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CIVIL ENGINEERING CORROSION CONTROL
VOLUME III. CATHODIC PROTECTION DESIGN

AIR FORCE CIVIL ENGINEERING CENTER

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) This report is specifically written for Air Force Civil Engineering personnel but can be useful to all Agencies of the Federal Govern- ment. It covers mainly Real Property and Real Property Installed Equipment. It deals with corrosion and corrosion control of buried and submerged metal structures. Causes and theory of corrosion, material selection, protective coatings, and cathodic protection application are included. The information contained herein will be usefull for solving all corrosion problems en- countered on real property and real property installed equipment.		

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ERRATA

APCEC-TR-74-6, Vol III should be corrected as follows:

- a. Sheet 183A, attached, insert after page 103.
- b. Page 129 - Label anode strings along the tank wall as -
"TANK ANODE STRINGS"
- c. Page 140, paragraph 3. - Change "pruposes" to "purposes"
- d. Report Documentation Page, block 13, Change "259" to
"260".

CIVIL ENGINEERING CORROSION CONTROL
VOLUME III - CATHODIC PROTECTION DESIGN

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FOREWORD

This report summarizes work done between May 1972 and Nov 1974. Thomas F. Lewicki was Project Officer. The major portion of the information in this report was compiled by the Hinchman Company under Investigation Engineering Project IE 16-72-1, control number F33615-72-C-0400 from sources listed in the acknowledgements section of this report. The authors contributed the remainder of the information for this report.

This report is published in three volumes, Volume I - Corrosion Control - General, Volume II - Cathodic Protection Testing Methods and Instruments, and Volume III - Cathodic Protection Design.

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This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.


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PREFACE

The Air Force's major guide to corrosion control of real property and real property installed equipment has been contained in Air Force Manual 88-9, Chapter 4 which was published August 1962. The corrosion control field has been progressing with new methods, materials and equipment constantly being introduced. Since the Air Force's corrosion manual was old and outdated, a need existed for searching, investigating and documenting the new methods, materials and equipment for corrosion control. It was decided that the most prompt and economical method of accomplishing this task was by procuring the services of a prominent corrosion engineering firm. Because of the large volume of the documented findings of this endeavor the information has been published in three volumes. The first volume is entitled Corrosion Control - General. The second and third volumes are entitled Cathodic Protection Testing Methods and Instruments and Cathodic Protection Design.

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<u>Figure</u>	<u>Source</u>
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9, 10, 11, 12, 14, 15	Goodall Electric, Inc.
22, 23, 24	Engelhard Industries, Inc.
30	Kaiser Magnesium
31	American Smelting & Refining Company, Inc.
54	<u>Corrosion</u> , Copyright National Association of Corrosion Engineers
<u>Table</u>	
1	Goodall Electric, Inc.
2, 3, 4, 5, 32	The Duriron Company, Inc.
6	Engelhard Industries, Inc.
10, 11, 12, 13, 14, 15	Kaiser Magnesium
16, 17, 18, 19, 20, 21	American Smelting & Refining Company, Inc.

CATHODIC PROTECTION DESIGN

1 INTRODUCTION. Cathodic protection is a common and effective means of mitigating or preventing corrosion. It is generally used together with coatings, test stations, bonds, and insulation. It is certainly not a "cure-all". Its economics and feasibility must always be carefully studied. An in-depth discussion of cathodic protection is presented here, including design and related corrosion control of buried or submerged structures.

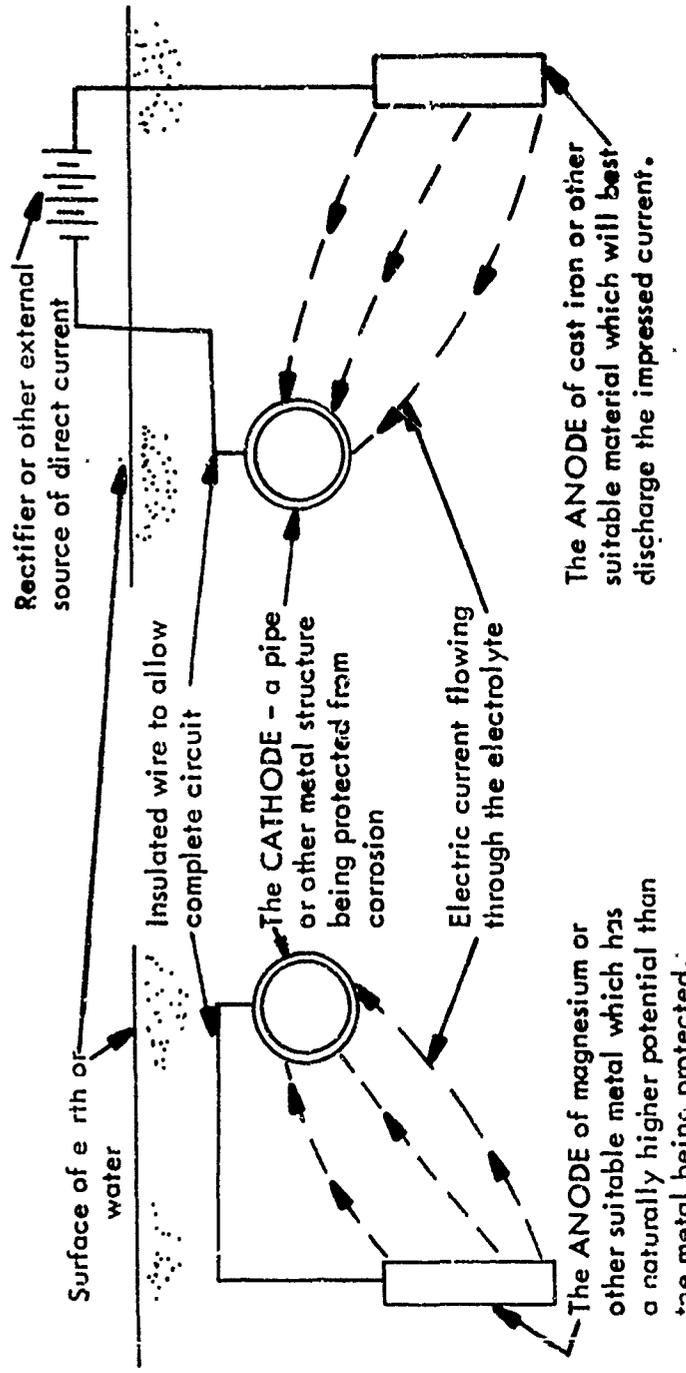
1.1 General Description of Cathodic Protection. Cathodic protection, as the name signifies, is the process by which an entire surface is transformed into a cathode. In other words, direct electric current is forced onto that surface from an "artificial" anode so that potential differences between anodic and cathodic areas are changed, and the entire surface receives current. Since corrosion occurs where current leaves the metal surfaces to enter an electrolyte, those surfaces receiving current do not corrode. Thus, where current flows onto corroding metal surfaces, a cathode is produced. Corrosion is transferred to the "artificial" anode and cathodic protection is achieved.

Cathodic protection is feasible wherever a continuous electrolyte is in contact with a metal surface. It is commonly used to protect pipelines, cables, tanks, locks, foundation piling, ship hulls, chemical process equipment, and almost any other metal structure in a moist environment. Cathodic protection is usually most economical when properly coordinated with insulation, coatings, and bonding. Its effect (interference) on adjacent structures must always be considered.

1.2 Comparison of Galvanic vs. Impressed Current Systems. There are two methods of applying cathodic protection (Figure 1): galvanic and impressed current. To be effective, both must have:

1. A power source.
2. Anodes which emit current into the electrolyte.
3. A continuous electrolyte to conduct current from anode to protected structure.
4. An external metallic connection between structure and anodes.
5. Electrical continuity in the protected structure between the metallic connection mentioned in (4) and protected surfaces.

1.2.1 Galvanic System. Galvanic cathodic protection is basically a controlled galvanic cell (Figure 1a). The structure to be protected is metallogically coupled (usually by means of insulated wire) to a metal of naturally higher



The ANODE of magnesium or other suitable metal which has a naturally higher potential than the metal being protected.

GALVANIC ANODE SYSTEM

(a)

The ANODE of cast iron or other suitable material which will best discharge the impressed current.

IMPRESSED CURRENT SYSTEM

(b)

Figure 1
BASIC CATHODIC PROTECTION SYSTEMS

(more negative) potential. A galvanic cell (the power source) is thereby established in which the protected structure is the cathode and the less noble metal, the galvanic anode. Current produced by the galvanic potential between the two metals flows through the electrolyte from anode to cathode. The system is designed so that sufficient current will flow from the anode to suppress all local action current on the surface of the protected structure. Galvanic anodes corrode at a rate proportional to their emitted current.

Galvanic anodes are usually either magnesium or zinc. Potential between such anodes and protected structure will never exceed one volt.

1.2.2 Impressed Current Systems. Impressed current cathodic protection uses external D.C. power to develop a potential between anode and protected structure to force current from the anode into the electrolyte (Figure 1b). The anodes, consisting of conducting material which discharge current (usually at a low rate), are connected through insulated wires and external power source to the structure to be protected. Impressed current flows out of the anode into the electrolyte (the anode corrodes). It passes through the electrolyte and is received by the surface of the protected structure which is now cathodic. An impressed current system does the same job as the galvanic system. However, the impressed current system is not limited by a low natural voltage (approximately one volt) between anode and protected structure.

Impressed current anodes are commonly high-silicon cast iron or graphite. The external power source may be any conveniently available provided it is continuous. Rectifiers are most often used for this purpose. However, motor-generator sets, gasoline engine generators, batteries, thermoelectric cell, solar cells, fluid turbines, and wind-driven generators have been used.

2 CRITERIA FOR PROTECTION. Different methods and criteria are available to determine effectiveness of cathodic protection. Proper criteria are both valid and practical to use for the given structure. Electrical criteria are in most general use for submerged and underground structures, because they are generally most practical to evaluate for installed structures.

2.1 Visual Criteria. For readily-accessible structures, visual inspection may be used. If the structure shows visible signs of corrosion - corrosion products, pitting, cracking, thinning or other deterioration - then adequate protection has not been achieved. This method is obvious but generally very impractical and, for that reason, is not in general use.

A variation of structure inspection is the use of "coupons" of structure metal electrically connected to the structure at various points. These coupons are usually installed in the electrolyte at extreme or critical locations where corrosion is most likely (areas of low resistivity, where concentrations of corrosives exist, etc.) The coupon is weighed and stamped with the weight prior to installation. After a given period (a year or more), the coupon is removed, weighed and visually analyzed for effects of corrosion. From the condition of the coupons, the structure's state is approximated. While this method is more feasible than removing an entire structure for examination, coupons are still relatively impractical for general application.

2.2 Non-Destructive Testing. Non-destructive testing of structural surfaces is sometimes used to determine if corrosion is occurring. Pit depths and wall thicknesses are among the most common tests. Where changes in these values occur, adequate protection is not achieved.

One in-place method of detecting internal and external corrosion pitting on pipelines uses an electronic pig-type device with self-contained recording and evaluation system. Fluid movement or gas pressure propels the instrument through the pipe under test. Location and severity of pitting are recorded for playback to a strip chart, for visual examination.

Non-destructive testing, like visual examination, is often too inconvenient, time-consuming, and expensive. Only readily accessible structures can be tested without requiring excavation or special equipment. This method may be effective for analyzing many above-ground structures, especially those (such as tanks or chemical equipment) containing corrosives.

2.3 Failure-Rate Analysis.

Corrosion failures increase logarithmically with time. When cathodic protection is applied to and effectively protects a corroding structure (such as a pipeline), the failure rate is greatly reduced. This does not occur immediately, however, because of metal already lost. Mechanical failures still occur but, with adequate cathodic protection, corrosion failures should cease after a year or so of operation.

If an accurate record of total cumulative failures is kept and plotted with time, the effectiveness of cathodic protection can be determined from the resulting graph. A record of failures which exhibits a rate less than logarithmic indicates a degree of corrosion mitigation.

2.4 Electrical Criteria (RP-01-69). For underground and submerged structures, the simplest and most often used method of determining adequate cathodic protection is by electrical measurements. These criteria are "rules-of-thumb", determined from experimental and laboratory tests, based on visual and non-destructive analysis of corroding samples.

The National Association of Corrosion Engineers in their Standard RP-01-69, "Recommended Practice for Control of External Corrosion on Underground or Submerged Metallic Piping Systems", lists accepted criteria for this method. These criteria are based on electrical structure-to-electrolyte potentials with respect to a copper-copper sulfate reference electrode and are quoted here from NACE Standard RP-01-69.

2.4.1 Introduction to RP-01-69. "The objective of using cathodic protection is to control the corrosion of metallic surfaces in contact with electrolytes.

"The selection of a particular criterion for achieving this objective depends, in part, upon past experience with similar structures and environments wherein the criterion has been used successfully.

The following criteria "have been developed through laboratory experiment or empirically determined by evaluating data obtained from successfully operated cathodic protection systems. It is not intended that the Corrosion Engineer be limited to these criteria if it can be demonstrated by other means that the control of corrosion has been achieved.

"Voltage measurements on pipelines are to be made with the reference electrode located on the electrolyte surface as close as practicable to the pipeline. Such measurements on all other structures are to be made with the reference electrode positioned as close as feasible to the structure surface being investigated. The Corrosion Engineer shall consider voltage (IR) drops other than those across the structure-electrolyte boundary, the presence of dissimilar metals, and the influence of other structures for valid interpretation of his voltage measurements.

"No one criterion for evaluating the effectiveness of cathodic protection has proven to be satisfactory for all conditions. Often a combination of criteria is needed for a single structure."

2.4.2 "Steel and Cast Iron Structures"

a. "A negative (cathodic) voltage of at least 0.85 volt as measured between the structure surface and a saturated copper-copper sulfate reference electrode contacting the electrolyte. Determination of this voltage is to be

made with the protective current applied.

b. "A minimum negative (cathodic) voltage shift of 300 millivolts, produced by the application of protective current. The voltage shift is measured between the structure surface and a saturated copper-copper sulfate reference electrode contacting the electrolyte. This criterion of voltage shift applies to structures not in contact with dissimilar metals.

c. "A minimum negative (cathodic) polarization voltage shift of 100 millivolts measured between the structure surface and a saturated copper-copper sulfate reference electrode contacting the electrolyte. This polarization voltage shift is to be determined by interrupting the protective current and measuring the polarization decay. When the current is initially interrupted, an immediate voltage shift will occur. The voltage reading after the immediate shift shall be used as the base reading from which to measure polarization decay.

d. "A structure-to-electrolyte voltage at least as negative (cathodic) as that originally established at the beginning of the Tafel segment of the E-log-I curve. This structure-to-electrolyte voltage shall be measured between the structure surface and a saturated copper-copper sulfate reference electrode contacting the electrolyte at the same location where voltage measurements were taken to obtain the E-log-I curve.

e. "A net protective current from the electrolyte into the structure surface as measured by an earth current technique applied at predetermined current discharge (anodic) points of the structure.

2.4.3 "Aluminum Structures.

a. "A minimum negative (cathodic) voltage shift of 150 millivolts, produced by the application of protective current. The voltage shift is measured between the structure surface and a saturated copper-copper sulfate reference electrode contacting the electrolyte. See precautionary notes in paragraph 2.4.3.c.

b. "A minimum negative (cathodic) polarization voltage shift of 100 millivolts measured between the structure surface and a saturated copper-copper sulfate reference electrode contacting the electrolyte. This polarization voltage shift is to be determined by interrupting the protective current and measuring polarization decay. When the current is initially interrupted, an immediate voltage shift will occur. The voltage reading, after the immediate shift, shall be used as the base reading from which to measure polarization decay. See precautionary notes in paragraph 2.4.3.c.

c. Precautions.

(1) High Potential. "Notwithstanding the alternative minimum criteria in paragraphs 2.4.3.a and 2.4.3.b, aluminum, if cathodically protected at voltages in excess of 1.20 volts measured between the structure surface and a

saturated copper-copper sulfate reference electrode contacting the electrolyte and compensated for the voltage (IR) drops other than those across the structure-electrolyte boundary, may suffer corrosion resulting from the build-up of alkali on the metal surface. A voltage in excess of 1.20 volts should not be used unless previous test results indicate no appreciable corrosion will occur in the particular environment.

(2) Alkaline Soil. "Since aluminum may suffer from corrosion under high pH conditions and since application of cathodic protection tends to increase the pH at the metal surface, careful investigation or testing should be made before applying cathodic protection to stop pitting attack on aluminum structures in environments with a natural pH in excess of 8.0.

2.4.4 "Copper Structures.

a. "A minimum negative (cathodic) polarization voltage shift of 100 millivolts measured between the structure surface and a saturated copper-copper sulfate reference electrode in the electrolyte. This polarization voltage shift is to be determined by interrupting the protective current and measuring the polarization decay. When the current is initially interrupted, an immediate voltage shift will occur. The voltage reading, after the immediate shift, shall be read as the base reading from which to measure polarization decay.

2.4.5 "Dissimilar Metal Structure.

a. "A negative (cathodic) voltage, between all structure surfaces and a saturated copper-copper sulfate reference electrode contacting the electrolyte, equal to that required for the most anodic metal should be maintained. If amphoteric structures are involved they could be damaged by high alkalinity (see precautions, paragraph 2.4.3.c), they should be electrically isolated with insulating flanges, or the equivalent."

2.4.6 "Lead Structures.

a. Although not part of RP-01-69, the accepted criteria for lead structures is the same as stated for aluminum in para 2.4.3. In addition, an accepted criteria for lead structures is a negative voltage of at least 0.75 volts as measured between the structure surface and a saturated copper-copper sulfate reference electrode contacting the electrolyte.

2.4.7 "Special Considerations.

a. "Special cases such as stray currents and stray electrical gradients may exist which require the use of criteria different from those listed above. Measurements of current loss and gain on the structure and current tracing in the electrolyte have been useful in such cases.

b. "Abnormal conditions sometimes exist where protection is ineffective or only partially effective. Such conditions may include elevated temperatures, disbonded coatings, shielding, bacterial attack, and unusual contaminants in the electrolyte."

3 PRECAUTIONS FOR CATHODIC PROTECTION DESIGN. Care must be taken to avoid unsafe or damaging currents and voltages. Designs which result in unsafe conditions cannot be

tolerated. High cathodic protection current density (over-protection) can sometimes damage coatings or structures and must be limited. Often soil of extreme pH (highly acid or highly alkaline) can interfere with effective cathodic protection. Precautions to consider are discussed here in more detail.

3.1 Interference with Other Structures.

Cathodic protection sometimes causes undesirable effects on structures not intended to be protected.

Current is received in one area and discharged in another in traveling back to its source. Current pickup areas where interference current is received are actually cathodically protected. Current discharge areas where current passes from metal surfaces to soil or water corrode. When pipe is joined by mechanical, nonconducting couplings, a complicated problem results if current bypasses these joints. Figure 2 illustrates a typical current flow pattern.

In designing cathodic protection with minimal interference problems, the most important single factor is location of anodes with respect to the unprotected structure. Figure 3 illustrates the effect of a point anode on various piping configurations. Anode and foreign structures are shown. Cathode is remote and does not affect anode field. It is assumed that the electrolyte is homogeneous. If the anode is alone with no other structure in the electrical field, the pattern of equipotential lines surrounding the anode is concentric circles (as when a pebble is dropped into a pond of still water). Potential is highest at the anode and drops off in all directions.

If another structure crosses this field of equipotential lines (concentric circles), the potential gradient between lines causes current to flow in the structure away from the anode in both directions, toward the largest diameter equipotential circle as indicated by arrows on Figure 3b. After passing beyond the largest circle, current begins to discharge into the electrolyte to return to the cathode.

As indicated in Figure 3c, the farther from the anode the structure crosses through equipotential lines, the smaller the gradient and the less the current flow on it.

The cathode field is similar to that of the anode with its equipotential lines, except that current flows toward the cathode. Also, unlike the anode which acts like a point structure, the cathode is frequently a long pipe or cable, with equipotential lines that are elongated ellipses (Figure 3d). If the foreign structure is close to the cathode, current flows along both structures in the same direction.

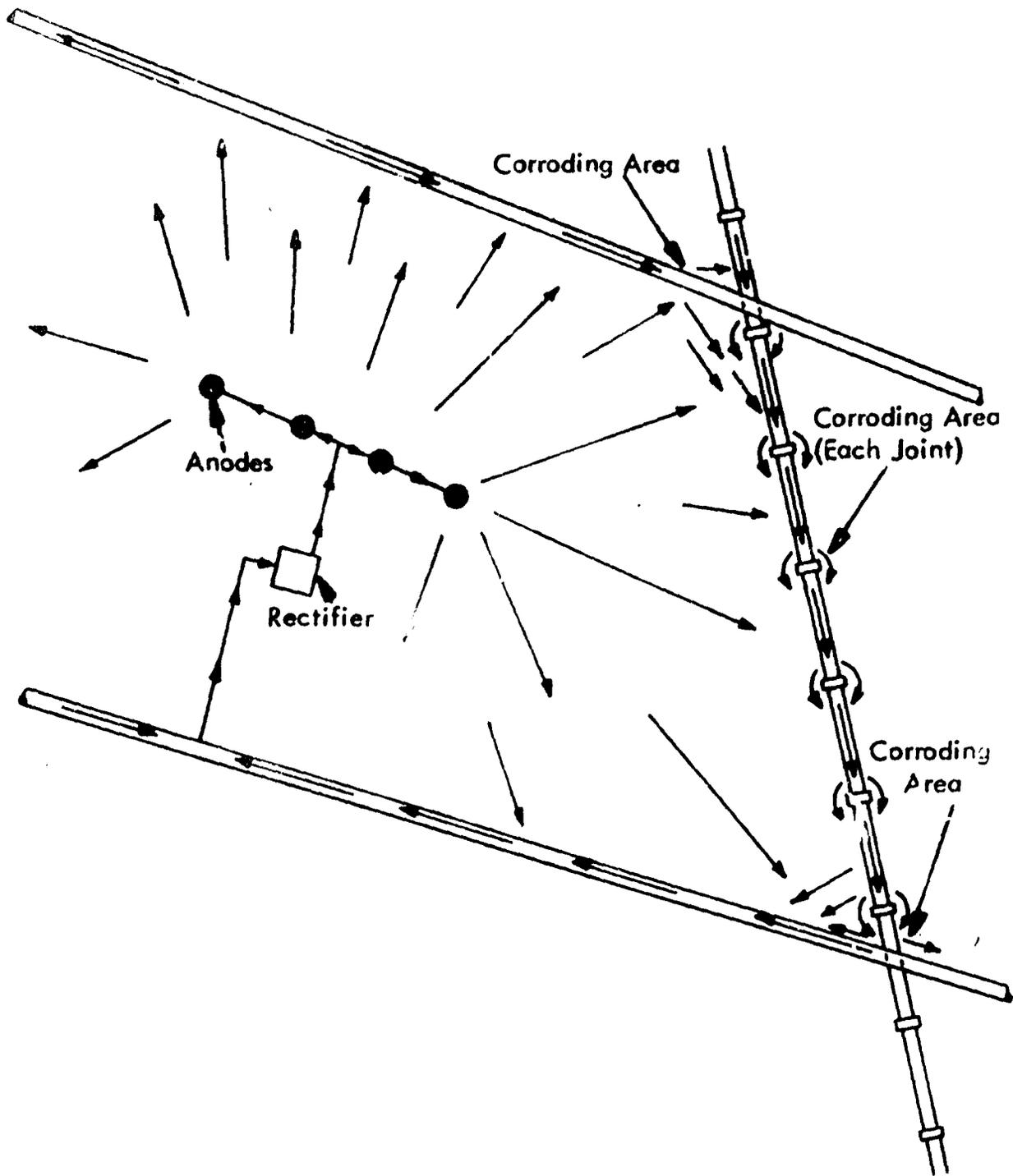
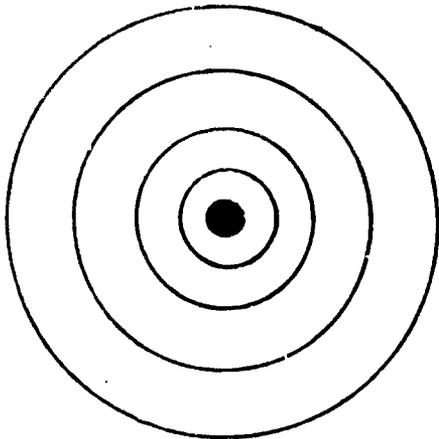
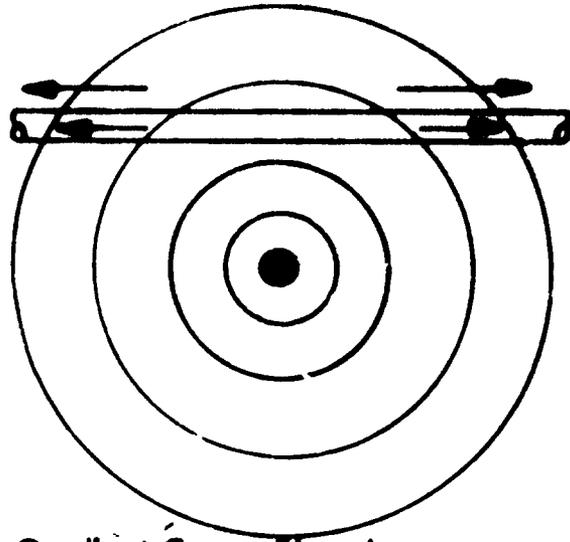


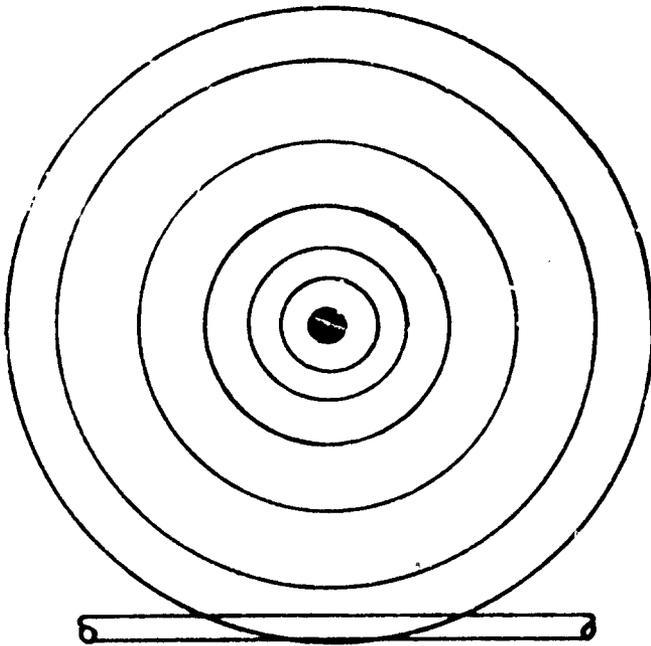
Figure 2
CATHODIC PROTECTION AND INTERFERENCE



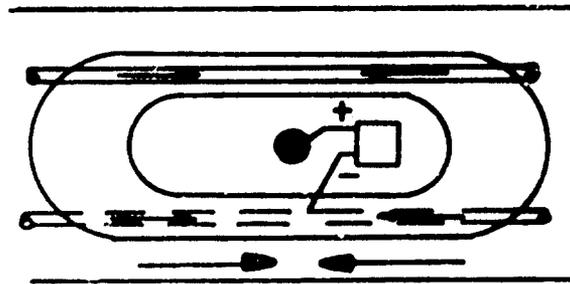
a) Equipotential Lines
Around Anode



b) Gradient Causes Flow Away
From Anode



c) No Flow on Pipe Because
of Distance from Anode



d) Flow Toward
Negative Cathode Connection

Figure 3
EQUIPOTENTIAL LINES

The discussion so far assumes anode, cathode, and foreign structure in approximately the same horizontal plane. The vertical plane is introduced with deep anodes. These anodes are placed below the earth's surface at a depth of 50 feet or more so that their field of influence will be farther away from most buried structures. If a deep anode is assumed to be a point, its field of influence is a concentric sphere. Nearby well casings, structural steel piling, etc. can easily be inside this field of influence; and the potential gradient will cause current flow (Figure 4).

Structures other than buried pipes and cables become involved in cathodic interference problems. Power line neutrals, which connect water pipes, telephone grounds, power grounds, and sometimes even gas lines, become a part of the circuit. Thus it is not surprising to find current flowing in pole guy cables, ground cables, etc. Power or communications cable sheaths, mounted on poles, occasionally go underground for short lengths. Here they can pick up or discharge current which flows along their entire length. Even well-ballasted railroad rails have been known to receive current in sufficient quantity to affect signals.

Cathodic interference can be detected by measuring structure-to-soil potentials and current flow (IR drop).

3.1.1 Ground Bed Location and Design. Type and location of impressed current around beds determine field of influence and, therefore, amount of interference received by unprotected structures in the area.

Types of ground beds to consider are:

- Point Surface
- Distributed
- Point Deep Well

The point surface type is easiest to design and construct but most likely to affect adjacent structures. However, it can be located at an optimum position where its effect will be minimal. Distributed systems use more anodes and/or power supplies to do the same job. In this way, potential gradient is limited by keeping ground current concentration small and allowing anode placement close to the protected structure. A distributed system also uses less current to protect the same area of metal. Deep anodes may minimize effects on surface structures. However, they cannot be repaired and may harmfully influence adjacent well casings and piling.

Figure 5 illustrates a surface anode installed between two foreign pipelines and connected to a remote cathode (not shown). It is seen that current flows in both directions

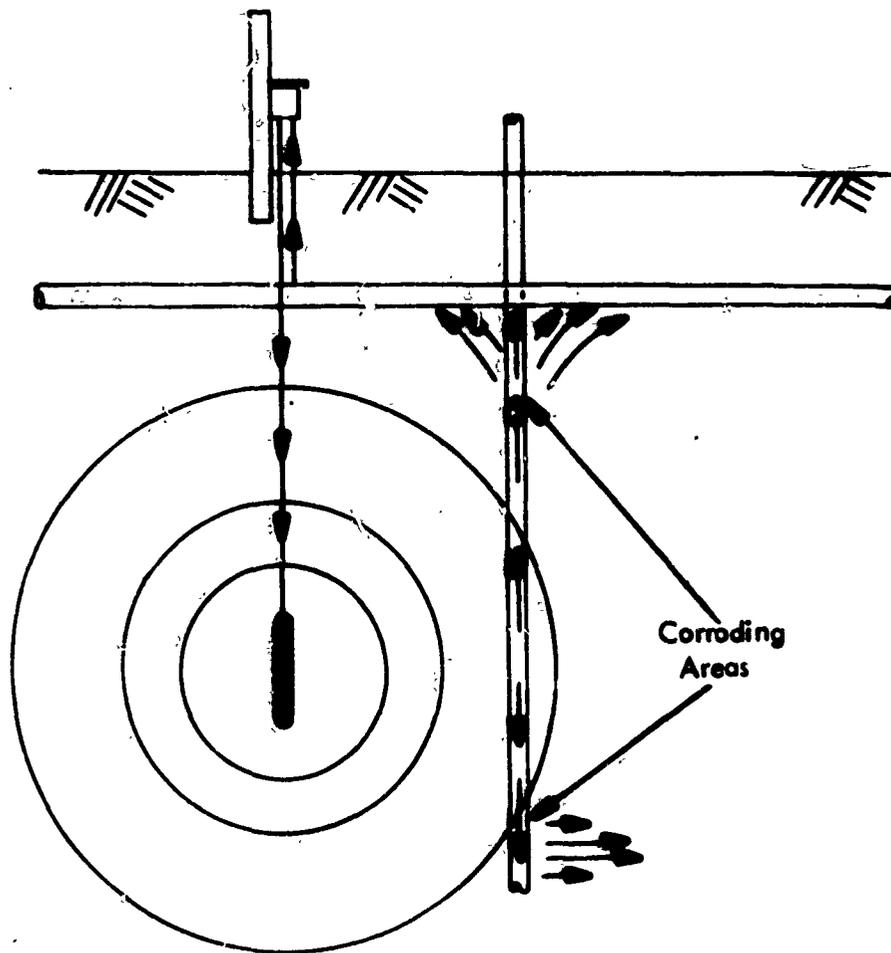


Figure 4
EQUIPOTENTIAL LINES: DEEP ANODE

away from the anode on the closest pipe when anode location is off-center. This anode can be moved to the 45° diagonal for minimum effect.

Figure 6 shows two parallel pipelines, one of which is cathodically protected. Current flow directions are indicated by arrows. Current flows away from the close anodes in Figure 6a. By moving the anodes out farther, current flow in the unprotected pipe is reversed as in Figure 6b. At some anode-to-pipe distance between those shown, current flow in the unprotected pipe is reduced to zero. In practice, however, it is usually not practical to locate a point where less than 5% of the anode current is on the unprotected structure. The anode should be placed on the far side of the balance point so that current flows toward the point of cathode attachment.

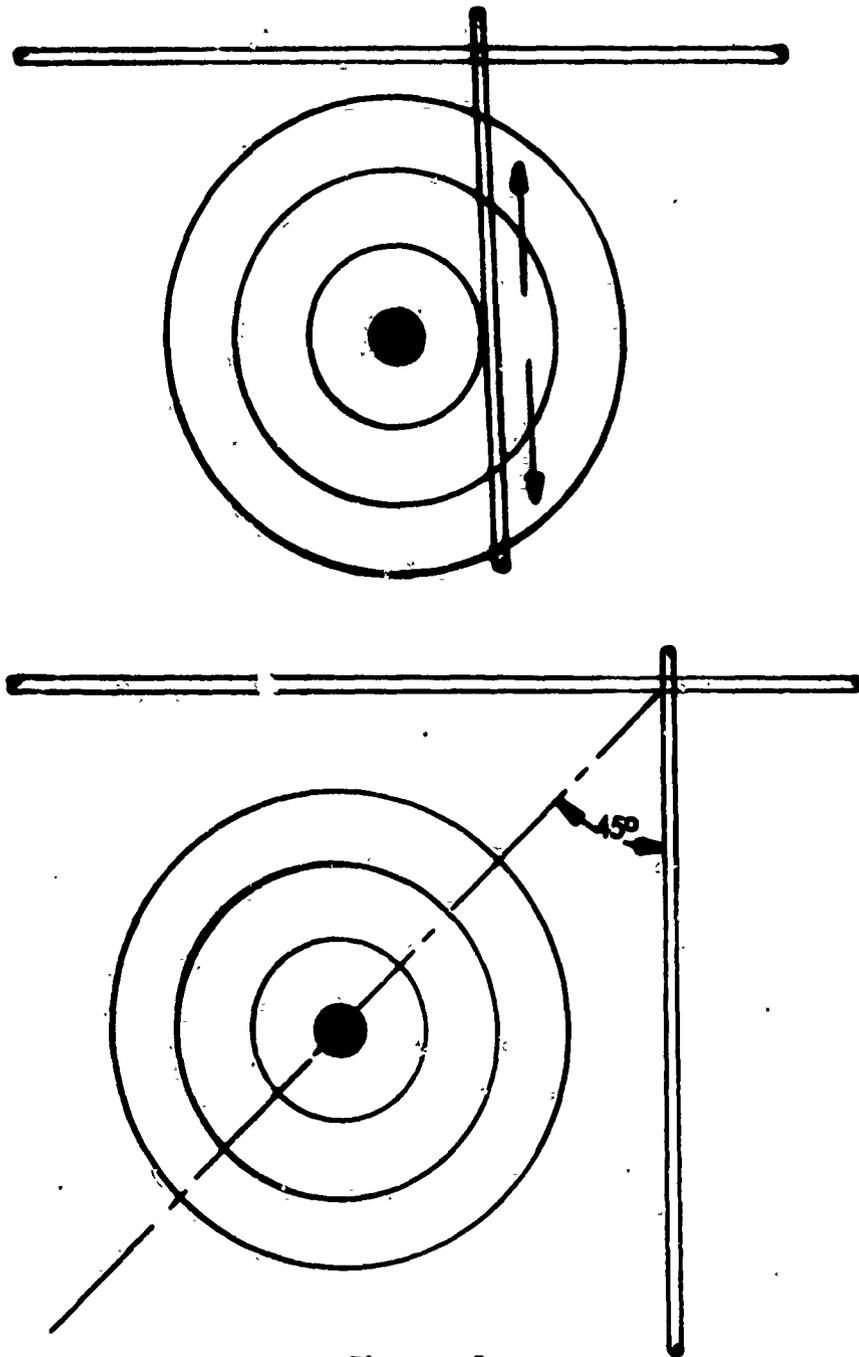


Figure 5
ANODE LOCATION - INTERSECTING PIPES

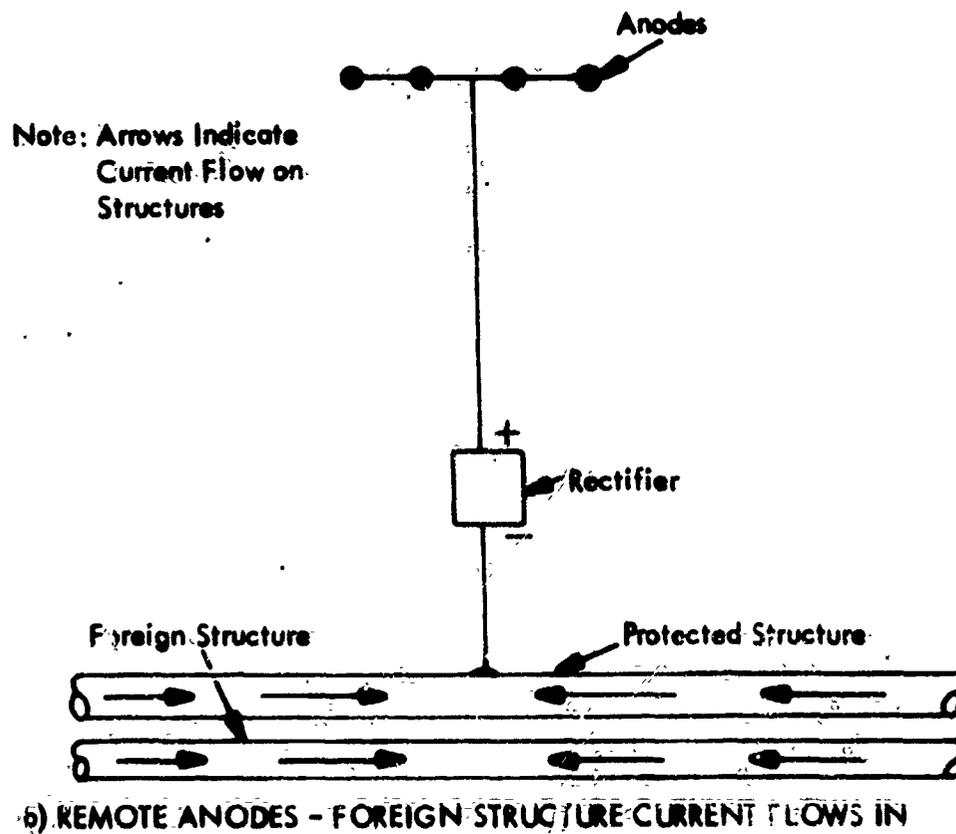
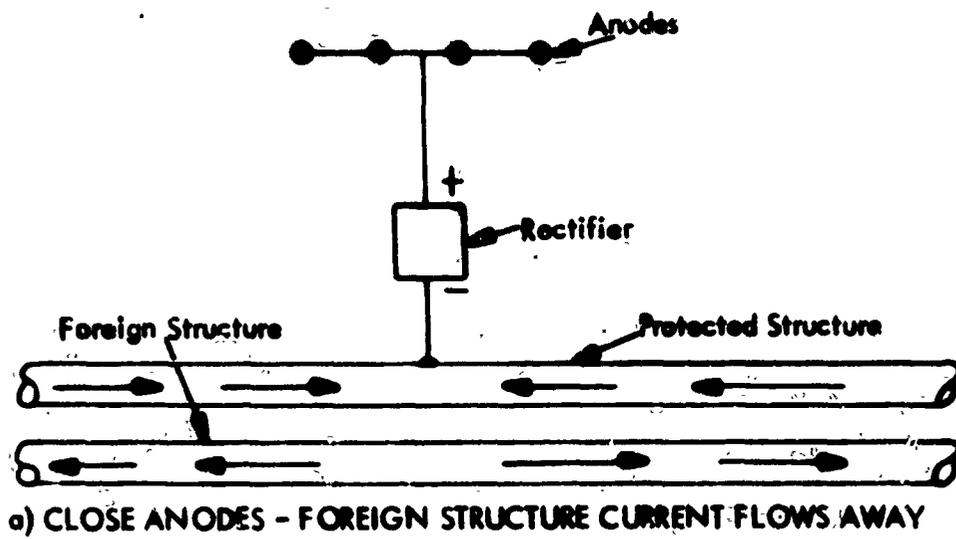
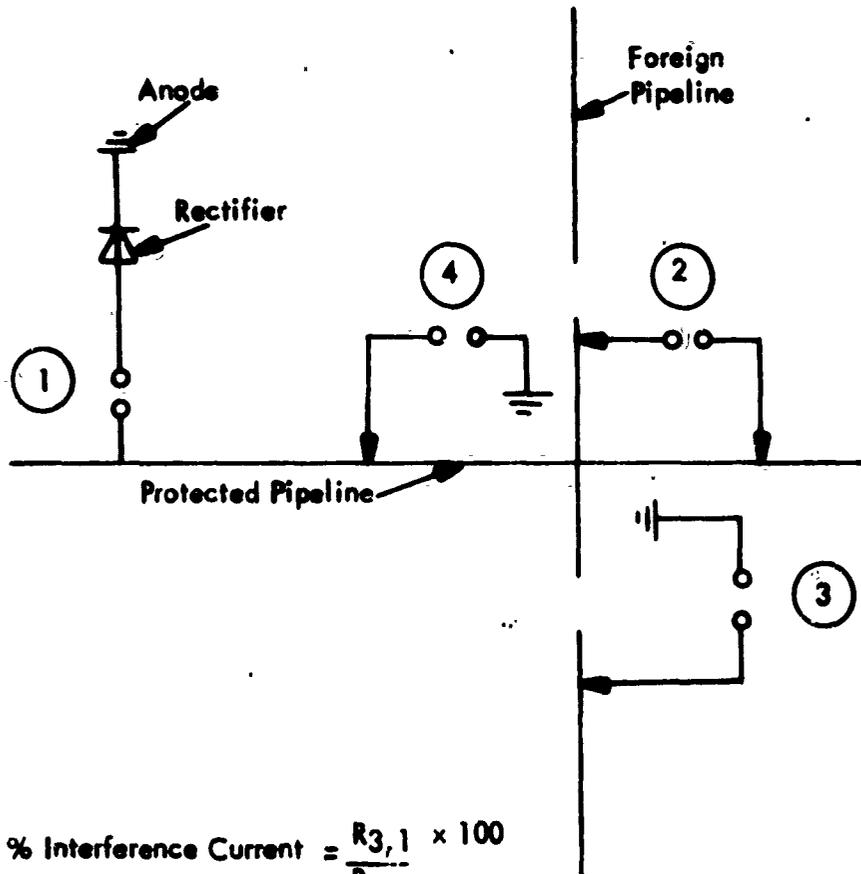


Figure 6
ANODE LOCATIONS - PARALLEL PIPES .

3.1.2 Mitigation: Tests must be made on all structures adjacent to a cathodic protection system to determine effects and design mitigation. (Usually a bond can be installed to drain current back to its source.)

Pipe-to-soil potential and current flow are measured at many locations before cathodic protection is turned on. Then measurements are repeated at exactly the same points with the system operating. The algebraic difference between on and off readings is the effect of cathodic protection. The location showing greatest pipe-to-soil potential change in the positive direction is called the "critical" or "control" point. This is often at the point where protected and unprotected pipes cross each other. Mitigation can usually be accomplished by installing a bond between the unprotected structure (at location of natural discharge) and protected structure (as close as possible to the negative connection). Mechanically jointed pipes must not be bonded into a cathodic protection system unless all joints are shorted across so that they carry current. If the "critical" point is corrected by this method to its original potential (reading before cathodic protection was turned on), other test points on the same structure will automatically be corrected. Sometimes, magnesium anodes are installed at the "critical" point. This will usually only correct the local area directly opposite the anodes.

When bonding structures together, it is necessary to drain only sufficient current or slightly more than enough to "clear" the "critical" point of exposure. The amount of current drainage is mutually agreed upon by representatives of owners of structures after cooperative testing. Bond resistance, to accomplish drainage, is often obtainable by trial and error, as was noted in paragraph 1.2.2.b. If long conductors are necessary, preliminary tests can be made to compute total bond resistance, including all connections, etc. The method and relationships for this computation are shown in Figure 7. Subscripts for couplings ($R_{3,1}$, for example) indicate location of voltage reading and current drain (voltage read at point 3, current drain at position 1). Current drained at "1" is rectifier output; at "2", it is the current flow through the bond. Two sets of readings are taken. For the first, voltages are read at locations 2, 3 and 4 with the rectifier on and off. For the second, voltages are read at the same points with the bond in and out of the circuit. Couplings for each location are then calculated, equaling voltage change between on and off readings divided by rectifier drainage current ($R_{2,1}$ $R_{3,1}$ $R_{4,1}$) or voltage change with bond in and out divided by bond drainage current ($R_{2,2}$ $R_{3,2}$ $R_{4,2}$).



$$\% \text{ Interference Current} = \frac{R_{3,1}}{R_{3,2}} \times 100$$

$$\text{or } I_2 = \frac{R_{3,1} I_1}{R_{3,2}} = \frac{E_2 + V_2}{R_b + R_{2,2}}$$

$$R_b = \frac{(E_2 + V_2) I_2}{I_1} - R_{2,2}$$

$$= \frac{R_{3,2} (E_2 + V_2) - R_{2,2} I_1}{R_{3,1} I_1}$$

Figure 7
INTERFERENCE BOND PROBLEM SOLUTION

The interference effect of the rectifier equals $R_{3,1}$ at critical point "3". The protective effect of the bond equals $R_{3,2}I_2$. When these quantities are equal, the interference effect is overcome. Therefore, the bond current I_2 is found:

$$I_2 = \frac{R_{3,1}}{R_{3,2}} I_1$$

The potential difference between the two structures is the combined effect of rectifier and bond installations ($R_{2,1}I_1 = V_2$) plus the galvanic potential (E_2). Circuit resistance equals the internal resistance ($R_{2,2}$) plus bond resistance (R_b). These relationships provide another expression of bond current:

$$I_2 = \frac{E_2 + V_2}{R_b + R_{2,2}}$$

Rearranging for bond resistance, we find:

$$R_b = \frac{E_2 + V_2}{I_2} - R_{2,2} = \frac{R_{3,2} (E_2 + V_2)}{R_{3,1} I_1} - R_{2,2}$$

This value (R_b) is the bond resistance in terms of measured quantities.

3.2 High Current Density. For effective cathodic protection, sufficient current must flow onto the corroding surface to make it entirely cathodic. If too little current reaches the surface, it may still corrode. However, too much current per unit area (current density) can also be harmful. Extremely high current densities reportedly may produce hydrogen embrittlement of steel by causing absorption of atomic hydrogen, although this phenomenon is not observed in the field.

Hydrogen produced by high current density at the cathode might also damage coatings. Above certain voltage characteristic of the specific metal, hydrogen bubbles form. These can exert great pressure at coating defects producing coating disbonding. For steel, this voltage is about 1.2 volts negative, relative to copper-copper sulfate. Disbonding is normally a problem only with thin or poor quality coatings or severe environments.

Reactions at the cathode produce alkalinity here. Alkaline material corrodes amphoteric metals such as lead or aluminum. For these metals, too much "protective" current is actually destructive. No voltage in excess of 1.20 volts negative (relative to copper-copper sulfate) should be impressed on aluminum or lead structures.

In addition, careful testing should be made before installing cathodic protection on amphoteric metals in environments of natural pH above 8.0.

3.3 Electrolyte pH. Extreme electrolyte acidity (low pH) or alkalinity (high pH) can adversely affect a cathodic protection system. As noted in paragraph 3.1, alkaline material corrodes amphoteric metals such as lead or aluminum. Alkaline soils or other environments such as concrete will corrode amphoteric metals and cathodic protection will not stop this. In fact, because cathode reactions produce alkaline material, cathodic protection may increase corrosion in this situation. Therefore, in cathodic protection of amphoteric metals, environment pH should be considered. If possible, amphoterics should not be installed in alkaline environments (pH greater than 8) without prior testing.

Highly acidic environments are not conducive to cathodic protection, for a different reason. When cathodic protection is applied to a structure, the structure polarizes. Once polarized, the structure requires lower current for adequate protection. This is a basic part of cathodic protection, greatly reducing operating costs. In acid environments, polarization is difficult or impossible to achieve. Consequently, cathodic protection in acid environments may be difficult or costly.

Another problem in acid environments is corrosion of cement and concrete. Because these materials are alkaline, they may rapidly deteriorate when placed in acid areas.

