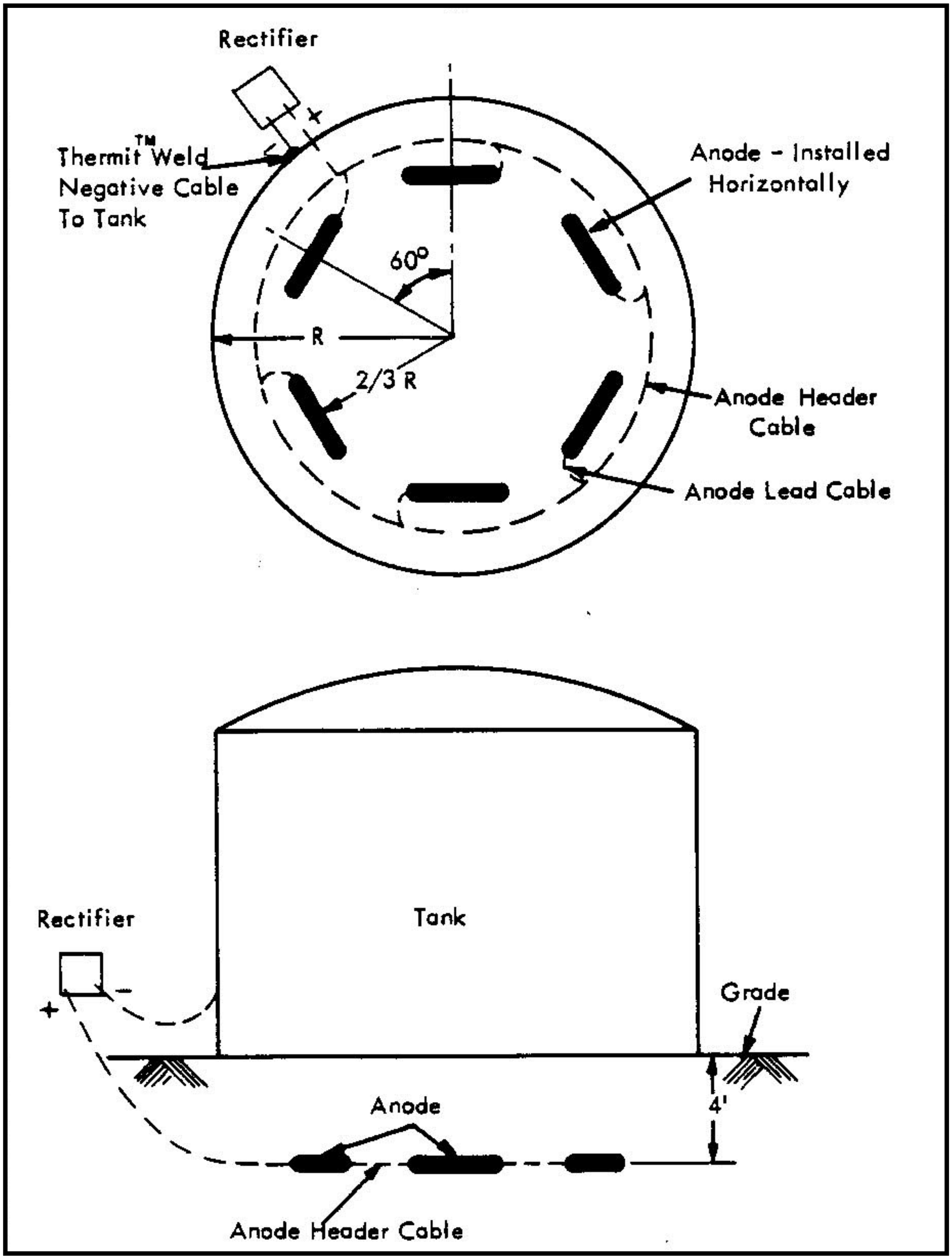

Figure 29
Impressed Current CP with Horizontal Anodes for On-Grade Storage Tank

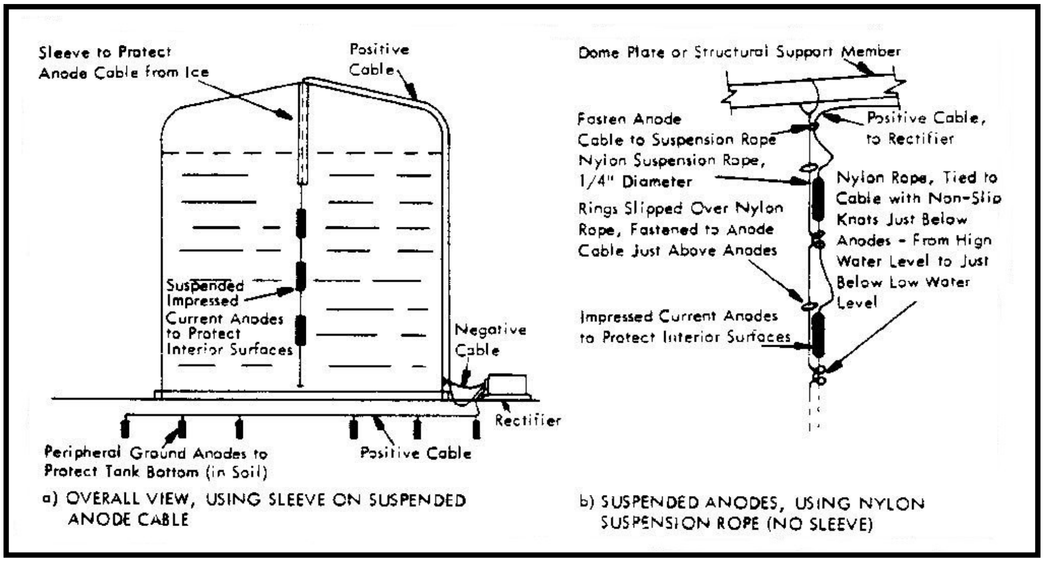

Figure 30
Impressed Current CP for Small Water Tank

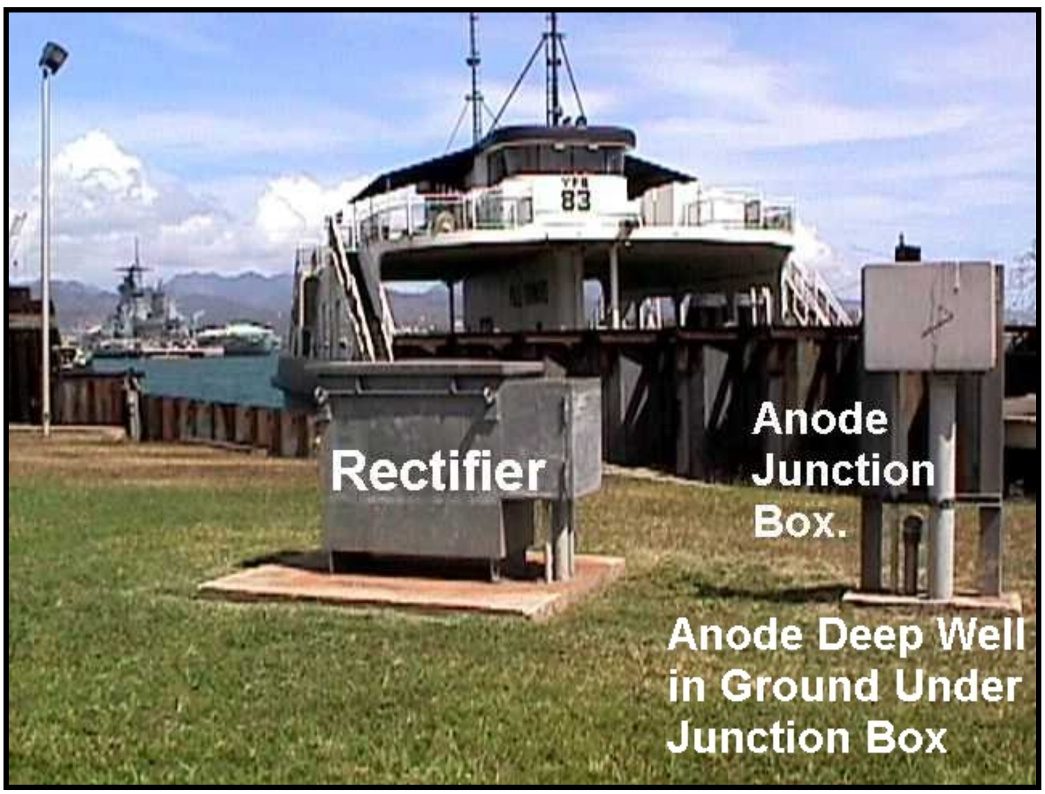

Figure 31
Deep Well Anode Impressed Current CP for Steel Sheet Pile Bulkhead

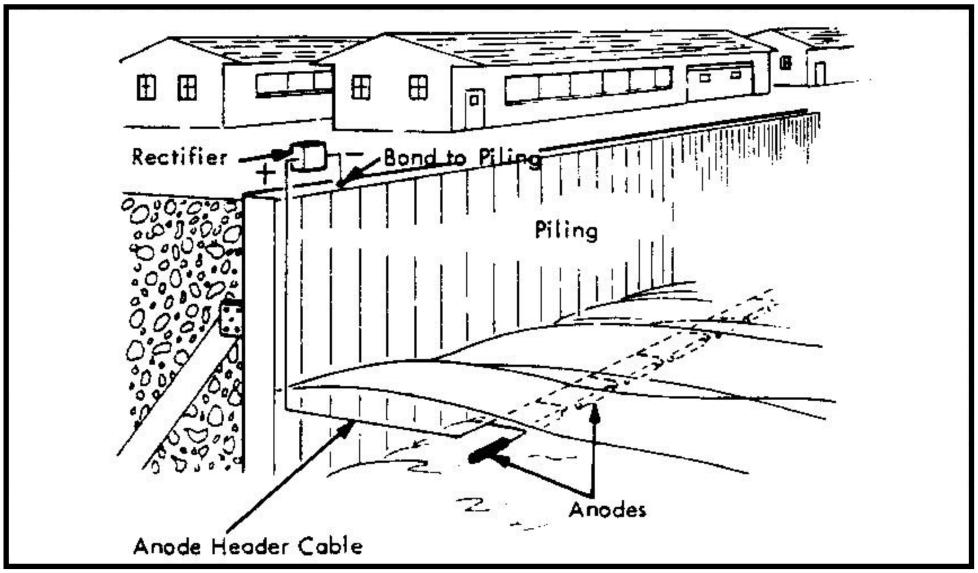

Figure 32
Impressed Current CP with Distributed Anodes for Water Side of a Steel Sheet Pile Bulkhead Wall

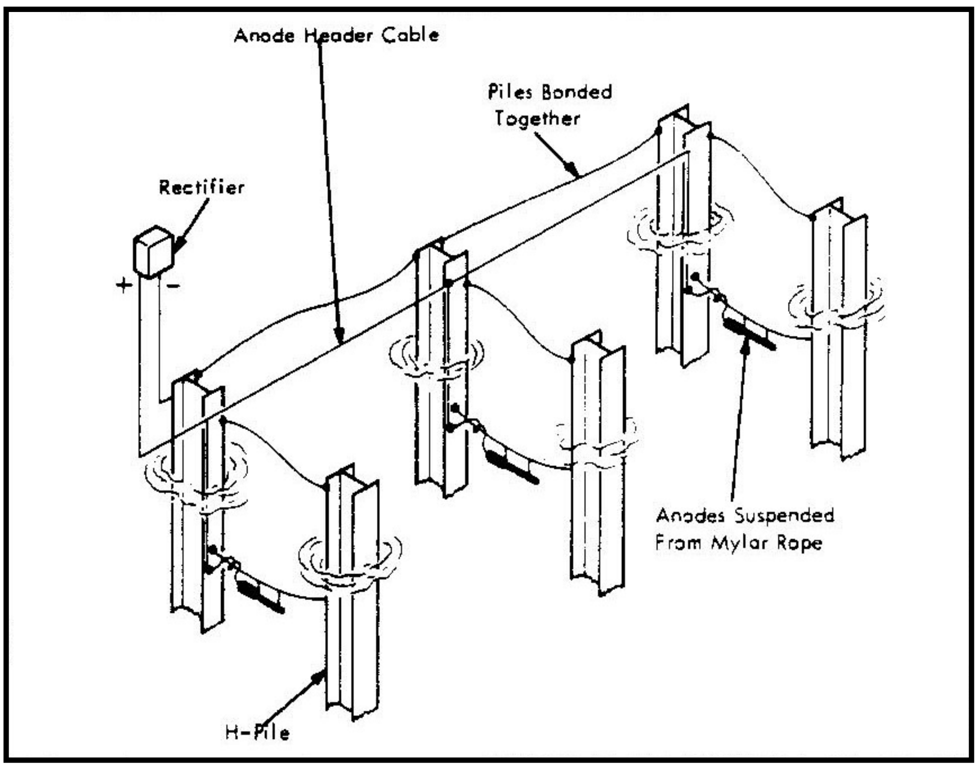

Figure 33
Suspended Anode Impressed Current CP for H-Piling in Seawater

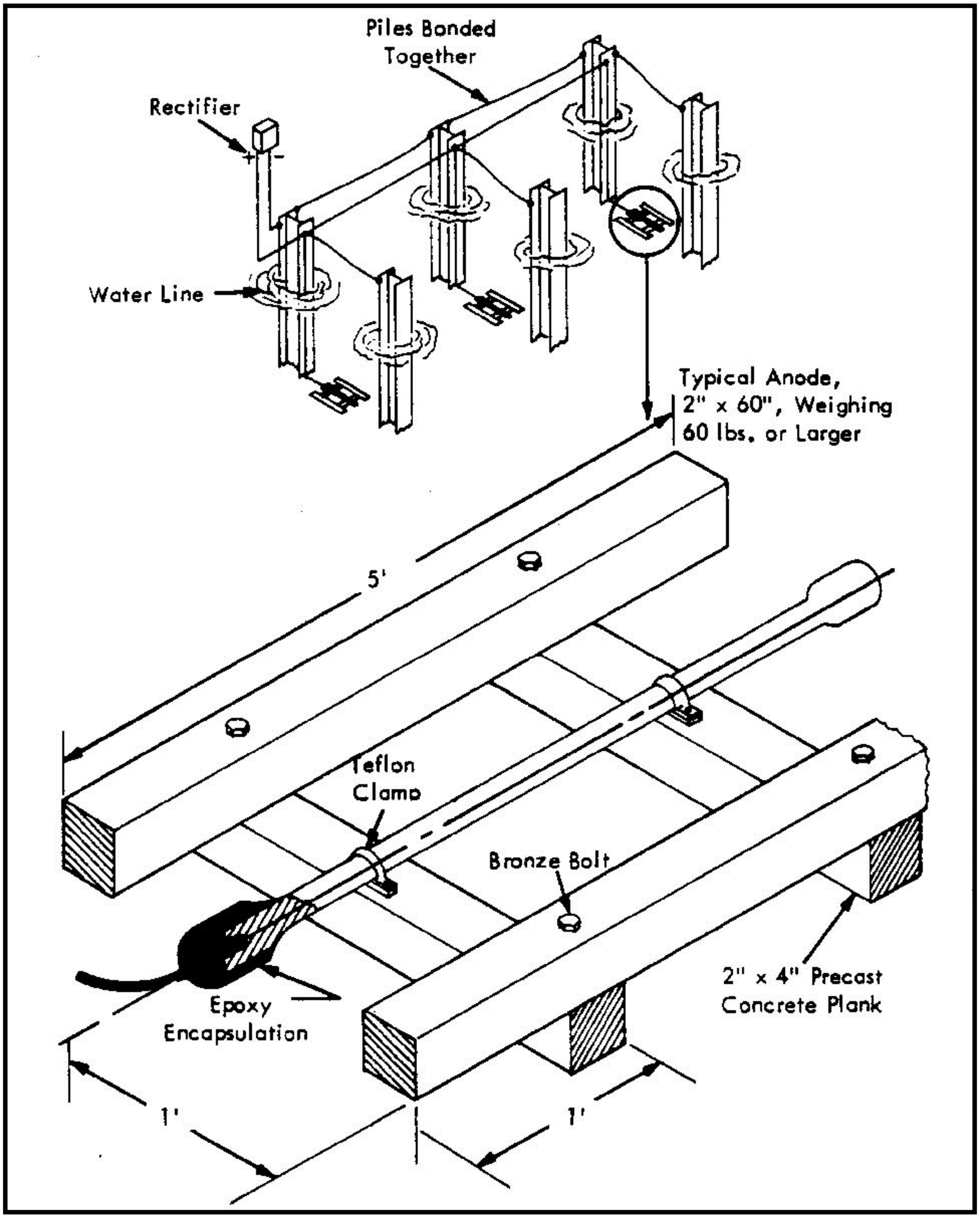

Figure 34
Impressed Current CP Sled Anode for H-Piling in Seawater

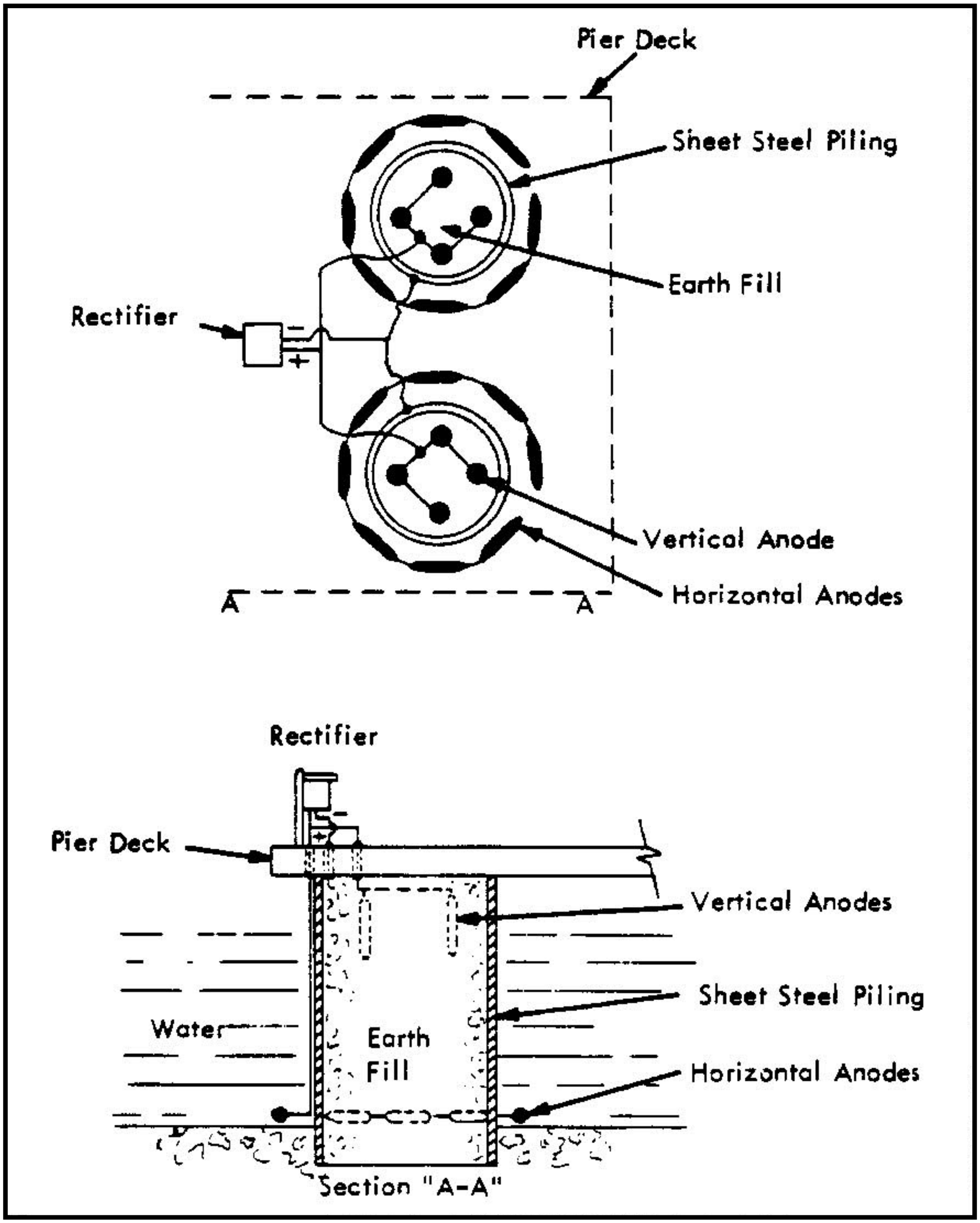

Figure 35
Impressed Current CP for Cellular Earth Fill Pier Supports

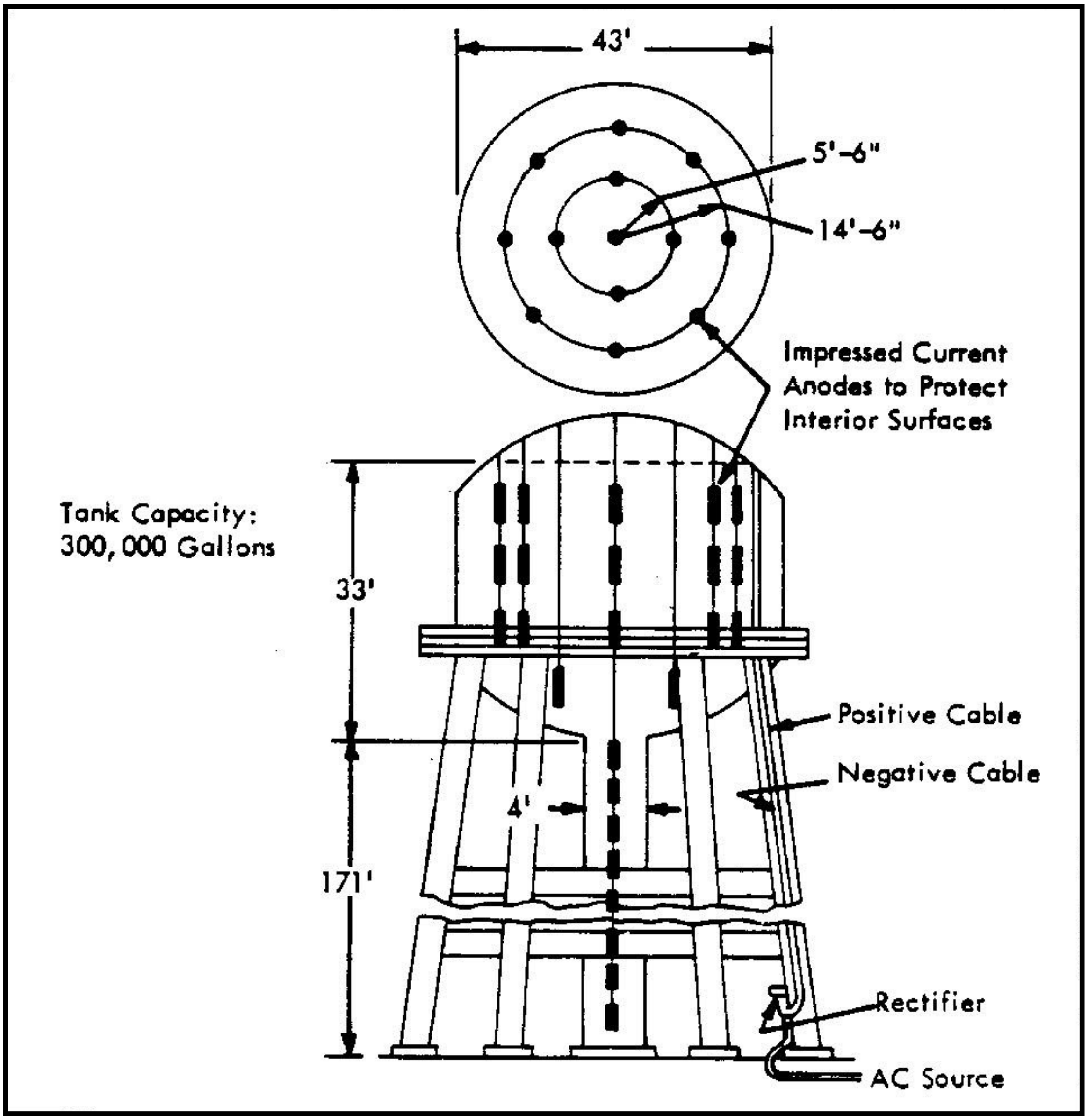

Figure 36
Impressed Current CP for Elevated Water Storage Tank Interior

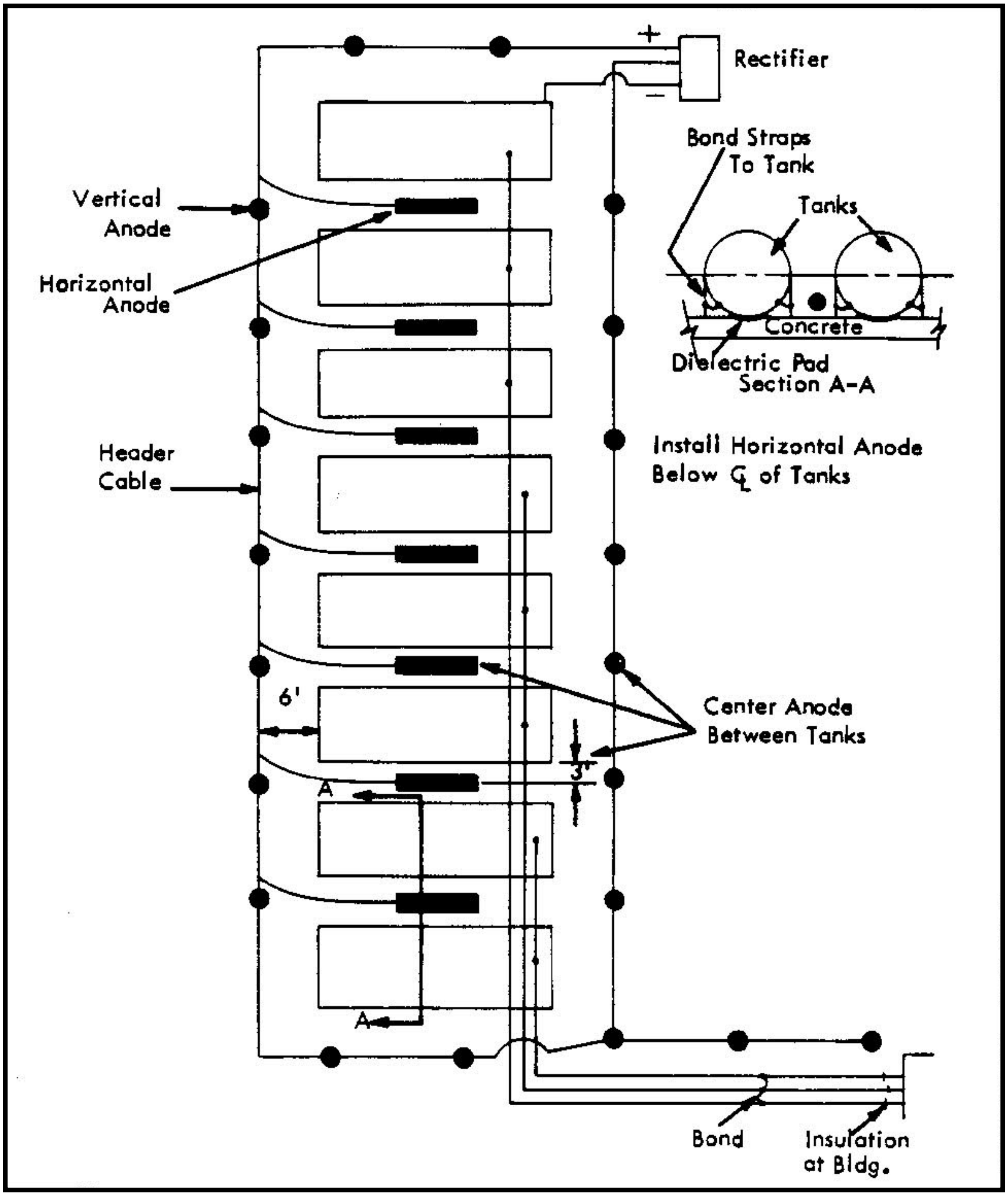

Figure 37
Typical Distributed Anode Impressed Current CP for Underground Storage Tank Farm

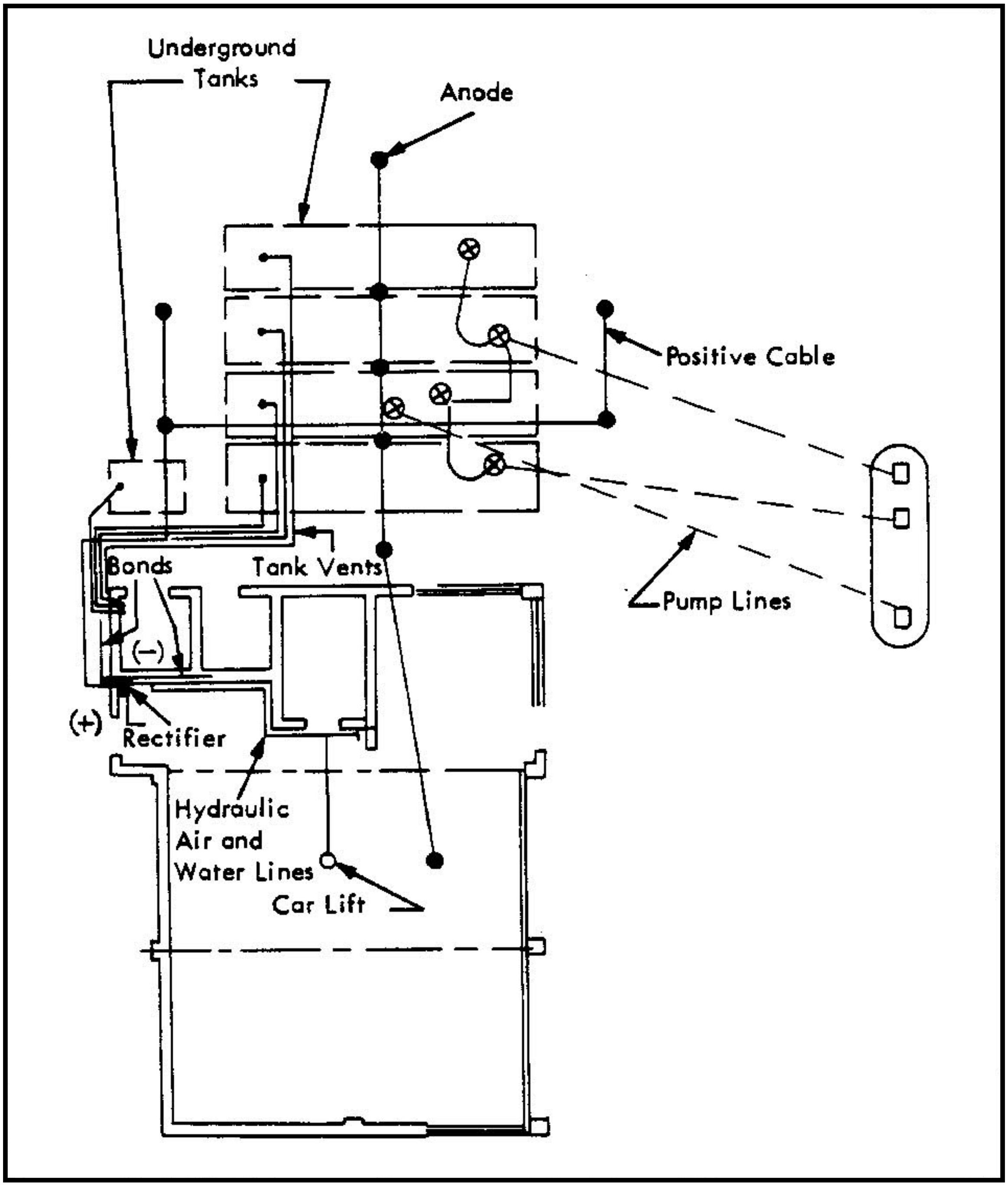

Figure 38
Impressed Current CP System for a Gasoline Service Station

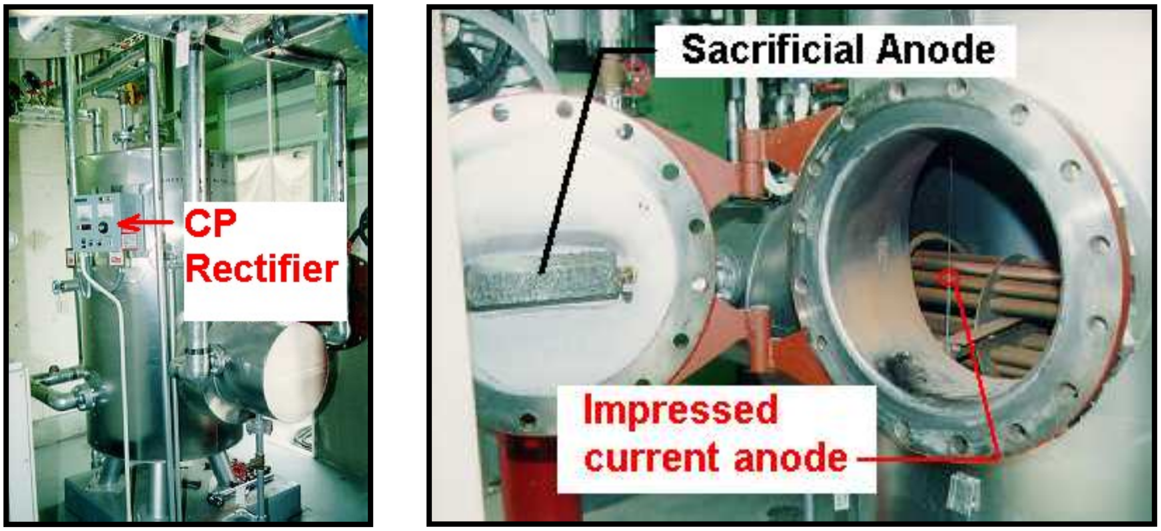

Figure 39
Impressed Current CP System for an Industrial Hot Water Storage Tank Interior, with Separate Galvanic Anode for the Electrically Isolated Manway Cover.

5.0 DESIGN EXAMPLES.

The following examples illustrate the application of the design principles outlined in this Technical Paper as well as UFC 3-570-01 Chapters 3 and 4. **They are intended to illustrate the design methods to be used, but are NOT standard designs. The examples are also not considered to be mandatory DOD policy and procedures. The policy is described in UFC 3-570-01.** Project engineers may use these examples as guides when technically reviewing project design submissions.

In these examples, interference to or from foreign structures is not considered. In practice, the design should be based upon field measurements whenever possible and not on calculated estimates. In some examples, longer calculations than are actually required are presented for illustrative purposes and shorter, more simplified calculations would give equally applicable estimates. It is important to note that all cathodic protection system designs make many assumptions, such as uniform environmental resistivity, which may or may not prove to be true.

When the system is installed, it will require adjustment and possible modification in order for effective protection to be achieved. In congested areas, interference problems are often difficult to correct and optimum levels of protection may not be practically achieved. In such cases, cathodic protection will reduce the incidence and degree of corrosion damage but corrosion may not be entirely eliminated.

5.1 **Pipeline Distribution Systems.** The project consists of providing cathodic protection to a new 3 inch diameter buried fuel pipeline. For the purpose of cathodic protection design, the pipeline is broken up into two zones:

Zone 1 Horizontal drilled segment from pump house at lower tank farm, up a hill, and across the airfield runway.

Zone 2 Trenched pipeline from airfield to upper tank farm and then to power plant.

5.1.1 **Design Data**.

A. Pipe diameter: 3" nominal with 3.4" outer diameter (OD).
B. Pipe length:
Zone 1: 3,335 feet
Zone 2: 12,276 feet
C. Pipe coating efficiency:
Zone 1: 50% (assume condition of coating may not be good after pulling the pipe through the horizontally drilled hole)
Zone 2: 95%
D. Current Requirements: Due to the fact that this CP system is for a new pipeline field current requirement test could not be conducted. Current requirements for cathodic protection were assumed to be 2 milliamps per square foot of exposed pipe surface area.
E. Soil resistivity: 3,500 ohm-cm
F. Initially assume that the entire pipeline (Zones 1 and 2) will be protected by a single impressed current system. Power is only available at either end of the pipeline. However, since the horizontally drilled segment starts at the bottom of a cliff, the rectifier would be best located at that end of the pipeline near the lower tank farm.

5.1.2 **Calculations**.

5.1.2.1 **Find the External Surface Area (A) of the Piping.**

$$A_P = \pi D_P L_P$$

where
A = Surface area of piping (ft²)
D_P = Diameter of pipe
L_P = Length of piping

A. Zone 1:

$$A_1 = 3.1416 \times 3.4''/12 \text{ in/ft} \times 3{,}335 \text{ ft}$$

$$= 2{,}969 \text{ ft}^2$$

B. Zone 2:

$$A_2 = 3.1416 \times 3.4\text{"}/12 \text{ in/ft} \times 12{,}276 \text{ ft}$$

$$= 10{,}927 \text{ ft}^2$$

C. Total Surface Area

$$A_T = A_1 + A_2$$

$$A_T = 2{,}969 + 10{,}927$$

$$= 13{,}896 \text{ ft}^2$$

5.1.2.2 **Calculate the Current Requirement (I).**

$$I = (A)\,(I')\,(1 - CE)$$

where
I = Current requirement (amps)
A = Surface area of piping
I' = Assumed current density = 2 mA/ft²
CE = Pipe coating efficiency

A. Zone 1:

$$I_1 = 2979 \times 2 \times (1 - 0.5)$$

$$= 2979 \text{ mA or } 2.98 \text{ amps}$$

B. Zone 2:

$$I_2 = 10927 \times 2 \times (1 - 0.95)$$

$$= 1093 \text{ mA or } 1.1 \text{ amps}$$

5.1.2.3 **Attenuation Calculations.**
Due to the relatively long length of this segment and the unknown quality of the coating of the piping, attenuation calculations are performed to determine the feasibility of utilizing a single rectifier system located at the end of the pipeline. The end of the pipeline is chosen for the groundbed location because that is the only spot where there is available power. Soil resistivity in this region was measured to be an average of 3,500 ohm-cm.

A. Determine the coating conductance (G).
   Since the actual coating condition is unknown and of a concern in this installation the coating conductance will be assumed to be 1 x 10^{-4} Siemens/ft^2.

