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An Introduction to Impressed Current Cathodic Protection

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1. INTRODUCTION. There are two principle methods of providing cathodic protection: sacrificial anode and impressed current. The primary advantage of impressed current cathodic protection systems over sacrificial anode cathodic protection systems is that the driving potential of the impressed current systems is not limited by the corrosion potential of an active metal. The ability to select appropriate driving potentials, and to adjust the driving potential after system installation, gives the designer and operator of impressed current cathodic protection systems additional flexibility to compensate for changing environmental conditions. The primary advantage of this variable driving potential in the design of impressed current cathodic protection systems is the ability to select the location of anode beds for an optimum distribution of protective current with a minimum of interference. The variable driving potential available in impressed current systems also allows the protection of structures in high resistivity environments where the output of sacrificial anodes is severely limited. The primary operational benefit of variable driving potential is the ability to adjust the system for changes in soil resistivity, anode condition, structure surface (coating) condition and additions to the structure.

2. DETERMINATION OF CIRCUIT RESISTANCE. In the design of impressed current cathodic protection systems the first step is the determination of the total current required for the system. This fixes the output current required for the system power supply. The next step is the determination of the required output or driving potential that will be required. As the output current is fixed, the required driving potential will be determined by the total circuit resistance and the back potential offered by the structure-to-anode potential. The equivalent circuit is shown in Figure 1. In most impressed current systems, the major factor in the determination of the total circuit resistance is the anode-to-electrolyte resistance.

2.1 ANODE-TO-ELECTROLYTE RESISTANCE. Also known as "ground bed resistance," this is often the highest resistance in the impressed current cathodic protection system circuit.

2.1.1 EFFECT ON SYSTEM DESIGN AND PERFORMANCE. As shown in Figure 1, the anode-to-electrolyte resistance, if high, is the most important factor in the determination of the driving potential required to provide the current required for effective cathodic protection in impressed current cathodic protection systems. Anode-to-electrolyte resistance can be varied within wide limits by the use of different sized anodes and the use of multiple anodes. The lowest anode-to-electrolyte resistance commensurate with total system cost is desirable since it will reduce the power costs by lowering the output potential of the power supply. This lower power supply output potential also results in higher reliability for other system components, particularly the insulation on cables, splices, and connections. In general, anode bed resistances below 2 ohms are desirable.

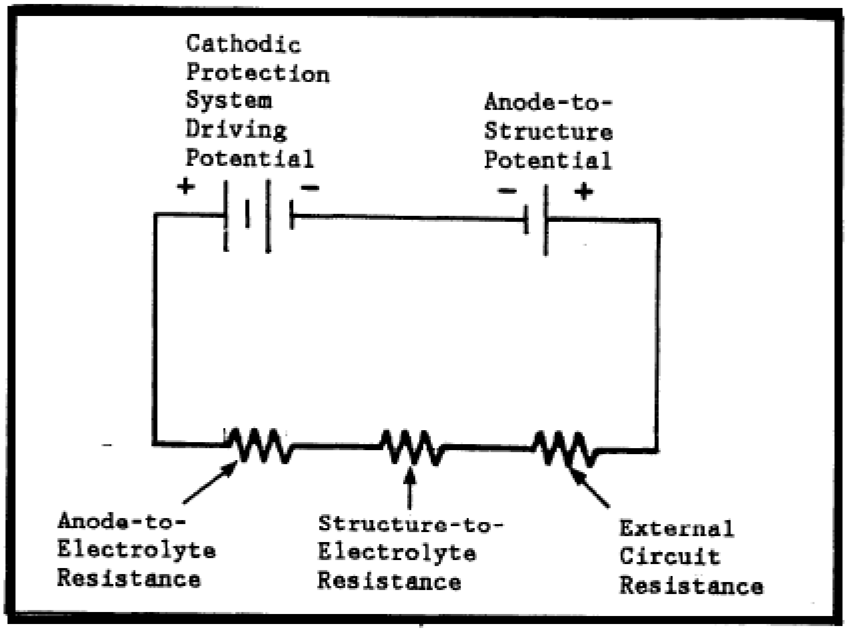


Figure 1

Equivalent Cathodic Protection Circuit

2.1.2 CALCULATION OF ANODE-TO-ELECTROLYTE RESISTANCE. Anode-to-electrolyte resistance can be computed from data on anode type, size, shape, and configuration of multiple anode arrays plus the soil resistivity. First, the type, size, and shape of the anode to be used is chosen. Then, the resistance of a single anode to be used is calculated. Then the effect of the use of multiple anodes is determined. However, as the actual environmental resistivity may not be uniform, or may undergo seasonal variations, the calculation of anode-to-electrolyte resistivity should only be considered to be an approximation of the actual resistance to be encountered. This can result in the actual driving potential required being somewhat different than the potential calculated using the approximate anode bed resistance. Thus, after installation, the driving potential must be adjusted to give the required current output. As the other potentials and resistances in the cathodic protection circuit vary, the system will also require periodic adjustments.

2.1.3 BASIC EQUATIONS. The formulae developed by H. B. Dwight for a single cylindrical anode can be used to determine the anode-to-electrolyte resistance. The formula for a vertically oriented anode is:

$$R_v = 0.0052\ P/L \times [\ln(8L/d)-1]$$

The formula for a horizontally oriented anode is:

$$R_h = 0.0052\ P/L \times \ln\{[4L^2 + 4L(S^2 + L^2)^{1/2}]/ds\} + s/L - (s^2 + L^2)^{1/2} - 1 \qquad (10)$$

where

- R_v = electrolyte-to-anode resistance for a single vertical anode to a remote reference (ohms)
- R_h = electrolyte-to-anode resistance for a single horizontal anode to a remote reference (ohms)
- P = electrolyte resistivity (ohms-cm) at the location and depth of the anode
- L = anode length or backfill column length if backfill is used (feet)
- d = effective diameter of anode or backfill column (feet)
- s = twice depth of anode (feet)

2.1.4 SIMPLIFIED EXPRESSIONS FOR COMMON SITUATIONS. For many common situations, the Dwight formulae have been simplified by combining terms and eliminating terms that have insignificant values in most cases. Some of these simplified formulae have been given in para. 2.6. In addition to these simplified formulae, the following simplified formula is often used:

2.1.4.1 RESISTANCE OF A SINGLE VERTICAL ANODE.

$$R_v = (P/L)K$$

where

R_v	=	electrolyte-to-anode resistance for a single vertical anode to remote reference (ohms)
P	=	electrolyte resistivity (ohms-cm) at the location and depth of the anode
L	=	anode length (feet) or backfill column length if backfill is used
K	=	shape function from table below where:
L/d	=	ratio of length-to-diameter of anode

L/d	K	L/d	K
1	0.008	16	0.0201
2	0.010	18	0.0207
3	0.012	20	0.0213
4	0.013	25	0.0224
5	0.0140	30	0.0234
6	0.0150	35	0.0242
7	0.0158	40	0.0249
8	0.0165	45	0.0255
9	0.0171	50	0.0261
10	0.0177	55	0.0266
12	0.0186	60	0.0270
14	0.0194		

2.1.4.2 PARALLELING OF ANODES. Common practice to reduce anode bed resistance is to connect several anodes in parallel in a group. The resistance of a group of anodes is less than the resistance for a single anode but is greater than that calculated from the usual parallel resistance formula due to interactions between the fields surrounding each anode. If the anodes are arranged in a parallel row, the resistance of a group of anodes can be approximated by the following formula:

$$R_n = (1/n)R_v + P_s F/S$$

where

Rn	-	total anode-to-electrolyte resistance for a group of vertical anodes, equally spaced and in a single row, to remote reference (ohms)
n	-	number of anodes
R_v	-	electrolyte-to-anode resistance for a single vertical anode to remote reference (ohms)
P_s	-	electrolyte resistivity (ohms-cm) with pin spacing equal to S
S	-	anode spacing (feet)
F	-	paralleling factor from table below:

n	F	n	F
2	0.00261	12	0.00182
3	0.00289	14	0.00168
4	0.00283	16	0.00155
5	0.00268	18	0.00145
6	0.00252	20	0.00135
7	0.00237	22	0.00128
8	0.00224	24	0.00121
9	0.00212	26	0.00114
10	0.00201	28	0.00109
		30	0.00104

If multiple rows of anodes are used where the spacing between rows is more than 4 times the spacing between the anodes in each row, the usual parallel resistance formula:

$$1/R = 1/R_1 + 1/R_2 + 1/R_3 + 1/R_4 + \ldots$$

may be used.

2.1.4.3 SPECIAL FORMULA FOR WATER TANKS. For water tanks where circular arrays of anodes are commonly used and where the structure surrounds the anodes and electrolyte, special formulae have been developed to calculate the anode-to-electrolyte resistance. For a single cylindrical anode, the formula developed by E. R. Shepard may be used. The formula is as follows:

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

where

R	-	anode-to-electrolyte resistance (ohms)
P	-	water resistivity (ohms-cm)
L	-	length of a single anode (feet) (backfill is not used)
D/d	-	ratio of anode diameter (d) to tank diameter (D) (same units for each)

The anodes are usually arranged in a circular array in the tank bowl. The optimum diameter of this array can be determined by the following formula:

$$r - DN/2(- + N)$$

where

r	-	radius of anode array (feet)
D	-	tank diameter (feet)
N	-	number of anodes

If four or more anodes are used in a circular array, the following modified Shepard formula should be used to calculate the resistance of the array:

$$R - 0.012\ P \log (D/a)/L$$

where

a - factor for equivalent diameter from table below, multiplied by the optimum diameter of the anode circle (calculated previously)

Number of Anodes in Circle	Factor for Equivalent Diameter
4	0.08
6	0.11
8	0.18
10	0.28
12	0.43
14	0.70

P	-	water resistivity (ohms-cm)
L	-	length of a single anode (feet)
D	-	tank diameter (feet)

2.1.5 FIELD MEASUREMENT. Calculations, as previously discussed, can give good approximations of anode-to-electrolyte resistance under actual conditions. While these calculations can be effectively used for system design, if the environment is well known, the actual anode-to-electrolyte resistance that is encountered is sometimes sufficiently different from the calculated value to require adjustment or modification of the system. The actual anode-to-electrolyte resistance can also be determined by actual field measurements.

2.1.5.1 ANODE FIRST METHOD. In this method of determining anode-to-electrolyte resistance, the anodes are installed as designed and the actual resistance between the anode or anode bed and the structure to be protected is measured. This measurement includes both the anode-to-electrolyte resistance and the structure-to-electrolyte resistance and can be used to determine the required driving potential so that the proper power supply can be ordered. This is the most accurate method of sizing the needed rectifier and should be used where practical.

2.1.5.2 POWER SUPPLY FIRST METHOD. In this method, the power supply is ordered based upon the calculated circuit resistance and is installed and connected to the structure. The anodes are installed as planned, but one at a time. The total circuit resistance is calculated based upon the actual power supply output in amperes and volts. If additional anodes are required in order to achieve the desired anode-to-electrolyte resistance, they can be installed at this time at a relatively low cost since the equipment required for installation is on site and excavations for the anode lead cables are open.

2.1.6 EFFECT OF BACKFILL. Backfill is very important and is usually used to surround impressed current anodes in order to reduce anode-to-electrolyte resistivity, to increase porosity around the anodes to insure that any gasses formed during operation will be properly vented, and to reduce polarization effects and reduce localized dissolution of the anode. Under favorable circumstances, the anode-to-electrolyte resistivity can be reduced to one-half through the use of backfill. In extremely low resistance environments such as seawater, graphite and high silicon cast iron anodes can be used without backfill; otherwise, impressed current anodes should always be used with backfill. In high resistivity environments where the use of backfill is impractical, graphite anodes should not be used. High silicon chromium bearing cast iron

(HSCBCI) anodes can be used with or without backfill in most instances. The cost of using backfill should be evaluated on an economic basis with the reduction in the power requirements or the of anodes required being the cost reduction factors. If the resistivity of the backfill is less than one-tenth the soil resistivity, then the voltage drop through the backfill becomes negligible.

a) Thus, the effective diameter of the anode is the diameter of the backfill rather than the diameter of the anode itself. As can be evaluated through calculation of anode-to-electrolyte resistance, this can result in a significant reduction in anode-to-electrolyte resistance which can be useful in reducing the number of anodes required, the required driving potential, or both. Backfill for impressed current anodes is carbonaceous material from several sources. It can be either coke breeze (crushed coke), flake graphite, or round particle petroleum coke. Experience has shown that round particle calcined petroleum coke has many advantages over coke breeze made from coal. Specification "Loresco DW-2" or equal should be used for surface anode beds and Loresco DW-3 or equal for deep anode beds. Because the material can be pumped and has good porosity and particle-to-particle contact, round particle petroleum coke backfill is the most desirable material and its higher cost will be justified for most installations, particularly for "deep anodes."

b) In areas where the soil is extremely wet or loose, such as in a swampy area, it may not be possible to properly install or tamp the backfill material. Packaged anodes with the backfill contained in metal cylinders (cans) surrounding the anodes may be useful in these circumstances but increase the cost. Anodes prepackaged with backfill, usually contained in metal cans which are rapidly corroded away during operation, are easier to install than separate installation of anode and backfill. The prepackaged anodes are higher in cost and have the following additional disadvantages:

(1) High unit weight reduces ease of handling.
(2) Possibility of voids developing in backfill during transportation and handling.
(3) The critical anode cable and connection between the anode and cable are hidden and difficult to inspect.

The choice of packaged versus unpackaged impressed current anodes must be made based upon economics and local site conditions. Packaged anodes are usually used only where unstable soil conditions exist, where the hole excavated for installation caves in, and where prepackaged anodes are stocked for augmenting systems.

2.2 STRUCTURE-TO-ELECTROLYTE RESISTANCE. The structure-to-electrolyte resistance is commonly disregarded in the design of impressed current cathodic protection systems since it is usually very small with respect to the anode-to-electrolyte resistance. When total circuit resistance is measured (refer to para. 2.1.5), the structure-to-electrolyte resistance is included in the value obtained.

2.3 CONNECTING CABLE RESISTANCE. The connecting cable resistance is determined by the size and length of cables used.

2.4 RESISTANCE OF CONNECTIONS AND SPLICES. In addition to the fact that connections and splices are sources of resistance in impressed current cathodic protection systems, they are a site of failure. These connections should be kept to an absolute minimum, and they should be very carefully assembled, insulated, inspected, and installed. The cable from the positive lead of the power source to the anodes carries a high positive charge and will deteriorate rapidly at any point where the insulation is breached and the conductor contacts the electrolyte. The number and location of each connection should be installed per the system design and not at the discretion of the installer.

3. DETERMINATION OF POWER SUPPLY REQUIREMENTS. The power supply requirements, namely current and voltage, are determined by Ohm's Law from the required current for protection of the structure and the calculated or measured total circuit resistance. The actual power supply requirement should allow for future loads and rectifier aging. Generally, a factor of 1.5 over calculated output is used.

4. 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 power supply depends upon local conditions at the site and should be evaluated based upon life cycle cost including maintenance and availability of ac power or fuel.

4.1 RECTIFIERS. 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.

4.2 THERMOELECTRIC GENERATORS. These power supplies convert heat directly into direct current electricity. This is accomplished through a series of thermocouples which are heated at one end by burning a fuel and cooled at the other, usually by cooling fins. Thermoelectric generators are highly reliable since they have few, if any, moving parts. They are available in sizes from 5 to 500 W. 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.

4.3 SOLAR. A photovoltaic solar cell converts sunlight directly into direct current electricity. The cost per W 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 supplies power to the system and recharges batteries when sunlight is received. When sunlight is not being received, the batteries supply the required current.

4.4 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.

4.5 GENERATORS. Engine- or wind-driven generators can be used to supply direct current power for impressed current cathodic protection systems at sites where ac power is not available.

5. RECTIFIER SELECTION. 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.

5.1 RECTIFIER COMPONENTS. Figure 2 is a circuit diagram for a typical single-phase full-wave bridge type rectifier showing the components found in most standard rectifiers of this type. The diagram also shows an external switch and circuit protection device which is mandatory for many rectifier installations.

5.1.1 TRANSFORMER COMPONENT. The transformer reduces the incoming alternating current voltage to the alternating current voltage required for the operation of the rectifing component. 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 voltage should be adjustable to vary the rectifier voltage from zero, through at least 20 equal steps, to its maximum capacity.

5.1.2 RECTIFYING ELEMENTS. The alternating current from the secondary windings of the transformer element is converted to direct current 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. The most common configurations of rectifying elements are the single-phase bridge, single-phase center tap, three-phase bridge, and three-phase wye. 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 percent 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 which 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:

$$\text{Efficiency (\%)} = \frac{\text{dc output power}}{\text{ac input power}} \times 100$$

Typical efficiencies of single-phase rectifying elements are in the order of 60 to 75 percent but can be increased by filtering the output or by using a three-phase circuit.

5.1.3 OVERLOAD PROTECTION. Overload protection in the form of either 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 ac input and dc output in order to prevent damage from lightning strikes or other short duration power surges. The respective firing voltages of the lightning arresters should be higher than the ac input and dcoutput voltage. Due to their susceptibility to damage from voltage surges, silicon diodes shall also be protected by selenium surge cells or varistors and by current limiting fuses against over-current surges. A high speed rectifier fuse should be installed in one leg of the ac secondary and one in the dc negative output leg.