In general, with either extreme acidity or alkalinity, special tests should be run to determine if cathodic protection will be effective.

3.4 Safety. Provisions should be made during design for possible operation safety hazards. Danger to personnel and environment should be considered and corrective measures taken.

3.4.1 Environmental Concerns (Explosions). In areas designated by electrical and general safety codes, special oil-immersed explosion-proof rectifiers should be used. Fittings should be installed in explosion-proof housings. Such locations include refineries, fuel terminals and fueling areas, manholes (sewer gas), ammunition depots, and wherever else flammable liquids or explosive gases may possibly exist. Special precautions should be taken where dynamite is used. To minimize danger of current flow from cathodic protection reaching detonator caps, cathodic protection systems should be turned off when dynamite is being used. It may also be desirable to turn off cathodic protection during loading or unloading of flammables from planes, trucks, or ships.

3.4.2 Bonding. Bonding for corrosion control purposes may be found in Volume I, TR-74-6. Bonding may also be needed for safety where ships, airplanes, or trucks are loaded or unloaded. This is good practice even if no cathodic protection is being used on a fueling system, because of danger from static or stray current voltages. A voltage gradient through soil or water may result in a difference in potential between vehicle and refueling system. This can produce sparks, causing explosions. A temporary bond providing good electrical contact between vehicle and refueling station will prevent this. Care must be taken to assure good contact and bond integrity.

Bonding is also used for safety during repairs of underground pipelines. Where stray or cathodic protection currents flow on a pipe containing volatile oils or gases, sparking can result in fires and explosions when the pipe is cut. A temporary bond across the cut provides an alternate path for current, preventing sparking. Where cathodic protection causes the only voltage difference, turning off the rectifier during repairs will also prevent sparking.

3.4.3 Induced Alternating Current. Alternating current can be induced on well-coated, underground structures located below overhead electrical transmission lines. A structure in such an electrical field acts as an induction coil to produce AC voltage across the coating. Besides producing possible corrosion to the structure, this induced AC may be a safety hazard to the corrosion engineer or anyone who may come in contact with the structure. Therefore, when designing cathodic protection or other corrosion control for well-coated, underground structures, location of overhead electrical transmission lines in the area should be noted. Location of test stations in areas where induced AC may exist should be avoided. Overhead electrical transmission lines should also be a consideration during testing.

4 IMPRESSED CURRENT SYSTEMS. Impressed current cathodic protection systems are always made up of three major components, in addition to the protected structure and electrolyte:

1. Direct current power source
2. Anodes (connected to positive of DC power source)
3. Connecting cables

4.1 Power Sources. The direct current power source will be one of the following:

- * Rectifier (adjustable transformer-rectifier unit)
- Thermoelectric generator
- Battery
- Generator - driven by engine, wind, or fluid turbine
- Direct current - from power used mainly by other equipment
- Solar cell
- * Most commonly used

4.1.1 Rectifier. Rectifiers are by far the most commonly used power source for impressed current cathodic protection. Standard units, constructed for cathodic protection, consist of an adjustable step-down transformer, rectifier stacks, meters, circuit breakers, and transformer tap connections all within one case. The rectifier converts alternating current to direct current for use in cathodic protection systems.

a. Typical Rectifier. A wiring diagram is shown in Figure 8 for a single phase full-wave bridge-type rectifier most commonly used in cathodic protection. This diagram also illustrates the switch recommended as a safety device with most rectifier installations. Elements of this and other rectifiers and optional features of commercially available types are described here.

(1) Transformer. The transformer steps down supply AC voltage to that required for operation of rectifier stacks. Transformer taps are usually included so that output voltage may be adjusted manually. These taps should permit adjustment of rectifier voltage from zero to maximum in even steps of not more than 5 percent rectifier rated voltage.

The transformer consists of an iron core with two electrically separate wire coils wound around it. A.C. supply voltage is applied to one coil ("primary winding") producing a magnetic field in the iron core which induces AC voltage in the second coil ("secondary winding"). The ratio of primary to secondary voltage equals the ratio of primary coil turns to secondary coil turns. Secondary voltage is varied by tapping off some of the turns (coarse and fine adjustment). The easily magnetized core is made of special steel which does not retain magnetism.

(2) Rectifying Elements. Rectifier "stacks" perform the actual conversion from alternating to direct current. The stack itself is an assembly of plates or diodes in various configurations (paragraph 4.1.1.b). These permit current flow in one direction only, producing pulsating DC output containing a "ripple" component of A.C. No rectifier is 100% efficient, and a minimum of 19% of output power is A.C. In addition, there are losses in efficiency because no rectifier diode blocks perfectly reverse current flow. Typical real efficiencies are 60 to 75% for a single phase rectifier. Circuitry (paragraph 4.1.1.b) affects this. Rectifier efficiency is calculated according to the equation:

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

Rectifiers used in cathodic protection are usually selenium-oxide plates or silicon diodes. Silicon exhibits superior

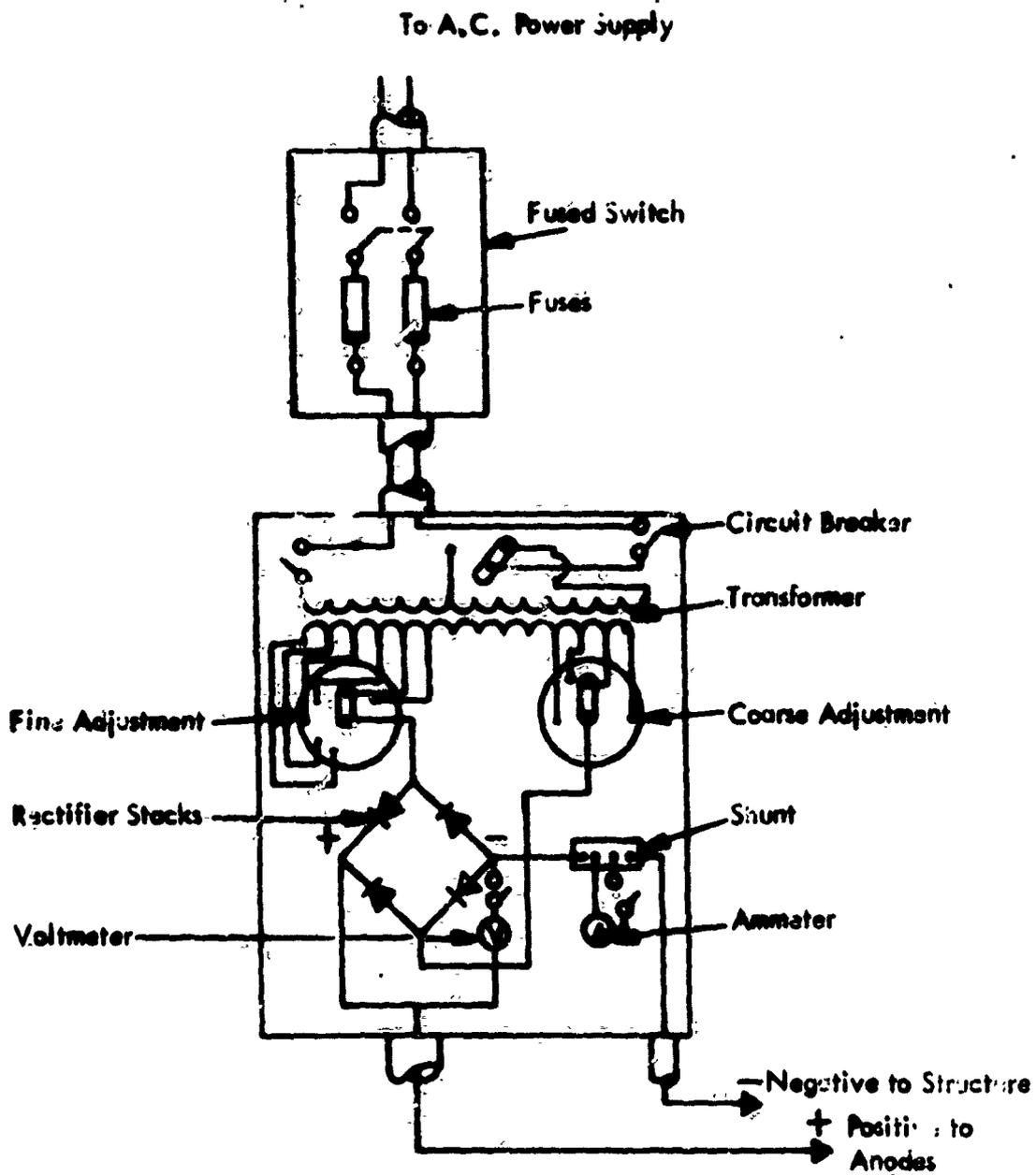


Figure 8
TYPICAL RECTIFIER WIRING DIAGRAM

efficiency and aging characteristics (selenium loses its efficiency as time passes). However, it is prone to power surge failures and will not be dependable, unless combined with a selenium circuit and special protective devices. Silicon and selenium are compared in paragraph 4.1.1.d(7).

(3) Circuit Breakers. Circuit breakers are another basic element of rectifiers. They provide protection from overload and a convenient on-off switch. Thermal, thermal-magnetic and magnetic types are used, although magnetic circuit breakers have found widest acceptance. Circuit breakers are located on each A.C. supply line. Where more than one direct current feeder is used, separate fuses are used in each branch circuit.

In addition, a fused switch should be installed on the A.C. side of the rectifier, for additional protection (Figure 8).

(4) Meters. Cathodic protection rectifiers should contain two direct current instruments to indicate output: a voltmeter and an ammeter. These may be separate circuits or "unimeter" construction (one meter provides both volt and ampere readings). Because they are easily damaged by lightning, these meters are separated (except when being read) from the operating circuit by switches.

Rectifier meters are generally standard D'Arsonval movements type, drawing 50 millivolts at full scale.

b. Rectifying Circuits. Various rectifier wiring arrangements are possible to produce different characteristics. Some of these circuits are:

- Single phase bridge
- Single phase center tap
- Three phase bridge
- Three phase wye

All these*produce full wave rectification. Although at least one special rectifier (paragraph 4.1.1.c(3)) uses half-wave rectification, the full wave type is most often used and generally considered most effective. The pulsating nature of half-wave rectification is likely to produce noise on communication lines.

In general, three-phase rectifiers are more expensive than single-phase rectifiers of the same size (if both are available in that size). They are, however, more efficient (paragraph 4.1.1.b(3)). A rule of thumb to determine which type is more economical is to consider D.C. output power (watts) (voltage in volts times current in amperes) (reference 18). If power is above 1000 watts, efficiency of the three-phase circuit generally outweighs higher initial cost. Below 1000, the single phase is more economical. Near 1000, both types should be considered and relative costs and efficiencies compared.

(*) The three-phase wye circuit actually produces half-wave rectification, but out of phase so that a.c. ripple and pulsation are minimal.

(1) Single Phase Bridge. Single phase bridge rectifiers are most commonly used in cathodic protection. (This is because they are cheaper and more easily adjusted than center tap units. A diagram of this circuit is shown in Figure 9b. It contains four cells. (If any one of these fails, or changes resistance, the other three fail.) Current always passes through two rectifying elements. One, on its way to the load, and one, on its return. At any time, two diodes are conducting current while two are blocking current. The result is full wave D.C. output, one-half of the A.C. wave rectified by each pair of diodes. Because of diode arrangement, current always flows through the load in the same direction (positive (+) to negative (-)) in Figure 9b).

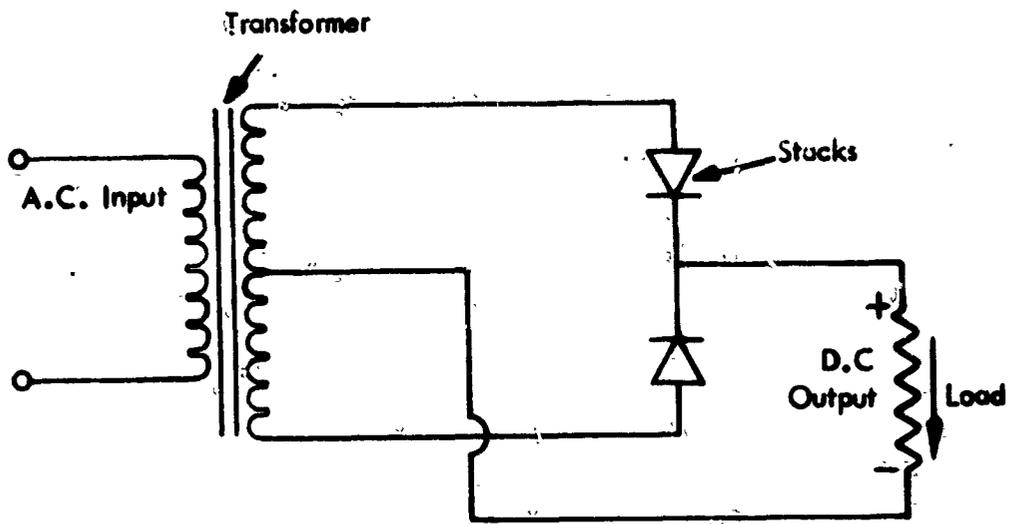
(2) Single Phase Center Tap. This circuit, shown in Figure 9a, contains only two rectifying elements. However, its transformer is heavier and less sensitive to adjustment than bridge units. Full-wave output, as in the bridge circuit, is obtained. However, only half the transformer output is applied to the load, as seen in the diagram. This type is more efficient than bridge wired units. However, it is also more expensive, physically heavier, and more bulky.

(3) Three Phase Bridge. The three-phase bridge rectifier, diagramed in Figure 10b, operates like three single phase bridges, except each bridge shares a pair of diodes with one other bridge. There are three transformers producing secondary voltages which reach their peaks at different times. This "out-of-phase" operation produces D.C. output with less A.C. ripple - only 4.5%.

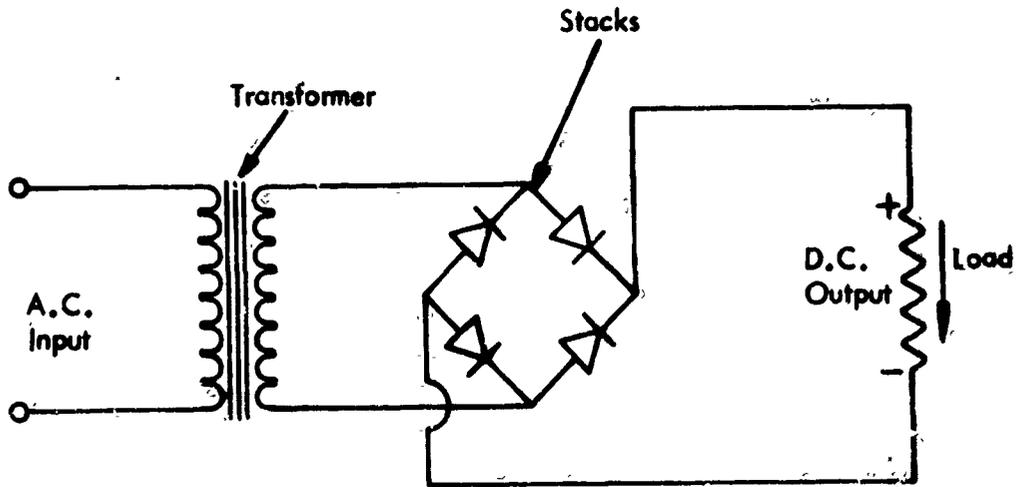
(4) Three-Phase Wye. This circuit, shown in Figure 10a, produces only half-wave rectification. The three-phase Wye contains only three diodes, each connected to a transformer. The three transformers produce A.C. voltage out-of-phase with each other. This type rectifier is practical only for low D.C. voltages.

c. Special Rectifier Types. Rectifiers have been developed with special characteristics, differing from standard circuits. Some are monitored to maintain constant structure-to-electrolyte potential or constant current output. These and other special units are discussed here.

(1) Constant Current Rectifier. A constant current rectifier uses automatic control to maintain constant direct current output over varying load resistance. This is generally achieved with a power amplifier-type device called a saturable reactor. A saturable reactor usually uses three separate windings on an iron core. The two outside or gate windings are connected to the transformer A.C. output. The inside or control winding is connected to a D.C. supply within the rectifier. When D.C. is supplied to the control winding, it saturates the iron core with magnetic flux to a degree proportional to the amount of D.C. This lowers gate impedance, in effect removing part of the core from the

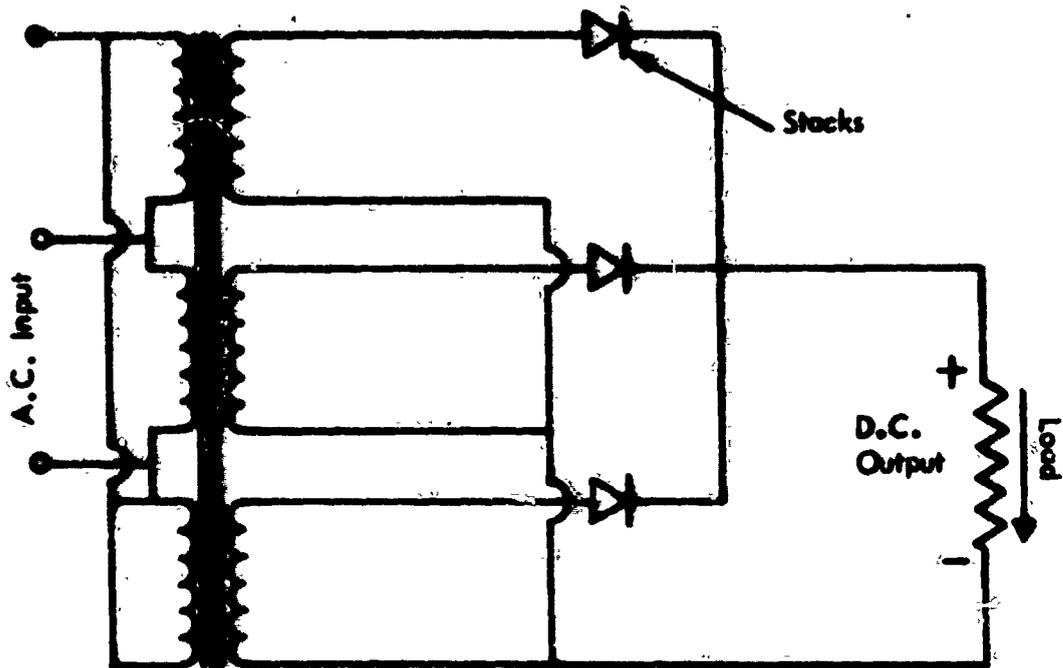


a) SINGLE PHASE CENTER TAP CIRCUIT

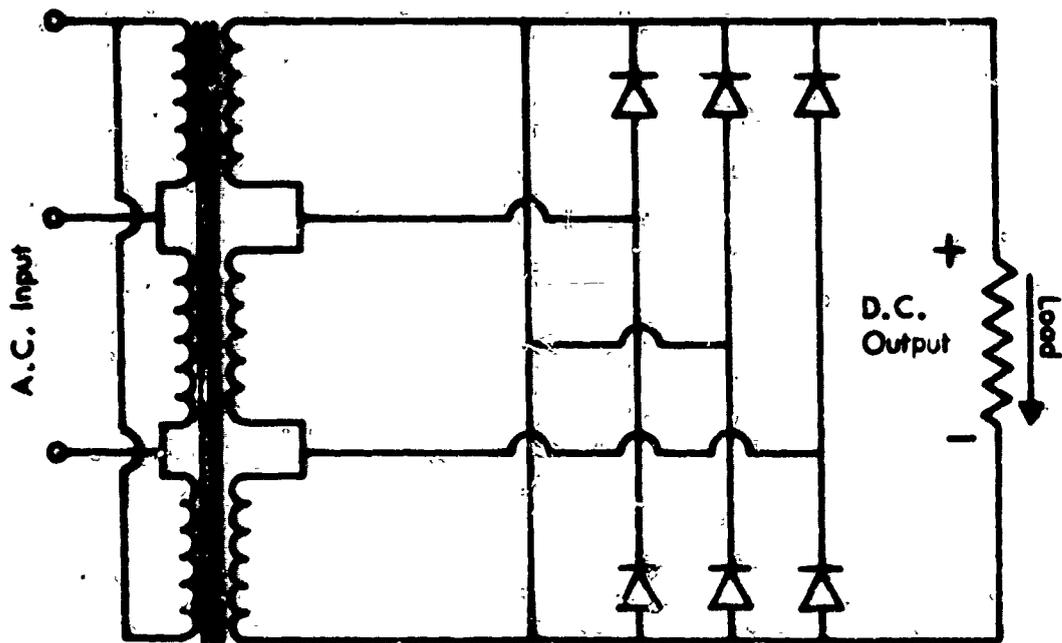


b) SINGLE PHASE BRIDGE CIRCUIT

Figure 9
SINGLE PHASE RECTIFIER CIRCUITS



a) THREE PHASE WYE (HALF-WAVE) CIRCUIT



b) THREE PHASE BRIDGE (FULL-WAVE) CIRCUIT

Figure 10
THREE PHASE RECTIFIER CIRCUITS

circuit and lowering resistance to current flow through the gates. A small deviation in D.C. input power can result in a large change in A.C. output power. Figure 11 shows a schematic of a constant current rectifier.

(2) Automatic Potential Control Rectifier. An automatic potential control rectifier uses a reference electrode installed near the structure and a saturable reactor or silicon controlled reactors (SCR) to maintain constant structure-to-electrolyte voltage. This voltage difference is the input to a control circuit which compares actual voltage with the pre-set desired voltage. The controller then varies rectifier output through SCR's or saturable reactor, if necessary (Figure 12).

Typical reference electrodes include zinc anodes, copper-copper sulfate electrodes, silver-silver-chloride electrodes, or stainless steel ground rods. These are located near the protected structure, but out of areas of high IR drop around anodes.

A saturable reactor is described in paragraph 4.1.1.c(1). Silicon controlled rectifiers are similar to silicon diodes in that they allow current flow in only one direction. They contain a third connection (gate). In order for any current to flow through the SCR, a positive voltage pulse must be applied to this gate. Current then flows for the remainder of the A.C. half-cycle. The amount of SCR output current depends on where in the half-cycle the pulse is applied. The control circuit, acted upon by reference voltage input, determines this.

SCR's may make up a portion of the rectifier stacks, or they may be a separate control varying, for example, transformer or stack output. SCR's require surge protectors and, like other silicon diodes, mounting on heat sinks.

Automatic potential control rectifiers are used for cathodic protection mainly where electrolyte resistivity varies widely with time. Typical applications include protection on ship hulls, on power-station traveling gates, or inside water storage tanks.

(3) Multi-Circuit, Constant Current Rectifier. This special, patented rectifier (Figure 13) contains separate circuits for energizing up to eight or twelve impressed current anodes, for use in protecting underground tanks, etc. These are relatively inexpensive and simple to install. Each anode is connected to a rectifying module containing a silicon diode and a resistor (400 to 500 ohms, approximate). The modules are mounted in a case and connected, through ammeter, fuse and switch, directly to the 110 volts A.C. line. This power is used directly; no step-down transformer is included. The rectifier negative is connected to the A.C. neutral, which is "grounded" to protected

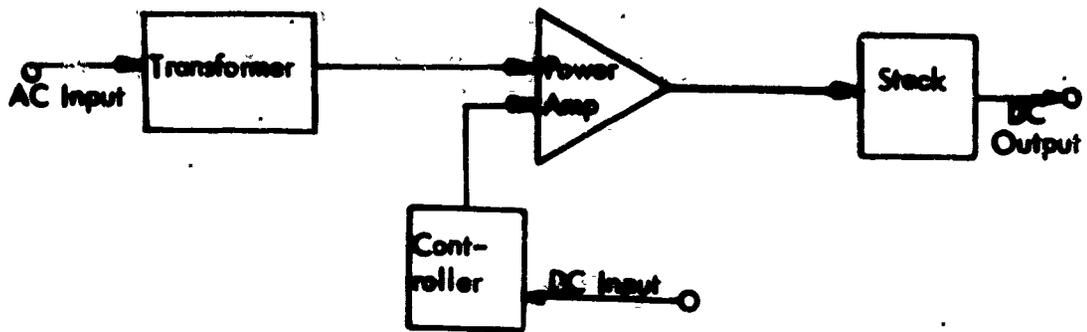


Figure 11
CONSTANT CURRENT RECTIFIER

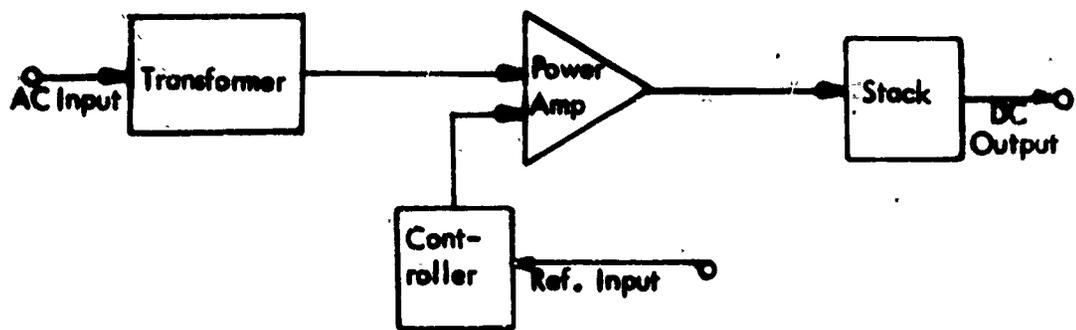


Figure 12
AUTOMATIC POTENTIAL CONTROL RECTIFIER

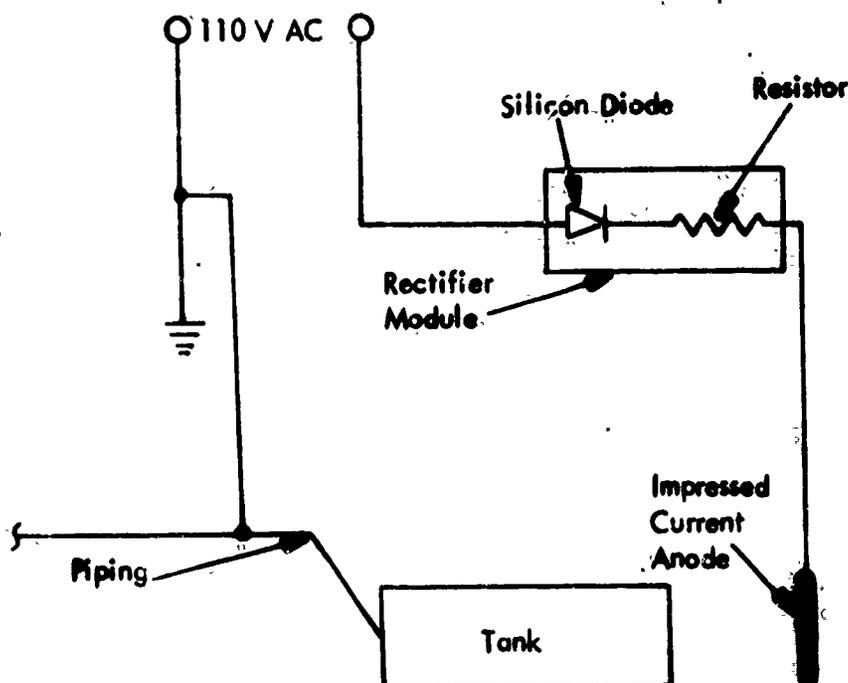


Figure 13
SIMPLIFIED DIAGRAM FOR MULTI-CIRCUIT
CONSTANT CURRENT RECTIFIER INSTALLATION

piping and tanks, etc. This ground must be checked prior to installation to assure connection.

The system is designed to deliver near constant current (100 milliamperes $\pm 10\%$) from each anode. Each module resistor controls current output because its value is large compared to other circuit resistance. A lamp is used in some models instead of a resistor. The system is quite simple, but problems can arise. Only one diode is used in each circuit, producing half-wave rectification. The pulsating current thus produced can cause noise problems on nearby communication lines. In addition, although small currents (comparable to those produced by galvanic anodes) are used by this system, the possibility of stray currents still exists. The 110 volt A.C. power is used directly, without a transformer, and current may pick up on structures other than the one to be protected and travel back to the power company's A.C. transformer several blocks away.

(4) Other Rectifiers. Standardized rectifiers have been developed for use mainly in gas and electric distribution. These combine attractive appearance with economy in a standard unit. Some may be buried or mounted on-trail.

Rectifiers are available containing several individual single phase bridge circuits in one unit. These produce a wide range of current and voltage outputs, depending on whether series or parallel circuits are employed. In some models, stacks may be added to increase current output.

d. **Commercially Available Types.** A number of manufacturers stock standard sized cathodic protection rectifiers, offer many optional "extra" features, and will build most special units to order. Features now available include:

Constant D.C. voltage or current output

Multiple circuits

Air cooled or oil immersed

All A.C. voltage inputs, three-phase or single phase

Center tap or bridge circuits

Variety of combinations of D.C. voltage and current output

Efficiency filters to minimize A.C. ripple

Interference noise filters

Explosion-proof

Small-arms proof

Lightning and surge protection (A.C. and D.C. cases)

Silicon diodes or selenium stacks

Painted or galvanized cases

Mounting legs or brackets

Direct burial

External "on-off" indicators

Variety in price and quality

(1) **Air Cooled or Oil Immersed.** Rectifiers are available as air-cooled, oil-immersed stack units and totally oil-immersed units. Most units are air-cooled, but oil-immersed rectifiers should be specified for corrosive, dirty, or explosive atmospheres. Air-cooled units have a lower initial cost, and are easier to install and repair. They are, however, subject to poor ventilation due to fouling of air screens by dust and dirt and stacks corrosion, which can produce loss in efficiency or complete failure of stacks from overheating. Oil-immersed rectifiers are completely enclosed and easily kept free of dust, dirt, and insects; they are essential in hazardous locations. In general, air-cooled units should be specified except where danger of explosions, high-ambient temperatures, corrosive atmospheres, or high humidity conditions exist, and in windy or dusty locations.

(2) **All A.C. Voltages, Three-Phase or Single Phase.** Choice between three-phase or single-phase rectifiers was discussed in paragraph 4.1.1.b. The bridge circuits are generally chosen because of higher efficiency and greater output ranges. Center-tap circuits are practical only for low D.C. voltages.

Rectifiers are available with all A.C. voltages used in industry. Input voltage has no effect on rectifier efficiency, but it may affect installation and operating costs. Rectifiers are built which can operate on two different A.C. inputs, such as 115 and 230 volts. If existing power lines are to be used, they must be compatible with rectifier input voltage.

Where a choice is available, Table 1 can be used to determine the most economical choice, in terms of installation and operation.

Table 1

Economical A.C. Supply Voltages (Reference 18)

<u>Rectifier D.C. Rating</u> (watts = volts x amps)	<u>Single-Phase Input</u> (volts A.C.)	<u>Three-Phase Input</u> (volts A.C.)
Up to 2700	115	208
2700 to 5400	230	230
Over 5400	440	230
Over 7500	440	440

(3) D.C. Voltage and Current Output. Cathodic protection rectifiers are commercially available in a wide range of direct current outputs. Direct current voltages from 12 volts to 120 volts and direct current amperage from 4 amperes to 200 amperes are common. Almost any direct current rating can be supplied, but from an economic standpoint it is generally best to consult a manufacturer's catalog and select a standard size.

(4) Filters. Filters increase A.C. to D.C. conversion efficiency and minimize noise interference for communications lines by reducing A.C. ripple in rectifier output. The D.C. output power level remains essentially the same, while A.C. input power is decreased. Such a filter can increase the efficiency of a single-phase rectifier 10 to 14%. Because three-phase rectifiers are more efficient to begin with, an efficiency filter will generally not increase their efficiency appreciably. For single-phase rectifiers, efficiency filters can save money on operating expenses and often pay for themselves in a very short time.

Noise interference filters are used to reduce interference in telephone and other communication equipment. Generally, these filters also appreciably reduce A.C. ripple in single-phase rectifiers.

(5) Explosion-Proof. In hazardous areas such as refineries and chemical plants, special explosion-proof rectifiers should be used. These are special oil-immersed with meters and circuit breakers in explosion-proof housings.

Such rectifiers conform to Safety Standards for Class I Group D hazardous locations.

(6) Lightning Arrestors. Lightning arrestors on input and/or output are frequently specified option. They are standard on many rectifiers containing silicon diodes because of potential destruction from surges. These arrestors prevent damage to rectifier and other circuit components in lightning areas by conducting the high current until it subsides. Lightning arrestors may be of several types including arc-gap, or rare gas.

(7) Selenium Stacks or Silicon Diodes. Rectifying elements are made from semiconductor crystals into which other elements ("impurities") have diffused. Diffusion is controlled so that the resulting crystal has increased resistance to current flow in one direction and decreased resistance in the other.

Semiconductors used for stacks in cathodic protection rectifiers are generally either selenium or silicon. Germanium rectifiers have found little use in the cathodic protection field. Early rectifiers used only copper oxide stacks, but these were replaced by the more efficient selenium stacks. Some old installations may still contain copper oxide rectifying elements.

Selenium rectifiers are used where efficiency is not a major consideration (for small power demands or where dependability is most important). Silicon rectifiers are used for larger installations because their greater efficiency can save on operating costs; they are, however, less dependable.

(a) Selenium Stacks. Selenium stacks consist of nickel-plated aluminum base plates coated on one side with several layers of selenium crystals. Selenium and desired impurities are vaporized and then deposited on the plates. A thin layer of metal, called the counter-electrode, covers the selenium surface, acting as a current collector. In some cells, an artificial barrier layer made of lacquer is included between the selenium and counter-electrode to increase reverse resistance. However, this material decreases efficiency and stack life, gradually deteriorating or "aging" from operational heat. Aging is accelerated by high forward current and high operating temperatures. Cells not containing this barrier layer age much more slowly, and therefore are sometimes called non-aging selenium. Selenium rectifiers may contain a number of stacks in series or parallel for increased current or voltage capacity.

Selenium plate life is determined almost entirely by plate operating temperature. Operating temperature is determined by amount of heat dissipation and amount of current delivered through the stack. The more current in the forward direction, the more power lost in the stack, and therefore

the more heating of the plate. Also, heating is produced by reverse current leakage. Therefore, the more voltage applied to a stack, the more heating from reverse current.

Heating produces higher operating temperatures and "aging". Aging increases resistance to forward current flow. Power loss for a given amount of current may increase to a point where conversion efficiency is too low for practical operation. The aging effect is somewhat predictable and can be determined by measuring forward voltage drop and reverse current of the unit (reference 18).

High current density and high temperatures will accelerate aging of selenium stacks. Temperature is the more destructive. If selenium stack temperature is kept moderate, high current densities produce little aging acceleration. On the other hand, if the temperature of the selenium plate rises excessively, even with very low current density, aging is accelerated greatly.

Extreme temperatures are generally produced by uneven stack heating, caused by a loose connection or damaged plate or by voltage surges. If a voltage surge is large enough, the stacks will be completely burned out, requiring replacement. Possibly the surge could damage only one stack in a unit. For instance, a bridge type rectifier containing four stacks has two pairs in a bridge, and a fault in one stack would limit the one path, forcing all the current to be carried in the other path. If this condition continues with two stacks carrying all the load, accelerated aging and early failure of the unit would result.

(b) Silicon Diodes. A silicon diode is made from a single crystal of silicon, into which impurities have diffused. A section of the crystal is sliced off and enclosed in a metal case which is then mounted on a copper or aluminum plate. This plate dissipates heat built up during normal operation.

Because a silicon diode is made from a single crystal, it does not age or fail gradually like selenium. This is a definite advantage over selenium. However, voltage surges or overload currents will cause a single crystal diode like silicon to fail completely whereas such conditions would only age a selenium stack. Protection, such as quick action fuses, voltage clamping devices, combination silicon-selenium circuits, and lightning arrestors can minimize the possibility of silicon diode failure.

Silicon rectifiers show increased efficiency of up to 10 percent over selenium on higher voltage ratings. Curves showing operating voltages versus stack efficiency for single and three-phase, full wave, bridge type rectifiers are shown in Figure 14 for selenium and Figure 15 for silicon.

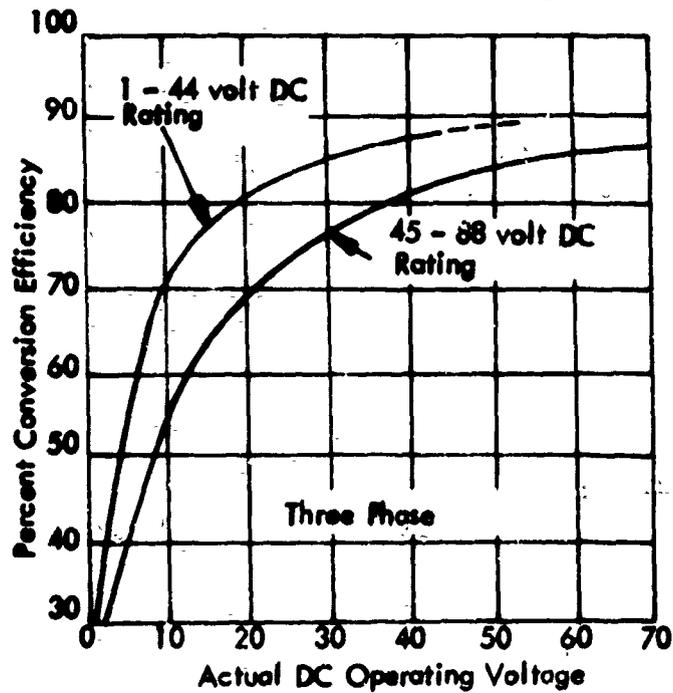
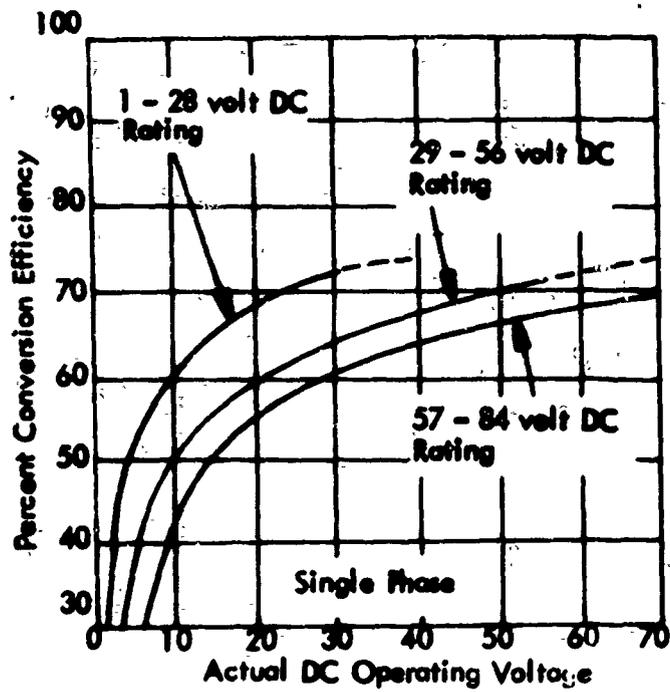


Figure 14
 EFFICIENCY VS. OPERATING VOLTAGE
 FOR FULL WAVE SELENIUM RECTIFIER

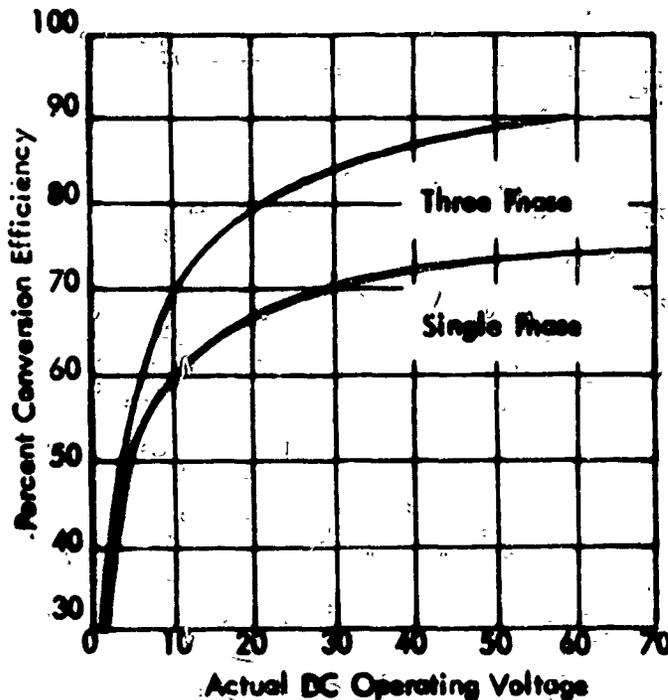


Figure 15

EFFICIENCY VS. OPERATING VOLTAGE FOR FULL WAVE SILICON RECTIFIERS

(8) Other Options. Numerous options, besides those already discussed, are available. Such things as special cabinets (explosion-proof, small arms proof, direct burial, special finishes), signal lights, or continuous-reading meters may be specified. In addition, virtually any other features may be included at added cost. Manufacturer's catalogs should be consulted for information on specific options.

4.1.2 Thermoelectric Generator. Thermoelectric generators can be considered where power is not available and current requirements are small. Heat is converted directly into electrical power. This is accomplished through a group of thermocouples arranged electrically in series and thermally in parallel (a thermopile). One end is heated by the burning fuel; the other is cooled by fins. Heat flux results from the temperature gradient in the thermopile, and electricity is produced through the thermocouples. Thermoelectric generators are presently available in sizes from 5 watts through approximately 500 watts. Their price is prohibitive for many applications. In order to achieve desired current output, they may be arranged in series, parallel, or combination setups. They are sometimes installed at isolated

locations along pipeline rights-of-way and powered by fuel from the line.

4.1.3 Battery. Batteries, like thermoelectric generators, may be used where power is not available and current requirements are small: a well-coated structure in a remote area, for example. Unlike thermo-electric generators, batteries require frequent replacement or recharging.

4.1.4 Other Sources. Other direct current sources are sometimes used, especially where no power exists. Engine-driven generators are one type. Wind-driven generators were used in the early days of cathodic protection before rectifiers were commonly available; some of these units are still operating. An experimental fluid and/or gas turbine has been developed for use in gas pipeline transmission to provide protection for a major water course crossing.

Solar cell-storage battery units are another experimental power source. These units contain solar panels which collect heat from sunlight and generate electricity during the day. At night, the storage battery supplies power.

Finally, where direct current is supplied for other electrical equipment, such as aboard ships, sometimes it is convenient and economical to use it also for cathodic protection.

4.2 Anodes. Impressed current anodes must be made of material with a deterioration rate (weight loss per unit of current emitted) that will provide reasonable anode life from a practical amount of material. These anodes must also be rugged enough to survive practical application in a variety of electrolyte environments, while being commercially available at reasonable cost.

A variety of materials can be used as anodes in impressed current cathodic protection systems. Scrap iron or steel might be employed. This can be in the form of junked engine blocks, rails, pipes, etc. Abandoned and "in-place" pipelines or rails are sometimes the most practical and economical anode for special situations. They are, however, consumed at about 20 lb./amp-yr. Important materials for impressed current anodes are discussed here. In addition to bare anodes, anodes packaged in selected backfill are also available.

4.2.1 Graphite. Graphite anodes are made by fusing coke or carbon particles at very high temperatures. This increases resistance to oxidation.

a. Specifications. Typical specifications for graphite anodes are given here.

<u>Chemical Properties</u>	<u>Percent by Weight</u>
Impregnant	6.5 max.
Ash	1.5 max.
Moisture and volatile matter	0.5 max.
Water soluble content	1.0 max.
<u>Physical Properties</u>	<u>Value</u>
Density	99.84 lb. per cu.ft. max.
Resistivity	11.00 x 10 ⁻⁴ ohm-cm. max.

The cable connection to the anode must be able to withstand a pull of 325 pounds.

b. Sizes Available.

<u>Weight, lb.</u>	<u>Size</u>	<u>Surface Area sq.ft.</u>
25 Graphite	3-in.dia. x 60 in.long	4.0
27 NA Graphite	3-in.dia. x 60 in.long	4.0
63 Graphite	4-in.dia. x 80 in.long	7.1
68 NA Graphite	4-in.dia. x 80 in.long	7.1

Graphite anodes are generally simple cylinders with the lead end impregnated with paraffin for a foot or so to minimize the possibility of moisture contacting the lead wire. The lead wire is not installed by the anode manufacturer, but by the distributor. One method of lead wire installation is indicated in Figure 16. Type NA graphite used in seawater applications is impregnated with linseed oil in a vacuum-pressure process to eliminate pores.

c. Characteristics. In graphite anode manufacture, petroleum coke crushed to less than 200-mesh size is mixed with coal-tar pitch. The coal-tar pitch serves as a binder to hold the coke together until processing to graphite is complete. The coke is converted into graphite in an electric resistance furnace at 2800°C. Any pitch not driven off is also converted into graphite so that the rod is essentially all graphite except for impurities equal to 1.5 percent maximum. However, the anode has a porosity ranging from 20 to 30 percent. Linseed oil is used to impregnate the anode to reduce porosity and prevent absorption of water. This is especially important in seawater anodes as chlorine produced by the anode will be formed internally leading to disintegration of the anode. Anode failure in this case is mechanical and not due to selective attack of the binder as such. In fresh water, the nascent oxygen formed reacts with graphite to form carbon dioxide.

All corrosion products from graphite anodes are gases. Oxygen, chlorine, and carbon dioxide are produced at the anode surface. In fresh water or soil, carbon dioxide and oxygen are produced. In seawater, the main gas formed is chlorine with lesser amounts of oxygen and carbon dioxide. If the gases formed do not diffuse away from the anode through the

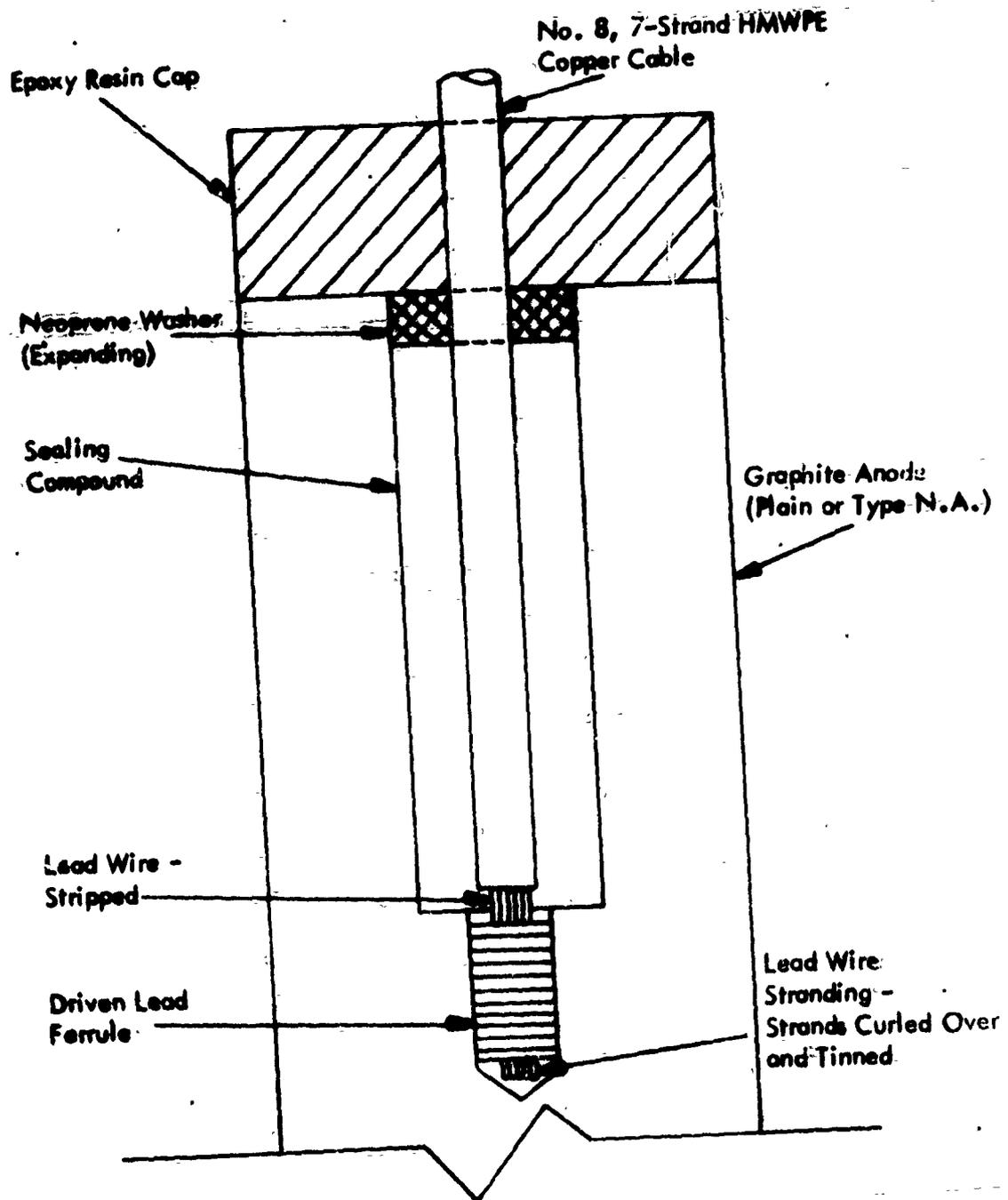


Figure 10
 TYPICAL GRAPHITE ANODE LEAD CONNECTION

electrolyte, the gases will displace moisture or water in the anode vicinity, effectively insulating the anode from the surrounding media. Anode resistance then becomes very large and remains at a high value as long as the anode is operated.