B. Calculate the pipe unit specific conductance (g).

$$g_p = (G)\,(A)$$

where
g_p = pipe specific conductance (Siemens)
G = coating conductance (Siemens/ft^2) = 1 x 10^{-4}
A = Surface area of piping = 13,896 ft^2

$$g_p = 1 \times 10^{-4} \times 13{,}896\ ft^2$$

$$= 1.39\ \text{Siemens}$$

Calculate the unit specific conductance for the pipe as follows:

$$g = \frac{g_p}{L_p/1000}$$

$$g = \frac{1.39}{15{,}611/1000}$$

$$= 0.089\ \text{per 1000 ft of pipe}$$

C. Calculate the attenuation constant (α).

$$\alpha = (r \times g)^{1/2}$$

where
α = attenuation constant
r = pipe resistance (ohms/1000 ft) = 0.021 ohms/1000 ft (schedule 80 pipe)
g = pipe unit specific conductance (Siemens/1000ft) = 0.089 S/1000 ft

$$\alpha = [(.021\text{ohm})(0.089\ S)]^{1/2}$$

$$= 0.043$$

D. Calculate the characteristic resistance (R_G).

$$R_G = (r/g)^{1/2}$$

$$R_G = (0.021 \text{ ohm}/0.089 \text{ S})^{1/2}$$

$$= 0.486 \text{ ohm}$$

E. Calculate resistance on opposite end of pipe from rectifier (R_{SO}).

$$R_{SO} = R_G \coth(\alpha x)$$

where
R_{SO} = resistance on opposite end of pipe from rectifier (ohm)
R_G = pipe characteristic resistance (ohm) = 0.486 ohm
x = length of pipe (1000 ft) = 15,611/1000 ft = 15.611

$$R_{SO} = (0.486) \text{ X } \coth[(0.043)(15.611)]$$

$$= 0.83 \text{ ohm}$$

$$R_{SO} = 0.83 \text{ ohm}$$

F. Calculate current (I_S) required to cause voltage shift of 1 volt at source

$$I_S = V_S/R_{SO}$$

where
I_S = current required to cause voltage shift of 1 volt at source (Amps)
V_S = Source voltage (volt) = 1.0 volt
R_{SO} = resistance on opposite end of pipe from rectifier (ohm) = 0.83 ohm

$$I_S = (1.0 \text{ volt})/0.83 \text{ ohm}$$

$$= 1.21 \text{ Amp}$$

G. Calculate potential at end of pipe with E_S = 1.0 volt

$$E = E_S \cosh(\alpha x) - R_G I_S \sinh(\alpha x)$$

where

E = potential at the opposite end of pipe from rectifier (volt)
E_S = potential of the pipe at the rectifier (volt) = 1.0 volt
I_S = current req'd to cause voltage shift of 1 volt at source = 1.21 Amp
x = length of pipe (1000 ft) = 15,611/1000 ft = 15.611

$$E = (1)\cosh[(0.043)(15.611)] - (0.486\text{ohm})(1.21\text{A})\sinh[(0.043)(15.611)]$$

$$= 1.234 - 0.425$$

$$= 0.809 \text{ volt}$$

This indicates that a single power source at the lower tank farm end of the pipeline could protect the entire line without greatly over protecting the end near the power source. This represents a decrease of 19.1%. Generally anything less than 25% is considered acceptable.

h. Calculate voltage shift at the mid-point along the distance of the pipe assuming rectifier and anode groundbed are located at the bottom of the hill near the lower tank farm.

$$E = E_S \cosh(\alpha x) - R_G I_S \sinh(\alpha x)$$

where
E = potential at the opposite end of pipe from rectifier (volt)
E_S = potential of the pipe at the rectifier (volt) = 1.0 volt
I_S = current req'd to cause voltage shift of 1 volt at source = 1.21 Amp
x = length of pipe to midpoint (1000 ft) = 7,805/1000 ft = 7.81

$$E = (1)\cosh[(0.043)(7.81)] - (0.486\text{ ohm})(1.21\text{A})\sinh[(0.043)(7.81)]$$

$$= 1.06 - 0.20$$

$$= 0.86 \text{ volt at the midpoint}$$

Again this indicates that a single power source at the end of the pipeline could protect the both segments of the line without greatly over protecting the end near the power source.

Although a single rectifier could protect this entire fuel pipeline, the cathodic protection designer expressed concerns over this system for the following reasons:

1) The extremely high cost of installing horizontal drilled segment which goes underneath the airfield and the lack of economical inspection options.

2) The uncertainty regarding the coating condition of the horizontally drilled segment and the fear of damaging the coating due to overprotection.
3) The remoteness of the outpost raised the concern that proper maintenance of the cathodic protection system may not be guaranteed.

Based on these concerns the cathodic protection system designers decided to separate the two pipeline segments.

1) The horizontal drilled segment will be protected by a single rectifier and anode ground bed consisting of 5 anodes.
2) The trenched segment of piping will be protected by a sacrificial anode cathodic protection system consisting of 40 high potential magnesium anodes with a cathodic protection test station at each anode installation.

The two zones will be electrically isolated from each other with a dielectric insulation flange. Provisions for bonding will be included to give versatility to the system.

End of Example

5.2 **Single Underground Storage Tank** (Technical Paper 17 provides example galvanic anode system design calculations for this same tank).

5.2.1 **Design data.**

A. Tank Dimensions: 12' dia. X 40' long
B. Coating Efficiency: 80%
C. Design Life: 15 Years
D. Current Requirement: 0.7 Amperes (700 milliamperes)
E. Soil Resistivity: 30,000 ohm-cm
F. Other structures: None - tank is effectively electrically isolated from pipelines and other structures

5.2.2 **Calculations.**

5.2.2.1 **Area to be Protected.**
Since we have conducted a current requirement test, there is no need to calculate the area to be protected and current required.

5.2.2.2 **Determine CP Current Requirements.**
Determined by current requirement test to be 0.7 Amperes

5.2.2.3 **Calculate The Quantity Of Impressed Current Anodes.**

1. Arbitrarily select a 2-21/32" dia. X 42" long, 31 Lb. tubular high silicon chromium bearing cast iron anode in a 10" dia. X 66" long backfill column. Try to design for a 2 ohm ground bed resistance.

$$R_a = [(0.0052\rho)/(N)(L)] \text{ X } [\ln (8L/d) - 1 + (2L/S)(\ln 0.656N)]$$

where

R_a = Anode ground bed resistance (ohms)
N = Quantity of anode/backfill columns
ρ = Soil resistivity = 30,000 ohm-cm
L = 5.5 feet
d = 0.83 feet
I = 0.7 amperes
S = Assume 10' spacing between anode/backfill columns

Trying different quantities of anodes, we get the following:

Qty of Anodes	Anode Bed Resistance
4	28. 6 ohms
6	21.2
8	17.0
80	2.6

The calculation shows that a 2-ohm ground bed is uneconomical. Choose 8 anode columns with a 17-ohm ground bed resistance.

2. Calculate current output per anode to ensure it does not exceed the maximum recommended by the manufacturer. The maximum recommended output for the 2-21/32" X 42" high silicon cast iron anode is 3.5 Amps

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

where

I_A = Current output per anode
I = Total system current
N = Number of anodes

$$I_A = \frac{0.7\text{ Amp}}{8\text{ Anodes}}$$

$$0.09\text{ Amps/anode}$$

This is well within the recommended maximum.

3. Calculate the life of the ground bed

$$L = \frac{N\,W\,u}{S\,I}$$

where,

N = Quantity of anodes = 8 anodes
L = Anode life = 15 years
W = Anode weight = 31 lb
S = Anode consumption rate = 1.0 lb/ampere-year
I = Total system current required = 0.7 amperes
u = Anode utilization factor - usually 85%

$$L = \frac{(8\text{ anodes})(31\text{ lb/anode})(0.85)}{(1.0\text{ lb/amp-yr})(0.7\text{ amps})}$$

$$= 300\text{ years}$$

This is well above the 15 year design life requirement.

5.2.2.4 **Determine Wire Size And Resistance (R_w) For Positive And Negative Header Cables.**

Assume that the rectifier will be near the tank. Therefore, the wire resistance is negligible.

5.2.2.5. **Determine System Circuit Resistance.**

$$R_T = R_a + R_w + R_x$$

where,

R_T = Total circuit resistance (ohms)
R_a = Anode bed resistance = 17 ohms
R_w = Wire resistance = negligible
R_x = 0 ohms (Assume no other resistance)

$$R_T = 17 + 0 + 0$$

$$= 17 \text{ ohms}$$

5.2.2.6. **Calculate Rectifier Voltage.**

$$V_r = (I)\,(R_T)\,(1.5)$$

where,

V_r = Rectifier Voltage (volts)
R_T = Total circuit resistance = 17 ohms
I = Total system current = 0.7 amp (say 1 amp)

$$V_r = 1 \text{ amp} \times 17 \text{ ohms} \times 1.5$$

$$= 25.5 \text{ Volts}$$

Select a commercially available rectifier with nominal DC output capacity of at least 26 Volts DC and 1 ampere DC. A nominal size rectifier 28 volts/4 amps is available.

5.2.2.7. **Calculate AC Power Requirements.**

$$P_A = \frac{V_r \times I}{e}$$

where,

P_A = AC power (VA)
V_r = Rectifier voltage = 28 volts
I = Rectifier current = 4 amps
E = Rectifier efficiency = 85%

$$P_A = \frac{28 \text{ Volts} \times 4 \text{ amps}}{0.85}$$

131 VA

Field survey confirmed that 120 volts (V_A) AC power is available.

$$I_{AC} = \frac{P_A}{V_A}$$

$$I_{AC} = \frac{131\ \text{VA}}{120\ \text{V}}$$

$$= 1.09 \text{ amps AC}$$

One 15 or 20 ampere circuit breaker in a nearby electrical panel will be sufficient.

End of Example

5.3 **Multiple Underground Storage Tanks.** The service station shown in Figure 40 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.

5.3.1 **Design Data.**

A. Soil resistivity is 4500 ohm-cm.

B. Pipe is 2 in., nominal size. Total length of all buried piping is 750 ft.

C. Tanks are 8000 gal, 96 in. diameter by 21 ft-3 in. long.

D. Electrical continuity of tanks and piping has been assured.

E. It is not feasible to install dielectric insulation; system is therefore not isolated electrically from other structures.

F. Design cathodic protection anodes for 20-year life.

G. Coating quality is unknown, assume bare.

H. The cathodic protection system circuit resistance should not exceed 2.5 ohms.

I. Electric power is available at 120 V single phase in the station building.

J. Current requirement test indicates that 8.2 amperes are needed for cathodic protection.

K. Ceramic anodes will be specified.

5.3.2 **Calculations.**

5.3.2.1 **Find the External Surface Area (A) of the Storage Tanks and Piping.**

A. Storage Tanks

$$A_T = 2 \pi r_T^{\,2} + \pi D_T L_T$$

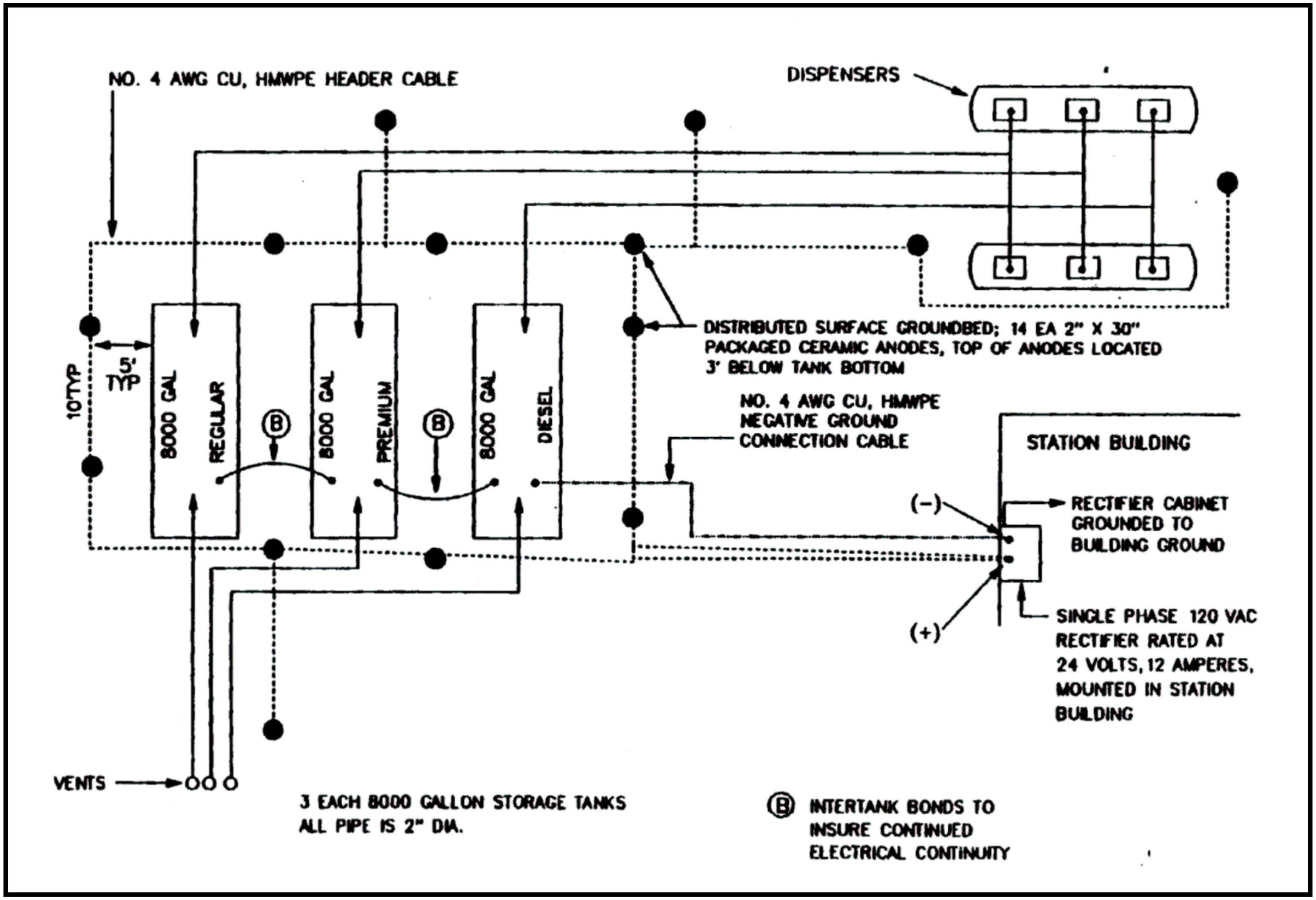

Figure 40
Cathodic Protection of Multiple Underground Storage Tanks

where

A_T = Surface area of storage tank (ft²)
r_T = Radius of tank = 48 in = 4 ft
D_T = Diameter of tank = 96 in = 8 ft
L_T = Length of tank = 21 ft - 3 in

$$A_T = [2 \times 3.1416 \times (4)^2] + 3.1416 \times 8 \times 21.25$$

$$= 634.6 \text{ say } 635 \text{ ft}^2$$

For all three tanks, the total surface area is

$$A_T = 3 \times 635 \text{ ft}^2$$

$$= 1905 \text{ ft}^2$$

B. Piping

$$A_P = \pi D_P L_P$$

where
A_P = Surface area of piping (ft²)
D_P = Diameter of pipe = 2.375 in. or 0.198 ft for 2 in. nominal size pipe
L_P = Length of piping = 750 ft

$$A_P = 3.1416 \times 0.198 \times 750$$

$$= 467 \text{ ft}^2$$

C. Total Surface Area

$$A_P = A_T + A_P$$

$$A = 1905 + 467$$

$$= 2372 \text{ ft}^2$$

5.3.2.2 **Verify the Current Requirement (I).**

$$I = (A)(I')(1 - CE)$$

where

I = Current requirement (amps)
A = Total surface area of tanks and piping = 2372 ft²
I' = Assumed current density = 2 mA/ft²
CE = Pipe/tank coating efficiency = 0.00 for bare steel

$$I = 2372 \times 2 \times (1 - 0)$$

$$= 4744 \text{ mA or } 4.7 \text{ amps}$$

The 4.7 amp would be reasonable for the facility if it were electrically isolated from other buried metals such as the building ground system. The actual current requirement of 8.2 amp occurs because of current loss to these other buried metal structures and is also reasonable in relation to that calculated for an isolated facility.

5.3.2.3 **Select An Anode and Calculate the Number of Anodes Required (N_L) to Meet the Design Life Requirements.**

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

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

where
I = Current requirement = 8.2 amps
I_A = Ceramic rod anode current rating = 1.0 amps/anode
N_L = Quantity of anodes to meet design life

$$N = \frac{8.2}{1.0}$$

$$= 8.2 \text{ use 9 anodes}$$

5.3.2.4 Calculate the Quantity of Anodes to Meet the Maximum Anode Bed Resistance of 2.5 Ohms (N_R).

$$R_a = [(0.0052\rho)/(N_R)(L)] \text{ X } [\ln (8L/d) - 1 + (2L/S)(\ln 0.656N_R)]$$

where

N_R = Quantity of anode/backfill columns
R_a = Anode ground bed resistance (2.5 ohms maximum)
ρ = Soil resistivity = 4,500 ohm-cm
L = Anode backfill column length = 5 feet
d = Anode backfill column diameter = 2 in. = 0.167 feet
I = Current requirement = 8.2 amperes
S = Spacing between anodes. Assume 10' spacing between anode/backfill columns. A distributed anode array does not lend itself to an exact calculation using the equation above because the anodes are positioned at various locations and are not located in a straight line. The above equation assumes a straight-line configuration; however, to approximate the total anode-to-earth resistance, the equation may be used.

Initially, try 9 anodes, the quantity required to meet the design life

$$R_A = \frac{0.0052 \times 4500}{9 \times 5} \left[\ln \left(\frac{8 \times 5}{0.167} \right) - 1 + \left(\frac{2 \times 5}{10} \right) (\ln (0.656 \times 9)) \right]$$

$$= 3.26 \text{ ohms}$$

The resistance for 9 anodes 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 2.24 ohms.

Of the above-calculated quantities for the anodes, 9 to meet the design life and 14 to meet the maximum anode bed resistance requirement, the larger quantity of the two must be used to ensure all conditions are satisfied. Therefore, use 14 each 0.125 in x 4 ft long ceramic rod anodes pre-packaged in backfill in 2-in. by 60-in. canisters.

5.3.2.5 Calculate the Total Circuit Resistance (R_T).

$$R_T = R_A + R_w + R_C$$

where,

R_T = Total circuit resistance
R_A = Anode bed resistance
R_w = Header cable/wire resistance
R_C = StructurTP16-to-earth resistance

A. Ground bed resistance (R_A) = 2.24 ohms from section TP16-5.3.2.4

B. Header cable/wire resistance (R_W):

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

where,

R_w = Header cable/wire resistance

L_W = 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 = ½ x 300 ft = 150 ft.)

R_{MFT} = Resistance per 1000 lineal feet of No. 4 AWG cable that has been selected for ease of handling = 0.254 ohms/1000 LF.

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

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

C. Structure-to-earth resistance (R_C):

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

D. Calculate total resistance (R_T):

$$R_T = R_A + R_w + R_C$$

$$= 2.26 + 0.04 + 0$$

$$= 2.30 \text{ ohms}$$

Since the design requirements call for a maximum ground bed 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.

5.3.2.6 **Calculate the Rectifier Voltage (V_{REC}).**

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

where,

V_{REC} = Rectifier Voltage (volts)
R_T = Total circuit resistance = 2.30 ohms
I = System current requirement = 8.2 amps
120% = Rectifier voltage capacity design safety factor

$$V_{REC} = 8.2 \text{ amp} \times 2.3 \text{ ohms} \times 1.2$$

$$= 22.6 \text{ Volts}$$

5.3.2.7 **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.

End of Example

5.4 **Elevated Steel Water Tank.** This impressed current CP design is for an elevated steel water tank that has not been built. Hence, it is not possible to determine the current requirements, etc., by actual measurements. Calculated estimates have been used.

5.4.1 **Design Data.**

A. Tank capacity - 500,000 gallons
B. Tank height (from ground to bottom of bowl) - 115 feet
C. Diameter of tank - 56 feet
D. High water level in tank - 35 feet
E. Overall depth of tank - 39 feet
F. Vertical shell height - 11 feet
G. Riser pipe diameter - 5 feet
H. Shape of tank - Ellipsoidal, both top and bottom
I. All internal surfaces are uncoated
J. Design for maximum current density - 2 mA/ft²
K. Electric power available 120/240 V ac, single-phase
L. String-type HSCBCI anodes are used
M. Design life - 10 years
N. Water resistivity - 4,000 ohm-cm
O. Tank water must not be subject to freezing
P. Assumed deterioration rate - 1.0 lbs/A yr
Q. Anode efficiency (assumed) - 50 percent

5.4.2 **Calculations.**

5.4.2.1 **Area of Wetted Surface of Tank Bowl (see Figure 41).**

A. Top section (T)

$$A_T = 2 \pi r x \text{ (approximate)}$$

where

r = 28 feet (radius of tank)
x = 10 feet
A_T = 2 x 3.1416 x 28 x 10
A_T = 1759 ft²

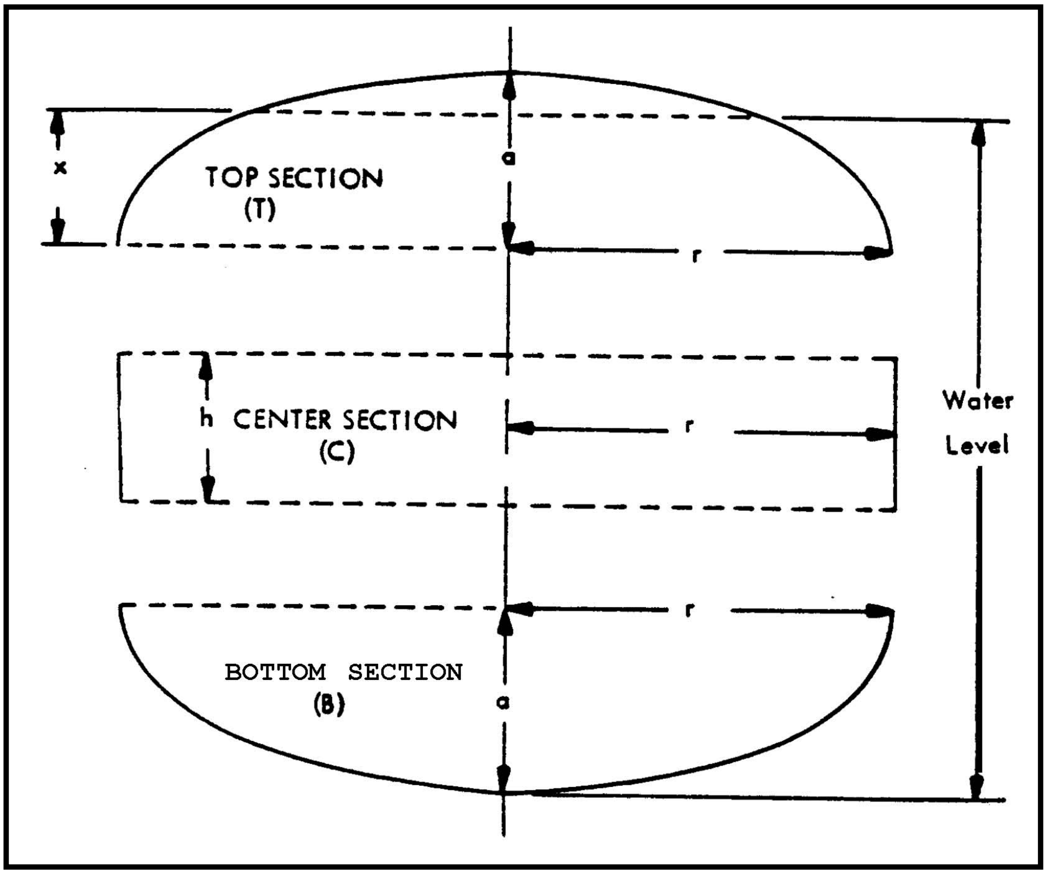

Figure 41
Segmented Elevated Tank for Area Calculations

B. Center section (C):

$$A_c = 2 \pi r h$$

where

r = 28 feet (radius of tank)
X = 11 feet
A_C = 2 x 3.1416 x 28 x 11
A_C = 1935 ft²

C. Bottom section (B):

$$A_B = \sqrt{2} \pi r \sqrt{a^2 + r^2}$$

where

r = 28 feet (radius of tank)
a = 14 feet

$$A_B = \sqrt{2} \times 3.1416 \times 28 \sqrt{14^2 + 28^2}$$
$$A_B = 3{,}894 \text{ ft}^2$$

D. Total wetted area of tank bowl:

$$\begin{aligned} A_{TB} &= A_T + A_C + A_B \\ &= 1{,}759 + 1{,}935 + 3{,}894 \\ &= 7{,}588 \text{ ft}^2 \end{aligned}$$

5.4.2.2 **Area of Riser Pipe.**

$$A = 2 \pi r_R h_R$$

where

r_R = 2.5 feet (radius of riser)
h_R = 115 feet (height of riser)

$$\begin{aligned} A_R &= 2 \times 3.1416 \times 2.5 \text{ feet} \times 115 \\ &= 1{,}806 \text{ ft}^2 \end{aligned}$$

5.4.2.3 **Maximum Design Current for Tank.**

$$\begin{aligned} I_T &= 2.0 \text{ mA/ft}^2 \times 7{,}588 \text{ ft}^2 \\ &= 15{,}176 \text{ mA or } 15.2 \text{ A} \end{aligned}$$

5.4.2.4 **Maximum Design Current for Riser.**

$$\begin{aligned} I_R &= 2.0 \text{ mA/ft}^2 \times 1{,}806 \text{ ft}^2 \\ &= 3{,}612 \text{ mA or } 3.6 \text{ A} \end{aligned}$$

5.4.2.5 **Minimum Weight of Tank Anode Material.**

$$W = YSI/E$$

where

W = weight of anode material =
Y = design life = 10 years
S = anode deterioration rate = 1.0 lb/A-yr
I = maximum design current = 15.2 A
E = anode efficiency = 0.50

$$W = \frac{10 \times 1.0 \times 15.2}{0.50}$$

$$= 304 \text{ pounds}$$

5.4.2.6 **Minimum Weight of Riser Anode material.**

$$W = YSI/E$$

where

Y = 10 years
S = 1.0 lbs/A yr
I = 3.62 A
E = 0.50

$$W = 10 \times 1.0 \times 3.62/0.50$$
$$= 72.4 \text{ pounds}$$

5.4.2.7 **Radius of Main Anode Circle.**

$$W = \frac{D\ N}{2\ (\pi + N)}$$

where

D = 56 feet
N = Assumed number of anodes = 10

$$W = \frac{56 \times 10}{2\ (3.1416 + 10)}$$

$$= 21.3 \text{ feet, use 22 feet}$$

5.4.2.8 **Spacing of 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 circumferential distance between anodes.

A. Circumferential spacing:

$$C = \frac{2\ \pi\ r}{N}$$

where

r = radius of anode circle = 22 feet
N = assumed number of anodes = 10

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

$$= 13.8 \text{ feet, use 14 feet}$$

B. Cord spacing is approximately the same as circumferential spacing: 14 feet will be used (see Figure 42).

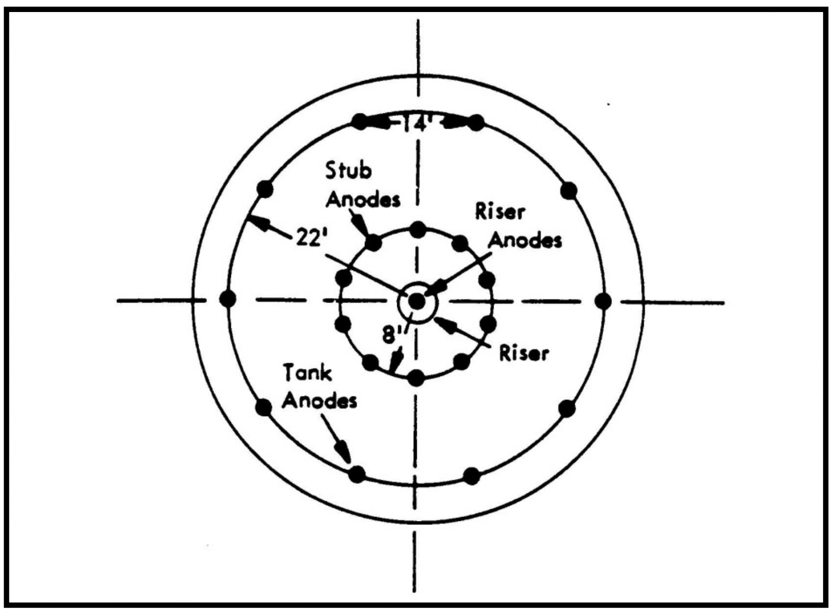

Figure 42
Anode Spacing for Elevated Water Tank

5.4.2.9 **Selection of Main Anodes.**

A. Size of anode units selected is 1-1/8 inch outer diameter by ¾ inch inside diameter by 9 inches long. This is a standard sausage type anode that weighs one pound, and has an effective surface area of 0.25 ft^2.

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

$$\text{Number of units} = \frac{304}{10 \times 1}$$

$$= 30.4 \text{ say } 31 \text{ units per string}$$

C. Because the internal tank surfaces are uncoated, a maximum structure-to-electrolyte potential is not a limiting factor. However, because it is desired to limit the anode current at or below the manufacturer's recommended discharge current rate of 0.025 Amp for this type of anode, the minimum number of anode units per string will be

$$\text{Number of units} = \frac{15.2 \text{ Amps}}{10 \times 0.025}$$

$$= 60.8 \text{ say } 61 \text{ units per string}$$

This quantity of anode units per string is not practical for the tank bowl since the distance between the anode hanger and the bottom of the bowl is only 28 feet. Table 15 shows the maximum recommended discharge current rate per anode for various types of anodes to ensure a minimum 10-year life. Using the type B anode, only three anode units per string are required. The manufacturer does not recommend the use of more than two type B anodes units per anode string assembly because of their fragile nature. Therefore, the best anode unit choices for the main anode strings are the type C or type 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 A x 10 strings = 20 A. These anodes are spaced as shown in Figure 43.

NOTE: The anodes chosen in this example were chosen to illustrate some of the many technical considerations during the design of cathodic protection. For this example if HSCBCI anodes are tubular anodes, 2-3/16 inch by 8 inch, weighing 4.3 pounds each, should be used instead of CDD anodes.

TABLE 15. TECHNICAL DATA - COMMONLY USED HSCBCI ANODES					
ANODE			ANODE MAX. DISCHARGE (A)	SURFACE AREA (ft²)	MAX. CURRENT DENSITY (A/ft²)
TYPE	SIZE (in.)	WEIGHT (lb)			
TA-FW	2-3/16 x 8	4.3	0.025	0.22	0.1
FW[1]	1-1/8 OD x 9	1	0.025	0.2	0.1
FC[2]	1-1/2 x 9	4	0.075	0.3	0.25
G-2	2 OD x 9	5	0.100	0.4	0.25
G-2-1/2	2-1/2 x 9	9	0.20	0.5	0.40
B[3,4]	1 x 60	12	0.50	1.4	0.36
C	1-1/2 x 60	25	1.00	2.0	0.50
CDD[3]	1-1/2 x 60	26	1.00	2.0	0.50
M[3]	2 x 60	60	2.5	2.8	0.9
SM	4-1/2 x 60	20	10.0	5.5	1.8
K-6	6 x 2-1/2	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	2-3/16 x 84	46	6.4	4.0	1.6

[1] For elevated fresh water tank.
[2] For distributed system in ground trench.
[3] Each end enlarged with cored opening for wire.
[4] Not more than 2 anodes per assembly.

D. Anode current density is computed as follows:

$$\text{Anode current density} = \frac{15.2 \text{ Amps}}{2 \times 10 \times 2}$$

$$= 0.38 \text{ A/ft}^2$$

5.4.2.10 **Resistance of Main Anodes.**

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

where

ρ = 4,000 ohm-cm
D = 56 feet
L = 2 x 5 feet = 10 feet
a = 44 x 0.275 = 12.1 feet (0.275-equivalent diameter factor from curve - see Figure 8-61)

$$R = \frac{0.012 \times 4{,}000 \times \log(56/12.1)}{10}$$

$$= 3.19 \text{ ohms}$$

A. However, the L/d ratio of two 1-1/2-inch diameter by 60-inch long anodes in tandem is less than 100 and thus the fringe factor must be used.

$$L/d = \frac{2 \times 60}{1.5}$$

$$= 80 < 100$$

B. The fringe factor from the curve in Figure TP16-45 corresponding to the L/d ratio is 0.95.

R (adjusted) = 0.95 R = 0.95 x 3.19 = 3.03 ohms

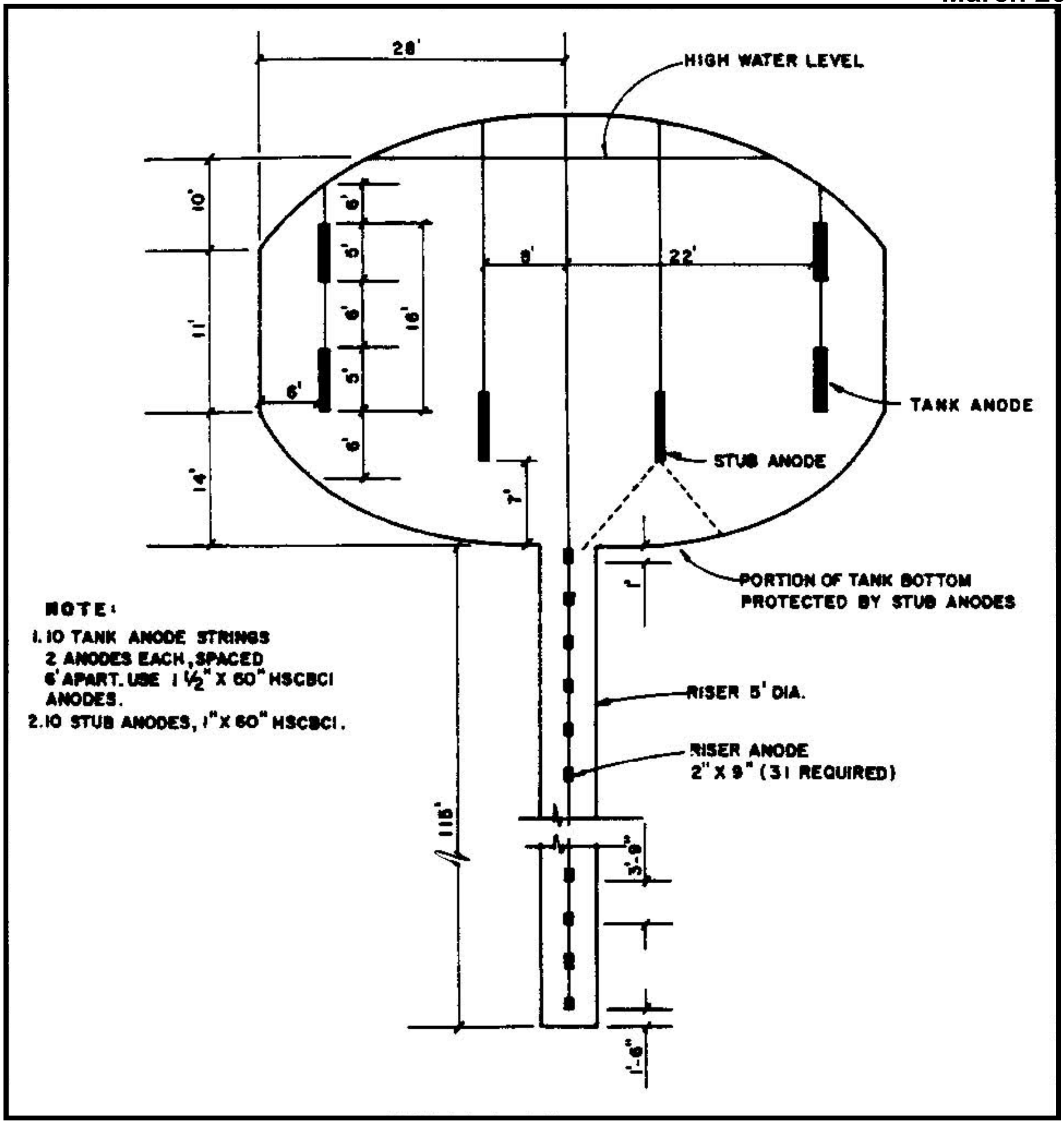

Figure 43
Anode Suspension Arrangement for Elevated Steel Water Tank

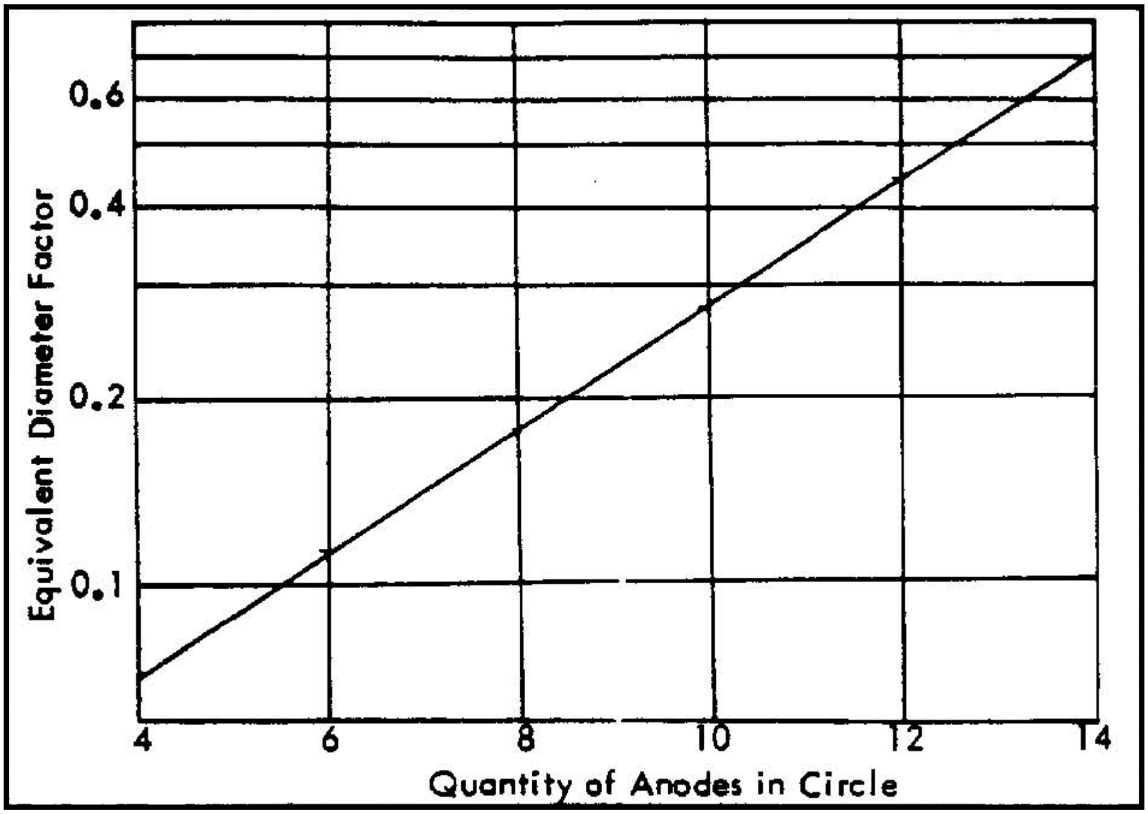

Figure 44
Equivalent Diameter for Anodes in a Circle in a Water Tank

5.4.2.11 **Stub Anodes.**

A. In the design of an elevated water tank, the need for stub anodes must be justified. The main anode radius has been calculated to b 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 1-1/2 times the spacing o the anode from the bottom.