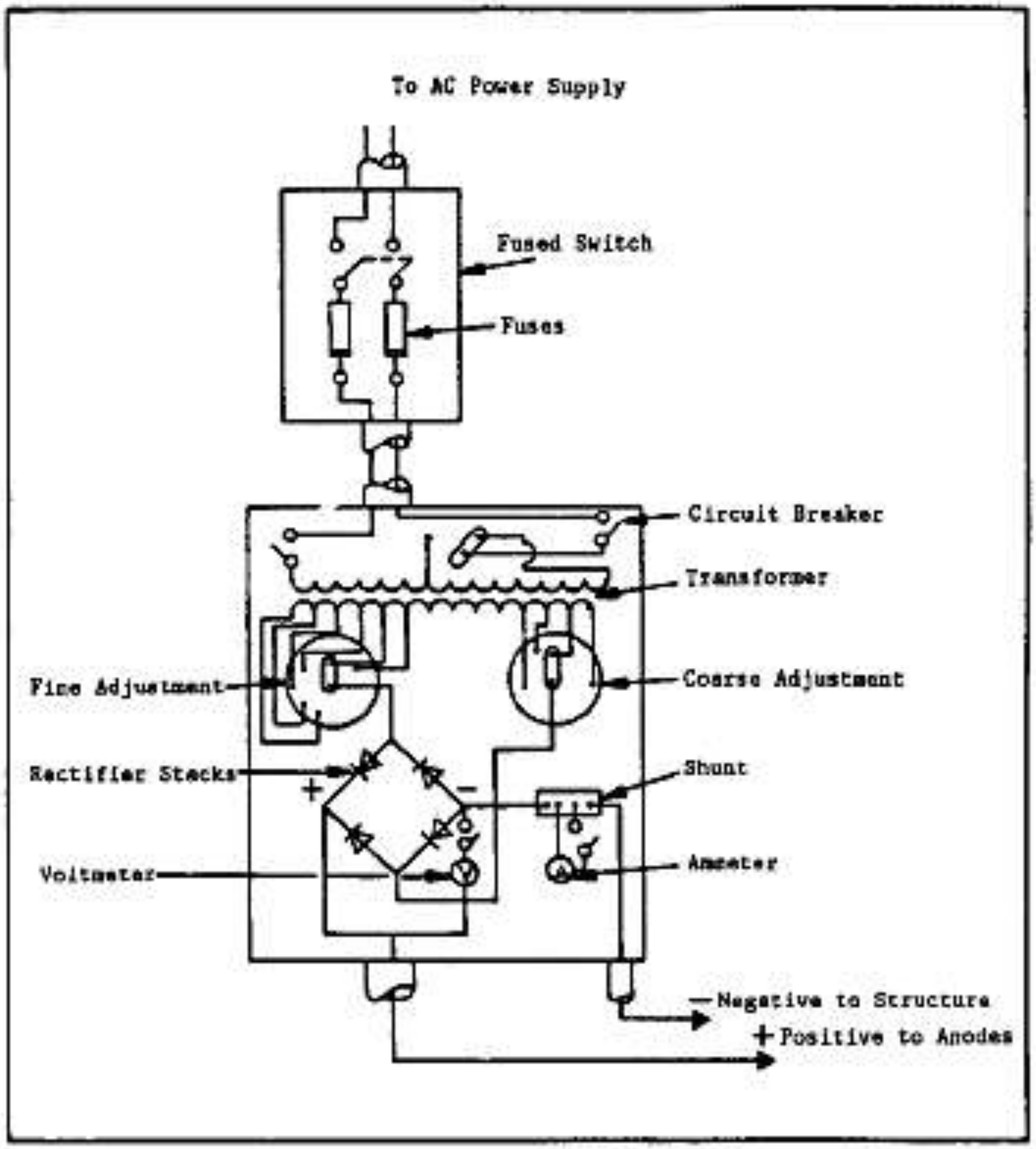


Figure 2

Single phase – full-wave bridge rectifier

5.1.4 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, it moves from zero to the indicated reading. Frozen meter movements are easily detected in this manner. Often, one meter and a two position switch are used to measure both potential and current. Current is usually measured using 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.

5.2 STANDARD RECTIFIER TYPES

5.2.1 SINGLE-PHASE BRIDGE. The circuit for this type of rectifier is shown in Figure 2. This type of rectifier is the most commonly used type of rectifier up to an output power of about 1,000 W. Above 1,000 W, 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 3.

5.2.2 SINGLE-PHASE CENTER TAP. The circuit of a single-phase center tap rectifier is shown in Figure 4. This type of rectifier has only two rectifying elements but produces full-wave rectified output. However, since 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.

5.2.3 THREE-PHASE BRIDGE. The circuit for a three-phase bridge rectifier is shown in Figure 5. 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 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, only 4.5 percent. 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 1,000 W capacity.

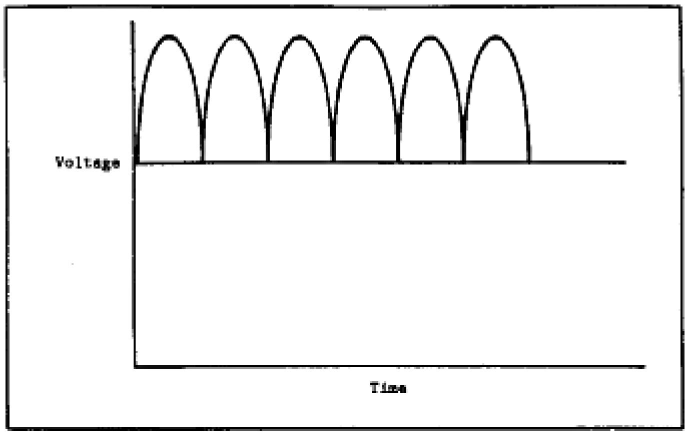


Figure 3

Full-wave rectified current

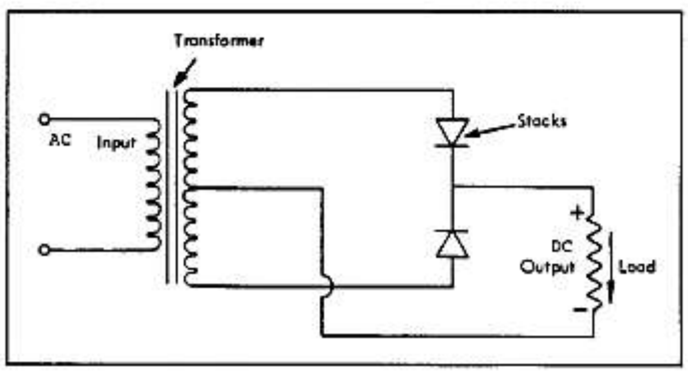


Figure 4

Single-phase – center tap circuit

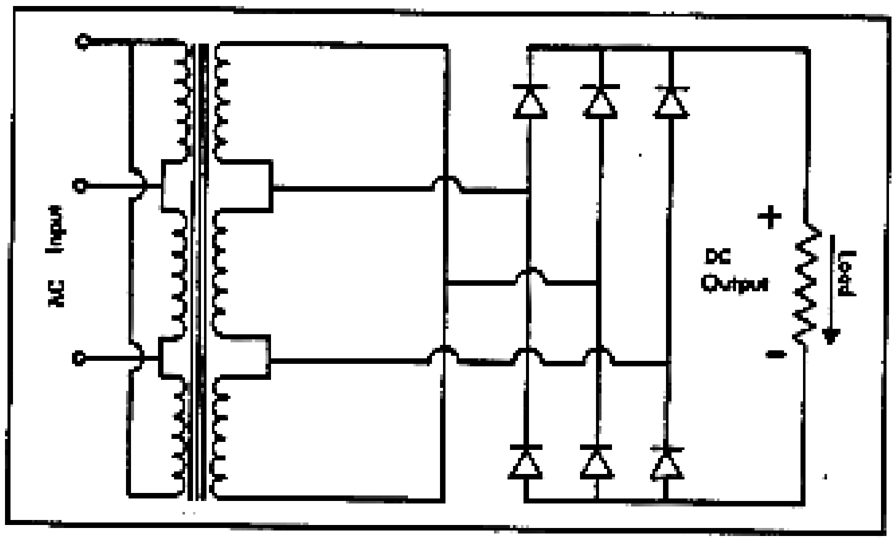


Figure 5

Three-phase bridge circuit

5.2.4 THREE-PHASE WYE. The circuit for a three-phase wye rectifier is shown in Figure 6. This type of rectifier supplies half-wave rectified current as shown in Figure 7. 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.

5.2.5 SPECIAL RECTIFIER TYPES. Several special 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.

(a) A constant current rectifier is depicted by a block diagram in Figure 8. A direct current input signal to the power amplifier is supplied from an adjustable resistor in the output signal. 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 is supplied. The power amplifier may either be of an electronic (silicon controlled rectifier) or saturable reactor type.

b) An automatic potential control type is shown by a block diagram in Figure 9. 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. These rectifiers are commonly used where the current requirement or circuit resistance varies greatly with time such as in the case of a a structure in an area with high periodic tidal currents or a water storage tank where the water level changes considerably.

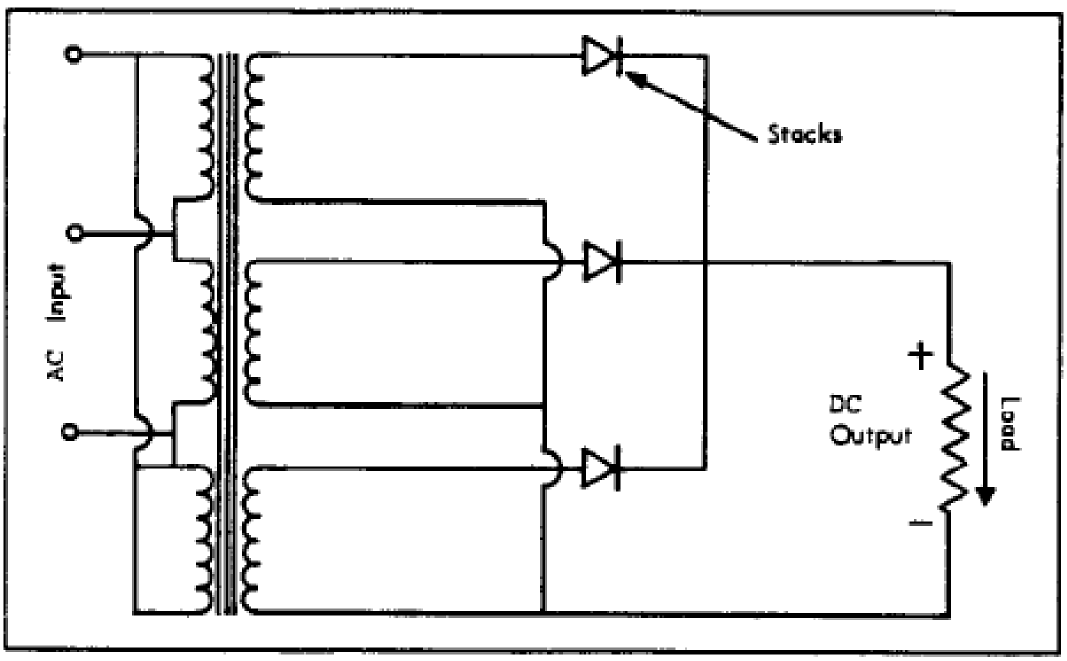


Figure 6

Three-phase wye circuit

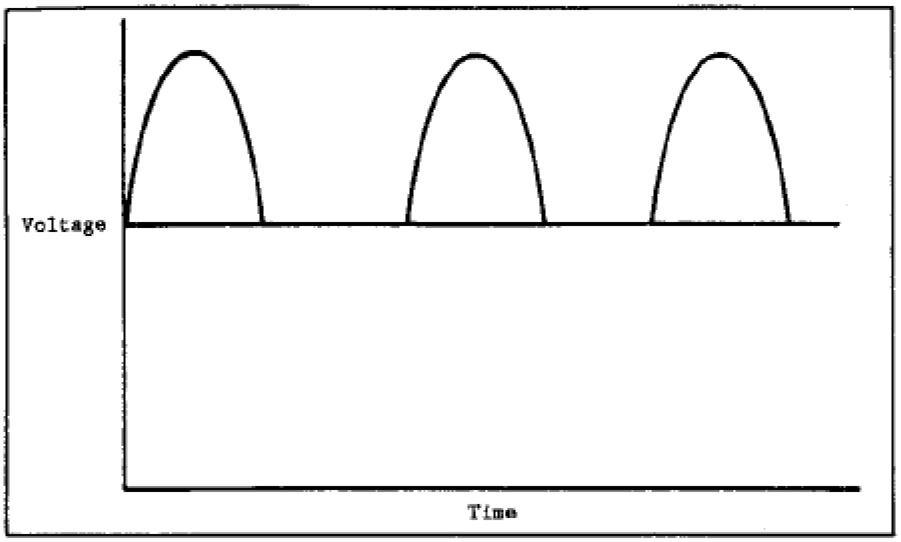


Figure 7

Half-wave rectified circuit

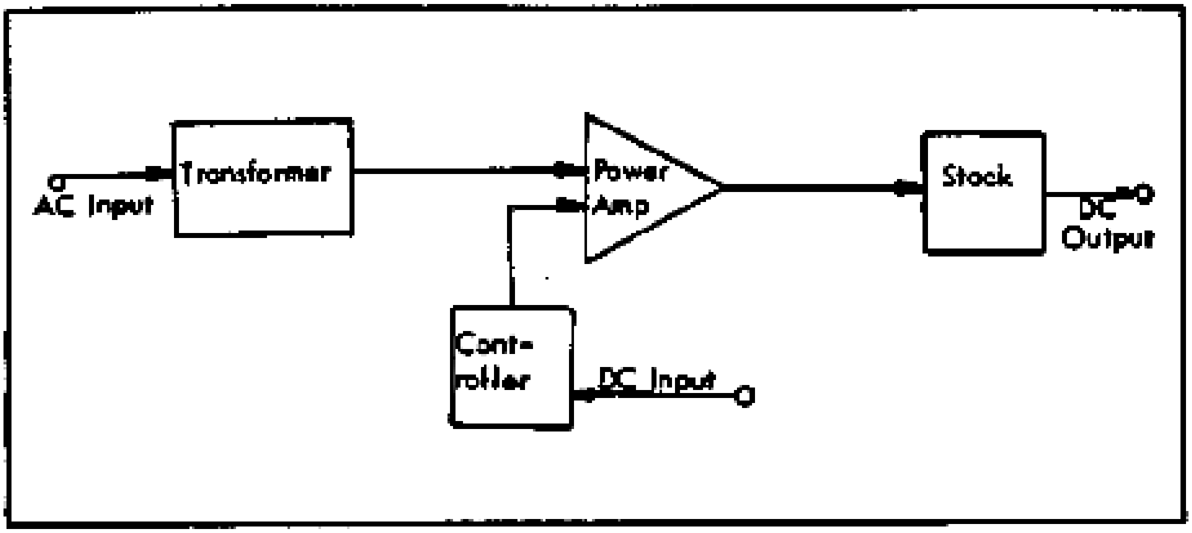


Figure 8

Constant current rectifier

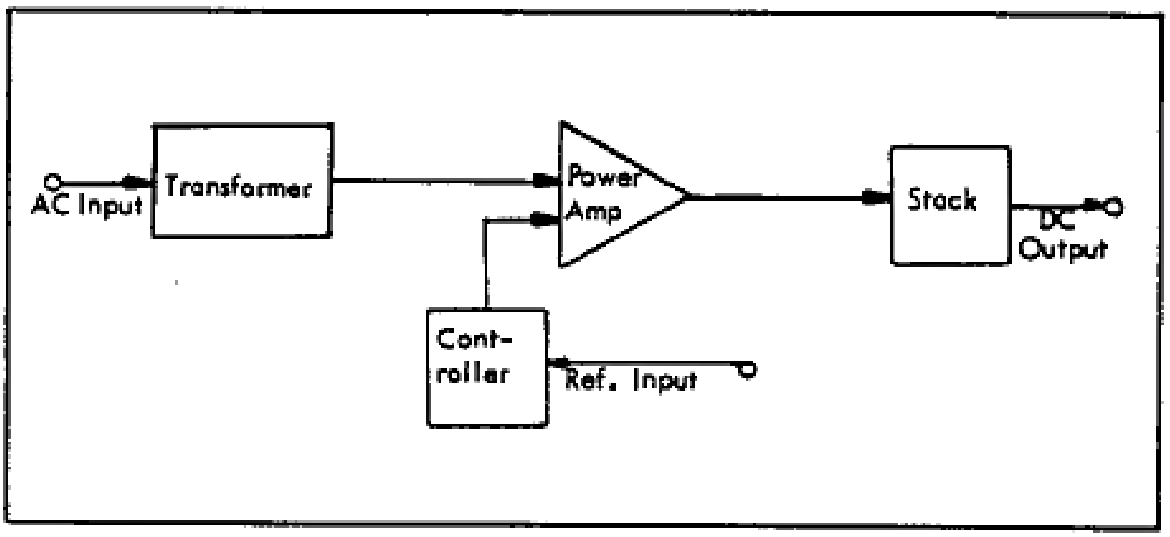


Figure 9

Constant potential rectifier

c) Multicircuit constant current type is depicted by a circuit diagram in Figure 10. This type of rectifier is designed to provide a small, constant current in the order of 100 mA to a single anode. As the resistance of the internal resistor is high when compared with the external circuit resistance, the output current is controlled by the value of this resistor. The output potential will vary up to the line voltage to supply the specified output current. In this type of circuit, the structure is connected directly to the neutral lead of the alternating current power supply. Due to problems associated with stray currents and the possible presence of high voltages external to the rectifier units, the use of this type of rectifier is not recommended. 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, the selection of a standardized type of rectifier should be considered.

5.3 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 "add on's" to stock units or in custom units.

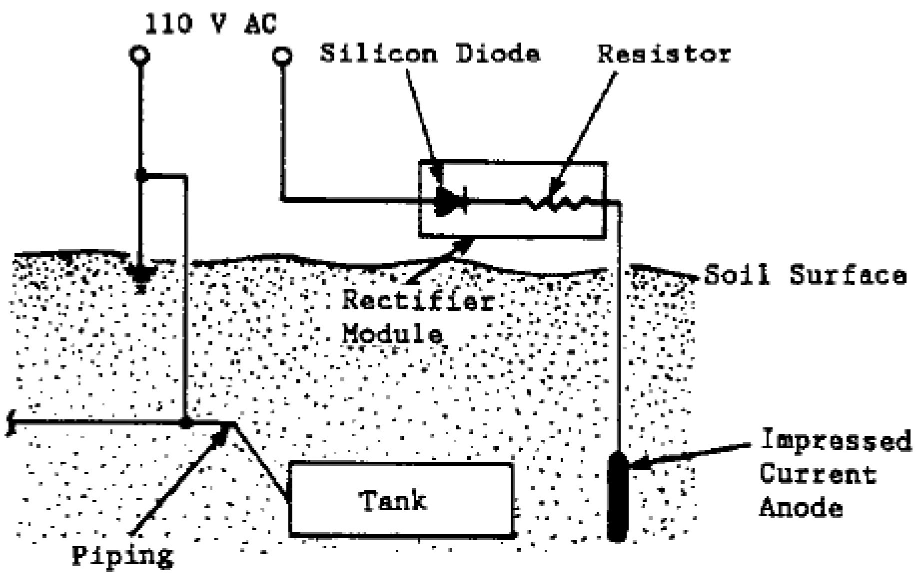


Figure 10

Multicircuit constant current rectifier

5.3.1 AVAILABLE FEATURES. Features now available on most units include:

- Constant voltage or current output
- Multiple circuits in the same enclosure

- c) Air cooled or oil immersed
- d) Any commercial input voltage
- e) Three phase or single phase
- f) Center tap or bridge
- g) Wide range of output currents and voltages
- h) Efficiency filters to reduce ac ripple
- Interference noise filters
- j) Explosion proof enclosures
- k) Small arms proof enclosures
- l) Lightning protection on both ac input and dc output
- m) Surge protection on both ac input and dc output
- n) Silicon diodes or selenium stacks
- o) Painted or galvanized cases
- p) Various mounting legs or brackets
- q) Units designed for direct burial
- r) External "on-off" indicators
- s) Variety of price, quality and warranty
- t) Maintenance free anodized aluminum enclosure

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

5.3.2 AIR COOLED VERSUS OIL IMMERSED. Rectifiers can be supplied as either entirely air cooled, entirely oil immersed or with the stacks only oil immersed. Air-cooled units are lowest in cost and easiest to install and repair. However, oil-cooled units should be specified where corrosive or dirty atmospheric conditions are encountered or where explosive gasses may be present. The controls should not be immersed in the oil. 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 polychlorinated biphenyls (PCBs) which have been determined to be carcinogenic and are no longer supplied with new units. Units containing PCBs should be treated according to current policy regarding PCBs.