Because graphite anodes do not produce an anodic film during operation, any portion of the anode in contact with low resistivity media deteriorates more rapidly than the remainder. After the anode has been consumed in the low-resistivity section, it is, for all intents, inoperative, due to high resistance caused by shorter length and higher resistance between anode and media. Graphite anodes are therefore very sensitive to nonuniform environment.

When the top of the anode is in contact with low-resistivity media, the entire anode may be lost in a short time from selective corrosion. This type selective attack, commonly referred to as "necking", occurs near the electrical connection to the anode, severing the lower portion of the anode. This may be corrected through use of carbonaceous backfill around the anode.

d. Operation. Graphite anodes should not be operated at current densities exceeding 1 ampere per square foot in soils and 0.25 ampere per square foot in fresh water. At current densities not exceeding these limits, the average deterioration rate will be about 2.5 pounds per ampere-year. If higher current densities are used, the anode tends to become less electrically conductive. Reduction in conductivity is due to attack along crystal boundaries which separates the graphite into individual crystals, softening the anode. Under these conditions, the anode quickly loses conductivity causing cathodic protection to become inoperative in as little as one or two years.

Graphite anodes should not be operated at current densities exceeding 3.75 amperes per square foot in seawater. At current densities not exceeding this limit, the average deterioration rate varies from 1.6 to 2.5 pounds per ampere-year. Deterioration of 2.5 pounds per ampere-year corresponds to a current density of 1.0 ampere per square foot or less; deterioration of 1.6 pound per ampere-year corresponds to a current density of 3.75 amperes per square foot. (Reference 19.)

The potential between steel and graphite in contact with soil or water is 2.0 volts. Thus, a voltage in excess of 2.0 volts must be impressed by the rectifier to cause current to flow from a graphite anode grounded.

4.2.2 High-Silicon Cast Iron. Cast iron containing 14 to 15 percent silicon plus 1 or 2 percent other elements (carbon, manganese, molybdenum) has been used effectively as anode material in the past, in low-chlorine environments.

This material has been used for over 50 years in engineering equipment such as pumps, valves, and special products for the chemical industry. The cast surface is readily and continually oxidized with a thin film of silica (SiO_2), developing a passive surface, which further retards corrosion, decreasing the deterioration rate from approximately 20 lbs./ampere-year to less than 1.0 lbs./ampere-year.

Where gases of the halogen family are generated and in intimate contact with the anode for an extended period of time, however, the film does not prevent attack. Localized corrosion and pitting occur with time. This is particularly applicable to chlorine, which is very aggressive and readily developed during electrolysis of water containing relatively low concentrations of chloride ion.

This observation resulted in the development of a modified high-silicon iron alloy resistant to these aggressive conditions. Nominal compositions are identical except the improved alloy (high-silicon, chromium-bearing cast iron, HSCBCI) contains about 4.5% chromium. This element, along with silicon, forms a more passive and stable film, resistant to chlorine under aggressive conditions. HSCBCI anodes have replaced the silicon alloy for cathodic protection use, and are presently the only ones commercially available.

4.2.3 High-Silicon Chromium-Bearing Cast Iron (HSCBCI). HSCBCI possesses basic properties that are common to all metals. They are dense and homogeneous, assuring uniformity throughout. They cannot absorb moisture and become soft, losing electrical conductivity. Typical composition is given in Table 2.

Table 2

<u>Element</u>	<u>Percent</u>
Silicon	14.35 min.
Chromium	4.50
Carbon	0.95
Manganese	0.75
Iron	Remainder

Table 3 lists some of the more important mechanical and physical properties. HSCBCI anodes have higher strength than nonmetallic anodes; however, their very low elongation makes them subject to fracture from severe mechanical or thermal shock.

Table 3

Mechanical and Physical Properties of HSCBCI Anodes

Tensile Strength (1/2" dia. bar), psi	15,000
Compressive Strength, psi	100,000
Hardness, Brinell	520
Density, gr/ml	7.0
Melting Point, °F	2,300
Specific Resistance, micro-ohms-cms (20°C)	72
Coefficient of expansion, 32° to 212°F	7.33 x 10 ⁻⁶

Because HSCBCI is an iron base alloy, it possesses the good electrical properties common to all metals. (Its specific resistance is 72 micro-ohm-centimeters at 20°C.) In addition, unlike graphite anodes which require several volts impressed at the rectifier to overcome the galvanic potential difference between carbon and steel for any current to flow, HSCBCI anodes produce current when only the slightest voltage is impressed. HSCBCI anodes exhibit superior conductivity and lower back EMF than nonmetallic anodes. Also, very little change in resistance is noted with time, unless the anode is damaged.

a. Standard Anode Shapes and Sizes. Typical standard sizes of HSCBCI anodes are listed in Table 4, along with some general applications. Type M (Figure 17) is generally used for military applications; this anode is available with both ends cored for joining.

Additional "special anodes" - variations of standard sizes and other shapes - are given in Table 5. Type G "duct" anode and Type K "button" anode are shown in Figures 18 and 19. HSCBCI anodes can be produced only as castings. This somewhat restricts their length, but allows considerable flexibility in design. Special anodes for specific problems can frequently be produced, but are generally more costly than standard anodes.

Table 4
Standard Anodes - HSCBCI

Type	Nominal Size	Weight Each Lbs.	Area Sq.Ft.	General Application	Special Features
B	1"x60"	12	1.4	Fresh water tanks.	Each end enlarged to 1-1/2" dia. with cored opening for joining.
C	1-1/2"x60"	25	2.0	Open box coolers requiring lengths greater than 5 ft.	Uniform 1-1/2" dia. with cored opening both ends for joining.
CD	1-1/2"x60"	26	2.0	Groundbed with backfill.	One end only enlarged to 2" dia. with cored opening for cable connection.
CDD	1-1/2"x60"	26	2.0	Groundbed with backfill permits joining in series.	Each end enlarged to 2" dia. with cored opening for cable connection.
D	2"x60"	44	2.6	Groundbed without backfill.	Uniform 2" dia. with cable connections on one end only.
M	2"x60"	60	2.8	Mild saline or deep well without backfill.	Each end enlarged to 3" dia. with cored opening for joining.
J	3"x36"	80	2.5	Severe ground, deep well or seawater without backfill.	One end only enlarged to 5" dia. with cored opening for cable connection.
E	3"x60"	110	4.0	Severe ground, deep well or seawater without backfill.	One end only enlarged to 4" dia. with cored opening for cable connection.
SM	4-1/2"x60"	220	5.5	Seawater with high current discharge per anode.	Uniform 4-1/2" dia. with cored opening each end. Permits two cable connections, if required.

Table .5
Special Anodes - HSCBCI

<u>Type</u>	<u>Nominal Size</u>	<u>Weight Area</u>		<u>General Application</u>	<u>Special Features</u>
		<u>Each Lbs.</u>	<u>Sq. Ft.</u>		
FW	1-1/8"x9"	1	0.2	Elevated fresh water tank.	Lightweight flexible assembly with continuous cable.
FC	1-1/2"x9"	4	0.3	Dist.system in ground trench.	Cored opening each end for joining anodes in series.
G	2"x9"	5	0.4	Underground cables in ducts.	Inside configuration permits single center cable to anode connection.
B-30	1"x30"	7	0.7	Telephone or electrical ground rod.	Cable connection end 1-1/2"dia. (Half of Type B Anode).
C-30	1-1/2"x30"	12-1/2	1.0	Dist.system for more difficult applications.	Cable connection end 1-1/2" dia. (Half of Type C Anode).
CD-30	1-1/2"x30"	13	1.0	Dist.system for more difficult applications.	Cable connection end 2"dia. (Half of Type CDD Anode).
M-30	2"x30"	30	1.3	Dist. system for more aggressive applications.	Cable connection end 3" dia. (Half of Type M Anode).
K-3	3"x3"	6	0.25	Small heat exchangers and like structures with limited mounting area.	"Button" anode with integral cast bolt for attaching to structure using suitable gasket.
K-6	6"x2-1/2"	16	0.5	Ship hull, lock gate, heat exchangers, or any other structure with large flat surface.	"Button" anode with integral cast bolt for attaching to structure using suitable gasket.
K-12	12"x3-7/16"	53	1.0	Ship hull, lock gate, heat exchangers, or any other structure with large flat surface.	"Button" anode with integral cast bolt for attaching to structure using suitable gasket.

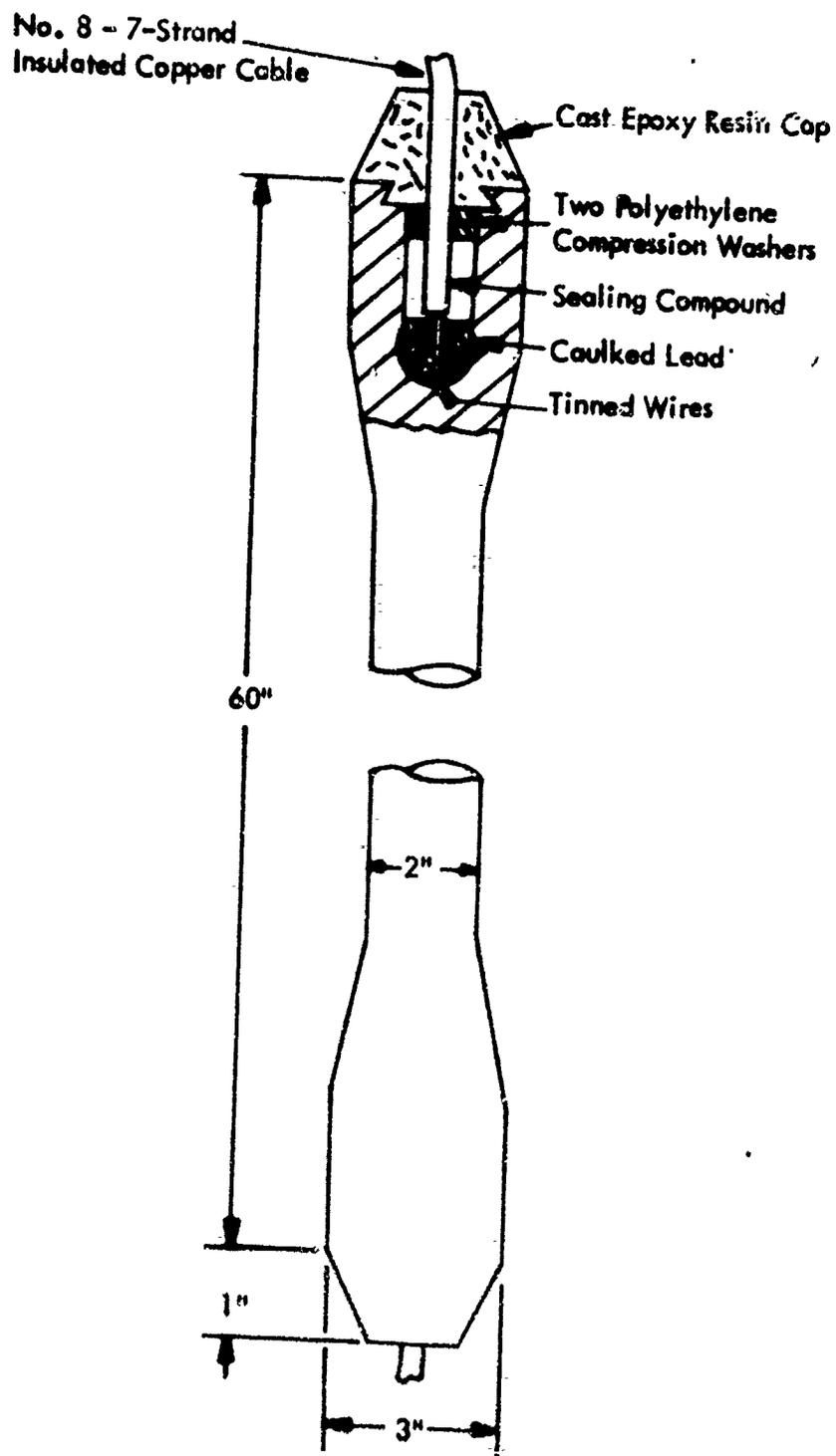
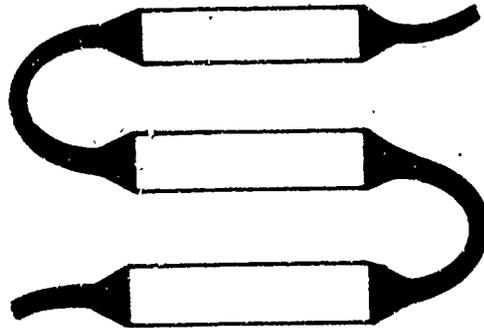
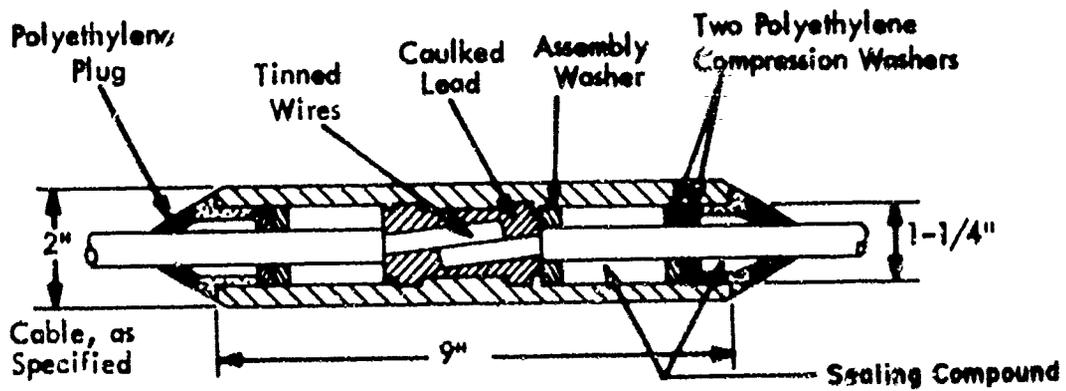


Figure 17
 HSCBCI TYPE "M" IMPRESSED CURRENT ANODE



a) FLEXIBLE DUCT ANODE ASSEMBLY



b) CROSS-SECTION OF TYPICAL DUCT ANODE

Figure 18
TYPICAL DUCT ANODE

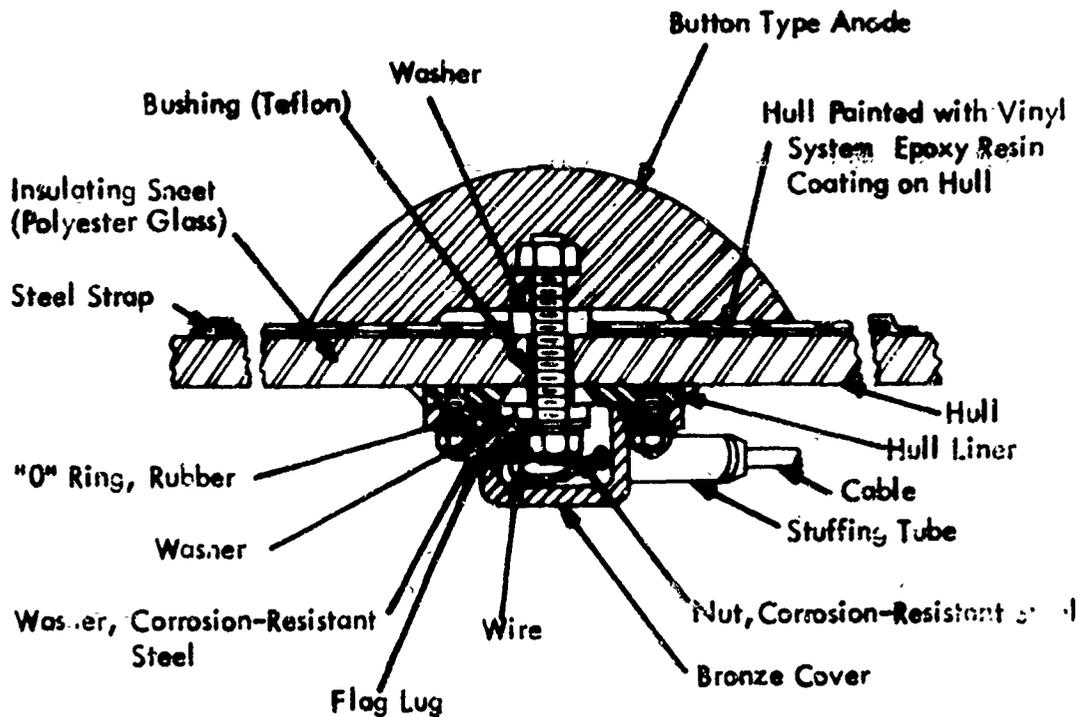


Figure 19
BUTTON TYPE ANODE

b. Electrical Connections. Because HSCDCI anodes are extremely hard and not easily drilled, the electrical connection is made using special techniques. Maximum acceptable resistance between cable and anode should be 0.01 ohms. High molecular weight polyethylene (HMWPE) insulated copper cable is fitted into a cored hole in the anode end. This hole, enlarged at the internal end, is partially filled with lead to secure the cable, and then carefully sealed to exclude moisture. An epoxy cap, 1-inch high minimum, covers the top (Figure 17 and Figure 20 show additional Teflon PEP seal).

It is desirable and has become more common practice to supplement the above moisture seal with an external epoxy encapsulation (Figure 21). When properly applied, this feature will preclude a current discharge and rounding of the anode end. (Leaking occurs here, as with graphite anodes.) This is mandatory for inaccessible locations such as deep groundbeds, aggressive applications involving salt water and/or temperatures above ambient.

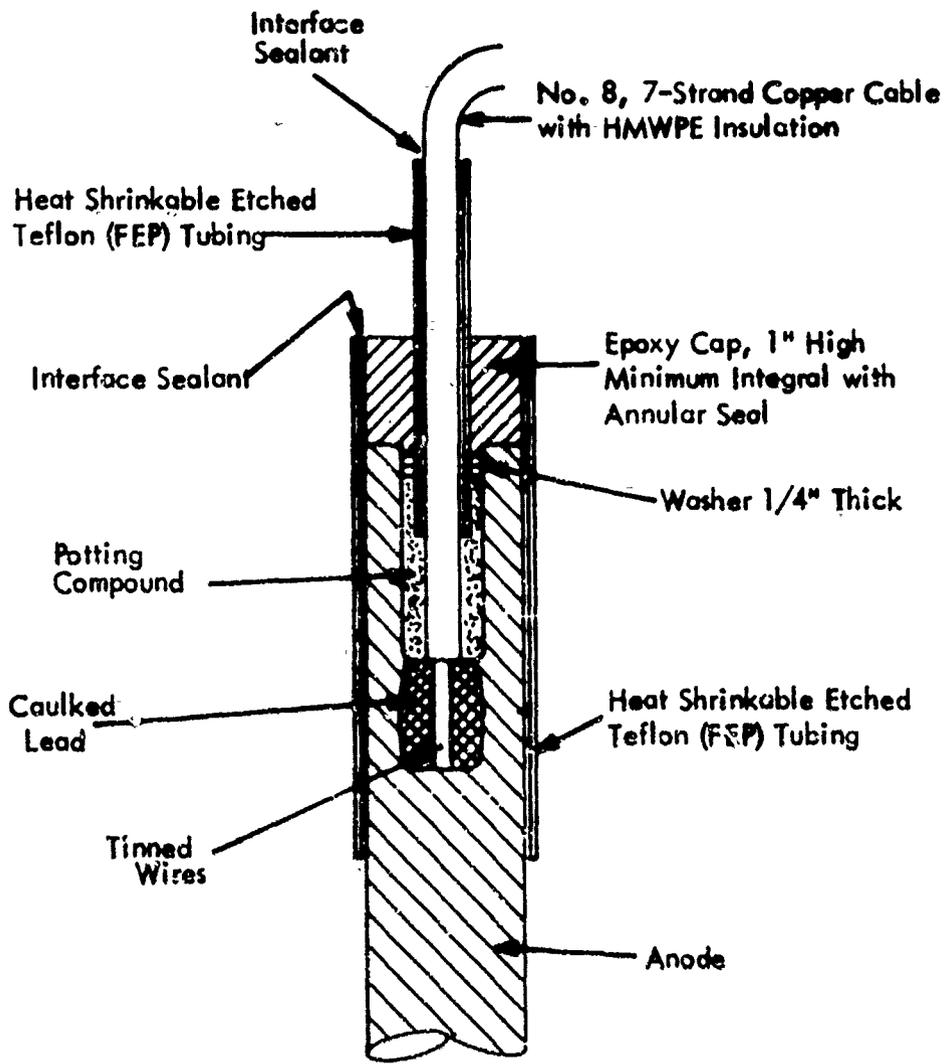


Figure 20
 ANODE-TO-CABLE CONNECTION - TEFLON SEAL

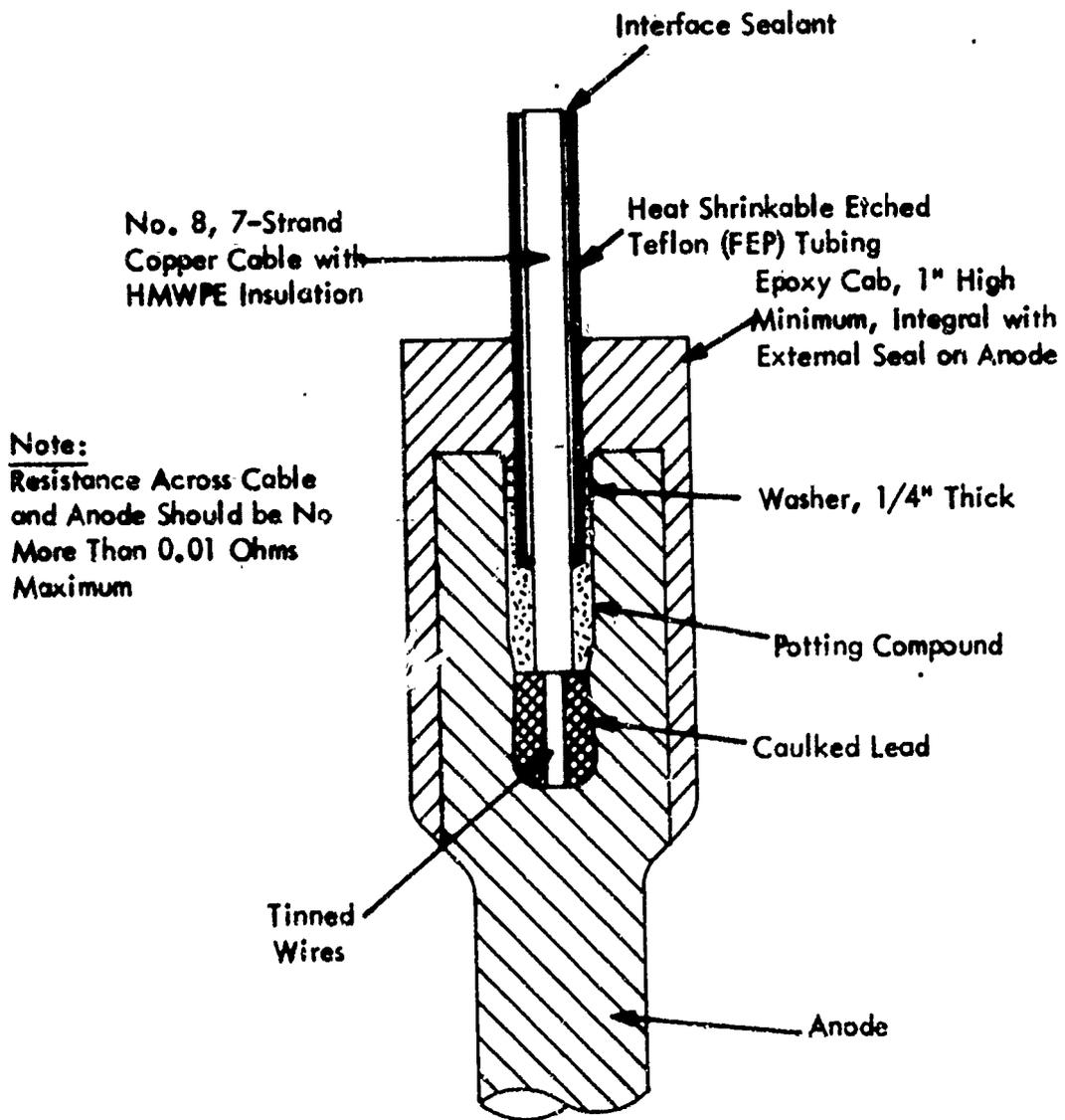


Figure 21
ANODE-TO-CABLE CONNECTION - EPOXY ENCAPSULATION

The anode-to-cable connection is the weakest point of any impressed current anode, and requires careful workmanship and quality materials. A representative number of any anode shipment should be carefully inspected and tested. Seals should be well-bonded and of specified materials. Anode-to-cable resistance should be below the minimum value stated above. Occasionally, spectrographic analyses of the alloy should be made.

Anode-to-cable connections may or may not be made and insulated by the anode casting manufacturer. If not made by him, the casting manufacturer assumes no responsibility for their quality.

4.2.4 Aluminum. Aluminum anodes are sometimes used for cathodic protection of the interior of water storage tanks. Their main advantages are lower initial cost and light weight. The corrosion products of the anode do not contaminate potable water. The deterioration rate of aluminum is 6.5 pounds per ampere-year. Commercially-available anodes are not over 75 percent efficient and are consumed at a rate of 9.0 pounds per ampere-year. This high consumption rate is undesirable and, because of it, HSCBCI anodes or graphite anodes are being used instead of aluminum. Aluminum anodes are generally used only where a one-year or so life is required (icing conditions in unheated tanks, etc.) In addition, alloying is extremely critical, making this material impractical for most applications.

4.2.5 Platinum. Platinum wire is sometimes employed as an anode, generally to protect internal surfaces where space is limited (internal surfaces of pumps, pipelines, wells, etc.). Platinum is essentially insoluble (approximately 0.00001 pound/ampere-year in flowing seawater at current densities from 50 to 500 amperes per square foot - see reference 20). However, this metal is fragile and prohibitively expensive, and is used mainly as a thin coating over other noble metals (paragraph 4.2.6).

4.2.6 Platinized Titanium (Tantalum, Niobium). Titanium is a highly-reactive metal which forms an adherent, inert oxide film in most corroding media. Very little current will leave this surface, once the oxide has formed, because the oxide has high electrical resistance. This eliminates the use of titanium itself as an anode. However, if a thin layer of platinum is plated onto titanium ("platinized titanium"), current flows from the titanium through the platinum into the electrolyte.

Platinized titanium anodes are easily fabricated and operate at high current densities (generally around 100 amperes/foot²). Only a very small platinized area is, therefore,

required for most applications. Fully platinized and partially platinized anodes are both manufactured. The partially platinized anodes allow current flow only from platinized areas. These anodes are stronger and less expensive than solid platinum. Deterioration rate is low, essentially that of solid platinum (0.00001 lb/ampere-year in seawater). Platinum thickness of 100 microinches is typical.

Anodes that are fully platinized can withstand extremely high voltages. However, those which are only partially platinized are subject to voltage limitation ("breakdown voltage"). The breakdown voltage is that at which titanium oxide decomposes. This value varies from 8.5 to 14 volts anode-to-electrolyte voltage (reference 21) depending on electrolyte, film thickness, surface roughness, and salinity of water. A system voltage of 12 volts is generally permissible.

A typical platinized titanium anode system is shown in Figure 22. It consists of five components: The metal to be protected; a reference electrode (Figure 23) mounted on or near the cathode surface; the anode(s) (Figure 24) mounted through the walls of a tank or similar structure, or suspended from a dock or pier (electrically insulated from the cathode); a control amplifier which signals the power source; and the power source itself.

In addition to titanium, platinized niobium or tantalum anodes are also available. These metals form oxide films like titanium. Numerous configurations are available; the anode of Figure 24 is typical. Commonly-available sizes of this anode are given in Table 6.

Table 6

Typical Sizes of Platinized Titanium Probe Anodes

<u>Diameter</u>	<u>Overall Length</u>	<u>Extended Length</u>	<u>Platinized Length</u>
3/4 inch	20 inches	15 inches	6 inches
3/4 inch	12 inches	7 inches	3 inches
3/4 inch	23 inches	18 inches	9 inches
3/4 inch	20 inches	15 inches	9 inches
1/2 inch	20 inches	15 inches	6 inches
1/2 inch	17 inches	12 inches	5 inches
1/2 inch	23 inches	18 inches	9 inches

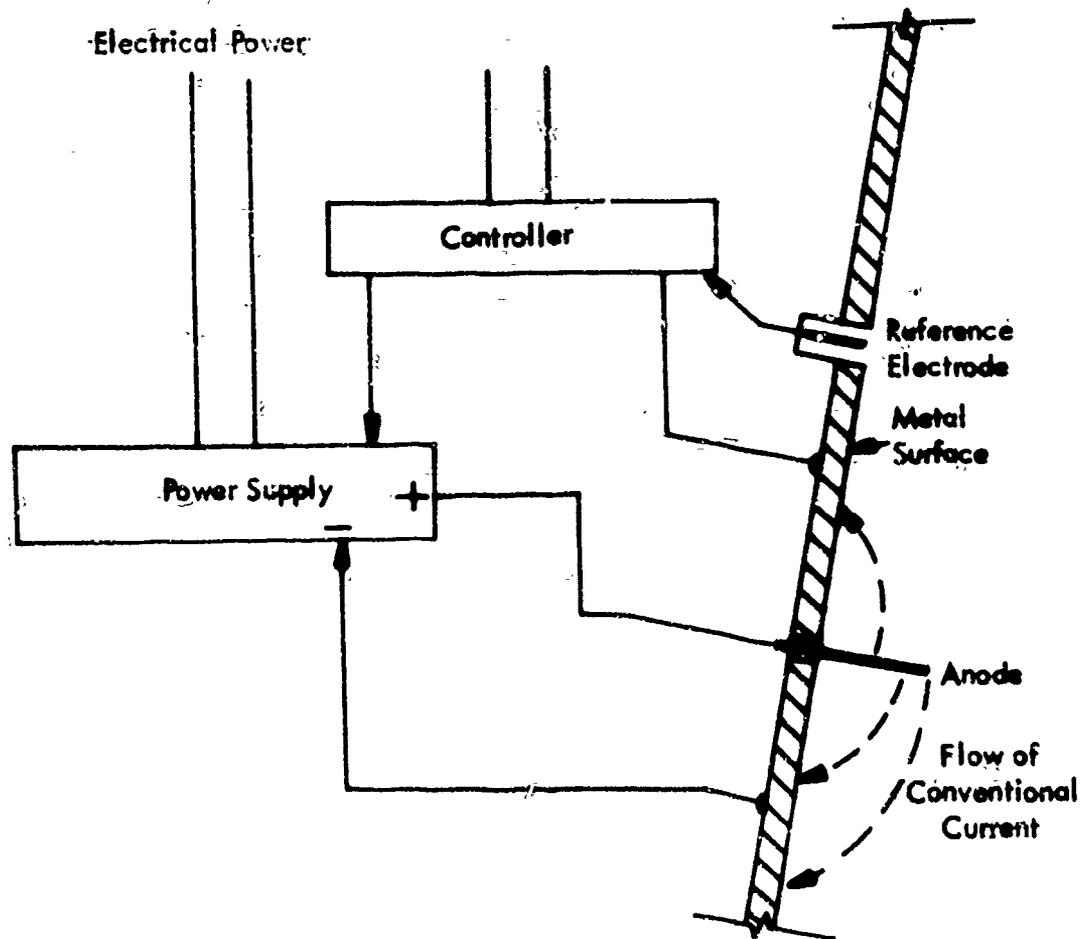
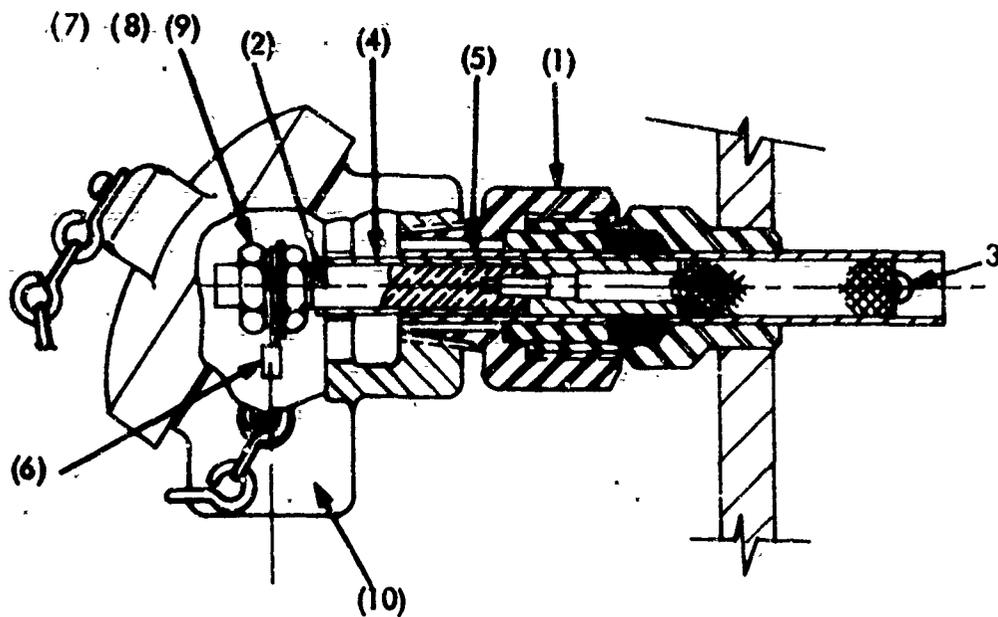
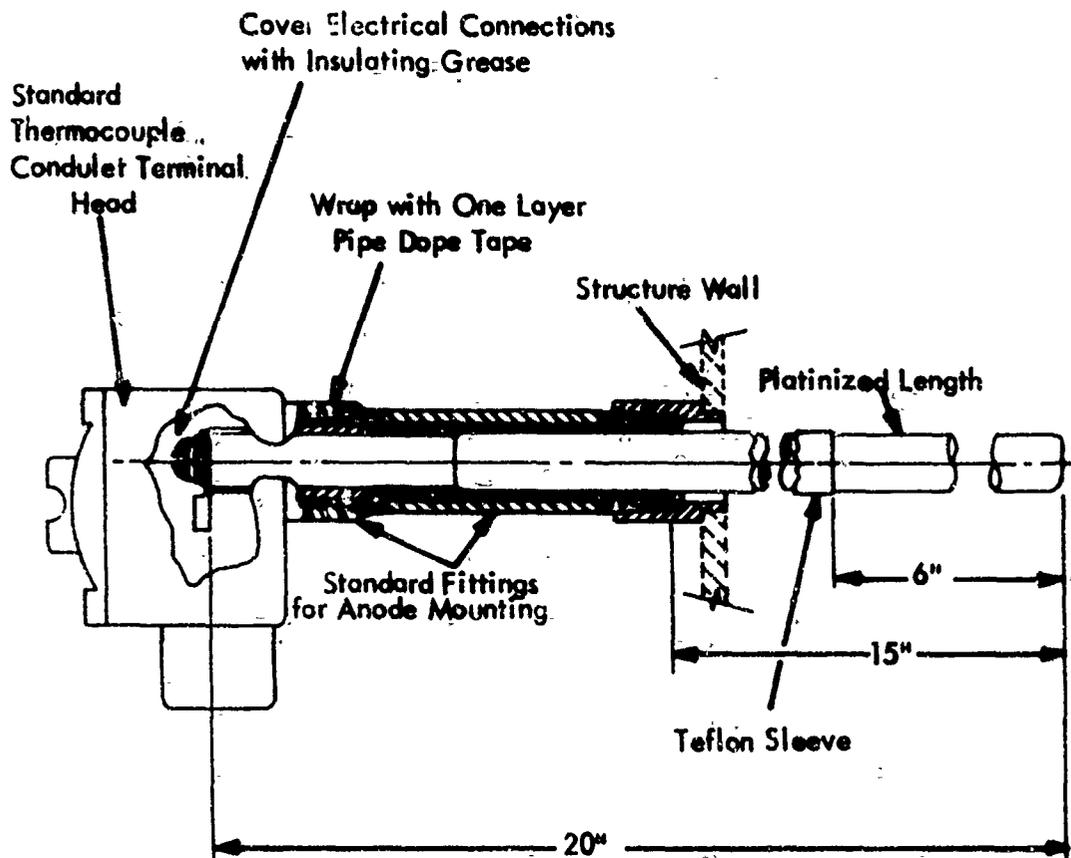


Figure 22
 TYPICAL CATHODIC PROTECTION SYSTEM
 WITH PLATINIZED TITANIUM ANODES



1. Gland - Packing
2. Extension - Electrode
3. Assembly - Element
4. Sleeve - Pilot
5. Sleeve - Insulator
6. Lug - Terminal
7. Washer - Plain, 3/8 - NI. PL. BRS.
8. Washer - Lock, Split 3/8 - CAD. PL. STL.
9. Nut - Hex, Lt. Jam - 3/8 - 16 UNC-2 B, NI. PL. BRS.
10. Head - Universal, T/C

Figure 23
 TYPICAL SILVER-SILVER CHLORIDE PROBE REFERENCE ELECTRODE
 ASSEMBLY FOR USE WITH PLATINIZED TITANIUM PROBE ANODE



Figures 24
 TYPICAL PLATINIZED TITANIUM PROBE ANODE ASSEMBLY (1/2-INCH)

4.2.7 Alloyed Lead. Alloyed lead has found some use as a seawater anode. Alloys of silver, antimony, tin, or combinations thereof in small percentage were considered. These form a surface film of lead dioxide (or lead peroxide) which is conductive. As the oxide film forms, the rate of lead deterioration drops off typically from 2 to 3 lbs./ampere-year to approximately 0.2 lbs./ampere-year. The oxide film tends to decompose at moderate current densities, and is thus limited to a range of about 3 to 25 amperes/foot². The alloyed lead anodes are seldom used because other materials have proven more dependable.

4.3 Other System Components. In addition to anodes and power sources, impressed current cathodic protection systems contain a number of other system components.

4.3.1 Connecting Cables. The cables which connect the rectifier power source to anodes and protected structures are usually buried or submerged in an electrolyte solution.

(However, sometimes it is advantageous to use overhead pole lines or "cable racks" on adjacent structures.) For that reason, high quality insulation must be used. This is especially critical on "positive" cables (those which are connected to the positive terminal of the rectifier and lead from it to anodes) because any break which would allow current to pass out of it and into the electrolyte will mean cable failure. A further discussion of cable insulation is found in paragraph 7.7.1.

The conductor is usually single conductor stranded copper. (ASTM Specification D-1248-70, Type 1, Class C, Category 5, Grade J-3 for HMWPE insulation, Specification ASTM B-3 for conductor.) Number 8, 7-strand is the size used for most impressed current anode lead wires (HSCBCI). Number 4, 7-strand is used for all bonding. Number 2, 7-strand or larger is required in military applications for the positive rectifier cable (rectifier to anodes). Test station wires are normally Number 12 solid copper test wire.

4.3.2 Splices and Connections. Splices and connections in an impressed current system should be kept to a minimum to avoid excessive circuit resistance and/or current leakage through pinholes. Wiring is most often buried or submerged in an electrolyte, where even the smallest pinhole in insulation will mean rapid failure. The loss of protection could be for long periods before detection and would represent costly repairs, usually involving excavation. Rectifier circuits are low voltage; thus, any increase in resistance will substantially increase power costs and may reduce protection effectiveness.

It is necessary to splice each individual anode into a "header" cable unless abnormally long individual leads are used between each anode and rectifier power supply. The cable-to-anode connection is critical point in all cathodic protection systems (paragraph 4.2.3.b). In addition, there is always a connection from the rectifier to the protected structure which is equally critical.

Every connection should be carefully inspected before and after insulation with material of a quality at least equal to that of the cable. Thermit-welding of cable-to-structure or cable-to-cable connections is preferable where possible. This provides the greatest likelihood of a low resistance connection, without sizable chance of breakage or corrosion buildup interfering with the connection. A cable connection to structure using a thermit weld is shown in Figure 25. A typical cable splice using a thermit weld was shown in Figure 7. Further description and detailed specifications for this is found in paragraph 7.8.

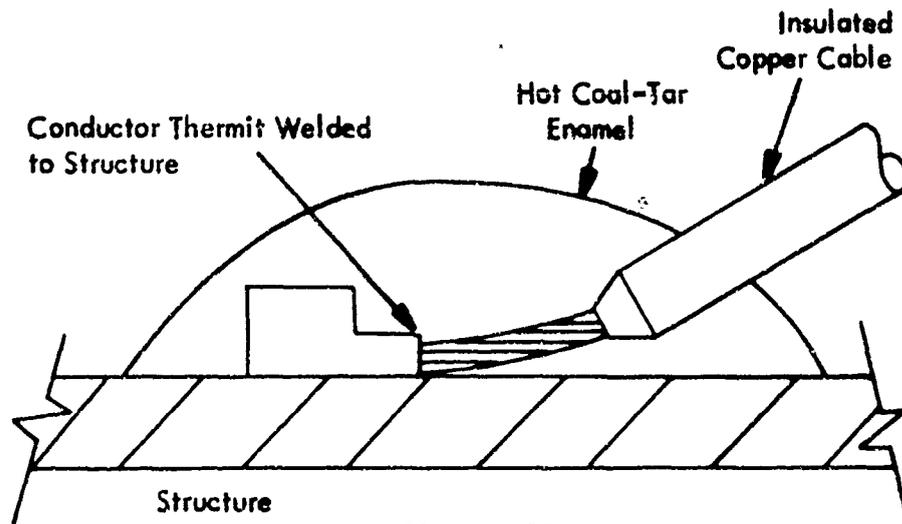


Figure 25
CABLE CONNECTION TO STRUCTURE

Alternate cable-to-structure connections is shown in Figure 26. These are applicable in areas where thermite welds may not be used, due to damage of fire or explosion from the exothermic weld process.

Alternate splice connections include mechanical connections of various types. Crimp-type and split-bolt connectors are most commonly encountered.

A cable connection to lead sheath cable is shown in Figure 27.

4.3.3 Resistor Box. Where several anode circuits are supplied current from one rectifier, it is sometimes useful to employ a "resistor box" (Figure 28). This is a terminal box containing variable resistors, each connected into one anode circuit. These resistors are varied to provide necessary current level to each circuit, in order to maintain adequate cathodic protection without overprotection (proper current distribution).

4.3.4 Backfill. Backfill is used around anodes installed in the ground to reduce contact resistance and local corrosion of the anode surface. It may also increase anode life by being consumed itself. Backfill also provides a uniform environment for the anodes and holds moisture around the anode surface.

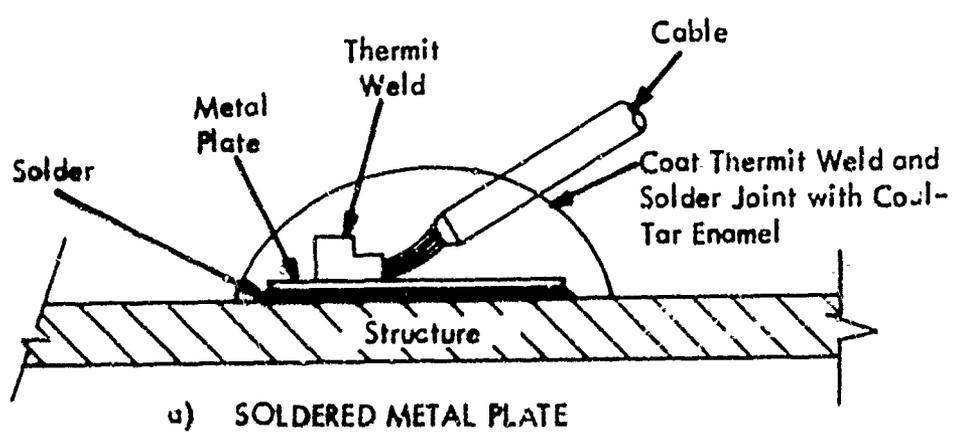
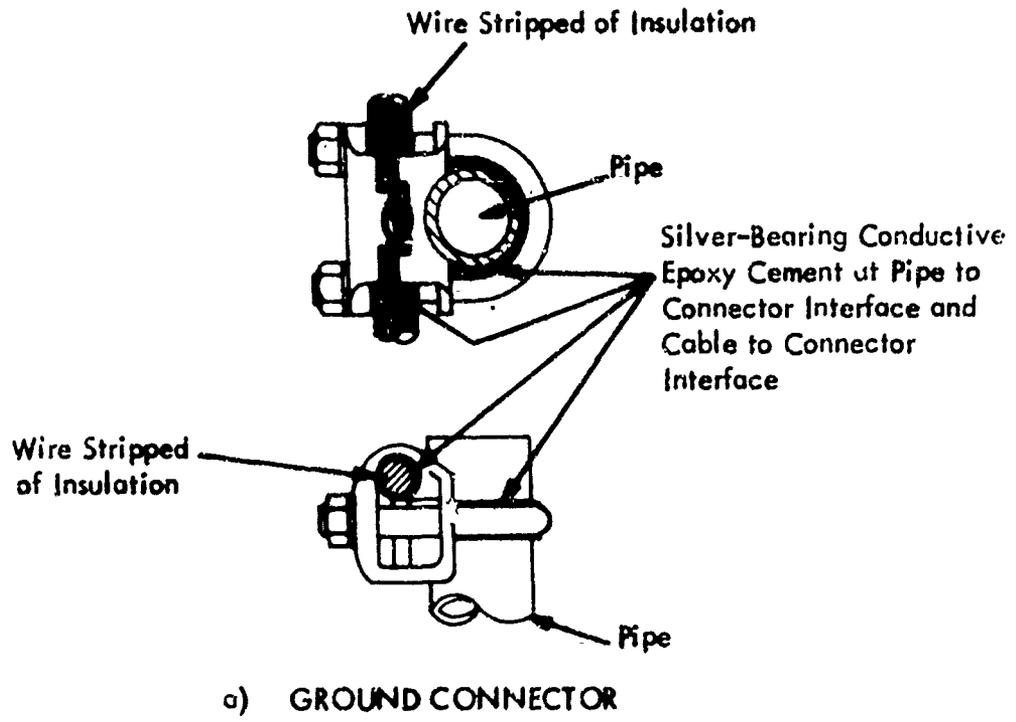


Figure 26

CABLE-TO-STRUCTURE CONNECTION WHERE THERMIT WELD PROHIBITED

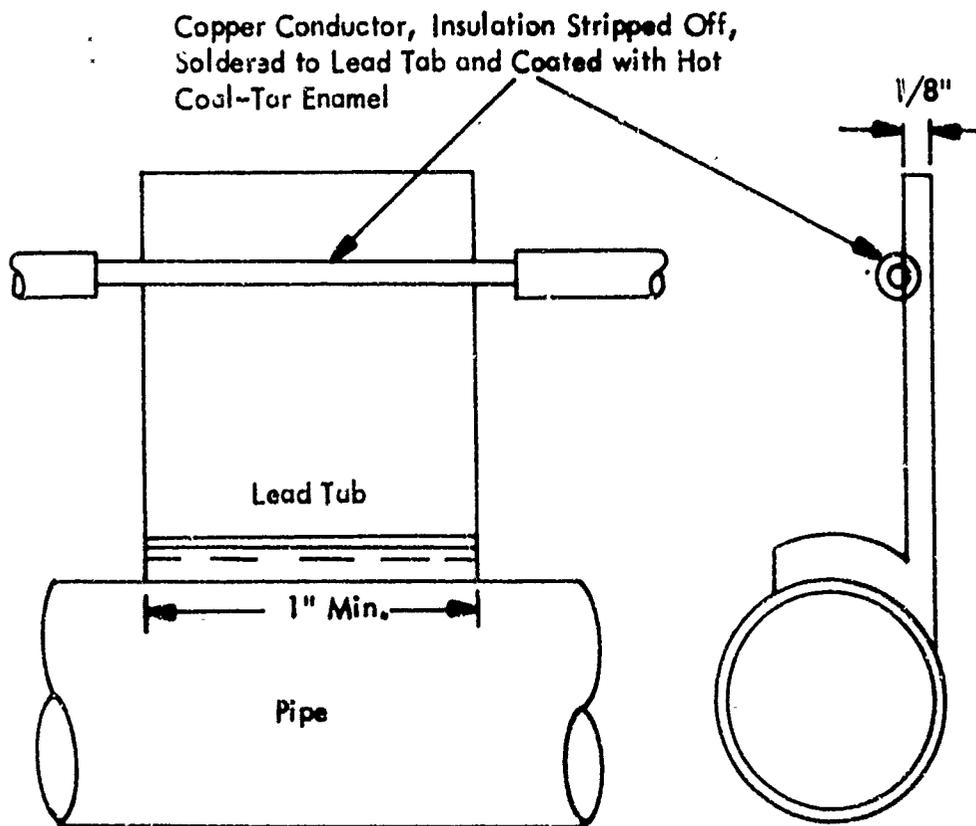


Figure 27
CONNECTION TO LEAD SHEATH CABLE

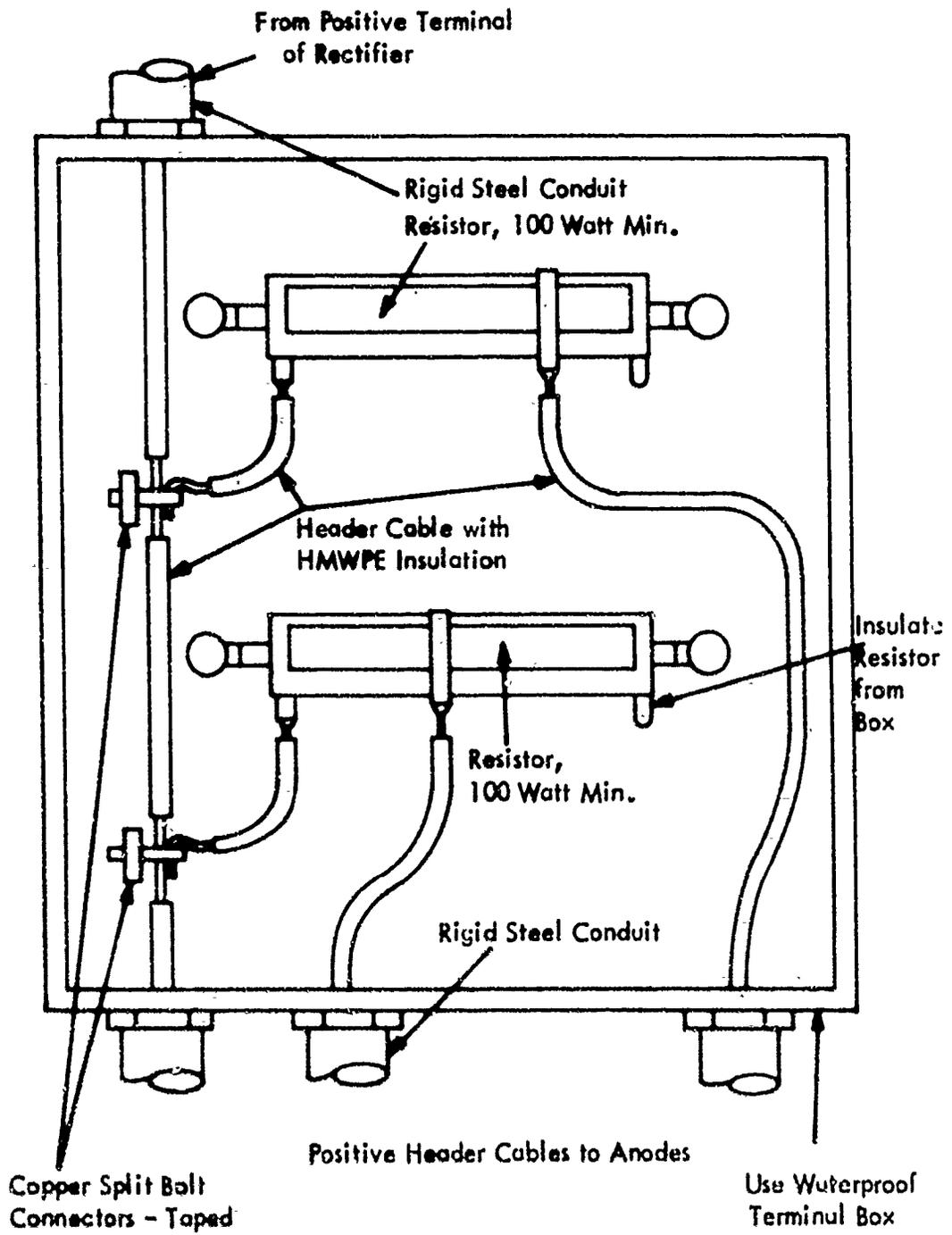


Figure 28
 TYPICAL RECTIFIER RESISTOR CIRCUIT.