B. The anode suspension arrangement for the tank under consideration is shown in Figure 43. Thus, it can be seen that stub anodes are required for this design. Ten stub anodes are arranged equally space on a circumference that has a radius of 8 feet in a manner illustrated in Figure 43. For smaller diameter tanks, stub anodes may not be required.

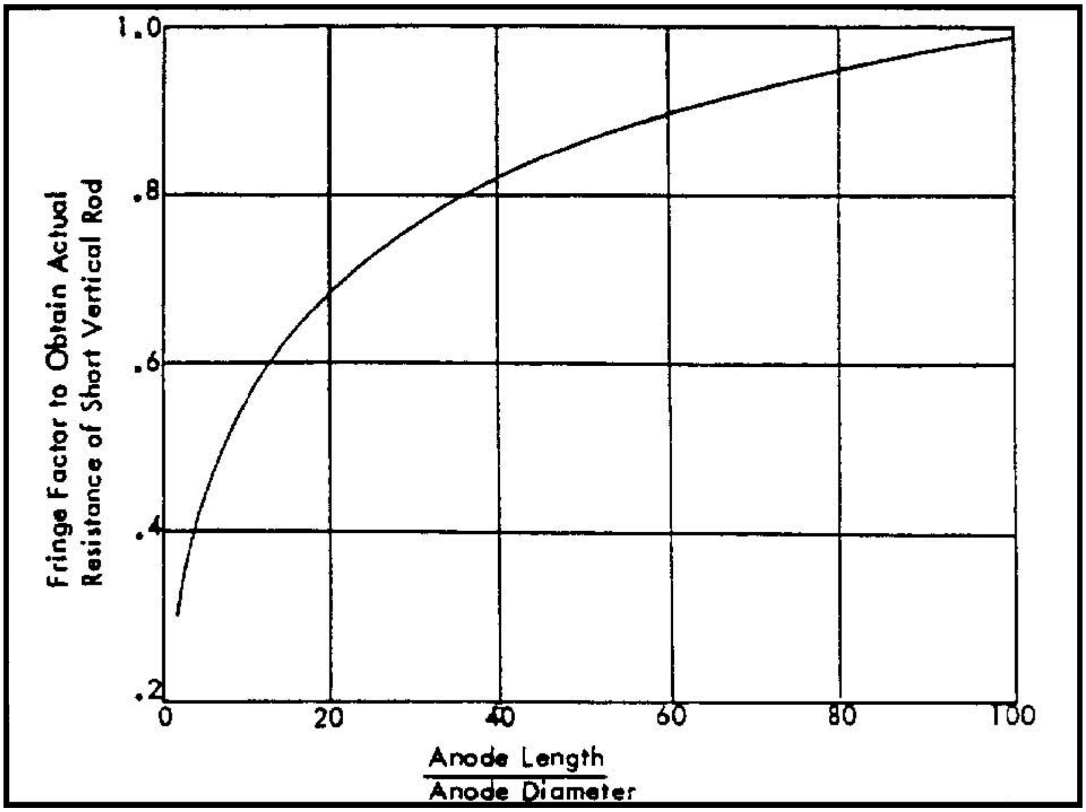

Figure 45
Fringe Factor for Stub Anodes

5.4.2.12 **Current Division Between Main and Stub Anodes.**

A. Area of tank bottom protected by stub anodes (see Figure 43):

$$A_s = \pi (r_2^2 - r_1^2)$$

where
r_2 = radius of protected segment (13 feet)
r_1 = radius of riser (2.5 feet)

$$\begin{aligned} A_s &= 3.1416\,(169 - 6.25) \\ &= 511.3\ \text{ft}^2 \end{aligned}$$

B. Maximum current for stub anodes:

$$\begin{aligned} I_s &= 2.0\ \text{mA/sf} \times 511.3\ \text{ft}^2 \\ &= 1022.6\ \text{mA or } 1.02\ \text{A} \end{aligned}$$

C. Maximum current for tank bowl = 15.2 A.

D. Maximum current for the main anodes:

$$I_m = 15.2 - 1.02$$
$$= 14.2 \text{ A}$$

5.4.2.13 **Rectifier Voltage Rating.**

A. Circuit resistance of electrical conductor to main anodes. Wire size No. 2 AWG, 0.159 ohm/1,000 feet, estimated length 200 feet:

$$R = \frac{200}{1000 \times 0.159}$$

$$= 0.032 \text{ ohm}$$

B. Voltage drop in main anode feeder:

$$E = IR$$

where

I = 14.2 A
R = 0.032 ohm

$$E = 14.2 \times 0.032$$
$$= 0.45 \text{ V}$$

C. Voltage drop through main anodes:

$$E = IR$$

where

I = 14.2 A
R = 3.03 ohms

$$E = 14.2 \times 3.03$$
$$= 43.0 \text{ V}$$

D. Total voltage drop in main anode circuit:

$$
\begin{aligned}
E_T &= 0.45 + 43.0 \\
&= 43.45 \text{ or } 45.0 \text{ V}
\end{aligned}
$$

Use a multiplying factor of 1.5, or 67.5 V.

E. The nearest commercially available rectifier meeting the above requirement is a single-phase, 80-V unit.

5.4.2.14 **Selection of 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 measuring 1-1/2-inch by 9 inches. Use one anode per string as shown in Figure 43. Compute anode current density as follows:

$$
\text{Output} = \frac{1.02}{10 \times 0.03}
$$

$$
= 0.34 \text{ A/ft}^2
$$

Because this exceeds the recommended maximum anode current density (refer to Table 15), the Type B anode is the best choice.

5.4.2.15 **Resistance of Stub Anodes.**

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

where

ρ = 4,000 ohm-cm
D = 56 feet
L = 5 feet
a = 16 x 0.275 = 4.4 feet (factor from Figure 44)

$$
R = \frac{0.012 \times 4{,}000 \times \log (56/4.4)}{5}
$$

$$
= 10.6 \text{ ohms}
$$

$$L/d = \frac{60}{1}$$

$$= 60 < 100$$

The fringe factor from the curve in Figure 45 corresponding to the L/d ratio is 0.9.

$$R\ (\text{adjusted}) = 10.6 \times 0.90\ R = 9.54\ \text{ohms}$$

5.4.2.16 **Voltage Drop in Stub Anode Circuit.**

A. Electrical conductor to stub anodes. Wire size No. 2 AWG, 0.159 ohms/1,000 feet, estimated length 200 feet:

$$R = \frac{200}{1000 \times 0.159}$$

$$= 0.032\ \text{ohm}$$

B. Voltage drop in stub anode feeder.

$$E = IR$$

where

I = 1.02 A
R = 0.032 ohm

$$E = 1.02 \times 0.032$$
$$= 0.033\ \text{V}$$

C. Voltage drop in anode suspension conductors. Estimated length 50 feet, No. 2 AWG, 0.159 ohms/1,000 feet:

$$R = \frac{50}{1000 \times 0.159}$$

$$= 0.008\ \text{ohm}$$

$$E = IR$$

where

$I = 1.02/10 = 0.102$ A
$R = 0.008$ ohm

$$E = \text{negligible}$$

D. Voltage drop through stub anodes:

$$E = IR$$

where

$I = 1.02$ A
$R = 9.54$ ohms

$$\begin{aligned} E &= 1.02 \times 9.54 \\ &= 9.73 \text{ V} \end{aligned}$$

E. Total voltage drop in stub anode circuit.

$$\begin{aligned} E_T &= 0.033 + 9.73 \\ &= 9.73 \text{ V} \end{aligned}$$

F. Since the stub anode voltage is below the 45 V calculated for the main tank anode circuit, the necessary current adjustment can be accomplished through a variable resistor in the stub anode circuit.

5.4.2.17 **Stub Anode Circuit Variable Resistor.**

A. Criteria for variable resistor. The resistor should be capable of carrying the maximum anode circuit current and have sufficient resistance to reduce anode current by one-half when full rectifier voltage is applied to the anode circuit.

B. Stub anode circuit data:

Rectifier output = 80 V
Anode current = 1.02 A
Anode resistance = 9.54 ohms

C. Variable resistor rating:

$$R = E/I$$

where

E = 80 V
I = 1.02/2 or 0.51 A

$$R = 80/0.51$$
$$= 156.9 \text{ ohms}$$

Ohmic value of resistor = 156.9 - 9.54 = 147.4 ohms
Wattage rating of resistor = $(1.02)^2$ x 147.4 = 153.4 W

The nearest commercially available resistor size meeting the above requirements is a 175-W, 200-ohm, 1-A resistor.

5.4.2.18 **Resistance of Riser Anodes.** In order to get the maximum desired current in the riser (3.62 A), the resistance limit is calculated as follows:

$$R = E/I$$

where

E = 43.45 V
I = 3.62 A

$$R = 43.5/3.62$$
$$= 12.0 \text{ ohms}$$

5.4.2.19 **Riser Anode Design.**

A. Type FW (1-1/8-inch by 9-inch) string type anodes cannot be used in the riser because the maximum anode current discharge of 0.025 A per anode would be exceeded. The number of type FW anodes required would be 145 and continuous throughout the riser. This is excessive. The best choice of anode for a flexible riser string is the type G-2 (2-inch by 9-inch) high-silicon cast iron anode.

B. Number of units required:

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

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

where

ρ = 4,000 ohm-cm
D = 5 feet
D = 2 inches or 0.166 feet
R = 12 ohms

$$L = \frac{0.012 \times 4000 \times \log (5/0.166)}{12}$$

$$= 5.92 \text{ feet}$$

Number of units = 5.92/0.75 = 7.9 or 8 units

In order to get 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 1-1/2 times the spacing of the anode from the riser pipe wall.

Riser height = 115 feet
Spacing (center of anode to tank wall) = 2.5 feet
Length of riser protected by one anode = 1.5 x 2.5 = 3.75 feet
Number of units required = 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 amp = 36

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

C. Anode resistance based on the use of 36 anode units:

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

where

r	=	4,000 ohm-cm
D	=	5 feet
D	=	2 inches or 0.166 feet
L	=	36 x 9 inches = 324 inches or 27 feet

$$L = \frac{0.012 \times 4000 \times \log(5/0.166)}{27}$$

$$= 2.63 \text{ ohms}$$

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

5.4.2.20 **Voltage Drop in Riser Anode Circuit.**

A. Electrical conductor to riser anodes. Wire size No. 2 AWG, 0.159 ohms/1,000 feet, estimated length 200 feet:

$$R = \frac{200}{1000 \times 0.159}$$

$$= 0.032 \text{ ohms}$$

B. Voltage drop in riser anode feeder:

$$E = IR$$

where

I	=	3.62 A
R	=	0.032 ohm

$$E = 3.62 \times 0.032$$
$$= 0.116 \text{ V}$$

C. Voltage drop in riser anode suspension cables. Wire size No. 2 AWG, 0.159 ohm/1,000 feet, estimated length 130 feet:

$$R = 130/1{,}000 \times 0.159 = 0.02 \text{ ohm}$$

$$E = IR$$

where

I = 3.62/2
= 1.81 A average (single current does not flow the full length of the anode string)
R = 0.02 ohm

$$E = 1.81 \times 0.02 = 0.04\ V$$

D. Voltage drop through riser anodes:

$$E = IR$$

where

I = 3.62 A
R = 2.63 ohms

$$E = 3.62 \times 2.63 = 9.52\ V$$

E. Total voltage drop in riser anode circuit:

$$E_T = 0.116 + 0.04 + 9.52 = 9.69\ V$$

5.4.2.21 **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 ohms

C. Variable resistor rating:

$$R = E/I$$

where

$E = 80$ V
$I = 3.62/2 = 1.81$ A

$$R = 80/1.81 = 44.2 \text{ ohms}$$

Ohmic value of resistor = 44.2 - 2.68 = 41.5 ohms.
Wattage rating of resistor = $(3.62)^2 \times 41.5$ = 543.8 W

The resistor should reduce anode current by one-half when full rectifier voltage is applied. The nearest commercially available resistor size that meets the above requirements is a 750-W, 50-ohm, 3.87-A resistor (rheostat). This rheostat is 10 inches in diameter and 3 inches in depth, and fairly expensive. This rheostat will not fit into most rectifier cases. In addition, the power consumed by the rheostat is considerable. This power creates substantial heat that may damage components within the rectifier case unless adequate ventilation is provided. The problems associated with using a large rheostat can be eliminated by using a separate rectifier for the riser anodes. Although initial cost may be slightly high, power savings will be substantial and damage by heat will be avoided.

5.4.2.22 **Sizing Rectifier for Riser.**

A. Requirements:

DC current output = 3.62 A
Anode circuit resistance = 2.68 ohms
DC voltage required = IR = 3.62 x 2.68 E = 9.70 V

B. Rectifier rating. Standard ratings for a rectifier in this size class are 18 Volts, 4 Amps.

5.4.2.23 **Rectifier DC Rating for Bowl.** Voltage output as previously determined, 80 V. Current rating is 15.2 A. The nearest commercially available rectifier meeting the above requirements is 80 V, 16 A.

5.4.2.24 **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 (see Figure 46).

5.4.2.25 **Discussion of the Design.**

A. The design points out the disadvantages of achieving corrosion control through cathodic protection without the aid of a protective coating. When the interior of a tank is coated, the current requirement is reduced from 60 to 80 percent. On large tanks without coating, larger size and more expensive anodes, wire, and rectifier units must be used. In addition, the power consumed by the uncoated tank is far greater. These additional costs usually exceed the cost of a quality coating system over 10-year period. Corrosion above the water line of a water storage tank is usually severe because of the corrosive nature of condensation. For this reason, protective coatings must be used above the water line on both large and small water storage tanks to mitigate corrosion.

B. For further assistance and guidance in the design of cathodic protection systems for elevated water storage tanks, see Figures 46 through 48.

C. The HSCBCI anodes were selected for this particular design purely for illustrative purposes. It does not mean that this material is superior to other types of anode material. Other acceptable anode materials include platinized titanium or niobium and mixed metal oxide (ceramic) anodes. With the advent of newer tubular center connected anodes, the designer should choose these anodes over the end connected in most cases because of their higher current capability and longer life.

D. For this design, silicon stacks should be specified for the rectifier that protects the bowl and selenium stacks should be specified for the rectifier that protects the riser. Silicon stacks operate more efficiently at high DC output voltages than selenium stacks do but require elaborate surge and overload protection. This protection is not economical in the low power consuming units. A guide for selection of rectifying cells is as follows:

- Use silicon stacks for single-phase rectifiers operated above 72 V dc or three-phase rectifiers operated above 90 V dc.
- Use newer selenium stacks for single-phase rectifiers operated below 72 V dc or threTP16-phase rectifiers operated below 90 V dc.

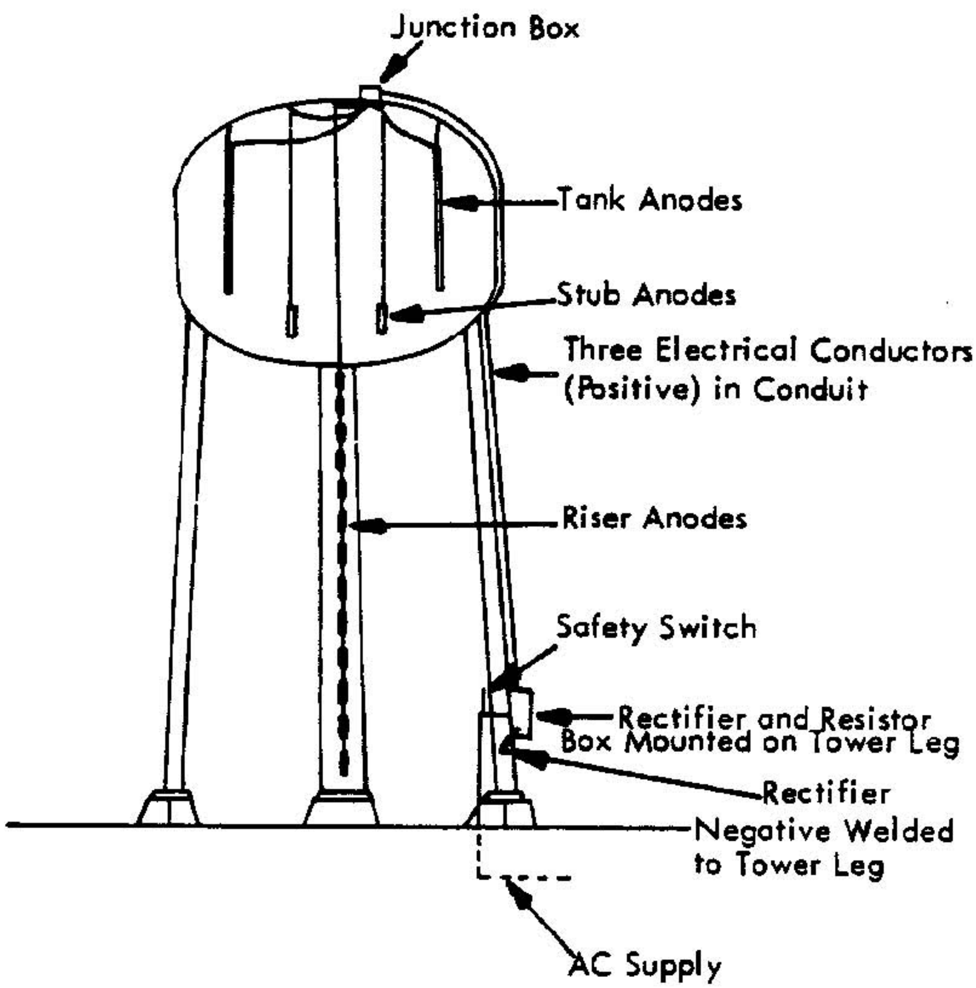

Figure 46
Elevated Steel Water Tank Showing Rectifier and Anode Arrangement

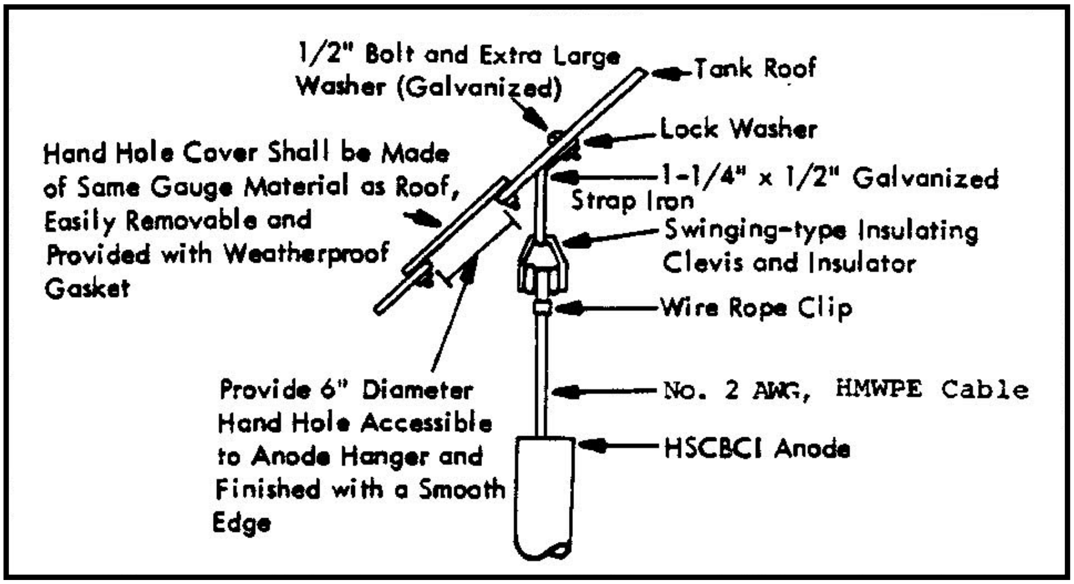

Figure 47
Hand Hole and Anode Suspension Detail for Elevated Water Tank

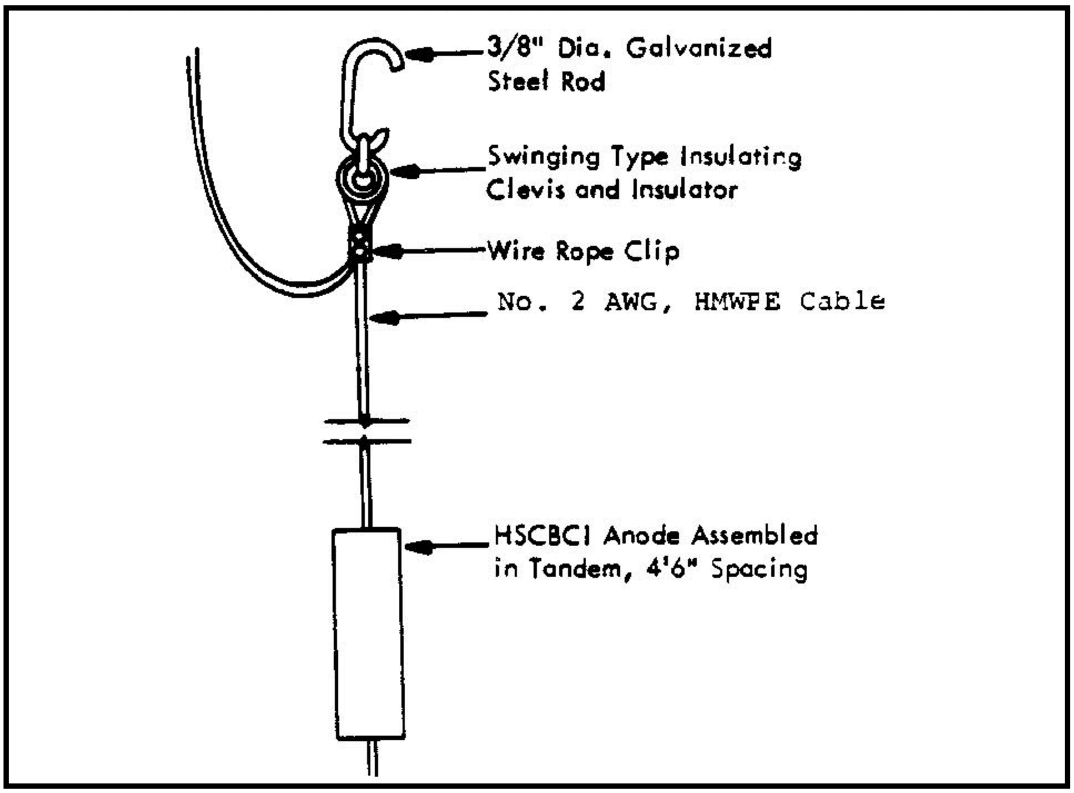

Figure 48
Riser Anode Suspension Detail for Elevated water Tank

End of Example

5.5 Elevated Steel Water Tank Where Ice Is Expected.

Impressed current cathodic protection is designed for an elevated steel water tank (Figure 49). The tank is already built and current requirement tests have been conducted. Anodes cannot be suspended from the tank roof because heavy ice (up to two feet thick) covers the water service during the 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.

5.5.1 Design Data.

a. The water tank is a pedestal spheroid with a ten-inch riser pipe. Only the bowl will be protected because the riser pipe is less than 30 inches in diameter.

b. Tank dimensions are:

   Capacity - 400,000 gallons
   Diameter of tank bowl – 51 ft 6 in
   High water level in tank - 35 feet
   Tank height (from ground to bottom of bowl) - 100 feet

c. Water resistivity - 2,000 ohm-cm

d. Anode Design life - 15 years

e. Wire type ceramic anodes to be used

f. All wetted surfaces are uncoated

g. Area above the high water level is kept well coated

h. Tank water is subject to freezing

i. The cathodic protection circuit resistance must not exceed 2 ohms

j. Electric power available is 120/240 V ac, singlTP16-phase

k. Based on structure current requirement testing on this tank, the current required for adequate cathodic protection is 25 amps. This high current requirement indicates that the tank internal coating is severely deteriorated.

5.5.2 Calculations.

5.5.2.1 Calculate the Length of Wire in Feet (LB) Needed for the Current Required.

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

where

I = Current requirement for adequate protection = 25 amps
I_A = Allowable amp per foot of anode wire (varies depending on desired anode life and diameter

Select the 0.0625 in. diameter copper cored anode wire based on the current requirement of 25 amps and design life of 15 years.

$$L_B = \frac{25}{0.31}$$

$$= 81 \text{ feet}$$

5.5.2.2 **Calculate the Desired Diameter of the Anode Wire Ring (D_R).** Experience shows that the diameter of the anode wire ring should be between 40 and 70 percent of the bowl diameter.

A. Try 40% for the first iteration.

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

Check to determine if the length is adequate for the desired anode life. For an anode ring diameter of 20.5 feet the circumference (anode wire length) is

$$C_R = \pi \times D_R$$

$$= 64.4 \text{ feet}$$

This length is inadequate for 0.0625 in. wire anode (which requires a minimum of 81 feet to meet the desired anode life). Therefore, increase the wire ring (hoop) diameter to 50 percent of the tank diameter.

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

and

$$C_R = \pi \times 25.75$$

$$= 80.9 \text{ feet}$$

This diameter yields an anode length that is still slightly less than that required for a 15-year anode life. Therefore, use a hoop diameter that is about 55 percent of the tank bowl diameter.

$$D_R = 51.5 \text{ ft} \times 55\% = 28.3, \text{ say } 29 \text{ ft}$$

and

$$C_R = \pi \times 29.0$$

$$= 91 \text{ feet}$$

5.5.2.3 **Calculate the Anode-to-Water Resistance (R_A) for the 0.0625 in. Diameter Anode Wire.**

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

where,

r = Water resistivity = 2,000 ohm-cm
D_R = Anode ring (hoop) diameter = 29 Ft
D_A = Diameter of the anode wire anode = 0.00521 Ft (0.0625 in.)
H = Anode depth below water surface determined from the following calculations (The anode depth below the high water line is about 60 percent of the distance between the high water line and the tank bottom).

$$H = 35 \text{ Ft} \times 60\% = 21 \text{ Ft}$$

$$R_A = \frac{0.0016 \times 2000}{29} \left(\ln \frac{8 \times 29}{0.00521} + \ln \frac{2 \times 29}{21} \right)$$

$$R_A = 0.110 \times (\ln 44{,}530 + \ln 2.76)$$

$$R_A = 1.29 \text{ ohms}$$

This is within the design limitation of 2.0 ohms

5.5.2.4 **Determine the Total Circuit Resistance (R_T).**

$$R_T = R_N + R_W + R_C$$

where,

R_N = Anode-to-water resistance
R_W = Wire resistance
R_C = Tank-to-water resistance

A. AnodTP16-to-water resistance (R_N) = 1.29 ohms from paragraph 5.5.2.3.

B. Header cable/wire resistance (R_W).

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

where,

L_W = 115 Ft (Effective wire length. The positive wires from the rectifier to each end of the anode ring will be about 115 feet long.

R_{MFT} = 0.57 Ohm (Effective wire resistance per 1000 lineal feet. Since there are positive wires from the rectifier to each end of the anode ring, each wire will carry about one half of the current [12.5 amp]. The wires selected are No. 10 AWG. Since the two wires are in parallel, the effective resistance is one half the single wire resistance [1.02 ohms per 1000 lineal feet/2 = 0.51 ohm])

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

$$= 0.06 \text{ ohm}$$

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

D. Calculate (R_T):

$$R_T = 1.29 + 0.06 + 0.00$$

$$= 1.35 \text{ ohm}$$

This is well below the design limitation of 2.0 ohms

5.5.2.4 **Calculate the Rectifier Voltage (V_{REC}).**

$$V_{REC} = I \times R_T \times 120\%$$

where,

I	=	Current requirement = 25 amps
R_T	=	Total circuit resistance = 1.35 ohms
120%	=	Rectifier voltage capacity design safety factor

$$V_{REC} = 25 \text{ amps} \times 1.35 \text{ ohms} \times 120\%$$

$$= 40.5 \text{ Volts}$$

5.5.3 **Select Rectifier.**

Based on the design requirements of 40.5 volts and 25 amps, a commercially available 48-volt, 28-amp unit is selected. Specify automatic potential control to prevent over or under protection as the water level varies. The controller maintains the tank-to-water potential through two permanent copper-copper sulfate reference electrodes suspended beneath the anode wire ring. The reference electrodes should have a life of at least five years. The tank-to-water potential measured by the controller should be free of IR drop error.

5.5.4 **Installation.**

Figure 49 shows a typical installation while Figure 50 illustrates a typical detail for a pressure entrance fitting for underwater power and reference electrode wire penetrations.

End of Example

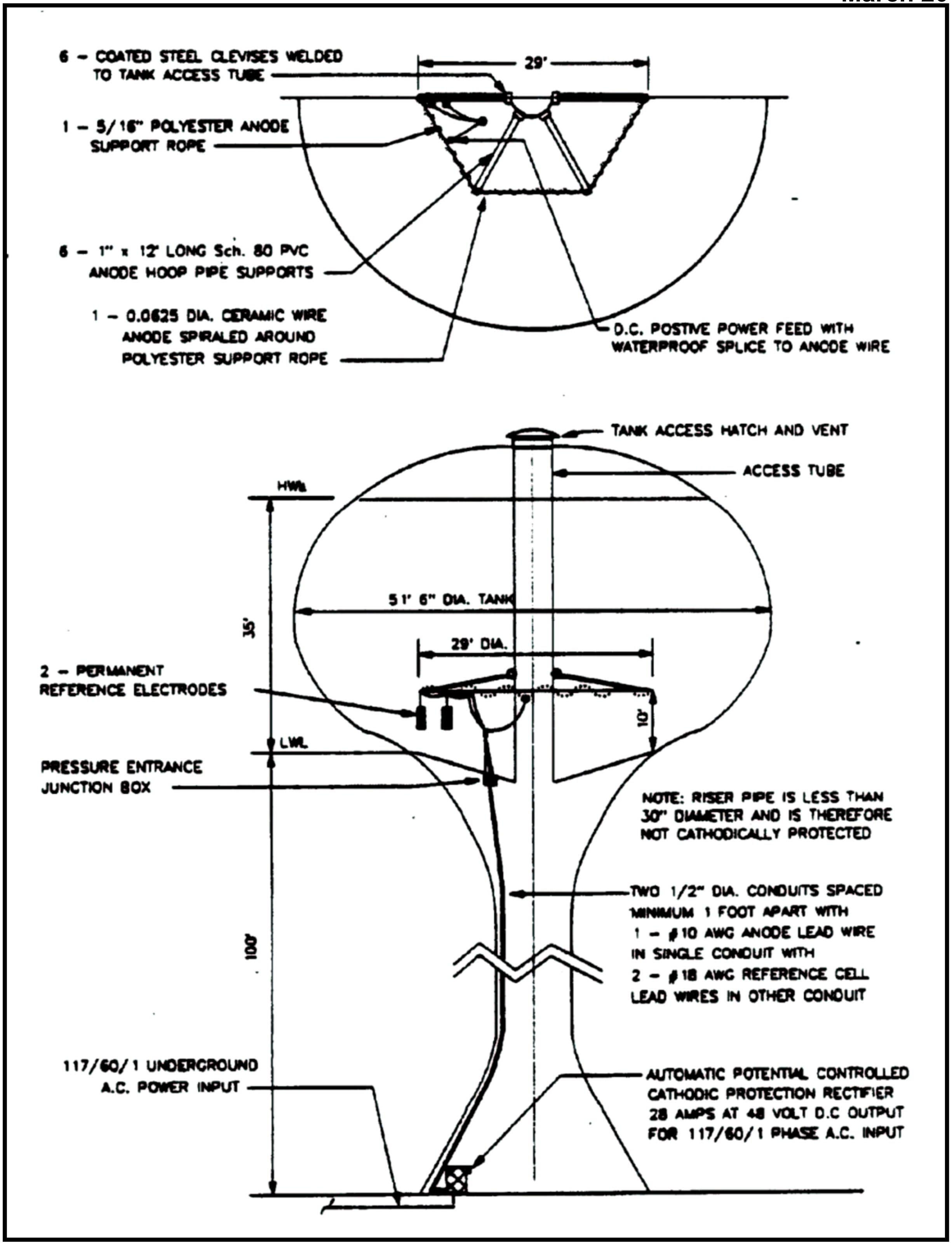

Figure 49
Elevated Pedestal tank with ceramic anode wire ring for icing conditions.

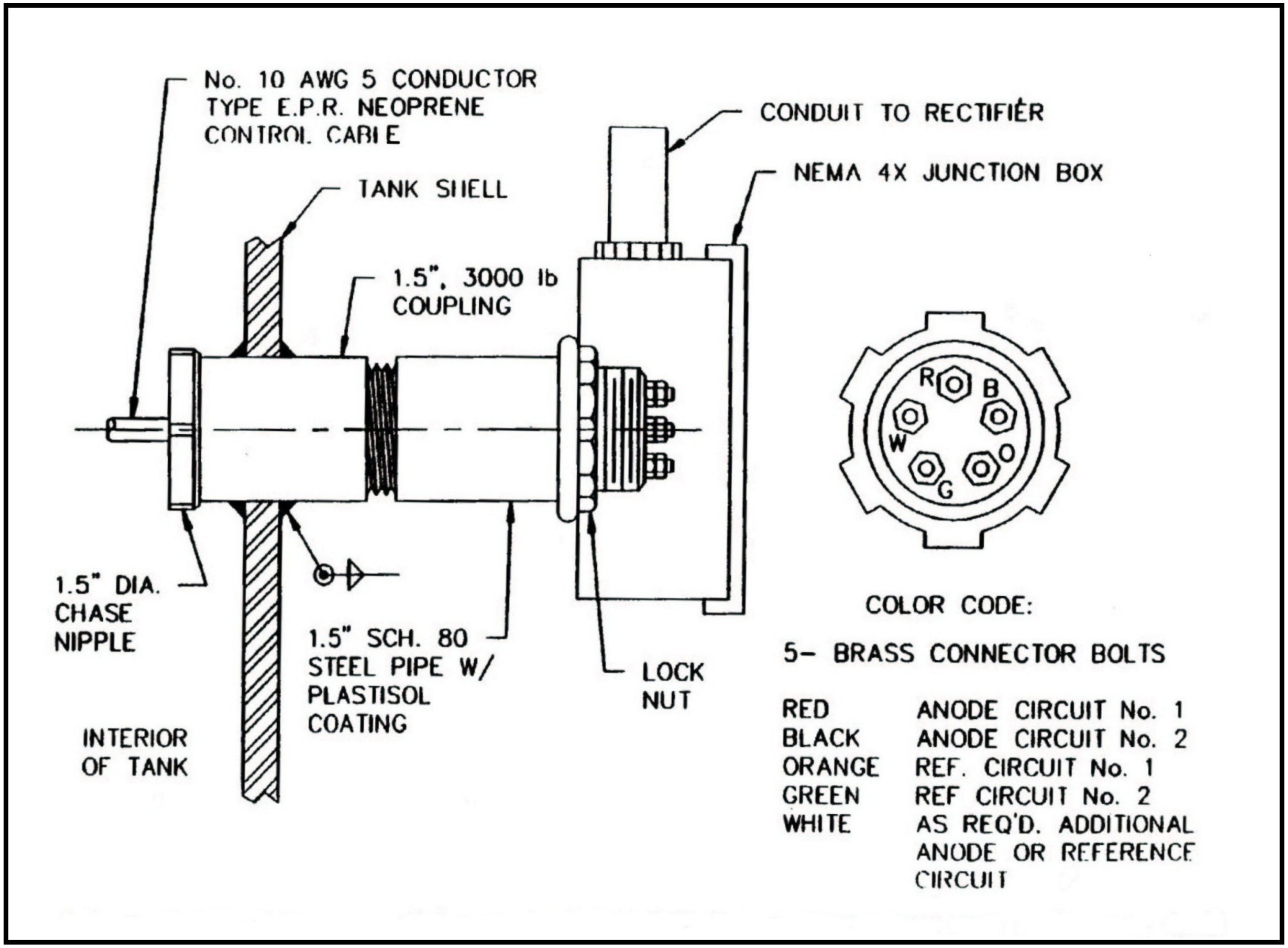

Figure 50
Pressure entrance fitting for underwater power and reference electrode wire penetrations in water storage tanks.

5.6 **Steel Gas Main.** Design an impressed current cathodic protection system for the 6-inch welded steel gas main shown in Figure 51. The pipeline has not yet been constructed, so current requirement tests cannot be conducted.

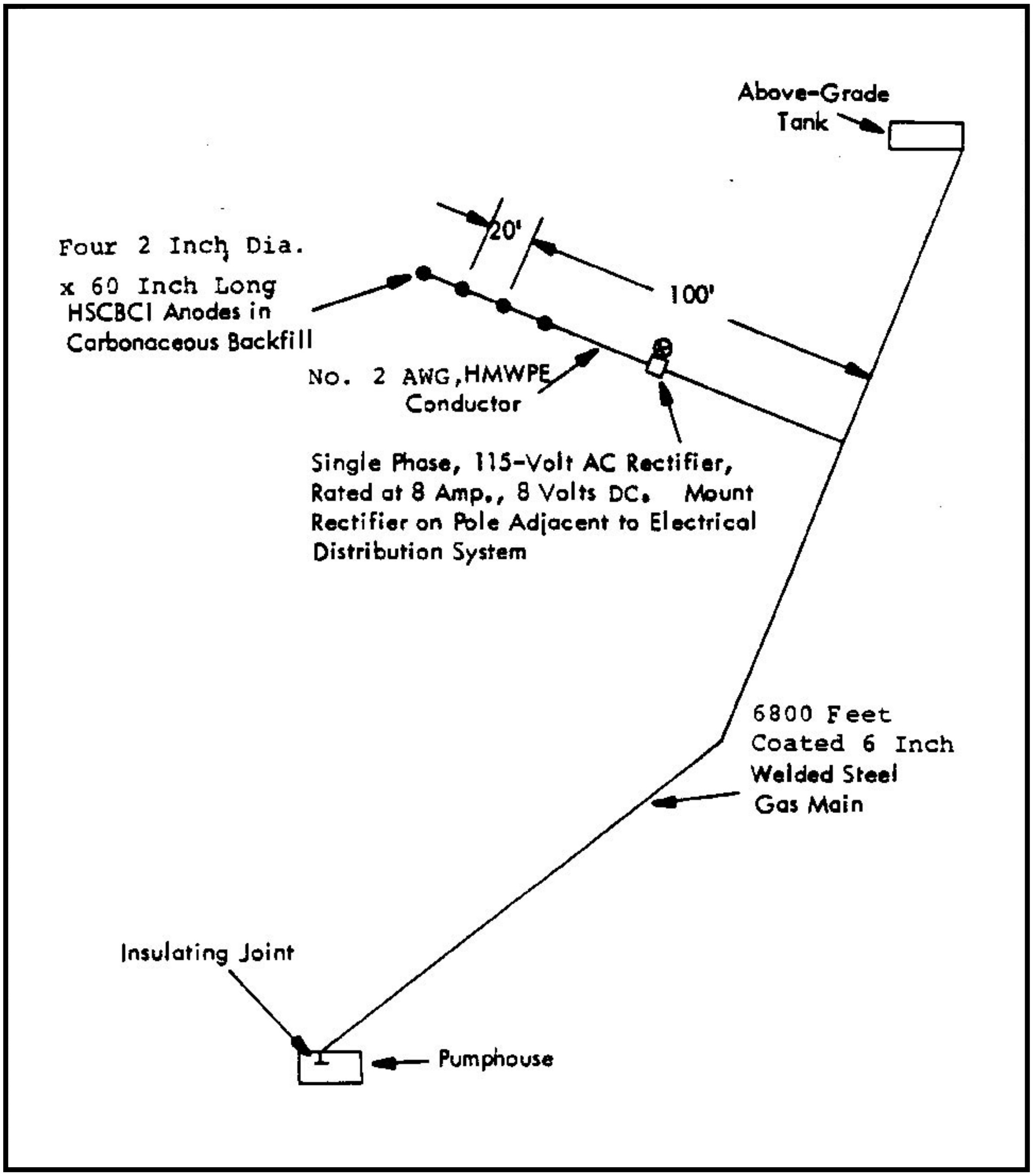

Figure 51
Cathodic Protection System for Gas Main

5.6.1 **Design Data.**

A. Average soil resistivity, 2,000 ohm-cm.

B. Pipe size, 6-inch outside diameter, schedule 80 pipe.

C. Pipe length, 6,800 feet.

D. Design for 15-year life.

E. Design for an estimated 2 mA/ft² of bare pipe.

F. Design for 90 percent coating efficiency, based on experience.

G. The pipeline must be isolated from the pump house with a dielectric insulating flange on the main line inside the pump house.