5.3.3 SELECTING AC VOLTAGE. Select alternating current voltages of almost any commercial power supply voltage. Units with either 115 V, 230-V or 440-V single-phase or 208-, 230-, or 440-V three-phase inputs are the most common. Some units are supplied with dual input voltage selected by wiring arrangements during installation. Choices between single-phase and three-phase units should be based upon a balance between first cost and efficiency. The following table can be used to select the combinations of rectifier capacity and input voltages which are commonly most economical if a selection of supply voltages is available:

RECTIFIER dc RATING (W)	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

5.3.4 DC VOLTAGE AND CURRENT OUTPUT. Direct current voltage outputs from 8 to 120 V and current outputs from 4 A to 100 A are common. Almost any current can be provided but it is generally best to select a smaller standard size rectifier unit such as 20 A and use multiple units if very large amounts of current are required. Many small units cause far less interference and provide more uniform current distribution along the protected structure than few large units.

5.3.5 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 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 units is inherently low. Noise interference filters should be used 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.

5.3.6 EXPLOSION PROOF RECTIFIERS. Rectifiers and other system components such as switch and circuit breakers are available in explosion proof enclosures conforming to Electrical Safety Standards for Class I Group D hazardous conditions that may be encountered in fuel or natural gas storage or distribution systems. Such enclosures should be specified whenever explosive hazards may exist.

5.3.7 LIGHTNING ARRESTERS. Lightning arresters should 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. The arresters on the output should have a firing voltage greater than the rectifier output voltages.

5.3.8 SELENIUM VERSUS SILICON STACKS. While some old installations used copper oxide rectifying elements, modern units use 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. 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. 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 11. Silicon diodes are mounted in metal cases which 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 12, are more efficient than selenium elements, particularly at higher voltage ratings. Silicon rectifying elements are more subject to complete failure from voltage surges which 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.

5.3.9 OTHER OPTIONS. Other features listed in para. 5.3.1 are available and should be selected as appropriate. In remote off-base areas, small arms proof enclosures may be required based upon local experience. Specifying clear anodized aluminum enclosure top coated with one clear coat of polyurethane will reduce maintenance painting.

5.3.10 RECTIFIER ALTERNATING CURRENT RATING. The ac current requirement for a rectifier can be determined based upon rectifier output and efficiency by the following formulae:

a) Single-Phase Rectifiers

EQUATION: $I_{ac} = (E_{dc} \times I_{dc})/F \times E_{ac}$

where

- I_{ac} = alternating current requirement (A)
- E_{dc} = direct current output voltage
- I_{dc} = direct current output amperage
- F = rectifier efficiency (%)
- E_{ac} = alternating current voltage (per phase)

b) Three-Phase Rectifiers

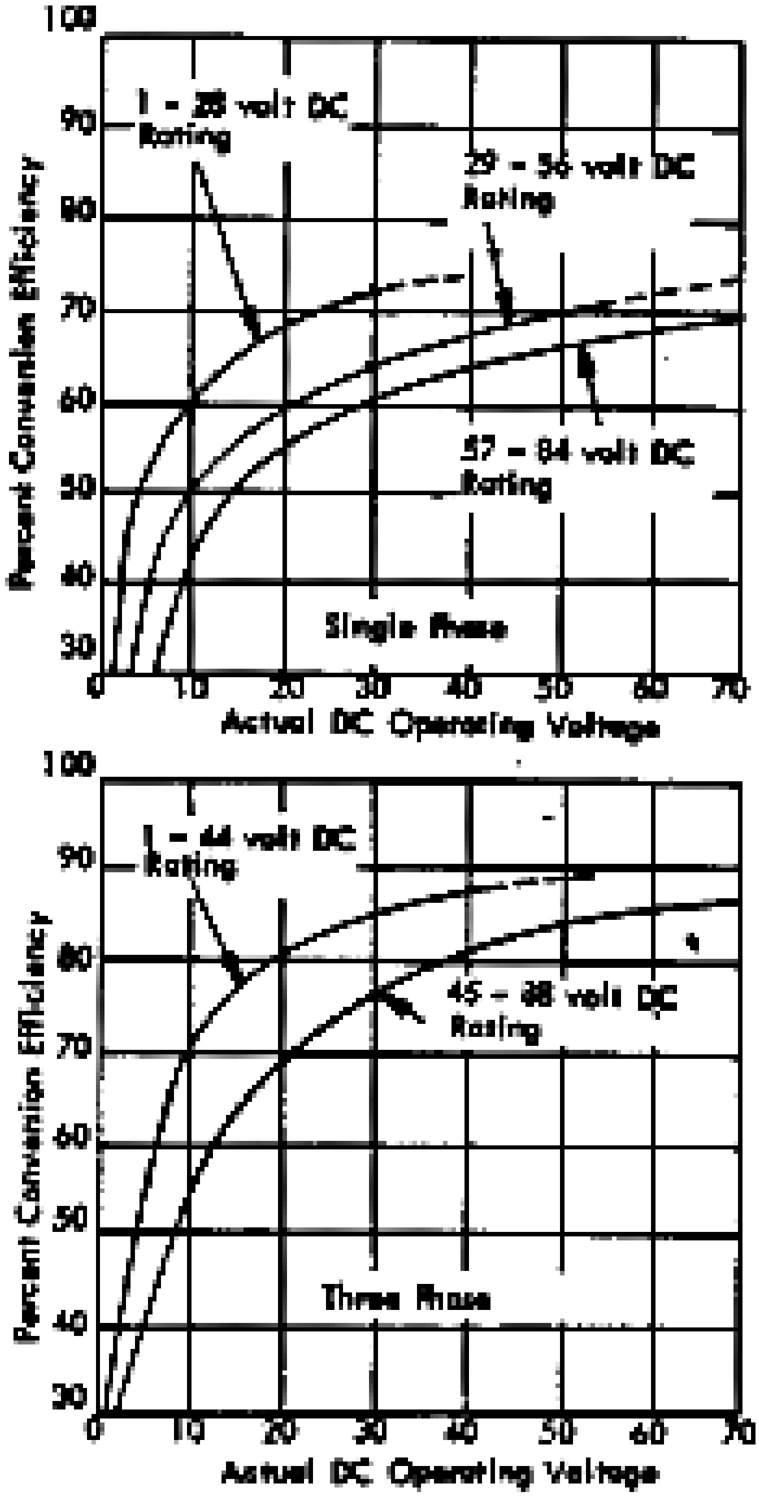


Figure 11

Efficiency versus voltage – selenium stacks

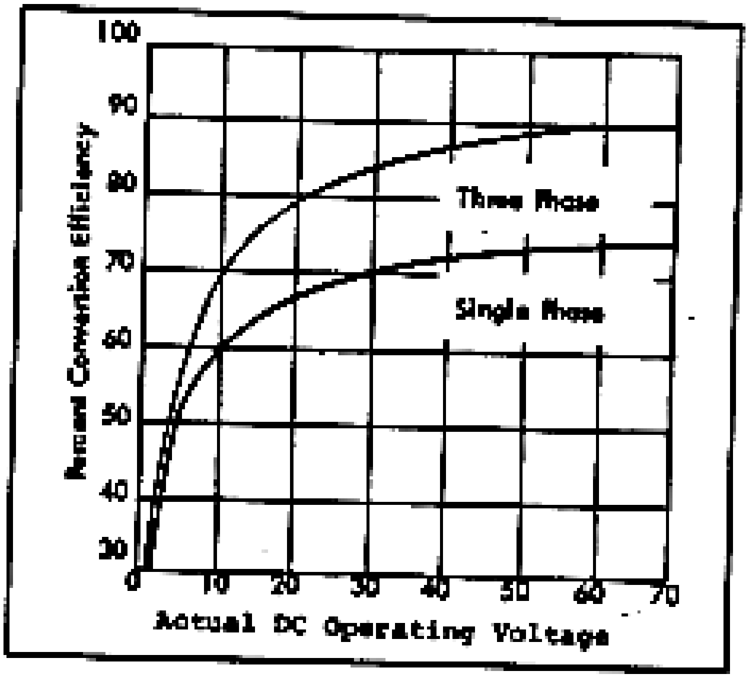


Figure 42
Efficiency Versus Voltage - Silicon Stacks

EQUATION: $I_{ac} = (E_{dc} \times I_{dc})/(\sqrt{3} \times F \times E_{ac})$

where

- I_{ac} = alternating current requirement (A)
- E_{dc} = direct current output voltage
- I_{dc} = direct current output amperage
- F = rectifier efficiency (%)
- E_{ac} = alternating current voltage (per phase to phase)

Figure 12

Efficiency versus voltage – silicon stacks

6. 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. These anode materials are available in a form and size suitable for application in impressed current cathodic protection systems at a low cost. While abandoned "in-place" steel such as pipelines and rails can, and are, used as anodes, they are consumed at a rate of about 20 lb/amp-year. The most commonly used purchased materials for impressed current anodes are graphite, high silicon cast iron, high silicon chromium bearing cast iron, aluminum, platinized titanium, platinized tantalum, platinized niobium and silverized lead. Newly developed anode materials such as oxide coated ceramics show considerable promise and should be evaluated based upon experience in similar applications, particularly if the more commonly used anode materials have proven unsatisfactory in a specific application.

6.1 GRAPHITE ANODES. Graphite anodes are the most commonly used material for impressed current anodes in underground applications. They are made by fusing coke or carbon at high temperatures and are sealed from moisture penetration by being impregnated with a synthetic resin, wax, or 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. The most important single improvement in high silicon cast iron and graphite anodes is placing the lead wire connection in the center of the anode instead of the end. This eliminates end-effect, where ends of the anode are consumed 1-1/2 times faster than the center. Although more expensive, the anode life is nearly doubled (tubular anodes will be 95 percent consumed, whereas end connected anodes will be only 50 percent consumed before the anode-to-lead wire connection is lost). This also allows for a more effective seal of the lead wire connection. Nearly all anode sizes are available in tubular form where the lead wire connection is located in the center. Typical anodes, connections, and seals are shown in Figures 13 and 14.

6.1.1 SPECIFICATIONS. The following are typical specifications for commercially available graphite anodes.

Composition

Impregnant (Linseed Oil Synthetic Resin or Wax)	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	525 lb minimum

6.1.2 AVAILABLE SIZES. Graphite anodes are commercially available in two sizes:

Weight (lb)	Diameter (in.)	Length (in.)	Surface area (ft²)
27	3	60	4.0
68	4	80	7.1

The weights given are for the graphite only and do not include the weight of the lead wire or connection.

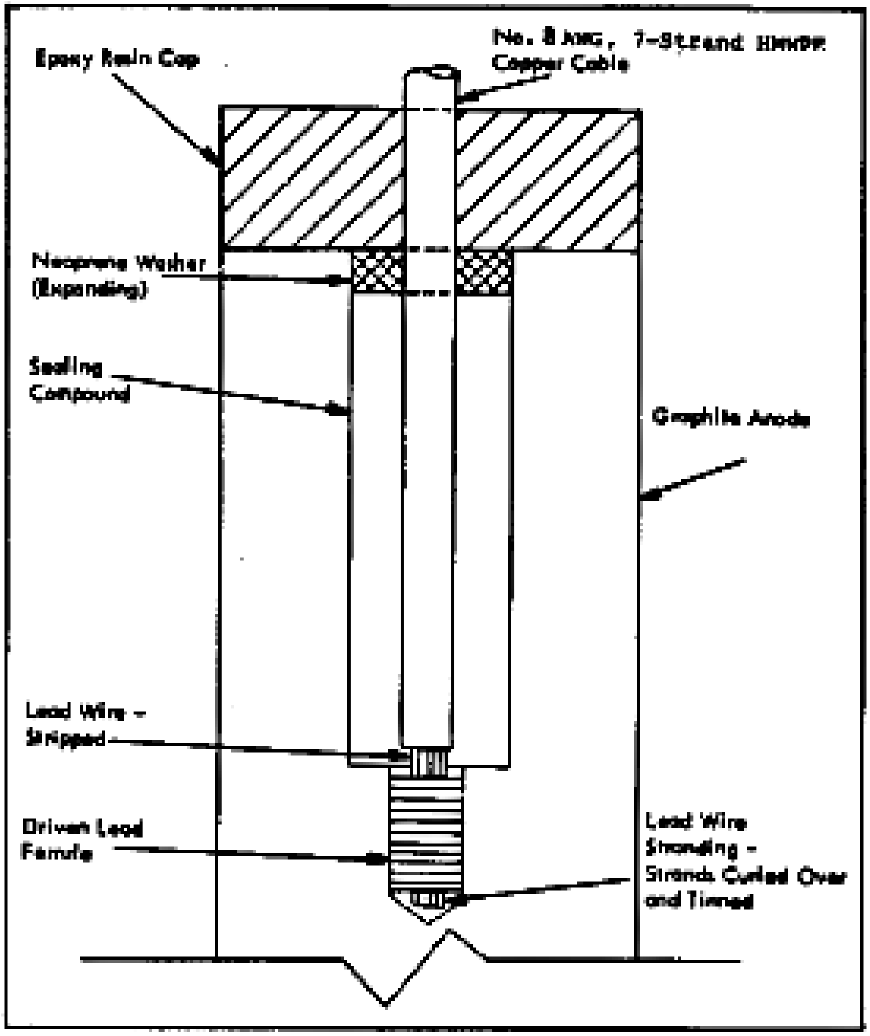


Figure 13

Anode to cable connection – graphite anode

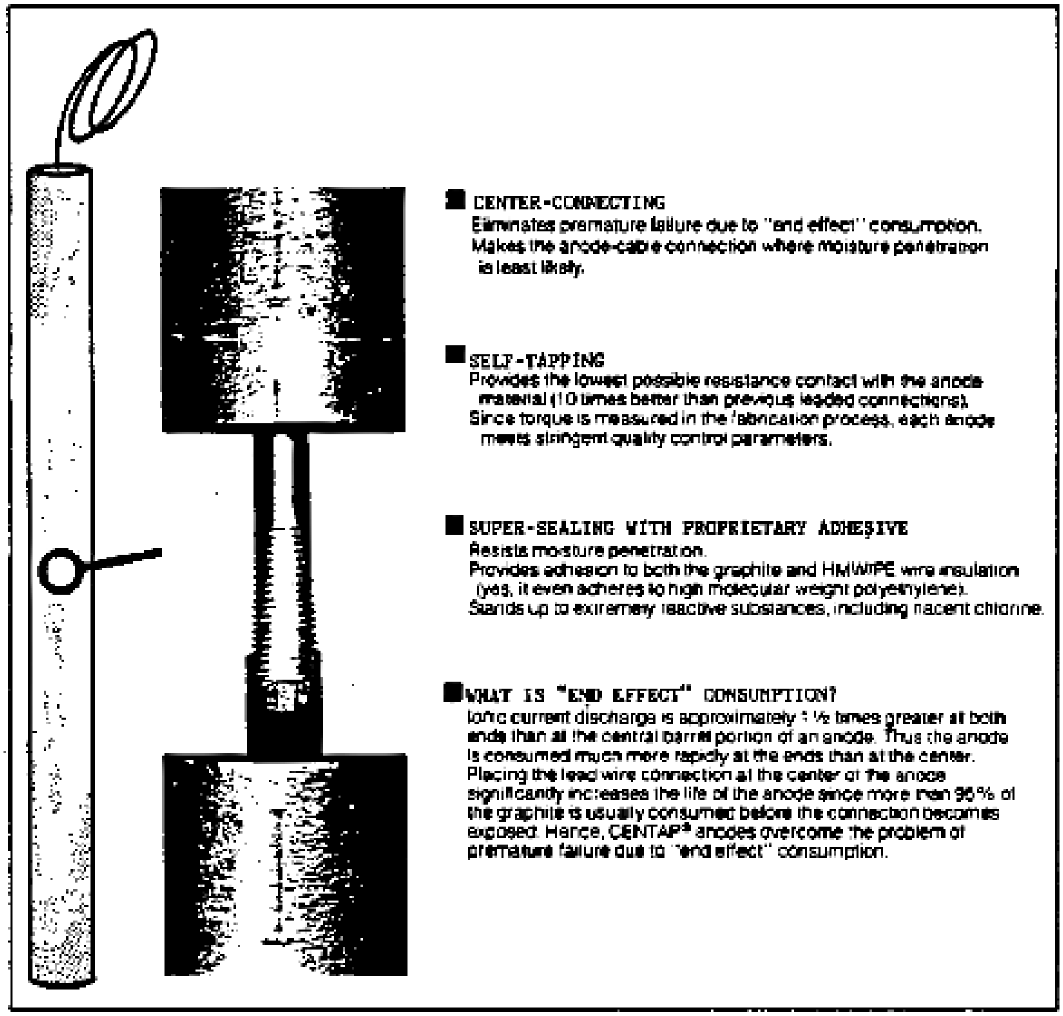


Figure 14

Center connected graphite anode

6.1.3 CHARACTERISTICS. All products from the operation or deterioration of graphite anodes are gasses. In fresh water or non-saline soil, the principal gasses produced 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 gasses 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.

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

6.1.4.1 CURRENT DENSITIES. The current densities in the following table should not be exceeded in order to obtain optimum anode life:

RECOMMENDED MAXIMUM CURRENT DENSITY FOR GRAPHITE ANODES

	SEAWATER	FRESH WATER	SOIL
Maximum Current Density (A/ft^2)	3.75	0.25	1.0
Equivalent Current on 3" x 60" Anode	15 A	1 A	4 A
Equivalent Current on 4" x 80" Anode	36.6 A	1.7 A	7.1 A

6.1.4.2 OPERATING POTENTIALS. Since the potential difference between steel and graphite is approximately 1.0 V 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 V must be added to the other voltage and IR drop requirements during the selection of proper power supply driving voltage.

6.1.4.3 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 lbs/A yr. The deterioration rate for graphite anodes in seawater ranges from 1.6 lbs/A yr at current densities below 1 A/ft^2 to 2.5 lbs/A yr at current densities of 3.75 A/ft^2.

6.1.4.4 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 attendant 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. The use of backfill of uniform resistivity is used when graphite anodes are used in soil in order to prevent uneven anode deterioration.

6.2 HIGH SILICON CAST IRON. Cast iron containing 14 to 15 percent silicon and 3/4 to 1 percent other alloying elements such as manganese and carbon, form a protective film of silicon dioxide when current is passed from their surface into the environment. This film is stable in many environments, with the exception of chloride rich environments. The formation of this film reduces the deterioration rate of this alloy from approximately 20 lbs/A yr, as for ordinary steel, to 1 lb/A yr. Due to the lack of resistance of this alloy to deterioration in environments containing chloride, a chromium bearing alloy of similar silicon and other alloy content has been developed. The chromium bearing alloy is now almost exclusively used.

6.3 HIGH SILICON CHROMIUM BEARING CAST IRON (HSCBCI). This material is widely used for impressed current anodes. Being a metal it 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.