"Carbonaceous" backfill material is usually used. This material is most often coke breeze (essentially finely divided, low resistance carbon particles). Typical physical and chemical specifications for impressed current anode backfill are given in Table 7. This material is used with both HSCBCI and graphite anodes.

Table 7

Coke Breeze Backfill for Impressed Current Anodes

<u>Physical Analysis</u>	
100%	to pass a 1/2" screen
35%	to pass a 3/8" screen
20%	minimum to remain on 1/8" screen
<u>Chemical Analysis (by weight)</u>	
Moisture	9.5 to 14.7%
Volatile Matter	3.0 to 3.14%
Fixed Carbon	78.22 to 78.40%
Ash	18.6%
Sulphur	1.20%

Resistivity shall be a maximum of 50 ohm-centimeters on a dry basis not under pressure.

Coal coke will usually meet these standards without extensive treatment. Petroleum coke must be calcined. Natural, or flake graphite might also be used.

Backfill is often used around impressed current anodes installed in the earth. It performs the following important functions:

- Lowers anode-to-soil resistance
- Helps eliminate gas blocking
- Permits use of greater current density
- Permits uniform deterioration of the anode
- Extends anode life.

In effect, backfill extends anode length and diameter to the dimensions of the surrounding backfill, thereby reducing anode resistance to ground. In some soils, particularly tight clays, the functioning of the anode may be impaired with time, unless backfill is used, because of oxygen that builds up on the anode surface. This condition is known as gas blocking, and retards current flow.

Backfill should be thoroughly tamped around the anodes to eliminate gas blocking, and to achieve good electrical contact to anode surface. Further information on backfilling holes for anodes is found in paragraph 7.5.

4.4 Advantages of Impressed Current Cathodic Protection.
Impressed current cathodic protection has several advantages over galvanic anodes. (Advantages of galvanic anodes are discussed in paragraph 5.4.)

Impressed current system output is not limited by a natural galvanic potential; consequently the output can be varied relatively easily. A change in rectifier output in a properly designed system will overcome the effects of changes in environment and structure surface. To change the output of galvanic anodes, the number of anodes must be altered. This requires costly excavations.

In high-resistance environment, impressed current can be supplied with comparatively few anodes and a minimum of effect to other structures. This is both a space and cost advantage over galvanic anodes.

Impressed current has another space advantage over galvanic systems: anode beds can be more readily located at the point where current will be supplied most efficiently. Possible ground orientations include:

- deep anodes (50 feet or deeper)
- distributed
- multiple, low-output units
- tank and vessel interiors
- inside duct systems.

(Examples of various cathodic protection systems are given in paragraph 6.)

4.4.1 Deep Anode Installations. A deep anode installation is defined as one with anodes located at a depth of 50 feet or greater below grade. Current is emitted at this depth so that only a small percentage is received by foreign structures close to the surface (those not being placed under protection).

4.4.2 Distributed. A distributed anode installation is generally considered as one made up of a greater number of anodes than usual, with all anodes placed relatively close (1 to 20') to the surface of the protected structure and the current distributed over the entire surface area.

4.4.3 Multiple Low-Output Units. This arrangement refers to a number of small installations consisting of few anodes and low output power source with each. These are used in place of fewer large units to reduce current densities and total power cost.

4.4.4 Tank and Vessel Interiors. Relatively small anodes are located in positions where they will emit current to surfaces needing protection without excessive

displacement and/or changes in fluid flow characteristics.

4.4.5 Inside Ducts. Connected multiple lead anodes are located in utility duct systems to protect metal-sheathed cables (a special type distributed anode system).

5 GALVANIC ANODE SYSTEMS. Galvanic anodes generate their own current. Each galvanic anode is connected to the structure to be protected. They are simply pieces of metal which develop an appreciable potential between themselves and the structure, discharging current into the electrolyte and onto the structure surface. For practical purposes, the amount of cathodic protection provided by a galvanic anode is considered proportional to:

1. Potential between galvanic anode and protected structure.
2. Resistance of electrolyte.

Therefore, anode output and effectiveness is best determined by trial and error (using test anodes, for example). Any other method is merely an estimate, based on the experience of the design engineer. Such factors as moisture content and composition of environment, coating quality, polarization characteristics, and seasonal variations greatly influence output. With impressed current, rectifier output is altered to overcome these variables. With galvanic anodes, output is set. Testing is important in determining galvanic anode output, just as in determining whether a structure will corrode in a given environment; the principal in both instances is the same: the corrosion behavior of a given metal in a given electrolyte. Therefore, experience is especially important with galvanic anode systems. Protection requirements can be computed; actual anode output can only be estimated unless data from actual installed anodes is used.

Galvanic anodes used for cathodic protection are usually magnesium, zinc, or aluminum. The maximum potential between these anodes and a protected structure will never exceed a value slightly in excess of one volt. Current flows out of a galvanic anode into the electrolyte. It passes through the electrolyte and is received by the surface of the protected structure. It passes through the protected structure to the insulated cable and follows this cable back to the galvanic anode.

5.1 Anodes. Galvanic anodes, like impressed current anodes, must be made of material with a deterioration rate that will provide reasonable anode life from a practical amount of material. Anodes cannot be too costly or fragile. The potential difference between anode and structure must be great enough to force adequate protective current onto the structure. Materials with these characteristics which

are currently used as practical galvanic anodes include magnesium, zinc and aluminum.

2.1.1 Magnesium. Magnesium anodes are commercially available as castings and extrusions in weights ranging from 1 to 200 pounds (Figure 29). A variety of shapes are available for application in soil, condensers, tanks, heat exchangers, and inside large gate valves, to mention a few practical applications.

a. Alloying. Two alloys are commonly used; these are referred to as standard and high-manganese (high-potential). Typical specifications for these alloys are shown in Tables 8 and 9. The high-manganese alloy yields approximately 20 to 30 percent more current output, with resulting shorter life, and an increased driving potential (open circuit) of -1.75 volts relative to copper-copper sulfate as opposed to -1.55 volts for the standard alloy. In addition, a so-called "High Current" anode is available. This is an elongated standard alloy anode which generates 40 to 50 percent higher currents because of increased surface area (ASTM Specification AZ63A).

Magnesium is subject to self-corrosion which varies with alloy composition and impurities. Metals considered impurities in magnesium anodes are usually: iron, nickel, copper, silicon, lead, and tin. All these impurities form intermetallic compounds with magnesium which are cathodic to the surrounding magnesium and tend to increase the amount of self-corrosion. Self-corrosion restricts the usable hours of magnesium anodes.

Of the listed impurities, nickel can be the most detrimental, producing a marked reduction in current efficiency when present in amounts exceeding 0.005 percent. Iron ranks second in detrimental effect, causing almost as much self-corrosion as nickel when present in the same quantity. Copper, lead, tin, and silicon have slightly less effect on magnesium anode efficiency in quantities over 0.005 percent, with silicon having the least effect.

Table 8
Chemical Analysis of Magnesium Anodes (Standard Alloy)¹

<u>Element</u>	<u>Percentage</u>
Aluminum	5.3 - 6.7%
Manganese	0.15% Minimum
Zinc	2.5 - 3.5%
Copper	0.02% Maximum
Silicon	0.10% Maximum
Iron	0.005% Maximum
Nickel	0.002% Maximum
Other Metallic Elements	0.3% Maximum
Magnesium	Remainder

¹ ASTM Specification AZ63.



Figure 29
MAGNESIUM ANODES

Table .9
Chemical Analysis of Magnesium Anodes (High Potential)

<u>Element</u>	<u>Percentage</u>
Aluminum	0.010% Maximum
Manganese	0.5 - 1.3%
Zinc	-
Copper	0.02% Maximum
Silicon	-
Iron	0.03% Maximum
Nickel	0.001% Maximum
Other Metallic Elements	0.05% each Maximum
	0.30% total Maximum
Magnesium	Remainder

(*) In the range 0.5 - 0.8%, Mn. is at least 0.5 + 60 x Al. % by weight.

All metals more noble than iron produce intermetallic compounds with magnesium. However, iron forms an unstable intermetallic compound with magnesium. At temperatures below the melting point of magnesium, iron occurs at isolated particles dispersed throughout the magnesium matrix. Manganese, zinc, and aluminum form intermetallic compounds with iron, thereby reducing self-corrosion of magnesium due to the presence of free iron. The reason for this is that manganese has a higher melting temperature than magnesium and that manganese is closer than iron to magnesium in the galvanic series. The manganese will usually freeze out as a magnesium-manganese intermetallic compound which has a higher freezing temperature than most intermetallic compounds formed in magnesium. This intermetallic compound will tend to freeze out of the molten magnesium around the iron (which is first to freeze out), forming an envelope around the iron. Iron thus is isolated and does not contribute to anode self-corrosion. Manganese is cathodic to magnesium but to a much lesser extent than iron, so that potential of a high manganese anode (more than 0.50 percent manganese) is -1.75 volts referred to a copper-copper sulfate half-cell as compared to -1.55 volts for a standard alloy magnesium anode. The efficiency of the high manganese anode, however, is somewhat lower than for standard alloy magnesium.

Aluminum and zinc are both cathodic to magnesium, but are both useful in the 6 percent aluminum, 3 percent zinc, magnesium alloy. Aluminum and zinc form intermetallic compounds with the cathodic group of metals and with magnesium, which improves the characteristics of magnesium as a galvanic anode, but in turn reduces the open circuit potential to -1.55 volts. The reduced potential does not indicate the amount of self-corrosion occurring; as high purity magnesium which has a higher potential, but suffers from more self-

corrosion than the standard alloy. The lower potential of standard 6 percent aluminum, 3 percent zinc, magnesium alloys is due partly to self-corrosion and partly to the lower potential of the intermetallic compounds of magnesium with aluminum and zinc.

b. Anode Efficiency. Theoretically, pure magnesium has an electrochemical equivalent of 8.8 pounds per ampere-year or 1000 ampere-hours per pound. Pure magnesium is impossible to produce; the commercially "pure" product achieves much lower values of ampere hours per pound (Figure 30). As discussed in paragraph 5.1.1.a, alloying can improve this efficiency.

Efficiency of magnesium as an anode varies with current density (Figure 30). At anode current densities greater than 500 milliamperes per square foot, the efficiency of standard alloy anodes will approach 65 percent and an electrochemical equivalent of 650 ampere-hours per pound. At current densities less than 100 milliamperes per square foot, this efficiency will usually not exceed 50 percent or an electrochemical equivalent of 500 ampere-hours per pound. At current densities below 25 milliamperes per square foot, self-corrosion is greater than the corrosion producing useful protective current so that efficiency of standard alloy anodes is below 50 percent.

High manganese-magnesium anode efficiency varies with current density much the same as a standard alloy anode except that the over-all efficiency is lower. At anode current densities greater than 500 milliamperes per square foot, efficiency of high manganese alloy anodes approaches 55 percent and an electrochemical equivalent of 550 ampere-hours per pound. At 100 milliamperes per square foot, efficiency is approximately 40 percent and at anode current densities below 25 milliamperes per square foot, efficiency is below 35 percent.

c. Potentials. Open circuit potential of standard alloy magnesium anodes is approximately -1.55 volts to a copper-copper sulfate half-cell. The open circuit potential of high manganese-magnesium anodes is approximately -1.75 volts to a copper-copper sulfate half-cell.

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

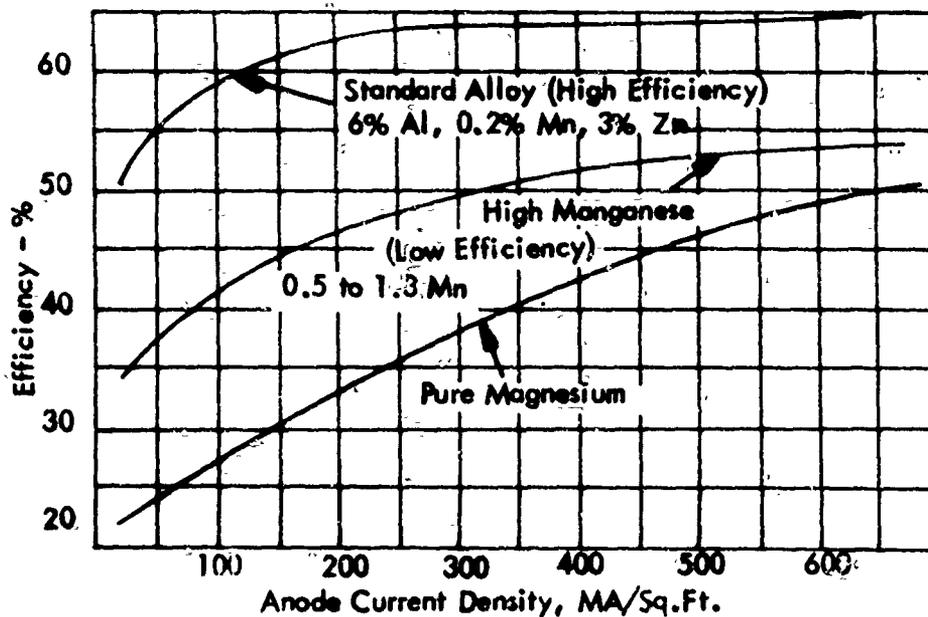


Figure 30
CURRENT EFFICIENCY OF MAGNESIUM ANODES

A more practical approach is to consider iron polarized to -0.85 volt. On this basis, standard alloy magnesium anodes have a driving potential of 0.70 volt ($1.55 - 0.85 = 0.70$) and high manganese-magnesium anodes have a driving potential of 0.90 volt ($1.75 - 0.85 = 0.90$). For cathodic protection design involving magnesium anodes, these potentials, 0.70 and 0.90 volts, should be used depending upon alloy selected.

d. Backfill. For reasons discussed in paragraph 4.3.4 for impressed current anodes, backfill is also often useful for magnesium anodes. Analysis of typical backfill for magnesium anodes is:

Gypsum	75%
Bentonite	20%
Sodium Sulfate	5%

Anodes are available prepackaged in a permeable cloth sack containing prepared backfill.

e. Sizes. Various sizes and shapes of magnesium anodes, bare or packaged in selected backfill, are listed here.

(1) Standard Alloy. Standard alloy sizes for various environments are given in Tables 10 - 12.

Table 10
Magnesium (Standard Alloy) Anodes
Standard Size for Use in Soil

<u>Weight Lbs.</u>	<u>Size, Inches</u>	<u>Packaged Wt., Lb.</u>	<u>Packaged Size Inches</u>
3	3 x 3 x 5	8	5.25 x 8
5	3 x 3 x 8	13	5.25 x 11.25
9	3 x 3 x 14	27	5.25 x 20
10	1.5 x 1.5 x 70	--	--
12	1 x 4 x 12	32	7.5 x 18
16	2 x 2 x 60	--	--
17	4 x 4 x 17	45	7.5 x 24
17	3 x 3 x 28	--	--
32	5 x 5 x 20-1/3	68	8.5 x 28
50	3 x 3 x 60	--	--
50	5 x 5 x 31	--	--
100	7 x 7 x 16	100	10 x 24
100	8 x 16	100	10 x 24
100	4 x 4 x 60	--	--

Note: Core material: regular core for soil anodes is a galvanized, open pitch, spiral-wound strip 3/8 in. ID, 1/2-in. OD.

Connecting wire: regular connecting wire for soil anodes is a 10-ft. length of single-strand No. 12 AWG TW insulated copper wire, silver-soldered to the core with the joints sealed against moisture. Special connecting wires of lengths other than 10 ft. are available.

Table 11
Magnesium (Standard Alloy) Anodes
Standard Size for Use in Water

<u>Weight Lbs.</u>	<u>Size, Inches</u>	<u>Type of Core</u>
20	3.5 x 3.5 x 26	3/4" dia., galvanized pipe core, flush ends.
50	7 x 7 x 16	Threaded 3/4" dia. galvanized pipe extending 1" both ends, flush ends optional.
50	7 x 7 x 16	1/2" dia. galvanized eyebolt core.
50	8 x 16	3/4" dia. galvanized pipe core, flush ends.
50	8 x 16	1/2" dia. galvanized eyebolt core.
100	7 x 7 x 32	3/4" dia. galvanized pipe core, flush ends.
100	7 x 7 x 32	1/2" dia. galvanized eyebolt core.
100	8 x 32	3/4" dia. galvanized pipe core, flush ends.
100	8 x 32	1/2" dia. galvanized eyebolt core.

Table 12
Magnesium (Standard Alloy) Anodes
Standard Sizes for Use in Condensers and Heat Exchangers

<u>Weight</u> <u>Lb.</u>	<u>Size, Inches</u>	<u>Type of Core</u>
15	4 x 8 x 8	3/4" bolt
24	2 x 9 x 18	1/4 x 2" straps
44	4 x 9 x 18	1/2 x 2" straps
60	7 x 9 x 18	3/4" bolt

(2) High Current Anodes. Elongated standard alloy anodes for use in high-resistance soils are given in Table 13.

Table 13
Magnesium (Standard Alloy) Elongated Anodes

<u>Weight</u> <u>Lb.</u>	<u>Size, Inches</u>	<u>Package</u>	
		<u>Wt., Lb.</u>	<u>Size</u> <u>Inches</u>
1	1.32 x 12	6	3 x 15.5
3	2.35 x 10.5	10	4 x 14
5	2.63 x 14	14	4.5 x 18
9	2.49 x 28	37	5 x 33
17	2.86 x 40	50	5.5 x 46
32	3.75 x 44	96	6.5 x 50
50	4.58 x 46	120	7 x 52

(3) High Manganese (High Potential). High manganese alloy sizes for soil or water (packaged for soil only) are given in Table 14.

Table 14

Magnesium (High-Potential Alloy) Anodes for Use in Soil or Water			
Weight Lb.	Size, Inches	Packaged	Packaged Size,
		Wt., Lb.	Inches
3	3.75 x 3.75 x 5	12	6 x 10
5	3.75 x 3.75 x 7.5	17	6 x 12
9	2.75 x 2.75 x 26	35	6 x 31
9	3.75 x 3.75 x 13.25	27	6 x 17
12	3.75 x 3.75 x 18	36	6 x 23
1	2.75 x 2.75 x 41	50	6 x 46
1	3.75 x 3.75 x 21	42	6.5 x 26
17	2.75 x 2.75 x 50	60	6 x 55
17	3.75 x 3.75 x 26	45	6.5 x 29
20	2.5 x 2.5 x 59.25	70	5 x 66
24	4.5 x 4.5 x 23	60	7 x 30
32	5.5 x 5.5 x 21	74	8 x 28
10	3.75 x 3.75 x 59.25	105	6.5 x 66
48	5.5 x 5.5 x 30	100	8 x 38
48	8 x 10	100	12 x 25
70	4.5 x 4.5 x 60	---	--

Note: Core material: regular core is galvanized 20-gauge perforated steel strip. Anodes longer than 24" have 9-gauge core.

Connecting wire: regular connecting wire is 10-ft. length of solid #12 AWG TW insulated copper wire, silver-soldered to the core with joints sealed against moisture. Special wires or other lengths are available.

(4) Extruded Rod Anodes. Standard alloy magnesium rod anodes for use in water tanks and water heaters are available in sizes given in Table 15.

Table 15

Magnesium (Standard Alloy) Extruded Rod Anodes for Use in Water Tanks and Heaters		
Weight, lb. per ft.	Size	Type of Core
0.36	0.75" dia x 1 ft to 20 ft	1/8" dia steel rod
0.45	0.84" dia x 1 ft to 20 ft	1/8" dia steel rod
0.68	1.05" dia x 1 ft to 20 ft	1/8" dia steel rod
1.06	1.315" dia x 1 ft to 20 ft	1/8" dia steel rod
1.50	1.561" dia x 1 ft to 20 ft	1/8" dia steel rod
2.50	2.024" dia x 1 ft to 20 ft	1/8" dia steel rod

(5) **Ribbon Anodes.** Standard alloy magnesium anodes are available for use in protecting buried conduit, utility cables, and in areas where more conventional shapes would be impractical. These anodes are available in coils of 200 and 1000 feet. They consist of a core of 10 gauge steel wire surrounded by standard alloy magnesium $3/8"$ x $3/4"$.

5.1.2 Zinc. Zinc anodes are commercially available in weights from 5 pounds to 250 pounds in plate, bars, ribbons, and rods. For anode installed in the earth, prepared backfill should be used.

a. **Alloying.** There are two basic alloys in common use. One is used for protection in soil or fresh water; the other, for marine uses. Typical specifications for these two types are shown in Tables 16 and 17.

Metals which are considered impurities in zinc anodes are: iron, lead, and copper. Iron is the most detrimental. Since iron has a limited solid solubility in zinc of approximately 0.0014 percent, any iron in excess of this percentage precipitates out as discrete particles. These particles of iron are cathodic to the surrounding zinc and serve as centers of self-corrosion. The corrosion product of this self-corrosion, zinc hydroxide, deposits on the iron, forming a dense adherent coating. This coating can spread during anode operation from the original iron particle center until the entire anode surface is coated with adherent zinc hydroxide coating. Zinc hydroxide is not electrically conductive. Therefore, the anode becomes ineffective because it is insulated from the electrolyte by built-up corrosion product.

Addition of other metals such as aluminum and cadmium in slight percentages (Tables 16 and 17) increase zinc's tolerance for iron, decrease the tendency to form insulating films, and provide for easier production.

b. **Anode Efficiency.** Zinc has an electrochemical equivalent of 23.5 pounds per ampere-year or 372 ampere-hours per pound. However, zinc operates at an efficiency of 90 percent or better or an actual electrochemical equivalent of 354 ampere-hours per pound. The self-corrosion of zinc anodes is approximately 5 to 10 percent under most conditions, regardless of current output.

c. **Potentials.** Open circuit potential of zinc is -1.10 volts to a copper-copper sulfate half-cell in moist soils and waters and backfills. The driving potential of zinc with reference to iron is 0.25 volt based on a polarization potential of -0.85 volt for steel relative to copper-copper sulfate. Where zinc anodes are considered for a cathodic protection design, a driving potential of 0.25 volt should be used to arrive at the number of anodes required. If a higher driving potential is used, an

Table 16

Chemical Analysis of Zinc Anodes
for Soil and Fresh Water Use ¹

<u>Element</u>	<u>Percentage</u>
Aluminum	0.005 Maximum
Cadmium	0.003 Maximum
Iron	0.0014 Maximum
Lead	0.003 Maximum
Zinc	0.003 Maximum

¹ Specifications: ASTM B-148-67, Type II

Table 17

Chemical Analysis of Zinc Anodes
for Marine Use ¹

<u>Element</u>	<u>Percentage</u>
Aluminum	0.10 - 0.50
Cadmium	0.025 - 0.15
Iron	0.005 Maximum
Lead	0.006 Maximum
Copper	0.005 Maximum
Silicon	0.125 Maximum
Zinc	Remainder

¹ Specifications: MIL-A-18001H or ASTM B418-67, Type I

insufficient number of anodes will be the result and the required protective current will not be attained.

The relative potential of steel and zinc in water has been found to reverse at temperatures above 140°F. Zinc anodes for steel protection should be avoided in water systems above this temperature, because increased corrosion of steel may result.

d. Backfill. Zinc anodes are greatly affected by nonuniform environment because of low driving potential. The relatively low driving potential between zinc and steel requires a long slender shape to obtain low anode-to-earth resistance. Length of zinc anodes increases the possibility of large soil resistivity variations along its length. Variations in soil resistivity produce variations in current flow which in turn cause uneven anode deterioration. Zinc anodes should be installed in prepared backfill in order to obtain more uniform current flow.

In addition, zinc anodes installed bare are more subject to production of various corrosion products. Zinc ions produced during the corrosion of a zinc anode are deposited at various distances from the surface of the anode. If oxygen, carbonates, or phosphate ions are present in the media, a dense adherent coating of high electrical resistance forms near the surface, effectively insulating the anode from the surrounding media. This stops corrosion of the anode and resulting protective current. However, most zinc anodes are installed below the water table and in soils with no free carbonates or phosphates, so that passivity does not usually occur. Sulfate ions reduce the tendency for formation of the high resistant film of corrosion products.

Soils containing gypsum generally produce most consistent anode behavior. Backfills based on this are recommended for underground use. Two typical specifications are:

Element	Type 1	Type 2
	Percentage	
Hydrated gypsum	75	50
Bentonite	25	50
Sodium sulfate	5	--

e. Sizes. Various sizes of bare zinc anodes are available in the two alloys. Most anodes for underground use are available bare or packaged in low resistance backfill.

(1) Under ground and Fresh Water Alloy. Anode sizes for underground or fresh water applications are given in Table 18.

Table 18

Standard Sizes of Zinc Anodes
for Use in Fresh Water or Underground

<u>Weight Lb.</u>	<u>Size, Inches</u>
5	1.4 x 1.4 x 9
12	1.4 x 1.4 x 60
13	1.4 x 1.4 x 36
30	1.4 x 1.4 x 60
40	2.2 x 30
45	2 x 2 x 45
60	2 x 2 x 60

Note: Core for standard anodes shown is 1/4" diameter E.G. Mild steel rod.

Special anodes are available in ranges given in Table 19.

Table 19

Special Sizes of Zinc Anodes
for Use in Fresh Water or Underground

<u>Weight, Lb. per Tub</u>	<u>Size, Inches</u>	<u>Length, Inches</u>
3.3	3 x 3	6 to 60
4.2	4 x 4	6 to 60
6.5	5 x 5	6 to 48
12.8	7 x 7	6 to 36
21	9 x 9	12 or 24
26	10 x 10	6 to 24

Note: Core is 1/4" diameter E.G. mild steel rod. Also available in 3/8", 1/2", or 5/8" diameter.

(2) Sea Water Alloy. Anode sizes for marine applications are found in Table 20.

Table 20

Standard Sizes of Zinc Anodes for Use in Sea Water

<u>Weight</u> <u>Lb.</u>	<u>Size, Inches</u>
5	1.25 x 3 x 9
12	1.25 x 3 x 12
24	1.25 x 6 x 12
50	2 x 2 x 48
150	4 x 4 x 36
250	9 x 9 x 12
250	4 x 4 x 60

Note: 24-pound and smaller anodes have galvanized steel mounting straps. 50-pound size contains 3/8" diameter galvanized steel rod for core. Larger sizes contain 3/4" or 1" diameter galvanized steel pipe cores.

Special anodes are available in ranges given in Table 21.

Table 21

Special Sizes of Zinc Anodes for Use in Sea Water

<u>Weight, Lb.</u> <u>per Inch</u>	<u>Size, Inches</u>	<u>Length, Inches</u>
0.5	1.4 x 1.4	6 to 60
1	2 x 2	6 to 60
2.3	3 x 3	6 to 60
4.2	4 x 4	6 to 60
6.5	5 x 5	6 to 48
12.8	7 x 7	6 to 36
21	9 x 9	9 to 24
23.4	9 x 10	9 to 24
26	10 x 10	9 to 24

Note: A variety of cores are available with the different sizes.

(3) Ribbon Anodes. Ribbon anodes are available in both alloys. These are useful for protecting pipeline interiors, for carrier pipe exteriors inside casings (Figure 31), for tank and duct interiors.

The seawater alloy is available in 200-foot coils; the anode size is 5/8" x 7/8" weighing 1.2 pounds per foot. Core is 1/10" diameter galvanized wire.

Two sizes are available for fresh water or underground use. The larger is available in 500-foot coils; anode size is 1/2" x 9/16" weighing 0.6 lb. per foot. The smaller comes in 1000 ft. coils; anode size is 11/32" x 15/32" weighing 0.25 lb. per foot. Core for both sizes is 1/10" diameter galvanized wire.

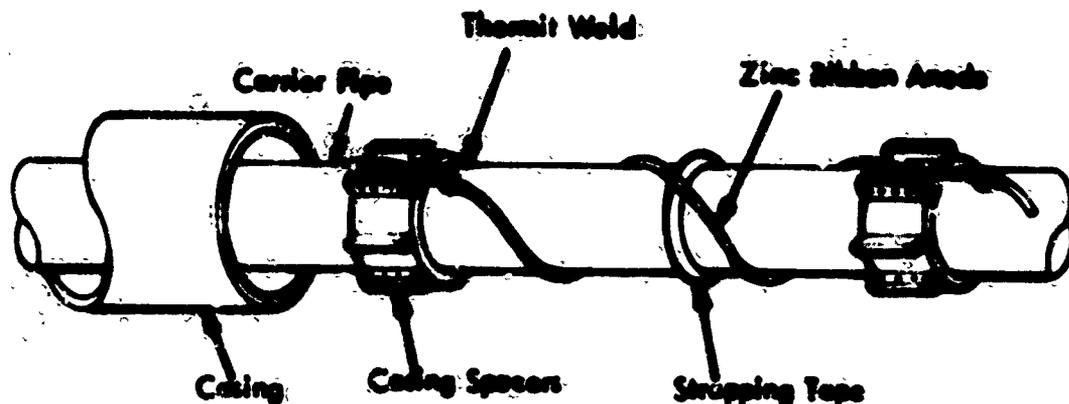


Figure 31
ZINC RIBBON ANODE FOR PROTECTION OF PIPE INSIDE CASING

5.1.3 Aluminum Anodes. Aluminum galvanic anodes have found some application in seawater. They are used to protect such structures as offshore drilling platforms and external ship hull surfaces.

The efficiency of aluminum anodes varies depending on operational conditions and alloys used. A value of 810 ampere-hours per pound based on 60% efficiency is typical.

Open circuit potential for aluminum is about -1.05 volts relative to copper-copper sulfate. The driving potential for an aluminum anode connected to a steel structure is therefore about 0.20 volt. Aluminum anode performance may be disappointing if alloys vary even slightly from specification, and manufacturers seem to have difficulties holding constant material content.

5.2 Other System Components. System components for galvanic anode systems are similar to those used for impressed current (paragraph 4.3) or as already discussed. Connecting cables are smaller than those used for impressed current, because of smaller current flow and less need for physical strength. Number 12 solid copper wire with Type TW, RHW-USE, or polyethylene insulation is used for connecting cables. Anode lead wires are normally 10 feet long, number 12 solid copper wire with TW insulation.

5.3 Advantages of Galvanic Anode Systems. Galvanic anodes have several advantages over impressed current systems. (Advantages of impressed current are discussed in paragraph 4.4).

Because galvanic anodes generate their own power, they require no external power source. This means they can often be used where rectifiers are difficult or impossible to power, such as in remote regions.

There are sometimes cost advantages to galvanic anodes. The systems are simpler than impressed current, and galvanic anodes can sometimes be "expensed", while impressed current cathodic protection is usually capitalized. Both installation and maintenance costs are low. There are no monthly power costs. In addition, rights-of-way or easement costs are minimal with this type installation.

Because of the low current outputs, galvanic anodes rarely produce interference to foreign structures. When interference is encountered, stray currents are small.

6 EXAMPLES OF CATHODIC PROTECTION SYSTEMS. Figures 32 through 52 illustrate various anode configurations and a suggested approach to the cathodic protection of many different structures in a variety of applications. These are not intended to represent firm designs for structures without a systematic evaluation of local conditions.

Paragraph 7 of this manual presents specific basic design information, and paragraph 8 gives specific examples of designing systems.

7 CATHODIC PROTECTION DESIGN. Cathodic protection is applied to many different types of structures. Each situation requires special consideration. There are, however, fundamental general procedures which must be applied to design of all cathodic protection systems. The detailed analysis of these procedures is different for an elevated water storage tank than for ship hulls or buried pipelines. However, the same steps should be followed in all cases.

7.1 General Procedure. A general summary of steps involved is given here. In the remainder of paragraph 7, design considerations are discussed in more detail. Useful data in the form of tables and graphs are included.

General design criteria are similar for galvanic and impressed current systems. One basic difference between the two is the usual method of anode layout. Galvanic anodes are usually designed and installed as individual anodes, distributed at a given separation along the structures (30 feet, for example). Impressed current systems more frequently employ banks of anodes (beds). Of course, either type anode may be installed in either way, but the distinction is most frequently as given above.

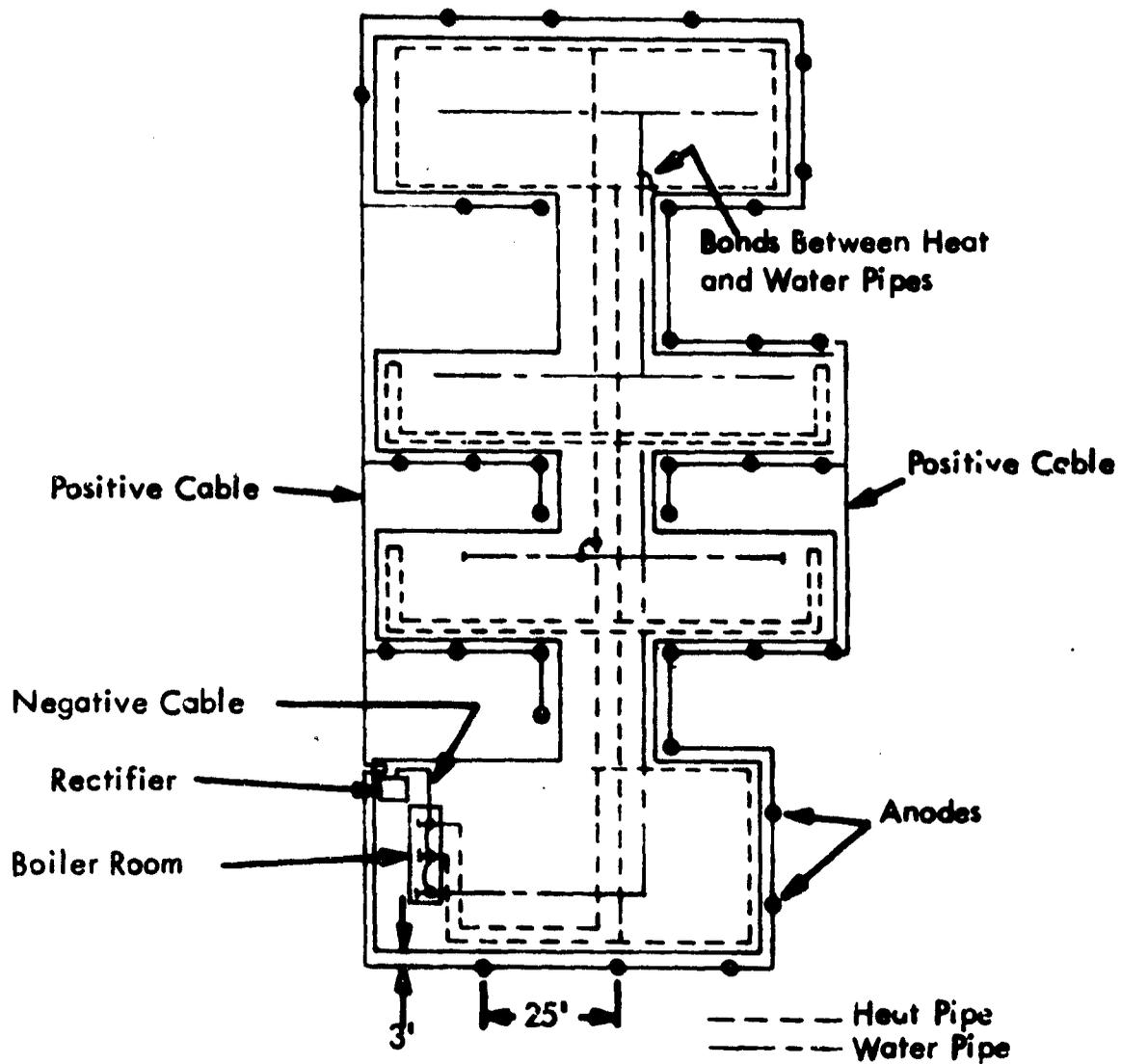


Figure 32
 TYPICAL BUILDING UNDERGROUND HEAT AND WATER LINES

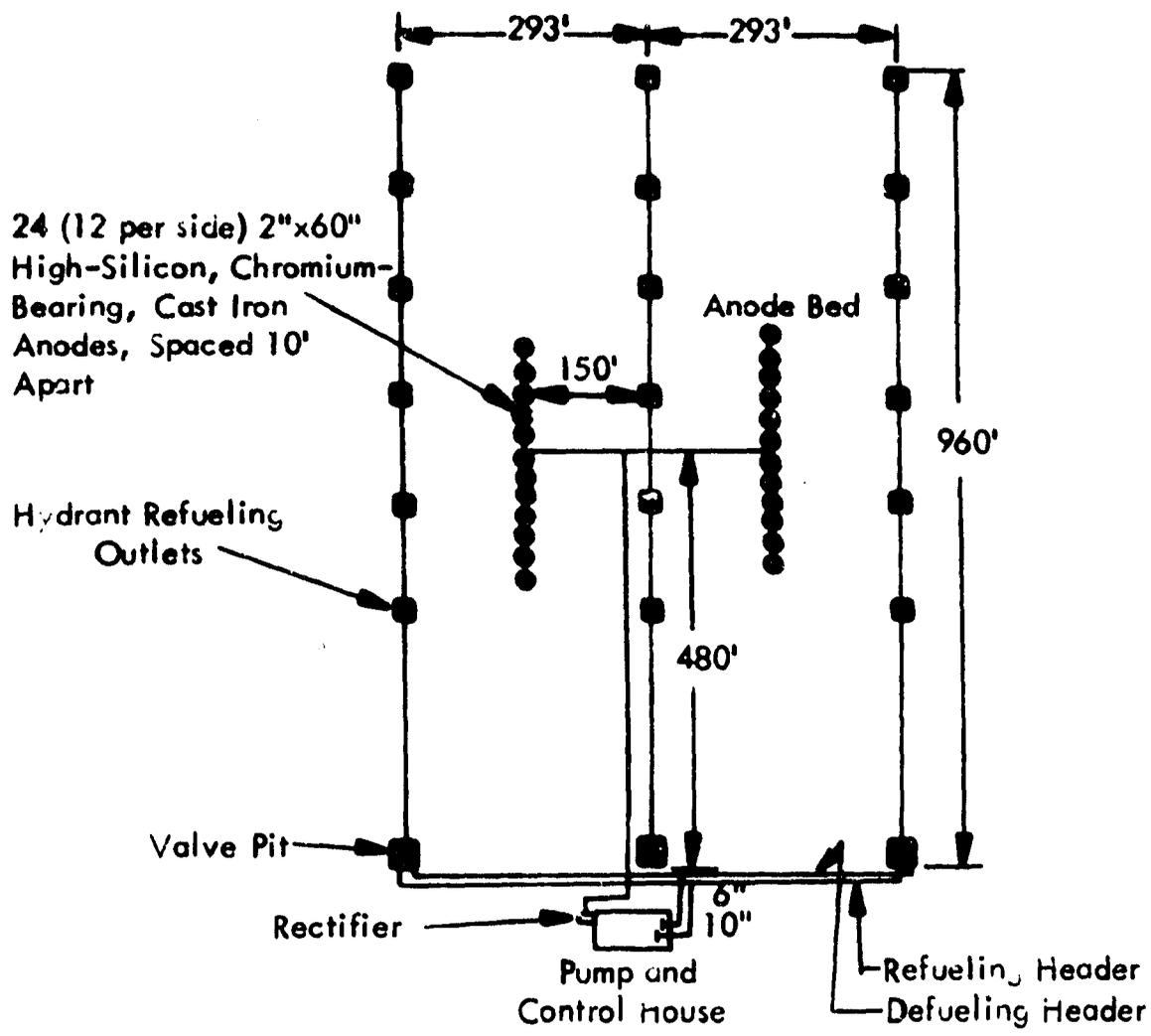


Figure 33
 IMPRESSED CURRENT POINT TYPE CATHODIC PROTECTION
 FOR AIRCRAFT HYDRANT REFUELING SYSTEM

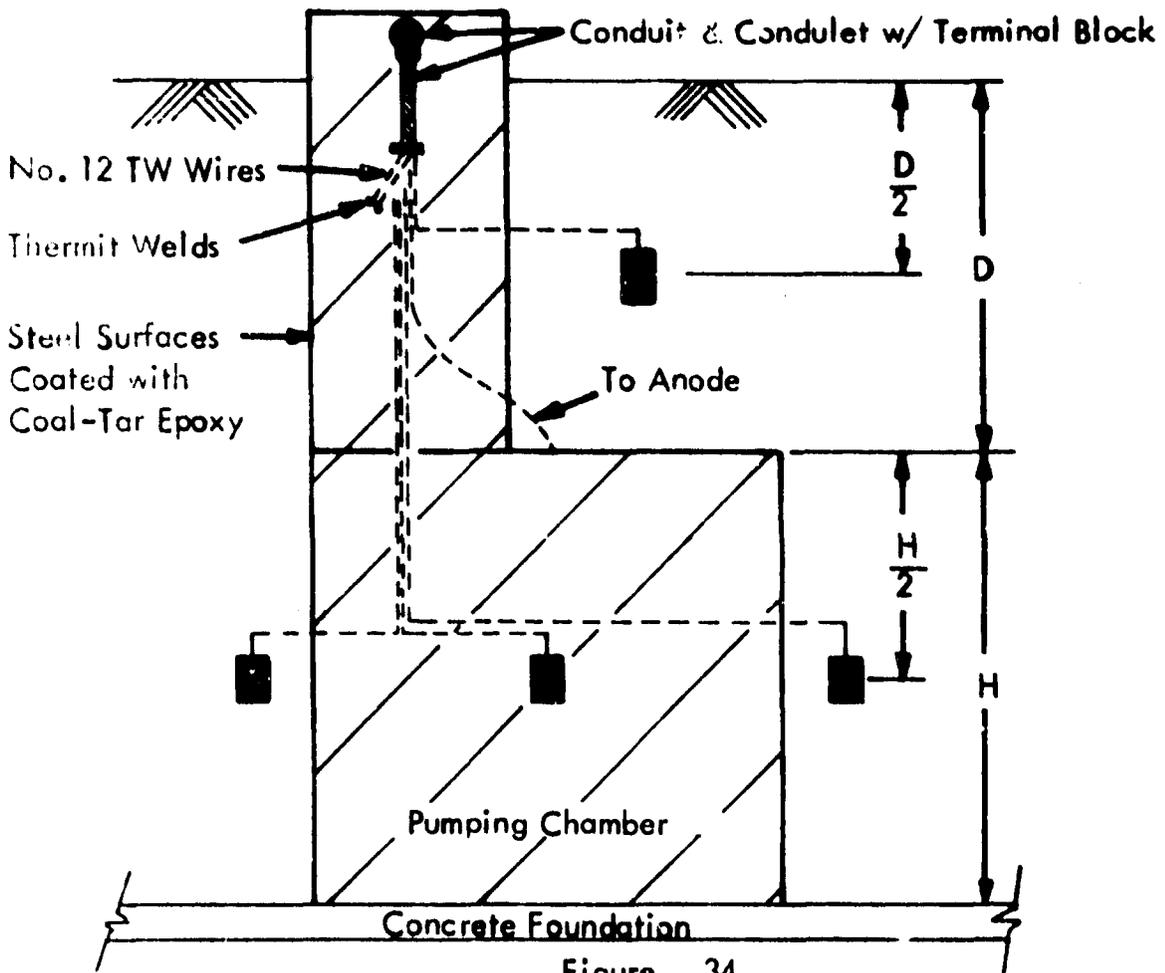
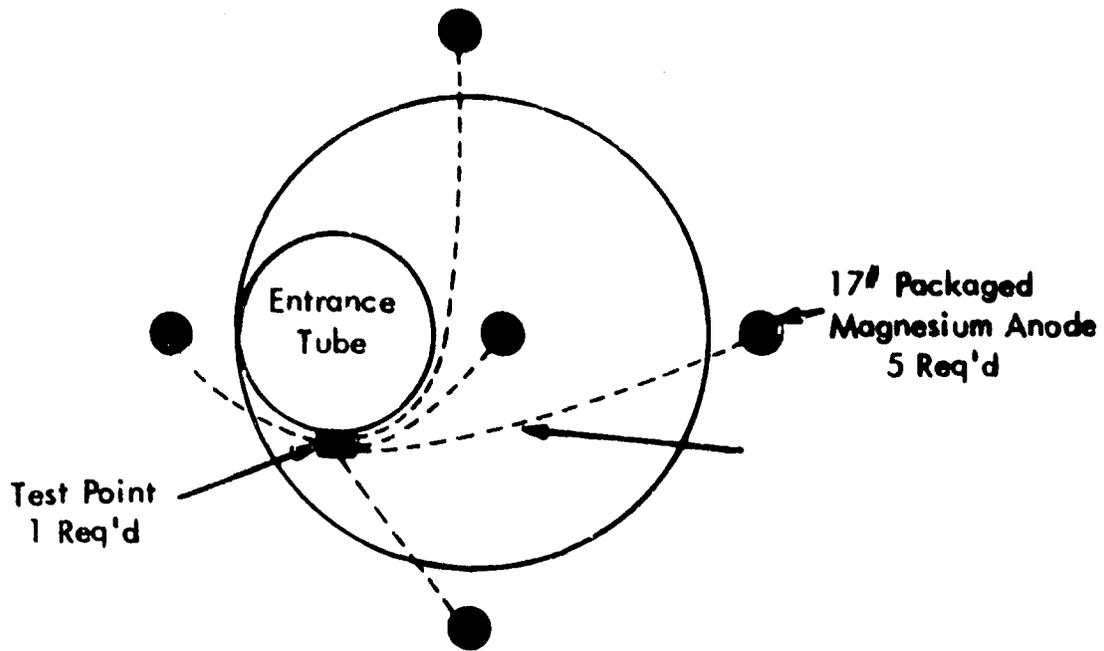