H. Use HSCBCI anodes with carbonaceous backfill.

I. The pipe is coated with hot-applied coal-tar enamel and holiday checked before installation.

J. Anode bed resistance must not exceed 2 ohms.

K. Electric power is available at 120/240 V ac, single phase, from a nearby overhead distribution system.

5.6.2 **Calculations.**

5.6.2.1 **Outside Area of Gas Main.**

$$A_P = \pi D L$$

where
A_P = Outside surface area of the pipe
D = Outer pipe diameter = 6.625 inches for a 6-inch nominal diameter pipe
= 6.625 in/12 in/ft = 0.552 feet
L = Pipe length = 6,800 feet

$$A_P = 3.1416 \times 0.552 \times 6800$$

$$= 11{,}792 \text{ ft}^2$$

5.6.2.2 **Area of Bare Pipe to Be Cathodically Protected Based on 90 Percent Coating Efficiency.**

$$A = A_P \times (1 - CE)$$

where
A = Area of bare pipe to be cathodically protected
A_P = Outside surface area of the pipe = 11,792 ft²
CE = Pipe coating efficiency = 90% or 0.9

$$A = 11{,}792 \text{ ft}^2 \times (1 - 0.9)$$

$$= 1{,}179 \text{ ft}^2$$

5.6.2.3 **Protective Current Required Based on 2 mA/ft² of Bare Metal.**

$$I = A \times CD$$

where
A = Area of bare pipe to be cathodically protected = 1,179 ft²
I = Current required for cathodic protection
CD = Current density = 2 mA/ft²

$$I = 1{,}179 \text{ ft}^2 \times 2 \text{ mA/ft}^2$$

$$= 2{,}358 \text{ mA or } 2.36 \text{ A}$$

5.6.2.4 **Ground Bed Design.**

A. Anode size: 2-inch x 60-inch (backfilled 10-inch x 84-inch), spaced 20 feet apart.

B. Resistance of a single anode to earth:

$$R_V = \frac{r}{L} K$$

where

r = Soil resistivity = 2,000 ohm-cm
K = Shape function (refer to para. 6.2.1.4a) = 0.0167
L = Backfilled anode length = 7.0 feet
L/D = 84 inches/10 inches backfill size

$$R_V = \frac{2{,}000}{7.0} \times 0.167$$

$$= 4.77 \text{ ohms}$$

C. Number of anodes required.

One of the design requirements is that the anode bed resistance is not to exceed 2 ohms. Anode size used is 2-inch diameter x 60 inches long with carbonaceous backfill having overall dimensions of 10-inch diameter x 84 inches long and spaced 20 feet apart:

$$R_n = \frac{1}{n} R_V + r_s \frac{p}{s}$$

where

R_n = Anode bed resistance = 2 ohms
n = number of anodes
R_V = Single anode resistance = 4.77 ohms
r_s = Earth resistivity with pin spacing equal to S = 2,000 ohm-cm
p = paralleling factor (refer to para. 6.2.1.4b)
s = spacing between adjacent anodes = 20 feet

NOTE: p is a function of n as referred in para. 6.2.1.4b, and n is the number of anodes which are determined by trial and error.

Rearranging the equation for n:

$$n = \frac{R_V}{R_n - \left(r_s \frac{p}{s} \right)}$$

$$n = \frac{4.77}{2 - \left(2000 \frac{p}{20} \right)}$$

$$n = \frac{4.77}{2 - 100p}$$

Try n = 4 anodes, p = 0.00283 (refer to para. 6.2.1.4b)

$$4 = \frac{4.77}{2 - (100 \times 0.00283)}$$

$$4 = 2.78 \text{ (not very close)}$$

Try n = 3 anodes, p = 0.00289 (refer to para. 6.2.1.4b)

$$3 = \frac{4.77}{2 - (100 \times 0.00289)}$$

$$3 = 2.79$$

This is the closest possible. In order to keep total resistance below 2.0 ohms, use 3 anodes.

D. Actual anode bed resistance:

$$R_3 = \left(\frac{1}{3}\ 4.77 \right) + \left(2000\ \frac{0.00289}{20} \right)$$

$$= 1.87 \text{ ohms which is less than 2.0}$$

5.6.2.4 **Next Calculate the Quantity of Anodes to Meet Recommended Maximum Anode Current Discharge.**

$$N_D = \frac{I}{A_A \times I_A}$$

where:

N_D = quantity of anodes to meet recommended maximum anode current discharge limits.
I = Current required (2.36 amps)
A_A = Anode surface area (ft^2) = 2.6 ft^2
I_A = Max. recommended anode discharge current density (1 amp/ ft^2)

$$N_D = \frac{2.36}{2.6 \times 1}$$

$$= 0.91 \text{ say 1 anode}$$

Only one anode is required to stay within the maximum anode current discharge limit. However, use the 3 anodes required to meet the 2-ohm ground bed resistance design requirement.

5.6.2.5 **Total Weight of Anodes for Ground Bed.**

A. Weight of anode unit, 60 pounds (size 2 inches x 60 inches)

B. Total weight = 3 x 60 = 180 pounds

5.6.2.6 **Theoretical Life of Anode Bed.**

$$W = \frac{Y\,S\,I}{E}$$

Rearranging the equation we get:

$$Y = \frac{W\,E}{S\,I}$$

where
Y = Theoretical anode bed life
W = Total anode bed weight = 180 pounds
S = Anode consumption rate = 1.0 lb/A yr
E = Anode efficiency = 0.50
I = Current required for cathodic protection = 2.36 A

$$Y = \frac{180 \times 0.50}{1.0 \times 2.36}$$

$$= 38.1 \text{ years}$$

It should be noted that the expected ground bed life greatly exceeds the design requirement of 15 years. This is brought about by the additional anode material required to establish a 2-ohm ground bed. The lower ground bed resistance saves energy (power, $P = I^2 R$).

5.6.2.7 **Resistance of the DC Circuit.**

A. Ground bed-to-soil resistance, 2.0 ohms maximum.
B. Resistance of ground bed feeder conductor (length 500 feet, type HMWPE, size No 2 AWG).

Conductor resistance (refer to Table 10): 0.159 ohm/1,000 feet

$$R = 500 \text{ ft} \times 0.159 \text{ ohm/1,000 feet}$$

$$= \quad 0.080 \text{ ohms}$$

C. Total resistance of circuit:

$$R_T = 2.0 + 0.080$$

$$= 2.08 \text{ ohms}$$

5.6.2.8 **Rectifier Rating.**

A. Minimum current requirement = 2.36 A.
B. Circuit resistance = 2.08 ohms.
C. Voltage rating:

$$E = IR$$

where
I = 2.36 A
R = 2.08 ohms

$$E = 2.36 \text{ A} \times 2.08 \text{ ohms}$$

$$= 4.9 \text{ say } 5.0 \text{ V}$$

To allow for rectifier aging, film formation, and seasonal changes in the soil resistivity, it is considered good practice to use a multiplying factor of 1.5 to establish the rectifier voltage rating.

$$E = 5.0 \times 1.5 = 8.0 \text{ V}$$

D. The commercial size rectifier meeting the above requirements is 115-V, single-phase, selenium, and full-wave bridge type having a dc output of 8 A, and 8 V.

5.6.2.9 **Rectifier Location.**

Mount the rectifier at eye level on a separate pole adjacent to an existing overhead electrical distribution system

End of Example

5.7 **Hot Water Storage Tank.** Design impressed current cathodic protection for the interior of the industrial hot water storage tank shown in Figure 52.

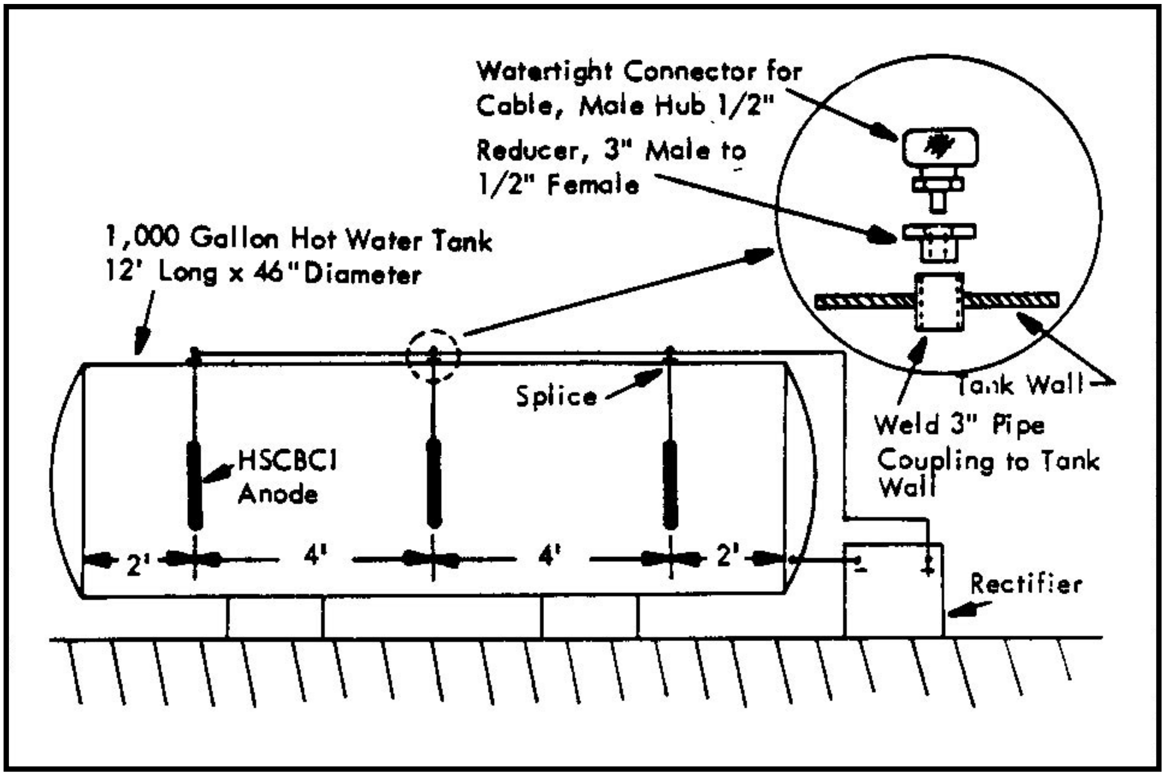

Figure 52
Cathodic Protection for an Industrial Hot Water Storage Tank

5.7.1 **Design Data.**

A. Tank capacity, 1,000 gallons.
B. Tank dimensions, 46 inches in diameter by 12 feet long.
C. Tank is mounted horizontally.
D. Water resistivity is 8,600 ohm-cm with a pH value of 8.7.
E. Tank interior surface is bare and water temperature is maintained at 180 degrees F (82.2 degrees C).
F. Design for maximum current density of 5 mA/ft².
G. Design life, 5 years.
H. Use HSCBCI anodes.
I. Alternating current is available at 115 V ac, single phase.

5.7.2 **Computations.**

5.7.2.1 **Interior Area of Tank.**

$$A_T = 2 \pi r^2 + \pi d L$$

where

r = Tank radius = 1.92 feet
d = Tank diameter = 3.83 feet
L = Tank length = 12 feet

$$A_T = 2 \times 3.1416 \times (1.92)^2 + 3.1416 \times 3.83 \times 12$$

$$= 167.5 \text{ ft}^2$$

5.7.2.2 **Maximum Protective Current Required.**

$$A = A_P \times (1 – CE)$$

where
A = Area of bare pipe to be cathodically protected
A_P = Outside surface area of the pipe = 11,792 ft²
CE = Pipe coating efficiency = 0% or 0

$$A = 167.5 \text{ ft}^2 \times (1 – 0)$$

$$= 167.5 \text{ ft}^2$$

$$I = A \times CD$$

where
A = Area of bare tank surface be cathodically protected = 167.5 ft²
I = Current required for cathodic protection
CD = Current density = 5 mA/ft²

$$I = 167.5 \text{ ft}^2 \times \text{ mA/ft}^2$$

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

5.7.2.3 **Minimum Weight of Anode Material for 5-Year Life.**

$$W = \frac{Y\ S\ I}{E}$$

where

Y = Anode design life = 5 years
S = Anode consumption rate = 1.0 lb/A yr
E = Anode efficiency = 0.50
I = Current required for cathodic protection = 0.84 A

$$W = \frac{5 \times 1.0 \times 0.84}{E}$$

$$= 8.4 \text{ pounds}$$

Number of anodes required. Anode size of 1-1/2 inches in diameter by 9 inches long weighing 4 pounds each is selected as the most suitable size.

$$N_L = \frac{W}{W_A}$$

where

W = Total weight of anodes = 8.4 lbs
W_A = Weight of a single anode = 4 lbs
N_L = Quantity of anodes to meet design life

$$N_l = \frac{8.4 \text{ lbs}}{4 \text{ lbs}}$$

$$N_l = 2.1 \text{ (say 3 anodes)}$$

In order to get proper current distribution, three anodes are required.

5.7.2.3 **Calculate the Resistance of a Single Anode.**

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

where

r = Water resistivity = 8,600 ohm-cm
D = Tank Diameter = 3.83 feet
L = Anode length = 9 inches or 0.75 foot
d = Anode diameter = 1-1/2 inches or 0.125 foot

$$R = \frac{0.012 \times 8{,}600 \times \log(3.83/0.125)}{0.75}$$

$$= 204.5 \text{ ohms}$$

This resistance must be corrected by the fringe factor because they are short anodes. The fringe factor is 0.48 from the curve in Figure 45 for an L/d = 9/1.5 = 6.

$$R \text{ (adjusted)} = 0.48\ R = 0.48 \times 204.5 = 98.2 \text{ ohms}$$

5.7.2.4 **Resistance of the 3-Anode Group.**

$$R_T = \frac{1}{n} R_V + r_s \frac{p}{s}$$

where
R_T = Total anode-to-electrolyte resistance
n = number of anodes
R_V = resistance-to-electrolyte of a single anode = 98.2 ohms
r_s = electrolyte resistivity = 8,600 ohm-cm
p = paralleling factor
s = spacing between adjacent anodes = 4 feet

$$R_T = \frac{1}{3}\ 98.2 + 8{,}600\ \frac{0.00289}{4}$$

$$= 38.94 \text{ ohms}$$

5.7.2.5 **Rectifier Rating.**

A. Calculate rectifier voltage

$$E = IR$$

where

I = Protection current required = 0.84 A
R = Anode group resistance = 38.94 ohms

$$E = 0.84\text{ A} \times 38.94\text{ ohms}$$

$$= 32.7\text{ V}$$

B. To allow for rectifier aging, film formation, it is considered good practice to use a multiplying factor of 1.5 to establish the rectifier voltage rating.

$$E = 32.7 \times 1.5 = 49.1\text{ V}$$

C. The nearest commercially available rectifier size meeting the above requirements is a 60-V, 4-amp, single-phase unit.

5.7.2.6 **Rectifier Location.** Locate the rectifier adjacent to tank for the following reasons:

A. Usually cheaper to install.
B. Easier to maintain.
C. Keeps DC voltage drop to a minimum.

5.7.2.6 **DC Circuit Conductors.**

A. External to tank: Use No. 2 AWG, HMWPE.
B. Interior of tank: Use No. 8 AWG, HMWPE.

No stressing or bending of the cable should be permitted.

End of Example

5.8 **Steam Heat Distribution System.** Provide cathodic protection for a pre-engineered steam conduit distribution system. Galvanic CP had been previously installed on the outer conduit of some sections of the steam distribution lines. The system was ineffective because of high soil resistivity, lack of adequate electrical isolation from adjacent buried metallic structures (e.g. building H-piles, copper grounding systems, water lines, electrical conduits, etc). The CP systems included in this design will be impressed current type. Existing PVC condensate return lines will be replaced with steel conduits in the near future.

5.8.1 **Design Data.**

A. Design life: 20 years

B. Current Density: 3 mA/ft^2.

C. Coating Efficiency: 85% for existing steam conduits and 95% for new condensate lines.

D. Conventional shallow anode beds were considered, but have a high failure rate due to third party damage. Deep well anode beds require less space than shallow anode beds, and are not as likely to cause stray current interference to nearby metallic structures. A number of small rectifier/deep well systems are anticipated with each system electrically isolated from all other systems to minimize the possibility of interference and facilitate troubleshooting of system shorts that may occur. The deep well will utilize mixed metal oxide tubular anodes in carbonaceous backfill.

E. Soil Resistivity: Soil resistivity measurements taken at various locations with various pin spacing yielded a maximum resistivity measured at the 15-foot depth of 22,700 ohm-cm. Although it is not practical to measure soil resistivity to the anticipated deep well depth, based on review of the available geological information indicates that the resistivity is anticipated to decline at deeper depths. However, for conservatism, the design is based on 22,700 ohm-cm.

F. The steam lines will have insulating flanges and unions at the building tie-ins. It is anticipated that the electrical isolation will be 90% effective. Dielectric insulation will be provided at critical locations to electrically segregate rectifier systems.

5.9.2 **Calculations.**

5.9.2.1 **Outside Surface Area of Steel Conduit.**

$$A_P = \pi D L$$

where
A_C = Outside surface area of the conduit

D = Outer steam conduit diameter = 8.625 inches average = 0.72 ft
Outer steam condensate diameter = 6.625 inches average = 0.55 ft
L = Pipe length

Steam Conduit Surface Area			
Location	Length (ft)	Diameter	Area (ft^2)
North Sector	50,000	0.72	113,098
South Sector	19,000	0.72	42,977
Total pipe surface area			156,075

Steam Condensate Conduit Surface Area			
Location	Length (ft)	Diameter	Area (ft^2)
North Sector	50,000	0.55	86,394
South Sector	19,000	0.55	32,830
Total pipe surface area			119,224

5.9.2.2 **Area of Bare Pipe to Be Cathodically Protected.**

$$A = A_C \times (1 - CE)$$

where
A = Area of bare conduit to be cathodically protected
A_C = Outside surface area of the conduit
CE = Conduit coating efficiency = 85% or 0.85
Condenstate coating efficiency = 95% or 0.95

Bare Surface Area			
Structure	Total Area (ft^2)	CE	Area (ft^2)
Steam Conduit	156,075	0.85	23,411
Condensate Conduit	119,224	0.95	5,961
Total pipe surface area			29,372

5.9.2.3 **Protective Current Required Based on 3 mA/ft² of Bare Metal.**

$$I = A \times CD$$

where
A = Area of bare pipe to be cathodically protected
I = Current required for cathodic protection
CD = Current density = 3 mA/ft²

Bare Surface Area			
Structure	Bare Area (ft²)	CD	I (ma)
Steam Conduit	23,411	3	70,233
Condensate Conduit	5,961	3	17,883
Total pipe surface area			88,116
		say	88 amps

In order to keep the systems small, limit the size of each system to 15 amps. The number of systems is

88 amps/15 amps per system = 6 systems

5.8.2.4 **Calculate the Quantity of Anodes.**

Use mixed metal oxide (MMO) tubular anodes in carbonaceous backfill. The quantity of MMO anodes must be calculated to meet two different parameters: design life based on anode maximum current discharge, and anode bed resistance. The required quantity of anodes will be the larger of the two calculated quantities.

1. First calculate the quantity of anodes to meet design life

$$N_L = \frac{Y\, I_R}{A_A\, S}$$

where:
I_R = Current required = 8.9 amps
N_L = Number of anodes to meet design life
S = Manufacturer's MMO anode life rating (years)
A_A = Manufacturer's MMO anode current rating (amps)
Y = CP system design life = 20 years

Example Manufacturer's MMO Anode Ratings			
Anode Size	Rated Output (Amperes)		
	10 years	15 years	20 years
1" x 45"	5.5 – 6.0	4.0 – 4.5	3.0 – 3.5
1" x 60"	7.0 – 8.0	5.0 – 6.0	4.0 – 5.0
1" x 90"	11.0 – 12.0	8.0 – 9.0	6.0 – 7.0

Use a 1" x 45" anode rated at an average of 3.25 amperes for a 20 year design life.

$$N_L = \frac{20 \times 15}{3.25 \times 20}$$

$$= 5 \text{ anodes}$$

***** IMPORTANT *****

Do not end calculations at this point. The quantity of anodes required to meet the ground bed resistance requirements must still be calculated.

2. Anode well resistance (R_S)

   The anodes will be installed in a vertical deep well. The resistance of the anode well can be approximated by the following equation:

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

where

R_S = anode bed design resistance (2 ohm maximum desired)
r = soil resistivity (22,700 ohm-cm)
L = length of the anode backfill column (ft)
d = diameter of anode backfill column (8 in or 0.67 ft)

For five anodes try an active well depth of 100 feet.

$$R_S = \frac{0.0052 \times 22{,}700}{100} \left[\ln \left(\frac{8 \times 100}{0.67} \right) - 1 \right]$$

$$= 7.2 \text{ ohms – too high}$$

Several iterations using several different backfill column lengths yield the following:

Anode Deep Well Resistance	
Backfill Column Length (ft)	Resistance (ohms)
100	7.2
150	5.1
200	4.0
250	3.3
300	2.8
400	2.2

A 2-ohm deep well ground bed is not economically feasible, therefore, select a 200 ft backfill column with 4.0 ohms resistance. Although 5 anodes are required to meet the design life, use 8 anodes to ensure anode current attenuation along the backfill column is minimized. Install the anodes so that the bottom of the anode is about ten feet above the bottom of the hole. Use an anode spacing of twenty feet. Provide anodes with factory connected lead wires of sufficient length to reach the anode junction box without splicing.

5.8.2.5 **Rectifier Rating.**

A. System current requirement = 15 A.
B. Circuit resistance = 4.0 ohms.
C. Voltage rating:

$$E = I R + 2 \text{ Volts}$$

where
I = 15 A
R = 4 ohms

2 volts are added to overcome the typical rectifier back voltage.

$$E = 15\text{ A} \times 4.0 + 2\text{ V}$$

$$= 62\text{ V}$$

To allow for rectifier aging, film formation, and seasonal changes in the soil resistivity, use a multiplying factor of 1.25 to establish the rectifier voltage and current ratings ratings.

$$V_R = 62\text{ Volts} \times 1.25 = 78\text{ Volts}$$
$$I_R = 15\text{ Amps} \times 1.25 = 19\text{ Amps}$$

D. The commercial size rectifier meeting the above requirements is 240V, single-phase, full-wave bridge type having a dc output of 22 Amperes, and 80 Volts.

5.8.2.4 **Calculate the AC Line Load (Full Output).**

1. First calculate the line current

$$I_L = \frac{V\ I_R}{240}$$

where:

I_L = Full output AC line current (amps).
I_R = Rectifier rated output current = 22 amps
V_R = Rectifier rated output current = 80 volts

$$I_L = \frac{80 \times 22}{240}$$

$$I_L = 8\text{ Amps}$$

The circuit overcurrent protection device shall not be less than 125 percent of the continuous load. The rectifier is a continuous load, therefore,

8 amps x 125% = 10 amps

Use a 15 ampere circuit as a minimum.

End of Example

5.9 **Aircraft Multiple Hydrant Refueling System.** Cathodic protection will be provided to new underground 18-inch diameter stainless steel hydrant refueling supply and return lines, 12-inch/10-inch diameter stainless steel lines supplying the direct refueling stations, and 32 single point and 17 dual point hydrant outlets with 4-inch/6-inch risers. The stainless steel lines will be coated with extruded polyethylene. Dielectric Isolating flanges will be provided to electrically isolate the buried pipelines. Bare galvanized steel grounding rods will be provided at the hydrant refueling pits. Also intermittent current loads will be imposed on the CP system where copper clad tie downs embedded in the concrete apron are connected to one or more aircraft that are refueling. Tie downs are bonded together by a bare copper conductor encased in the concrete apron.

5.9.1 **Design Data.**

A. Design life: 25 years

B. Current Density: 0.5 mA/ft² for soil, 5 mA/ft² for structures embedded in concrete.

C. Coating Efficiency: 90% for the extruded polyethylene coating. Bare (0%) for the hydrant outlet risers.

G. A conventional anode bed with high silicon cast iron tubular anodes installed horizontally is planned. Due to the soft sand environment, use ten-inch diameter pre-packaged anodes to simplify installation.

H. The anode bed design resistance should not exceed 2 ohms.

I. Soil Resistivity: Soil resistivity measurements taken at various locations with various pin spacing yielded soil resistivities ranging from 374 ohm-cm to 21,500 ohm-cm. The maximum resistivity measured at the 10-foot depth was 8,600 ohm-cm. Therefore, the design is based on a resistivity of 8,600 ohm-cm, and the anodes must be installed at this depth.

5.9.2 **Calculations.**

5.9.2.1 **Outside Surface Area of Stainless Steel Pipe.**

$$A_P = \pi D L$$

where
A_P = Outside surface area of the pipe
D = Outer pipe diameter
L = Pipe length

Stainless Steel Distribution Pipe		
Diameter (in)	Length (ft)	Area (ft²)
18	9,000	42,412
12	830	2,770
10	180	507
Total pipe surface area		45,689

There are 32 single point and 17 dual point hydrant outlet pits for a total of 66 hydrant outlet risers.

Stainless Steel Hydrant Riser Pipe			
Diameter	Length (ft)	Qty	Area (ft²)
4"-6" Reducer (5" Avg. Dia)	1	66*	86.4
4" Riser (4.5" OD)	2	66*	155.6
Total pipe surface area			242.0

5.9.2.2 **Surface Area of Hydrant Pit Ground Rods.** There are32 single point and 17 dual point hydrant outlet pits for a total of 49 pits and therefore, 49 ground rods.

$$A_R = \pi D L N_R$$

where
A_R = Surface area of the ground rod
D = Ground rod diameter = ¾ inch = 0.0625 ft
L = Ground rod length = 10 ft
N_R = Quantity of Ground Rods = 49

$$A_P = 3.1416 \times 0.0625 \times 10 \times 49$$

$$= 96.2 \text{ ft}^2$$

5.9.2.3 **Surface Area of Aircraft Tiedown/Ground System.**

$$A = \pi D L$$

where
A = Surface area
D = Ground rod/wire diameter
L = Ground rod/wire length

The tiedown/ground consists of ¾ inch diameter by 19 inches long rod plus a ¾ inch diameter by 11 inches long rod, a 2-inch diameter by 3-inch long area receptacle, #4 bare copper wire, and a major ground bed.

Surface Area of Tiedown/Ground System

Component	Dia (in)	Length (ft)	Qty	Area (ft²)
Ground rod (19” + 11”)	0.75	2.5	613	301
Receptacle	2	0.25	613	80
#4 Copper Wire	0.232	8490		515
Total pipe surface area				896

5.9.2.4 **Area of Bare Structure to Be Cathodically Protected.**

$$A = A_S \times (1 - CE)$$

where
A = Area of bare structure to be cathodically protected
A_S = Surface area of the structure
CE = Structure coating efficiency

Area of Bare Structure to be Protected			
Structure	Surface Area (ft²)	CE	Area (ft²)
SS Distribution Pipe	45,689	0.9	4,569.0
SS Hydrant Risers	242	0	242.0
Hydrant Pit Ground Rods	96.2	0	96.2
Tiedown/Ground System	896	0	896

5.9.2.5 **Protective Current Required.**

$$I = A \times CD$$

where
A = Area of bare pipe to be cathodically protected
I = Current required for cathodic protection
CD = Current density = 0.5 mA/ft² for pipe and ground rods in soil
= 5 mA/ft² for grounding encased in concrete

Area of Bare Structure to be Protected			
Structure	Surface Area (ft^2)	CD (mA/ft^2)	I (mA)
SS Distribution Pipe	4,569.0	0.5	2,285
SS Hydrant Risers	242.0	0.5	121
Hydrant Pit Ground Rods	96.2	0.5	48
Tiedown/Ground System	896	5	4,480
Total pipe surface area			6,934
		Say 6.9 Amps	

In order to account for leakage current through insulating flanges and unanticipated coating damage, add an additional 2 amperes for a total of 8.9 Amperes. To allow for rectifier aging, film formation, and seasonal changes in the soil resistivity, select a standard size 12 ampere rectifier.

5.9.2.6 **Calculate the Quantity of Anodes.**

Use high silicon chromium bearing cast iron (HSCBCI) tubular anodes. The quantity of anodes must be calculated to meet three different parameters, design life, anode bed resistance, and anode maximum current discharge. The required quantity of anodes will be the largest of the three calculated quantities.

1. First calculate the quantity of anodes to meet design life

$$N_L = \frac{Y\, S\, I_R}{W\, U}$$

where:

I_R = Current required = 8.9 amps
N_L = Number of anodes to meet design life
S = Anode consumption rate = 1 lb/amp-yr)
U = Anode utilization factor = 0.8
W = Weight of one anode (lb)
Y = CP system design life = 25 years

***** IMPORTANT *****
Do not end calculations at this point. The quantity of anodes required to meet the recommended maximum anode discharge and the ground bed resistance requirements must still be calculated.

2. Next calculate the quantity of anodes to meet recommended maximum anode current discharge

$$N_D = \frac{I}{A_A \times I_A}$$

where:

I = Current required = 8.9 amps)

A_A = Anode surface area (SF)

I_A = Max. recommended anode discharge current density (1 amp/SF)

***** IMPORTANT *****

Do not end calculations at this point. The quantity of anodes required to meet the ground bed resistance requirements must still be calculated.

3. Calculate quantity of anodes to meet 2-ohm ground bed design

   The anodes will be installed in a shallow, distributed, horizontal anode bed. The resistance of the horizontal anode bed can be approximated by the following equation:

$$R_S = \frac{1.64\,\rho}{\pi L} \times [\ln(48L/d) + \ln(L/h) - 2 + (2h/L)]$$

where

d = diameter of anode backfill column = 10 inches

L = length of the anode backfill column (feet)

R_S = anode bed design resistance = 2 ohms

ρ = soil resistivity = 86 ohm-m

h = anode depth = 10 feet

Assume one foot of backfill column beyond the ends of each anode.

4 Determine quantity of anodes. The following table summarizes the above calculations for various common tubular anode sizes:

CALCULATED ANODE QUANTITIES							
Anode Size	**Weight (LB)**	**Area (SF)**	**Backfill Length (LF)**	**Backfill Dia. (ft)**	N_L	N_D	N_R
2.66" x 42"	31	2.4	5.42	0.833	9	4	32
2.66" x 60"	46	3.5	9.0	0.833	7	3	20
2.66" x 84"	63	4.9	9.0	0.833	5	2	20
3.75" x 84"	85	6.9	9.0	0.833	4	2	20

Of the three calculated quantities for a particular anode, the larger quantity of the three must be used to ensure all conditions are satisfied. The 46, 63 and 85 pound anodes utilize the same size backfill columns, and therefore, yield the same quantity of anodes to meet the 2.0 ohm maximum ground bed resistance requirement. For economic considerations, use the 20 each 46 LB, 2.66 inch diameter X 60 inch long anodes. Install the anodes so that there is one foot of backfill column beyond each end of each anode (two feet between consecutive anodes). Provide anode with factory connected lead wires of sufficient length to reach the anode junction box without splicing.

5.9.2.7 **Resistance of the DC Circuit.**

A. Ground bed-to-soil resistance, 2.0 ohms maximum.
B. Calculate electrical conductor resistance.

Calculate R_n: #4 rectifier negative header cable resistance (90 feet):

$$R_n = 90\text{ ft}/1000 \times 0.269\text{ ohm}/1{,}000\text{ feet}$$

$$= 0.024\text{ ohms}$$

Calculate R_p: # rectifier positive header cable resistance (1,085 feet):

$$R_p = 1{,}085\text{ ft}/1000 \times 0.169\text{ ohm}/1{,}000\text{ feet}$$

$$= 0.208\text{ ohms}$$

C. Total resistance of circuit:

$$R_T = R_S + R_n + R_p$$

$$= 2.0 + 0.024 + 0.208$$

$$= 2.23 \text{ ohms}$$

5.9.2.8 **Rectifier Rating.**

A. Rectifier current rating = 12 A.
B. Circuit resistance = 2.23 ohms.
C. Voltage rating:

$$E = I\,R + 2 \text{ Volts}$$

where
I = 12 A
R = 2.23 ohms

2 volts are added to overcome the typical rectifier back voltage.

$$E = 12 \text{ A} \times 2.23 + 2 \text{ V}$$

$$= 28.8 \text{ V}$$

D. The commercial size rectifier meeting the above requirements is 115V, single-phase, full-wave bridge type having a dc output of 12 Amperes, and 30 V.

End of Example

5.10 **On-Grade Fuel Storage Tanks.** Provide impressed current cathodic protection for the exterior bottoms of five existing on-grade fuel storage tanks:

TANK ID NO.	CAPACITY (BBL)	DIAMETER (FT)
Tank No. 1	55,000	93
Tank No. 2	55,000	93
Tank No. 3	2,300	27
Tank No. 4	10,000	45
Tank No. 5	20,000	58

Review of historical records indicates that the tanks have not had cathodic protection in the past.

5.10.1 **Design Data.**

A. Design life: 25+ years

B. Current Density: Record drawings and field inspection indicates the tanks have been constructed on an “impermeable layer” of compacted coral with a minimum thickness of 12 inches. The compacted coral may affect the even distribution of current and higher than normal current densities may be necessary to ensure the entire tank bottom is adequately protected. Usually, 1 - 1.5 ma/sf of current is sufficient to protect a tank bottom if the current is evenly distributed. With the compacted coral layer beneath the tanks, a current of 2 ma/sf will be used.

C. Coating Efficiency: 0% (Bare tank bottoms)

D. 120 Volt power and a spare circuit breaker is available in a panel in a nearby pump house. Space is available in the pump house to install a wall mount rectifier.

E. A deep well anode will be specified to: (1) improve current distribution of current to the entire tank bottom because of the compacted coral bed; (2) minimize excavation (historic preservation laws require an archaeologist to monitor all excavations full time which would add significant cost; (3) minimize disruption of on-going operations; and (4) minimize cathodic interference on other buried metallic structures in the tank farm.

F. The anode bed design resistance shall not exceed 1 ohm.

G. Soil Resistivity: Soil resistivity measurements taken at eight points within the tank farm were generally in the 2,000 to 4,000 ohm-cm range. Use 2,000 ohm-cm.

5.10.2 **Design Calculations.**

5.10.2.1 **Calculate Tank Bottom Surface Area.**

The surface area of the tank bottoms can be calculated using the following equation:

$$A_T \ = \ \pi r^2$$

where
A_T = Surface area of a tank bottom (ft^2)
r = tank bottom radius (ft)

The following table summarizes the tank bottom surface areas.

Tank ID. NO.	Diameter (FT)	Surface Area (ft^2)
Tank No. 1	93	6,790
Tank No. 2	93	6,790
Tank No. 3	27	570
Tank No. 4	45	1,590
Tank No. 5	58	2,640

5.10.2.2 **Calculate Current Requirement/Rectifier Output Current.**

$$I_R \ = \ A_T \ x \ (1 \ - \ CE) \ x \ CD$$

where
I_R = Current requirement/rectifier output current
A_T = Surface area of a tank bottom = 2,640 (ft^2)
CE = Coating efficiency = 0 for bare surfaces
CD = Current density = 2 ma/ ft^2

The following tables summarize the current requirements.

Tank ID No.	Surface Area (ft^2)	CE	CD (ma/ft^2)	Current Req'd (ma)
Tank No. 1	6,790	0	2	13,580
Tank No. 2	6,790	0	2	13,580
Subtotal				27,160
Tank No. 3	570	0	2	1,140
Tank No. 4	1,590	0	2	3,180
Tank No. 5	2,640	0	2	5,280
Total Current Required (I_R)				36,760
			or	37 amperes

In order to account for current that will be drained away by the grounding systems, use 40 amperes.

5.10.2.3 **Calculate Quantity of Anodes.**

Use high silicon chromium bearing cast iron (HSCBCI) tubular anodes.

A. Quantity of anodes to meet design life

$$N_L = \frac{Y\ S\ I_R}{W\ U}$$

where:
N_L = Number of anodes to meet design life
Y = CP system design life = 25 years
S = Anode consumption rate = 1 lb/amp-yr)
I_R = Current required (amps) = 40 amps
W = Weight of one anode (lb)
U = Anode utilization factor (0.85)

B. Quantity of anodes to meet recommended maximum anode current discharge

$$N_D = \frac{I_R}{A_A \ X\ I_A}$$

where:

I_R = Current required (amps) = 40
A_A = Anode surface area (ft^2)
I_A = Max. recommended anode discharge current density (1 amp/ ft^2)

The following tables summarize the above calculations for various common tubular anode sizes:

Anode Size	Weight (LB)	Area (SF)	N_L	N_D
2.19" x 84" (TA2)	46	4.0	25	10
2.66" x 84" (TA3)	63	4.9	19	9
3.75" x 84" (TA4)	85	6.9	14	6

Of the above-calculated quantities for the anodes, the larger quantity of the two must be used to ensure all conditions are satisfied. Considering CP current distribution in the well, use the 85 LB, 3.75 inch diameter X 84 inch long (TA-4) anode. The TA-4 appears to be a better choice to minimize drilling.

C. Anode well resistance (R_S)

The anodes will be installed in a vertical deep well. The resistance of the anode well can be approximated by the following equation:

$$R_S = \frac{0.0052\,\mathtt{r}}{L}\left[\ln\left(\frac{8L}{d}\right) - 1\right]$$

where

R_S = anode bed design resistance (1 ohm maximum)
$\mathtt{r}$ = soil resistivity (2,000 ohm-cm)
L = length of the anode backfill column (ft)
d = diameter of anode backfill column (10 in or 0.83 ft)

Based on the above a minimum anode well active depth of about 55 feet minimum is required.