6.3.1 SPECIFICATIONS. The nominal composition of HSCBCI is as follows: (conforms to ASTM Specification A518-GR.2).

ELEMENT	PERCENT
Silicon	14.50
Chromium	4.50
Carbon	0.95
Manganese	0.75
Iron	Remainder

The typical mechanical and physical properties of HSCBCI are as follows:

Tensile strength	15,000 psi
Compressive strength	100,000 psi
Hardness	520 Brinell
Specific gravity	7.0
Melting point	2,300 °F
Specific resistance	72 μohms/cu cm
Coefficient of expansion	7.33 μin./in./°F

The maximum acceptable resistance between the cable and the anode should be 0.01 ohms.

6.3.2 AVAILABLE SIZES. HSCBCI anodes are available in a wide variety of standard sizes and shapes as shown in Tables 8 and 9. 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. Typical HSCBCI anode configurations are shown in Figures 15 through 19. The cable-to-anode connection is, as in the case of all impressed current anodes, critical. Three common methods of achieving the cable-to-anode connection and seal are shown in Figures 20, 21, and 22. The use of the center connected tubular anode as shown in Figure 23 is preferable as necking of the anode at the connection point is avoided and life of the anode is extended 90 percent (50 percent anode material expended before failure versus 95 percent anode material expended before failure for center connected anode).

6.3.3 OPERATION. HSCBCI anodes are consumed at a rate of 1 lb/A yr when used at a current not exceeding their nominal discharge rates. The potential difference between steel and HSCBCI can be neglected in the selection of impressed current rectifiers. HSCBCI anodes will operate without backfill in most applications, but backfill will reduce the anode-to-electrolyte resistance and extend the life of the anodes. Because metal-to-metal contact is made between the anode and the round particle calcined petroleum coke breeze, the outside of the coke breeze becomes the anode. Also, the lower output voltage required will save power and reduce the initial cost of the rectifier unit. Because of these reasons, petroleum coke backfill is recommended where it can be feasibly installed.

6.4 ALUMINUM. Aluminum anodes are sometimes used for the protection of the interior of water storage tanks. They are consumed at a fairly high rate of approximately 9 lbs/A yr in most applications. The main advantages of using aluminum anodes in the protection of water storage tanks is their low cost, light weight, and lack of water contamination from the products of deterioration of the anodes. They are commonly used when seasonal icing of the tank would damage the anodes. The aluminum anodes are sized to last 1 year and are replaced each spring. HSCBCI and graphite anodes are more commonly used in water tanks and, when installed on a floating raft, can be made resistant to icing conditions.

6.5 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 A/ft^2 is 0.00001 lb/A yr. Due to the high cost of platinum, this material is more commonly used as a thin coating on other metals as described in para. 6.6.

6.6 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 which prevents current flow from their surfaces, even when exposed to high anodic potentials. All of the current flows from the platinum coated portion of the anode surface. 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 in seawater. Their use in soils has been limited occasionally to deep well applications.

ANODE TYPE	NOMINAL SIZE in (MM)	WEIGHT lb (kg)	AREA SQ FT M2	NOMINAL DISCHARGE-Amps	SPECIAL FEATURES
B	1 x 60 (25 x 1,524)	12 (5.4)	1.4 (.13)	0.5	Each end enlarged to 1-1/2 in. (38mm) dia with cored opening for joining.
TAB	2-3/16 x 24 (56 x 609)	13 (5.9)	1.1 (.10)	0.5-1.0	Lightweight flexible assembly with continuous cable.
TABB	2-21/32 x 24 (67 x 609)	18 (8.2)	1.4 (.13)	0.5-1.0	Lightweight flexible assembly with continuous cable.
CD	1-1/2 x 60 (38 x 1,524)	25 (11.4)	2.0 (.19)	1.0	One end only enlarged to 2 in. (51mm) dia with cored opening for cable connection.
TACD	2-3/16 x 60 (56 x 1,524)	32 (14.5)	2.8 (.26)	2.5-3.0	Center connection in series on center cable of or one lead only.
TA2A	2-3/16 x 42 (56 x 1,067)	23 (10.4)	2.0 (.19)	1.5-2.0	Center connection in series on continuous cable or one lead only.
TA1	2-21/32 x 42 (67 x 1,067)	31 (14.1)	2.4 (.22)	1.5-2.0	Center connection in series on continuous cable or one lead only.
TAJA	4-3/4 x 24 (121 x 609)	31 (14.1)	2.5 (.23)	1.5-2.0	Center connection in series on continuous cable or one lead only.
D	2 x 60 (51 x 1,525)	44 (20.0)	2.5 (.24)	1.5	Uniform 2 in. (51mm) dia with cable connection on one end only.
TAD	2-21/32 x 60 (67 x 1,524)	45 (20.4)	3.5 (.32)	2.3-3.5	Center connection in series on continuous cable or one lead only.
TA2	2-3/16 x 84 (56 x 2,133)	46 (20.9)	4.0 (.37)	3.0-4.0	Center connection in series on continuous cable or one lead only.
M	2 x 60 (51 x 1,524)	60 (27.2)	2.8 (.26)	2.0-2.5	Each end enlarged to 3 in (76mm) dia with cord opening for joining.
TAM	3-3/4 x 60 (95 x 1,524)	60 (27.2)	4.9 (.46)	3.5-5.0	Center connection in series on continuous cable or one lead only.

Table 8
Standard HSCBCI Anodes

ANODE TYPE	NOMINAL SIZE in (mm)	WEIGHT lb (kg)	AREA SQ FT (M2)	NOMINAL DISCHARGE-Amps	SPECIAL FEATURES
TA2	2-11/32 x 84 (67 x 2,134)	43 (19.6)	4.9 (.46)	3.5-5.0	Center connection in series on continuous cable or one lead only.
J	3 x 36 (76 x 914)	44 (20.0)	2.5 (.23)	1.5-3.0	One end only enlarged to 5 in (127mm) dia w/cored opening for cable connection.
TA3	4-3/4 x 60 (121 x 1,524)	78 (35.4)	6.2 (.58)	5.0-6.0	Center connection and tubular design gives greater surface area.
TA4	3-3/4 x 84 (95 x 2,133)	85 (38.6)	6.9 (.64)	6.0-7.0	Center connection and tubular design gives greater surface area.
K	3 x 60 (76 x 1,524)	110 (49.9)	4 (.37)	4-6	One end only enlarged to 4 in (102mm) dia with cored opening for cable connection.
TA5	4-3/4 x 60 (121 x 1,524)	125 (56.7)	6.2 (.58)	6-8	Center connection eliminates loss due to "end effect."
TA5	4-3/4 x 84 (121 x 2,133)	110 (49.9)	8.7 (.81)	6-8.5	Center connection eliminates loss due to "end effect."
M	4-1/2 x 60 (114 x 1,524)	220 (99.8)	5.5 (.51)	5-8	Uniform 4-1/2 in. (114mm) dia with cored opening each end. Permits 2 cable connections, if required.
TA5A	4-3/4 x 84 (121 x 2,133)	175 (79.4)	8.7 (.81)	8-10	Center connection and tubular design gives longer life.
FW	1-1/8 x 9 (29 x 229)	1 (.5)	0.22 (.02)	0.035	Lightweight flexible assembly with continuous cable.
TAFW	2-3/16 x 8 (54 x 203)	4.3 (1.9)	0.38 (.04)	0.40	Lightweight flexible assembly with continuous cable.
G2	2 x 9 (51 x 229)	5 (2.3)	0.40 (.04)	0.38	Inside configuration permits single center cable-to-anode connection on continuous cable.
TAG	2-21/32 x 8 (67 x 203)	6 (2.7)	0.47 (.05)	0.55	Center connection in series on continuous cable or one lead only.
TAFWA	2-3/16 x 12 (54 x 304)	6.4 (2.9)	0.57 (.06)	0.60	Center connection in series on continuous cable or one lead only.

Table 8 (continued)
Standard HSCBCI Anodes

TYPE	NOMINAL SIZE (inches)	WEIGHT EACH (lb)	AREA sq ft	APPLICATION	SPECIAL
K-3	3 x 3	6	0.25	Small heat exchangers and like structures with limited mount-ing area.	"Button" with int cast bol taching ture usi able gas
K-6	6 x 2-1/2	16	0.5	Ship hull, lock gate, heat exchangers, or any other structure with large flat surface.	"Button" with int cast bol taching ture usi able gas
K-12	12 x 3-7/16	53	1.0	Ship hull, lock gate, heat exchangers, or any other structure with large flat surface.	"Button" with int cast bol taching ture usi able gas
Bridge Deck I	12 dia x 1-1/2	40	1.96	Bridge decks	Lead-one only
Bridge Deck II	9 oval x 9/16	6	0.74	Bridge decks	Assemble tandem o uous 8/7 cable.

Table 9
Special HSCBCI anodes

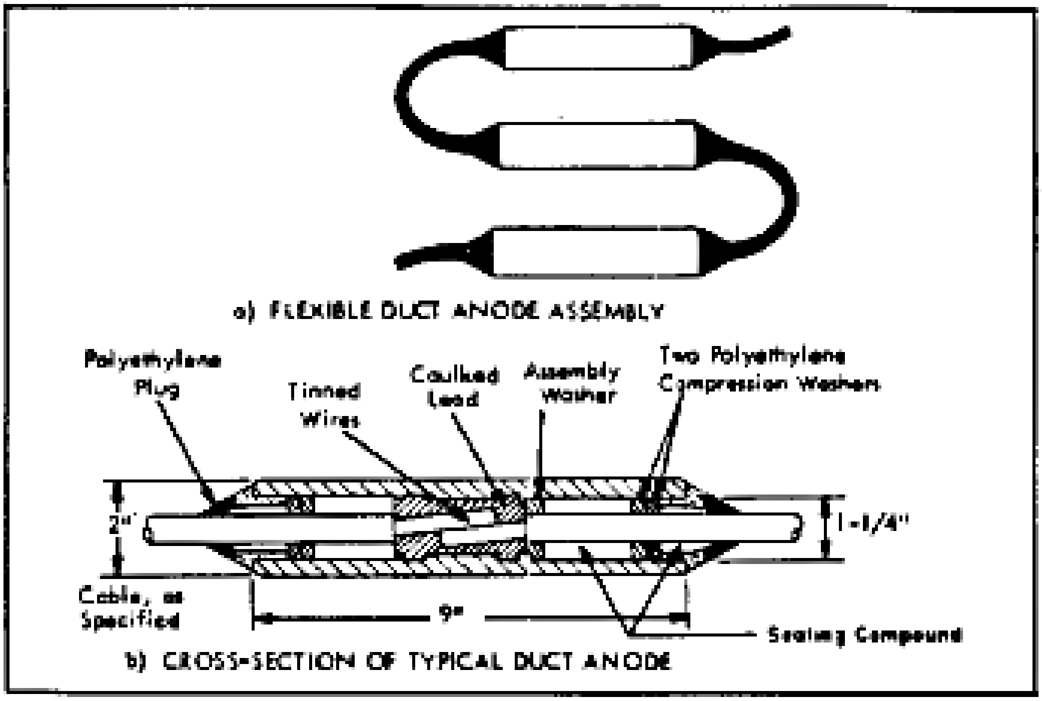


Figure 15
Duct anode

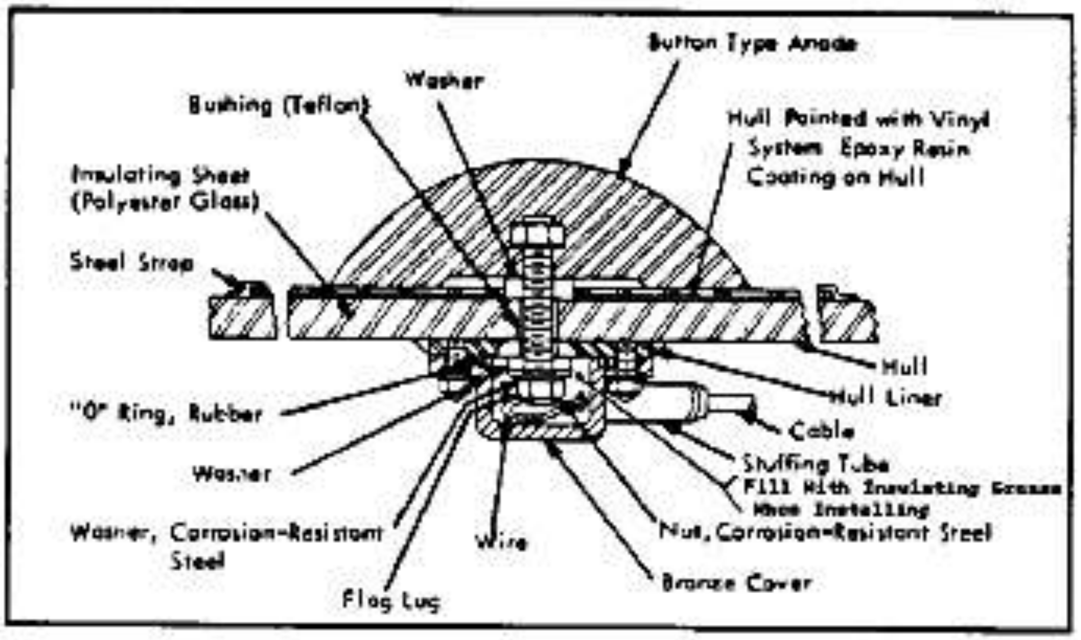
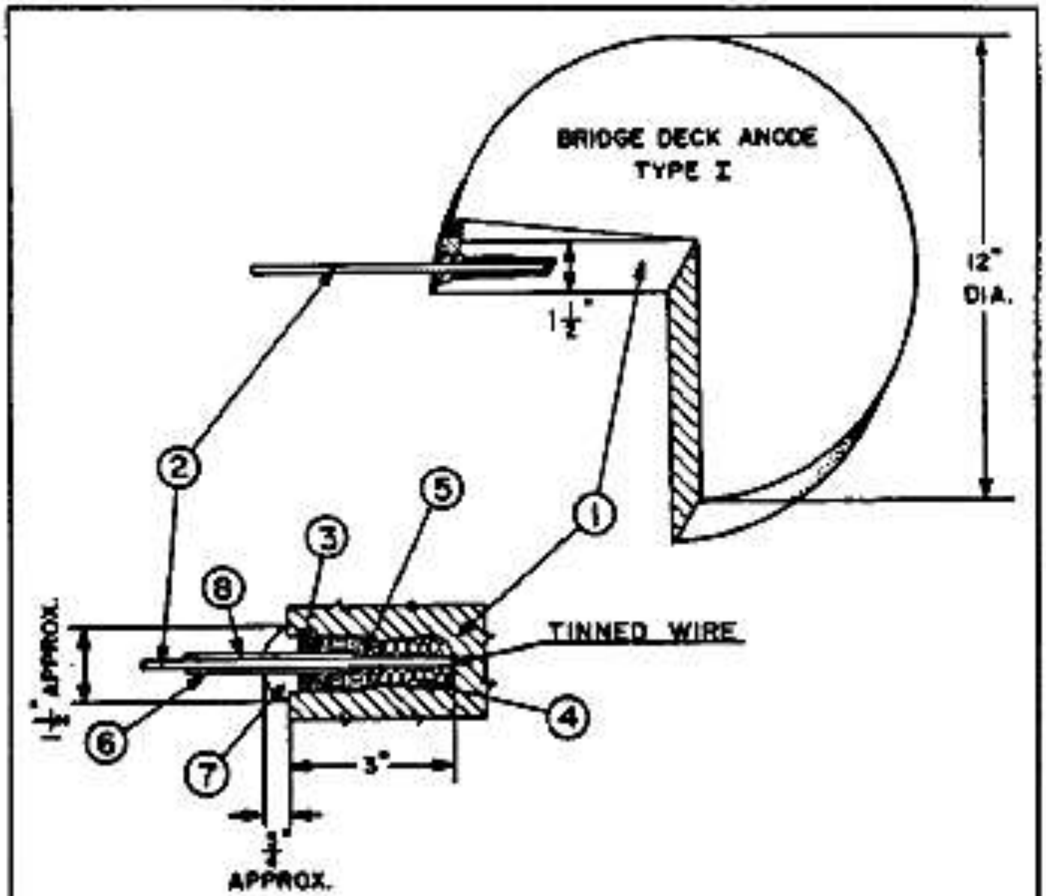
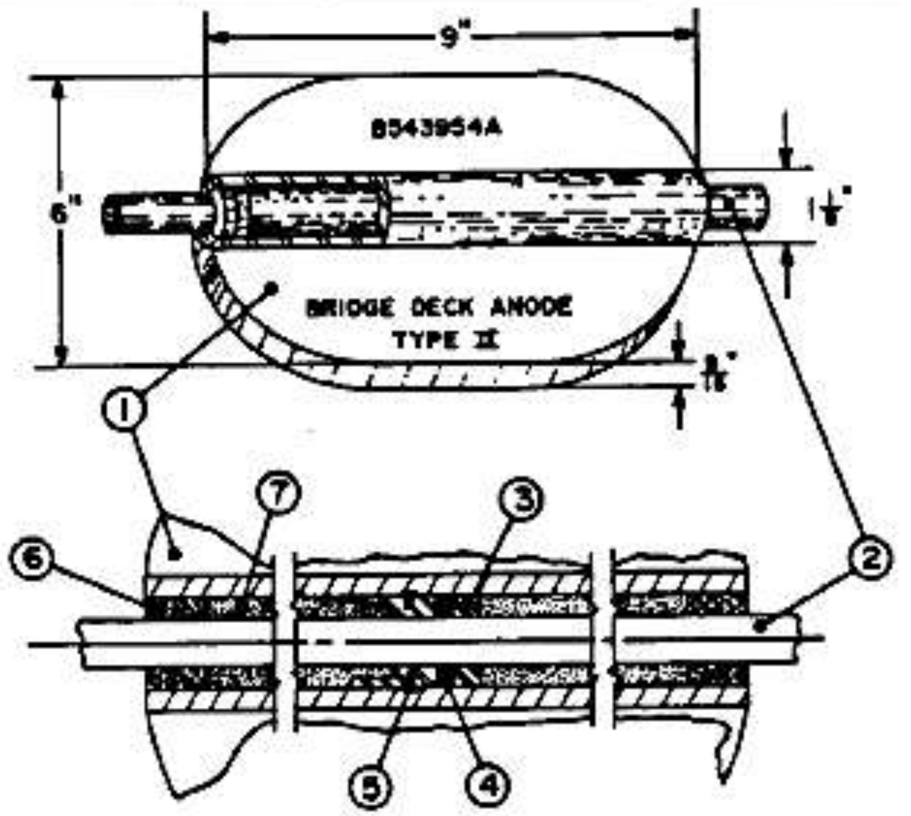