Figure 34
 GALVANIC ANODE TYPE CATHODIC PROTECTION
 FOR COATED UNDERGROUND SEWAGE LIFT STATION

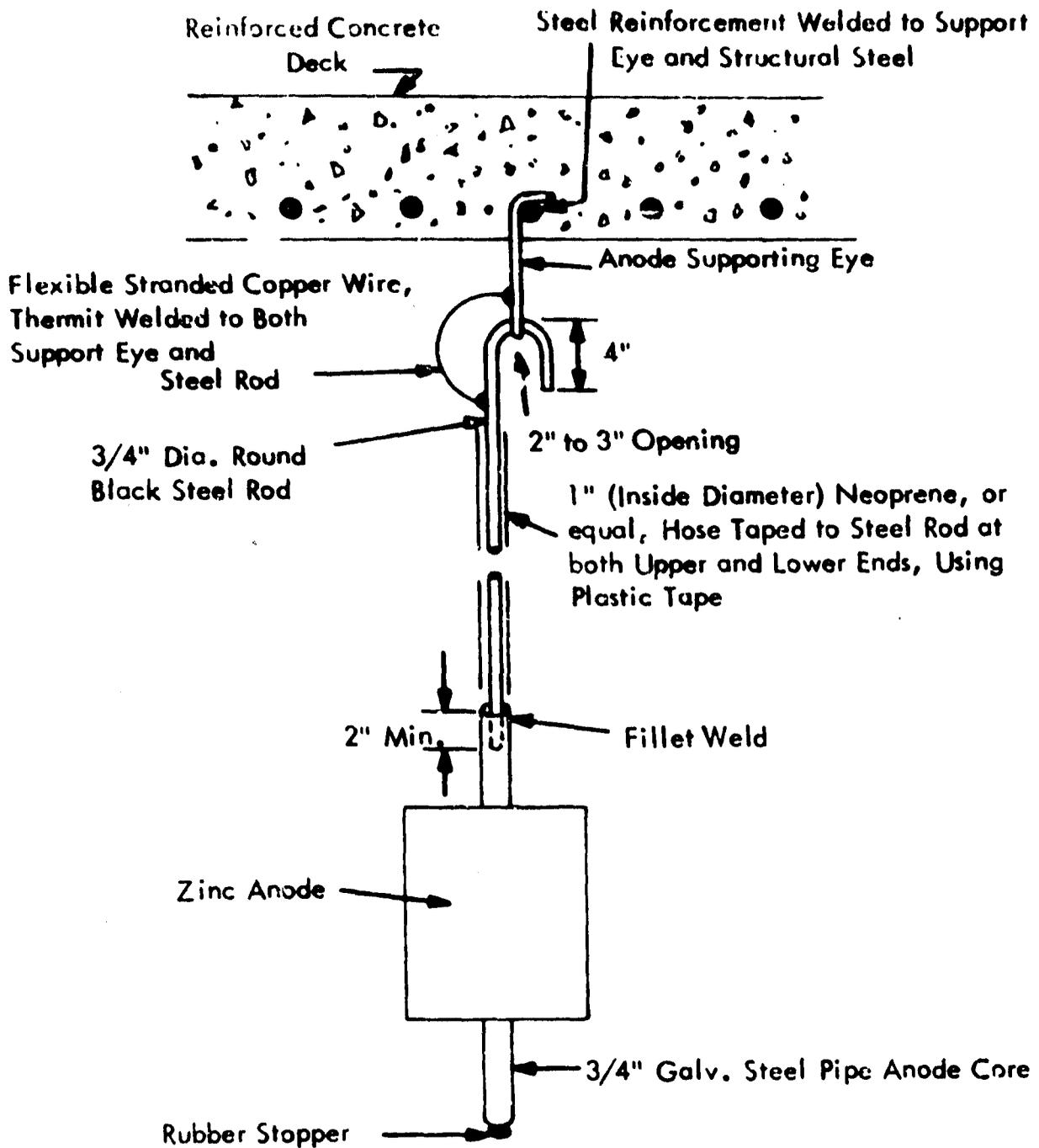


Figure 35
 ZINC ANODE ON REINFORCED CONCRETE BLOCK

Plan View Building

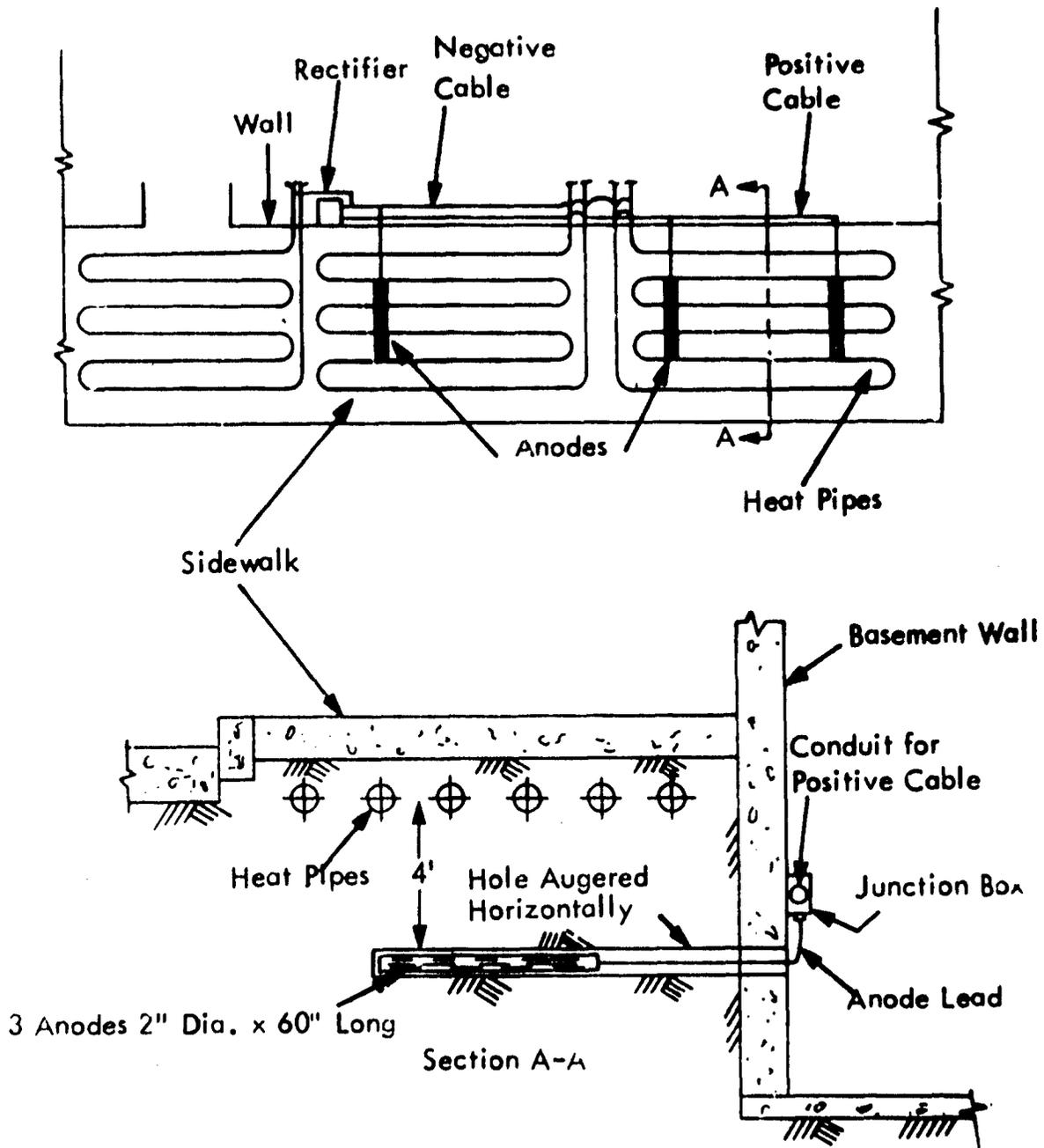


Figure 36
RADIANT HEAT OR SNOW-MELTING PIPING

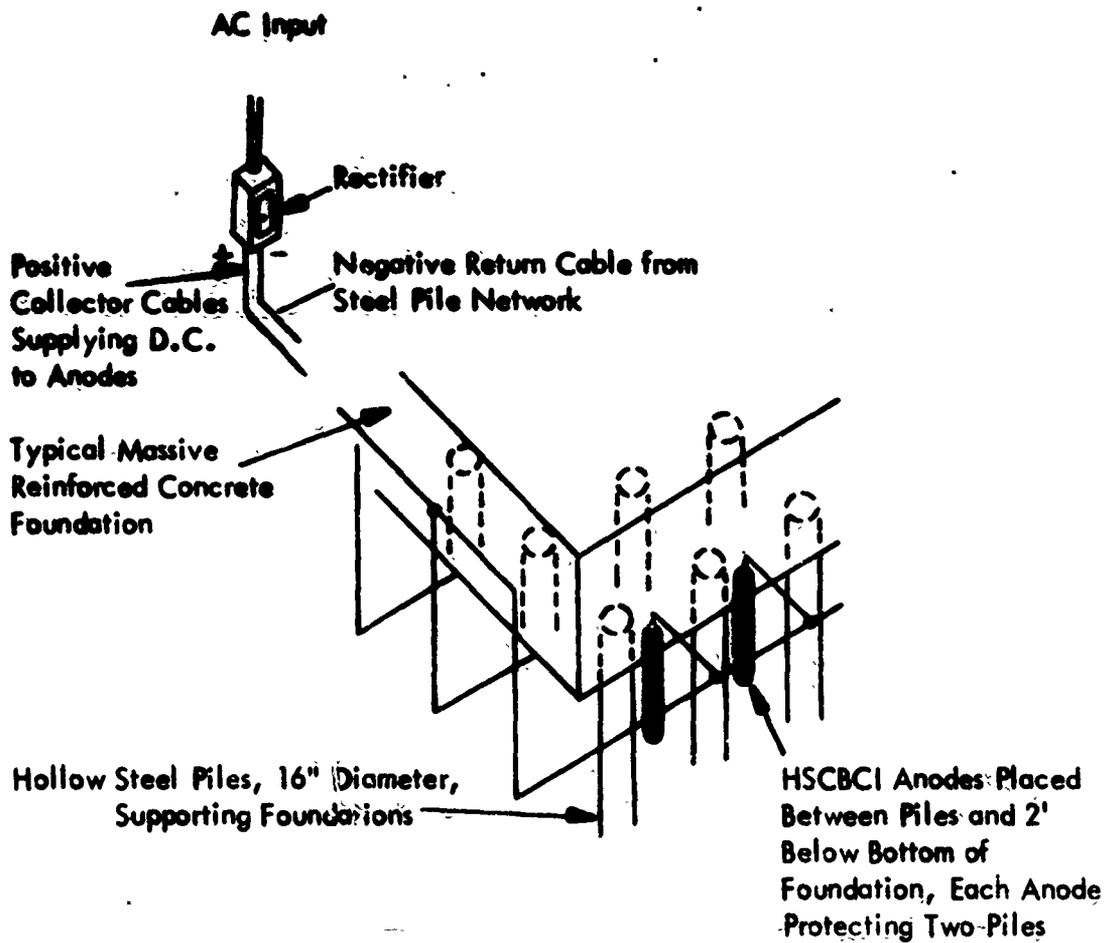


Figure 37
 CATHODIC PROTECTION OF FOUNDATION PILES

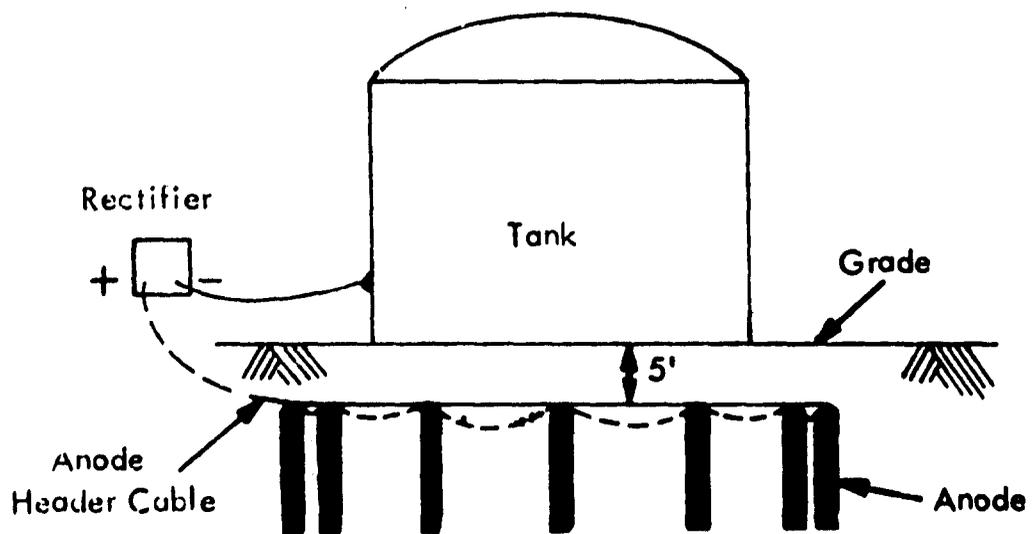
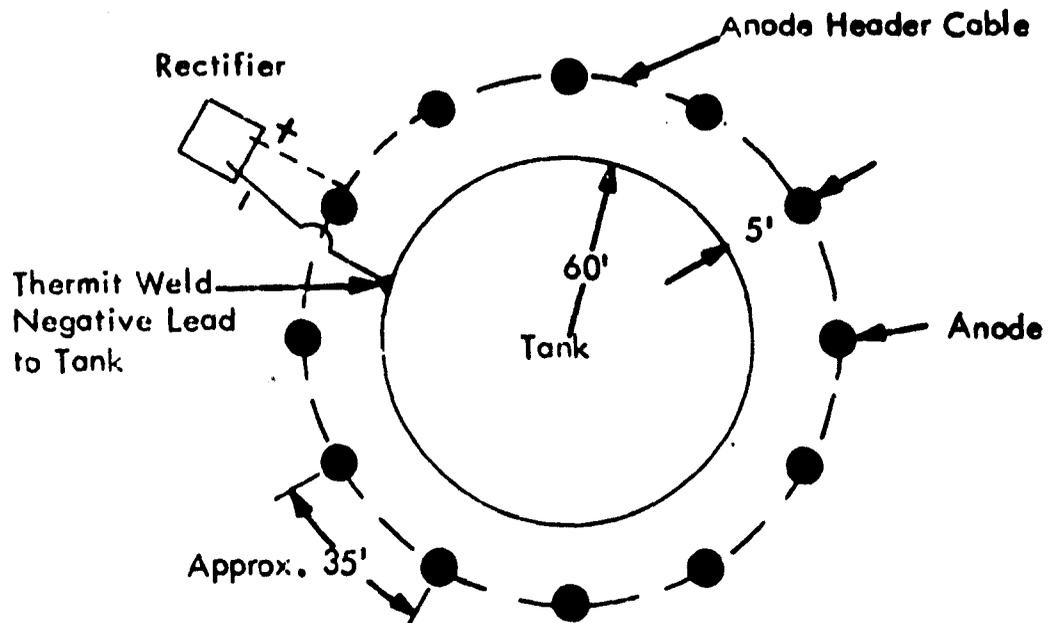


Figure 38
 IMPRESSED CURRENT CATHODIC PROTECTION
 FOR EXISTING ON-GRADE STORAGE TANK

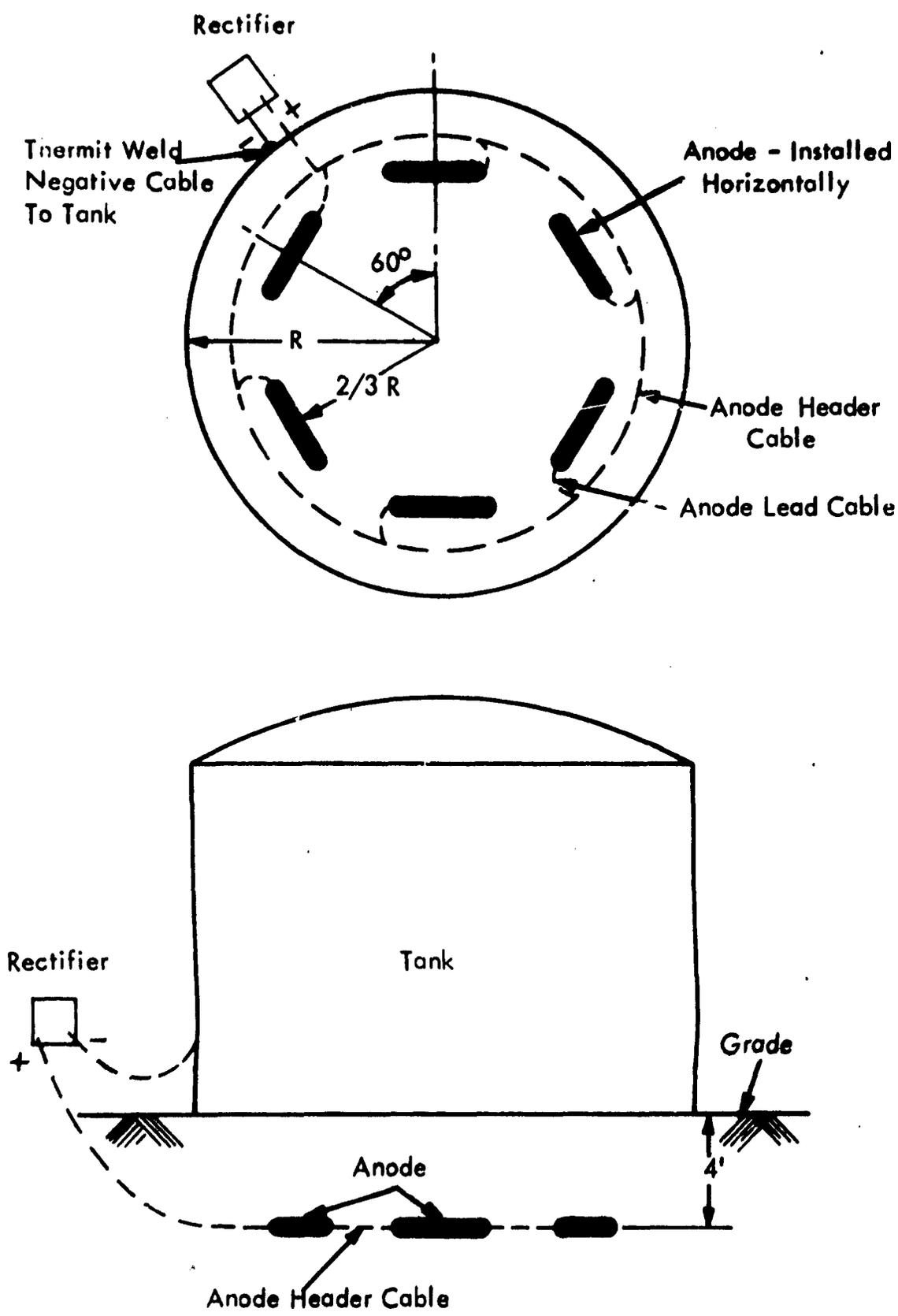
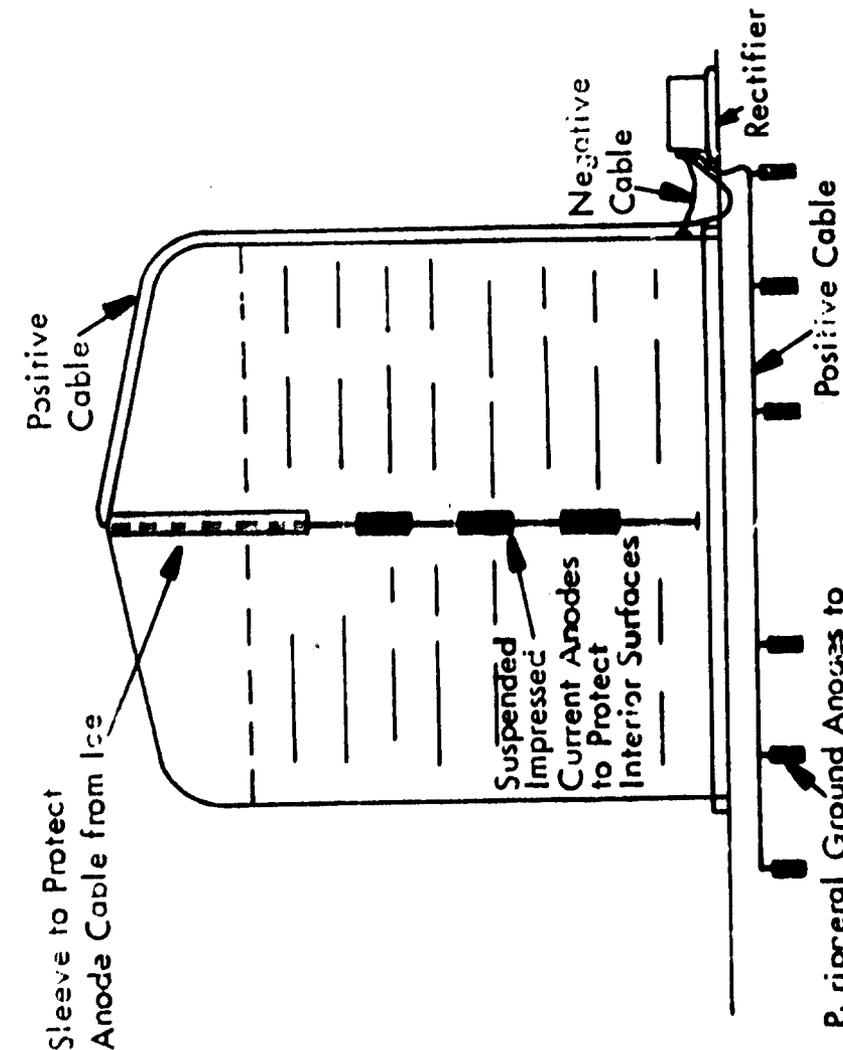
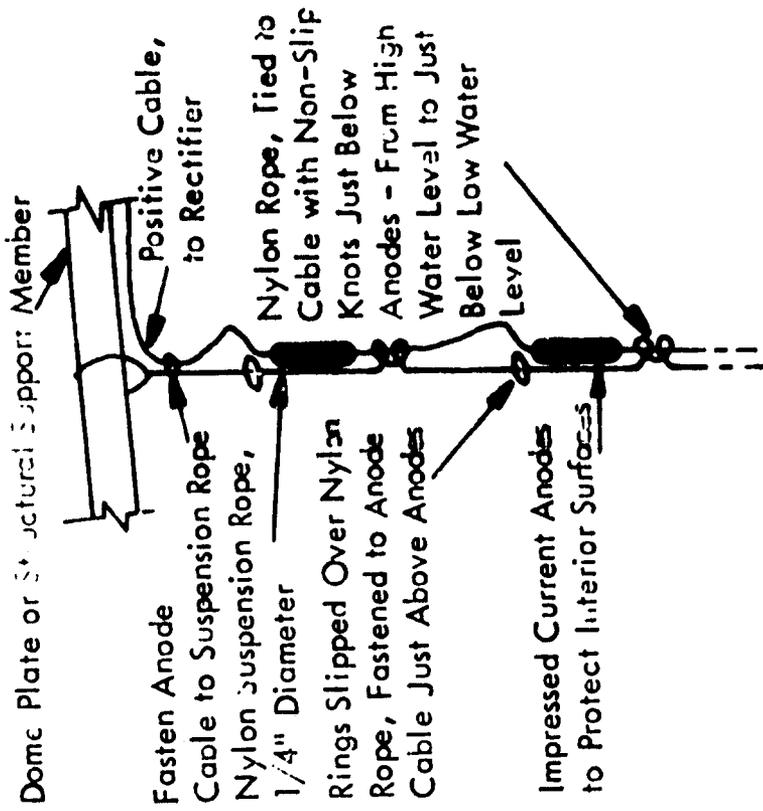


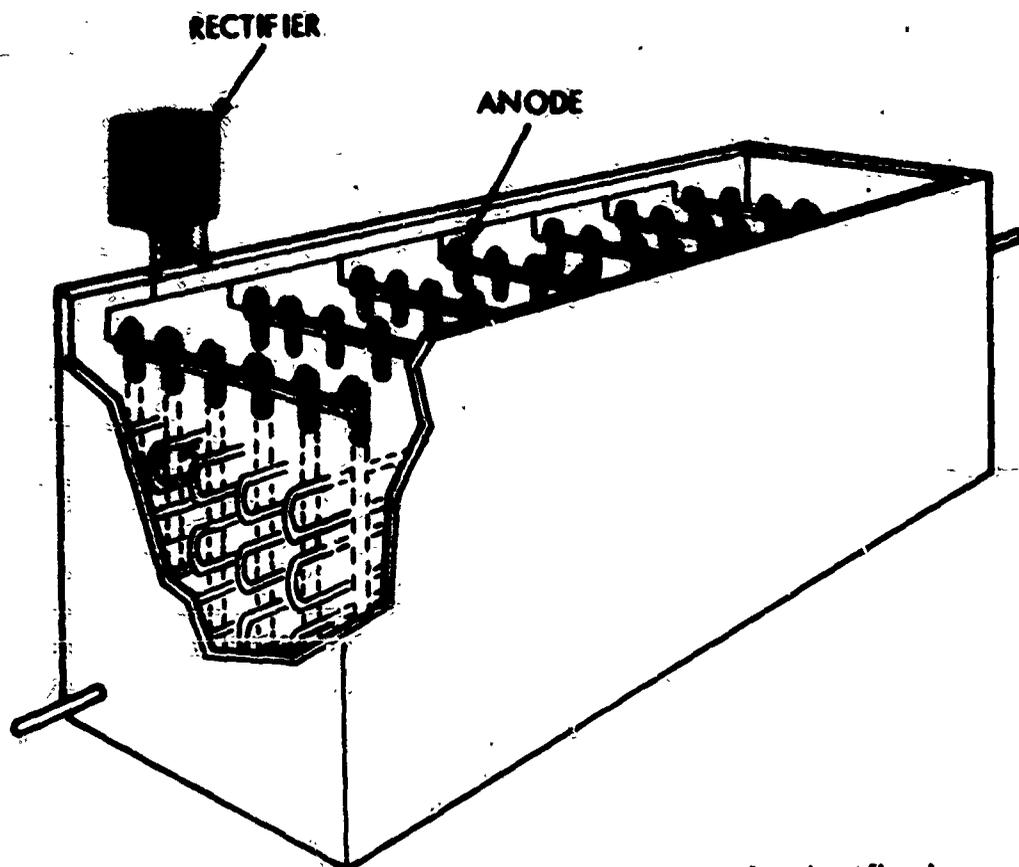
Figure 39
 IMPRESSED CURRENT CATHODIC PROTECTION WITH HORIZONTAL ANODES FOR ON-GRADE STORAGE TANK - NEW INSTALLATION



b) SUSPENDED ANODES, USING NYLON SUSPENSION ROPE (NO SLEEVE)

a) OVERALL VIEW, USING SLEEVE ON SUSPENDED ANODE CABLE

Figure 40 ON-GRADE FRESH WATER TANK USING SUSPENDED ANODES



These units are widely used for cooling purposes, often in refineries. Corrosion conditions are very aggressive. Space is limited between coils, and anodes 1-1/2" dia. x 60" long have been successfully used. They can be joined together to produce lengths 7-1/2 feet long.

Figure 41
OPEN WATER BOX COOLER

Horizontal tanks only support anode with 1/2 section of 2" pipe x 3" welded to head

1.315" dia. steel cored magnesium anode - thread 1" NPS one end

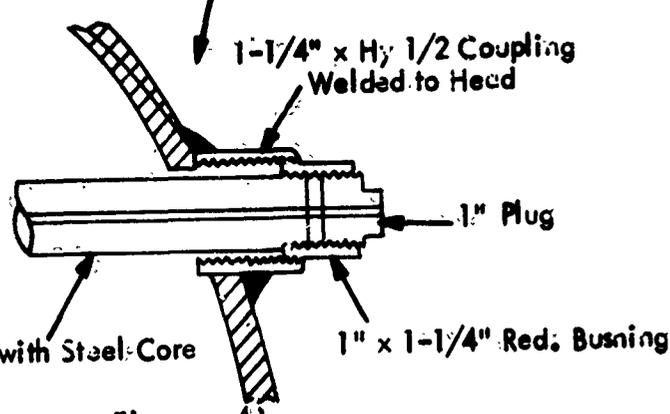
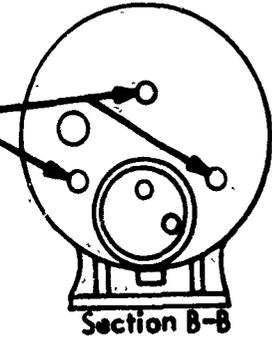
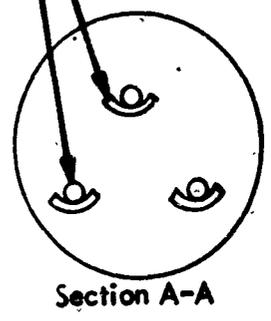
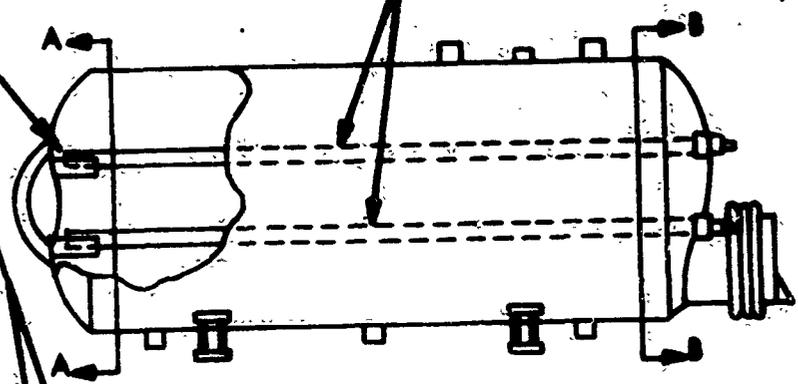


Figure 42

HORIZONTAL HOT-WATER TANK - MAGNESIUM ANODE INSTALLATION

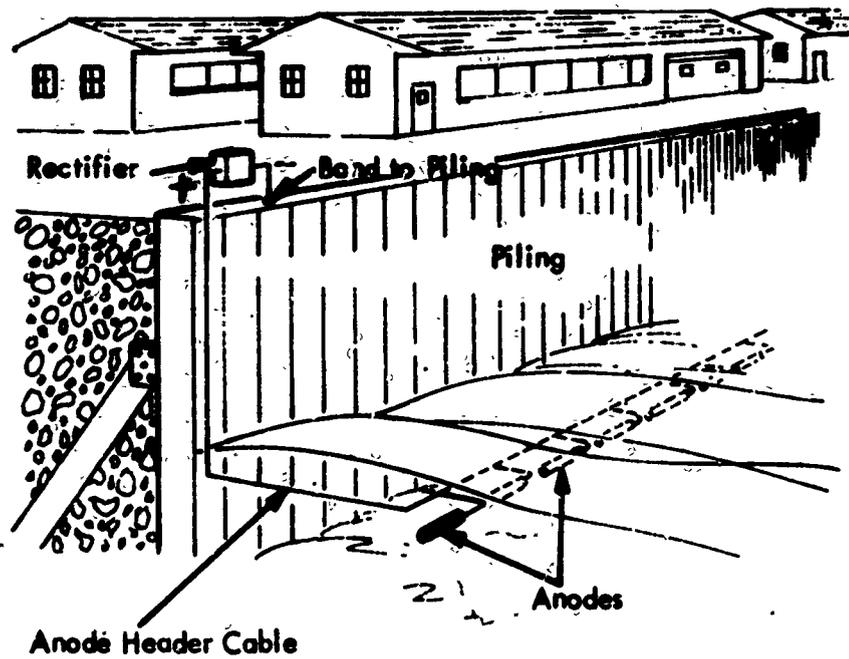


Figure 43
IMPRESSED CURRENT CATHODIC PROTECTION SYSTEM
FOR SHEET PILING FOR WHARF CONSTRUCTION

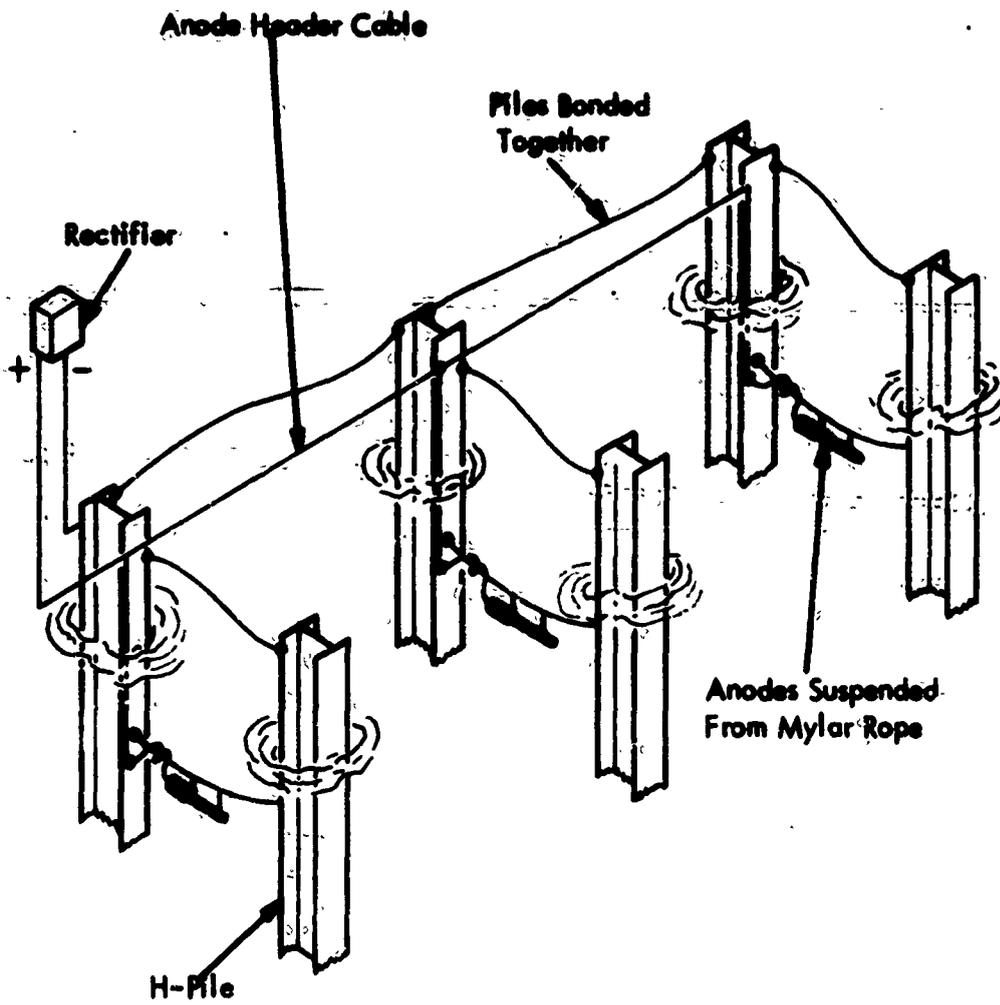


Figure 44
 SUSPENDED ANODE CATHODIC PROTECTION FOR H-PILING IN SEA WATER

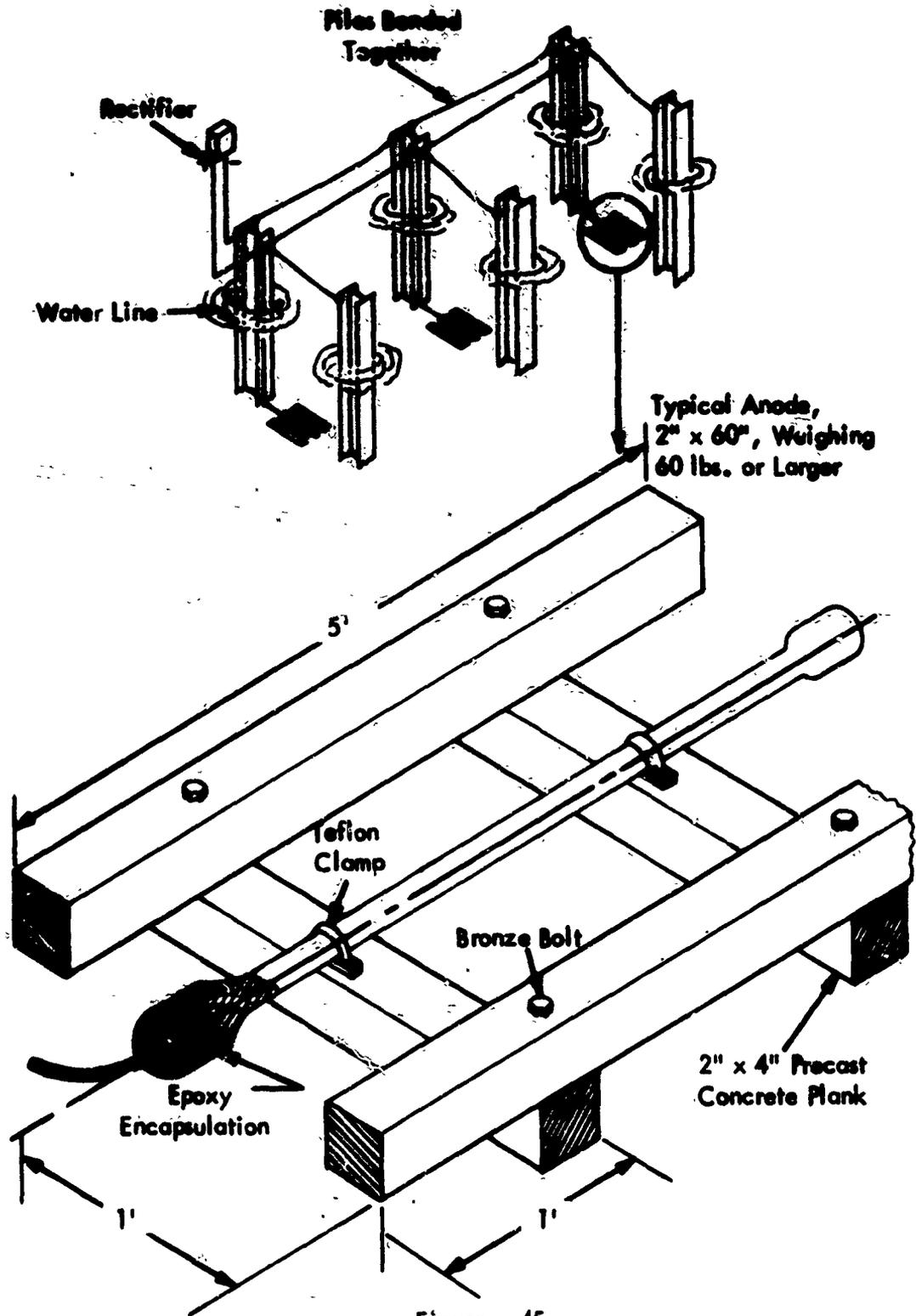


Figure 45
 CATHODIC PROTECTION FOR H-PILING IN SEA WATER

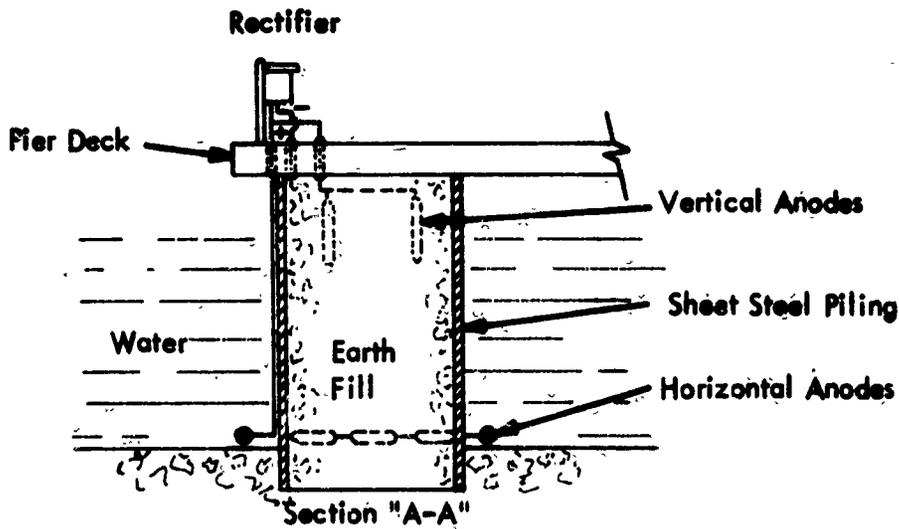
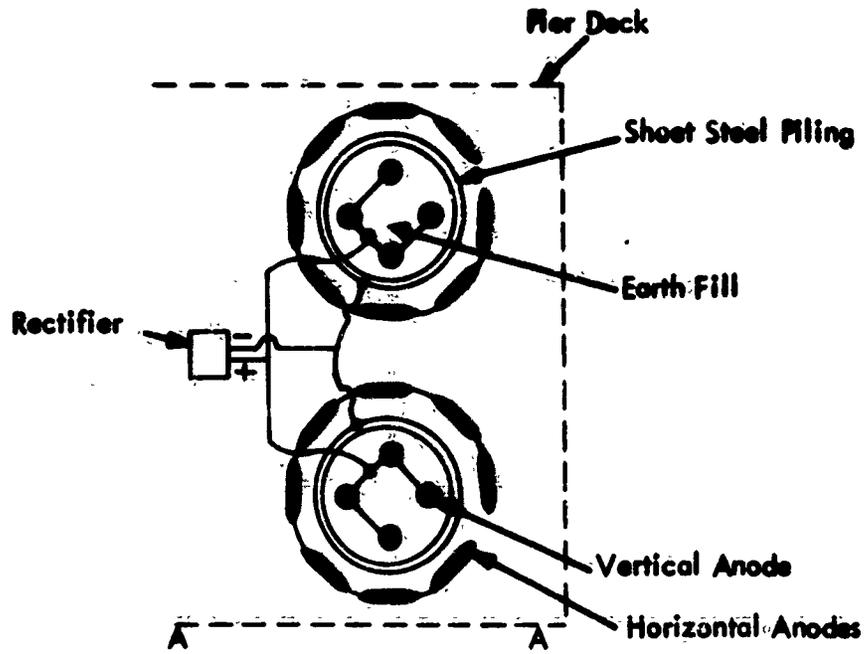