Considering the number of anodes required and backfill life, use two wells of 101 feet active depth with seven anodes in each well. Install the anodes so that the bottom of the anode is about five feet above the bottom of the hole. Use an anode spacing of seven feet. Provide anodes with factory connected lead wires of sufficient length to reach the anode junction box without splicing. Calculate the anode bed circuit resistance of each well using the appropriate numbers from the above table:

$$R_S = \frac{0.0052 \times 2000}{101} \left[\ln \left(\frac{8 \times 101}{0.83} \right) - 1 \right]$$

$$= 0.61 \text{ ohm for each of the wells}$$

5.10.2.4 **Calculate Rectifier Circuit Output Voltage.**

A. Anode bed resistance (R_A) is the equivalent resistance of the two wells in parallel. Calculate the equivalent resistance of the two wells:

$$R_A = \frac{1}{R_1} + \frac{1}{R_2}$$

where,
R_A = Equivalent anode well circuit resistance
R_1 = Circuit resistance of the first anode well
R_2 = Circuit resistance of the second anode well

$$R_A = \frac{1}{0.61} + \frac{1}{0.61}$$

$$= 0.31 \text{ ohm}$$

B. Electrical Cable Resistance

Anode Well Cable Resistance (R_{AW}). Use No. 8 copper wire for the anode leads. Each of the anode leads will run directly back to the anode junction box, so the parallel cable resistance is estimated as follows:

$$\frac{1}{R_{AW}} = \frac{1}{R_{A1}} + \frac{1}{R_{A2}} + \cdots + \frac{1}{R_{An}}$$

where,

R_{AW} = Anode well cable resistance
R_{A1} = Cable resistance of the first anode in the well
R_{A2} = Cable resistance of the second anode in the well
R_{An} = Cable resistance of the nth anode in the well

$$\frac{1}{R_{AW}} = \frac{1}{R_{A1}} + \frac{1}{R_{A2}} + \cdots + \frac{1}{R_{A7}}$$

$$\frac{1}{R_{AW}} = \frac{1}{R_{A1}} + \frac{1}{R_{A2}} + \cdots + \frac{1}{R_{An}}$$

$$= 0.01 \text{ ohm for each well (negligible)}$$

Anode Header Cable Resistance(R_{HC}). Use No. 2 copper wire for the anode header cable runs. After a 100 ft run of cable to a junction box, there are two parallel runs of 200 ft and 450 ft. The equivalent resistance is 0.053 ohm.

Structure Header Cable Resistance. Use No. 2 copper wire for the structure leads. After a 450 ft run of cable to anode junction box no. 1, there are two parallel runs of 100 ft to (tanks 3, 4 and truck stand piping) and 225 ft (tank 5 piping and tanks 1 and 2). The equivalent resistance for all of these cable runs is 0.11 ohm.

C. Total Circuit Resistance. The total circuit resistance is

$$R_T = R_A + R_{AW} + R_{HC} + R_{SC}$$

$$0.31 \text{ ohm} + 0 + 0.05 + 0.11$$

$$= 0.47 \text{ ohm say } 0.5 \text{ ohm}$$

D. Calculate the rectifier output voltage using Ohm's Law:

$$V_R = I_{rect} \times R_T \times 150\%$$

$$40 \text{ amps} \times 0.5\,\Omega \times 1.5$$

$$= 30 \text{ volts}$$

Use the nearest nominal size rectifiers, or 30 volts/42 amps.

5.10.2.5 **Calculate Rectifier Input Power.**

Available power is 120 volts. For rectifiers of the size specified above, use single phase 120 volt AC input voltage. Rectifier input power is calculated as follows:

$$P = \frac{V_R \times I_R}{\text{rectifier efficiency}}$$

$$= \frac{30 \text{ volts} \times 42 \text{ amps}}{0.85}$$

$$= 1{,}500 \text{ VA}$$

AC input current is calculated to be:

$$I_{AC} = \frac{P}{V_{AC}}$$

$$= \frac{1{,}500 \text{ VA}}{120}$$

$$= 12.5 \text{ amperes}$$

5.10.2.6 **Summary.**

A. Anodes: 14 each high silicon chromium bearing cast iron tubular anodes, with dimensions of 3.75 inches in diameter x 84 inches long, and weighing 85 LB. Anodes to be installed in two 130 foot deep well, seven anodes per well, with an active depth of 101 feet. Locate the first anode so that the bottom anode is 5 feet above the bottom of the well. Install remaining anodes with a 14 foot spacing on center between the anodes. Anode supplied by manufacturer with #8 AWG lead wire with HMWPE insulation. One end is factory connected to the anode. The anode leads should be long enough to extend to the junction box without splicing.

B. Rectifier:

Type:	Air cooled
AC Input:	120 volt, 60 Hz, single phase
DC Output:	30 volts, 42 amperes
Efficiency:	85% minimum

End of Example

5.11 **On-Grade Storage Tanks with Impermeable Containment Liner.** Two each 27,000 barrel on-grade vertical fuel storage tanks are protected by an existing impressed current CP system. However, a project proposes to install a new tank bottom above the existing tank bottom, creating a double tank bottom. A high-density polyethylene containment liner will be installed over the existing tank bottom. The existing tank bottom and new polyethylene liner will prevent the existing CP system from providing protection to the new tank bottom. Galvanic corrosion between the new and old tank bottoms can result in rapid corrosion of the new tank bottom. Therefore, a new CP system will be installed between the two tank bottoms to provide corrosion protection to the new tank bottom. The space between the new and existing tank bottoms will be 4 inches minimum; therefore, the new CP anode system must be installable in this small space.

5.11.1 **Design Data.**

A. Design life: 25+ years

B. Current Density: 1 ma/ft^2 for a grid system. Generally, 2 ma/ft^2 is required for protection in neutral soils. Past experience and current literature indicates that 1 ma/ft^2 is sufficient due to the even distribution of current when using a grid system.

C. Tank bottom diameter: 70 ft

D. Tank bottom is steel

E. Slope of the new tank bottom will result in only 4 inches clearance between the existing and new tank bottom at its lowest point. Therefore, the proposed new CP system will be an impressed current system consisting of mixed metal oxide coated titanium ribbon anodes.

F. Each tank will have its own independent system to allow independent system adjustment for each tank. The rectifier will have two independent DC output circuits, one for each tank, contained in one enclosure.

5.11.2 **Calculations.**

5.11.2.1 **Tank Bottom Surface Area.**

The tank bottom is a circular surface for which its surface area can be calculated from the following equation:

$$A = \pi \times r^2$$

The area of each tank bottom is

$$A = (3.14)\ (70\ SF/2)^2$$
$$= 3847 \text{ say } 3850\ SF$$

5.11.2.1 **Current Requirement/Rectifier Output Current**

The current requirement for each tank is calculated using the equation:

$$I_{req} = A \times \text{current density}$$
$$= 3850\ SF \times 1\ ma/SF$$
$$= 3850\ ma \text{ or } 3.85 \text{ amps}$$

Allow an additional 25% to account for unknown factors in the sand backfill that will be used, for rectifier aging and other long term additional requirement:

$$I_R = 3.85 \text{ amps} \times 125\%$$
$$= 4.8 \text{ amps}$$

Use the next nominal size rectifier circuit of 8 amperes for each tank.

5.11.2.2 **Quantity of Anode Ribbons**

Commonly used mixed metal oxide coated titanium ribbon anodes are 0.25 inch wide by 0.025 inch thick. Manufacturer's literature indicates this material to have a current rating of 5 ma/LF for 50 year life.

The quantity of anode ribbon required for a 25+ year life for each tank is

$$N = 3850\ ma \times 5\ ma/LF$$
$$= 770\ LF$$

The ribbons will be spaced in evenly spaced parallel strips to ensure uniform distribution of CP current. This will result in 14 strips of ribbon spaced 5 feet on center.

The anode ribbons will be connected together by titanium ribbon conductor bars placed in a grid spaced at 30 feet on center ribbons to form a grid. The conductor bars are 0.5 inch wide by 0.04 inch thick. The conductor bars will be fed by multiple power feed leads. This will minimize the voltage drop through the grid, thereby allowing an even distribution of cathodic protection current to the tank bottom.

5.11.2.3 Circuit Resistance of Anode Ribbons

The strips are of different lengths due to the circular perimeter of the tank bottom. The theoretical resistance of a strip of metal can be calculated using the following equation from reference (c):

$$R_S = \frac{\rho}{4\pi L}\left(\ln\frac{4L}{a} + \frac{a^2 - \pi ab}{2(a+b)^2} + \ln\frac{4L}{S} - 1\right)$$

where

L = ½ the length of the anode strip (cm) = 335 LF or 11,735 cm
a = width of the strip (cm) = 0.25 in or 0.635 cm
b = thickness of the strip (cm) = 0.025 in or 0.0635 cm
S = twice the depth of the anode = 6 in or 15.24 cm
ρ = sand resistivity = 10,000 - 45,000 ohm-cm. Sand resistivity is dependent on many factors dependent on the actual sand used. Typically, the resistivity of clean sand will vary from 10,000 ohm-cm when wet to 45,000 when dry. While the sand may be dry when first installed, moisture will eventually intrude from rain during installation, water used during compaction, and leakage through deteriorated edge seals.

The resulting resistance after substituting the above numbers is

R_s = 5.7 Ω for 45,000 ohm-cm sand, and

R_s = 1.3 Ω for 10,000 ohm-cm sand

5.11.2.4 Rectifier Circuit Output Voltage

The rectifier output voltage is calculated by Ohm's Law. Use the resistance for 45,000 ohm-cm sand to ensure proper operation when sand is dry:

$$\begin{aligned} V_R &= I_{req} \times R_s \\ &= 3.85 \text{ amps} \times 5.7\ \Omega \\ &= 21.9 \text{ volts} \end{aligned}$$

Use the next highest nominal size rectifier of 24 volts to account for rectifier back voltage, circuit resistance for the power feed leads and conductor bars, and compensation for system aging.

5.11.2.5 Rectifier Input Power

Rectifier input power for each circuit can be calculated as follows:

$$VA = \frac{V_R \times I_R}{\text{rectifier efficiency}}$$

$$= \frac{24 \text{ volts} \times 8 \text{ amps}}{0.65}$$

$$= 295 \quad \text{say } 400 \text{ VA to account for 25\% safety factor}$$

The total power for the two circuits is 800 VA or 0.8 KVA. For rectifiers of this size, use single phase 120 volt AC input voltage. AC input current is calculated to be:

$$I_{AC} = VA/V_{AC}$$
$$= 800 \text{ VA}/120 \text{ volts}$$
$$= 6.67 \quad \text{say } 7 \text{ amps}$$

5.11.3 Summary

Anode material: Mixed metal oxide coated titanium ribbon, 0.25" wide x 0.025" thick. The anode grid requires 770 LF per tank placed in 14 parallel rows spaced at 5 FT on center.

Conductor bar: Conductor bars are uncoated titanium ribbons, 0.5" wide x 0.04" thick. Estimated quantity is 320 LF per tank.

Power feed leads: Supplied by manufacturer consisting of #8 AWG wire with HMWPE insulation. One end is factory connected to a 5" length of conductor bar, which will be field welded to the anode grid conductor bars. The power feed leads should be long enough to extend to the junction box without splicing. 7 power feed leads per tank are required.

Rectifier:
- Type: Oil cooled, enclosure suitable for class I, division 2.
- AC Input: 120 volt, 7 amps, 60 Hz, single phase
- DC Output: Two independent circuits, each circuit rated at 24 volts, 8 amperes
- Efficiency: 65% minimum

Reference electrodes: Combination cell of copper copper-sulfate and zinc, each component having a #14 AWG lead wire long enough to reach the junction box without splicing. 5 each combination cells per tank are required.

Due to the proximity of the tank bottom to the anode, especially at its lowest point, dielectric mesh will be installed between the anode and new tank bottom to prevent electrical short circuits.

End of Example

5.12 **Land Side of Steel Sheet Piling (Impressed Current).**

Due to high soil resistivity, and high current requirements, an impressed current system is to be provided for an existing sheet pile bulkhead about 660 LF in length by 48 FT high and is constructed of PZ 27 steel sheet piles. The sheet pile was coated between the 8 and 40 Ft depths, and the top 10 FT of the sheet pile was encased in a reinforced concrete pile cap. Electrical continuity across each pile is provided by existing bonding straps welded across each pile joint. The bonding straps are electrically connected together by bonding wires. The bulkhead is anchored via steel tie rods to an 625 FT long by eight feet high steel sheet pile deadman set back 85 FT from the bulkhead. The tie rods are coated, wrapped and enclosed in PVC sleeves along its entire length except near the turnbuckle. Electrical continuity to and across the turnbuckles is provided by existing bond wires between the turnbuckle and the rod connected to each side of the turnbuckle. The deadman is constructed of coated steel PZ 27 sheet piles. Electrical continuity across each pile is provided by existing bonding straps welded across each pile joint. Refer to Technical Paper 17 for example calculations for a water side galvanic anode system.

5.12.1 **Design Data.**

A. Seawater Resistivity - 20 ohm-centimeters
B. Design for 2 milliamperes per square foot in the soil, and 1 ma/SF for steel in concrete.
C. High silicon chromium bearing cast iron anodes will be used.
D. The design structure to electrolyte potential for the protected structure will be – 850 mv.
E. Design life: 15+ years
F. Coating Efficiency:

Steel sections encased in concrete:	90% (0.9)
Steel sections exposed to seawater:	80% (0.8)
Steel sections below mudline:	70% (0.7)

5.12.2 **Calculations.**

5.12.2.1 **Calculate Total Surface Area of Sheet Pile.**

1. Bulkhead. The bulkhead is constructed of PZ-27 steel sheet piles. PZ-27 sheet pile has a width of 18 inches and a surface area of 2.5 SF/LF on face of the pile. The number of sheet piles (N_{SP}) can be calculated as follows:

$$N_{SP} = \frac{\text{Running Length of sheet pile wall (in inches)}}{\text{18 inches}}$$

The lengths of the bulkhead and deadman anchor wall are 660 LF and 625 LF respectively. The following table summarizes the number of piles in each wall.

SHEET PILE	WALL RUNNING LENGTH (INCHES)	NO. OF SHEET PILES (N_{SP})
BULKHEAD	7,920	440
ANCHOR WALL	7,500	417

The surface area for the bulkhead can be calculated using the following equation:

$$A_{SP} = N_{SP} \text{ X Length of sheet pile X 2.5 SF/LF}$$

The bulkhead can be divided into the following zones:

- Land side, encased in concrete, sheet pile bare
- Land side, encased in concrete, sheet pile coated
- Land side, exposed to soil, sheet pile coated
- Land side, exposed to soil, sheet pile bare

The following table summarizes the surface areas for each zone.

Sheet Pile Zone			No. of Piles	Pile Length (LF)	Surface Area (SF)
Land side	**Concrete**	**Bare**	440	8	8,800
		Coated	440	2	2,200
	Soil	**Bare**	440	8	8,800
		Coated	440	30	33,000

2. Tie Rods. There are 153 tie rods, coated, wrapped, and installed in PVC sleeves. Only the portions of the tie rod at the turnbuckle and on the back side of the anchor wall are exposed to the soil. An estimated length of two LF will account for the exposed tie rod and turnbuckle. The tie rods are 2.5 inches in diameter. Since the tie rods are threaded at the turnbuckle and anchor wall, assume that the steel is bare. Calculate the surface area as follows.

$$\begin{aligned} A_{TR} &= \pi \text{ x } d \text{ x } L \text{ x Number of tie rods} \\ &= 3.14 \text{ x } ({}^{2.5"}/_{12"}) \text{ x } 2 \text{ LF x } 153 \\ &= 200 \text{ SF} \end{aligned}$$

3. Anchor Wall. Both sides of the anchor wall are coated and exposed to the soil. The surface area for both sides of the pile is 5 SF/LF. The

length of each anchor wall pile is 8 LF. The total anchor wall surface area is:

$$A_{AW} = 417 \text{ piles } X \ 8 \text{ LF } \ 5 \text{ SF/LF}$$
$$= 16{,}680 \text{ SF}$$

5.12.2.2 **Calculate the Current Required for Protection of the Sheet Pile.** The current requirement is calculated using the equation:

$$I_R = \text{Surface area } X \ (1 - CE) \times J$$

where
I_R = Cathodic protection current required
CE = coating efficiency
J = current density

The following table summarizes the current requirements.

LAND SIDE						
Structures/Zones			**Surface area (SF)**	**CE**	**J (ma/SF)**	**Current Req'd (ma)**
Sheet pile Bulkhead	**Concrete**	**Bare**	8,800	0	1	8,800
		Coated	2,200	0.9	1	220
		25% of above for concrete cap rebar				2,255
	Soil	**Bare**	8,800	0	2	17,600
		Coated	33,000	0.7	2	19,800
Tie Rods	**Soil**	**Bare**	200	0	2	400
Sheet pile Anchor Wall	**Soil**	**Coated**	16,680	0.7	2	10,008
Total Land Side Current Required						59,083
					or	59.1 amps

Use an 80 ampere rectifier. The extra current capacity will allow for additional coating deterioration, system aging, and current loss to the water side of the sheet pile.

5.12.2.3 **Calculate the Quantity of Anodes.**

Use high silicon chromium bearing cast iron (HSCBCI) tubular anodes. The quantity of anodes must be calculated to meet three different parameters, design life, anode bed resistance, and anode maximum current discharge. The required quantity of anodes will be the largest of the three calculated quantities.

1. First calculate the quantity of anodes to meet design life

$$N_L = \frac{Y\ S\ I_R}{W\ U}$$

where:

I_R = Current required = 59.1 amps
N_L = Number of anodes to meet design life
S = Anode consumption rate = 1 lb/amp-yr)
U = Anode utilization factor = 0.8
W = Weight of one anode (lb)
Y = CP system design life = 20 years

*** **IMPORTANT** ***

Do not end calculations at this point. The quantity of anodes required to meet the recommended maximum anode discharge and the ground bed resistance requirements must still be calculated.

2. Next calculate the quantity of anodes to meet recommended maximum anode current discharge

$$N_D = \frac{I}{A_A \times I_A}$$

where:

I = Current required (59.1 amps)
A_A = Anode surface area (SF)
I_A = Max. recommended anode discharge current density (1 amp/SF)

*** **IMPORTANT** ***

Do not end calculations at this point. The quantity of anodes required to meet the ground bed resistance requirements must still be calculated.

3. Calculate quantity of anodes to meet 1-ohm ground bed design

   The anodes will be installed in a shallow, distributed, vertical anode bed. The resistance of the anode bed can be approximated by the following equation:

$$N_R = \frac{0.0052\,\rho}{R_S \times L} \times [\ln(8L/d) - 1]$$

where
d = diameter of anode backfill column (1 FT)
L = length of the anode backfill column (LF)
N_R = quantity of anodes to meet the anode bed design resistance
R_S = anode bed design resistance (1 ohm)
ρ = soil resistivity (6,000 ohm-cm)

4 Determine quantity of anodes. The following table summarizes the above calculations for various common tubular anode sizes:

CALCULATED ANODE QUANTITIES							
Anode Size	**Weight (LB)**	**Area (SF)**	**Backfill Length (LF)**	**Backfill Dia. (ft)**	**N_L**	**N_D**	**N_R**
2.66" x 42" (TA1)	31	2.4	5.5	1	46	25	16
2.19" x 42" (TA2A)	23	2.0	5.5	1	62	30	16
2.19" x 60" (TACD)	32	2.8	7.0	1	45	22	14
2.66" x 60" (TAD)	45	3.5	7.0	1	32	18	14
3.75" x 60" (TAM)	60	4.9	7.0	1	23	13	14
4.75" x 60" (TAJ)	78	6.2	7.0	1	19	10	14
2.66" x 84" (TA3)	63	4.9	9.0	1	23	13	12
3.75" x 84" (TA4)	85	6.9	9.0	1	17	9	12
4.75" x 84" (TA5)	110	8.7	9.0	1	13	7	12

Of the three calculated quantities for a particular anode, the larger quantity of the three must be used to ensure all conditions are satisfied. Considering CP current distribution, use the 23 each 60 LB, 3.75 inch diameter X 60 inch long anodes. Install the anodes so that the bottom of the anode is about one foot above the bottom of the hole. Provide anode with factory connected lead wires of sufficient length to reach the anode junction box without splicing.

5.12.2.4 **Calculate the Total Circuit Resistance (R_T).**

1. Calculate the anode bed circuit resistance (Rs) using the appropriate numbers from the above table:

$$R_S = \frac{0.0052\ \rho}{N \times L} \times [\ln(8L/d) - 1]$$

$$= 0.56 \text{ ohm}$$

2. Calculate the anode cable resistance (R_C)

   Each anode lead will run directly back to the anode junction box, so the parallel cable resistance is estimated to be equivalent to a 230 LF length of cable. Use No. 4 copper wire for the anode leads. The cable resistance is estimated as follows:

$$R_C = R_{\#4} \times \text{length of cable}$$

$$= 0.00025 \text{ ohm/LF} \times 230 \text{ LF}$$
$$= 0.06 \text{ ohm}$$

3. Calculate total circuit resistance (R_T)

   The total circuit resistance is 0.56 ohm + 0.06 ohm = 0.62 ohm

5.12.2.5 **Calculate the Rectifier Output Voltage (V_R) Using Ohm's Law.**

$$V_R = I_{rect} \times R_T \times 125\%$$
$$= 59.1 \text{ amps} \times 0.62\ \Omega \times 1.25$$
$$= 45.8 \text{ volts}$$

Use the next highest nominal size rectifier rated for 50 volts DC.

5.12.2.6 **Calculate the Rectifier Input Power**

Available power is 480/277 volts. For rectifiers of the size specified above, use three phase 480 volt AC input voltage. Three phase rectifiers are more efficient and long term power costs outweigh the higher initial costs for the rectifier. Rectifier input power is calculated as follows:

$$P = \frac{V_R \times I_R}{\text{rectifier efficiency}}$$

$$= \frac{50 \text{ volts} \times 80 \text{ amps}}{0.85}$$

$$= 4{,}705 \text{ VA say } 5 \text{ KVA}$$

AC input current is calculated to be:

$$I_{AC} = \frac{P}{V_{AC} \times 1.732}$$

$$= \frac{5{,}000 \text{ VA}}{480 \text{ volts} \times 1.732}$$

$$= 6 \text{ amps}$$

The sheet pile bulkhead is not located near a building where an electrical panel can be used. Therefore, the rectifier will be located adjacent to a three phase, 480 volt transformer station.

5.12.2.7 **Short Circuit Calculations**

A. Transformer Full Load Current (I_{FL})

$$I_{FL} = \frac{VA}{V_{AC} \times \sqrt{3}}$$

$$= \frac{500{,}000 \text{ VA}}{480 \text{ volts} \times 1.732}$$

$$= 601 \text{ amps}$$

B. Fault Current at Transformer Secondary (I_{SC}).

$$I_{SC} = \frac{I_{FL}}{\%Z_T/100}$$

$$= \frac{601}{4.5/100}$$

= 13,356 Amps

Therefore, use 18,000 amp I.C. service breaker.

5.12.2.7 **Summary**

Anodes: 23 each high silicon chromium bearing cast iron tubular anodes, with dimensions of 3.75 inches in diameter x 60 inches long, and weighing 63 LB. Locate the anodes 22 feet from each end of the bulkhead and at 28 feet spacing in between.

Anode Supplied by manufacturer consisting of #4 AWG wire with HMWPE insulation. One end is factory connected to the anode. The anode leads should be long enough to extend to the junction box without splicing.

Rectifier:
Type: Oil cooled, enclosure suitable for outdoors use.
AC Input: 480 volt, 6 amps, 60 Hz, three phase
DC Output: 50 volts, 80 amps
Efficiency: 85% minimum

End of Example

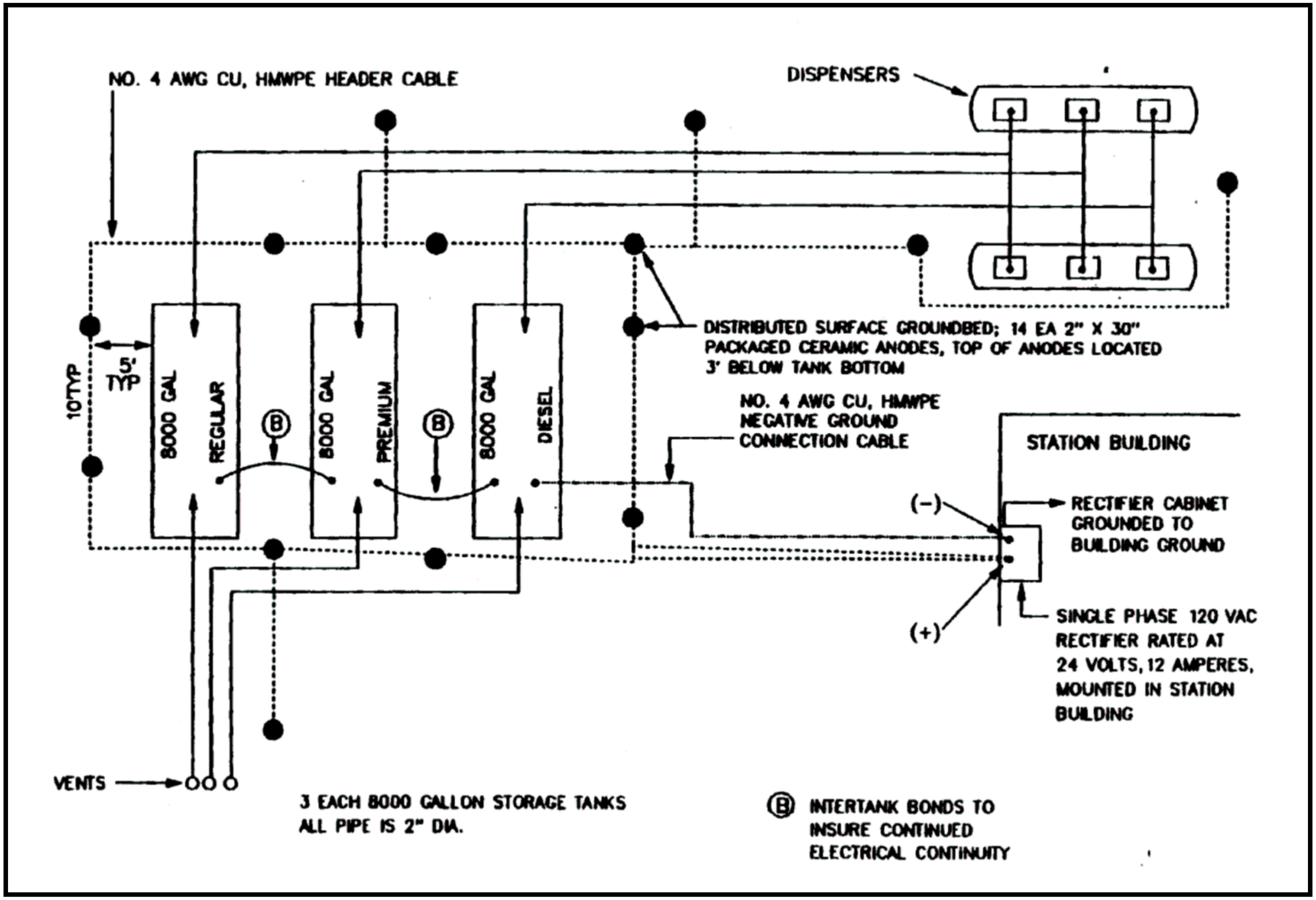

Figure 40
Cathodic Protection of Multiple Underground Storage Tanks

where

A_T = Surface area of storage tank (ft²)
r_T = Radius of tank = 48 in = 4 ft
D_T = Diameter of tank = 96 in = 8 ft
L_T = Length of tank = 21 ft - 3 in

$$A_T = [2 \times 3.1416 \times (4)^2] + 3.1416 \times 8 \times 21.25$$

$$= 634.6 \text{ say } 635 \text{ ft}^2$$

For all three tanks, the total surface area is

$$A_T = 3 \times 635 \text{ ft}^2$$

$$= 1905 \text{ ft}^2$$

B. Piping

$$A_P = \pi D_P L_P$$

where
A_P = Surface area of piping (ft²)
D_P = Diameter of pipe = 2.375 in. or 0.198 ft for 2 in. nominal size pipe
L_P = Length of piping = 750 ft

$$A_P = 3.1416 \times 0.198 \times 750$$

$$= 467 \text{ ft}^2$$

C. Total Surface Area

$$A_P = A_T + A_P$$

$$A = 1905 + 467$$

$$= 2372 \text{ ft}^2$$

5.3.2.2 **Verify the Current Requirement (I).**

$$I = (A)(I')(1 - CE)$$

where

I = Current requirement (amps)
A = Total surface area of tanks and piping = 2372 ft²
I' = Assumed current density = 2 mA/ft²
CE = Pipe/tank coating efficiency = 0.00 for bare steel

$$I = 2372 \times 2 \times (1 - 0)$$

$$= 4744 \text{ mA or } 4.7 \text{ amps}$$

The 4.7 amp would be reasonable for the facility if it were electrically isolated from other buried metals such as the building ground system. The actual current requirement of 8.2 amp occurs because of current loss to these other buried metal structures and is also reasonable in relation to that calculated for an isolated facility.

5.3.2.3 **Select An Anode and Calculate the Number of Anodes Required (N_L) to Meet the Design Life Requirements.**

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

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

where
I = Current requirement = 8.2 amps
I_A = Ceramic rod anode current rating = 1.0 amps/anode
N_L = Quantity of anodes to meet design life

$$N = \frac{8.2}{1.0}$$

$$= 8.2 \text{ use 9 anodes}$$

5.3.2.4 **Calculate the Quantity of Anodes to Meet the Maximum Anode Bed Resistance of 2.5 Ohms (N_R).**

$$R_a = [(0.0052\rho)/(N_R)(L)] \ X \ [\ln (8L/d) - 1 + (2L/S)(\ln 0.656N_R)]$$

where

N_R = Quantity of anode/backfill columns
R_a = Anode ground bed resistance (2.5 ohms maximum)
ρ = Soil resistivity = 4,500 ohm-cm
L = Anode backfill column length = 5 feet
d = Anode backfill column diameter = 2 in. = 0.167 feet
I = Current requirement = 8.2 amperes
S = Spacing between anodes. Assume 10' spacing between anode/backfill columns. A distributed anode array does not lend itself to an exact calculation using the equation above because the anodes are positioned at various locations and are not located in a straight line. The above equation assumes a straight-line configuration; however, to approximate the total anode-to-earth resistance, the equation may be used.

Initially, try 9 anodes, the quantity required to meet the design life

$$R_A = \frac{0.0052 \times 4500}{9 \times 5} \left[\ln \left(\frac{8 \times 5}{0.167} \right) - 1 + \left(\frac{2 \times 5}{10} \right) (\ln (0.656 \times 9)) \right]$$

$$= 3.26 \text{ ohms}$$

The resistance for 9 anodes 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 2.24 ohms.

Of the above-calculated quantities for the anodes, 9 to meet the design life and 14 to meet the maximum anode bed resistance requirement, the larger quantity of the two must be used to ensure all conditions are satisfied. Therefore, use 14 each 0.125 in x 4 ft long ceramic rod anodes pre-packaged in backfill in 2-in. by 60-in. canisters.

5.3.2.5 **Calculate the Total Circuit Resistance (R_T).**

$$R_T = R_A + R_w + R_C$$

where,

R_T = Total circuit resistance
R_A = Anode bed resistance
R_w = Header cable/wire resistance
R_C = StructurTP16-to-earth resistance

A. Ground bed resistance (R_A) = 2.24 ohms from section TP16-5.3.2.4

B. Header cable/wire resistance (R_W):

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

where,

R_w = Header cable/wire resistance

L_W = 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 = ½ x 300 ft = 150 ft.)

R_{MFT} = Resistance per 1000 lineal feet of No. 4 AWG cable that has been selected for ease of handling = 0.254 ohms/1000 LF.

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

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

C. Structure-to-earth resistance (R_C):

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

D. Calculate total resistance (R_T):

$$R_T = R_A + R_w + R_C$$

$$= 2.26 + 0.04 + 0$$

$$= 2.30 \text{ ohms}$$

Since the design requirements call for a maximum ground bed 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.

5.3.2.6 **Calculate the Rectifier Voltage (V_{REC}).**

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

where,
V_{REC} = Rectifier Voltage (volts)
R_T = Total circuit resistance = 2.30 ohms
I = System current requirement = 8.2 amps
120% = Rectifier voltage capacity design safety factor

$$V_{REC} = 8.2 \text{ amp} \times 2.3 \text{ ohms} \times 1.2$$

$$= 22.6 \text{ Volts}$$

5.3.2.7 **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.

End of Example

5.4 **Elevated Steel Water Tank.** This impressed current CP design is for an elevated steel water tank that has not been built. Hence, it is not possible to determine the current requirements, etc., by actual measurements. Calculated estimates have been used.

5.4.1 **Design Data.**

A. Tank capacity - 500,000 gallons
B. Tank height (from ground to bottom of bowl) - 115 feet
C. Diameter of tank - 56 feet
D. High water level in tank - 35 feet
E. Overall depth of tank - 39 feet
F. Vertical shell height - 11 feet
G. Riser pipe diameter - 5 feet
H. Shape of tank - Ellipsoidal, both top and bottom
I. All internal surfaces are uncoated
J. Design for maximum current density - 2 mA/ft²
K. Electric power available 120/240 V ac, single-phase
L. String-type HSCBCI anodes are used
M. Design life - 10 years
N. Water resistivity - 4,000 ohm-cm
O. Tank water must not be subject to freezing
P. Assumed deterioration rate - 1.0 lbs/A yr
Q. Anode efficiency (assumed) - 50 percent

5.4.2 **Calculations.**

5.4.2.1 **Area of Wetted Surface of Tank Bowl (see Figure 41).**

A. Top section (T)

$$A_T = 2 \pi r x \text{ (approximate)}$$

where

r = 28 feet (radius of tank)
x = 10 feet
A_T = 2 x 3.1416 x 28 x 10
A_T = 1759 ft²

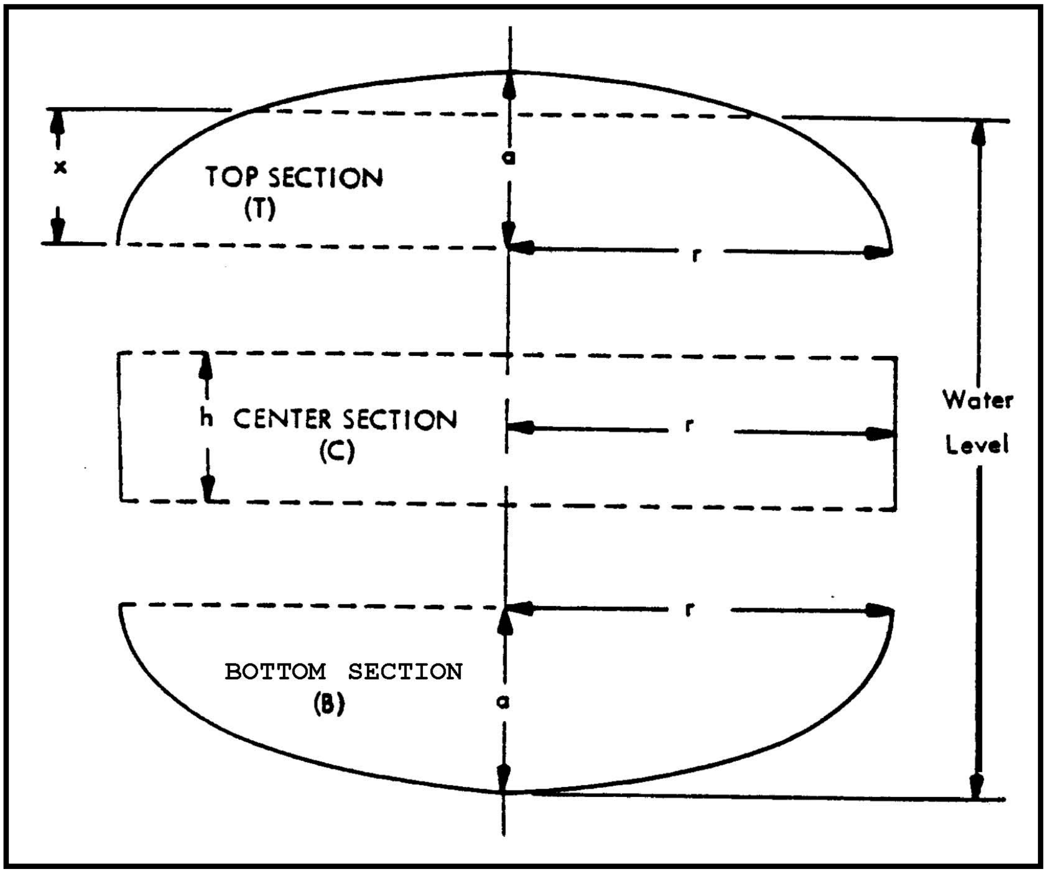

Figure 41
Segmented Elevated Tank for Area Calculations

B. Center section (C):

$$A_c \;=\; 2\,\pi\,r\,h$$

where

r = 28 feet (radius of tank)
X = 11 feet
A_C = 2 x 3.1416 x 28 x 11
A_C = 1935 ft²

C. Bottom section (B):

$$A_B \;=\; \sqrt{2}\,\pi\,r\,\sqrt{a^2 + r^2}$$

where

r = 28 feet (radius of tank)
a = 14 feet

$$A_B = \sqrt{2} \times 3.1416 \times 28 \sqrt{14^2 + 28^2}$$
$$A_B = 3{,}894 \text{ ft}^2$$

D. Total wetted area of tank bowl:

$$\begin{aligned} A_{TB} &= A_T + A_C + A_B \\ &= 1{,}759 + 1{,}935 + 3{,}894 \\ &= 7{,}588 \text{ ft}^2 \end{aligned}$$

5.4.2.2 **Area of Riser Pipe.**

$$A = 2 \pi r_R h_R$$

where

r_R = 2.5 feet (radius of riser)
h_R = 115 feet (height of riser)

$$\begin{aligned} A_R &= 2 \times 3.1416 \times 2.5 \text{ feet} \times 115 \\ &= 1{,}806 \text{ ft}^2 \end{aligned}$$

5.4.2.3 **Maximum Design Current for Tank.**

$$\begin{aligned} I_T &= 2.0 \text{ mA/ft}^2 \times 7{,}588 \text{ ft}^2 \\ &= 15{,}176 \text{ mA or } 15.2 \text{ A} \end{aligned}$$

5.4.2.4 **Maximum Design Current for Riser.**

$$\begin{aligned} I_R &= 2.0 \text{ mA/ft}^2 \times 1{,}806 \text{ ft}^2 \\ &= 3{,}612 \text{ mA or } 3.6 \text{ A} \end{aligned}$$

5.4.2.5 **Minimum Weight of Tank Anode Material.**

$$W = YSI/E$$

where

W = weight of anode material =
Y = design life = 10 years
S = anode deterioration rate = 1.0 lb/A-yr
I = maximum design current = 15.2 A
E = anode efficiency = 0.50

$$W = \frac{10 \times 1.0 \times 15.2}{0.50}$$

$$= 304 \text{ pounds}$$

5.4.2.6 **Minimum Weight of Riser Anode material.**

$$W = YSI/E$$

where

Y = 10 years
S = 1.0 lbs/A yr
I = 3.62 A
E = 0.50

$$W = 10 \times 1.0 \times 3.62/0.50$$
$$= 72.4 \text{ pounds}$$

5.4.2.7 **Radius of Main Anode Circle.**

$$W = \frac{D\ N}{2\ (\pi + N)}$$

where

D = 56 feet
N = Assumed number of anodes = 10

$$W = \frac{56 \times 10}{2\ (3.1416 + 10)}$$

$$= 21.3 \text{ feet, use 22 feet}$$

5.4.2.8 **Spacing of 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 circumferential distance between anodes.