Figure 16
Button anode



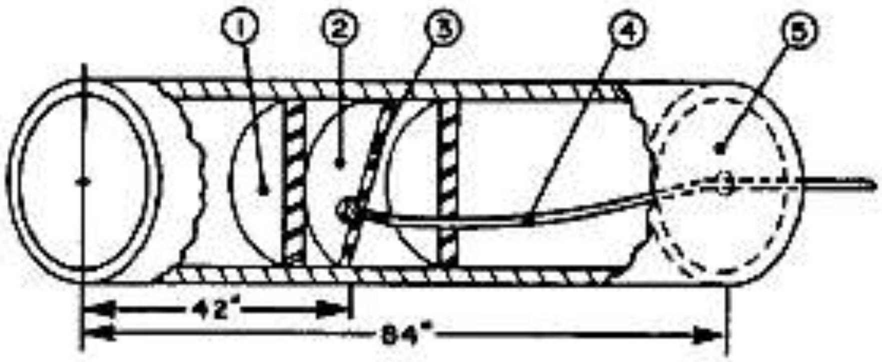
ITEM	DESCRIPTION
1	Anode - Wt 40 Lbs
2	Cable 8/7 Str., HMPE
3	Washer
4	Lead
5	Mastic
6	Tubing
7	Epoxy Seal
8	Interface Sealant "F"

Figure 17
Bridge deck anode – Type I



ITEM	DESCRIPTION
1	Anode Wt. 6 lbs.
2	8/7 Str. Cable, HMPE
3	Connector
4	Connector Pin
5	Spring
6	Washer
7	Mastic

Figure 18
Bridge deck anode – Type II



Item	Description
1	Epoxy Seal
2	Mastic
3	Plate
4	Cable
5	Guide

Figure 19
Tubular anode

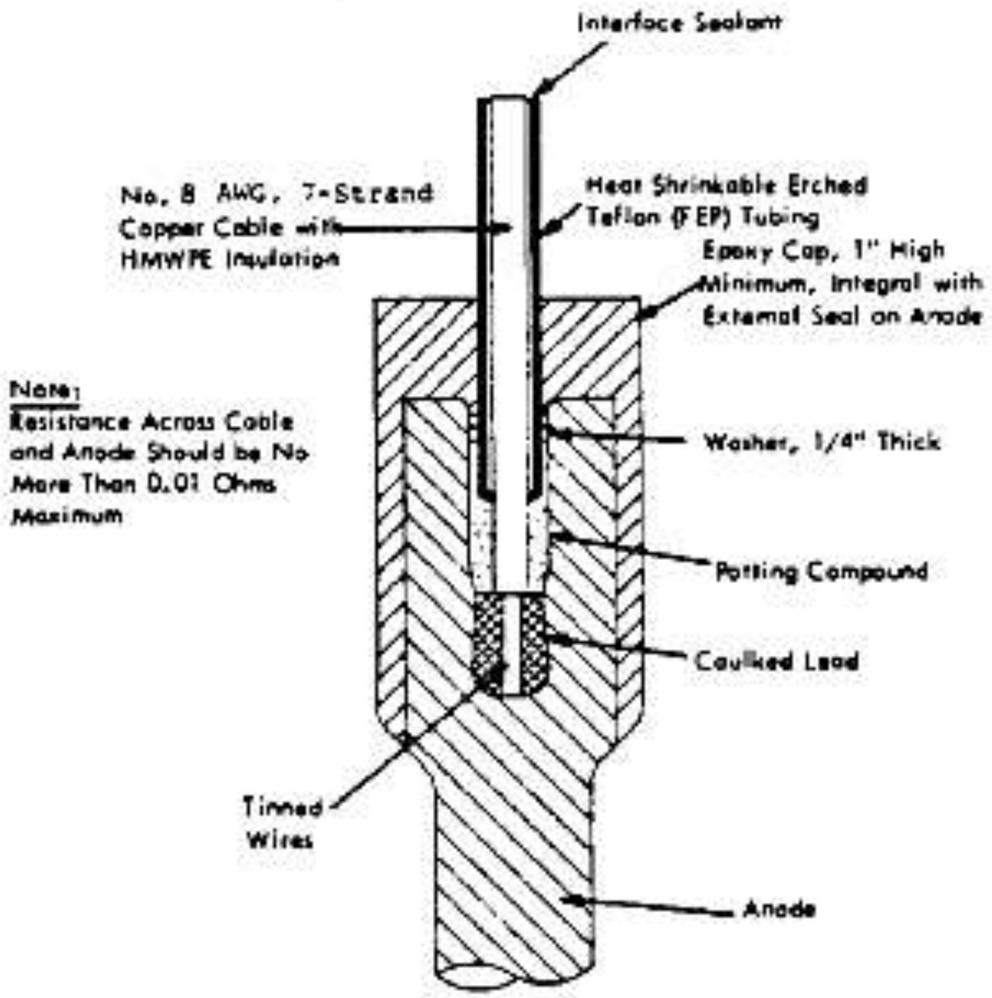


Figure 20
Anode to cable connection – epoxy seal

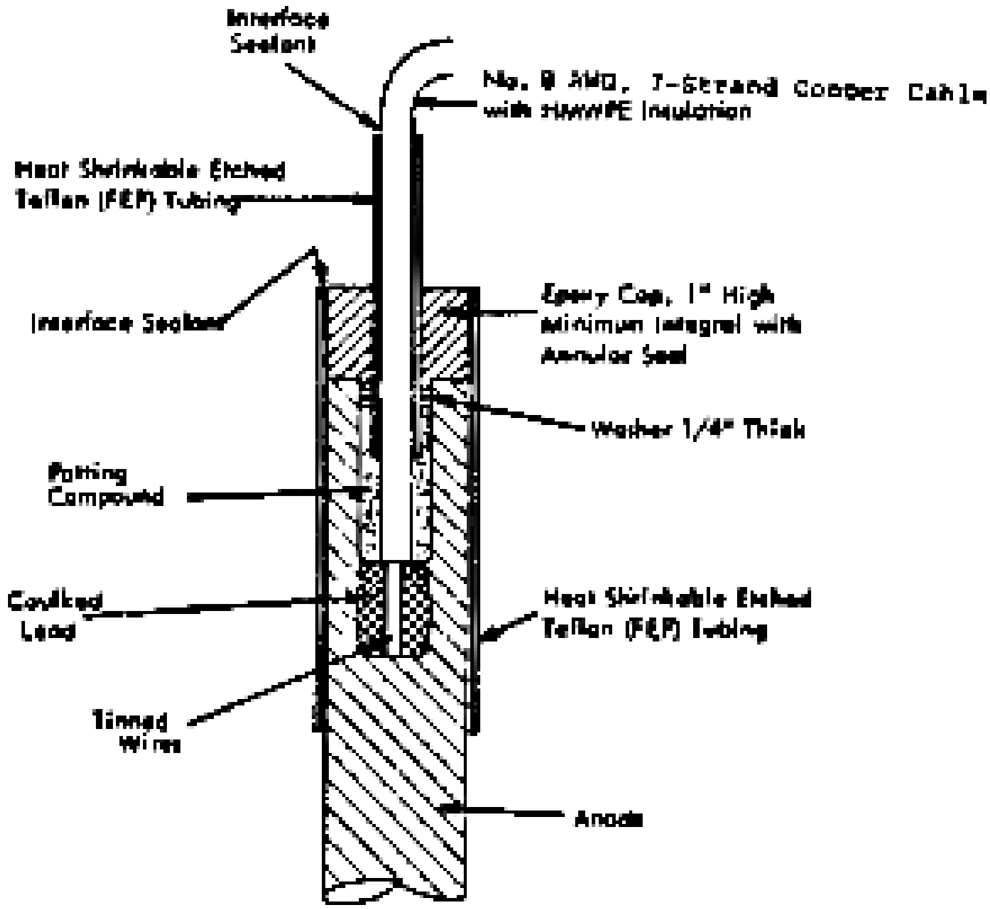


Figure 21
Anode to cable connection – teflon seal

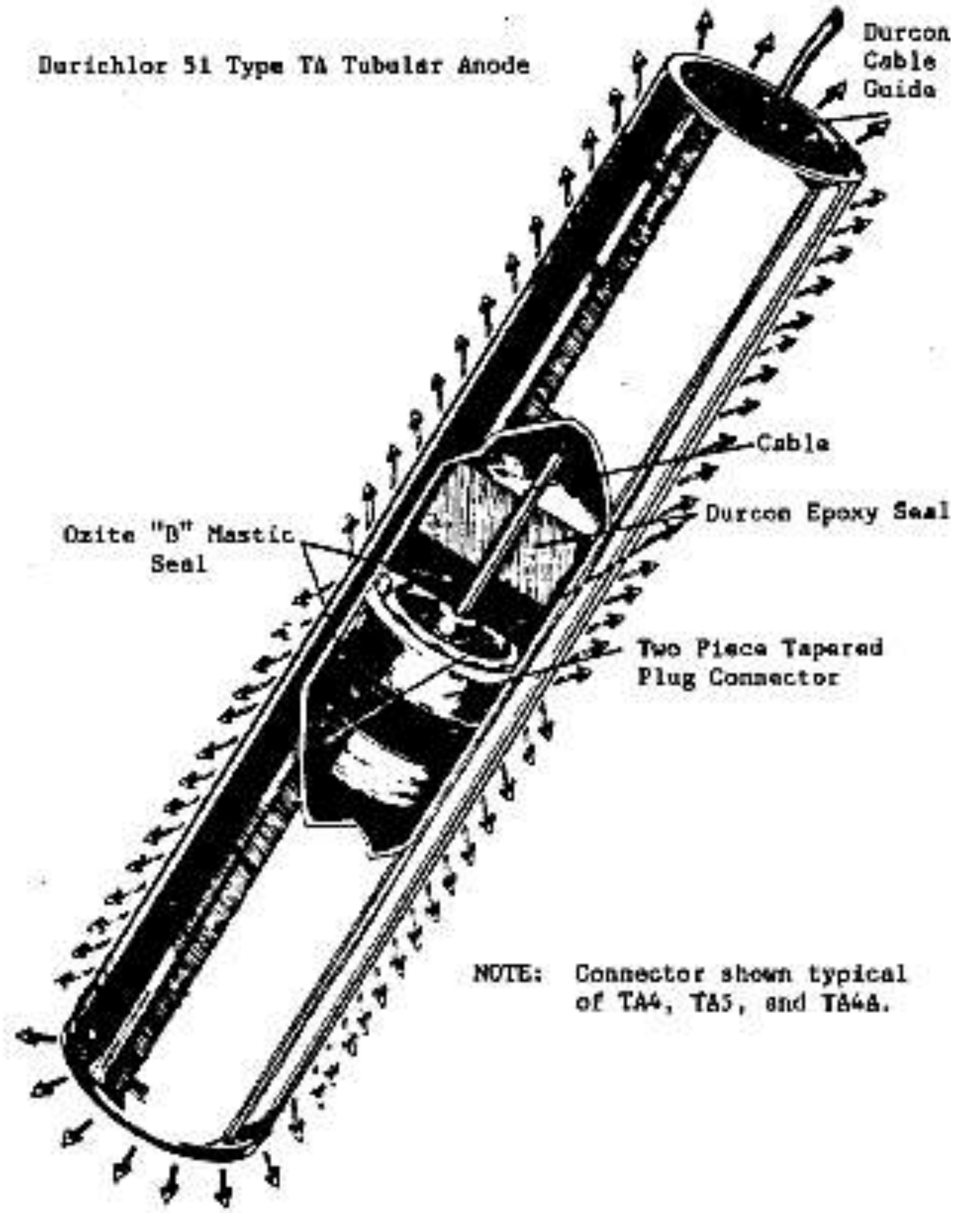


Figure 22
Center connected high silicon chromium bearing cast iron anode

6.6.1 TYPES. PLATINIZED ANODES are available in a wide variety of sizes and shapes. Sizes of standard platinized titanium anodes are shown below:

DIAMETER (in.)	LENGTH (in.)	EXTENDED LENGTH (in.)	PLATINIZED LENGTH (in.)
3/4	20	15	6
3/4	12	7	3
3/4	23	18	9
3/4	20	15	9
1/2	20	15	6
1/2	17	12	5
1/2	23	18	9

A typical anode configuration is shown in Figure 23.

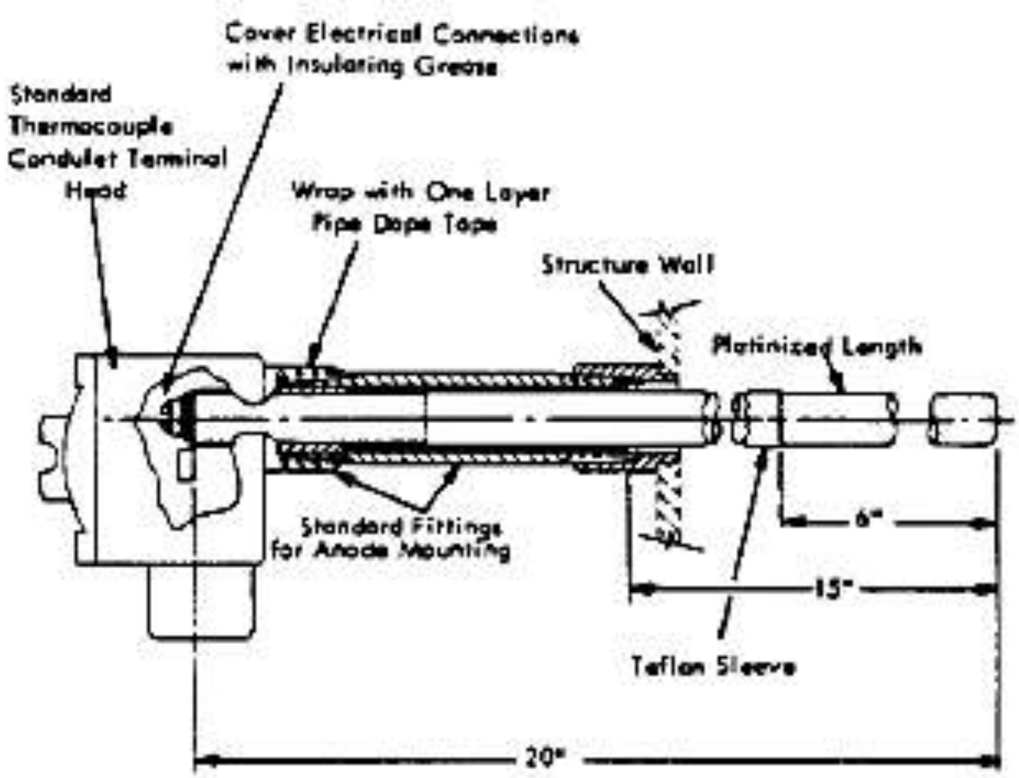


Figure 23

Typical platinized anode

6.6.2 OPERATION. Platinized anodes can be operated at very high current densities (100 A/ft² are typical). 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 V. Platinized niobium can be used at potentials as high as 100 V. Since these anodes are small in size, their resistance-to-electrolyte is high and therefore, higher voltages are required to obtain high current.

6.7 ALLOYED LEAD. Lead alloyed with silver, antimony, or tin have been used as anodes for impressed current cathodic protection systems in seawater. The chief advantage of lead anodes is their low cost. The consumption rate for silverized lead is 2- to 3-lbs/A yr initially but drops off to approximately 0.2 lbs/A yr after 2 years. The current density from silverized lead anodes is typically 10 A/ft². Alloyed lead anodes have been unreliable in many specific applications either because they failed to passivate and their consumption rate remained in the

2-to 3-lbs/A yr range and they were completely consumed, or they became so highly passivated that the anode-to-electrolyte resistance increased substantially.

7. OTHER SYSTEM COMPONENTS. In addition to the source of power for cathodic protection and the anodes used, cathodic protection systems contain other important components. The entire system must be reliable in order to provide effective protection.

7.1 CONNECTING CABLES. The connecting cables used between the various components of cathodic protection systems are vital to the proper performance of the system. Any break in the primary circuit will result in failure of the system and will require repair to restore the flow of protective current. Breaks in the auxiliary connections such as those used to test the system will also result in difficulties in proper adjustment and inspection of the system. Proper selection of cable size, type of insulation, and routing is necessary for proper and reliable system operation. Only insulated copper cables should be used in any cathodic protection installation. High connection resistances and difficulty in making welded connections associated with the use of aluminum wires precludes their use in cathodic protection installations.

7.1.1 FACTORS TO BE CONSIDERED. Connecting cables should be selected based upon consideration of the following factors:

- Current carrying capacity
- Voltage attenuation (IR Drop)
- Mechanical strength
- Economics (first cost versus power costs)
- Dielectric strength of insulation
- Durability (abrasion & cut resistance) of insulation

Standard wire sizes, weights, and breaking strengths are given in Table 10.

SIZE AWG	OVERALL DIAMETER NOT INCLUDING INSULATION (in.)	APPROX. WEIGHT NOT INCLUDING INSULATION (lb/M ft)	MAXIMUM BREAKING STRENGTH (lb)	MAXIMUM DC RESISTANCE AT 20 °C (ohms/M ft)	MAXIMUM ALLOWABLE dc CURRENT CAPACITY (A)
14	0.0726	12.68	130	2.5800	15
12	0.0915	20.16	207	1.6200	20
10	0.1160	32.06	329	1.0200	30
8	0.1460	50.97	525	0.6400	45
6	0.1840	81.05	832	0.4030	65
4	0.2320	128.90	1320	0.2540	85
3	0.2600	162.50	1670	0.2010	100
2	0.2920	204.90	2110	0.1590	115
1	0.3320	258.40	2660	0.1260	130
1/0	0.3730	325.80	3350	0.1000	150
2/0	0.4190	410.90	4230	0.0795	175
3/0	0.4700	518.10	5320	0.0631	200
4/0	0.5280	653.30	6453	0.0500	230
250 MCM	0.5750	771.90	7930	0.0423	255

Table 10
Standard wire characteristics

7.1.2 INSULATION. The connections between the cathodic protection power source and the anodes are usually submerged or buried at least over part of their length. These cables are extremely susceptible to failure as they are operated at highly positive potentials. Any contact between the metallic conductors and the environment will result in rapid deterioration of the conductor and loss of continuity of the protective circuit. Anode lead wires should never be used to suspend, carry, or install the anode except in water storage tanks. High molecular weight polyethylene (HMWPE) insulation has proven to give satisfactory service for the insulation of this critical connection in most shallow buried applications. Where exposure to chlorine is encountered, such as in seawater or in deep anode applications, chlorine resistant insulation such as fluorinated ethylene propylene (FEP), tetrafluorethylene (TFE), and polyvinylidene fluoride (PVF2) are used either singly or in combinations with thicknesses of up to 0.150 inches. These materials are also used over a primary insulation of extruded polyalkene, 0.30 inches thick, or are covered with a jacket of high molecular weight polyethylene for mechanical protection.

A highly successful insulation for such highly critical applications has been a system consisting of a 0.065-inch-thick high molecular weight polyethylene outer jacket for abrasion resistance combined with a 0.040-inch-thick ethylene-monochlorotrifluroethylene copolymer (E-CTFE).

For less critical applications such as the negative lead to the rectifier, test wires and aboveground wiring, thermoplastic insulation (type TW), synthetic rubber (RHW-USE), or polyethylene may be used.