Figure 46
CELLULAR EARTH FILL PIER SUPPORTS

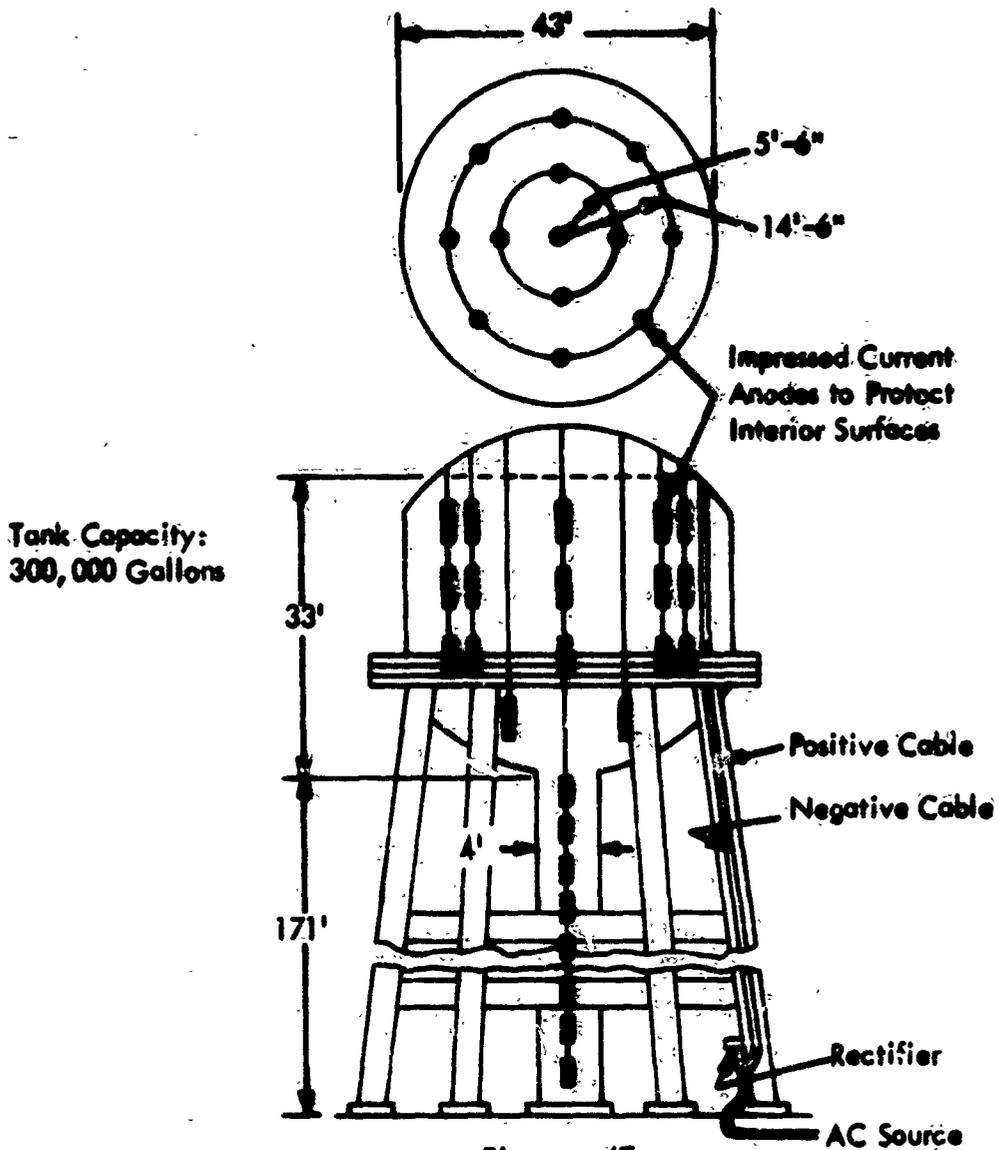


Figure 47
ELEVATED FRESH WATER TANK USING SUSPENDED ANODES

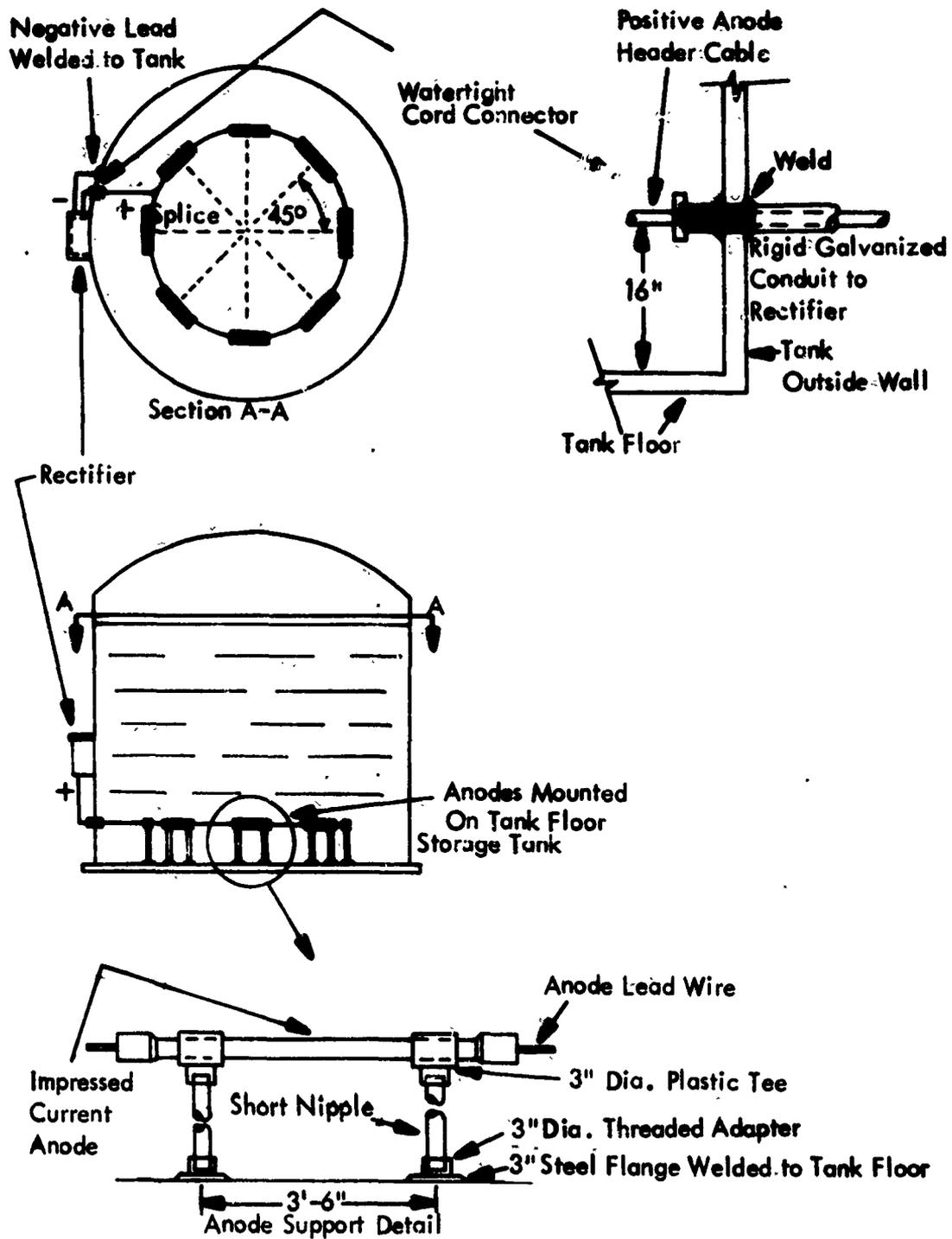
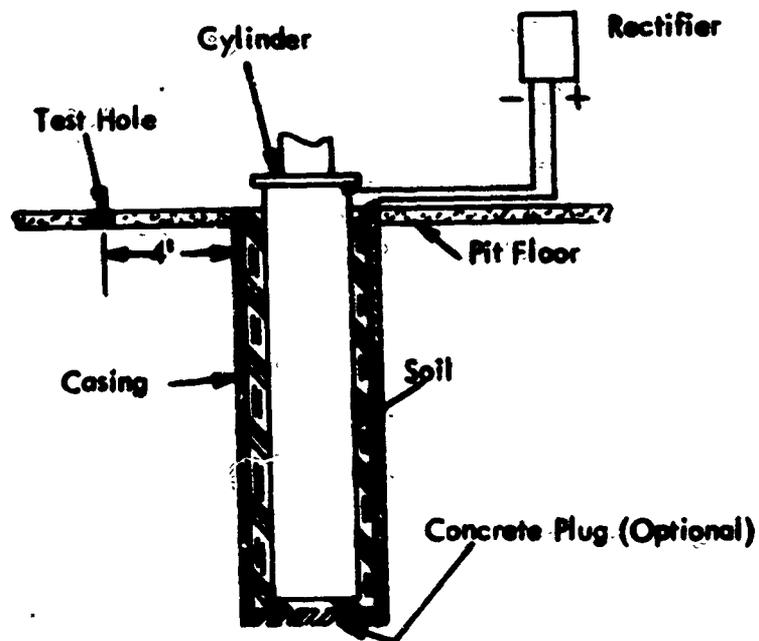
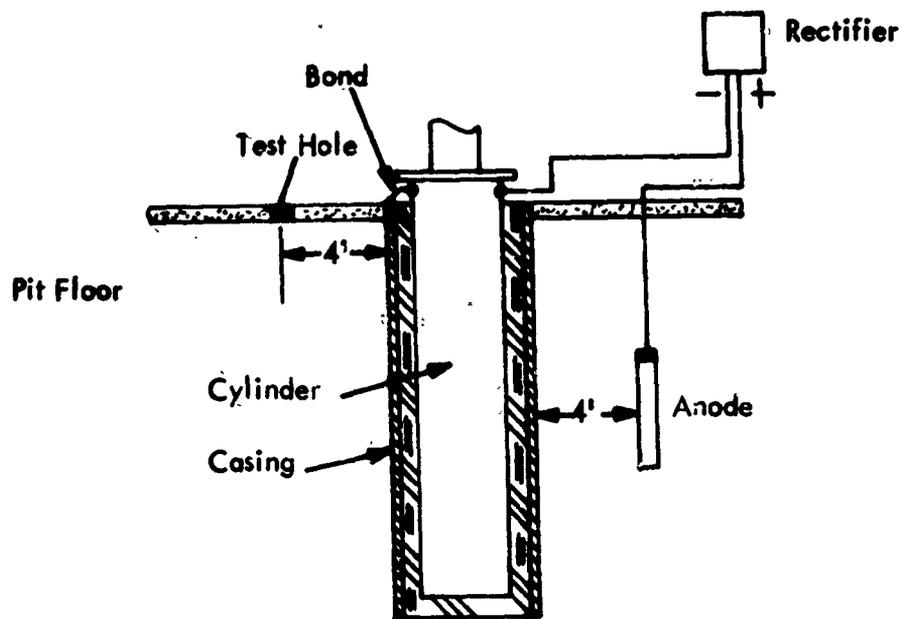


Figure 48
 CATHODIC PROTECTION OF TANKS USING RIGID FLOOR MOUNTED ANODES



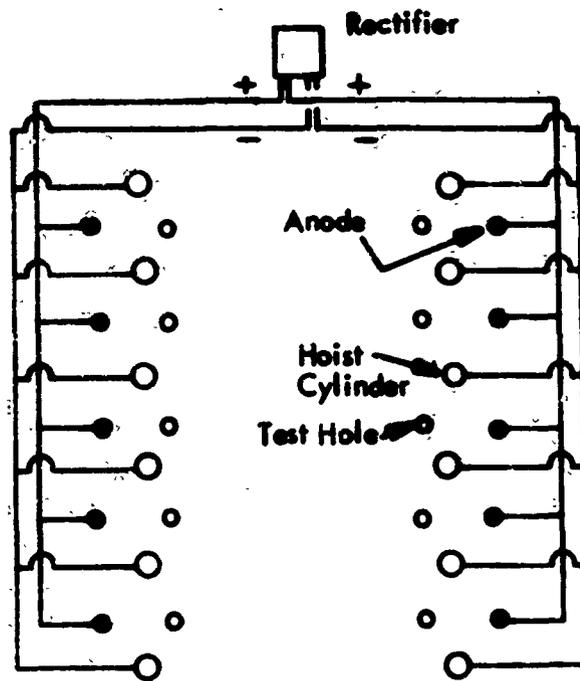
a) CASING AS ANODE. (TYPICAL) (CYLINDER NOT "SHORTED" TO CASING)



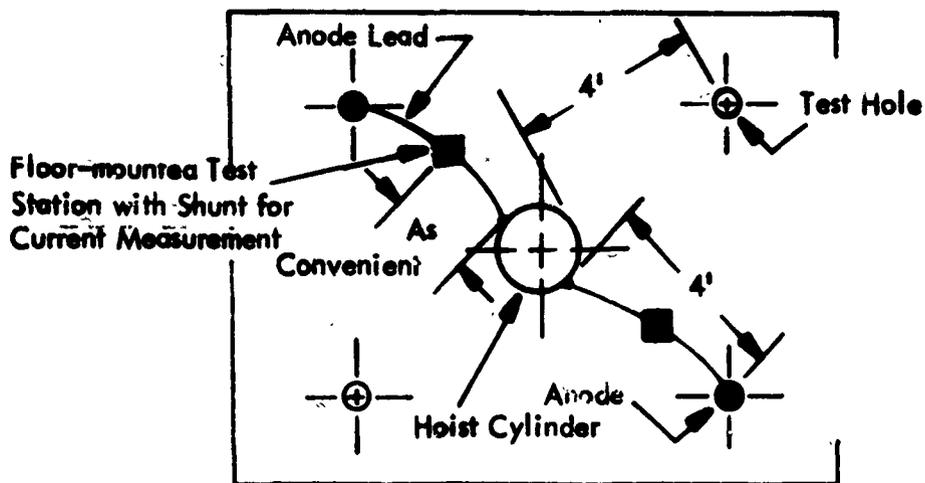
b) CYLINDERS WITHOUT CASINGS OR WITH "SHORTED" CASINGS (TYPICAL)

Figure 49

CATHODIC PROTECTION OF HYDRAULIC ELEVATOR CYLINDERS



a) IMPRESSED CURRENT CATHODIC PROTECTION (TYPICAL)



b) GALVANIC ANODE CATHODIC PROTECTION (TYPICAL) FOR ONE HOIST

Figure 50
HYDRAULIC HOIST CYLINDER

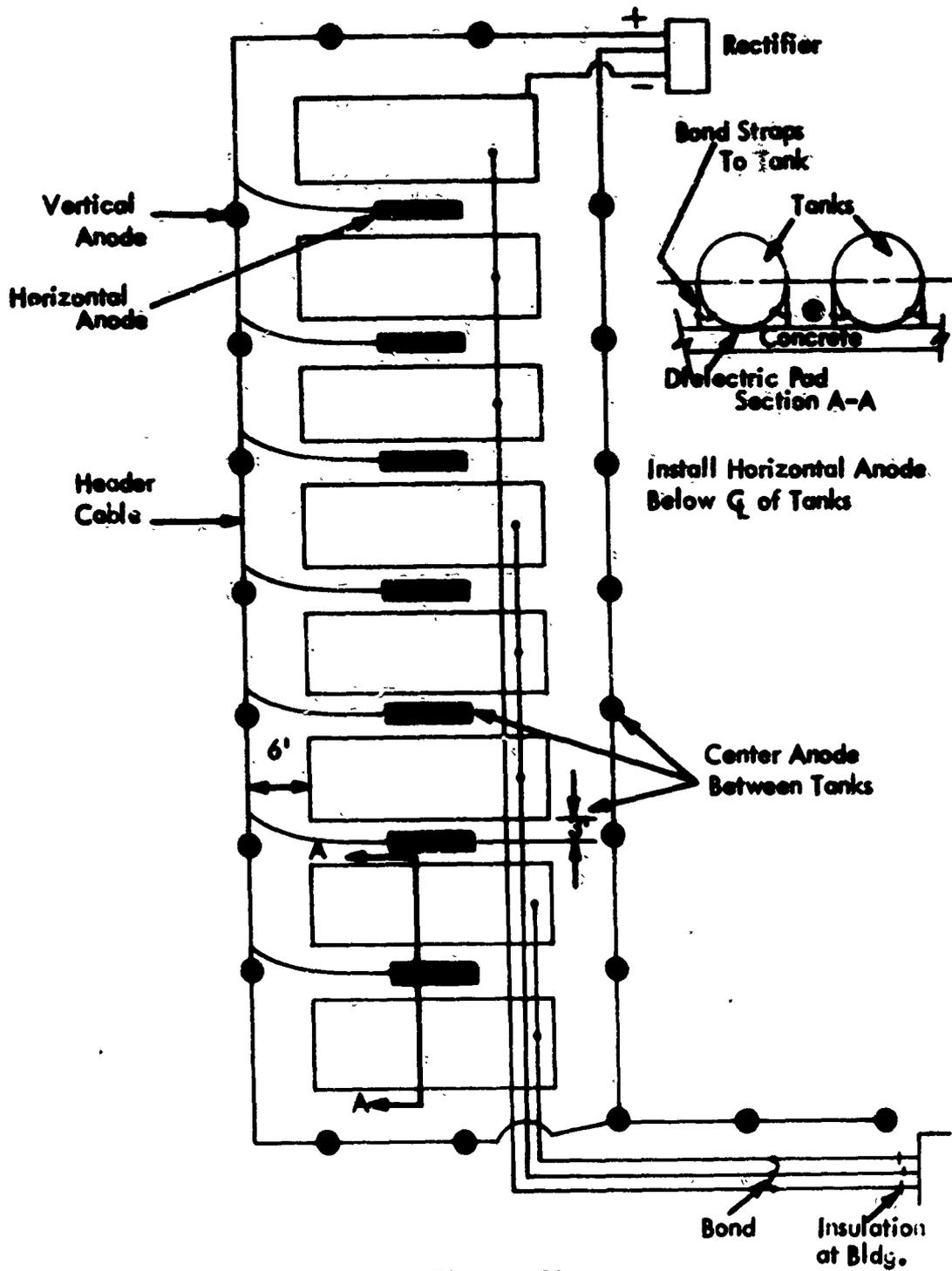


Figure 51
 TYPICAL CATHODIC PROTECTION OF UNDERGROUND TANK FARM

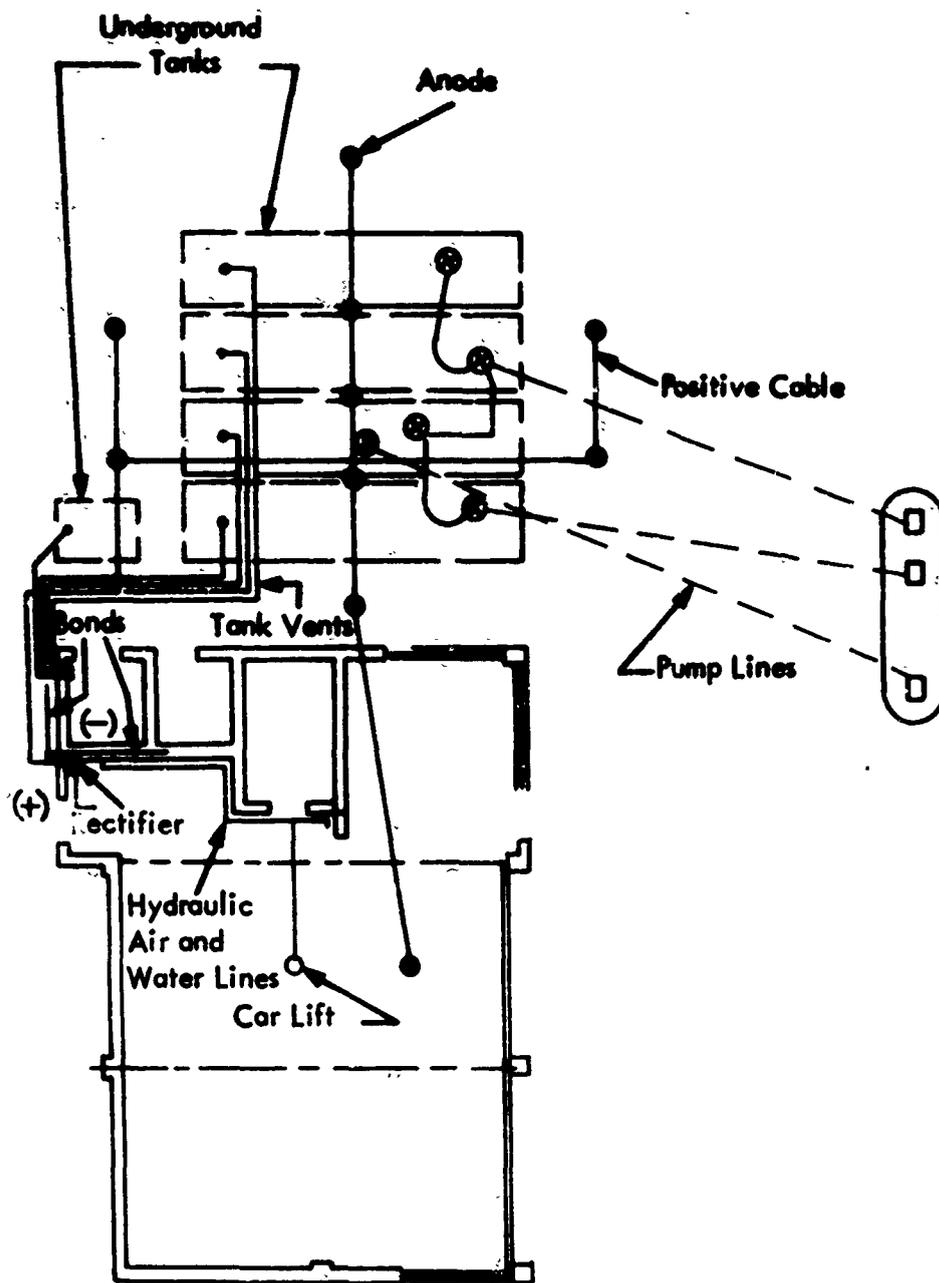


Figure 52
GASOLINE SERVICE STATION SYSTEM

An important aspect of design for either galvanic or impressed current cathodic protection is the current required to protect the structure. It is important to realize that structure current requirements are best determined by actual field tests whenever possible. Calculations based on estimated current densities (so many milliamperes/ft²) and surface areas are at best approximate. (Table 22 gives surface area per length of some standard size pipes and estimated current densities for various environments.)

Actual current requirements depend on many factors including number of points of current impression (attenuation), distribution of coating holidays, and homogeneity of electrolyte. These factors vary greatly from structure to structure and are difficult or impossible to predict. Only where current requirements cannot be determined in the field should calculations be used, and then it must be remembered that the results are only a rough estimate.

Table 22b may be used as a rough guide for expected current densities required for cathodic protection. This list is for bare steel. To arrive at a current density for coated steel, the percentage of uncoated metal should be determined or estimated and the proper factor applied to the tabulated current densities. Numerous exceptions to the table will be found to exist in practice, and it is emphasized that these figures should not be used in the design of a cathodic protection system without field test confirmation.

It should be noted that current requirements for the protection of galvanic couples far exceed the tabulated values given herein. In order to protect steel which is coupled to copper, with approximately equal areas of steel and copper, 10 to 30 times more current is required than is required to protect the steel only.

7.1.1 Examine Drawings and Specifications of the Structure to be Protected. Some approximation of metal surface conditions should be known. This may be limited to an investigation of whether the structure is coated or bare, the type coating used, years in service, etc.

Other structures (those not being cathodically protected) should be located, as should any electrically insulated parts of the structure being placed under protection. An abandoned metal pipe could possibly be used as an anode.

Table 22
a.) Pipe Surface Area

Pipe Size Inches	Outside Area, sq. ft. per lin. ft. of Pipe
2	0.622
3	0.916
4	1.178
6	1.734
8	2.258
10	2.82
12	3.34
14	3.67
16	4.19
18	4.71
20	5.24
24	6.28
30	7.85

b.) Estimated Current Densities for Bare Steel Structures¹

Environment	Ma. per sq. ft.
Neutral soil or water (pH 7)	0.4 to 1.5
Well-aerated, neutral soil or water (pH 7)	2.0 to 3.0
Sea water	3.0 to 10.0
Moving fresh water (velocity above 5 ft. per sec.)	9.0 to 25.0
Wet soils	1.0 to 6.0
Heated, in soil or moist concrete	3.0 to 25.0
Highly-acid soil	3.0 to 15.0
Anaerobic soil with active sulfate-reducing bacteria, initial requirement	6.0 to 42.0
Fresh water that is relatively still	1.0 to 6.0
Fresh water that is highly turbulent and contains much dissolved oxygen	5.0 to 15.0
Hot water	5.0 to 15.0
Mildly acid or alkaline solution in process tanks, depending on turbulence and temperature	1.0 to 25.0
Brine tanks	8.0 to 10.0

¹ Taken from AFM 88-9 Chapter 4 "Corrosion Control" - original source unknown.

Fixtures, brackets, and available mountings which could be used for mounting cathodic protection appurtenances should be noted. If the installation is to be connected to a buried pipeline, simplest location from the construction viewpoint should be noted and property owner's name and address determined.

Location and type (phase, voltage, capacity) of A.C. power supplies should be determined.

A cursory analysis of the above gives the engineer basis for selection and/or revision of a tentative location and general positioning of anodes.

7.1.2 Obtain "Field", or At-The-Site Data. Resistivity of the electrolyte should be measured. Field measurements are sometimes supplemented or replaced by laboratory tests on samples; pH and sulfide content of electrolyte are often included.

If practical, current requirement tests should be conducted. Temporary anodes can be placed in the electrolyte and current can be forced out of them with a generator, batteries, or other D.C. power source. Effects on both the structure to be protected and others in the area (including electrically insulated portions of the protected structure) should be carefully noted.

Physical measurements should be taken to verify location and dimensions of the structure to be protected and, at the same time, position of other structures. Existence and availability of power should be verified.

Base operating and/or maintenance personnel should be consulted, to determine their feelings as to the practicality of the proposed installation. Their cooperation is important.

7.1.3 Choice of Galvanic or Impressed Current. The type cathodic protection best to use is decided mainly from two factors: feasibility and relative costs. Feasibility includes analysis of physical and electrical conditions at the structure location. Superficial economic analysis determines approximate costs.

Factors to consider include desired structure life, power availability, location of other structures, environmental conditions, possible changes in environment or structure, accessibility, and possible damage from vandalism or natural conditions. It is usually feasible to use either impressed current or galvanic anodes, and an economic analysis tempered by the above considerations determines the choice.

Economics include initial operating, maintenance, and replacement costs. Based on current requirements, the cost per ampere-year is estimated. This figure, combined with the analysis of system feasibility, determines whether galvanic or impressed current cathodic protection should be used.

7.1.4 Notify Operators of Other Structures in the Area. The operators of any other structures in the area should be notified of tentative plans for impressed current cathodic protection. This notification should also include the local corrosion coordinating committee, if there is one in the area. The notification procedure is primarily of importance in underground and submerged installations. However, process equipment, tanks, etc., may also become involved.

7.1.5 Design Cathodic Protection System. All data and information gathered in the preceding steps must be assembled, analyzed and developed into a cathodic protection system design. During this design phase, coordination with base operating and maintenance personnel is necessary to insure that the completed system does not interfere with other equipment and/or normal operations. It is also advantageous to have the interest of all personnel behind the project to insure proper operation and maintenance.

7.2 Fundamentals of Design. A cathodic protection system is an electrical circuit. To design cathodic protection, the various parts of this circuit must be related and analyzed. In this section, a basic cathodic protection circuit is examined, factors to consider in actual design are discussed, and information required prior to design is considered. This information is general, applying to both galvanic and impressed current unless otherwise noted.

7.2.1 Total Circuit Resistance. The total circuit resistance (external to the power source in impressed current systems) must be considered and kept in mind at all times. Critical components which control this are:

- a. Anode to electrolyte interface
- * b. Structure to electrolyte interface
- c. Connecting cables
- d. All connections and splices

* Note: Structure-to-electrolyte interface resistance is usually a minor portion of the total circuit resistance and cannot be controlled by the engineer. This usually increases with the passage of time and increased current density.

Anode-to-electrolyte resistance is usually the controlling factor (greatest single influence) which must be given more consideration than any other item in cathodic protection

design. This quantity is made up of the total resistances of all anodes used. Since each anode-to-electrolyte resistance is parallel to the others, the more anodes used the lower the "effective" anode-to-electrolyte resistance, and the lower the total circuit resistance becomes.

Anode-to-electrolyte resistance can be computed from data on anode size, shape, and configuration plus soil resistivity. This method is sometimes in error because of the infinite number of anode configurations possible which require extrapolation from limited empirical data, and also because of its dependence on reliable electrolyte resistivity measurements. (Resistivity - especially in soil - varies with moisture, temperature and location of test.)

Errors in anode to electrolyte resistance calculated from empirical data will result in errors in anode current output. This can be very serious with a galvanic anode system, because additional current can be supplied only by adding more galvanic anodes. This is costly and time-consuming. For impressed current cathodic protection, the error usually requires a change in rectifier output; if the installed rectifier is not of sufficient capacity, replacement may be required. Efficiency may be decreased. For these reasons, many engineers first measure structure to anode resistance by actually impressing current into installed impressed current anodes or using a test anode installation for galvanic systems. In this way, a rectifier can be sized to actually "fit" the circuit resistance or a reasonable number of galvanic anodes selected without reliance upon questionable test and empirical data. This has the disadvantage of delaying completion of an installation. However, it means that sufficient cathodic protection current will be supplied in an efficient manner.

7.2.2 Design Factors Requiring Analysis. The following items should always be analyzed when cathodic protection is being designed.

a. Anode-to-electrolyte resistance, as previously mentioned, often controls the entire circuit resistance and therefore must be analyzed in detail. The following factors must be studied:

- (1) Electrolyte resistivity (soil, water, or chemical)
- (2) Resistance between a single anode and surrounding electrolyte (anode-to-electrolyte interface resistance)
- (3) Effects of anode configuration and spacing between them
- (4) Anode(s) location, with respect to structure being cathodically protected as well as other structures
- (5) Anode position (vertical or horizontal). If either position is practical, both should be explored.

b. Weight of anode required to give the desired life. This can be estimated from approximate anode deterioration rates and efficiencies (Table 23). These values vary depending on electrolyte and other conditions.

Table 23

<u>Approximate Anode Deterioration Rates</u>		
<u>Anode Material</u>	<u>Deterioration Rate (lbs./amp.-year)</u>	<u>Efficiency (percent)</u>
Steel	20	50
HSCBCI	1	50
Graphite	2	50
Magnesium	8.8	50
Zinc	23.5	90

c. Special backfill around anodes (other than soil) is often advantageous. This should be carefully considered because it does add extra cost to an installation which may or may not be justified.

d. Resistance of positive and negative cables is a portion of total circuit resistance which adds to power costs. On the other hand, money spent on cable which is larger than necessary is not wisely used.

e. Vulnerability to physical damage must always be considered. Anodes, cables, connections, etc. must all be carefully placed to minimize this possibility. Cathodic protection must operate continuously to be effective. Damage to components not only interrupts protection, but also means costly repairs.

7.2.3 Measurements and Other "Job-Site" Data.

a. Electrolyte resistivity should be measured. This is usually done by use of field instruments or soil box. It is an important item in the computation of anode-to-electrolyte resistance, and may affect anode life.

b. Chemical analysis and/or other information on the electrolyte into which anodes are to be placed should be obtained. This information is used as a guide in the selection of the proper alloy anode, and special precautions to be taken with the installation. Anode life can be extended by using the anode suited for its environment.

c. Physical characteristics of the site where the system is to be installed must be studied and understood. This will insure a long life with trouble-free operation because with this information the design can be tailored to the specific situation.

7.3 Preliminary Field Data. As mentioned previously, the cathodic protection system designer must first obtain information from the actual job site. This information consists of electrolyte resistivity, chemical content,

measurement, location of the other structures, verification of dimensions, operational data on existing anodes, general data relating to coatings, unusual features, etc.

7.3.1 Electrolyte Resistivity. Electrolyte resistivity may be measured in the field or by laboratory analysis of a sample. The data are used to compute anode-to-electrolyte resistance, number of anodes required, and estimated anode life. If the electrolyte is soil, electrolyte resistivity measurement will also help establish the most favorable location to install anodes. In the field, electrolyte resistivity can be measured by the 4 pin vibroground method. Sample of water, chemicals, or soil can be tested in a "soil box."

7.3.2 Chemical Analysis. A partial chemical analysis of the electrolyte is often helpful to indicate corrosivity. pH, presence of sulfates, and any other applicable factors may be determined by field or laboratory methods.

7.3.3 General Information on Structure to be Protected. General information on the structure must be obtained before beginning design of the cathodic protection. This can be gathered by visiting the site, examining the structure itself plus available plans and specifications, and measuring key dimensions so that actual "as-built" data are available. Base personnel and/or others should be consulted. Data on the following is the minimum requirement:

- a. Material and type of construction (metal alloy, type pipe joints, etc.)
- b. Coatings used. (Type, method of application, inspection procedure, etc.)
- c. Density of soil and/or other characteristics of electrolyte. (Moisture content, seasonal variations, tidal conditions, current or turbulence, etc.)
- d. Any unusual characteristics and miscellaneous. (Areas of concentrated corrosion attack, configuration of structure, tentative anode configuration, location of A.C. power lines, abandoned structures which might serve as anodes, etc.)

7.3.4 Foreign Structures. The location of any other structures in the vicinity of the protected structure should be determined. All available drawings must be carefully examined. Discussions with base personnel and also personnel known to be operating plants in the area often reveal the presence of buried structures not otherwise noticed. This step is especially important when cathodic protection current is being impressed into the soil to protect buried pipelines, cables, or tanks.

If other such structures are discovered in the area, the

engineer should first find out, by consultation with the owner's representative, whether or not cathodic protection is being used. If it is, he should then conduct tests with the other parties in order to determine any effect to his own structure. If cathodic protection is not now being used in the area by other organizations, consultation with representatives of these groups will determine their interest and willingness to cooperate. Occasionally, it is possible to design "cooperative" or "jointly-owned" cathodic protection systems. This possibility should be investigated and may become practical if other companies are interested in cathodic protection. Considerable savings may result by sharing installation and operating costs.

7.4 Anode-to-Electrolyte Resistance. As mentioned earlier, anode-to-electrolyte resistance is an important part of total cathodic protection system circuit resistance. In general, the more anodes used, the lower this resistance. Also, with a fixed number of anodes, lower electrolyte resistance will mean lower anode-to-electrolyte resistance. The anode-to-electrolyte resistance of a vertical cylindrical anode is somewhat lower than that of a horizontal cylindrical anode suspended in the same electrolyte.

High anode-to-electrolyte resistance means high power costs for the impressed current cathodic protection system. By adding anodes, anode-to-electrolyte resistance is reduced but initial investment in material and labor is increased. The designer must balance the economics of operating expense vs. initial capital investment to the advantage of his accounting system.

High anode-to-electrolyte resistance means low current output for galvanic anodes, because voltage is constant - a function of anode, structure, and electrolyte composition. Additional anodes are required to obtain greater galvanic current output; this also increases initial investment.

If the anode size, anode position (vertical or horizontal), and electrolyte resistivity are known, anode-to-electrolyte resistance of a single impressed current or galvanic anode can be computed by application of various empirical formulae. Total anode-to-electrolyte resistance of an anode group can be computed by considering all in parallel and then applying the applicable "spacing factor". (Parallel anodes influence each other to increase their effective resistance. This influence is greater with closely-spaced anodes and decreases as distance between anodes increases.)

The resistance of anodes buried in soil can be lowered by surrounding them with carbonaceous backfill. This is beneficial in high-resistance soils. If soil resistivity is ten or more times backfill resistivity, the voltage drop of

anode current passing through backfill may become negligible with respect to voltage drop through soil. Thus, a back-filled anode's resistance may be considered lower than that of a bare anode because it is effectively longer and of greater diameter.

Increasing diameter and/or length of a cylindrical anode decreases anode-to-electrolyte resistance. However, changes in length have a greater effect than changes in diameter.

7.4.1 Basic Equations for Resistance Calculations.

The following expressions can be used to estimate anode-to-electrolyte resistance for horizontal and vertical anodes. These equations apply to both galvanic and impressed current anodes, and can be used for either standard or other cylindrical anodes. Simplified expressions for resistance of standard size impressed current anodes and current output of standard size galvanic anodes are given in paragraph 7.4.2.

a. Resistance of Single Vertical or Horizontal Anode.

The following formulae are relations developed by H.B. Dwight for a single cylindrical anode:

$$R_v = \frac{.0052 \varphi}{L} (2.3 \log \frac{8L}{d} - 1)$$

$$R_h = \frac{.0052 \varphi}{L} (2.3 \log \frac{4L^2 + 4L \sqrt{s^2 + L^2}}{ds} + \frac{s}{L} - \frac{\sqrt{s^2 + L^2}}{L} - 1)$$

where

- R_v = Electrolyte to anode resistance, single vertical anode to remote reference (ohms).
- R_h = Electrolyte to anode resistance, single horizontal anode to remote reference (ohms).
- φ = Electrolyte resistivity (ohm-centimeters)
- L = Anode length (feet)
- d = Diameter of anode (feet)
- s = Twice anode depth (feet)

For a single vertical anode, the following simplified expression can be used:

$$R_v = \frac{\varphi}{L} K$$

where

- R_v = Electrolyte to anode resistance, single vertical anode to remote reference (ohms).
- φ = Electrolyte resistivity (ohm-centimeters)
- L = Anode length (feet)
- K = "Shape Function", a function of anode length/anode radius which can be obtained from Table 24
- L/d = Ratio of length to diameter of anode (any units)

Table 24
The Shape Function (K)
(HSCBCI or Graphite Anodes)

<u>L/d</u>	<u>K</u>	<u>L/d</u>	<u>K</u>
5	.0140	20	.0213
6	.0150	25	.0224
7	.0158	30	.0234
8	.0165	35	.0242
9	.0171	40	.0249
10	.0177	45	.0255
12	.0186	50	.0261
14	.0194	55	.0266
16	.0201	60	.0270
18	.0207		

b. Resistance of Vertical Anode Group (One Row).
 The total anode-to-electrolyte resistance for a group of vertical anodes, connected in parallel and equally spaced in one row is expressed as follows:

$$R_n = \frac{1}{n} R_v + \frac{\rho_p P}{S}$$

R_n = Total anode to electrolyte resistance for a group of vertical anodes equally spaced and in one row (ohms).
 (A remote cathode is assumed.)

n = Number of anodes

R_v = Anode-to-electrolyte resistance of single vertical anode to remote reference, (ohms).

ρ_p = Electrolyte resistivity, measured with pin spacing equal to S , (ohm-centimeters).

P = "Paralleling Factor" can be obtained from Table 25.

S = Spacing between adjacent anodes (feet).

Table 25
Paralleling Factor, P

n	P	n	P
2	.00261	12	.00182
3	.00289	14	.00168
4	.00283	16	.00155
5	.00268	18	.00145
6	.00252	20	.00135
7	.00237	22	.00128
8	.00224	24	.00121
9	.00212	26	.00114
10	.00201	28	.00109
		30	.00104

c. Resistance of Vertical Anode Group (Two or More Rows). An anode group composed of two or more rows of vertical anodes, separated by a distance substantially larger than that between the anodes within a single row, has a total resistance approximately equal to the total parallel resistance of all the rows. The usual formula for paralleling resistances ($\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots$) is used.

7.4.2 Simplified Expressions for Resistance of Impressed Current Anodes.

a. Anodes in Soils. If vertical anode dimensions are assumed to be 8 to 12 inches in diameter and 10 feet in length, while horizontal anode dimensions are assumed to be one foot square in cross-section, 10 feet in length and 6 feet below the surface of the electrolyte; the following empirical formulae may be used. (These assumptions are useful when designing anode systems with 60-inch cylindrical impressed current anodes in soils where effective backfill has been installed around the anodes.)

$$R_v = \frac{\rho F}{537}$$

$$R_h = \frac{\rho F}{483}$$

R_v = Electrolyte to anode resistance, any number of vertical anodes to remote reference, (ohms).

R_h = Electrolyte to anode resistance, any number of horizontal anodes to remote reference, (ohms).

ρ = Electrolyte resistivity, (ohm-centimeters).

F = Adjusting Factor for groups of anodes (from Table 26).

Note: F = 1.0 where only one anode is used.

Table 26
Adjusting Factors for Parallel Anodes

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

Approximate anode-to-electrolyte resistance values for single anodes are quickly and easily obtained from the following:

$R_v = 0.0018\mathcal{P}$ for a vertically installed 60" anode in a 10-foot column of backfill, one foot in diameter.

$R_v = 0.0022\mathcal{P}$ for a vertically installed 60" anode in a 7 foot column of backfill, one foot in diameter.

$R_v = 0.0047\mathcal{P}$ for a vertically installed 2" x 60" anode, without backfill.

$R_v = 0.0050\mathcal{P}$ for a vertically installed 1-1/2" x 60" anode, without backfill.

R = Anode-to-electrolyte resistance for a single anode, in ohms.

where

\mathcal{P} = Resistivity of electrolyte (ohm-centimeters).

b. Anodes in a Water Tank. The following is a formula developed by E. R. Shepard for a single cylindrical anode:

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

where

R = resistance, (ohms).
 ρ = water resistivity (ohm-cm).
L = anode length (ft.)
d = anode diameter (same units as D).
D = tank diameter (same units as d).

If four or more anodes are used in a circle in a water tank, this equation is modified to read:

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

where

a = equivalent diameter factor from curve in Figure 53 times diameter of anode circle.

When short stub anodes are used in a water tank, considerable current fringing effects are prevalent at both ends. The actual resistance of a short anode is the fringe factor from curve in Figure 54 times R as calculated from the above equations.

A short anode is considered as one which has an L/d ratio less than 100. When a short anode is used singly, the L/d ratio is figured for the individual anode. However, when short anodes are used in a string, the L/d ratio is figured for the entire string. For example, five 1-1/2-in. dia. by 12-in. long anodes in a string would have an L/d ratio of 60/1.5 or 40. The L/d ratio for one of these anodes when used alone would be 12/1.5 = 8.

(1) Anode Spacing for Water Tanks. When impressed current anodes are used in a circle in a water tank, the following formula may be used to determine optimum radius of this circle:

$$r = DN/2(\pi + N)$$

r = radius of anode mounting from center of tank (ft.).
D = tank diameter (ft.).
N = number of anodes.

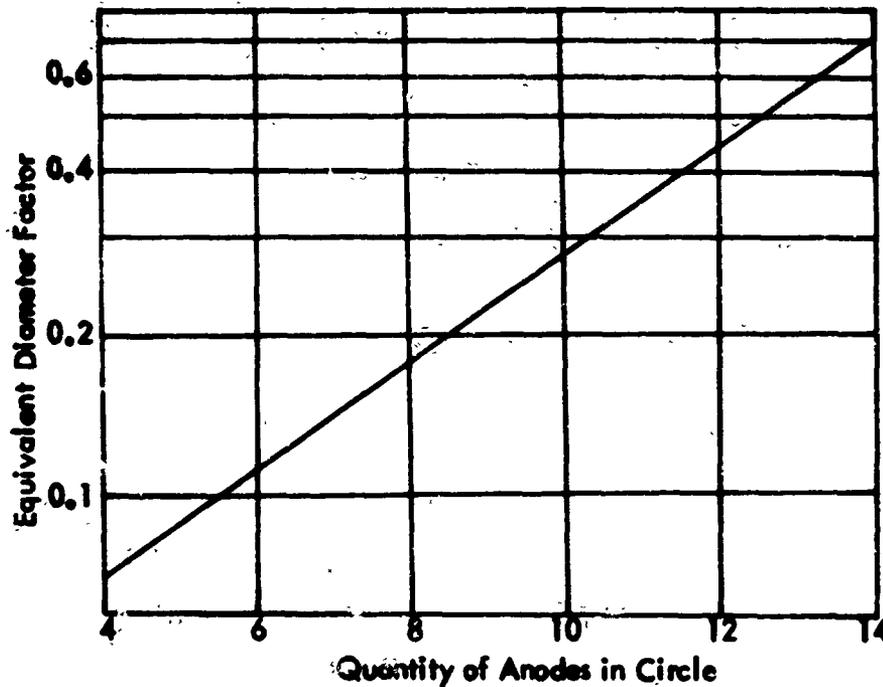


Figure 53

EQUIVALENT DIAMETER FACTOR FOR ANODES IN A CIRCLE IN WATER TANK

7.4.3 Simplified Expressions for Galvanic Anode Current Output. Current output for a standard size magnesium or zinc anode can be estimated from the equation:

$$i = \frac{Cfy}{\rho}$$

where

- i = current output (milliamperes)
- C = a constant (50,000 for zinc; 150,000 for magnesium)
- f = anode size factor, obtained from Table 27
- y = structure potential factor, obtained from Table 28
- ρ = electrolyte resistivity (ohm-centimeters)

This equation assumes a bare or very poorly coated structure, electrolyte resistivity above 500 ohm-centimeters, and distance between structure and anode of 10 feet. For well-coated structures, structure-to-electrolyte resistance is greater, making anode output current less. For a well-coated structure, then, constant "C" becomes 40,000 for zinc and 120,000 for magnesium.

Table 27 (Reference 21)
Galvanic Anode Size Factor, f
Standard Anodes

<u>Anode Weight (Pounds)</u>		<u>Size Factor, .f</u>
3	(packaged)	0.53
5	(packaged)	0.60
9	(packaged)	0.71
17	(packaged)	1.00
32	(packaged)	1.06
50	(packaged-anode dimension 8 in dia. x 16 in)	1.09
50	(packaged-anode dimension 5 in x 5 in x 31 in)	1.29
Long Anodes		
9	(2.75 in x 2.75 in x 26 in backfill 6 in x 31 in)	1.01
10	(1.5 in x 1.5 in x 72 in backfill 4 in x 78 in)	1.71
18	(2 in x 2 in x 72 in backfill 5 in x 78 in)	1.81
20	(2.5 in x 2.5 in x 60 in backfill 5 in x 66 in)	1.60
40	(3.75 in x 3.75 in x 60 in backfill 6.5 in x 66 in)	1.72
42	(3 in x 3 in x 72 in backfill 6 in x 78 in)	1.90
Extra Long Anodes		
15	(1.6 in dia. x 10 ft backfilled to 6 in dia.)	2.61
20	(1.3 in x 20 ft backfilled to 6 in dia.)	4.28
25	(2 in dia. x 10 ft backfilled to 8 in dia.)	2.81

Table 28 (Reference 28)
Structure Potential Factor, y

<u>Structure-to-Electrolyte Potential (Volts, Relative to Copper-Copper Sulfate)</u>	<u>Structure Factor, y (Magnesium)</u>	<u>Structure Factor, y (Zinc)</u>
-0.70	1.14	1.60
-0.80	1.07	1.20
-0.85	1.00	1.00
-0.90	0.93	0.80
-1.00	0.79	0.40
-1.10	0.64	0.00
-1.20	0.50	0.00

For a grounded bed of more than one vertical magnesium anode, total current output is a multiple, not linear, of single anode output. The multiplying factor is a function of anode number and spacing as well as size. Table 29 (reference 22) gives values of this factor for vertical 17-pound packaged magnesium anodes. This table can be used to approximate current output values for other size magnesium anodes as well as zinc anodes.

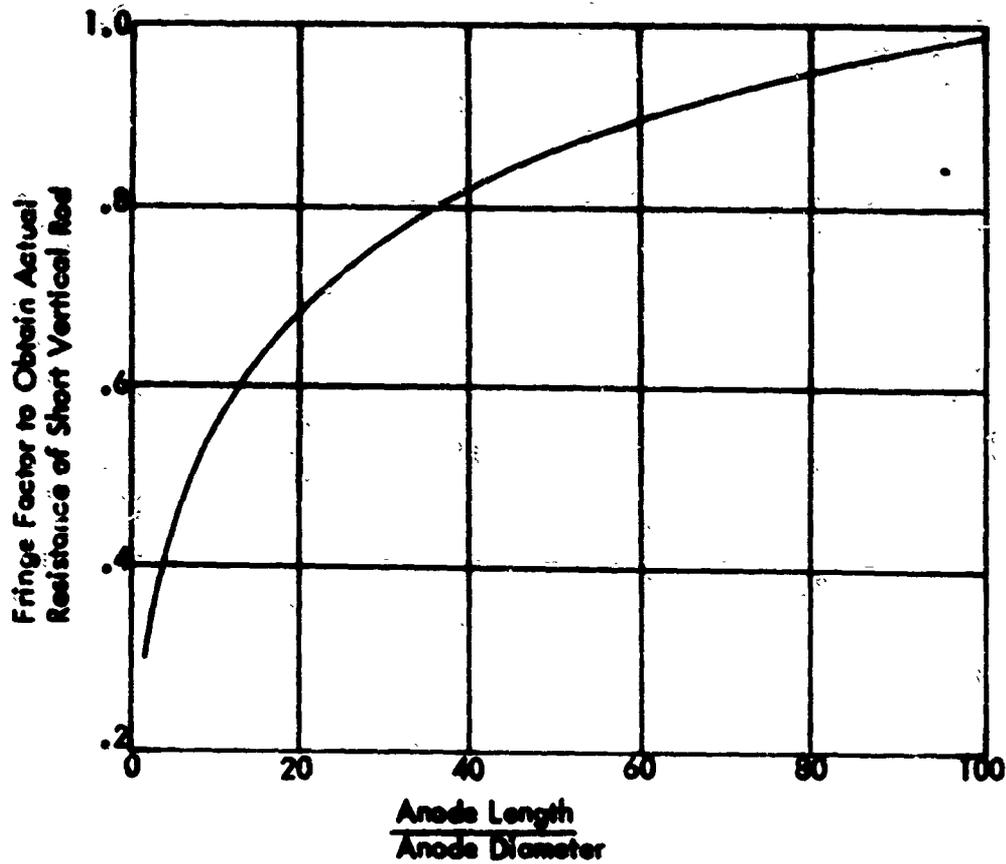


Figure 54
FRINGE FACTOR FOR STUB ANODES

Table 29 (Reference 21)
Multiplying Factor for Magnesium Anode Groups
Multiplying Factor (Anode Spacing in Feet)

No. of Anodes in Parallel	5	10	15	20
2	1.839	1.920	1.946	1.964
3	2.455	2.705	2.795	2.848
4	3.036	3.455	3.625	3.714
5	3.589	4.188	4.429	4.563
6	4.125	4.902	5.223	5.411
7	4.652	5.598	6.000	6.232
8	5.152	6.277	6.768	7.036
9	5.670	6.964	7.536	7.875
10	6.161	7.643	8.304	8.679

7.4.4 Determining Anode-to-Electrolyte Resistance by Testing. Tables and formulae provide only a rough estimate of anode-to-electrolyte resistance or galvanic anode current output. These values are determined by many factors and can only be truly determined after installation of anodes.

Two practical methods of determining total anode-to-electrolyte resistance by direct measurement can also be used for impressed current systems.

The first of these consists of the following steps:

- a. Install anodes complete with all connecting cables.
- b. Test the resistance between structure to be cathodically protected and installed anodes. Step "b" will yield the circuit resistance so that proper size rectifier can be ordered.

The second method consists of the following steps:

- a. Install rectifier, complete with power supply, before installing any anodes.
- b. As each anode is installed, calculate circuit resistance by reading rectifier D.C. amperage and voltage.

When readings indicate the desired resistance, anode installation is discontinued.

These methods are useful when it is impractical to obtain electrolyte resistivity readings. Also, they eliminate the effect of errors in computations caused by variable electrolyte resistivity and allow the engineers to size the cathodic protection unit very closely.

For galvanic cathodic protection, a temporary or test grounded of the type anode to be used may be installed. Resistance, current output, and actual protection can then be tested.

7.5 Backfill Around Anodes in Soil. Backfill, carefully tamped around anodes installed in soil, generally increases their effectiveness. It reduces anode-to-electrolyte resistance; under favorable conditions, this resistance may be reduced to one-half to one-third bare anode resistance. In addition, backfill provides a uniform, favorable environment, reducing polarization effects and uneven dissolution. This minimizes high-resistance build-up on anode surfaces and often helps increase operational life. For these reasons, use of backfill should be considered in cathodic protection design.

Backfill adds to the cost of cathodic protection. However, power savings may warrant its use. If soil resistivity is ten or more times backfill resistivity (in the neighborhood of 500 to 1000 ohm-centimeters), the voltage drop of anode current through backfill becomes negligible with respect to the anode and the backfill becomes the effective anode.

In many cases it is impossible to use backfill at all, or impossible to get it properly tamped and/or distributed around anodes. Examples of this are swamps, quick sand, and

some "Deep Well" installations. However, "packaged" anodes may be the answer to some problems. In addition, backfill always requires additional inspection care during installation because it should be tested before being used, carefully tamped, and distributed uniformly around anodes. Packaged anodes should be carefully inspected because anode-to-cable connection is hidden from view.

7.5.1 Impressed Current Anode (HSCBCI or Graphite) Backfill. Carbonaceous backfill (paragraph 4.3.4), suitable for use around impressed current anodes, can be coke breeze (crushed coke) or flake graphite. The coke must originate from coal, or be recalcined petroleum coke. Flake graphite is usually more expensive than coke breeze, but may be best to use for "Deep Wells" because the particles tend to slip over each other.

HSCBCI anodes do not require backfill for operation, but lower circuit resistance may result from its use.

Backfill should always be used with graphite anodes in soil, to provide a low resistance environment. Otherwise, the large difference in resistance at the anode surface (anode to soil) will cause rapid dissolution of the anode and greatly shorten its life. Graphite anodes can be used without backfill in extremely low resistance homogeneous environments (such as sea water). In high resistance electrolytes (usual where backfill cannot be used (such as swamps, etc.), graphite anodes are not recommended.