A. Circumferential spacing:

$$C = \frac{2\ \pi\ r}{N}$$

where

r = radius of anode circle = 22 feet
N = assumed number of anodes = 10

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

$$= 13.8 \text{ feet, use 14 feet}$$

B. Cord spacing is approximately the same as circumferential spacing: 14 feet will be used (see Figure 42).

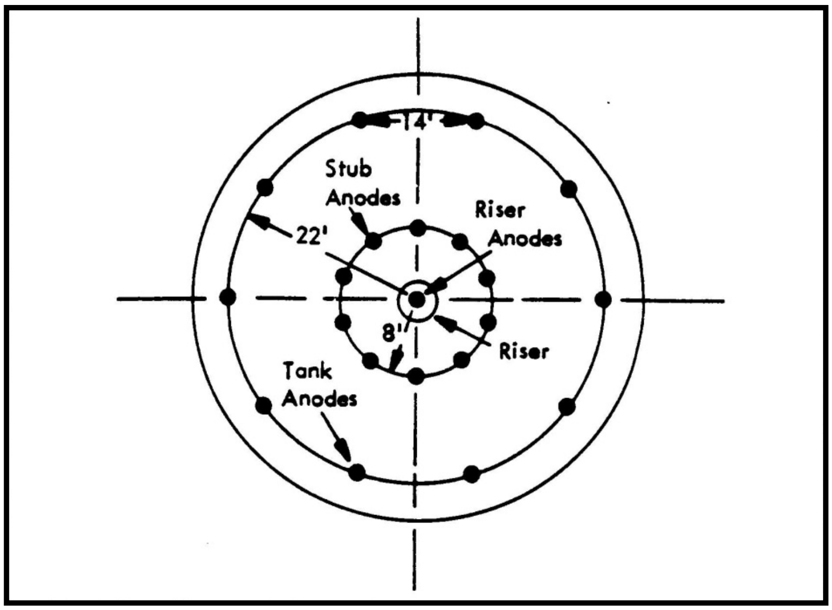

Figure 42
Anode Spacing for Elevated Water Tank

5.4.2.9 **Selection of Main Anodes.**

A. Size of anode units selected is 1-1/8 inch outer diameter by ¾ inch inside diameter by 9 inches long. This is a standard sausage type anode that weighs one pound, and has an effective surface area of 0.25 ft^2.

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

$$\text{Number of units} = \frac{304}{10 \times 1}$$

$$= 30.4 \text{ say } 31 \text{ units per string}$$

C. Because the internal tank surfaces are uncoated, a maximum structure-to-electrolyte potential is not a limiting factor. However, because it is desired to limit the anode current at or below the manufacturer's recommended discharge current rate of 0.025 Amp for this type of anode, the minimum number of anode units per string will be

$$\text{Number of units} = \frac{15.2 \text{ Amps}}{10 \times 0.025}$$

$$= 60.8 \text{ say } 61 \text{ units per string}$$

This quantity of anode units per string is not practical for the tank bowl since the distance between the anode hanger and the bottom of the bowl is only 28 feet. Table 15 shows the maximum recommended discharge current rate per anode for various types of anodes to ensure a minimum 10-year life. Using the type B anode, only three anode units per string are required. The manufacturer does not recommend the use of more than two type B anodes units per anode string assembly because of their fragile nature. Therefore, the best anode unit choices for the main anode strings are the type C or type 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 A x 10 strings = 20 A. These anodes are spaced as shown in Figure 43.

NOTE: The anodes chosen in this example were chosen to illustrate some of the many technical considerations during the design of cathodic protection. For this example if HSCBCI anodes are tubular anodes, 2-3/16 inch by 8 inch, weighing 4.3 pounds each, should be used instead of CDD anodes.

TABLE 15. TECHNICAL DATA - COMMONLY USED HSCBCI ANODES					
ANODE			ANODE MAX. DISCHARGE (A)	SURFACE AREA (ft²)	MAX. CURRENT DENSITY (A/ft²)
TYPE	SIZE (in.)	WEIGHT (lb)			
TA-FW	2-3/16 x 8	4.3	0.025	0.22	0.1
FW[1]	1-1/8 OD x 9	1	0.025	0.2	0.1
FC[2]	1-1/2 x 9	4	0.075	0.3	0.25
G-2	2 OD x 9	5	0.100	0.4	0.25
G-2-1/2	2-1/2 x 9	9	0.20	0.5	0.40
B[3,4]	1 x 60	12	0.50	1.4	0.36
C	1-1/2 x 60	25	1.00	2.0	0.50
CDD[3]	1-1/2 x 60	26	1.00	2.0	0.50
M[3]	2 x 60	60	2.5	2.8	0.9
SM	4-1/2 x 60	20	10.0	5.5	1.8
K-6	6 x 2-1/2	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	2-3/16 x 84	46	6.4	4.0	1.6

[1] For elevated fresh water tank.
[2] For distributed system in ground trench.
[3] Each end enlarged with cored opening for wire.
[4] Not more than 2 anodes per assembly.

D. Anode current density is computed as follows:

$$\text{Anode current density} = \frac{15.2 \text{ Amps}}{2 \times 10 \times 2}$$

$$= 0.38 \text{ A/ft}^2$$

5.4.2.10 **Resistance of Main Anodes.**

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

where

ρ = 4,000 ohm-cm
D = 56 feet
L = 2 x 5 feet = 10 feet
a = 44 x 0.275 = 12.1 feet (0.275-equivalent diameter factor from curve - see Figure 8-61)

$$R = \frac{0.012 \times 4{,}000 \times \log (56/12.1)}{10}$$

$$= 3.19 \text{ ohms}$$

A. However, the L/d ratio of two 1-1/2-inch diameter by 60-inch long anodes in tandem is less than 100 and thus the fringe factor must be used.

$$L/d = \frac{2 \times 60}{1.5}$$

$$= 80 < 100$$

B. The fringe factor from the curve in Figure TP16-45 corresponding to the L/d ratio is 0.95.

R (adjusted) = 0.95 R = 0.95 x 3.19 = 3.03 ohms

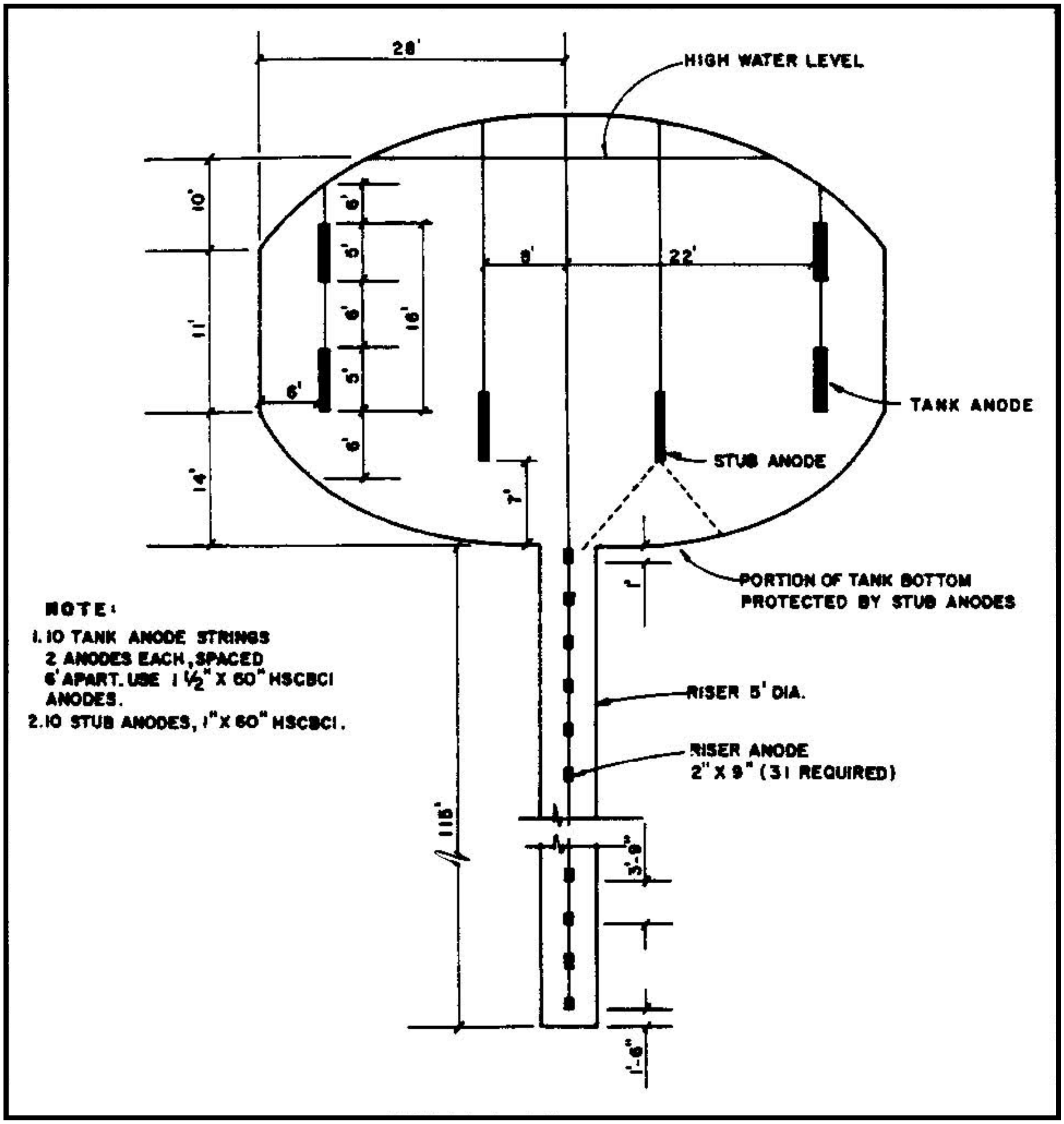

Figure 43
Anode Suspension Arrangement for Elevated Steel Water Tank

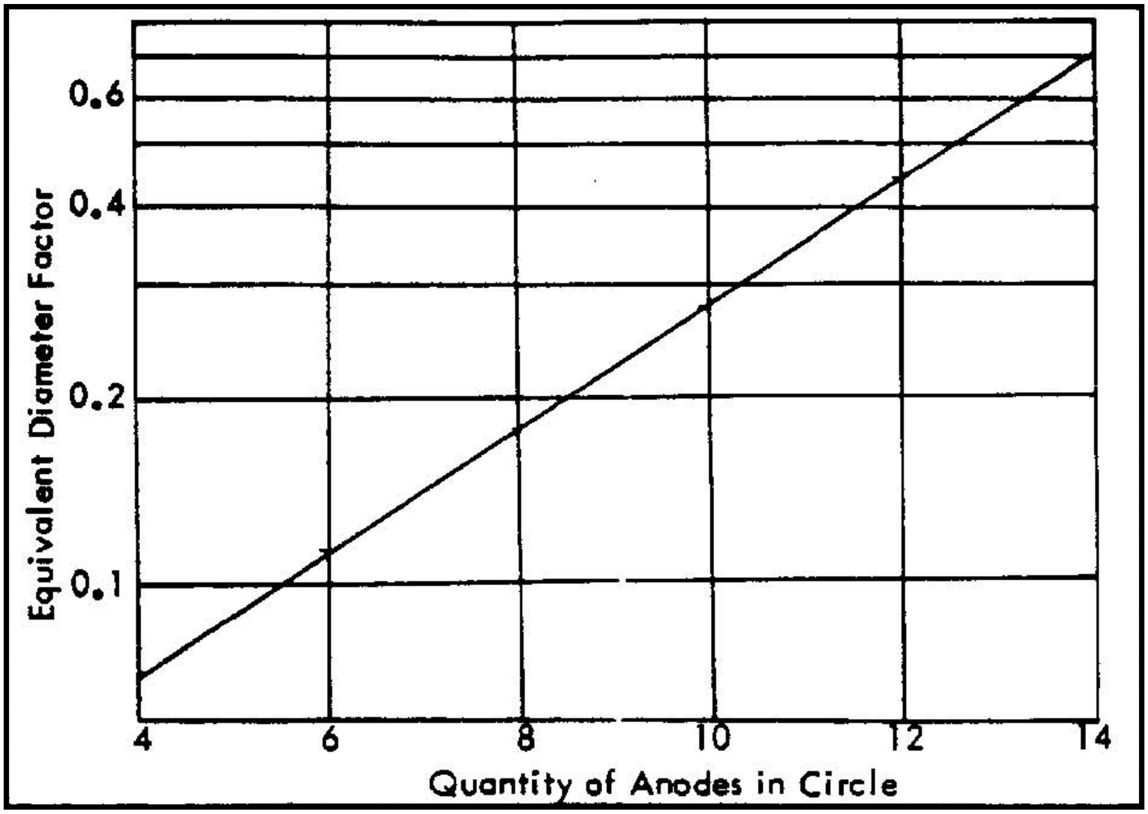

Figure 44
Equivalent Diameter for Anodes in a Circle in a Water Tank

5.4.2.11 **Stub Anodes.**

A. In the design of an elevated water tank, the need for stub anodes must be justified. The main anode radius has been calculated to b 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 1-1/2 times the spacing o the anode from the bottom.

B. The anode suspension arrangement for the tank under consideration is shown in Figure 43. Thus, it can be seen that stub anodes are required for this design. Ten stub anodes are arranged equally space on a circumference that has a radius of 8 feet in a manner illustrated in Figure 43. For smaller diameter tanks, stub anodes may not be required.

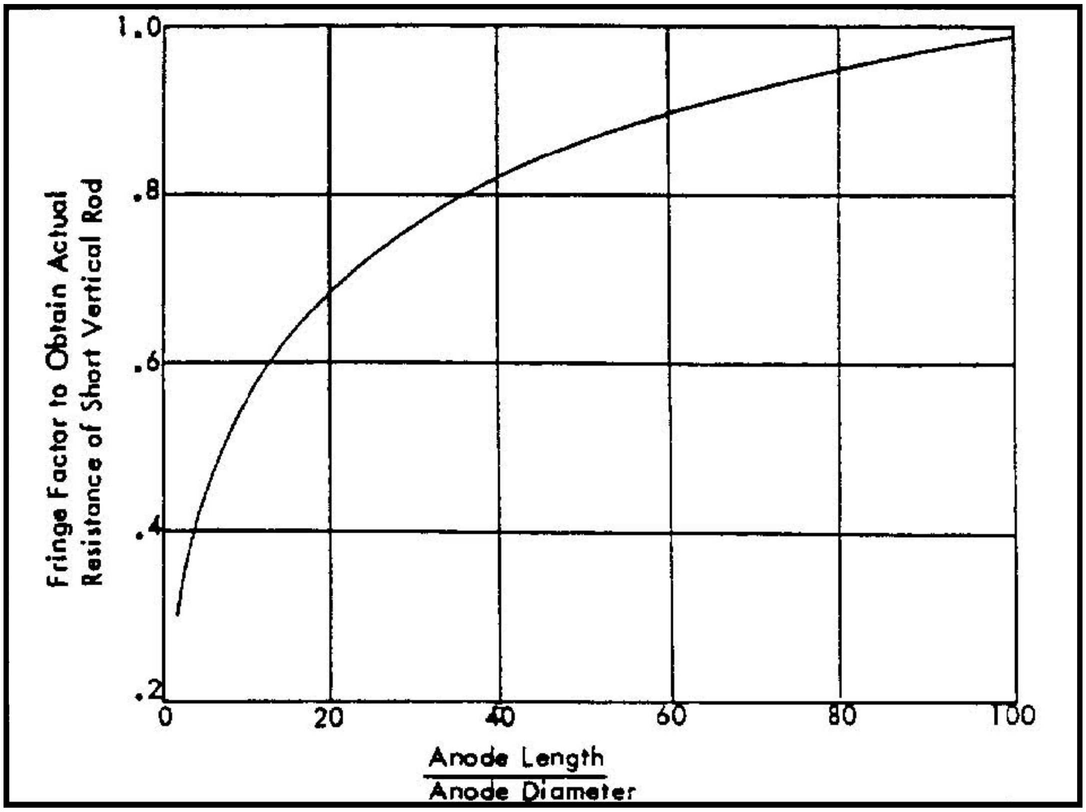

Figure 45
Fringe Factor for Stub Anodes

5.4.2.12 **Current Division Between Main and Stub Anodes.**

A. Area of tank bottom protected by stub anodes (see Figure 43):

$$A_s = \pi (r_2^2 - r_1^2)$$

where
r_2 = radius of protected segment (13 feet)
r_1 = radius of riser (2.5 feet)

$$A_s = 3.1416\ (169 - 6.25)$$
$$= 511.3\ ft^2$$

B. Maximum current for stub anodes:

$$I_s = 2.0\ mA/sf \times 511.3\ ft^2$$
$$= 1022.6\ mA \text{ or } 1.02\ A$$

C. Maximum current for tank bowl = 15.2 A.

D. Maximum current for the main anodes:

$$I_m = 15.2 - 1.02$$
$$= 14.2 \text{ A}$$

5.4.2.13 **Rectifier Voltage Rating.**

A. Circuit resistance of electrical conductor to main anodes. Wire size No. 2 AWG, 0.159 ohm/1,000 feet, estimated length 200 feet:

$$R = \frac{200}{1000 \times 0.159}$$

$$= 0.032 \text{ ohm}$$

B. Voltage drop in main anode feeder:

$$E = IR$$

where

$I = 14.2$ A
$R = 0.032$ ohm

$$E = 14.2 \times 0.032$$
$$= 0.45 \text{ V}$$

C. Voltage drop through main anodes:

$$E = IR$$

where

$I = 14.2$ A
$R = 3.03$ ohms

$$E = 14.2 \times 3.03$$
$$= 43.0 \text{ V}$$

D. Total voltage drop in main anode circuit:

$$E_T = 0.45 + 43.0$$
$$= 43.45 \text{ or } 45.0 \text{ V}$$

Use a multiplying factor of 1.5, or 67.5 V.

E. The nearest commercially available rectifier meeting the above requirement is a single-phase, 80-V unit.

5.4.2.14 **Selection of 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 measuring 1-1/2-inch by 9 inches. Use one anode per string as shown in Figure 43. Compute anode current density as follows:

$$\text{Output} = \frac{1.02}{10 \times 0.03}$$

$$= 0.34 \text{ A/ft}^2$$

Because this exceeds the recommended maximum anode current density (refer to Table 15), the Type B anode is the best choice.

5.4.2.15 **Resistance of Stub Anodes.**

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

where

ρ = 4,000 ohm-cm
D = 56 feet
L = 5 feet
a = 16 x 0.275 = 4.4 feet (factor from Figure 44)

$$R = \frac{0.012 \times 4{,}000 \times \log (56/4.4)}{5}$$

$$= 10.6 \text{ ohms}$$

$$L/d = \frac{60}{1}$$

$$= 60 < 100$$

The fringe factor from the curve in Figure 45 corresponding to the L/d ratio is 0.9.

$$R\ (\text{adjusted}) = 10.6 \times 0.90\ R = 9.54\ \text{ohms}$$

5.4.2.16 **Voltage Drop in Stub Anode Circuit.**

A. Electrical conductor to stub anodes. Wire size No. 2 AWG, 0.159 ohms/1,000 feet, estimated length 200 feet:

$$R = \frac{200}{1000 \times 0.159}$$

$$= 0.032\ \text{ohm}$$

B. Voltage drop in stub anode feeder.

$$E = IR$$

where

$I = 1.02$ A
$R = 0.032$ ohm

$$E = 1.02 \times 0.032$$
$$= 0.033\ \text{V}$$

C. Voltage drop in anode suspension conductors. Estimated length 50 feet, No. 2 AWG, 0.159 ohms/1,000 feet:

$$R = \frac{50}{1000 \times 0.159}$$

$$= 0.008\ \text{ohm}$$

$$E = IR$$

where

$I = 1.02/10 = 0.102\ A$
$R = 0.008\ ohm$

$$E = \text{negligible}$$

D. Voltage drop through stub anodes:

$$E = IR$$

where

$I = 1.02\ A$
$R = 9.54\ ohms$

$$\begin{aligned} E &= 1.02 \times 9.54 \\ &= 9.73\ V \end{aligned}$$

E. Total voltage drop in stub anode circuit.

$$\begin{aligned} E_T &= 0.033 + 9.73 \\ &= 9.73\ V \end{aligned}$$

F. Since the stub anode voltage is below the 45 V calculated for the main tank anode circuit, the necessary current adjustment can be accomplished through a variable resistor in the stub anode circuit.

5.4.2.17 **Stub Anode Circuit Variable Resistor.**

A. Criteria for variable resistor. The resistor should be capable of carrying the maximum anode circuit current and have sufficient resistance to reduce anode current by one-half when full rectifier voltage is applied to the anode circuit.

B. Stub anode circuit data:

Rectifier output = 80 V
Anode current = 1.02 A
Anode resistance = 9.54 ohms

C. Variable resistor rating:

$$R = E/I$$

where

$E = 80$ V
$I = 1.02/2$ or 0.51 A

$$R = 80/0.51 = 156.9 \text{ ohms}$$

Ohmic value of resistor = 156.9 - 9.54 = 147.4 ohms
Wattage rating of resistor = $(1.02)^2 \times 147.4$ = 153.4 W

The nearest commercially available resistor size meeting the above requirements is a 175-W, 200-ohm, 1-A resistor.

5.4.2.18 **Resistance of Riser Anodes.** In order to get the maximum desired current in the riser (3.62 A), the resistance limit is calculated as follows:

$$R = E/I$$

where

$E = 43.45$ V
$I = 3.62$ A

$$R = 43.5/3.62 = 12.0 \text{ ohms}$$

5.4.2.19 **Riser Anode Design.**

A. Type FW (1-1/8-inch by 9-inch) string type anodes cannot be used in the riser because the maximum anode current discharge of 0.025 A per anode would be exceeded. The number of type FW anodes required would be 145 and continuous throughout the riser. This is excessive. The best choice of anode for a flexible riser string is the type G-2 (2-inch by 9-inch) high-silicon cast iron anode.

B. Number of units required:

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

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

where

ρ = 4,000 ohm-cm
D = 5 feet
D = 2 inches or 0.166 feet
R = 12 ohms

$$L = \frac{0.012 \times 4000 \times \log (5/0.166)}{12}$$

$$= 5.92 \text{ feet}$$

Number of units = 5.92/0.75 = 7.9 or 8 units

In order to get 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 1-1/2 times the spacing of the anode from the riser pipe wall.

Riser height = 115 feet
Spacing (center of anode to tank wall) = 2.5 feet
Length of riser protected by one anode = 1.5 x 2.5 = 3.75 feet
Number of units required = 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 amp = 36

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

C. Anode resistance based on the use of 36 anode units:

$$R = (0.012\ \mathbf{r} \log D/d)/L$$

where

r	=	4,000 ohm-cm
D	=	5 feet
D	=	2 inches or 0.166 feet
L	=	36 x 9 inches = 324 inches or 27 feet

$$L = \frac{0.012 \times 4000 \times \log(5/0.166)}{27}$$

$$= 2.63 \text{ ohms}$$

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

5.4.2.20 **Voltage Drop in Riser Anode Circuit.**

A. Electrical conductor to riser anodes. Wire size No. 2 AWG, 0.159 ohms/1,000 feet, estimated length 200 feet:

$$R = \frac{200}{1000 \times 0.159}$$

$$= 0.032 \text{ ohms}$$

B. Voltage drop in riser anode feeder:

$$E = IR$$

where

I	=	3.62 A
R	=	0.032 ohm

$$E = 3.62 \times 0.032$$
$$= 0.116 \text{ V}$$

C. Voltage drop in riser anode suspension cables. Wire size No. 2 AWG, 0.159 ohm/1,000 feet, estimated length 130 feet:

$$R = 130/1{,}000 \times 0.159 = 0.02 \text{ ohm}$$

$$E = IR$$

where

I = 3.62/2
= 1.81 A average (single current does not flow the full length of the anode string)
R = 0.02 ohm

$$E = 1.81 \times 0.02$$
$$= 0.04 \text{ V}$$

D. Voltage drop through riser anodes:

$$E = IR$$

where

I = 3.62 A
R = 2.63 ohms

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

E. Total voltage drop in riser anode circuit:

$$E_T = 0.116 + 0.04 + 9.52$$
$$= 9.69 \text{ V}$$

5.4.2.21 **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 ohms

C. Variable resistor rating:

$$R = E/I$$

where

E = 80 V
I = 3.62/2 = 1.81 A

$$R = 80/1.81 = 44.2 \text{ ohms}$$

Ohmic value of resistor = 44.2 - 2.68 = 41.5 ohms.
Wattage rating of resistor = $(3.62)^2 \times 41.5$ = 543.8 W

The resistor should reduce anode current by one-half when full rectifier voltage is applied. The nearest commercially available resistor size that meets the above requirements is a 750-W, 50-ohm, 3.87-A resistor (rheostat). This rheostat is 10 inches in diameter and 3 inches in depth, and fairly expensive. This rheostat will not fit into most rectifier cases. In addition, the power consumed by the rheostat is considerable. This power creates substantial heat that may damage components within the rectifier case unless adequate ventilation is provided. The problems associated with using a large rheostat can be eliminated by using a separate rectifier for the riser anodes. Although initial cost may be slightly high, power savings will be substantial and damage by heat will be avoided.

5.4.2.22 **Sizing Rectifier for Riser.**

A. Requirements:

DC current output = 3.62 A
Anode circuit resistance = 2.68 ohms
DC voltage required = IR = 3.62 x 2.68 E = 9.70 V

B. Rectifier rating. Standard ratings for a rectifier in this size class are 18 Volts, 4 Amps.

5.4.2.23 **Rectifier DC Rating for Bowl.** Voltage output as previously determined, 80 V. Current rating is 15.2 A. The nearest commercially available rectifier meeting the above requirements is 80 V, 16 A.

5.4.2.24 **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 (see Figure 46).

5.4.2.25 **Discussion of the Design.**

A. The design points out the disadvantages of achieving corrosion control through cathodic protection without the aid of a protective coating. When the interior of a tank is coated, the current requirement is reduced from 60 to 80 percent. On large tanks without coating, larger size and more expensive anodes, wire, and rectifier units must be used. In addition, the power consumed by the uncoated tank is far greater. These additional costs usually exceed the cost of a quality coating system over 10-year period. Corrosion above the water line of a water storage tank is usually severe because of the corrosive nature of condensation. For this reason, protective coatings must be used above the water line on both large and small water storage tanks to mitigate corrosion.

B. For further assistance and guidance in the design of cathodic protection systems for elevated water storage tanks, see Figures 46 through 48.

C. The HSCBCI anodes were selected for this particular design purely for illustrative purposes. It does not mean that this material is superior to other types of anode material. Other acceptable anode materials include platinized titanium or niobium and mixed metal oxide (ceramic) anodes. With the advent of newer tubular center connected anodes, the designer should choose these anodes over the end connected in most cases because of their higher current capability and longer life.

D. For this design, silicon stacks should be specified for the rectifier that protects the bowl and selenium stacks should be specified for the rectifier that protects the riser. Silicon stacks operate more efficiently at high DC output voltages than selenium stacks do but require elaborate surge and overload protection. This protection is not economical in the low power consuming units. A guide for selection of rectifying cells is as follows:

- Use silicon stacks for single-phase rectifiers operated above 72 V dc or three-phase rectifiers operated above 90 V dc.
- Use newer selenium stacks for single-phase rectifiers operated below 72 V dc or threTP16-phase rectifiers operated below 90 V dc.

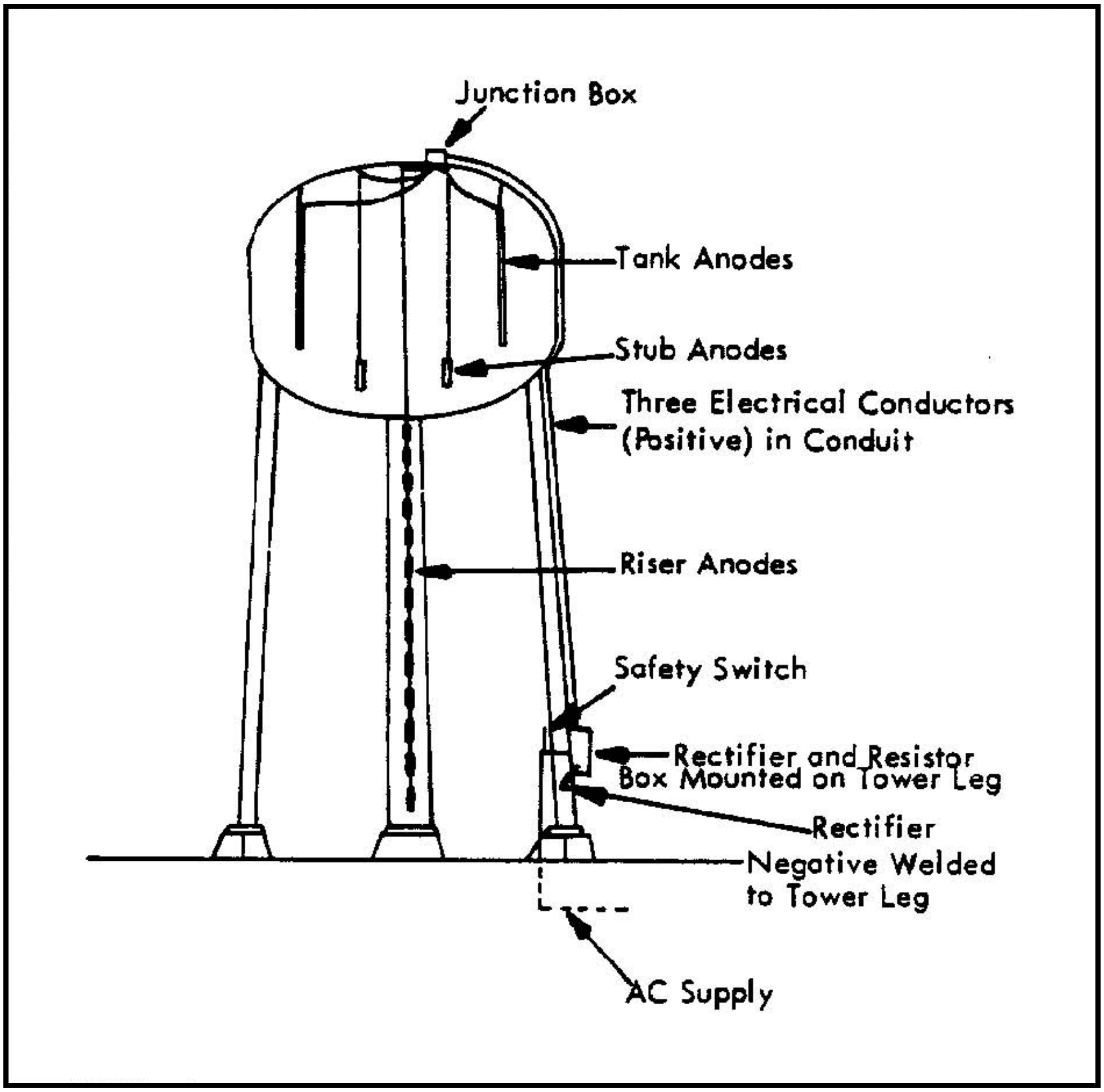

Figure 46
Elevated Steel Water Tank Showing Rectifier and Anode Arrangement

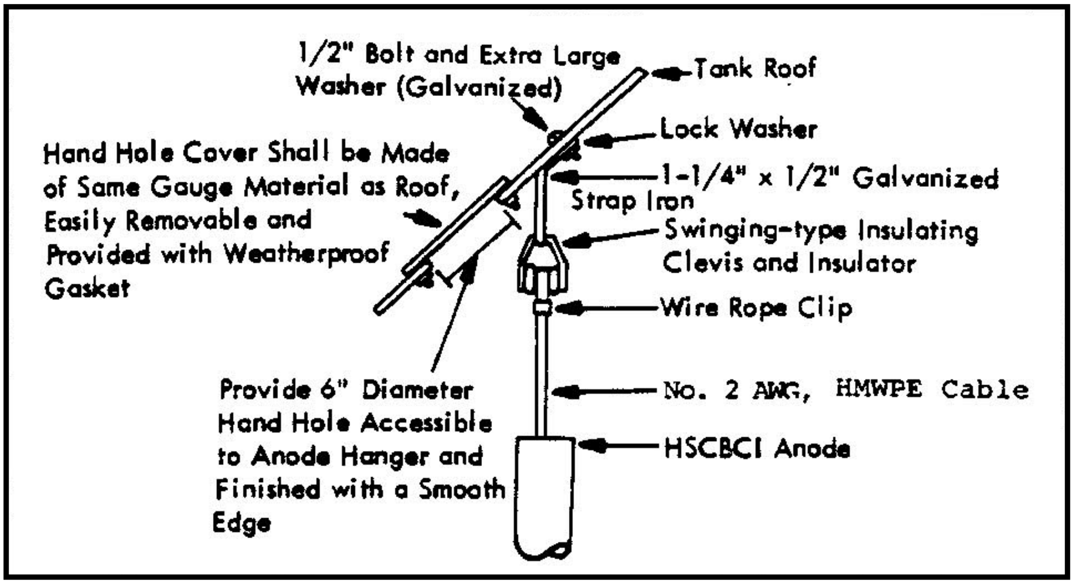

Figure 47
Hand Hole and Anode Suspension Detail for Elevated Water Tank

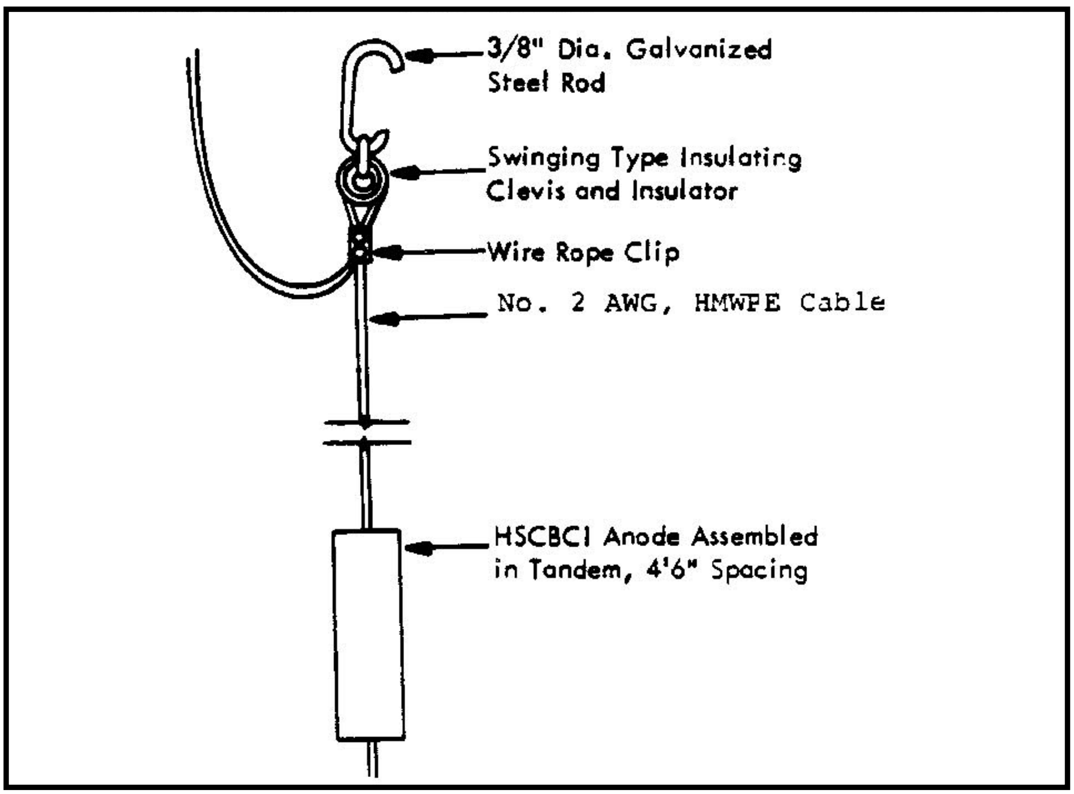

Figure 48
Riser Anode Suspension Detail for Elevated water Tank

End of Example

5.5 Elevated Steel Water Tank Where Ice Is Expected.

Impressed current cathodic protection is designed for an elevated steel water tank (Figure 49). The tank is already built and current requirement tests have been conducted. Anodes cannot be suspended from the tank roof because heavy ice (up to two feet thick) covers the water service during the 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.

5.5.1 Design Data.

a. The water tank is a pedestal spheroid with a ten-inch riser pipe. Only the bowl will be protected because the riser pipe is less than 30 inches in diameter.

b. Tank dimensions are:

   Capacity - 400,000 gallons
   Diameter of tank bowl – 51 ft 6 in
   High water level in tank - 35 feet
   Tank height (from ground to bottom of bowl) - 100 feet

c. Water resistivity - 2,000 ohm-cm

d. Anode Design life - 15 years

e. Wire type ceramic anodes to be used

f. All wetted surfaces are uncoated

g. Area above the high water level is kept well coated

h. Tank water is subject to freezing

i. The cathodic protection circuit resistance must not exceed 2 ohms

j. Electric power available is 120/240 V ac, singlTP16-phase

k. Based on structure current requirement testing on this tank, the current required for adequate cathodic protection is 25 amps. This high current requirement indicates that the tank internal coating is severely deteriorated.

5.5.2 Calculations.

5.5.2.1 Calculate the Length of Wire in Feet (LB) Needed for the Current Required.

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

where

I = Current requirement for adequate protection = 25 amps
I_A = Allowable amp per foot of anode wire (varies depending on desired anode life and diameter

Select the 0.0625 in. diameter copper cored anode wire based on the current requirement of 25 amps and design life of 15 years.

$$L_B = \frac{25}{0.31}$$

$$= 81 \text{ feet}$$

5.5.2.2 **Calculate the Desired Diameter of the Anode Wire Ring (D_R).** Experience shows that the diameter of the anode wire ring should be between 40 and 70 percent of the bowl diameter.