7.1.3 RECOMMENDED CABLES FOR SPECIFIC APPLICATIONS. Because of similarities in required characteristics of the various connecting cables in many impressed current cathodic protection systems, general specifications for cable sizes and types for many cathodic protection system requirements have been established and are given below:

a) Test Wires: These wires carry only very small currents and, as they are themselves cathodically protected, insulation requirements are not critical. Solid copper wires, No. 12 gauge AWG with type TW, RHW-USE or polyethylene insulation should be used for this application unless otherwise indicated by experience.

b) Bond Wires: These wires carry more current than test wires. No. 4 AWG, 7-strand copper cable with Type TW, RHW-USE or polyethylene insulation is recommended for all bonds unless a larger wire size is required for current carrying capacity.

c) Power Supply to Structure Cables: The power supply is HMWPE insulated 7-strand cable, usually in the size range of No. 2 or No. 4 AWG. The actual wire size should be determined by economic analysis, but wire no smaller than No. 4 AWG should be used because of mechanical strength required.

d) Power Supply to Anode Cable: The insulation in these cables is critical. HMWPE insulation, 0.110 inches thick, as a minimum, is required on these cables. The anode connection wire is usually No. 8 AWG with HMWPE insulation. The wire used to interconnect the anodes and to connect the anode bed with the power supply is commonly in the range of No. 2 AWG or larger. The actual wire size should be selected based upon the economic analysis, but should not be smaller than No. 4 AWG because of strength.

7.1.4 ECONOMIC WIRE SIZE. The size of the connection between the structure, anode bed, and power supply in impressed current cathodic protection systems should be selected to minimize overall cost. This can be determined by calculating the annual fixed cost of the selected wire and comparing it with the cost of power losses for the system. When the annual fixed cost and the cost associated with power losses are equal, their sum is minimum and the most economical selection of wire size is confirmed. If the power losses exceed the annual costs, a larger wire size is indicated; if the annual fixed costs exceed the power loss, then a selection of a smaller wire size would be appropriate. The formula for determining power loss costs is:

$$V = MK_m$$

where

M = $0.0876\ I^2R$
K_m = LP/E

and

V = annual cost of power losses ($)
I = current flow (A)
R = resistance of 100 feet of cable
P = power cost (cents/kWh)
E = power source (rectifier) efficiency (%)
L = length of cable (feet)

Values for M for commonly used wire sizes and various currents from 10 to 100 A are given in Table 11.

The formula for determining the annual cost of fixed charges is:

$$F = E\ S\ L$$

where

F = annual fixed charges ($/yr)
E = estimated annual charges (see a) below)
S = initial cable cost ($/ft)
L = cable length (ft)

a) The estimated annual charges used will vary. They are the sum of depreciation, interest, taxes, insurance, operation, and maintenance. As shown below, a value of 0.11 is typical for government installations where taxes and insurance are not considered:

Depreciation	=	0.02
Interest	=	0.06
Taxes	=	0
Insurance	=	0
Operation & Maintenance	=	0.03
Total (E)	=	0.11

7.2 WIRE SPLICES AND CONNECTIONS. Wire splices and connections are a source of undesirable circuit resistance and are a weak point in the reliability of the system since they often fail due to corrosion or mechanical damage. The number of connections should be kept to an absolute minimum and the type of connection used should have low resistance, high reliability, and good resistance to corrosion. Both

CABLE SIZE	CURRENT (amps) 10	20	30	40	50	60	70	80
10	0.893	3.57	8.04					
8	0.561	2.25	5.05	9.00	14.00			
6	0.360	1.44	3.24	5.76	9.00	13.00	17.64	
4	0.226	0.905	2.03	3.62	5.65	8.14	11.08	14.46
2	0.1424	0.570	1.08	2.28	3.56	5.13	6.98	9.11
1	0.113	0.451	1.02	1.81	2.82	4.06	5.54	7.24
1/0	0.0893	0.357	0.804	1.425	2.23	3.21	4.47	5.71
2/0	0.0710	0.284	0.639	1.135	1.77	2.56	3.48	4.55
3/0	0.0562	0.257	0.506	0.900	1.40	2.03	2.76	3.60
4/0	0.0446	0.178	0.401	0.715	1.115	1.61	2.19	2.86
250 MCM	0.0378	0.151	0.340	0.605	0.945	1.36	1.85	2.42
300	0.0316	0.1265	0.284	0.506	0.790	1.14	1.55	2.02
350	0.0270	0.108	0.243	0.432	0.675	0.972	1.32	1.73
400	0.0237	0.0948	0.213	0.379	0.593	0.854	1.16	1.52
450	0.0210	0.0840	0.189	0.336	0.525	0.755	1.03	1.342
500	0.0189	0.0755	0.170	0.302	0.472	0.680	0.925	1.21
550	0.0172	0.0689	0.155	0.275	0.430	0.619	0.842	1.10
600	0.0158	0.0632	0.142	0.253	0.395	0.569	0.775	1.01
650	0.0145	0.0580	0.1305	0.232	0.362	0.522	0.710	0.928
700	0.0135	0.0540	0.1215	0.216	0.338	0.486	0.661	0.865
750	0.0126	0.0504	0.1132	0.202	0.315	0.454	0.616	0.805
1000	0.00945	0.0378	0.0970	0.151	0.236	0.340	0.463	0.605

Table 11

M Factors for Determining Economic Wire Size

(Cost of losses in 100 feet of copper cable at 1 cent per kW mechanical connections and thermo-weld connections are used in the installation of cathodic protection systems. Mechanical connections are less expensive t thermo-weld connections but often have higher resistance and are more susceptible to corrosion and mechanical damage. All connections must be carefully insulated, particularly in the anode-to-power supply portion of the circuit where any loss of insulation integrity will result in rapid system failure. All connections in the power source to anode bed portion the circuit and all cable-to-cable connections should be insulated by encapsulation in epoxy using commercially available kits made expressly for this purpose. The cable-to-structure connection is less critical and either epoxy encapsulation or insulation with hot coal-tar enamel followed by wrapping with pipeline felt may be used on this connection. The following connections are required for impressed current systems:

a) Connection between power source and structure
b) Connection between anode bed(s) and power source (anode head cable)
c) Connection between anode header cable and each anode
d) Connection between cable and anode (usually factory made)
e) Necessary bonds and test wires

The need for additional connections and splices should be carefully evaluated. The location of all necessary splices and connections should be specifically shown on the design drawings. The need for additional splices and connections should be determined by the designer of the system and not be left to the discretion of the installer.

7.3 TEST STATIONS. There are six basic types of test stations used in impressed current cathodic protection systems: the potential test station, the soil contact test station, the line current (IR Drop) test station, the insulating joint test station, the casing insulation test station, and the bond test station. The wiring for each of these test stations is shown in Figures 24 through 29. Test wires should be solid copper, No. 10 AWG, either TW or RHW-USE insulated. If future bonding across flanges or between structures may be required, 7-strand copper cables, No. 4 AWG or larger if required, should be connected to the structure(s) and brought into a test station for future use. Test stations may either be located flush with the surface of pavement or soil as shown in Figure 24 or in an above grade test station as shown in Figure 27, manufactured specifically for this purpose. Flush-mounted test stations are preferred in paved areas or other areas where damage by vehicles, etc., is anticipated. Above grade test stations are preferable in unpaved areas. In addition to test stations, balancing resistors are sometimes required when multiple anode beds are used with a single rectifier. These resistors should be installed in an above grade terminal box as shown in Figure 30. The location and wiring of all test stations should be included in the system design. All test wires should be color coded, and marked with non-corroding metal or plastic identification tags indicating what they are connected to.

7.4 BONDS. Bonds between sections of the protected structure or between the protected structure and a foreign structure should use 7-strand copper cable, No. 4 AWG or larger insulated cable. All resistive bonds should be brought into a test station for adjustment. Direct bonds may also be brought into test stations if future adjustments or connections may be required. All bond-to-structure connections should be made using thermo-weld connections, insulated by epoxy encapsulation. Standard details for bonding are shown in Figures 31 through 38.

7.5 INSULATING JOINTS. Insulating joints between sections of a structure are often installed in order to break (electrically) the structure into sections that can be protected by independent cathodic protection systems, or to separate sections that require cathodic protection from those that do not. These joints can either be directly buried, be located in valve pits, or be located above grade. If they are directly buried, they should be furnished with a test station as shown in Figures 39 through 42.

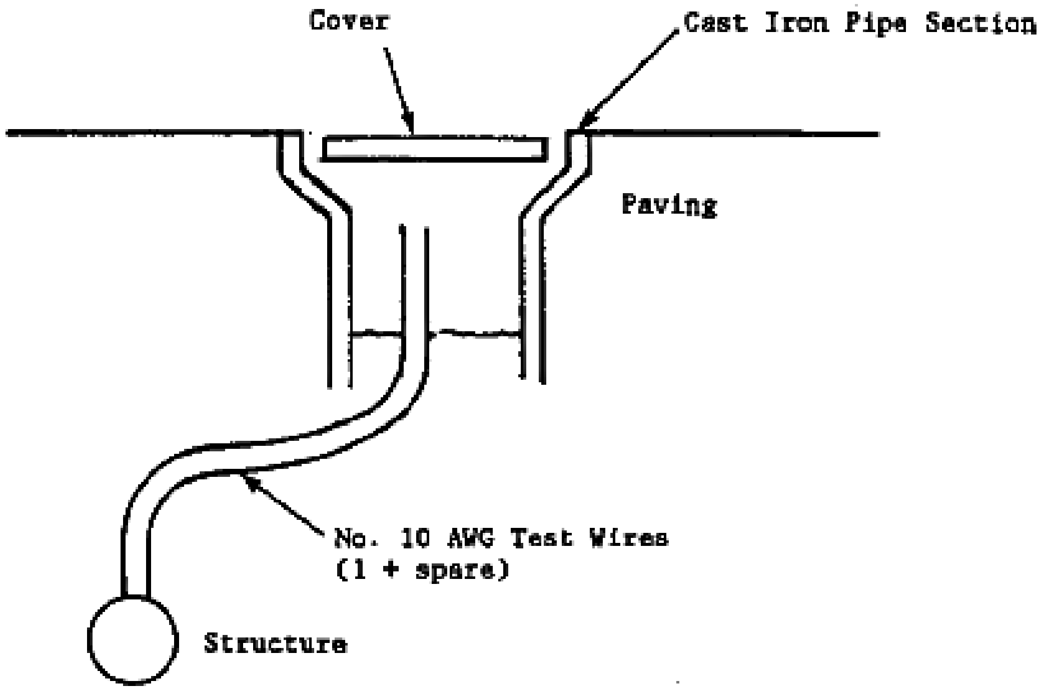


Figure 24
Flush-mounted potential test station

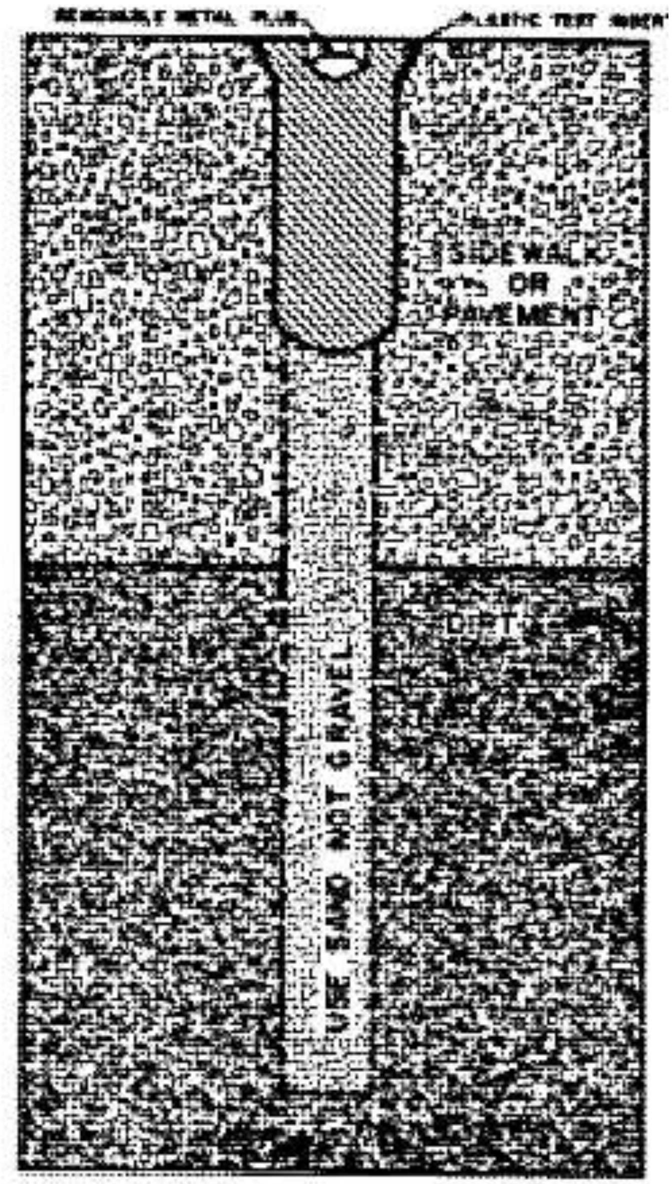


Figure 25
Soil contact test station

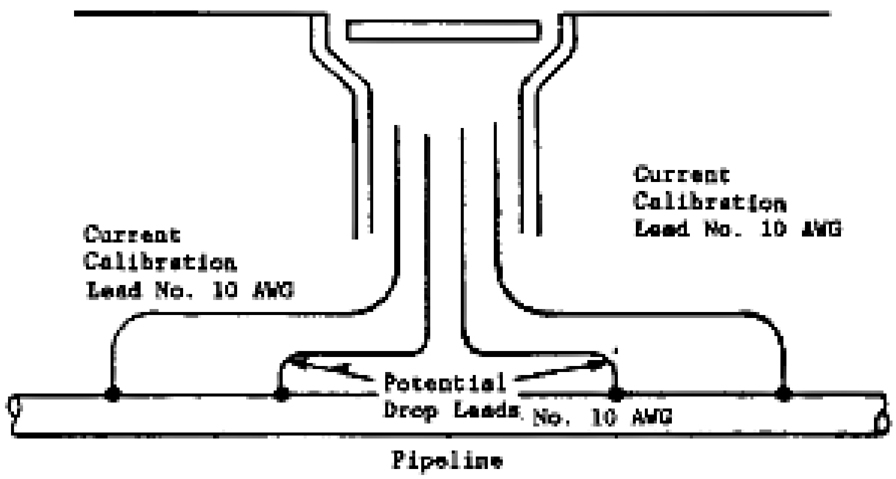


Figure 26
IR drop test station

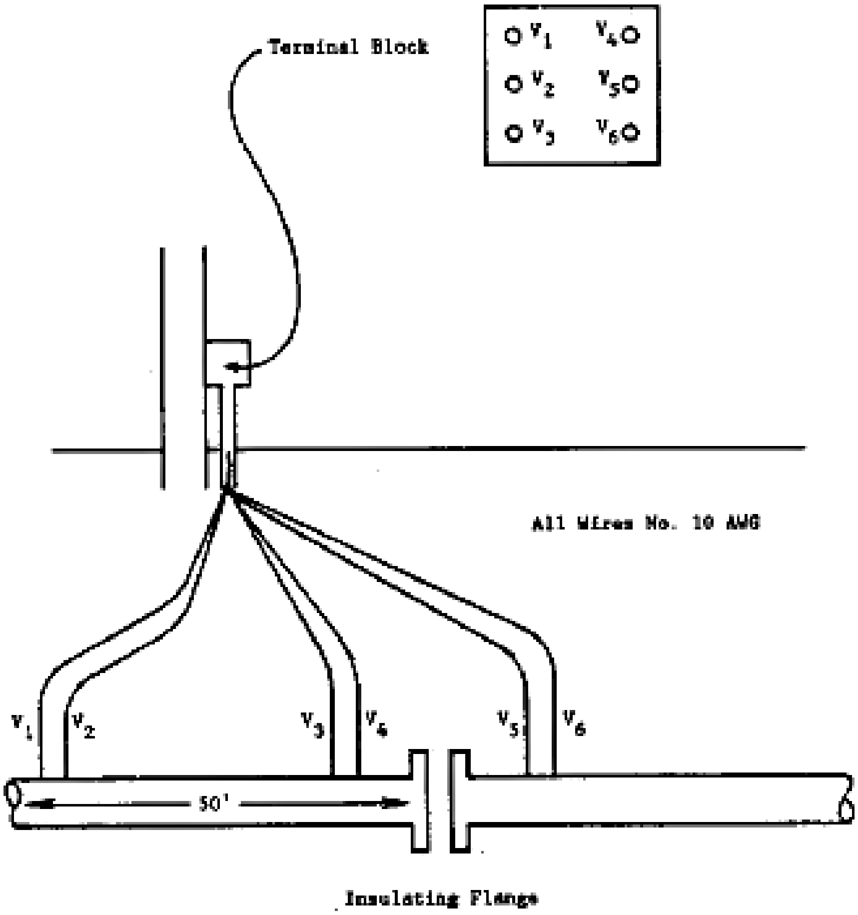


Figure 27
Insulating flange test station (six wire)