7.5.2 Galvanic Anode Backfill. Backfill for galvanic anodes consists of a combination of material (paragraphs 5.1.1.d and 5.1.2.d). It is essentially gypsum (moulding plaster), bentonite clay, and sodium sulfate. Sodium sulfate lowers anode-to-electrolyte resistance. Bentonite acts as a sponge, holding moisture around the anode. Gypsum is a binder which holds the backfill together preventing leaching of the components. If backfill is needed and, for some reason, none is available, bags of "moulding plaster" (actually gypsum) can be substituted; this is available at most local building supply houses. Hairless moulding plaster is preferred.

Backfill should always be used with zinc anodes in soil. Zinc requires an environment free from damaging compounds such as carbonates, which react with the metal causing it to "seal over". This naturally stops the anode's effectiveness, because little or no current will flow. (High-resistance surface film is formed.)

Magnesium anodes experience little or no corrosion product build-up and thus do not absolutely require backfill. However, backfill is usually employed to increase current output.

7.5.3 Packaged and Unpackaged Anodes. Both galvanic and impressed current (cast iron or graphite) anodes are available prepackaged in the appropriate backfill, for ease of installation. Galvanic anodes are generally packaged in cloth bags, whereas impressed current anodes are packaged in metal cylinders ("stove pipes").

Prepackaged anodes are relatively simple to install; the backfill is already tamped in place, and the entire installation is ready for direct burial. This is of particular use in areas where backfilling is impractical such as swamps or caving sand. Unpackaged anodes are less expensive, but require more installation time for use in backfill. Backfill must be thoroughly compacted in layers by hand or power tamping. Particular care must be taken in placing and tamping backfill around anodes to assure complete and intimate contact, free of voids, between anodes and backfill. However, a more intimate contact with soil results.

Disadvantages of packaged anodes are:

- a. High additional cost of material.
- b. Added cumbersome weight to transport and handle.
- c. Possibility of voids developing during transportation.
- d. Anode inspection and lead wire connection is difficult. Breaks or defects could be present, prior to installation, which could affect anode operation.

The choice of packaged or unpackaged anodes depends on economics and site conditions. In general, packaged impressed current anodes are not justified for military use except in unstable excavations.

7.6 Rectifier Alternating Current Rating. Based on the definition of rectifier efficiency, the A.C. rating for a single-phase rectifier can be calculated:

$$I_{ac} = \frac{E_{dc} \times I_{dc}}{F \times E_{ac}} \quad (1\text{-phase})$$

where

- I_{ac} = alternating current (amp).
 E_{dc} = direct current (volts).
 I_{dc} = direct current (amps).
 F = rectifier efficiency.
 E_{ac} = alternating current (volts).

For a three-phase rectifier the equation becomes:

$$I_{ac} = \frac{E_{dc} \times I_{dc}}{\sqrt{3} \times F \times E_{ac}} \quad (3\text{-phase})$$

where the letter nomenclature is the same as shown for single-phase.

7.7 Cable Specifications and Data. Connecting cables can be selected after consideration of the following factors:

1. Current carrying capacity (heating)
2. Voltage attenuation (IR drop which can reduce anode voltage below required level).
3. Mechanical strength
4. Economics (power losses vs. initial investment)
5. Dielectric strength of insulation in electrolyte environment.

Table 30 lists properties of single conductor stranded copper cables (high molecular weight polyethylene or RR-USE in direct burial service). Both high molecular weight single extrusion polyethylene and RR-USE insulations give satisfactory service in cathodic protection.

The positive rectifier cable (rectifier to anodes) of impressed current systems must be well-insulated. This cable is positive relative to earth; cable insulation breaks result in current discharge and rapid corrosion. Failure of part or all of the system may occur. For this reason, cable insulation, in this part of an impressed current system, must be chosen with care.

The negative rectifier cable (rectifier to structure) of impressed current systems and the connecting cables (anode to structure) of galvanic anode systems do not require such high-quality insulation. These, as well as test wires and other cables connected to the protected structure, are themselves protected. In order to avoid wasting cathodic protection current, and to prevent corrosion if the cathodic protection is turned off, however, well-insulated cables should be used. In addition to possible loss of current, galvanic cells (requiring more current to neutralize than other corrosion) between copper cable and steel are also possible if bare or poorly-insulated cable were employed.

Table 30
Concentric Stranded Copper Single Conductors
Direct Burial Service Suitably Insulated

Size AWG	Overall Diameter Not Including Insulation (Inches)	Approx. Weight Not.Inc. Insulation (lbs./M ft)	Maximum Breaking Strength (lbs.)	Maximum D.C. Resistance @ 20°C (ohms/M ft)	Maximum Allow. D.C. Current Capacity (Amperes)
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

7.7.1 Insulation. Some manufacturers have labeled this "cathodic protection" cable. The original product was polyethylene (PE) insulated and polyvinylchloride (PVC) jacketed. The latter was not intimate or a close fit to the former. Therefore, moisture entered cable to anode connections, causing rapid failure. This is not a problem with single extrusion cable insulation.

The most widely used cable insulation for cathodic protection service today is probably high molecular weight polyethylene (HMWPE) 110 mils thick. This is used for lead wires, rectifier cables, and bond wires. It is recommended over high density polyethylene (HDPE) which is only 60 mils thick - further, this material reportedly is subject to stress cracking. Although relatively expensive, HMWPE exhibits superior performance and is recommended for all positive header cables in inaccessible locations (buried or submerged, for example), or where moisture can reach the cable, or where damage is likely. Less expensive insulation will generally suffice in other applications.

Synthetic rubber insulations (Type RHW-USE) consisting of a butyl sheath and neoprene jacket with a nominal total thickness of 100 mils continue to be used. The reported disadvantages of dual plastic insulations are not applicable because the two rubber compounds have good elastic "fit". These

materials give excellent service unless they are exposed to liquid hydrocarbons (gasoline, etc.).

In deep groundbeds, where conventional cable insulation may be subject to degradation from chlorine, economics sometimes justify use of more costly materials. The highly inert fluorocarbons plastics, such as fluorinated ethylene propylene (FEP), tetrafluorethylene (TFE), and polyvinylidene fluoride (PVF₂), are used both as a primary insulation and outer jacket, respectively, by different cable manufacturers. The outer jacket of these more exotic materials is about 10 mils per side. The primary insulation, usually a cross-linked extruded polyalkene, is about 30 mils per side. A thin outer jacket is subject to mechanical damage during installation. Even these sometimes fail.

One newly developed insulation used for deep groundbed installations consists of an outer jacket of high-molecular weight polyethylene (40 mils) and a primary insulation of a copolymer E-CTFE (ethylene and monochlorotrifluoroethylene, 20 mils). This combination shows promise, but has not been fully proven in the field.

Type TW insulation, which may consist of a variety of materials, is adequate for certain applications - test wires, galvanic anode connections, above-grade rectifier wiring, etc. - where cables are not exposed to the electrolyte or high positive voltages.

7.7.2 General Application. Recommended wire sizes and insulation types for general use in military cathodic protection installations are given here.

a. Test Wires. Test wires are to be No. 12 solid copper cable with Type TW, RHW-USE, or polyethylene insulation. These wires handle only small amounts of current and are themselves cathodically protected. Therefore, the wire size is small, and choice of insulation material is not as strict.

b. Bond Wires. All bond wires are to be No. 4, 7-strand copper cable with high molecular weight polyethylene (HMWPE) insulation. Bonding is an important part of cathodic protection, insuring electrical continuity where required.

c. Galvanic Anode Lead Wires. Galvanic anodes generally are supplied with standard lead wires: 10 feet of No. 12 solid copper cable with TW insulation. Since galvanic anodes produce little current and A.C. fault currents are unlikely, this size wire is generally satisfactory. Type TW insulation can be used because galvanic voltages are low.

d. Impressed Current System Cables. Impressed current anodes are generally supplied with standard lead wires: 5 feet of No. 8, 7-strand copper cable with HMWPE insulation.

These leads are spliced into a header cable going to the positive rectifier terminal. For military installations, this cable is to be 7-strand copper cable with HMWPE insulation; size is No. 2 or larger, depending on current requirements. This cable is especially important, being a major component of the circuit. In addition, it is subject to corrosion and rapid failure at each cable insulation or splice insulation defects.

Rectifier negative (rectifier to structure) cable is also important to circuit integrity, but this cable is actually being cathodically protected and therefore not as likely to cause problems as the positive one. It is good practice to use well-insulated cable here also, however, to avoid current losses and possible galvanic cells between copper cable and steel structure. (This could be a problem if the system is ever turned off.) HMWPE insulated, 7-strand cable - usually No. 4 or No. 6, is used. Economical wire size can be determined according to Kelvin's Law (paragraph 7.7.3).

7.7.3 Economic Wire Size. Conformance to Kelvin's Economic Law is one of the governing factors in design of cable conductors for cathodic protection systems. This law states: "The proper size of cable is that for which the cost of the losses equals the annual fixed charges." or "The proper cable size is one which makes the sum of the annual cost of losses and the annual fixed charges a minimum."

The following relationship permits computation of the annual cost of losses:

$$V = MK_m$$

where

$$M = 0.0876 I^2 R, \text{ and } K_m = \frac{LP}{E}$$

- V = Annual cost of losses, (dollars per year)
- I = Current flow in cables (amperes)
- R = Resistance of 100 feet of cable (ohms)
- P = Cost of power (cents per kwh)
- E = Efficiency of rectifier, or other current source (%)
- L = Length of cable (feet)

Table 31 lists the M factors for various wire sizes and conductor currents. The annual cost of fixed charges of a cable can be computed from:

$$F = 0.15 SL$$

- F = Annual fixed charge (dollars per year)
- S = Initial cable cost (dollars per foot)
- L = Cable length (feet)

Tab. 5 51
M Factors

Cost of losses in 100 feet of copper cable at one cent per kw-hr.

Cable Size	10	20	30	40	50	60	70	80	90	100
10	0.893	3.57	8.04	9.00	14.00	13.00	17.64	14.46	18.30	22.60
8	0.561	2.25	5.05	5.76	9.00	8.14	11.08	9.11	11.54	14.24
6	0.360	1.44	3.24	3.62	5.65	5.13	6.98	7.24	9.15	11.30
4	0.226	0.905	2.03	2.28	3.56	4.06	5.54	5.71	7.23	8.93
2	0.1424	0.570	1.28	1.81	2.82	3.21	4.47	4.55	5.75	7.10
1	0.113	0.451	1.02	1.425	2.23	2.56	3.48	3.60	4.55	5.62
1/0	0.0893	0.357	0.804	1.135	1.77	2.03	2.76	2.86	3.62	4.45
2/0	0.0710	0.284	0.639	0.900	1.40	1.61	2.19	2.42	3.06	3.78
3/0	0.0562	0.257	0.506	0.715	1.115	1.36	1.85	2.02	2.56	3.16
4/0	0.0446	0.178	0.401	0.565	0.945	1.14	1.55	1.73	2.18	2.70
250 MCM	0.0378	0.151	0.340	0.506	0.790	0.972	1.32	1.52	1.92	2.37
300	0.0316	0.1265	0.284	0.432	0.675	0.854	1.15	1.342	1.70	2.10
350	0.0270	0.108	0.243	0.379	0.593	0.755	1.03	1.21	1.53	1.89
400	0.0237	0.0948	0.213	0.335	0.525	0.680	0.925	1.10	1.39	1.72
450	0.0210	0.0840	0.189	0.302	0.472	0.619	0.842	1.01	1.28	1.58
500	0.0189	0.0755	0.170	0.275	0.430	0.569	0.775	0.928	1.17	1.45
550	0.0172	0.0689	0.155	0.253	0.395	0.522	0.710	0.865	1.09	1.35
600	0.0158	0.0632	0.142	0.232	0.362	0.486	0.661	0.805	1.02	1.26
650	0.0145	0.0580	0.1305	0.216	0.338	0.454	0.616	0.765	1.02	1.26
700	0.0135	0.0540	0.1215	0.202	0.315	0.430	0.583	0.730	0.945	1.16
750	0.0126	0.0504	0.1132	0.191	0.296	0.401	0.545	0.690	0.915	1.14
1000	0.00945	0.0378	0.0970	0.151	0.236	0.340	0.463	0.605	0.765	0.945

0.15 = Estimated annual charges (dollars)

Note: This factor will vary. However, the following estimate is used here:

0.02 Depreciation
0.06 Interest
0.04 Taxes and Insurance
0.03 Operation and Maintenance

Total annual costs will equal the sum of the annual cost of losses and the annual cost of fixed charges ($I = V + F$).

7.8 Connections and Splices. The designer must not allow any more connections and splices in cathodic protection D.C. wiring than absolutely necessary. This is because all systems are basically low voltage and increased resistance will increase power costs and reduce protection effectiveness. Also, wiring is often buried or submerged in an electrolyte where even the smallest pinhole in insulation will mean rapid failure, and repairs are difficult because of inaccessibility.

Every connection should be carefully inspected before and after being insulated with material of quality at least equal to that of the cable insulation. Thermit welds or solder should be used as connections. Mechanical connections sometimes result in higher resistance, fail prematurely, and are often not as foolproof to install. Care must be taken not to damage cable insulation and/or structure coatings more than necessary. As previously mentioned, any break in splice or cable insulation in positive D.C. wiring, when these are suspended in the electrolyte, will mean rapid and premature failure of these positive feeders.

Necessary connections for galvanic anode systems include:
cable to anode (each anode)
cable to structure (each anode)

In addition, bonds or test wires require connections, if these are to be installed.

Necessary connections for impressed current systems include:
cable to anode (each anode)
negative cable to structure

In addition, it is necessary to splice each individual impressed current anode into a "header" cable unless long individual leads are used between each anode and the rectifier power supply. As with galvanic systems, bonds or test wires may also be required, necessitating additional cable to structure connections. If more than one header cable is required because of structure geometry, additional splices may be required to join these.

(Note: all splices should be indicated on design layouts and not left to the discretion of installation contractors. No

splices other than those indicated on drawings should be allowed without permission from the engineer.)

Cable to anode connections were discussed with individual anode types. These connections are crucial and their strength should be at least as great as the cable breaking strength.

Cable to cable connections (such as splices between anode lead wires and header cable) require insulation to remain moisture-proof. Recommended insulation is epoxy connection coverings which come in kit form.

Cable to structure connections (paragraph 4.3) do not require epoxy splice kits, although these are available. It is more practical and equally effective to coat the connection with hot coal-tar enamel (or material equivalent to structure coating) and wrap with pipeline felt.

8 EXAMPLES OF CATHODIC PROTECTION DESIGN. Several design examples are detailed here for guidance and assistance in proper use of this manual. Conditions are assumed. They are shown for illustration only, and no consideration is given to cathodic interference on neighboring structures. These illustrations do not fix design criteria or indicate any one material superior to another.

Design calculations should be based on field measurements rather than calculated estimates. In this way, actual conditions are considered, and cathodic protection is designed around an existing situation. Frequently, cathodic protection must be designed prior to structure installation, necessitating the use of calculated current requirement and resistance estimates. These calculations are, of course, more involved than those based on field measurements. These longer calculations are followed in some examples, with the understanding that this method should only be used when it is impractical or impossible to obtain actual field measurements.

a. Elevated, Steel Water Tank. This impressed current design is for a tank which has not been built; hence, it is not possible to determine current requirements, etc. by actual measurement. Calculated estimates are used.

(1) Design Data.

(a)	Tank capacity	500,000 gal.
(b)	Tank height (from ground to bottom of bowl)	115 ft.
(c)	Diameter of tank	56 ft.
(d)	High water level in tank	35 ft.
(e)	Over-all depth of tank	39 ft.
(f)	Vertical shell height	11 ft.
(g)	Riser pipe diameter	5 ft.

- | | | |
|-----|---|--|
| (h) | Shape of tank | Ellipsoidal,
both top and
bottom |
| (i) | All internal surfaces are uncoated | |
| (j) | Design for maximum
current density | 2 ma./sq.ft. |
| (k) | Electric power available | 120/240 VAC,
single phase |
| (l) | String-type HSCBCI anodes are used | |
| (m) | Design life | 10 years |
| (n) | Water resistivity | 4000 ohm-cm. |
| (o) | Tank water will not be
subject to freezing | |
| (p) | Assumed deterioration rate | 1.0 lb/amp-yr. |
| (q) | Anode efficiency (assumed) | 50% |

(2) Computations.

- (a) Area of wetted surface of tank bowl (Figure 7-55)

Top section (T)

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

where

$$\begin{aligned} r &= 28 \text{ ft.} \\ x &= 10 \text{ ft.} \\ A_T &= 2 \times 3.1416 \times 28 \times 10 \\ A_T &= 1760 \text{ sq. ft.} \end{aligned}$$

Center section (C)

$$A_C = 2\pi rh$$

where

$$\begin{aligned} r &= 28 \text{ ft.} \\ h &= 11 \text{ ft.} \\ A_C &= 2 \times 3.1416 \times 28 \times 11 \\ A_C &= 1935 \text{ sq. ft.} \end{aligned}$$

Bottom section (B)

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

where

$$\begin{aligned} r &= 28 \text{ ft.} \\ a &= 14 \text{ ft.} \\ A_B &= 2 \times 3.1416 \times 28 \times \sqrt{14^2 + 28^2} \\ A_B &= 3900 \text{ sq. ft.} \end{aligned}$$

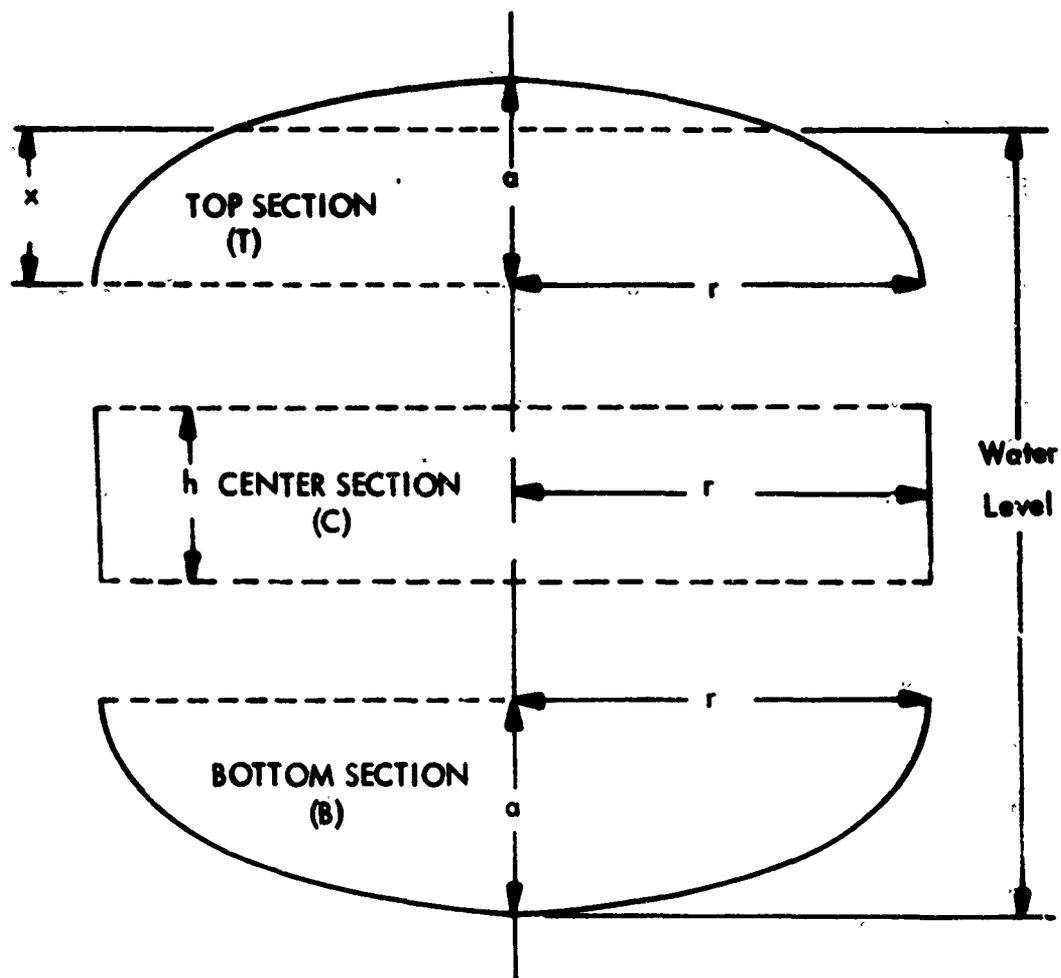


Figure 55
SEGMENTED ELEVATED TANK FOR AREA CALCULATIONS

Therefore

$$A_T = 1760 \text{ sq. ft.}$$

$$A_C = 1935 \text{ sq. ft.}$$

$$A_B = 3900 \text{ sq. ft.}$$

Total = 7595 sq. ft. (wetted area of tank bowl).

(b) Area of riser pipe.

$$A_R = 2\pi r_R h_R$$

where

$$r_R = 2.5 \text{ ft. (radius of riser)}$$

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

$$A_R = 2 \times 3.1416 \times 2.5 \times 115$$

$$A_R = 1810 \text{ sq. ft.}$$

(c) Maximum design current for tank.

$$I_T = 2.0 \times 7595$$

$$I_T = 15,190 \text{ ma. or } 15.2 \text{ amp.}$$

(d) Maximum design current for riser.

$$I_R = 2.0 \times 1810$$

$$I_R = 3620 \text{ ma. or } 3.62 \text{ amp.}$$

(e) Minimum weight of tank anode material.

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

where

$$Y = 10 \text{ yr.}$$

$$S = 1.0 \text{ lb./amp.-yr.}$$

$$E = .50$$

$$I = 15.2 \text{ amp.}$$

$$W = \frac{10 \times 1.0 \times 15.2}{.50}$$

$$W = 304 \text{ lb.}$$

(f) Minimum weight of riser anode material.

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

where

$$\begin{aligned} Y &= 10 \text{ yr.} \\ S &= 1.0 \text{ lb./amp.-yr.} \\ I &= 3.62 \text{ amp.} \\ E &= 0.50 \\ W &= \frac{10 \times 1.0 \times 3.62}{0.50} \\ W &= 72.4 \text{ lb.} \end{aligned}$$

(g) Radius of main anode circle.

$$r = (DN)/2 (\pi + N)$$

where

$$\begin{aligned} D &= 56 \text{ ft.} \\ N &= 10 \text{ (assumed)} \\ r &= \frac{56 \times 10}{2(3.1416 + 10)} \\ r &= 560/26.28 \\ r &= 21.3 \text{ ft., use 22 ft.} \end{aligned}$$

(h) 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.

1. Circumferential spacing.

$$C = (2\pi r)/N$$

where

$$\begin{aligned} r &= 22 \text{ ft. (radius of anode circle)} \\ N &= 10 \text{ (assumed number of anodes)} \\ C &= \frac{2 \times 3.1416 \times 22}{10} \\ C &= 13.8 \text{ ft., use 14 ft.} \end{aligned}$$

2. Cord spacing is approximately the same as circumferential spacing; 14 ft. will be used; see Figure 56.

(1) Selection of main anodes.

1. Size of anode units selected is 1-1/8" O.D. x 3/4 I.D. x 9" long. This is a standard sausage-type anode which weighs 1 lb., and has a surface area of 0.25 sq ft.

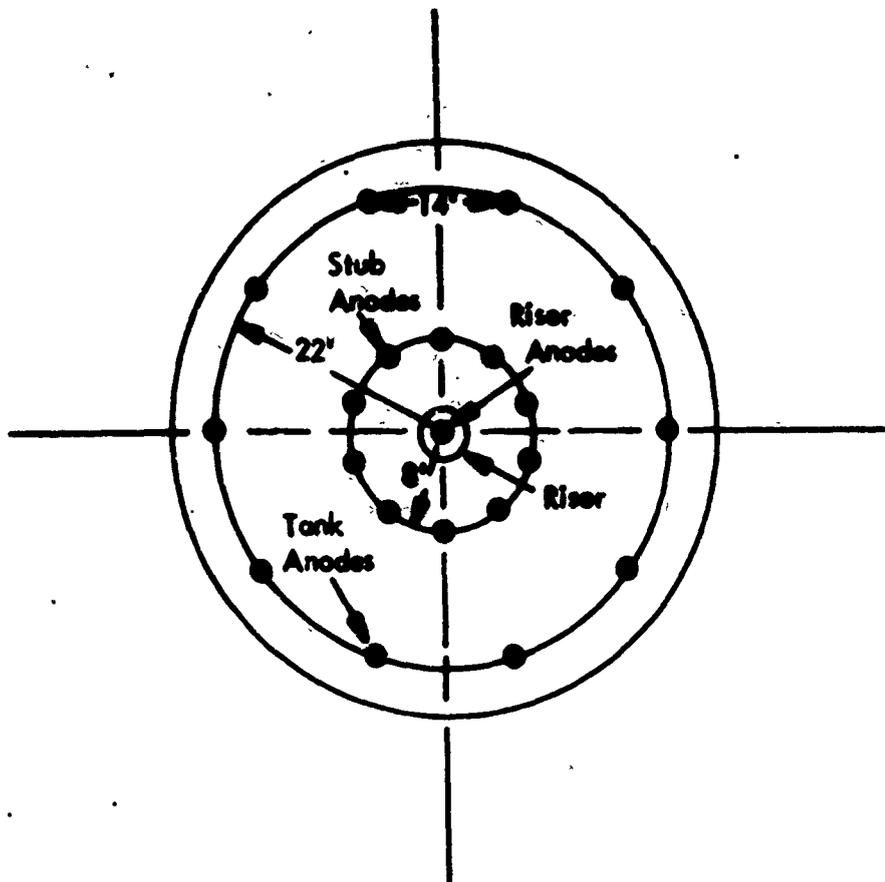


Figure 56
ANODE SPACING FOR ELEVATED STEEL WATER TANK

2. The minimum number of anode units per anode string, based on a required weight of 304 lb. and 10 anode strings is computed as follows:
 Number of units = $304 / (10 \times 1) = 30.4$;
 say 31 units per string.

Since the internal tank surfaces are uncoated, a maximum structure-to-electrolyte voltage is not a limiting factor. However, since it is desired to hold the anode current at or below the manufacturers recommended discharge rate of 0.025 amps per anode for this type anode, $\frac{15.2 \text{ AMP}}{10 \times 0.025 \text{ amps}} = 61$ anodes

per string. This number of anodes per string is not practical for the bowl since the distance between the anode hanger and the bottom of tank is only 28 feet. Table 32, Technical

Data commonly used HSCBCI anodes, shows the maximum recommended current discharge per anode for various type anodes to insure ten year minimum life. Using type B anode, 3 anodes per string will be required. The manufacturer does not recommend more than 2 type B anodes per string assembly because of their fragile nature. Therefore, the best choice of anode for the main anode strings is type C or type CDD. Type CDD is recommended because the lead wire connection will be protected longer by the thicker wall of the enlarged ends. Two type CDD anodes per string will provide a current capacity of 2 amps x 10 strings = 20 amps. These anodes will be spaced as shown in figure 57.

TABLE 32

Technical Data - Commonly Used HSCBCI Anodes

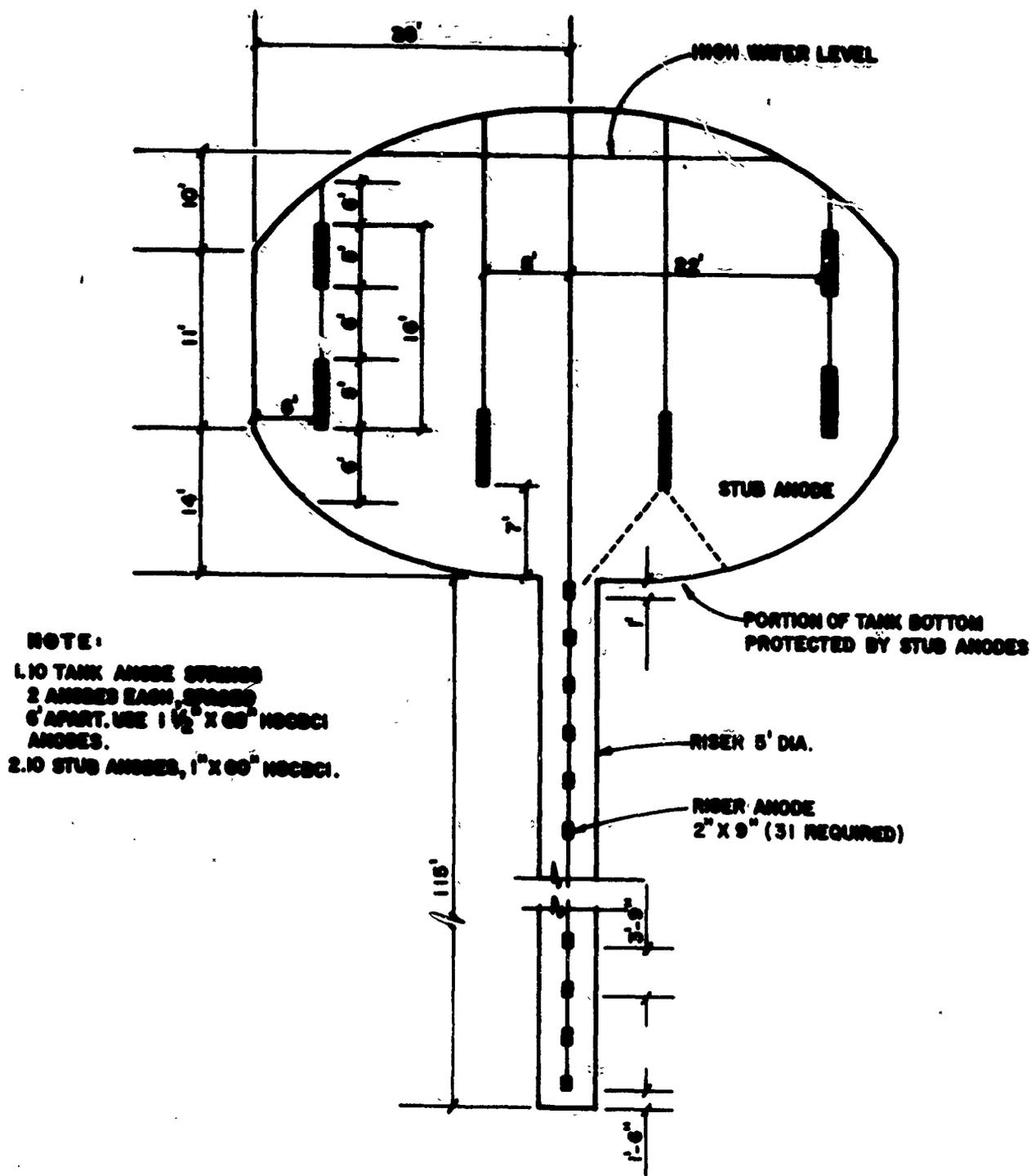
Anode Type	Size	Weight (Lbs)	Anode Max Discharge (amps)	Max Current Density amp/sq.ft.
FW**	1 1/8" O.D. x 3/4" I.D. x 9"	1	0.025	0.1
FC***	1 1/2" x 9"	4	0.075	0.25
G-2	2" O.D. x 1 1/4" I.D. x 9"	5	0.100	0.25
B*†	1" x 60"	12	0.50	0.36
C	1 1/2" x 60"	25	1.00	0.50
CDD*	1 1/2" x 60"	26	1.00	0.50
M*	2" x 60"	60	2.5	0.9
SM	4 1/2 x 60	220	10.0	1.8

* Each end enlarged with cored opening for wire.

** For elevated fresh water tank.

*** For distributed system in ground trench.

† Not more than 2 anodes per assembly.



ANODE SUSPENSION ARRANGEMENT FOR ELEVATED STEEL WATER TANK

NO SCALE

3. Anode current density is computed as follows:

$$\text{Output} = \frac{15.2}{2 \times 10 \times 2} = 0.38 \text{ amp./sq.ft.}$$

(j) Resistance of main anodes.

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

where

$$\rho = 4000 \text{ ohm-cm.}$$

$$D = 56 \text{ ft.}$$

$$L = 2 \times 5 \text{ ft.} = 10 \text{ ft.}$$

$$a = 44 \times 0.275 = 12.1 \text{ ft. (0.275 -- equivalent diameter factor from curve Figure 53).}$$

$$R = \frac{0.012 \times 4000 \log 56/12.1}{10}$$

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

$$R = 3.19 \text{ ohms.}$$

However, the L/d ratio of twelve 1-1/2-in. diam. x 9-in. long anodes in tandem is less than 100 and thus the fringe factor must be used.

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

$$L/d = 80 < 100$$

The fringe factor from curve Figure 54 corresponding to this L/d ratio is 0.95

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

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

(k) Stub anodes. In the design of an elevated water tank, the need for stub anodes must be justified. The main anode radius has been calculated to be 22 ft. 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 of the anode from the bottom.

Figure 57 shows the anode suspension arrangement for the tank under consideration. Thus, it can be seen that stub anodes are required for this design. Ten stub anodes are arranged equidistant apart on a circumference

having a radius of 8 ft. in a manner illustrated in Figure 56. For smaller diameter tanks, stub anodes may not be required.

(1) Current division between main and stub anodes.

1. Area of tank bottom protected by stub anodes (Figure 57):

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

where

$r_2 = 13$ ft. (radius of protected segment)

$r_1 = 2.5$ ft. (radius of riser)

$A_s = 3.1416 (13^2 - 2.5^2)$

$A_s = 3.1416 \times 163$

$A_s = 512.1$ sq. ft.

2. Maximum current for stub anodes.

$I_s = 2.0 \times 512.1$

$I_s = 1024$ ma. or 1.02 amp

3. Maximum current for tank bowl = 15.2 amp.

4. Maximum current for main anodes.

$I_m = 15.2 - 1.02$

$I_m = 14.2$ amp.

(m) Rectifier voltage rating.

1. Electrical conductor to main anodes.

Wire size #2 AWG, 0.159 ohm/1000 ft.,
estimated length 200 ft.

$$(R) = \frac{200}{1000} \times .159 = .032 \text{ ohm}$$

2. Voltage drop in main anode feeder.

$$E = IR$$

where

$I = 14.2$ amp.

$R = .032$ ohm

$E = 14.2 \times .032$

$E = 0.45$ volts.

3. Voltage drop through main anodes.

$$E = IR$$

where

$$\begin{aligned} I &= 14.2 \text{ amp.} \\ R &= 3.03 \text{ ohms} \\ E &= 14.2 \times 3.03 \\ E &= 43.0 \text{ volts.} \end{aligned}$$

4. Total voltage drop in main anode circuit.

$$\begin{aligned} E_T &= 0.45 + 43.0 \\ E_T &= 43.45 \text{ or } 45 \text{ volts} \end{aligned}$$

Use a multiplying factor of 1.5, or 67.5 volts.

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

- (n) Selection of stub anodes. Since it is desirable to use as small an anode as possible without exceeding the manufacturers recommended rate, type FC, HSCBCI anode measuring 1 1/2" x 9" will be tried. One anode per string will be used as shown in figure 57. Anode current density is computed as follows.

$$\text{Output} = 1.02 / (10 \times .03) = 0.34 \text{ amp. per sq. ft.}$$

Since this exceeds the recommended max anode current density (table 32), type B anode is the best choice

- (o) Resistance of stub anodes.

$$R = \frac{0.012 \varphi \log D/a}{L}$$

where

$$\begin{aligned} \varphi &= 4000 \text{ ohm-cm} \\ D &= 56 \text{ ft.} \\ L &= 5 \text{ ft.} \\ a &= 16 \times 0.275 = 4.4 \text{ ft.} \\ R &= \frac{0.012 \times 4000 \log 56/4.4}{5} \\ R &= \frac{48 \log 12.73}{5} \\ R &= \frac{48 \times 1.105}{5} \\ R &= 10.08 \text{ ohms} \end{aligned}$$

$L/d = 60/1 = 60$
Fringe factor from curve Figure 54, 0.85
 $R_{\text{(adjusted)}} = 10.08 \times 0.85 = 8.57 \text{ ohms}$

(p) Voltage drop in stub anode circuit.

1. Electrical conductor to stub anodes.
Wire size #2 AWG, .159 ohms/1000 ft.,
estimated length 200 ft.

$$(R) = (200/1000) \times .159 = .032 \text{ ohm}$$

2. Voltage drop in stub anode feeder.

$$E = IR$$

where

$$\begin{aligned} I &= 1.02 \text{ amp.} \\ R &= .032 \text{ ohm} \\ E &= 1.02 \times .032 \\ E &= .033 \text{ volt.} \end{aligned}$$

3. Voltage drop in anode suspension
conductors. Estimated length 50 ft.,
#2 AWG, .159 ohms/1000 ft.

$$\begin{aligned} (R) &= (50/1000) \times .159 = .008 \text{ ohm} \\ E &= IR \end{aligned}$$

where

$$\begin{aligned} I &= 1.02/10 = 0.102 \text{ amp.} \\ R &= .008 \text{ ohm} \\ E &= 1.02 \times .008 \\ E &= \text{negligible.} \end{aligned}$$

4. Voltage drop through stub anodes.

$$E = IR$$

where

$$\begin{aligned} I &= 1.02 \text{ amp} \\ R &= 8.57 \text{ ohms} \\ E &= 1.02 \times 8.57 \\ E &= 8.74 \text{ volts} \end{aligned}$$

5. Total voltage drop in stub anode circuit.

$$E_T = .033 + 8.74$$

$$E_p = 8.77 \text{ volts}$$

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

(q) Stub anode circuit variable resistor.

1. Criteria for variable resistor.

The resistor should be capable of carrying 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.

2. Stub anode circuit data.

Rectifier output, 80 volts

Anode current, 1.02 amp.

Anode resistance, 8.57 ohms.

3. Variable resistor rating.

$$R = E/I$$

where

$$E = 80 \text{ volts}$$

$$I = 1.02/2 \text{ or } 0.51 \text{ amp.}$$

$$R = 80/0.51$$

$$R = 156.9 \text{ ohms}$$

Ohmic value of resistor,

$$156.9 - 8.57 = 148.3 \text{ ohms}$$

Wattage rating of resistor,

$$(1.02)^2 \times 148.3 = 154.2 \text{ watts}$$

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

(r) Resistance of riser anodes. In order to obtain the maximum desired current in the riser (3.62 amp.), the resistance limit is calculated as follows:

$$R = E/I$$

$$E = 43.45 \text{ volts}$$

$$I = 3.62 \text{ amp.}$$

$$R = 43.5/3.62$$

$$R = 12.0 \text{ ohms.}$$

(s) Riser anode design.

1. Type FW (1 1/8" x 9") string type anodes cannot be used in the riser because the maximum anode current discharge of 0.025 amps per anode would be exceeded. The best choice of anode for flexible riser string is type G-2 (2" x 9") high silicon cast iron anode.

2. Number of units required.

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

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

where

$$\rho = 4000 \text{ ohm-cm.}$$

$$D = 5 \text{ ft.}$$

$$d = 2 \text{ in or } .166 \text{ ft.}$$

$$R = 12 \text{ ohms}$$

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

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

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

$$L = 5.92 \text{ ft.}$$

$$\text{Number of units} = \frac{5.92}{0.75} = 7.9$$

or 8 units

In order to obtain 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 will protect a length along the riser pipe equal to 1-1/2 times the spacing of the anode from the riser pipe wall.

$$\text{Riser height} = 115 \text{ ft.}$$

$$\text{Spacing (center of anode to tank wall)} = 2.5 \text{ ft.}$$

$$\text{Length of riser protected by one anode} =$$

$$1.5 \times 2.5 = 3.75 \text{ ft.}$$

Number of units required = $115/3.75 = 30.7$ or
31 units.

3. Anode resistance based on the use of 31
anode units.

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

where

$$\rho = 4000 \text{ ohm-cm.}$$

$$D = 5 \text{ ft.}$$

$$d = 2 \text{ in. or } 0.166 \text{ ft.}$$

$$L = 31 \times 9 \text{ in.} = 279 \text{ in or } 23.25 \text{ ft.}$$

$$R = \frac{0.012 \times 4000 \log 5/0.166}{23.25}$$

$$R = \frac{48 \log 30.1}{23.25}$$

$$R = 3.05 \text{ ohms.}$$

L/d ratio for the riser anode string is
 $279/2$ or 139.5 ; thus no fringe factor cor-
rection is applied.

(t) Voltage drop in riser anode circuit.

1. Electrical conductor to riser anodes. Wire
size, #2 AWG .159 ohms/1000 ft., estimated
length 200 ft.

$$(R) = 200/1000 \times .159 = .032 \text{ ohm.}$$

2. Voltage drop in riser anode feeder.

$$E = IR$$

where

$$I = 3.62 \text{ amp.}$$

$$R = .032 \text{ ohm}$$

$$E = 3.62 \times .032$$

$$E = .116 \text{ volt.}$$

3. Voltage drop in riser anode suspension
cables. Wire size #2 AWG, .159 ohm/1000 ft.,
estimated length 130 ft.

$$(R) = 130/1000 \times .159 = .02 \text{ ohm}$$

$$E = IR$$

where

$$\begin{aligned} I &= 3.62/2 = 1.81 \text{ amp. average} \\ R &= .02 \text{ ohm} \\ E &= 1.81 \times .02 \\ E &= .04 \text{ volt.} \end{aligned}$$

4. Voltage drop through riser anodes.

$$E = IR$$

where

$$\begin{aligned} I &= 3.62 \text{ amp.} \\ R &= 3.05 \text{ ohms} \\ E &= 3.62 \times 3.05 \\ E &= 11.04 \text{ volts.} \end{aligned}$$

5. Total voltage drop in riser anode circuit.

$$\begin{aligned} E_T &= .116 + .04 + 11.04 \\ E_T &= 11.20 \text{ volts.} \end{aligned}$$

(u) Riser anode circuit variable resistor.

1. Criteria for variable resistor are the same as given for stub anode resistor.

2. Riser anode circuit data.

$$\begin{aligned} \text{Rectifier output, } &80 \text{ volts} \\ \text{Anode current, } &3.62 \text{ amp.} \\ \text{Anode resistance} &= 3.05 + .032 + .02 = 3.10 \text{ ohms} \end{aligned}$$

3. Variable resistor rating.

$$P = E/I$$

where

$$\begin{aligned} E &= 80 \text{ volts} \\ I &= 3.62/2 = 1.81 \text{ amp.} \\ R &= 80/1.81 \\ R &= 44.2 \text{ ohms.} \end{aligned}$$

$$\begin{aligned} \text{Ohmic value of resistor} &= \\ 44.2 - 3.10 &= 41.1 \text{ ohms.} \\ \text{Wattage rating of resistor} &= \\ (3.62)^2 \times 41.1 &= 538.6 \text{ watts.} \end{aligned}$$

The nearest commercially available resistor size meeting the above requirements is a 750-watt, 50-ohm, 3.87-amp. resistor. This rheostat is ten inches in diameter and three 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.

(v) Sizing rectifier for riser.

1. Requirements.

DC current output = 3.62 amp
Anode circuit resistance = 3.10 ohms.
DC voltage required = $IR = 3.62 \times 3.10$
 $ER = 11.22$ volts.

2. Rectifier rating. Standard ratings for a rectifier in this size class is 18 volt, 4 amp.

(w) Rectifier rating for bowl.

1. DC side. Voltage output as previously determined, 80 volts. Current rating is 15.2 amp. The nearest commercially available rectifier meeting the above requirements is a 80 volt, 16 amp.

(x) Wire sizes and types.

All positive feeder and suspension cables (rectifier to anodes) shall be #2 AWG, HMWPE insulated copper cable. To avoid complication, the negative rectifier cable (rectifier to structure) shall be of the same size and type (Figure 58).

(y) Discussion.

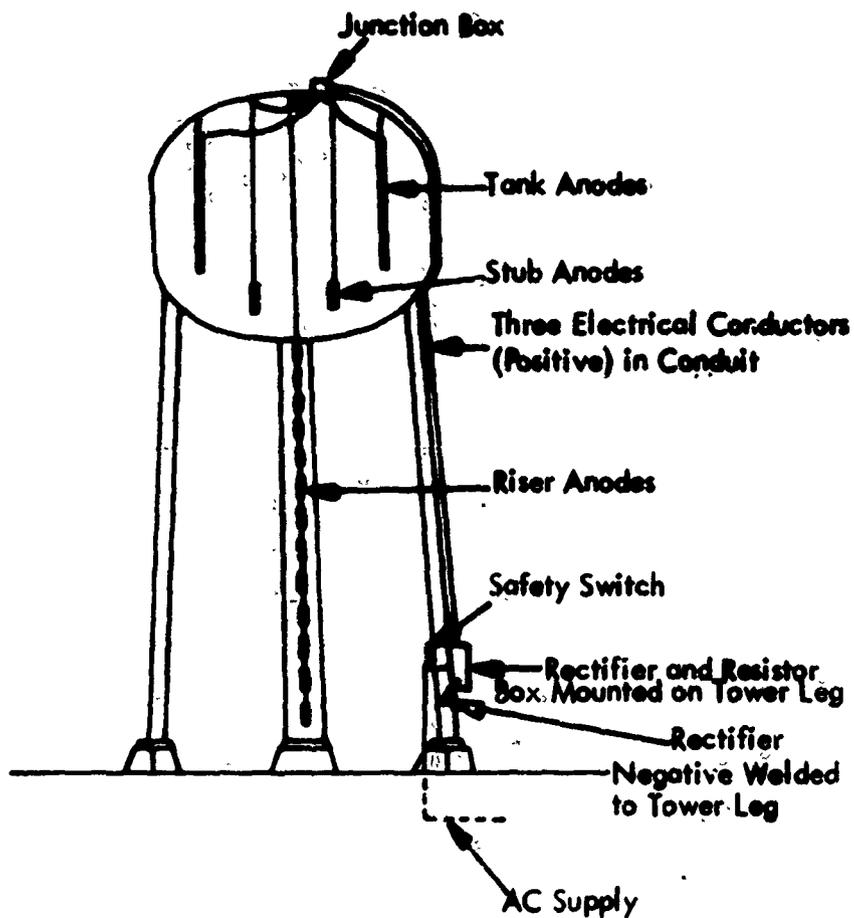


Figure 58
 ELEVATED STEEL WATER TANK SHOWING
 RECTIFIER AND ANODE ARRANGEMENT

1. This 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 50 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 will usually exceed the cost of a quality coating system over a ten 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.
2. For further assistance and guidance in the design of cathodic protection systems for elevated cold water storage tanks, see Figures 59 and 60.
3. HSCBCI was 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 aluminum and platinized titanium.
4. For this design, silicon cells should be specified for the rectifier protecting the bowl and selenium cells should be specified for the rectifier protecting the riser. Silicon cells operate more efficiently at high DC output voltages than selenium cells 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 cells for single phase rectifiers operated above 72 volts DC or three phase rectifiers operated above 90 volts DC. Use newer non-aging selenium for single phase rectifiers operated below 72 volts DC or three phase rectifiers operated below 90 volts DC.

b. Elevated Water Tank (Where Ice is Expected). Impressed current cathodic protection is designed for an elevated water tank shown in Figure 61. The tank is already built, and current requirement tests have been made. Anodes will not be suspended from tank roof because heavy ice (up to 2 feet thick) covers the water surface during winter. The weight of this ice could not be tolerated on anode cables, so another method is employed. Button anodes will be mounted on the floor of the tank and lightweight platinized titanium anodes will be suspended in the riser from the tank bottom.