A. Try 40% for the first iteration.

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

Check to determine if the length is adequate for the desired anode life. For an anode ring diameter of 20.5 feet the circumference (anode wire length) is

$$C_R = \pi \times D_R$$

$$= 64.4 \text{ feet}$$

This length is inadequate for 0.0625 in. wire anode (which requires a minimum of 81 feet to meet the desired anode life). Therefore, increase the wire ring (hoop) diameter to 50 percent of the tank diameter.

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

and

$$C_R = \pi \times 25.75$$

$$= 80.9 \text{ feet}$$

This diameter yields an anode length that is still slightly less than that required for a 15-year anode life. Therefore, use a hoop diameter that is about 55 percent of the tank bowl diameter.

$$D_R = 51.5 \text{ ft} \times 55\% = 28.3, \text{ say } 29 \text{ ft}$$

and

$$C_R = \pi \times 29.0$$

$$= 91 \text{ feet}$$

5.5.2.3 **Calculate the Anode-to-Water Resistance (R_A) for the 0.0625 in. Diameter Anode Wire.**

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

where,

r = Water resistivity = 2,000 ohm-cm
D_R = Anode ring (hoop) diameter = 29 Ft
D_A = Diameter of the anode wire anode = 0.00521 Ft (0.0625 in.)
H = Anode depth below water surface determined from the following calculations (The anode depth below the high water line is about 60 percent of the distance between the high water line and the tank bottom).

$$H = 35 \text{ Ft} \times 60\% = 21 \text{ Ft}$$

$$R_A = \frac{0.0016 \times 2000}{29} \left(\ln \frac{8 \times 29}{0.00521} + \ln \frac{2 \times 29}{21} \right)$$

$$R_A = 0.110 \times (\ln 44{,}530 + \ln 2.76)$$

$$R_A = 1.29 \text{ ohms}$$

This is within the design limitation of 2.0 ohms

5.5.2.4 **Determine the Total Circuit Resistance (R_T).**

$$R_T = R_N + R_W + R_C$$

where,

R_N = Anode-to-water resistance
R_W = Wire resistance
R_C = Tank-to-water resistance

A. AnodTP16-to-water resistance (R_N) = 1.29 ohms from paragraph 5.5.2.3.

B. Header cable/wire resistance (R_W).

$$R_W = \frac{L_W \times R_{MFT}}{1000\ Ft}$$

where,

L_W = 115 Ft (Effective wire length. The positive wires from the rectifier to each end of the anode ring will be about 115 feet long.

R_{MFT} = 0.57 Ohm (Effective wire resistance per 1000 lineal feet. Since there are positive wires from the rectifier to each end of the anode ring, each wire will carry about one half of the current [12.5 amp]. The wires selected are No. 10 AWG. Since the two wires are in parallel, the effective resistance is one half the single wire resistance [1.02 ohms per 1000 lineal feet/2 = 0.51 ohm])

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

$$= 0.06\ ohm$$

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

D. Calculate (R_T):

$$R_T = 1.29 + 0.06 + 0.00$$

$$= 1.35\ ohm$$

This is well below the design limitation of 2.0 ohms

5.5.2.4 **Calculate the Rectifier Voltage (V_{REC}).**

$$V_{REC} = I \times R_T \times 120\%$$

where,

I = Current requirement = 25 amps
R_T = Total circuit resistance = 1.35 ohms
120% = Rectifier voltage capacity design safety factor

$$V_{REC} = 25 \text{ amps} \times 1.35 \text{ ohms} \times 120\%$$

$$= 40.5 \text{ Volts}$$

5.5.3 **Select Rectifier.**

Based on the design requirements of 40.5 volts and 25 amps, a commercially available 48-volt, 28-amp unit is selected. Specify automatic potential control to prevent over or under protection as the water level varies. The controller maintains the tank-to-water potential through two permanent copper-copper sulfate reference electrodes suspended beneath the anode wire ring. The reference electrodes should have a life of at least five years. The tank-to-water potential measured by the controller should be free of IR drop error.

5.5.4 **Installation.**

Figure 49 shows a typical installation while Figure 50 illustrates a typical detail for a pressure entrance fitting for underwater power and reference electrode wire penetrations.

End of Example

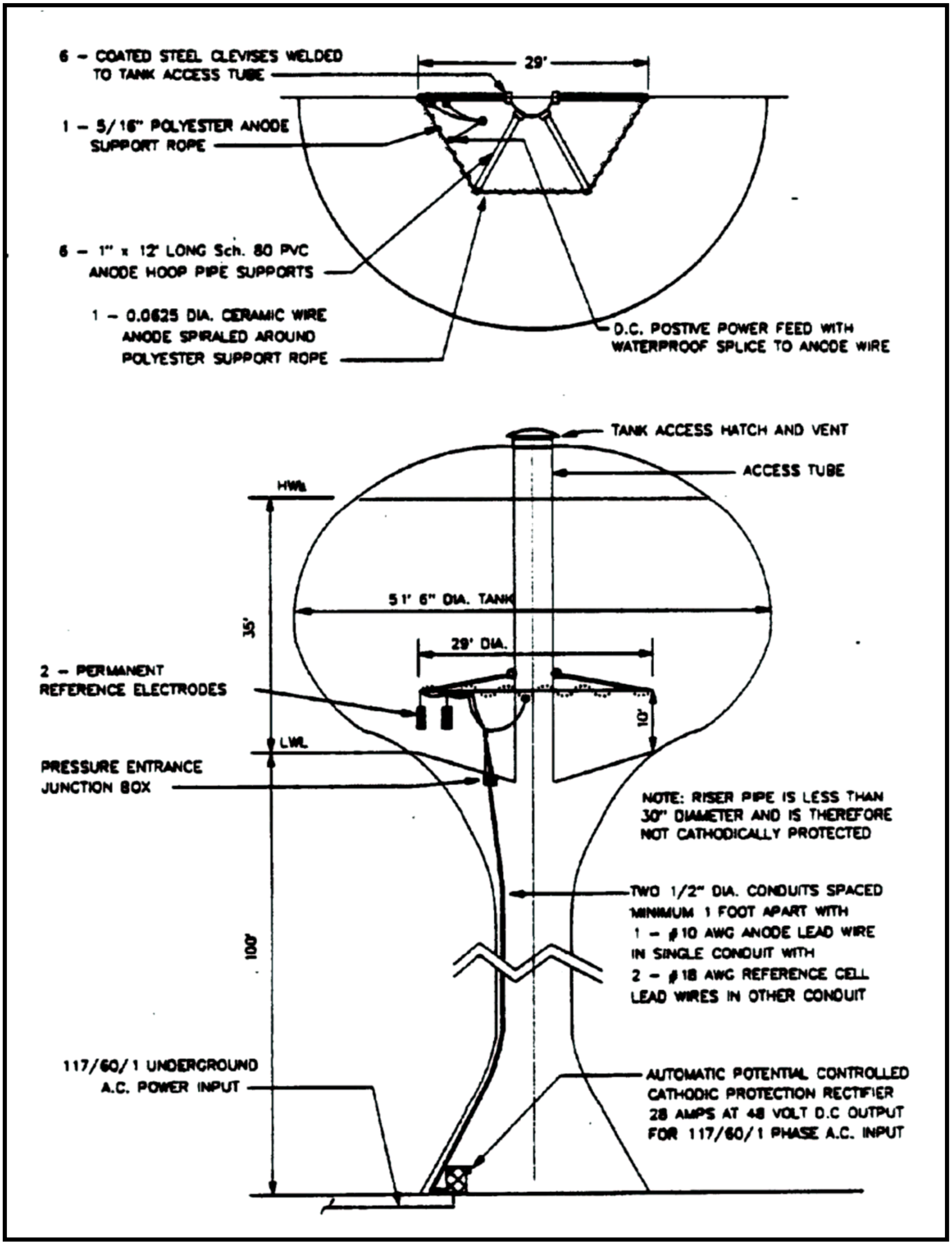

Figure 49
Elevated Pedestal tank with ceramic anode wire ring for icing conditions.

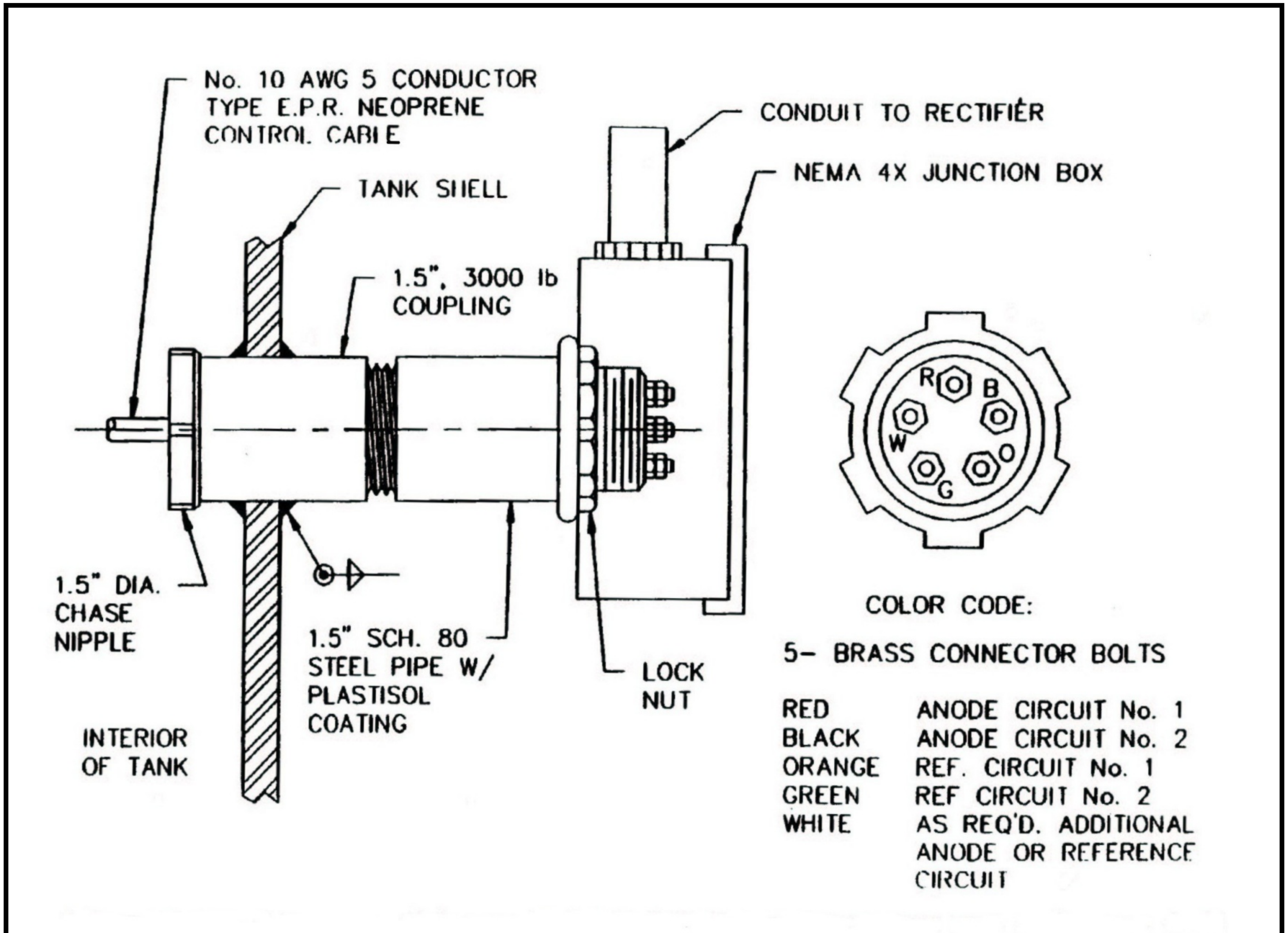

Figure 50
Pressure entrance fitting for underwater power and reference electrode wire penetrations in water storage tanks.

5.6 **Steel Gas Main.** Design an impressed current cathodic protection system for the 6-inch welded steel gas main shown in Figure 51. The pipeline has not yet been constructed, so current requirement tests cannot be conducted.

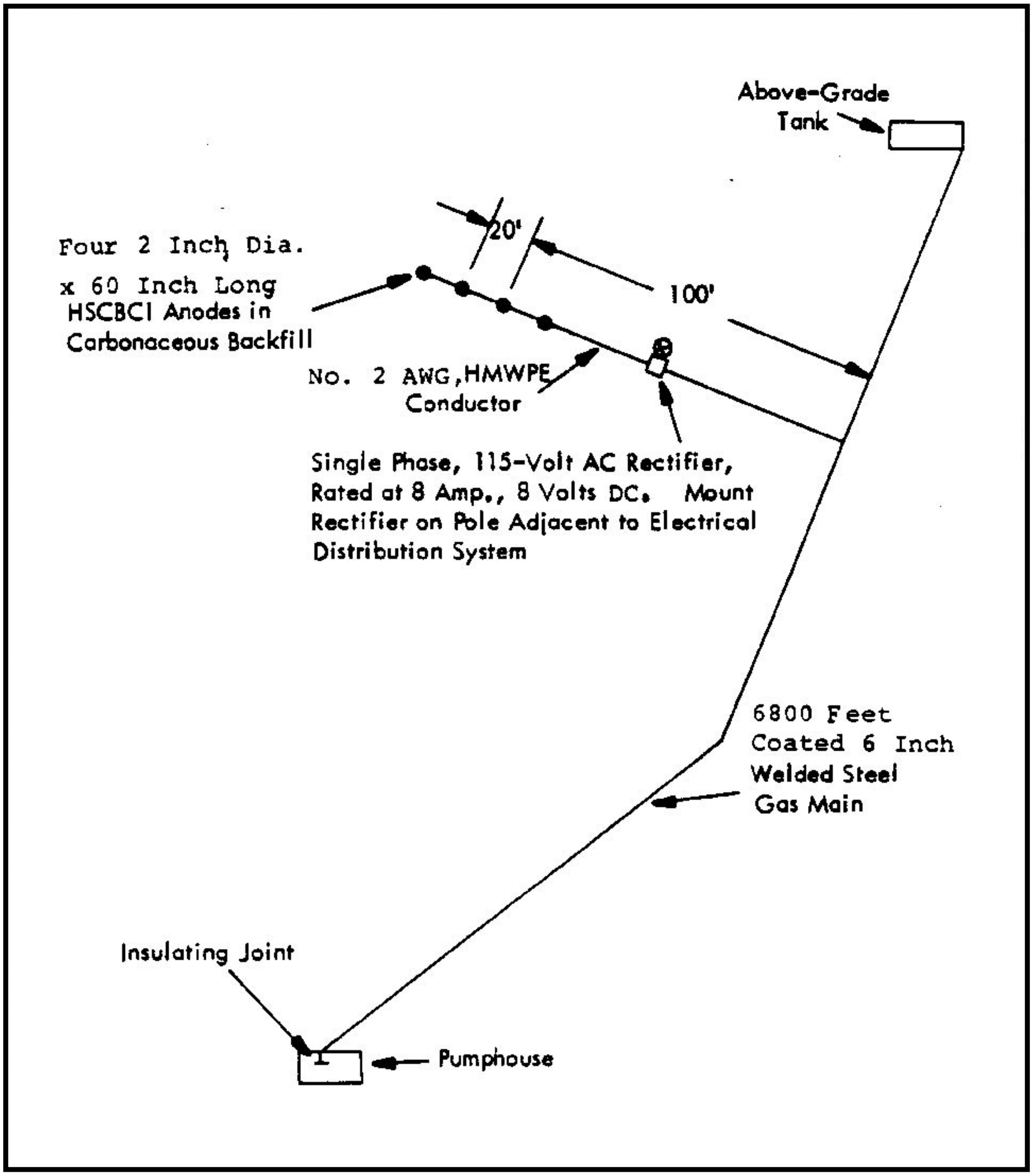

Figure 51
Cathodic Protection System for Gas Main

5.6.1 **Design Data.**

A. Average soil resistivity, 2,000 ohm-cm.

B. Pipe size, 6-inch outside diameter, schedule 80 pipe.

C. Pipe length, 6,800 feet.

D. Design for 15-year life.

E. Design for an estimated 2 mA/ft² of bare pipe.

F. Design for 90 percent coating efficiency, based on experience.

G. The pipeline must be isolated from the pump house with a dielectric insulating flange on the main line inside the pump house.

H. Use HSCBCI anodes with carbonaceous backfill.

I. The pipe is coated with hot-applied coal-tar enamel and holiday checked before installation.

J. Anode bed resistance must not exceed 2 ohms.

K. Electric power is available at 120/240 V ac, single phase, from a nearby overhead distribution system.

5.6.2 **Calculations.**

5.6.2.1 **Outside Area of Gas Main.**

$$A_P = \pi D L$$

where

A_P = Outside surface area of the pipe
D = Outer pipe diameter = 6.625 inches for a 6-inch nominal diameter pipe
= 6.625 in/12 in/ft = 0.552 feet
L = Pipe length = 6,800 feet

$$A_P = 3.1416 \times 0.552 \times 6800$$

$$= 11{,}792 \text{ ft}^2$$

5.6.2.2 **Area of Bare Pipe to Be Cathodically Protected Based on 90 Percent Coating Efficiency.**

$$A = A_P \times (1 - CE)$$

where
A = Area of bare pipe to be cathodically protected
A_P = Outside surface area of the pipe = 11,792 ft²
CE = Pipe coating efficiency = 90% or 0.9

$$A = 11{,}792 \text{ ft}^2 \times (1 - 0.9)$$

$$= 1{,}179 \text{ ft}^2$$

5.6.2.3 **Protective Current Required Based on 2 mA/ft² of Bare Metal.**

$$I = A \times CD$$

where
A = Area of bare pipe to be cathodically protected = 1,179 ft²
I = Current required for cathodic protection
CD = Current density = 2 mA/ft²

$$I = 1{,}179 \text{ ft}^2 \times 2 \text{ mA/ft}^2$$

$$= 2{,}358 \text{ mA or } 2.36 \text{ A}$$

5.6.2.4 **Ground Bed Design.**

A. Anode size: 2-inch x 60-inch (backfilled 10-inch x 84-inch), spaced 20 feet apart.

B. Resistance of a single anode to earth:

$$R_V = \frac{r}{L} K$$

where

r = Soil resistivity = 2,000 ohm-cm
K = Shape function (refer to para. 6.2.1.4a) = 0.0167
L = Backfilled anode length = 7.0 feet
L/D = 84 inches/10 inches backfill size

$$R_V = \frac{2{,}000}{7.0} \times 0.167$$

$$= 4.77 \text{ ohms}$$

C. Number of anodes required.

One of the design requirements is that the anode bed resistance is not to exceed 2 ohms. Anode size used is 2-inch diameter x 60 inches long with carbonaceous backfill having overall dimensions of 10-inch diameter x 84 inches long and spaced 20 feet apart:

$$R_n = \frac{1}{n} R_V + r_s \frac{p}{s}$$

where

R_n = Anode bed resistance = 2 ohms
n = number of anodes
R_V = Single anode resistance = 4.77 ohms
r_s = Earth resistivity with pin spacing equal to S = 2,000 ohm-cm
p = paralleling factor (refer to para. 6.2.1.4b)
s = spacing between adjacent anodes = 20 feet

NOTE: p is a function of n as referred in para. 6.2.1.4b, and n is the number of anodes which are determined by trial and error.

Rearranging the equation for n:

$$n = \frac{R_V}{R_n - \left(r_s \frac{p}{s} \right)}$$

$$n = \frac{4.77}{2 - \left(2000 \frac{p}{20} \right)}$$

$$n = \frac{4.77}{2 - 100p}$$

Try n = 4 anodes, p = 0.00283 (refer to para. 6.2.1.4b)

$$4 \quad = \quad \frac{4.77}{2 - (100 \times 0.00283)}$$

$$4 \quad = \quad 2.78 \text{ (not very close)}$$

Try n = 3 anodes, p = 0.00289 (refer to para. 6.2.1.4b)

$$3 \quad = \quad \frac{4.77}{2 - (100 \times 0.00289)}$$

$$3 \quad = \quad 2.79$$

This is the closest possible. In order to keep total resistance below 2.0 ohms, use 3 anodes.

D. Actual anode bed resistance:

$$R_3 \quad = \quad \left(\frac{1}{3} \; 4.77 \right) \quad + \quad \left(2000 \; \frac{0.00289}{20} \right)$$

$$= \quad 1.87 \text{ ohms which is less than 2.0}$$

5.6.2.4 **Next Calculate the Quantity of Anodes to Meet Recommended Maximum Anode Current Discharge.**

$$N_D \quad = \quad \frac{I}{A_A \times I_A}$$

where:

N_D = quantity of anodes to meet recommended maximum anode current discharge limits.
I = Current required (2.36 amps)
A_A = Anode surface area (ft^2) = 2.6 ft^2
I_A = Max. recommended anode discharge current density (1 amp/ ft^2)

$$N_D \quad = \quad \frac{2.36}{2.6 \times 1}$$

$$= \quad 0.91 \text{ say 1 anode}$$

Only one anode is required to stay within the maximum anode current discharge limit. However, use the 3 anodes required to meet the 2-ohm ground bed resistance design requirement.

5.6.2.5 **Total Weight of Anodes for Ground Bed.**

A. Weight of anode unit, 60 pounds (size 2 inches x 60 inches)

B. Total weight = 3 x 60 = 180 pounds

5.6.2.6 **Theoretical Life of Anode Bed.**

$$W = \frac{Y\,S\,I}{E}$$

Rearranging the equation we get:

$$Y = \frac{W\,E}{S\,I}$$

where
Y = Theoretical anode bed life
W = Total anode bed weight = 180 pounds
S = Anode consumption rate = 1.0 lb/A yr
E = Anode efficiency = 0.50
I = Current required for cathodic protection = 2.36 A

$$Y = \frac{180 \times 0.50}{1.0 \times 2.36}$$

$$= 38.1 \text{ years}$$

It should be noted that the expected ground bed life greatly exceeds the design requirement of 15 years. This is brought about by the additional anode material required to establish a 2-ohm ground bed. The lower ground bed resistance saves energy (power, $P = I^2 R$).

5.6.2.7 **Resistance of the DC Circuit.**

A. Ground bed-to-soil resistance, 2.0 ohms maximum.
B. Resistance of ground bed feeder conductor (length 500 feet, type HMWPE, size No 2 AWG).

Conductor resistance (refer to Table 10): 0.159 ohm/1,000 feet

$$R = 500 \text{ ft} \times 0.159 \text{ ohm}/1{,}000 \text{ feet}$$

$$= 0.080 \text{ ohms}$$

C. Total resistance of circuit:

$$R_T = 2.0 + 0.080$$

$$= 2.08 \text{ ohms}$$

5.6.2.8 **Rectifier Rating.**

A. Minimum current requirement = 2.36 A.
B. Circuit resistance = 2.08 ohms.
C. Voltage rating:

$$E = IR$$

where
I = 2.36 A
R = 2.08 ohms

$$E = 2.36 \text{ A} \times 2.08 \text{ ohms}$$

$$= 4.9 \text{ say } 5.0 \text{ V}$$

To allow for rectifier aging, film formation, and seasonal changes in the soil resistivity, it is considered good practice to use a multiplying factor of 1.5 to establish the rectifier voltage rating.

$$E = 5.0 \times 1.5 = 8.0 \text{ V}$$

D. The commercial size rectifier meeting the above requirements is 115-V, single-phase, selenium, and full-wave bridge type having a dc output of 8 A, and 8 V.

5.6.2.9 **Rectifier Location.**

Mount the rectifier at eye level on a separate pole adjacent to an existing overhead electrical distribution system

End of Example

5.7 **Hot Water Storage Tank.** Design impressed current cathodic protection for the interior of the industrial hot water storage tank shown in Figure 52.

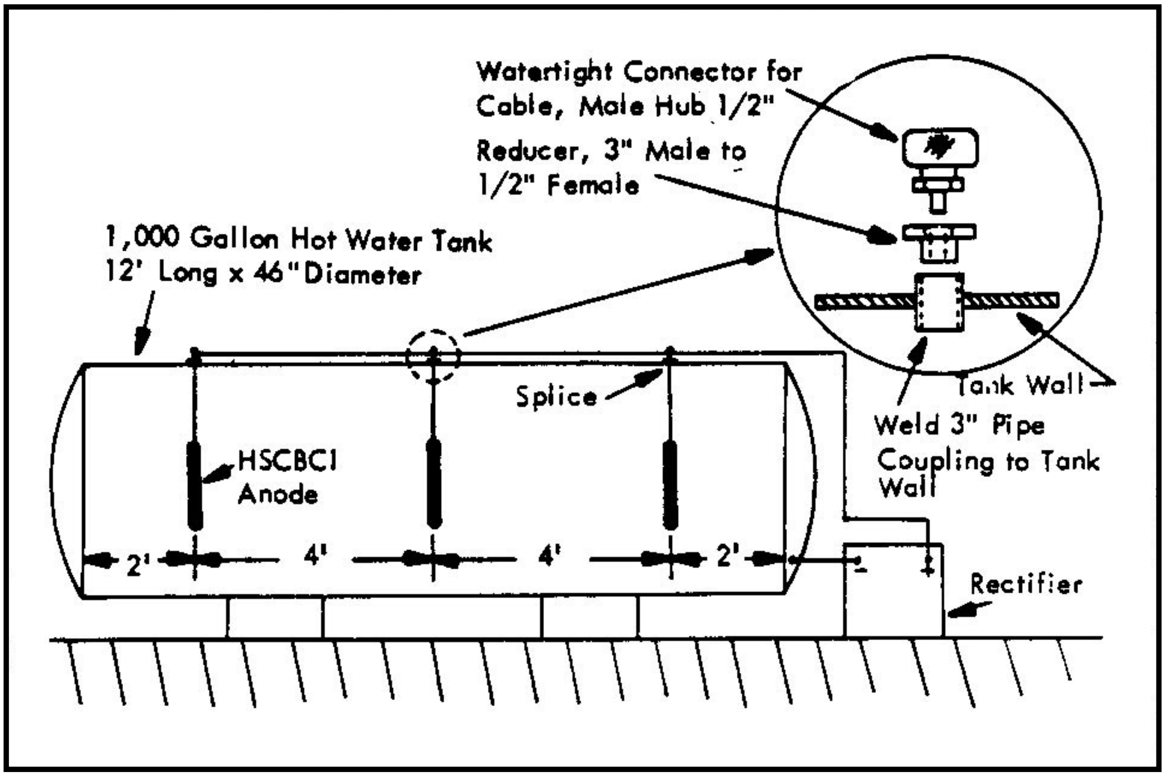

Figure 52
Cathodic Protection for an Industrial Hot Water Storage Tank

5.7.1 **Design Data.**

A. Tank capacity, 1,000 gallons.
B. Tank dimensions, 46 inches in diameter by 12 feet long.
C. Tank is mounted horizontally.
D. Water resistivity is 8,600 ohm-cm with a pH value of 8.7.
E. Tank interior surface is bare and water temperature is maintained at 180 degrees F (82.2 degrees C).
F. Design for maximum current density of 5 mA/ft².
G. Design life, 5 years.
H. Use HSCBCI anodes.
I. Alternating current is available at 115 V ac, single phase.

5.7.2 **Computations.**

5.7.2.1 **Interior Area of Tank.**

$$A_T = 2\,\pi\, r^2 + \pi\, d\, L$$

where

r = Tank radius = 1.92 feet
d = Tank diameter = 3.83 feet
L = Tank length = 12 feet

$$A_T = 2 \times 3.1416 \times (1.92)^2 + 3.1416 \times 3.83 \times 12$$

$$= 167.5 \text{ ft}^2$$

5.7.2.2 **Maximum Protective Current Required.**

$$A = A_P \times (1 – CE)$$

where
A = Area of bare pipe to be cathodically protected
A_P = Outside surface area of the pipe = 11,792 ft²
CE = Pipe coating efficiency = 0% or 0

$$A = 167.5 \text{ ft}^2 \times (1 – 0)$$

$$= 167.5 \text{ ft}^2$$

$$I = A \times CD$$

where
A = Area of bare tank surface be cathodically protected = 167.5 ft²
I = Current required for cathodic protection
CD = Current density = 5 mA/ft²

$$I = 167.5 \text{ ft}^2 \times \ \text{mA/ft}^2$$

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

5.7.2.3 **Minimum Weight of Anode Material for 5-Year Life.**

$$W = \frac{Y\,S\,I}{E}$$

where

Y = Anode design life = 5 years
S = Anode consumption rate = 1.0 lb/A yr
E = Anode efficiency = 0.50
I = Current required for cathodic protection = 0.84 A

$$W = \frac{5 \times 1.0 \times 0.84}{E}$$

$$= 8.4 \text{ pounds}$$

Number of anodes required. Anode size of 1-1/2 inches in diameter by 9 inches long weighing 4 pounds each is selected as the most suitable size.

$$N_L = \frac{W}{W_A}$$

where

W = Total weight of anodes = 8.4 lbs
W_A = Weight of a single anode = 4 lbs
N_L = Quantity of anodes to meet design life

$$N_l = \frac{8.4 \text{ lbs}}{4 \text{ lbs}}$$

$$N_l = 2.1 \text{ (say 3 anodes)}$$

In order to get proper current distribution, three anodes are required.

5.7.2.3 **Calculate the Resistance of a Single Anode.**

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

where

r = Water resistivity = 8,600 ohm-cm
D = Tank Diameter = 3.83 feet
L = Anode length = 9 inches or 0.75 foot
d = Anode diameter = 1-1/2 inches or 0.125 foot

$$R = \frac{0.012 \times 8{,}600 \times \log(3.83/0.125)}{0.75}$$

$$= 204.5 \text{ ohms}$$

This resistance must be corrected by the fringe factor because they are short anodes. The fringe factor is 0.48 from the curve in Figure 45 for an L/d = 9/1.5 = 6.

$$R \text{ (adjusted)} = 0.48\ R = 0.48 \times 204.5 = 98.2 \text{ ohms}$$

5.7.2.4 **Resistance of the 3-Anode Group.**

$$R_T = \frac{1}{n} R_V + r_s \frac{p}{s}$$

where
R_T = Total anode-to-electrolyte resistance
n = number of anodes
R_V = resistance-to-electrolyte of a single anode = 98.2 ohms
r_s = electrolyte resistivity = 8,600 ohm-cm
p = paralleling factor
s = spacing between adjacent anodes = 4 feet

$$R_T = \frac{1}{3}\, 98.2 + 8{,}600\, \frac{0.00289}{4}$$

$$= 38.94 \text{ ohms}$$

5.7.2.5 **Rectifier Rating.**

A. Calculate rectifier voltage

$$E = IR$$

where
I = Protection current required = 0.84 A
R = Anode group resistance = 38.94 ohms

$$E = 0.84 \text{ A} \times 38.94 \text{ ohms}$$
$$= 32.7 \text{ V}$$

B. To allow for rectifier aging, film formation, it is considered good practice to use a multiplying factor of 1.5 to establish the rectifier voltage rating.

$$E = 32.7 \times 1.5 = 49.1 \text{ V}$$

C. The nearest commercially available rectifier size meeting the above requirements is a 60-V, 4-amp, single-phase unit.

5.7.2.6 **Rectifier Location.** Locate the rectifier adjacent to tank for the following reasons:

A. Usually cheaper to install.
B. Easier to maintain.
C. Keeps DC voltage drop to a minimum.

5.7.2.6 **DC Circuit Conductors.**

A. External to tank: Use No. 2 AWG, HMWPE.
B. Interior of tank: Use No. 8 AWG, HMWPE.

No stressing or bending of the cable should be permitted.

End of Example

5.8 **Steam Heat Distribution System.** Provide cathodic protection for a pre-engineered steam conduit distribution system. Galvanic CP had been previously installed on the outer conduit of some sections of the steam distribution lines. The system was ineffective because of high soil resistivity, lack of adequate electrical isolation from adjacent buried metallic structures (e.g. building H-piles, copper grounding systems, water lines, electrical conduits, etc). The CP systems included in this design will be impressed current type. Existing PVC condensate return lines will be replaced with steel conduits in the near future.

5.8.1 **Design Data.**

A. Design life: 20 years

B. Current Density: 3 mA/ft².

C. Coating Efficiency: 85% for existing steam conduits and 95% for new condensate lines.

D. Conventional shallow anode beds were considered, but have a high failure rate due to third party damage. Deep well anode beds require less space than shallow anode beds, and are not as likely to cause stray current interference to nearby metallic structures. A number of small rectifier/deep well systems are anticipated with each system electrically isolated from all other systems to minimize the possibility of interference and facilitate troubleshooting of system shorts that may occur. The deep well will utilize mixed metal oxide tubular anodes in carbonaceous backfill.

E. Soil Resistivity: Soil resistivity measurements taken at various locations with various pin spacing yielded a maximum resistivity measured at the 15-foot depth of 22,700 ohm-cm. Although it is not practical to measure soil resistivity to the anticipated deep well depth, based on review of the available geological information indicates that the resistivity is anticipated to decline at deeper depths. However, for conservatism, the design is based on 22,700 ohm-cm.

F. The steam lines will have insulating flanges and unions at the building tie-ins. It is anticipated that the electrical isolation will be 90% effective. Dielectric insulation will be provided at critical locations to electrically segregate rectifier systems.

5.9.2 **Calculations.**

5.9.2.1 **Outside Surface Area of Steel Conduit.**

$$A_P = \pi D L$$

where

A_C = Outside surface area of the conduit
D = Outer steam conduit diameter = 8.625 inches average = 0.72 ft
Outer steam condensate diameter = 6.625 inches average = 0.55 ft
L = Pipe length

Steam Conduit Surface Area			
Location	Length (ft)	Diameter	Area (ft²)
North Sector	50,000	0.72	113,098
South Sector	19,000	0.72	42,977
Total pipe surface area			156,075

Steam Condensate Conduit Surface Area			
Location	Length (ft)	Diameter	Area (ft²)
North Sector	50,000	0.55	86,394
South Sector	19,000	0.55	32,830
Total pipe surface area			119,224

5.9.2.2 **Area of Bare Pipe to Be Cathodically Protected.**

$$A = A_C \times (1 - CE)$$

where
A = Area of bare conduit to be cathodically protected
A_C = Outside surface area of the conduit
CE = Conduit coating efficiency = 85% or 0.85
Condenstate coating efficiency = 95% or 0.95

Bare Surface Area			
Structure	Total Area (ft²)	CE	Area (ft²)
Steam Conduit	156,075	0.85	23,411
Condensate Conduit	119,224	0.95	5,961
Total pipe surface area			29,372

5.9.2.3 **Protective Current Required Based on 3 mA/ft² of Bare Metal.**

$$I = A \times CD$$

where
A = Area of bare pipe to be cathodically protected
I = Current required for cathodic protection
CD = Current density = 3 mA/ft²

Bare Surface Area			
Structure	Bare Area (ft²)	CD	I (ma)
Steam Conduit	23,411	3	70,233
Condensate Conduit	5,961	3	17,883
Total pipe surface area			88,116
		say	88 amps

In order to keep the systems small, limit the size of each system to 15 amps. The number of systems is

88 amps/15 amps per system = 6 systems

5.8.2.4 **Calculate the Quantity of Anodes.**

Use mixed metal oxide (MMO) tubular anodes in carbonaceous backfill. The quantity of MMO anodes must be calculated to meet two different parameters: design life based on anode maximum current discharge, and anode bed resistance. The required quantity of anodes will be the larger of the two calculated quantities.

1. First calculate the quantity of anodes to meet design life

$$N_L = \frac{Y\, I_R}{A_A\, S}$$

where:
I_R = Current required = 8.9 amps
N_L = Number of anodes to meet design life
S = Manufacturer's MMO anode life rating (years)
A_A = Manufacturer's MMO anode current rating (amps)
Y = CP system design life = 20 years

Example Manufacturer's MMO Anode Ratings			
Anode Size	Rated Output (Amperes)		
	10 years	15 years	20 years
1" x 45"	5.5 – 6.0	4.0 – 4.5	3.0 – 3.5
1" x 60"	7.0 – 8.0	5.0 – 6.0	4.0 – 5.0
1" x 90"	11.0 – 12.0	8.0 – 9.0	6.0 – 7.0

Use a 1" x 45" anode rated at an average of 3.25 amperes for a 20 year design life.

$$N_L = \frac{20 \times 15}{3.25 \times 20}$$

$$= 5 \text{ anodes}$$

***** IMPORTANT *****

Do not end calculations at this point. The quantity of anodes required to meet the ground bed resistance requirements must still be calculated.

2. Anode well resistance (R_S)

The anodes will be installed in a vertical deep well. The resistance of the anode well can be approximated by the following equation:

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

where

R_S = anode bed design resistance (2 ohm maximum desired)
r = soil resistivity (22,700 ohm-cm)
L = length of the anode backfill column (ft)
d = diameter of anode backfill column (8 in or 0.67 ft)

For five anodes try an active well depth of 100 feet.

$$R_S = \frac{0.0052 \times 22{,}700}{100} \left[\ln \left(\frac{8 \times 100}{0.67} \right) - 1 \right]$$

$$= 7.2 \text{ ohms – too high}$$

Several iterations using several different backfill column lengths yield the following:

Anode Deep Well Resistance	
Backfill Column Length (ft)	Resistance (ohms)
100	7.2
150	5.1
200	4.0
250	3.3
300	2.8
400	2.2

A 2-ohm deep well ground bed is not economically feasible, therefore, select a 200 ft backfill column with 4.0 ohms resistance. Although 5 anodes are required to meet the design life, use 8 anodes to ensure anode current attenuation along the backfill column is minimized. Install the anodes so that the bottom of the anode is about ten feet above the bottom of the hole. Use an anode spacing of twenty feet. Provide anodes with factory connected lead wires of sufficient length to reach the anode junction box without splicing.

5.8.2.5 **Rectifier Rating.**

A. System current requirement = 15 A.
B. Circuit resistance = 4.0 ohms.
C. Voltage rating:

$$E = I R + 2 \text{ Volts}$$

where
$I = 15$ A
$R = 4$ ohms

2 volts are added to overcome the typical rectifier back voltage.

$$E = 15\ A \times 4.0 + 2\ V$$

$$= 62\ V$$

To allow for rectifier aging, film formation, and seasonal changes in the soil resistivity, use a multiplying factor of 1.25 to establish the rectifier voltage and current ratings ratings.

$$V_R = 62\ \text{Volts} \times 1.25 = 78\ \text{Volts}$$
$$I_R = 15\ \text{Amps} \times 1.25 = 19\ \text{Amps}$$

D. The commercial size rectifier meeting the above requirements is 240V, single-phase, full-wave bridge type having a dc output of 22 Amperes, and 80 Volts.

5.8.2.4 **Calculate the AC Line Load (Full Output).**

1. First calculate the line current

$$I_L = \frac{V\ I_R}{240}$$

where:
I_L = Full output AC line current (amps).
I_R = Rectifier rated output current = 22 amps
V_R = Rectifier rated output current = 80 volts

$$I_L = \frac{80 \times 22}{240}$$

$$I_L = 8\ \text{Amps}$$

The circuit overcurrent protection device shall not be less than 125 percent of the continuous load. The rectifier is a continuous load, therefore,

8 amps x 125% = 10 amps

Use a 15 ampere circuit as a minimum.