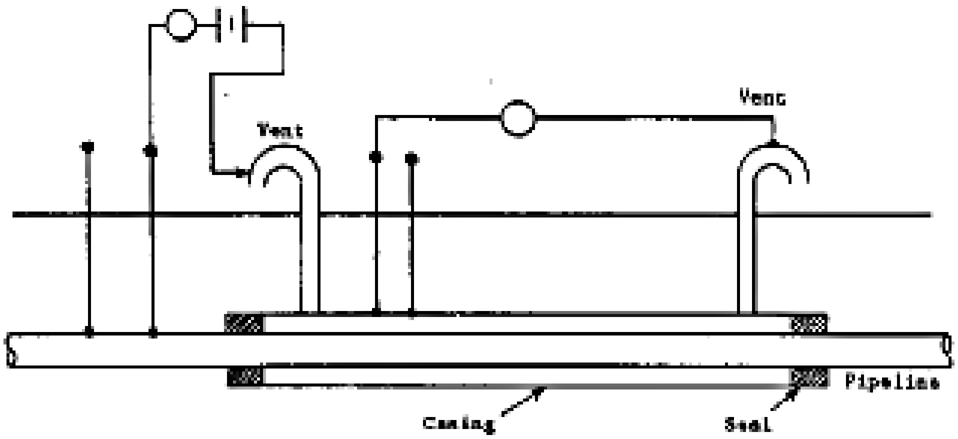


Figure 28
Wiring for casing isolation test station

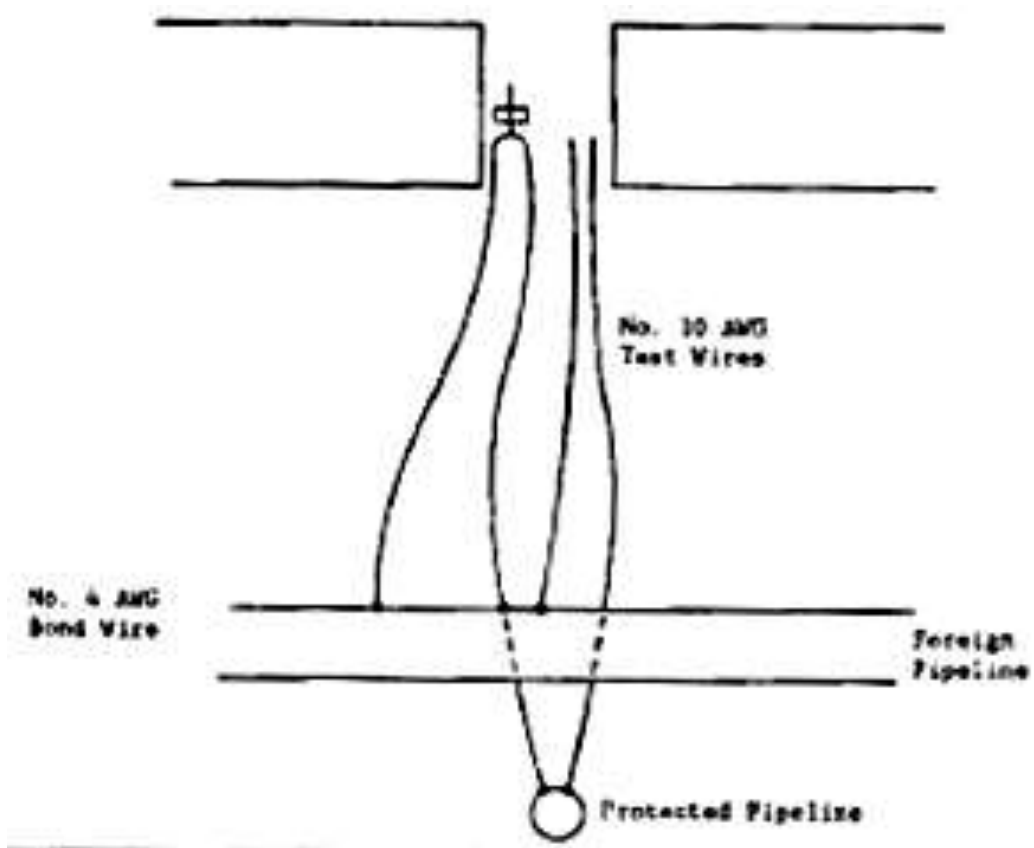


Figure 29
Bond test station

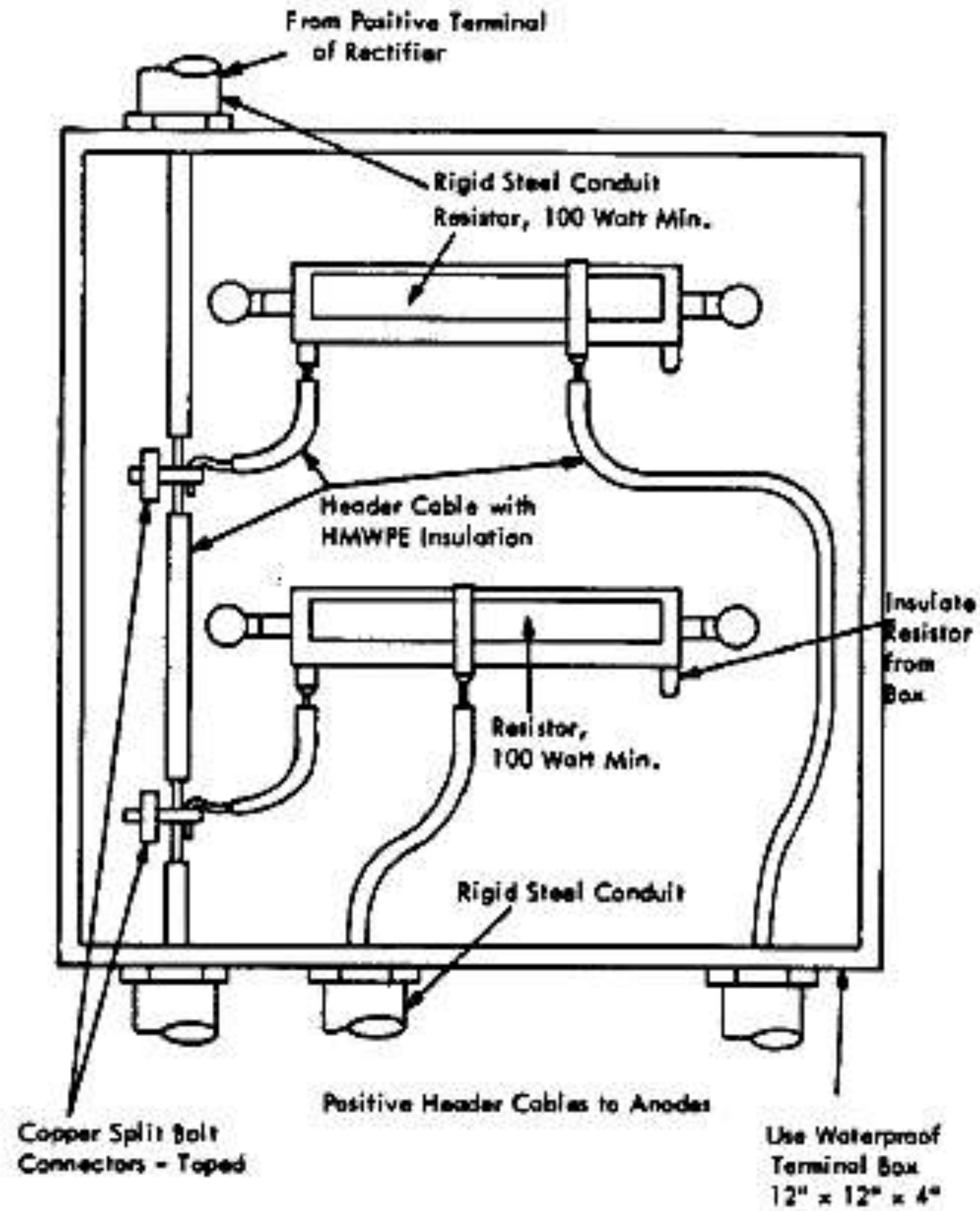


Figure 30
Anode balancing resistors

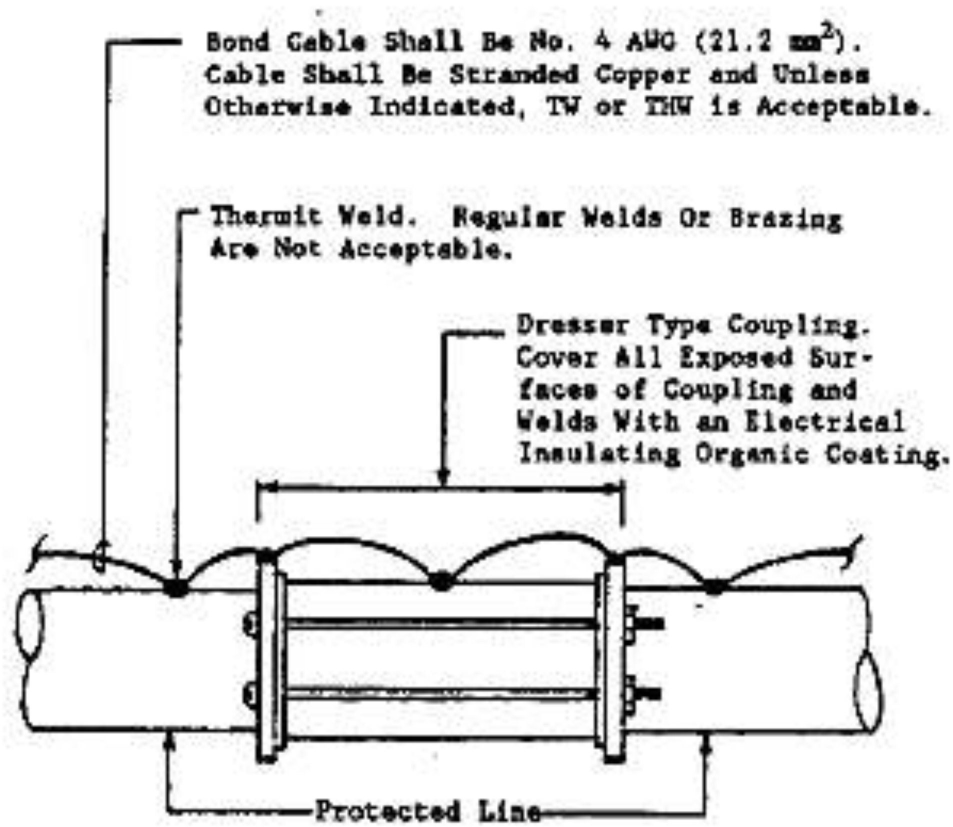


Figure 31
Bonding of a Dresser-style coupling

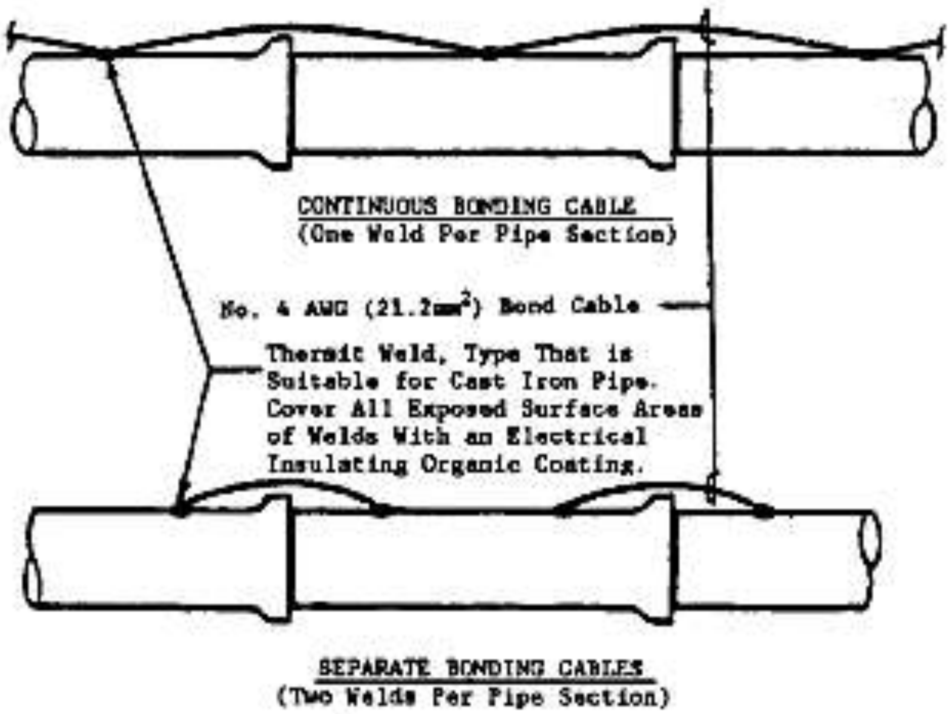


Figure 32
Bonding methods for cast iron bell-and-spigot pipe

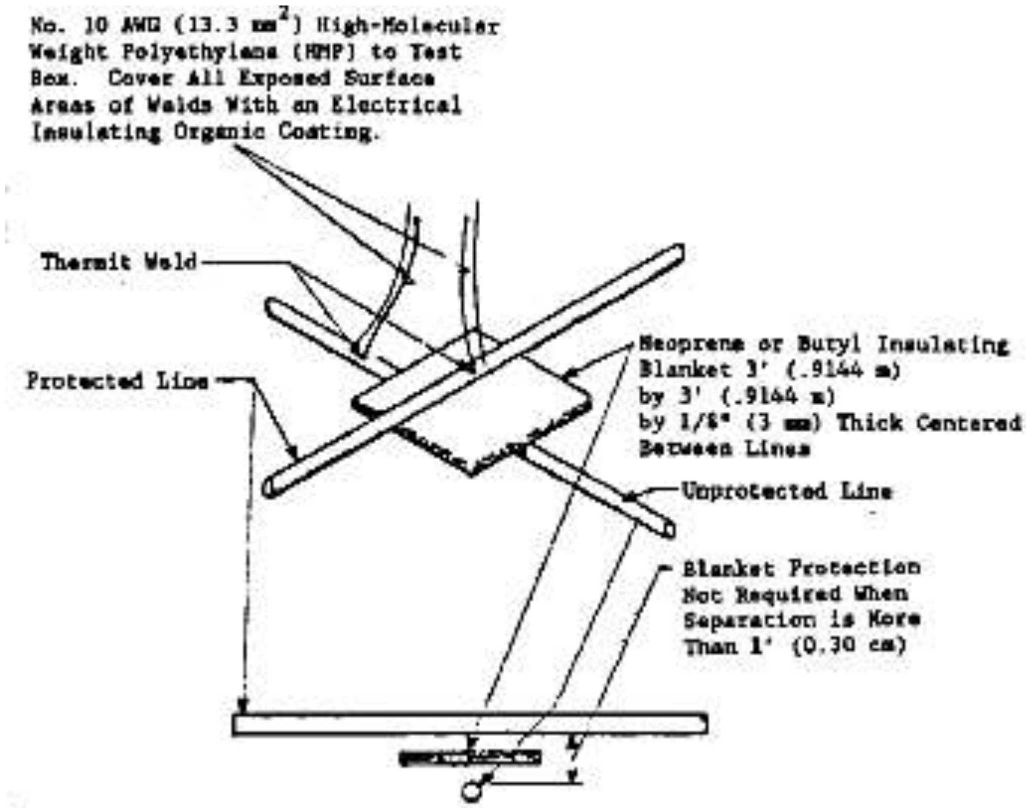


Figure 33
Isolating a protected line from an unprotected line

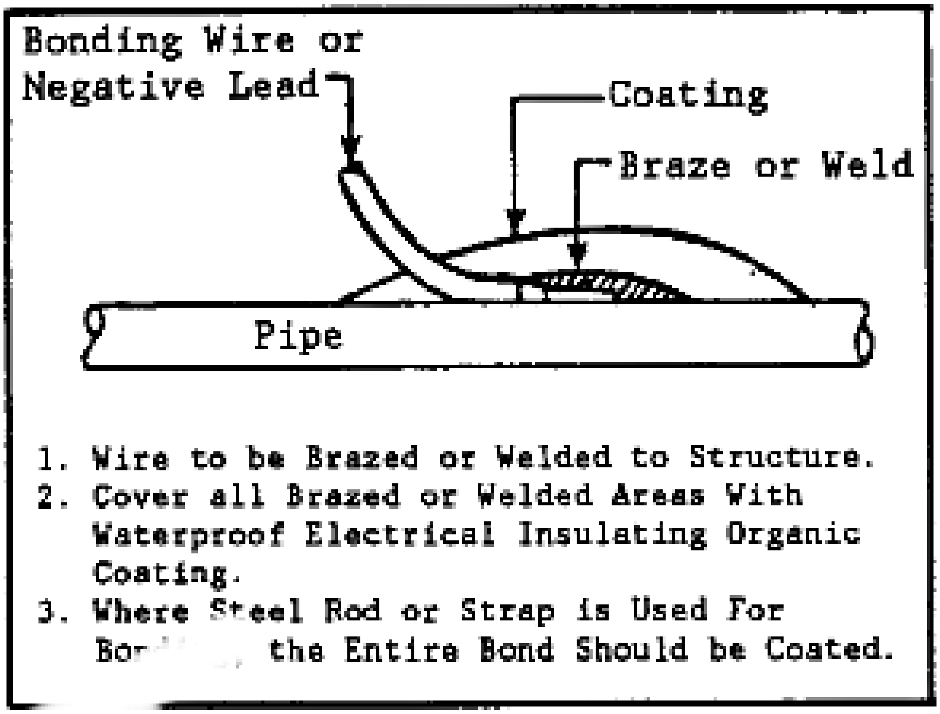


Figure 34
Electrical bond

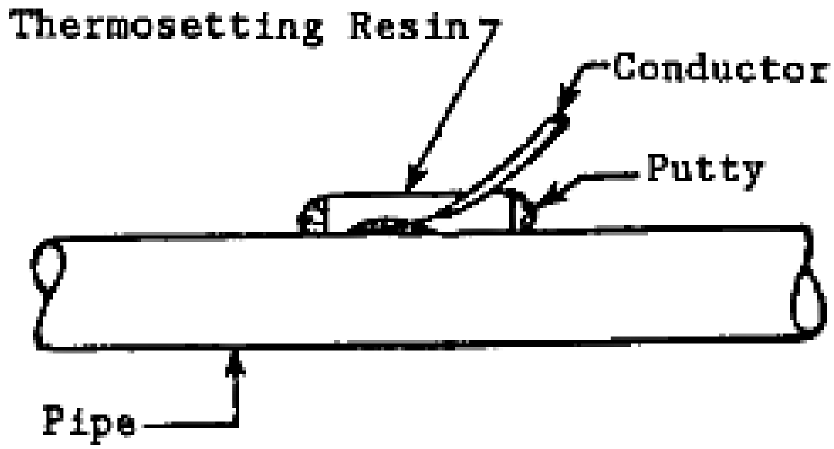


Figure 35
Thermosetting resin pipe connection

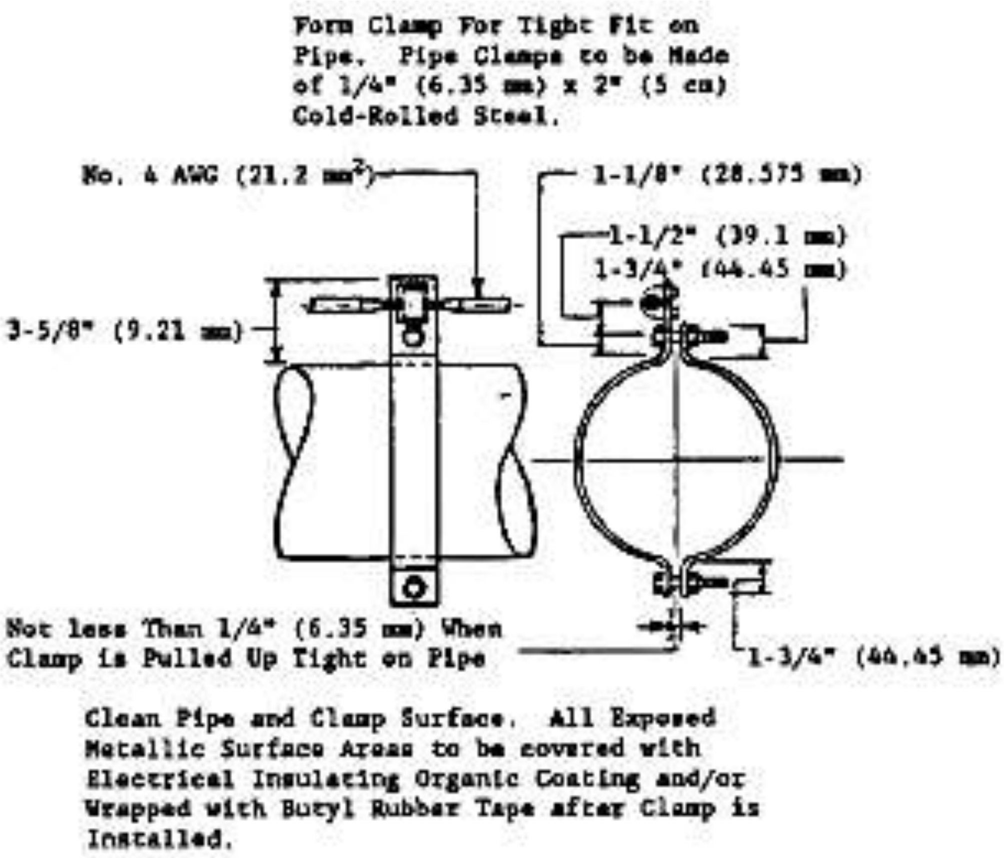


Figure 36
Clamp-type bonding joint

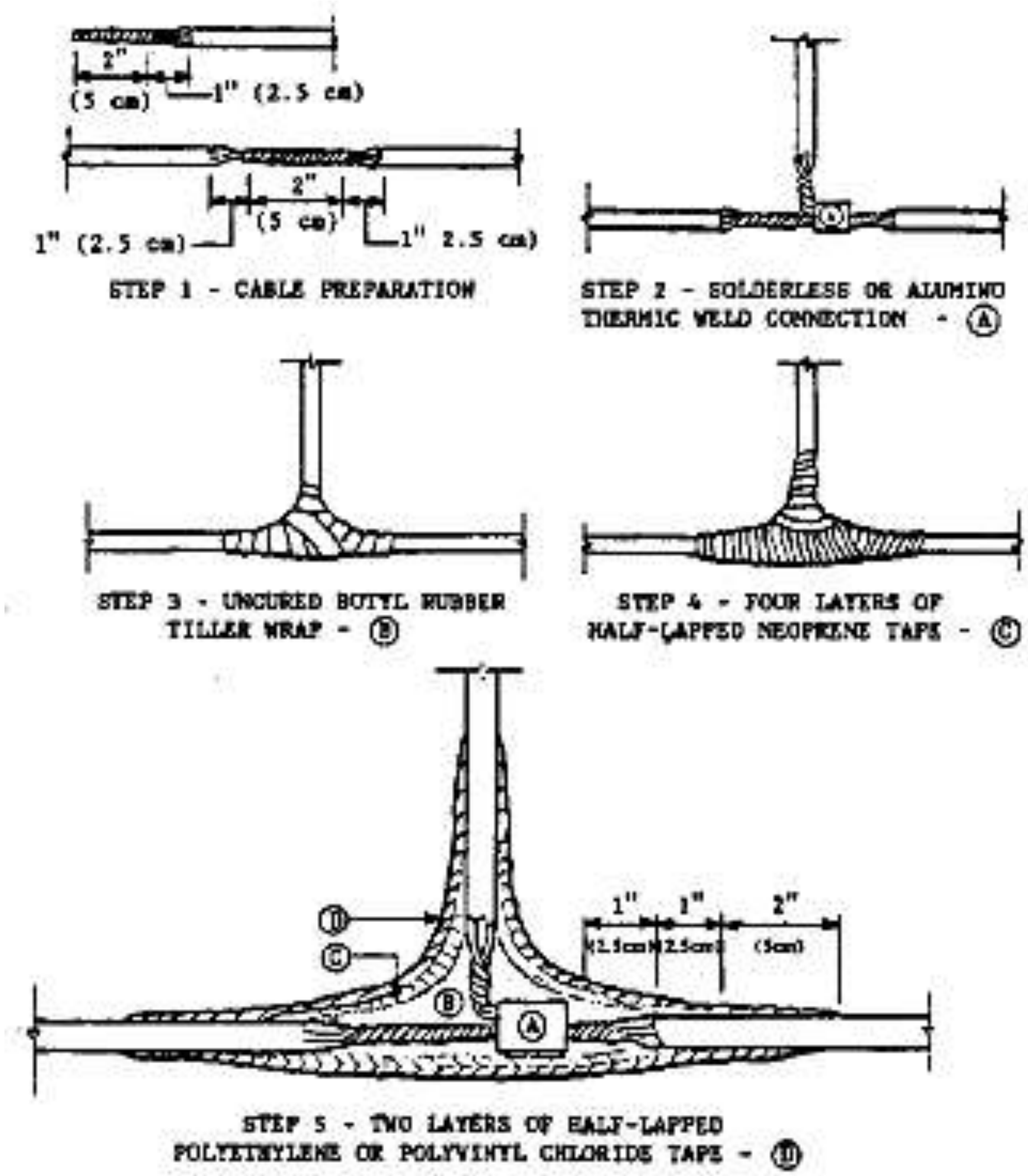
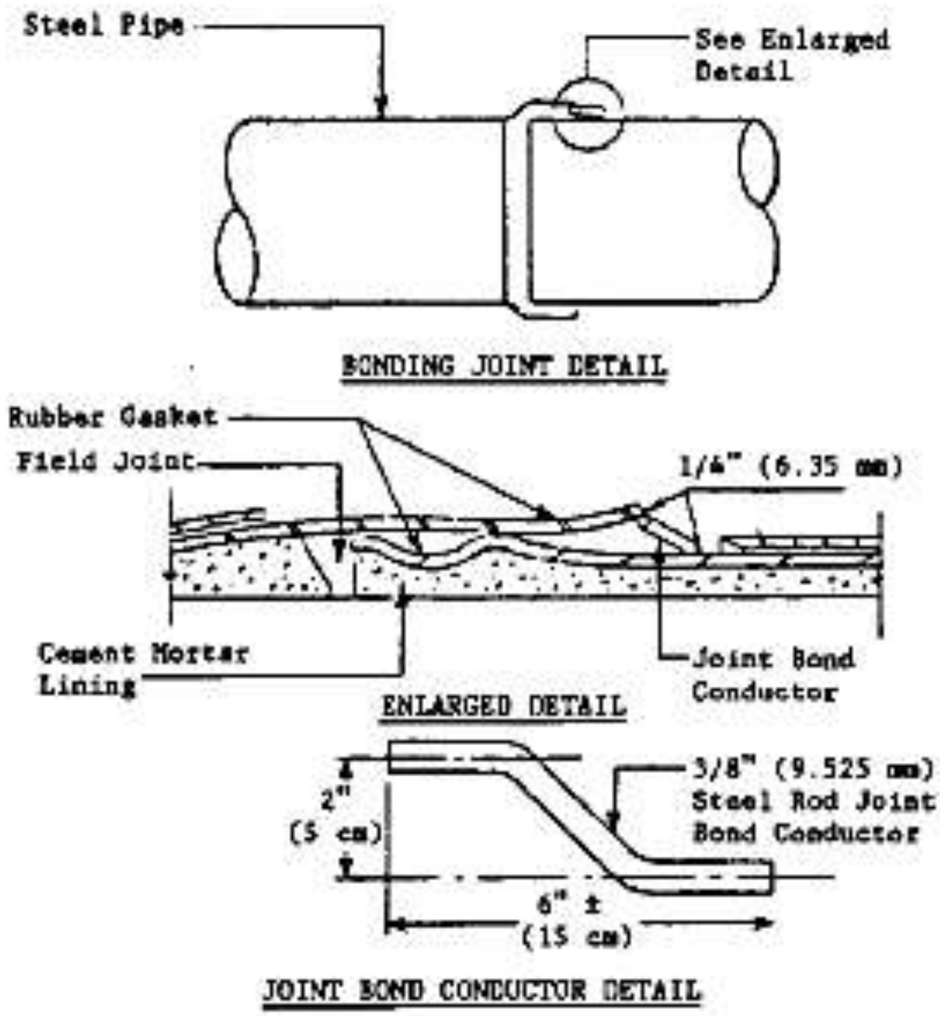


Figure 37
Underground splice



Note:
All exposed metallic surface areas to be covered with electrical insulating organic coating and/or wrapped with butyl rubber tape.

Figure 38
Welded type bonding joint for slip-on pipe installed above ground

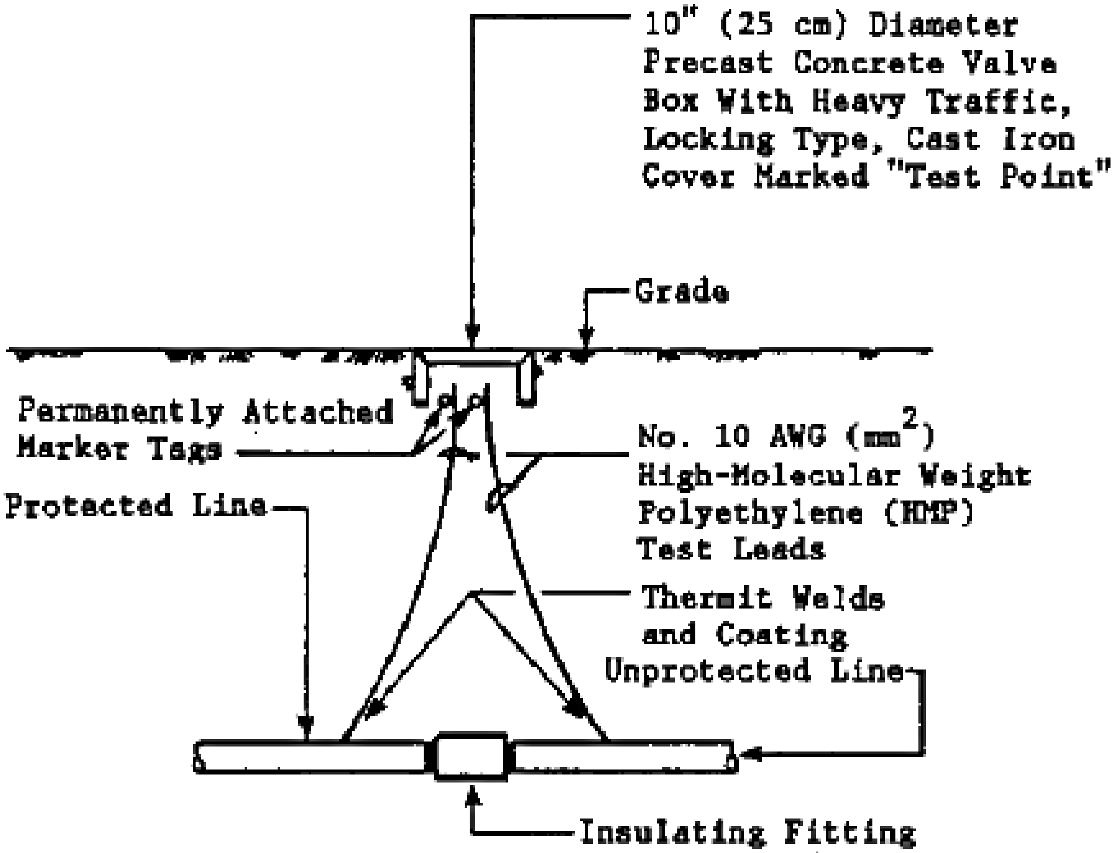


Figure 39
Test box for an insulating fitting

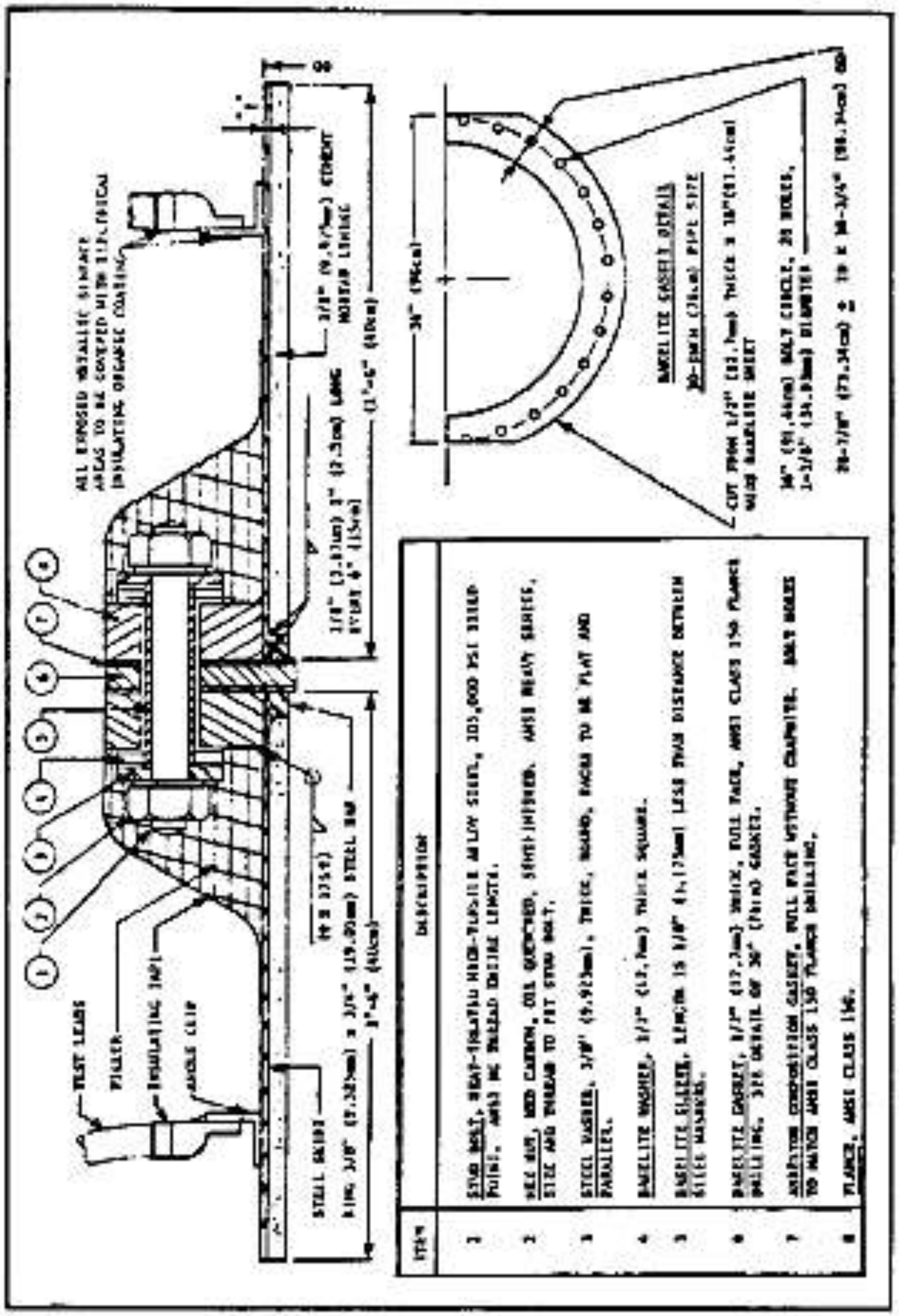


Figure 40
Steel insulating joint details for flanged pipe installed below grade

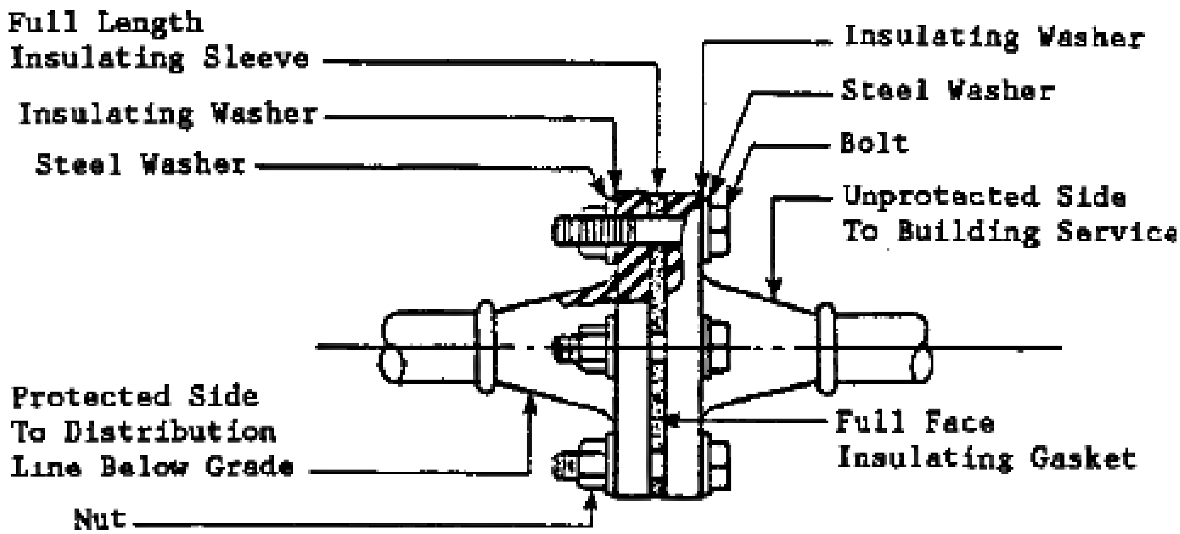


Figure 41
Steel insulating joint details for above ground flanged pipe

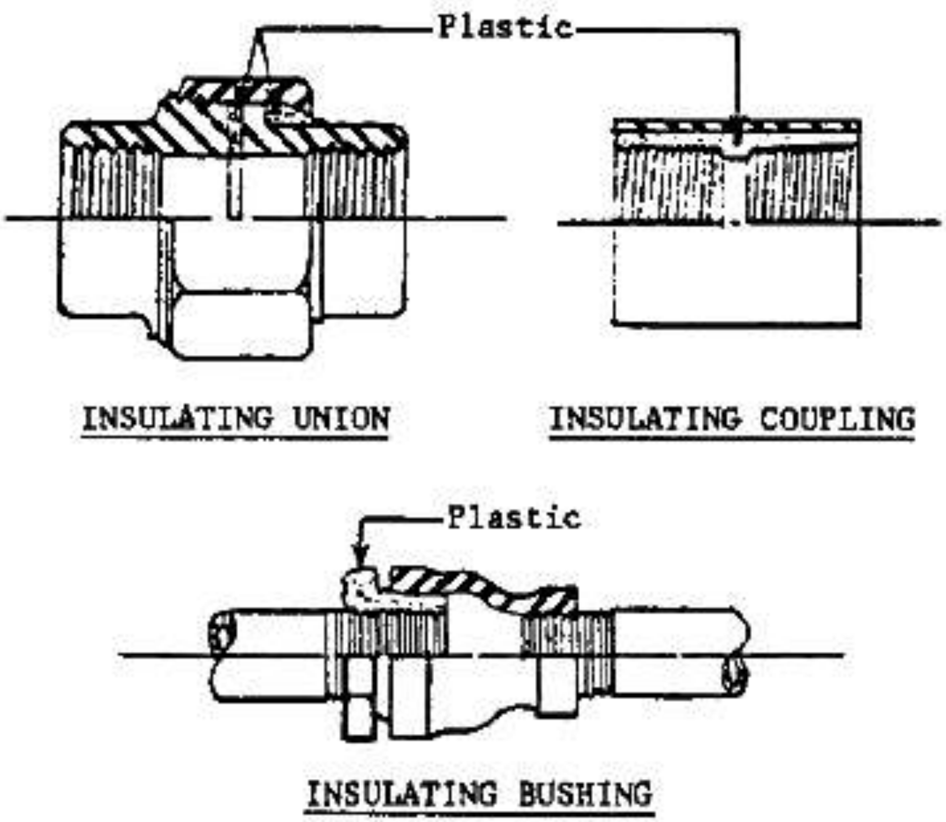


Figure 42
Insulating joint details for screwed pipe connections