End of Example

5.9 **Aircraft Multiple Hydrant Refueling System.** Cathodic protection will be provided to new underground 18-inch diameter stainless steel hydrant refueling supply and return lines, 12-inch/10-inch diameter stainless steel lines supplying the direct refueling stations, and 32 single point and 17 dual point hydrant outlets with 4-inch/6-inch risers. The stainless steel lines will be coated with extruded polyethylene. Dielectric Isolating flanges will be provided to electrically isolate the buried pipelines. Bare galvanized steel grounding rods will be provided at the hydrant refueling pits. Also intermittent current loads will be imposed on the CP system where copper clad tie downs embedded in the concrete apron are connected to one or more aircraft that are refueling. Tie downs are bonded together by a bare copper conductor encased in the concrete apron.

5.9.1 **Design Data.**

A. Design life: 25 years

B. Current Density: 0.5 mA/ft² for soil, 5 mA/ft² for structures embedded in concrete.

C. Coating Efficiency: 90% for the extruded polyethylene coating. Bare (0%) for the hydrant outlet risers.

G. A conventional anode bed with high silicon cast iron tubular anodes installed horizontally is planned. Due to the soft sand environment, use ten-inch diameter pre-packaged anodes to simplify installation.

H. The anode bed design resistance should not exceed 2 ohms.

I. Soil Resistivity: Soil resistivity measurements taken at various locations with various pin spacing yielded soil resistivities ranging from 374 ohm-cm to 21,500 ohm-cm. The maximum resistivity measured at the 10-foot depth was 8,600 ohm-cm. Therefore, the design is based on a resistivity of 8,600 ohm-cm, and the anodes must be installed at this depth.

5.9.2 **Calculations.**

5.9.2.1 **Outside Surface Area of Stainless Steel Pipe.**

$$A_P = \pi D L$$

where
A_P = Outside surface area of the pipe
D = Outer pipe diameter
L = Pipe length

Stainless Steel Distribution Pipe		
Diameter (in)	Length (ft)	Area (ft²)
18	9,000	42,412
12	830	2,770
10	180	507
Total pipe surface area		45,689

There are 32 single point and 17 dual point hydrant outlet pits for a total of 66 hydrant outlet risers.

Stainless Steel Hydrant Riser Pipe			
Diameter	Length (ft)	Qty	Area (ft²)
4”-6” Reducer (5” Avg. Dia)	1	66*	86.4
4” Riser (4.5” OD)	2	66*	155.6
Total pipe surface area			242.0

5.9.2.2 **Surface Area of Hydrant Pit Ground Rods.** There are32 single point and 17 dual point hydrant outlet pits for a total of 49 pits and therefore, 49 ground rods.

$$A_R = \pi D L N_R$$

where
A_R = Surface area of the ground rod
D = Ground rod diameter = ¾ inch = 0.0625 ft
L = Ground rod length = 10 ft
N_R = Quantity of Ground Rods = 49

$$A_P = 3.1416 \times 0.0625 \times 10 \times 49$$

$$= 96.2 \text{ ft}^2$$

5.9.2.3 **Surface Area of Aircraft Tiedown/Ground System.**

$$A = \pi D L$$

where
A = Surface area
D = Ground rod/wire diameter
L = Ground rod/wire length

The tiedown/ground consists of ¾ inch diameter by 19 inches long rod plus a ¾ inch diameter by 11 inches long rod, a 2-inch diameter by 3-inch long area receptacle, #4 bare copper wire, and a major ground bed.

Surface Area of Tiedown/Ground System				
Component	Dia (in)	Length (ft)	Qty	Area (ft²)
Ground rod (19” + 11”)	0.75	2.5	613	301
Receptacle	2	0.25	613	80
#4 Copper Wire	0.232	8490		515
Total pipe surface area				896

5.9.2.4 **Area of Bare Structure to Be Cathodically Protected.**

$$A = A_S \times (1 - CE)$$

where
A = Area of bare structure to be cathodically protected
A_S = Surface area of the structure
CE = Structure coating efficiency

Area of Bare Structure to be Protected			
Structure	Surface Area (ft²)	CE	Area (ft²)
SS Distribution Pipe	45,689	0.9	4,569.0
SS Hydrant Risers	242	0	242.0
Hydrant Pit Ground Rods	96.2	0	96.2
Tiedown/Ground System	896	0	896

5.9.2.5 **Protective Current Required.**

$$I = A \times CD$$

where
A = Area of bare pipe to be cathodically protected
I = Current required for cathodic protection
CD = Current density = 0.5 mA/ft² for pipe and ground rods in soil
= 5 mA/ft² for grounding encased in concrete

Area of Bare Structure to be Protected			
Structure	Surface Area (ft²)	CD (mA/ft²)	I (mA)
SS Distribution Pipe	4,569.0	0.5	2,285
SS Hydrant Risers	242.0	0.5	121
Hydrant Pit Ground Rods	96.2	0.5	48
Tiedown/Ground System	896	5	4,480
Total pipe surface area			6,934
		Say 6.9 Amps	

In order to account for leakage current through insulating flanges and unanticipated coating damage, add an additional 2 amperes for a total of 8.9 Amperes. To allow for rectifier aging, film formation, and seasonal changes in the soil resistivity, select a standard size 12 ampere rectifier.

5.9.2.6 **Calculate the Quantity of Anodes.**

Use high silicon chromium bearing cast iron (HSCBCI) tubular anodes. The quantity of anodes must be calculated to meet three different parameters, design life, anode bed resistance, and anode maximum current discharge. The required quantity of anodes will be the largest of the three calculated quantities.

1. First calculate the quantity of anodes to meet design life

$$N_L = \frac{Y\,S\,I_R}{W\,U}$$

where:

I_R = Current required = 8.9 amps
N_L = Number of anodes to meet design life
S = Anode consumption rate = 1 lb/amp-yr)
U = Anode utilization factor = 0.8
W = Weight of one anode (lb)
Y = CP system design life = 25 years

***** IMPORTANT *****

Do not end calculations at this point. The quantity of anodes required to meet the recommended maximum anode discharge and the ground bed resistance requirements must still be calculated.

2. Next calculate the quantity of anodes to meet recommended maximum anode current discharge

$$N_D = \quad I$$

$$A_A \ x \ I_A$$

where:
I = Current required = 8.9 amps)
A_A = Anode surface area (SF)
I_A = Max. recommended anode discharge current density (1 amp/SF)

***** IMPORTANT *****

~~Do not end calculations at this point. The quantity of anodes required to meet~~ the ground bed resistance requirements must still be calculated.

3. Calculate quantity of anodes to meet 2-ohm ground bed design

   The anodes will be installed in a shallow, distributed, horizontal anode bed. The resistance of the horizontal anode bed can be approximated by the following equation:

$$R_S = \frac{1.64\,\rho}{\pi L} \times [\ln (48L/d) + \ln (L/h) - 2 + (2h/L)]$$

where
d = diameter of anode backfill column = 10 inches
L = length of the anode backfill column (feet)
R_S = anode bed design resistance = 2 ohms
ρ = soil resistivity = 86 ohm-m
h = anode depth = 10 feet

Assume one foot of backfill column beyond the ends of each anode.

4 Determine quantity of anodes. The following table summarizes the above calculations for various common tubular anode sizes:

CALCULATED ANODE QUANTITIES							
Anode Size	**Weight (LB)**	**Area (SF)**	**Backfill Length (LF)**	**Backfill Dia. (ft)**	N_L	N_D	N_R
2.66" x 42"	31	2.4	5.42	0.833	9	4	32
2.66" x 60"	46	3.5	9.0	0.833	7	3	20
2.66" x 84"	63	4.9	9.0	0.833	5	2	20
3.75" x 84"	85	6.9	9.0	0.833	4	2	20

Of the three calculated quantities for a particular anode, the larger quantity of the three must be used to ensure all conditions are satisfied. The 46, 63 and 85 pound anodes utilize the same size backfill columns, and therefore, yield the same quantity of anodes to meet the 2.0 ohm maximum ground bed resistance requirement. For economic considerations, use the 20 each 46 LB, 2.66 inch diameter X 60 inch long anodes. Install the anodes so that there is one foot of backfill column beyond each end of each anode (two feet between consecutive anodes). Provide anode with factory connected lead wires of sufficient length to reach the anode junction box without splicing.

5.9.2.7 **Resistance of the DC Circuit.**

A. Ground bed-to-soil resistance, 2.0 ohms maximum.
B. Calculate electrical conductor resistance.

Calculate R_n: #4 rectifier negative header cable resistance (90 feet):

$$R_n = 90 \text{ ft}/1000 \times 0.269 \text{ ohm}/1{,}000 \text{ feet}$$

$$= 0.024 \text{ ohms}$$

Calculate R_p: # rectifier positive header cable resistance (1,085 feet):

$$R_p = 1{,}085 \text{ ft}/1000 \times 0.169 \text{ ohm}/1{,}000 \text{ feet}$$

$$= 0.208 \text{ ohms}$$

C. Total resistance of circuit:

$$R_T = R_S + R_n + R_p$$
$$= 2.0 + 0.024 + 0.208$$
$$= 2.23 \text{ ohms}$$

5.9.2.8 **Rectifier Rating.**

A. Rectifier current rating = 12 A.
B. Circuit resistance = 2.23 ohms.
C. Voltage rating:

$$E = I\,R + 2 \text{ Volts}$$

where
$I = 12$ A
$R = 2.23$ ohms

2 volts are added to overcome the typical rectifier back voltage.

$$E = 12 \text{ A} \times 2.23 + 2 \text{ V}$$
$$= 28.8 \text{ V}$$

D. The commercial size rectifier meeting the above requirements is 115V, single-phase, full-wave bridge type having a dc output of 12 Amperes, and 30 V.

End of Example

5.10 **On-Grade Fuel Storage Tanks.** Provide impressed current cathodic protection for the exterior bottoms of five existing on-grade fuel storage tanks:

TANK ID NO.	**CAPACITY (BBL)**	**DIAMETER (FT)**
Tank No. 1	55,000	93
Tank No. 2	55,000	93
Tank No. 3	2,300	27
Tank No. 4	10,000	45
Tank No. 5	20,000	58

Review of historical records indicates that the tanks have not had cathodic protection in the past.

5.10.1 **Design Data.**

A. Design life: 25+ years

B. Current Density: Record drawings and field inspection indicates the tanks have been constructed on an "impermeable layer" of compacted coral with a minimum thickness of 12 inches. The compacted coral may affect the even distribution of current and higher than normal current densities may be necessary to ensure the entire tank bottom is adequately protected. Usually, 1 - 1.5 ma/sf of current is sufficient to protect a tank bottom if the current is evenly distributed. With the compacted coral layer beneath the tanks, a current of 2 ma/sf will be used.

C. Coating Efficiency: 0% (Bare tank bottoms)

D. 120 Volt power and a spare circuit breaker is available in a panel in a nearby pump house. Space is available in the pump house to install a wall mount rectifier.

E. A deep well anode will be specified to: (1) improve current distribution of current to the entire tank bottom because of the compacted coral bed; (2) minimize excavation (historic preservation laws require an archaeologist to monitor all excavations full time which would add significant cost; (3) minimize disruption of on-going operations; and (4) minimize cathodic interference on other buried metallic structures in the tank farm.

F. The anode bed design resistance shall not exceed 1 ohm.

G. Soil Resistivity: Soil resistivity measurements taken at eight points within the tank farm were generally in the 2,000 to 4,000 ohm-cm range. Use 2,000 ohm-cm.

5.10.2 **Design Calculations.**

5.10.2.1 **Calculate Tank Bottom Surface Area.**

The surface area of the tank bottoms can be calculated using the following equation:

$$A_T = \pi r^2$$

where

A_T = Surface area of a tank bottom (ft^2)
r = tank bottom radius (ft)

The following table summarizes the tank bottom surface areas.

Tank ID. NO.	Diameter (FT)	Surface Area (ft^2)
Tank No. 1	93	6,790
Tank No. 2	93	6,790
Tank No. 3	27	570
Tank No. 4	45	1,590
Tank No. 5	58	2,640

5.10.2.2 **Calculate Current Requirement/Rectifier Output Current.**

$$I_R = A_T \times (1 - CE) \times CD$$

where

I_R = Current requirement/rectifier output current
A_T = Surface area of a tank bottom = 2,640 (ft^2)
CE = Coating efficiency = 0 for bare surfaces
CD = Current density = 2 ma/ ft^2

The following tables summarize the current requirements.

Tank ID No.	Surface Area (ft^2)	CE	CD (ma/ft^2)	Current Req'd (ma)
Tank No. 1	6,790	0	2	13,580
Tank No. 2	6,790	0	2	13,580
Subtotal				27,160
Tank No. 3	570	0	2	1,140
Tank No. 4	1,590	0	2	3,180
Tank No. 5	2,640	0	2	5,280
Total Current				36,760
Required (I_R)			**or**	37 amperes

In order to account for current that will be drained away by the grounding systems, use 40 amperes.

5.10.2.3 **Calculate Quantity of Anodes.**

Use high silicon chromium bearing cast iron (HSCBCI) tubular anodes.

A. Quantity of anodes to meet design life

$$N_L = \frac{Y\ S\ I_R}{W\ U}$$

where:

N_L = Number of anodes to meet design life
Y = CP system design life = 25 years
S = Anode consumption rate = 1 lb/amp-yr)
I_R = Current required (amps) = 40 amps
W = Weight of one anode (lb)
U = Anode utilization factor (0.85)

B. Quantity of anodes to meet recommended maximum anode current discharge

$$N_D = \frac{I_R}{A_A \text{ X } I_A}$$

where:

I_R = Current required (amps) = 40
A_A = Anode surface area (ft^2)
I_A = Max. recommended anode discharge current density (1 amp/ ft^2)

The following tables summarize the above calculations for various common tubular anode sizes:

Anode Size	Weight (LB)	Area (SF)	N_L	N_D
2.19" x 84" (TA2)	46	4.0	25	10
2.66" x 84" (TA3)	63	4.9	19	9
3.75" x 84" (TA4)	85	6.9	14	6

Of the above-calculated quantities for the anodes, the larger quantity of the two must be used to ensure all conditions are satisfied. Considering CP current distribution in the well, use the 85 LB, 3.75 inch diameter X 84 inch long (TA-4) anode. The TA-4 appears to be a better choice to minimize drilling.

C. Anode well resistance (R_S)

The anodes will be installed in a vertical deep well. The resistance of the anode well can be approximated by the following equation:

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

where

R_S = anode bed design resistance (1 ohm maximum)
r = soil resistivity (2,000 ohm-cm)
L = length of the anode backfill column (ft)
d = diameter of anode backfill column (10 in or 0.83 ft)

Based on the above a minimum anode well active depth of about 55 feet minimum is required.

Considering the number of anodes required and backfill life, use two wells of 101 feet active depth with seven anodes in each well. Install the anodes so that the bottom of the anode is about five feet above the bottom of the hole. Use an anode spacing of seven feet. Provide anodes with factory connected lead wires of sufficient length to reach the anode junction box without splicing. Calculate the anode bed circuit resistance of each well using the appropriate numbers from the above table:

$$R_S = \frac{0.0052 \times 2000}{101} \left[\ln\left(\frac{8 \times 101}{0.83} \right) - 1 \right]$$

$$= 0.61 \text{ ohm for each of the wells}$$

5.10.2.4 **Calculate Rectifier Circuit Output Voltage.**

A. Anode bed resistance (R_A) is the equivalent resistance of the two wells in parallel. Calculate the equivalent resistance of the two wells:

$$R_A = \frac{1}{R_1} + \frac{1}{R_2}$$

where,
R_A = Equivalent anode well circuit resistance
R_1 = Circuit resistance of the first anode well
R_2 = Circuit resistance of the second anode well

$$R_A = \frac{1}{0.61} + \frac{1}{0.61}$$

$$= 0.31 \text{ ohm}$$

B. Electrical Cable Resistance

Anode Well Cable Resistance (R_{AW}). Use No. 8 copper wire for the anode leads. Each of the anode leads will run directly back to the anode junction box, so the parallel cable resistance is estimated as follows:

$$\frac{1}{R_{AW}} = \frac{1}{R_{A1}} + \frac{1}{R_{A2}} + \cdots + \frac{1}{R_{An}}$$

where,

R_{AW} = Anode well cable resistance
R_{A1} = Cable resistance of the first anode in the well
R_{A2} = Cable resistance of the second anode in the well
R_{An} = Cable resistance of the nth anode in the well

$$\frac{1}{R_{AW}} = \frac{1}{R_{A1}} + \frac{1}{R_{A2}} + \cdots + \frac{1}{R_{A7}}$$

$$\frac{1}{R_{AW}} = \frac{1}{R_{A1}} + \frac{1}{R_{A2}} + \cdots + \frac{1}{R_{An}}$$

$=$ 0.01 ohm for each well (negligible)

Anode Header Cable Resistance(R_{HC}). Use No. 2 copper wire for the anode header cable runs. After a 100 ft run of cable to a junction box, there are two parallel runs of 200 ft and 450 ft. The equivalent resistance is 0.053 ohm.

Structure Header Cable Resistance. Use No. 2 copper wire for the structure leads. After a 450 ft run of cable to anode junction box no. 1, there are two parallel runs of 100 ft to (tanks 3, 4 and truck stand piping) and 225 ft (tank 5 piping and tanks 1 and 2). The equivalent resistance for all of these cable runs is 0.11 ohm.

C. Total Circuit Resistance. The total circuit resistance is

$$R_T = R_A + R_{AW} + R_{HC} + R_{SC}$$

$$0.31 \text{ ohm} + 0 + 0.05 + 0.11$$

$$= 0.47 \text{ ohm say } 0.5 \text{ ohm}$$

D. Calculate the rectifier output voltage using Ohm's Law:

$$V_R = I_{rect} \times R_T \times 150\%$$

$$40 \text{ amps} \times 0.5\ \Omega \times 1.5$$

$$= 30 \text{ volts}$$

Use the nearest nominal size rectifiers, or 30 volts/42 amps.

5.10.2.5 **Calculate Rectifier Input Power.**

Available power is 120 volts. For rectifiers of the size specified above, use single phase 120 volt AC input voltage. Rectifier input power is calculated as follows:

$$P = \frac{V_R \text{ x } I_R}{\text{rectifier efficiency}}$$

$$= \frac{30 \text{ volts x } 42 \text{ amps}}{0.85}$$

$$= 1{,}500 \text{ VA}$$

AC input current is calculated to be:

$$I_{AC} = \frac{P}{V_{AC}}$$

$$= \frac{1{,}500 \text{ VA}}{120}$$

$$= 12.5 \text{ amperes}$$

5.10.2.6 **Summary.**

A. Anodes: 14 each high silicon chromium bearing cast iron tubular anodes, with dimensions of 3.75 inches in diameter x 84 inches long, and weighing 85 LB. Anodes to be installed in two 130 foot deep well, seven anodes per well, with an active depth of 101 feet. Locate the first anode so that the bottom anode is 5 feet above the bottom of the well. Install remaining anodes with a 14 foot spacing on center between the anodes. Anode supplied by manufacturer with #8 AWG lead wire with HMWPE insulation. One end is factory connected to the anode. The anode leads should be long enough to extend to the junction box without splicing.

B. Rectifier:

Type:	Air cooled
AC Input:	120 volt, 60 Hz, single phase
DC Output:	30 volts, 42 amperes
Efficiency:	85% minimum

End of Example

5.11 **On-Grade Storage Tanks with Impermeable Containment Liner.** Two each 27,000 barrel on-grade vertical fuel storage tanks are protected by an existing impressed current CP system. However, a project proposes to install a new tank bottom above the existing tank bottom, creating a double tank bottom. A high-density polyethylene containment liner will be installed over the existing tank bottom. The existing tank bottom and new polyethylene liner will prevent the existing CP system from providing protection to the new tank bottom. Galvanic corrosion between the new and old tank bottoms can result in rapid corrosion of the new tank bottom. Therefore, a new CP system will be installed between the two tank bottoms to provide corrosion protection to the new tank bottom. The space between the new and existing tank bottoms will be 4 inches minimum; therefore, the new CP anode system must be installable in this small space.

5.11.1 **Design Data.**

A. Design life: 25+ years

B. Current Density: 1 ma/ft^2 for a grid system. Generally, 2 ma/ft^2 is required for protection in neutral soils. Past experience and current literature indicates that 1 ma/ft^2 is sufficient due to the even distribution of current when using a grid system.

C. Tank bottom diameter: 70 ft

D. Tank bottom is steel

E. Slope of the new tank bottom will result in only 4 inches clearance between the existing and new tank bottom at its lowest point. Therefore, the proposed new CP system will be an impressed current system consisting of mixed metal oxide coated titanium ribbon anodes.

F. Each tank will have its own independent system to allow independent system adjustment for each tank. The rectifier will have two independent DC output circuits, one for each tank, contained in one enclosure.

5.11.2 **Calculations.**

5.11.2.1 **Tank Bottom Surface Area.**

The tank bottom is a circular surface for which its surface area can be calculated from the following equation:

$$A = \pi \times r^2$$

The area of each tank bottom is

$$A = (3.14)(70\ SF/2)^2$$
$$= 3847 \text{ say } 3850\ SF$$

5.11.2.1 **Current Requirement/Rectifier Output Current**

The current requirement for each tank is calculated using the equation:

$$I_{req} = A \text{ x current density}$$
$$= 3850\ SF \text{ x } 1\ ma/SF$$
$$= 3850\ ma \text{ or } 3.85 \text{ amps}$$

Allow an additional 25% to account for unknown factors in the sand backfill that will be used, for rectifier aging and other long term additional requirement:

$$I_R = 3.85 \text{ amps x } 125\%$$
$$= 4.8 \text{ amps}$$

Use the next nominal size rectifier circuit of 8 amperes for each tank.

5.11.2.2 **Quantity of Anode Ribbons**

Commonly used mixed metal oxide coated titanium ribbon anodes are 0.25 inch wide by 0.025 inch thick. Manufacturer's literature indicates this material to have a current rating of 5 ma/LF for 50 year life.

The quantity of anode ribbon required for a 25+ year life for each tank is

$$N = 3850\ ma \text{ x } 5\ ma/LF$$
$$= 770\ LF$$

The ribbons will be spaced in evenly spaced parallel strips to ensure uniform distribution of CP current. This will result in 14 strips of ribbon spaced 5 feet on center.

The anode ribbons will be connected together by titanium ribbon conductor bars placed in a grid spaced at 30 feet on center ribbons to form a grid. The conductor bars are 0.5 inch wide by 0.04 inch thick. The conductor bars will be fed by multiple power feed leads. This will minimize the voltage drop through the grid, thereby allowing an even distribution of cathodic protection current to the tank bottom.

5.11.2.3 **Circuit Resistance of Anode Ribbons**

The strips are of different lengths due to the circular perimeter of the tank bottom. The theoretical resistance of a strip of metal can be calculated using the following equation from reference (c):

$$R_S = \frac{\rho}{4\pi L}\left(\ln\frac{4L}{a} + \frac{a^2 - \pi ab}{2(a+b)^2} + \ln\frac{4L}{S} - 1\right)$$

where

L	=	½ the length of the anode strip (cm) = 335 LF or 11,735 cm
a	=	width of the strip (cm) = 0.25 in or 0.635 cm
b	=	thickness of the strip (cm) = 0.025 in or 0.0635 cm
S	=	twice the depth of the anode = 6 in or 15.24 cm
ρ	=	sand resistivity = 10,000 - 45,000 ohm-cm. Sand resistivity is dependent on many factors dependent on the actual sand used. Typically, the resistivity of clean sand will vary from 10,000 ohm-cm when wet to 45,000 when dry. While the sand may be dry when first installed, moisture will eventually intrude from rain during installation, water used during compaction, and leakage through deteriorated edge seals.

The resulting resistance after substituting the above numbers is

R_s = 5.7 Ω for 45,000 ohm-cm sand, and

R_s = 1.3 Ω for 10,000 ohm-cm sand

5.11.2.4 **Rectifier Circuit Output Voltage**

The rectifier output voltage is calculated by Ohm's Law. Use the resistance for 45,000 ohm-cm sand to ensure proper operation when sand is dry:

$$\begin{aligned} V_R &= I_{req} \times R_s \\ &= 3.85 \text{ amps} \times 5.7\ \Omega \\ &= 21.9 \text{ volts} \end{aligned}$$

Use the next highest nominal size rectifier of 24 volts to account for rectifier back voltage, circuit resistance for the power feed leads and conductor bars, and compensation for system aging.

5.11.2.5 **Rectifier Input Power**

Rectifier input power for each circuit can be calculated as follows:

$$VA = \frac{V_R \times I_R}{\text{rectifier efficiency}}$$

$$= \frac{24 \text{ volts} \times 8 \text{ amps}}{0.65}$$

= 295 say 400 VA to account for 25% safety factor

The total power for the two circuits is 800 VA or 0.8 KVA. For rectifiers of this size, use single phase 120 volt AC input voltage. AC input current is calculated to be:

I_{AC} = VA/V_{AC}
= 800 VA/120 volts
= 6.67 say 7 amps

5.11.3 **Summary**

Anode material: Mixed metal oxide coated titanium ribbon, 0.25" wide x 0.025" thick. The anode grid requires 770 LF per tank placed in 14 parallel rows spaced at 5 FT on center.

Conductor bar: Conductor bars are uncoated titanium ribbons, 0.5" wide x 0.04" thick. Estimated quantity is 320 LF per tank.

Power feed leads: Supplied by manufacturer consisting of #8 AWG wire with HMWPE insulation. One end is factory connected to a 5" length of conductor bar, which will be field welded to the anode grid conductor bars. The power feed leads should be long enough to extend to the junction box without splicing. 7 power feed leads per tank are required.

Rectifier:
- Type: Oil cooled, enclosure suitable for class I, division 2.
- AC Input: 120 volt, 7 amps, 60 Hz, single phase
- DC Output: Two independent circuits, each circuit rated at 24 volts, 8 amperes
- Efficiency: 65% minimum

Reference electrodes: Combination cell of copper copper-sulfate and zinc, each component having a #14 AWG lead wire long enough to reach the junction box without splicing. 5 each combination cells per tank are required.

Due to the proximity of the tank bottom to the anode, especially at its lowest point, dielectric mesh will be installed between the anode and new tank bottom to prevent electrical short circuits.

End of Example

5.12 **Land Side of Steel Sheet Piling (Impressed Current).**

Due to high soil resistivity, and high current requirements, an impressed current system is to be provided for an existing sheet pile bulkhead about 660 LF in length by 48 FT high and is constructed of PZ 27 steel sheet piles. The sheet pile was coated between the 8 and 40 Ft depths, and the top 10 FT of the sheet pile was encased in a reinforced concrete pile cap. Electrical continuity across each pile is provided by existing bonding straps welded across each pile joint. The bonding straps are electrically connected together by bonding wires. The bulkhead is anchored via steel tie rods to an 625 FT long by eight feet high steel sheet pile deadman set back 85 FT from the bulkhead. The tie rods are coated, wrapped and enclosed in PVC sleeves along its entire length except near the turnbuckle. Electrical continuity to and across the turnbuckles is provided by existing bond wires between the turnbuckle and the rod connected to each side of the turnbuckle. The deadman is constructed of coated steel PZ 27 sheet piles. Electrical continuity across each pile is provided by existing bonding straps welded across each pile joint. Refer to Technical Paper 17 for example calculations for a water side galvanic anode system.

5.12.1 **Design Data.**

A. Seawater Resistivity - 20 ohm-centimeters
B. Design for 2 milliamperes per square foot in the soil, and 1 ma/SF for steel in concrete.
C. High silicon chromium bearing cast iron anodes will be used.
D. The design structure to electrolyte potential for the protected structure will be – 850 mv.
E. Design life: 15+ years
F. Coating Efficiency:

Steel sections encased in concrete:	90% (0.9)
Steel sections exposed to seawater:	80% (0.8)
Steel sections below mudline:	70% (0.7)

5.12.2 **Calculations.**

5.12.2.1 **Calculate Total Surface Area of Sheet Pile.**

1. Bulkhead. The bulkhead is constructed of PZ-27 steel sheet piles. PZ-27 sheet pile has a width of 18 inches and a surface area of 2.5 SF/LF on face of the pile. The number of sheet piles (N_{SP}) can be calculated as follows:

$$N_{SP} = \frac{\text{Running Length of sheet pile wall (in inches)}}{\text{18 inches}}$$

The lengths of the bulkhead and deadman anchor wall are 660 LF and 625 LF respectively. The following table summarizes the number of piles in each wall.

SHEET PILE	WALL RUNNING LENGTH (INCHES)	NO. OF SHEET PILES (N_{SP})
BULKHEAD	7,920	440
ANCHOR WALL	7,500	417

The surface area for the bulkhead can be calculated using the following equation:

$$A_{SP} = N_{SP} \text{ X Length of sheet pile X 2.5 SF/LF}$$

The bulkhead can be divided into the following zones:

- Land side, encased in concrete, sheet pile bare
- Land side, encased in concrete, sheet pile coated
- Land side, exposed to soil, sheet pile coated
- Land side, exposed to soil, sheet pile bare

The following table summarizes the surface areas for each zone.

Sheet Pile Zone			No. of Piles	Pile Length (LF)	Surface Area (SF)
Land side	**Concrete**	**Bare**	440	8	8,800
		Coated	440	2	2,200
	Soil	**Bare**	440	8	8,800
		Coated	440	30	33,000

2. Tie Rods. There are 153 tie rods, coated, wrapped, and installed in PVC sleeves. Only the portions of the tie rod at the turnbuckle and on the back side of the anchor wall are exposed to the soil. An estimated length of two LF will account for the exposed tie rod and turnbuckle. The tie rods are 2.5 inches in diameter. Since the tie rods are threaded at the turnbuckle and anchor wall, assume that the steel is bare. Calculate the surface area as follows.

$$\begin{aligned} A_{TR} &= \pi \text{ x } d \text{ x } L \text{ x Number of tie rods} \\ &= 3.14 \text{ x } (^{2.5"}/_{12"}) \text{ x } 2 \text{ LF x } 153 \\ &= 200 \text{ SF} \end{aligned}$$

3. Anchor Wall. Both sides of the anchor wall are coated and exposed to the soil. The surface area for both sides of the pile is 5 SF/LF. The length of each anchor wall pile is 8 LF. The total anchor wall surface area is:

$$
\begin{aligned}
A_{AW} &= 417 \text{ piles } X \ 8 \text{ LF } \ 5 \text{ SF/LF} \\
&= 16{,}680 \text{ SF}
\end{aligned}
$$

5.12.2.2 **Calculate the Current Required for Protection of the Sheet Pile.** The current requirement is calculated using the equation:

$$I_R = \text{Surface area } X \ (1 - CE) \times J$$

where
I_R = Cathodic protection current required
CE = coating efficiency
J = current density

The following table summarizes the current requirements.

<table>
<tr><th colspan="7">LAND SIDE</th></tr>
<tr><th colspan="3">Structures/Zones</th><th>Surface area (SF)</th><th>CE</th><th>J (ma/SF)</th><th>Current Req'd (ma)</th></tr>
<tr><td rowspan="5">Sheet pile Bulkhead</td><td rowspan="3">Concrete</td><td>Bare</td><td>8,800</td><td>0</td><td>1</td><td>8,800</td></tr>
<tr><td>Coated</td><td>2,200</td><td>0.9</td><td>1</td><td>220</td></tr>
<tr><td colspan="4">25% of above for concrete cap rebar</td><td>2,255</td></tr>
<tr><td rowspan="2">Soil</td><td>Bare</td><td>8,800</td><td>0</td><td>2</td><td>17,600</td></tr>
<tr><td>Coated</td><td>33,000</td><td>0.7</td><td>2</td><td>19,800</td></tr>
<tr><td>Tie Rods</td><td>Soil</td><td>Bare</td><td>200</td><td>0</td><td>2</td><td>400</td></tr>
<tr><td>Sheet pile Anchor Wall</td><td>Soil</td><td>Coated</td><td>16,680</td><td>0.7</td><td>2</td><td>10,008</td></tr>
<tr><td colspan="6">Total Land Side Current Required</td><td>59,083</td></tr>
<tr><td colspan="6">or</td><td>59.1 amps</td></tr>
</table>

Use an 80 ampere rectifier. The extra current capacity will allow for additional coating deterioration, system aging, and current loss to the water side of the sheet pile.

5.12.2.3 **Calculate the Quantity of Anodes.**

Use high silicon chromium bearing cast iron (HSCBCI) tubular anodes. The quantity of anodes must be calculated to meet three different parameters, design life, anode bed resistance, and anode maximum current discharge. The required quantity of anodes will be the largest of the three calculated quantities.

1. First calculate the quantity of anodes to meet design life

$$N_L = \frac{Y\ S\ I_R}{W\ U}$$

where:

I_R = Current required = 59.1 amps
N_L = Number of anodes to meet design life
S = Anode consumption rate = 1 lb/amp-yr)
U = Anode utilization factor = 0.8
W = Weight of one anode (lb)
Y = CP system design life = 20 years

*** IMPORTANT ***

Do not end calculations at this point. The quantity of anodes required to meet the recommended maximum anode discharge and the ground bed resistance requirements must still be calculated.

2. Next calculate the quantity of anodes to meet recommended maximum anode current discharge

$$N_D = \frac{I}{A_A \times I_A}$$

where:

I = Current required (59.1 amps)
A_A = Anode surface area (SF)
I_A = Max. recommended anode discharge current density (1 amp/SF)

*** IMPORTANT ***

Do not end calculations at this point. The quantity of anodes required to meet the ground bed resistance requirements must still be calculated.

3. Calculate quantity of anodes to meet 1-ohm ground bed design

The anodes will be installed in a shallow, distributed, vertical anode bed. The resistance of the anode bed can be approximated by the following equation:

$$N_R = \frac{0.0052\,\rho}{R_S \times L} \times [\ln(8L/d) - 1]$$

where
d = diameter of anode backfill column (1 FT)
L = length of the anode backfill column (LF)
N_R = quantity of anodes to meet the anode bed design resistance
R_S = anode bed design resistance (1 ohm)
ρ = soil resistivity (6,000 ohm-cm)

4 Determine quantity of anodes. The following table summarizes the above calculations for various common tubular anode sizes:

CALCULATED ANODE QUANTITIES							
Anode Size	**Weight (LB)**	**Area (SF)**	**Backfill Length (LF)**	**Backfill Dia. (ft)**	**N_L**	**N_D**	**N_R**
2.66" x 42" (TA1)	31	2.4	5.5	1	46	25	16
2.19" x 42" (TA2A)	23	2.0	5.5	1	62	30	16
2.19" x 60" (TACD)	32	2.8	7.0	1	45	22	14
2.66" x 60" (TAD)	45	3.5	7.0	1	32	18	14
3.75" x 60" (TAM)	60	4.9	7.0	1	23	13	14
4.75" x 60" (TAJ)	78	6.2	7.0	1	19	10	14
2.66" x 84" (TA3)	63	4.9	9.0	1	23	13	12
3.75" x 84" (TA4)	85	6.9	9.0	1	17	9	12
4.75" x 84" (TA5)	110	8.7	9.0	1	13	7	12

Of the three calculated quantities for a particular anode, the larger quantity of the three must be used to ensure all conditions are satisfied. Considering CP current distribution, use the 23 each 60 LB, 3.75 inch diameter X 60 inch long anodes. Install the anodes so that the bottom of the anode is about one foot above the bottom of the hole. Provide anode with factory connected lead wires of sufficient length to reach the anode junction box without splicing.

5.12.2.4 **Calculate the Total Circuit Resistance (R_T).**

1. Calculate the anode bed circuit resistance (Rs) using the appropriate numbers from the above table:

$$R_S = \frac{0.0052\ \rho}{N \times L} \times [\ln(8L/d) - 1]$$

$$= 0.56 \text{ ohm}$$

2. Calculate the anode cable resistance (R_C)

   Each anode lead will run directly back to the anode junction box, so the parallel cable resistance is estimated to be equivalent to a 230 LF length of cable. Use No. 4 copper wire for the anode leads. The cable resistance is estimated as follows:

$$R_C = R_{\#4} \times \text{length of cable}$$

$$= 0.00025 \text{ ohm/LF} \times 230 \text{ LF}$$
$$= 0.06 \text{ ohm}$$

3. Calculate total circuit resistance (R_T)

   The total circuit resistance is 0.56 ohm + 0.06 ohm = 0.62 ohm

5.12.2.5 **Calculate the Rectifier Output Voltage (V_R) Using Ohm's Law.**

$$V_R = I_{rect} \times R_T \times 125\%$$
$$= 59.1 \text{ amps} \times 0.62\ \Omega \times 1.25$$
$$= 45.8 \text{ volts}$$

Use the next highest nominal size rectifier rated for 50 volts DC.

5.12.2.6 **Calculate the Rectifier Input Power**

Available power is 480/277 volts. For rectifiers of the size specified above, use three phase 480 volt AC input voltage. Three phase rectifiers are more efficient and long term power costs outweigh the higher initial costs for the rectifier. Rectifier input power is calculated as follows:

$$P = \frac{V_R \text{ x } I_R}{\text{rectifier efficiency}}$$

$$= \frac{\text{50 volts x 80 amps}}{0.85}$$

$$= \text{4,705 VA say 5 KVA}$$

AC input current is calculated to be:

$$I_{AC} = \frac{P}{V_{AC} \text{ x } 1.732}$$

$$= \frac{\text{5,000 VA}}{\text{480 volts x 1.732}}$$

$$= \text{6 amps}$$

The sheet pile bulkhead is not located near a building where an electrical panel can be used. Therefore, the rectifier will be located adjacent to a three phase, 480 volt transformer station.

5.12.2.7 Short Circuit Calculations

A. Transformer Full Load Current (I_{FL})

$$I_{FL} = \frac{VA}{V_{AC} \text{ x } \sqrt{3}}$$

$$= \frac{\text{500,000 VA}}{\text{480 volts x 1.732}}$$

$$= \text{601 amps}$$

B. Fault Current at Transformer Secondary (I_{SC}).

$$I_{SC} = \frac{I_{FL}}{\%Z_T/100}$$

$$= \frac{601}{4.5/100}$$

= 13,356 Amps

Therefore, use 18,000 amp I.C. service breaker.

5.12.2.7 **Summary**

Anodes: 23 each high silicon chromium bearing cast iron tubular anodes, with dimensions of 3.75 inches in diameter x 60 inches long, and weighing 63 LB. Locate the anodes 22 feet from each end of the bulkhead and at 28 feet spacing in between.

Anode Supplied by manufacturer consisting of #4 AWG wire with HMWPE insulation. One end is factory connected to the anode. The anode leads should be long enough to extend to the junction box without splicing.

Rectifier:
Type: Oil cooled, enclosure suitable for outdoors use.
AC Input: 480 volt, 6 amps, 60 Hz, three phase
DC Output: 50 volts, 80 amps
Efficiency: 85% minimum

End of Example