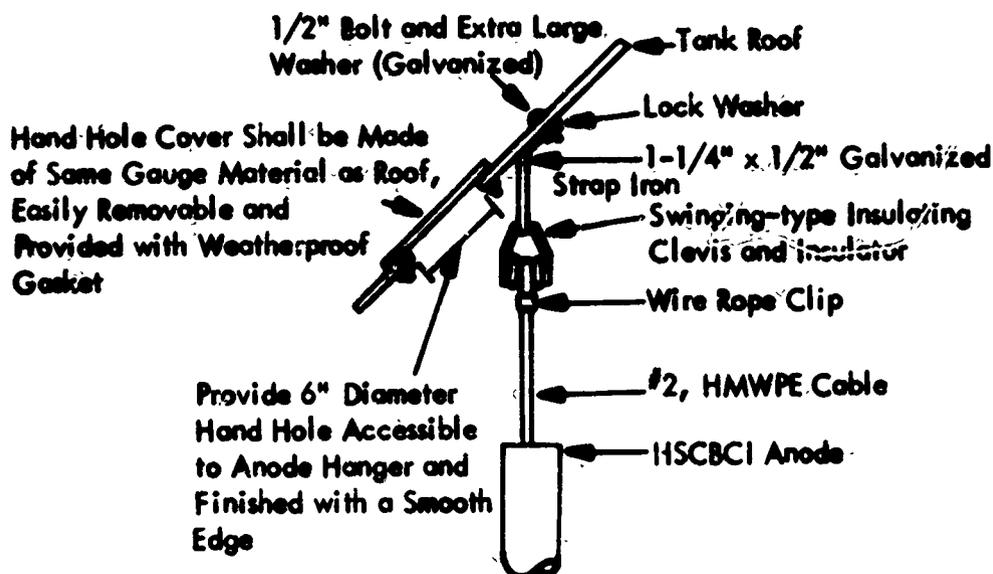


Figure 59

HAND HOLE AND ANODE SUSPENSION DETAIL FOR ELEVATED WATER TANK

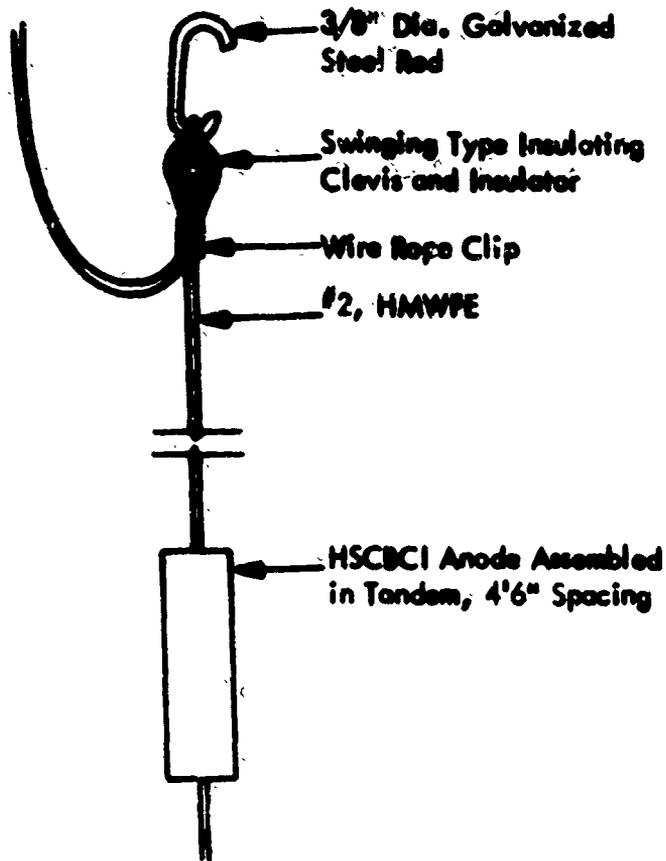


Figure 60
 RISER ANODE SUSPENSION DETAIL FOR ELEVATED WATER TANK

- (1) Design Data
- | | | |
|-----|---|--|
| (a) | Tank height (from ground to bottom of bowl) | 37 ft. |
| (b) | Tank diameter | 24 ft. |
| (c) | High water level in tank | 34.5 ft. |
| (d) | Overall depth of tank | 34.5 ft. |
| (e) | Vertical shell height | 22.5 ft. |
| (f) | Riser pipe diameter | 4 ft. |
| (g) | Shape of tank | Semicircular bottom |
| (h) | All internal surfaces uncoated | |
| (i) | Current required for protection | bowl - 7.0 amperes
riser - 1.0 ampere |
| (j) | Electrical power available | 120/240 VAC
single-phase |
| (k) | Tank is subject to freezing | |
| (l) | Design life | 15 years |
| (m) | Water resistivity | 4000 ohm-cm. |
| (n) | Button type HSCBCI anodes are used for tank | |
| (o) | Riser anodes are platinized titanium wire. | |

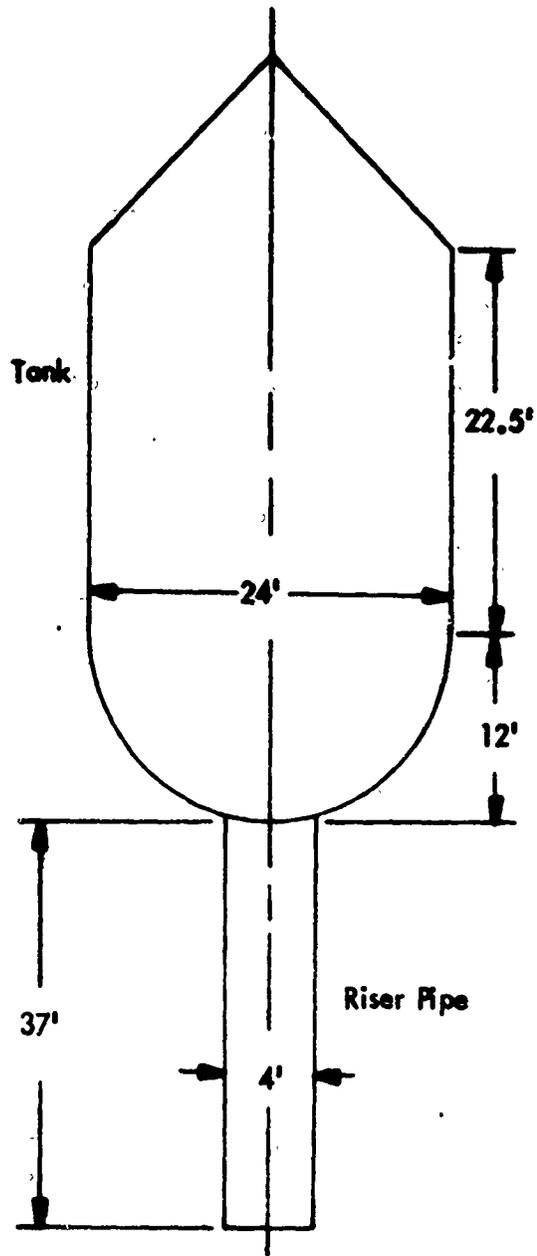


Figure 61
DIMENSIONS: ELEVATED STEEL WATER TANK

(2) Computations:

- (a) Minimum weight of button anode material required for tank.

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

where

$$\begin{aligned} Y &= 15 \text{ yr.} \\ S &= 1.0 \text{ lb/amp.-yr.} \\ I &= 7.0 \text{ amp.} \\ E &= 0.50 \end{aligned}$$

$$W = \frac{15 \times 1.0 \times 7.0}{0.50}$$

$$W = 210 \text{ lb.}$$

- (b) Number of tank anodes.
Button anodes weigh 55 lbs.

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

- (c) Minimum weight of riser anode material required for riser.

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

where

$$\begin{aligned} Y &= 15 \text{ yr.} \\ S &= 1.32 \times 10^{-5} \text{ lb./amp-yr.} \\ I &= 1.0 \text{ amp.} \\ E &= 0.50 \end{aligned}$$

$$W = \frac{15 \times 1.32 \times 10^{-5} \times 1.0}{0.50}$$

$$W = 3.96 \times 10^{-4} \text{ lb.}$$

- (d) Number of riser anodes.

Platinized titanium wire 0.1-in. dia., 3 ft. long, with .001-in. thick platinum over titanium will be used for each anode. The weight of platinum on each anode is 8.8×10^{-5} lbs.

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

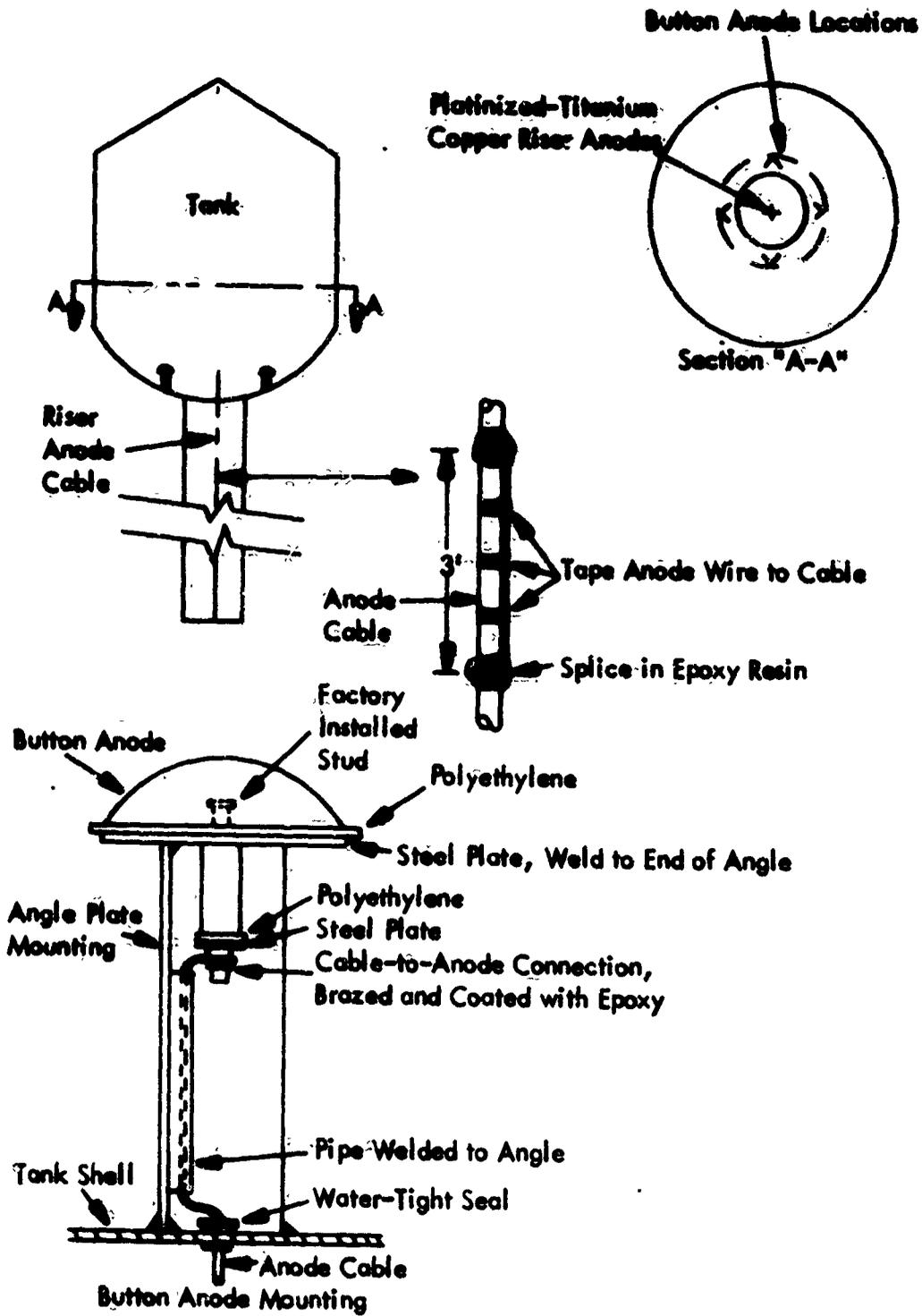


Figure 62
 CATHODIC PROTECTION FOR TANKS USING
 RIGID-MOUNTED BUTTON-TYPE ANODES

(e) Location of anodes (Figure 62)

Button anodes are mounted on base of tank at a distance of $1/4$ the tank diameter (5 ft.) from the center. They are mounted on metal angles and plates welded to the tank bottom; polyethylene insulation is required to separate anode from metal mounting. Riser anodes are suspended in the center of the riser pipe, spliced to a No. 4 cable. The top anode is placed 1 ft. from the tank base. The remaining four anodes are spaced at 4 ft. intervals.

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

c. Aircraft Multiple Hydrant Refueling System. Galvanic cathodic protection is designed for a standard aircraft hydrant refueling system shown in Figure 63. This design is for a system not yet installed.

(1) Design data.

- (a) Average soil resistivity, 5000 ohm-cm.
- (b) Design for 90% coating efficiency, based on experience.
- (c) Design for 15-yr. life.
- (d) Design for 1 ma./sq. ft. of bare pipe after polarization.
- (e) Magnesium packaged type anodes will be used.
- (f) System is adequately insulated from foreign structures.
- (g) All pipe was mill-coated with hot applied coal-tar enamel and wrapped with asbestos felt. Coating was tested over the trench for holidays, and defects were corrected. Coating is assumed better than 99.5% perfect at installation.

(2) Computations. Refer to Figure 63 and Table 22.

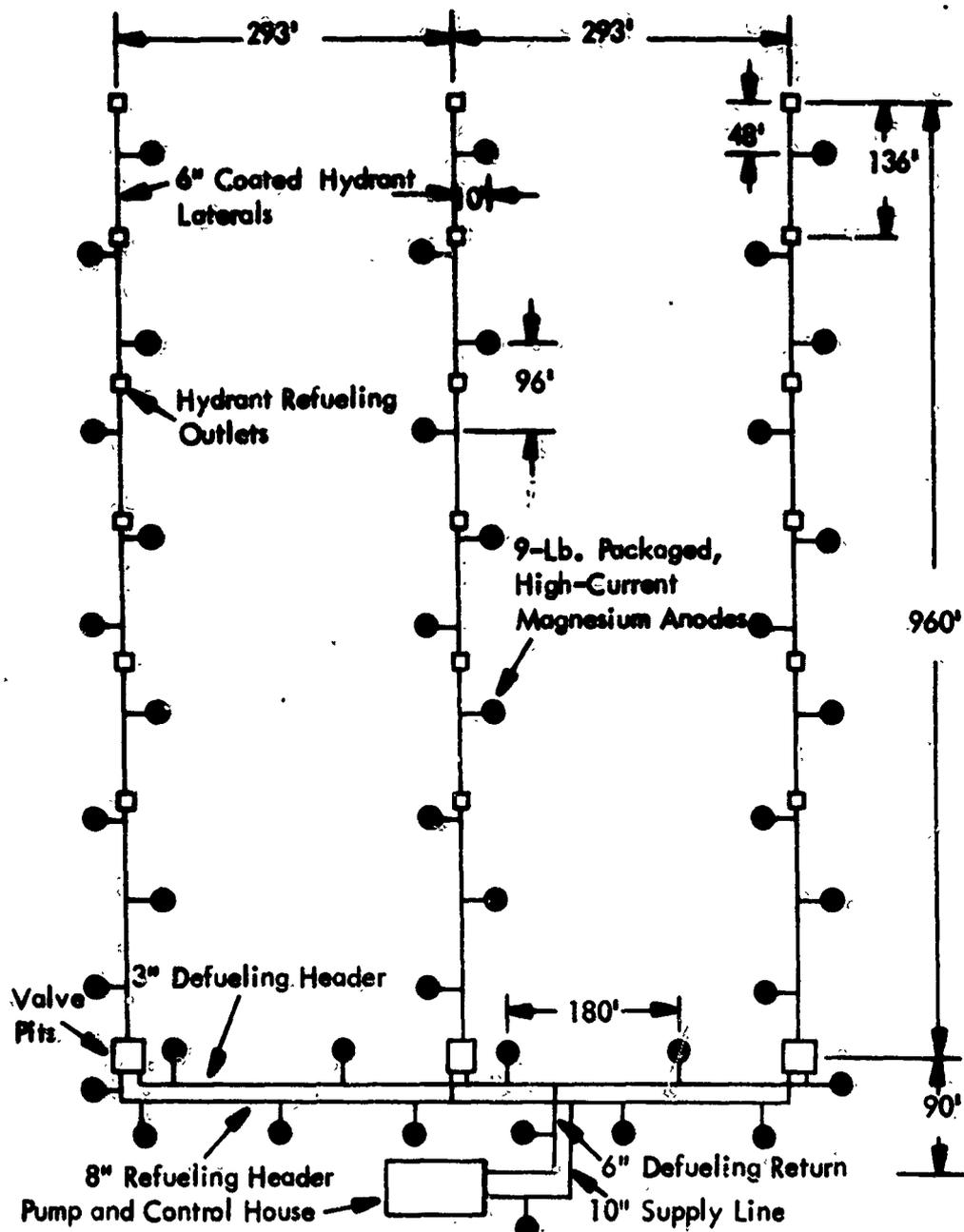


Figure 63
**GALVANIC ANODE CATHODIC PROTECTION
 FOR HYDRANT REFUELING SYSTEM**

(a) Total outside area of POL piping serving the hydrant refueling area.

Pipe Size in.	Pipe Length ft.	Pipe Area, sq.ft./ft. (Table)
3 (defueling header)	2 x 293 = 586	586 x .916 = 538
6 (defueling return)	90	90 x 1.734 = 156
8 (refueling header)	2 x 293 = 586	586 x 2.258 = 1,321
10 (supply line)	90	90 x 2.82 = 254
6 (hydrant laterals)	3 x 960 = 2880	2880 x 1.734 = <u>4,991</u>
Total area of POL pipe in sq. ft.		7,260

(b) Area of bare pipe based on 90% coating efficiency.

$$A = 7260 \times 0.1$$

$$A = 726 \text{ sq.ft.}$$

(c) Maximum current required based on 1 ma./sq. ft. of bare pipe.

$$I = 1.0 \times 726$$

$$I = 726 \text{ ma. or } 0.73 \text{ amp.}$$

(d) Minimum weight of anode material.

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

where

$$Y = 15 \text{ yrs.}$$

$$S = 8.8 \text{ lb./amp.-yr.}$$

$$E = 0.50$$

$$I = 0.73 \text{ amp.}$$

$$W = \frac{15 \times 8.8 \times 0.73}{0.50}$$

$$W = 193 \text{ lb.}$$

It should be noted that the 193 lb. arrived at above is based upon an output current of 0.73 amp. for the full designed life of the cathodic protection system, 15 years. Strictly speaking, this is not the case because the current output following a new installation is much less due to the high coating efficiency. The average current requirement at first may be as low as 0.015 ma./sq. ft. of pipe.

- (e) Current output of a single 9-lb. packaged, "high current" magnesium anode.

$$i = \frac{Cfy}{\rho}$$

where

$$C = 120,000$$

$$f = 0.71$$

$$y = 1.00$$

$$\rho = 5000 \text{ ohm-cm.}$$

$$i = \frac{120,000 \times 0.71 \times 1.00}{5000}$$

$$i = 17.0 \text{ milliamperes}$$

Since the structure is well-coated, the anode spacing is relatively great. Therefore the "Multiplying Factor for Magnesium Anode Groups" is not used.

- (f) Number of anodes (n).

$$n = \frac{I}{i}$$

where

$$I = 726 \text{ milliamperes}$$

$$i = 17.0 \text{ milliamperes}$$

$$n = \frac{726}{17}$$

$$n = 42.7 \text{ (use 43 anodes).}$$

- (g) Anode distribution.

1. Area of pipe protected by one anode.

$$A = 7260/43$$

$$A = 169 \text{ sq.ft.}$$

2. Division of anodes.

Laterals	4991/169 = 30 anodes
Header	1859/169 = 11 anodes
Supply and return lines	410/169 = 2 anodes

d. Steel Gas Main. Impressed current cathodic protection is designed for the 6-in. welded gas main shown in Figure 64. This pipeline is not constructed, so measurements may not be made.

(1) Design data.

- (a) Average soil resistivity, 2000 ohm-cm.
- (b) Pipe size, 6-in. OD.
- (c) Pipe length, 6800 ft.
- (d) Design for 15-yr. life.
- (e) Design for 2-ma./sq.ft. of bare pipe.
- (f) Design for 90% coating efficiency, based on experience.
- (g) The pipeline will be isolated from the pump-house with an insulating joint on the main line inside the pumphouse.
- (h) HSCBCI anodes will be used with carbonaceous backfill.
- (i) The pipe is coated with hot-applied coal-tar enamel and holiday-checked before installation.
- (j) Anode bed shall not exceed 2 ohms.
- (k) Electric power is available at 120/240 volts, single phase, from a nearby overhead distribution system.

(2) Computations.

- (a) Outside area of gas main.

Pipe size - 6 in.
Pipe length - 6800 ft.
Pipe area - $6800 \times 1.734 = 11,800$ sq.ft.

- (b) Area of bare pipe to be cathodically protected based upon 90% coating efficiency.

$A = 11,800 \times 0.1$
 $A = 1180$ sq.ft.

- (c) Protective current required based upon 2 ma./sq.ft. of bare metal.

$I = 1180 \times 2$
 $I = 2360$ ma. or 2.36 amp.

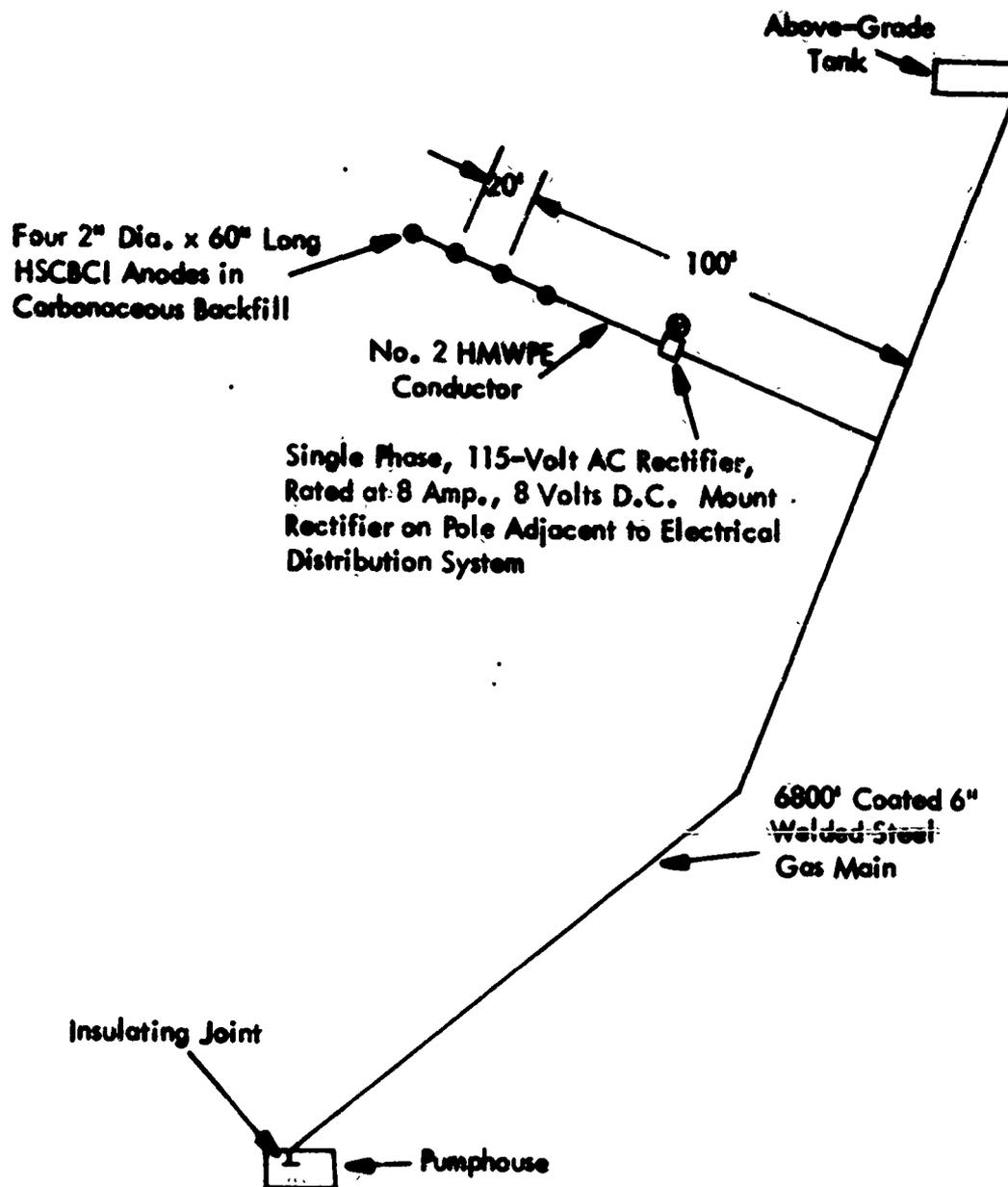


Figure 64
 CATHODIC PROTECTION SYSTEM FOR GAS MAIN

(d) Ground Bed Design.

1. Anode size, 2 in. x 60 in. (backfilled 10 in. x 84 in.), spaced 20 feet apart.

2. Resistance of a single anode to earth.

$$R_v = \frac{\rho}{L} K$$

where

$$\rho = 2000 \text{ ohm-cm.}$$

$$L = 7.0 \text{ ft.}$$

$$K = 0.0189 \text{ (from Table 7-24)}$$

$$R_v = 2000 \times .0189 / 7.0$$

$$R_v = 5.4 \text{ ohms.}$$

3. Number of anodes required. It was stated in the design data that the anode bed resistance is not to exceed 2 ohms. Anode size used is 2-in diam. x 60 in. long with carbonaceous backfill having over-all dimensions of 10-in. diam. x 84 in. long and spaced 20 ft. apart.

$$R = \frac{1}{n} R_v + \frac{\rho P}{S}$$

where

$$\bar{R} = 2 \text{ ohms}$$

$$R_v = 5.40 \text{ ohms}$$

$$\rho = 2000 \text{ ohm-cm.}$$

$$S = 20 \text{ ft.}$$

P, a function of n (Table 25), and n, the number of anodes, will be determined by trial and error.

Rearranging the equation for n,

$$n = \frac{R_v}{\bar{R} - (\rho P) / S}$$

$$n = \frac{5.40}{2 - (2000 P) / 20}$$

$$n = \frac{5.40}{2 - 100 P}$$

Try n = 4 anodes,

$$P = .00283$$
$$4 \frac{?}{\cdot} \frac{5.40}{2} = 0.283$$
$$4 \frac{?}{\cdot} \frac{5.40}{1.717}$$
$$4 \frac{?}{\cdot} 3.15 \text{ (close)}$$

Try n = 3 anodes,

$$P = .00289$$
$$3 \frac{?}{\cdot} \frac{5.40}{2} = 0.289$$
$$3 \frac{?}{\cdot} \frac{5.40}{1.711}$$
$$3 \frac{?}{\cdot} 3.16$$

This is closest possible. In order to keep total resistance below 2.0 ohms, use 4 anodes.

4. Actual resistance.

$$R = 1/4(5.40) + \frac{2000 (.00283)}{20}$$
$$R = 1.35 + 0.28$$
$$R = 1.63 < 2 \text{ ohms.}$$

(f) Total weight of anodes for ground bed.

1. Weight per anode unit, 60 lb.
(size 1 in. x 60 in.)

2. Total weight = 4 x 60 = 240 lb.

(g) Theoretical life of anode bed.

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

Rearranging gives

$$Y = \frac{WE}{SI}$$

where

$$\begin{aligned}W &= 240 \text{ lb.} \\S &= 1.0 \text{ lb./amp.-yr.} \\E &= 0.50 \\I &= 2.36 \text{ amp.} \\Y &= \frac{240 \times .50}{1.0 \times 2.36} = 50.9 \text{ years.}\end{aligned}$$

It should be noted 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.

(h) Resistance of DC circuit.

1. Groundbed-to-soil resistance, 2.0 ohms max.
2. Resistance of groundbed feeder conductor.
(length 500 ft., type HMWPE, size #2 AWG).

Conductor resistance
0.159 ohm/1000 ft.

$$\begin{aligned}R &= 500/1000 \times 0.159 \\R &= .079\end{aligned}$$

3. Total resistance of DC circuit.

$$R_T = 2.0 + .079 = 2.08 \text{ ohms.}$$

(i) Rectifier rating.

1. Minimum current requirement, 2.36 amp.
2. Circuit resistance, 2.08 ohms.
3. Voltage rating.

$$E = IR$$

where

$$\begin{aligned}I &= 2.36 \text{ amp.} \\R &= 2.08 \text{ ohms} \\E &= 2.36 \times 2.08 \\E &= 4.9 \text{ or } 5.0 \text{ volts.}\end{aligned}$$

To allow for rectifier aging, film formations, 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.

$$E = 5.0 \times 1.5 = 8.0 \text{ volts.}$$

4. The commercial size rectifier meeting the above requirements is 115-volt, single phase, selenium, full wave bridge type unit having a DC output of 8 amp. and 8 volts.

(y) Rectifier location. Mount rectifier at eye level on a separate pole adjacent to an existing overhead electrical distribution system.

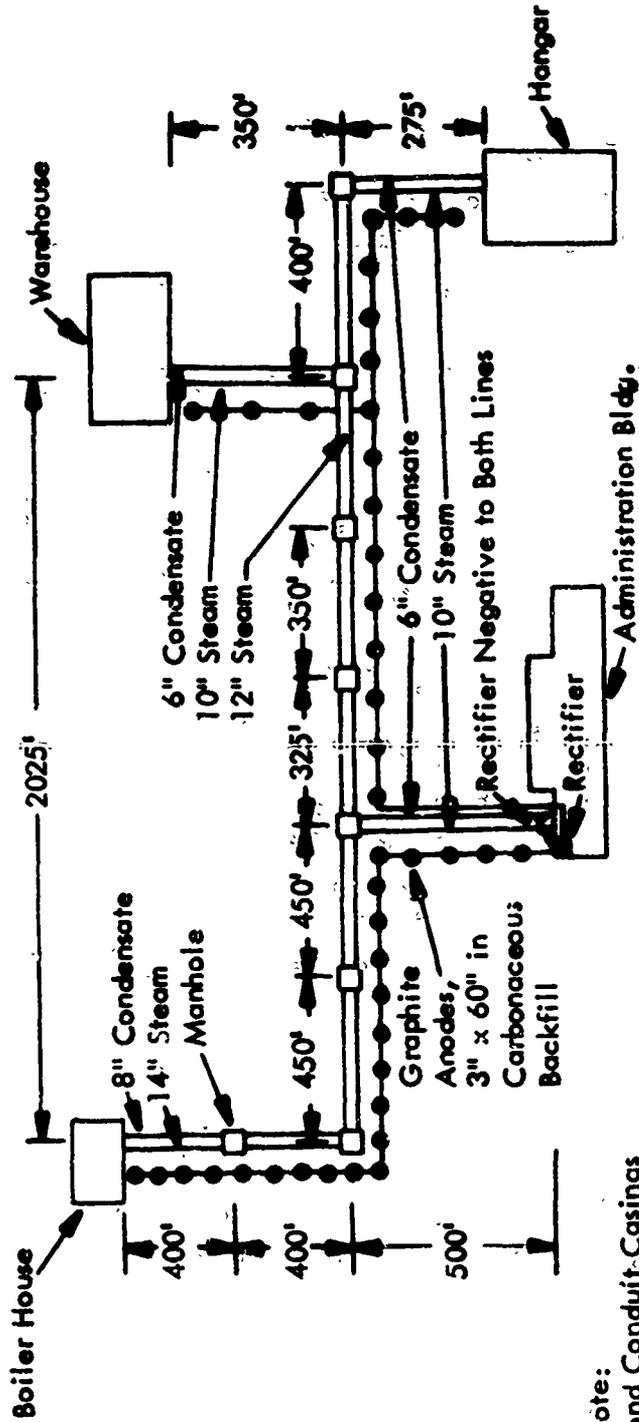
e. Heating Distribution System. Impressed current cathodic protection is designed for a well-coated buried heating distribution system shown in Figure 55. The distribution system has not yet been installed, so current requirements, etc. can not be made. Rectifier size need not be calculated, because it will be sized in the field after installation of anodes.

(1) Design data.

- (a) Average soil resistivity, 1000 ohm-cm.
- (b) Design for 80% coating efficiency, based on experience.
- (c) Design for 4 ma./sq.ft. of bare metal heating conduits.
- (d) Groundbed resistance shall not exceed 1.5 ohms.
- (e) Graphite anodes will be installed with carbonaceous backfill.
- (f) Design for 15-yr. life.
- (g) Insulating joints will be provided on both steam and condensate lines at the first flange connection inside of all buildings.
- (h) All conduit will be metallicly bonded together in each manhole.
- (i) All conduit is pre-coated at the factory and at no time is it holiday-checked.
- (j) Single phase electric power is available at 120/240 volts from administration building.

(2) Computations.

- (a) Total outside area of conduit. Since the gauge of the metal from which conduit is fabricated ranges between 14 and 16, the outside diameter of the pipe is considered to be the same as the inside diameter.



Note:
Bond Conduit Casings
in Each Manhole

Figure 65
IMPRESSED CURRENT CATHODIC PROTECTION FOR HEATING CONDUIT SYSTEM

1. Steam conduit.

<u>Conduit Size</u> in.	<u>Conduit Length</u> ft.	<u>Conduit Area</u> sq. ft./ lin. ft.	<u>Area of</u> <u>Conduit</u> sq. ft.
14	1700	3.66	6,220
12	1125	3.14	3,540
10	1525	2.62	<u>4,000</u>
Total area of steam conduit			13,760

2. Condensate return conduit.

<u>Conduit Size</u> in.	<u>Conduit Length</u> ft.	<u>Conduit Area</u> sq. ft./ lin. ft.	<u>Area of</u> <u>Conduit</u> sq. ft.
8	1700	2.1	3,570
6	2650	1.57	<u>4,160</u>
Total area of condensate return conduit			7,730
Total outside area of all conduit			21,490

- (b) Area of bare pipe to be cathodically protected based upon 80% coating efficiency.

$$A = 21,490 \times 0.2$$
$$A = 4300 \text{ sq. ft.}$$

- (c) Maximum protective current required based upon 4 ma./sq.ft. of bare metal.

$$I = 4300 \times 4$$
$$I = 17,200 \text{ ma. or } 17.2 \text{ amp.}$$

- (d) Maximum weight of anode material for 15 years life.

1. Graphite anodes are used.

2. Average deterioration rate of graphite is 2.0 lb./amp.-yr.

3. Maximum weight of anode material required.

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

where

$$\begin{aligned} Y &= 15 \text{ yr.} \\ S &= 2.0 \text{ lb./amp.-yr.} \\ I &= 17.2 \text{ amp.} \\ E &= 0.50 \\ W &= \frac{15 \times 2.0 \times 17.2}{0.5} \\ W &= 1032 \text{ lb.} \end{aligned}$$

(3) Ground bed design.

(a) Anode size, 3 in. x 60 in., (backfilled 10" x 84") weighing 25 lb. per anode unit.

(b) Resistance of a single anode to earth.

$$R_v = \frac{\rho}{L} K$$

where

$$\rho = 1000 \text{ ohm-cm.}$$

$$L = 7.0 \text{ ft.}$$

$$K = 0.0189$$

$$R_v = \frac{1000 \times .0189}{7.0}$$

$$R_v = 2.70 \text{ ohms}$$

(c) Number of anodes required.

The low resistance (2.70 ohms) of a single anode and the large weight of anode material required (1032 lb.) for a 15-year life indicates that the controlling factor is amount of anode material, not groundbed resistance. The minimum number of anodes required is

$$N = 1032/25 = 41.3 \text{ or } 41 \text{ anodes.}$$

These are arranged in a distributed groundbed as shown in Figure 65 based on the following estimates.

(d) Anode distribution.

1. Area of conduit in sections 1 through 6.

<u>Section</u>	<u>Length (ft.)</u>	<u>Surface Area (sq.ft.)</u>
1	1700	3560 + 6220 = 9780
2	500	780 + 1310 = 2090
3	1125	1770 + 3540 = 5310
4	350	550 + 920 = 1470
5	400	630 + 1050 = 1680
6	275	430 + 720 = 1150

2. Area of conduit protected by one anode.

$$A = 21,480/41$$

$$A = 524 \text{ sq.ft./anode}$$

3. Division of anodes.

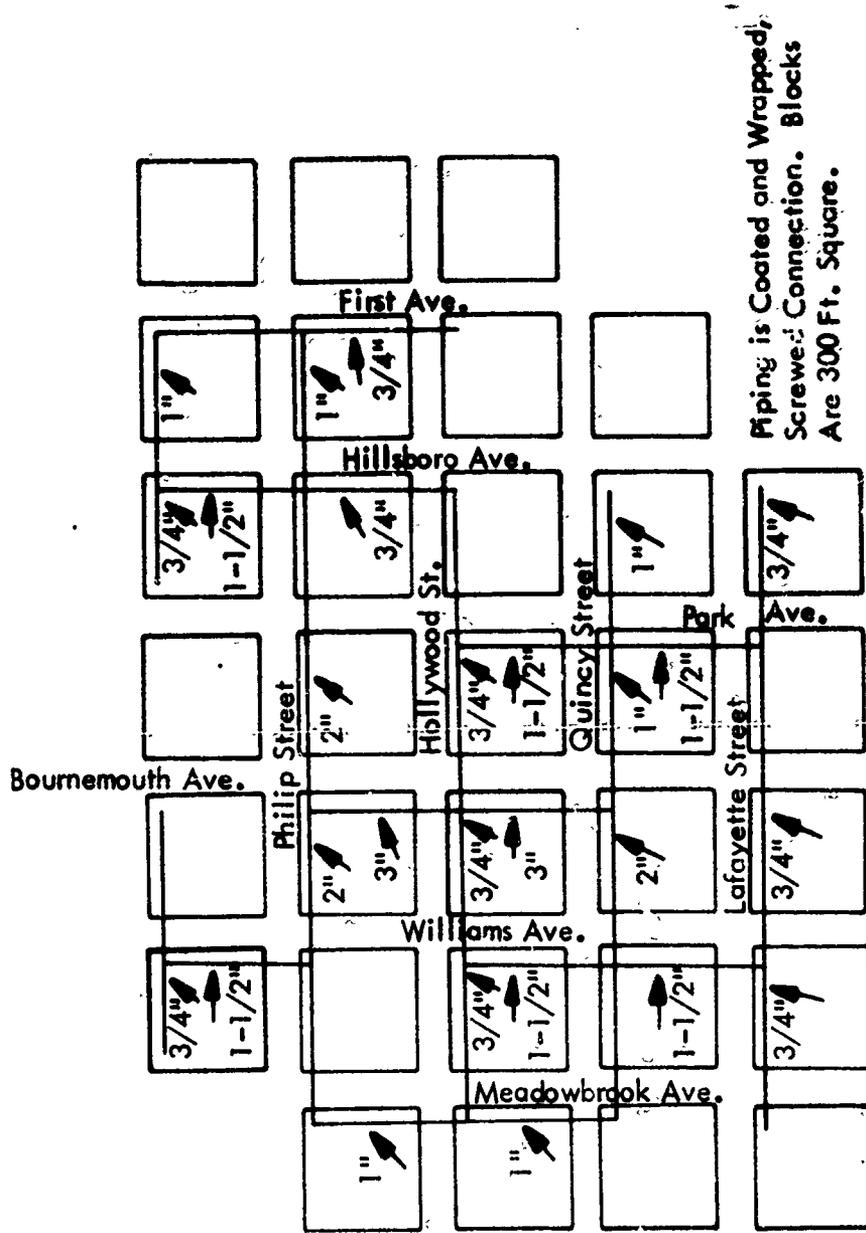
Section 1	$9780/524 = 19$	anodes
Section 2	$2090/524 = 4$	anodes
Section 3	$5310/524 = 10$	anodes
Section 4	$1470/524 = 3$	anodes
Section 5	$1680/524 = 3$	anodes
Section 6	$1150/524 = 2$	anodes

- (4) Rectifier Location. Locate rectifier in front of administration building as shown. Rectifier will be sized after anodes are installed.

f. Gas Distribution System. Galvanic cathodic protection is to be designed for a gas distribution system in a housing area shown in Figure 66.

(1) Design data.

- (a) Average soil resistivity, 4500 ohm-cm.
- (b) Design for 90% coating efficiency, based on experience.
- (c) Design for 15-yr. life.
- (d) Design for 2 ma./sq.ft. of bare pipe
- (e) Packaged type magnesium anodes will be used.
- (f) Insulating couplings are used on all service taps. The mains are electrically isolated from all other metal structures in the area.
- (g) All pipe was pre-coated at the factory and wrapped with asbestos felt. The coating was tested over the trench for holidays and defects corrected. The coating is considered to be better than 99.5% perfect at the time of installation.



Piping is Coated and Wrapped,
Screwed Connection. Blocks
Are 300 Ft. Square.

Figure 56
LAYOUT OF GAS PIPING IN RESIDENTIAL DISTRICT

<u>Pipe Size</u> <u>in.</u>	<u>Pipe Length</u> <u>ft.</u>	<u>Pipe Area</u> <u>sq. ft./</u> <u>lin. ft.</u>	<u>Area of Pipe</u> <u>sq. ft.</u>
3	800	0.916	735
2	1600	0.623	1000
1-1/2	2400	0.497	1195
1	3600	0.346	1245
3/4	4500	0.275	1240
Total area of pipe in square feet			5415

(b) Area of bare pipe to be cathodically protected based upon 90% coating efficiency.

$$A = 5415 \times 0.1$$

$$A = 542 \text{ sq. ft.}$$

(c) Maximum protective current required based upon 2 ma./sq. ft. of bare metal.

$$I = 2 \times 542$$

$$I = 1084 \text{ ma. or } 1.084 \text{ amp.}$$

(d) Weight of anode material required based upon maximum current requirement and 15-yr. life.

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

where

$$Y = 15 \text{ years}$$

$$S = 8.8 \text{ lb./amp-year}$$

$$I = 1.084 \text{ amp.}$$

$$E = 0.50$$

$$W = \frac{15 \times 8.8 \times 1.084}{0.50}$$

$$W = 286 \text{ lbs.}$$

It should be noted that 286 lb. is based on an output current of 0.85 amp. for the full design life of the cathodic protection system, 15 years. Strictly speaking, this is not the true condition, because current output following a new installation is much less due to the high coating efficiency. The average current requirement at first may be as low as 0.03 ma./sq.ft. of pipe area.

(c) Current output of a single 17-lb. standard packaged magnesium anode to ground.

$$i = \frac{Cfy}{\rho}$$

where

$$C = 120,000$$

$$f = 1.00$$

$$y = 1.00$$

$$\rho = 4500 \text{ ohm-cm.}$$

$$i = \frac{120,000 \times 1.00 \times 1.00}{4500}$$

$$i = 26.7 \text{ milliamperes}$$

Since the structure is well-coated, the anode spacing is relatively great. Therefore the "Multiplying Factor for Magnesium Anode Groups" is not used.

(f) Number of anodes (n).

$$n = \frac{I}{i}$$

where

$$I = 1084 \text{ milliamperes}$$

$$i = 26.7 \text{ milliamperes}$$

$$n = \frac{1084}{26.7}$$

$$n = 40.6 \text{ (use 41 anodes)}$$

(g) Anode distribution.

1. Area of pipe protected by one anode.

$$A = 5415/41$$

$$A = 133 \text{ sq.ft./anode}$$

2. Division of anodes.

Pipe Size in.	Pipe Area sq. ft.	Pipe Length ft.	Number of Anodes	Anode Spacing ft.
3	735	800	6	135
2	1000	1600	8	200
1-1/2	1195	2400	9	270
1	1245	3600	9	400
3/4	1240	4500	9	500

Total number of anodes

41

g. Black Iron, Hot Water Storage Tank. Impressed current cathodic protection is designed for the interior of a black iron, hot water storage tank shown in Figure 67.

(1) Design data.

- (a) Tank capacity, 1000 gal.
- (b) Tank dimensions, 46-in. diam. by 12 ft. long.
- (c) Tank is mounted horizontally.
- (d) Water resistivity is 8600 Ω -cm. with a pH value of 8.7.
- (e) Tank interior surface is bare and water temperature is maintained at 180°F.
- (f) Design for maximum current density of 5 ma./sq.ft.
- (g) Design life, 5 yr.
- (h) Use HSCBCI anodes.
- (i) Alternating current is available at 115 volts, single phase.

(2) Computations.

- (a) Interior area of tank.

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

where

$$r = 1.92 \text{ ft.}$$

$$d = 3.83 \text{ ft.}$$

$$L = 12 \text{ ft.}$$

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

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

- (b) Maximum protective current required.

$$I = 167.5 \times 5$$

$$I = 838 \text{ ma. or } 0.84 \text{ amp.}$$

- (c) Minimum weight of anode material for 5-yr. life.

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

where

$$Y = 5 \text{ yr.}$$

$$S = 1.0 \text{ lb./amp.-yr.}$$

$$I = 0.84 \text{ amp.}$$

$$E = 0.50$$

$$W = \frac{5 \times 1.0 \times 0.84}{0.50}$$

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

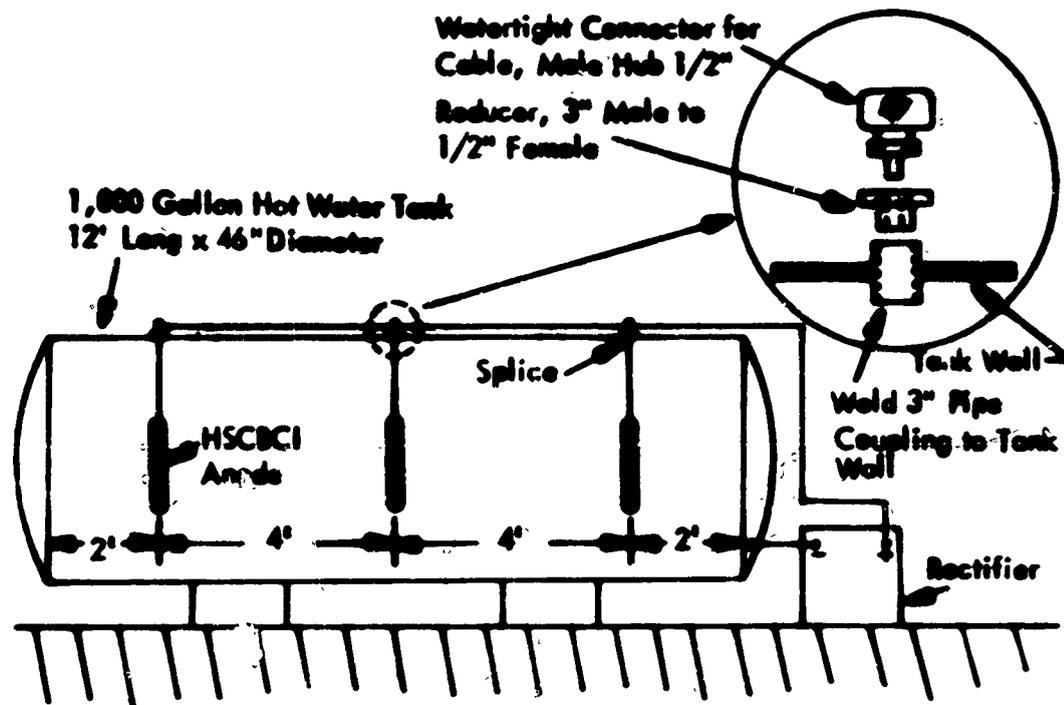


Figure 67

CATHODIC PROTECTION FOR BLACK IRON, HOT WATER STORAGE TANK

(d) Number of anodes required. Anode size 1-1/2 in. diam. by 9 in. long weighing 4 lb. each is selected as the most suitable size for this application. In order to obtain proper current distribution, three anodes are required.

(e) Resistance of anodes.

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

where

$$\rho = 8600 \text{ ohm-cm.}$$

$$D = 3.83 \text{ ft.}$$

$$d = 1\text{-}1/2 \text{ in. or } 0.125 \text{ ft.}$$

$$L = 18 \text{ in. or } 1.5 \text{ ft.}$$

$$R = \frac{0.012 \times 8600 \log 3.83/0.125}{1.5}$$

$$R = \frac{103.2 \times \log 30.7}{1.5}$$

$$R = \frac{103.2 \times 1.487}{1.5}$$

$$R = 102.5 \text{ ohms}$$

This resistance must be corrected by the fringe factor since they are short anodes. The fringe factor is 0.48 from curve in Figure 54 for an $L/d = 9/1.5 = 6$.

$$R = 102.5 \times 0.48$$
$$R = 49.2 \text{ ohms.}$$

(f) Rectifier rating.

1. $E = IR$

where $I = 0.84 \text{ amp.}$
 $R = 49.2 \text{ ohms}$
 $E = 0.84 \times 49.2$
 $E = 41.3 \text{ volts}$

2. To allow for rectifier aging and film formation, it is considered good practice to use a 1.5 multiplying factor.

$$E = 1.5 \times 41.3 = 62.0 \text{ volts.}$$

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

(g) Rectifier location. Locate the rectifier adjacent to tank for the following reasons:

1. Usually cheaper to install.
2. Easier to maintain.
3. Keeps DC voltage drop to a minimum.

(h) DC circuit conductors.

1. External to tank: use #2, HMWPE.
2. Interior of tank: use #8, HMWPE. No stressing or bending of the cable should be permitted.

h. Underground Steel Storage Tank. Galvanic cathodic protection is designed for an underground steel storage tank shown in Figure 68. The tank is already installed and current requirements tests have been made.

(1) Design data.

- (a) Tank diameter 12 ft.
- (b) Tank length 40 ft.
- (c) Design for 80% coating efficiency, based on experience.
- (d) Design for 15-year life.
- (e) Current requirements 0.7 amp.
- (f) Packaged, 17-lb. standard magnesium anodes will be used.
- (g) The tank is adequately insulated from foreign structures.

(2) Computations.

- (a) Minimum weight of anodes required for tank.

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

where

$$\begin{aligned} Y &= 15 \text{ yr.} \\ S &= 8.8 \text{ lb./amp.-yr.} \\ I &= 0.7 \text{ amp.} \\ E &= 0.50 \end{aligned}$$

$$W = \frac{15 \times 8.8 \times 0.7}{0.50}$$

$$W = 184.8 \text{ lb.}$$

- (b) Number of magnesium anodes

$$N = \frac{184.8}{17} = 10.8 \text{ (use 12 anodes for symmetry).}$$

Anodes are placed as shown in Figure 68.

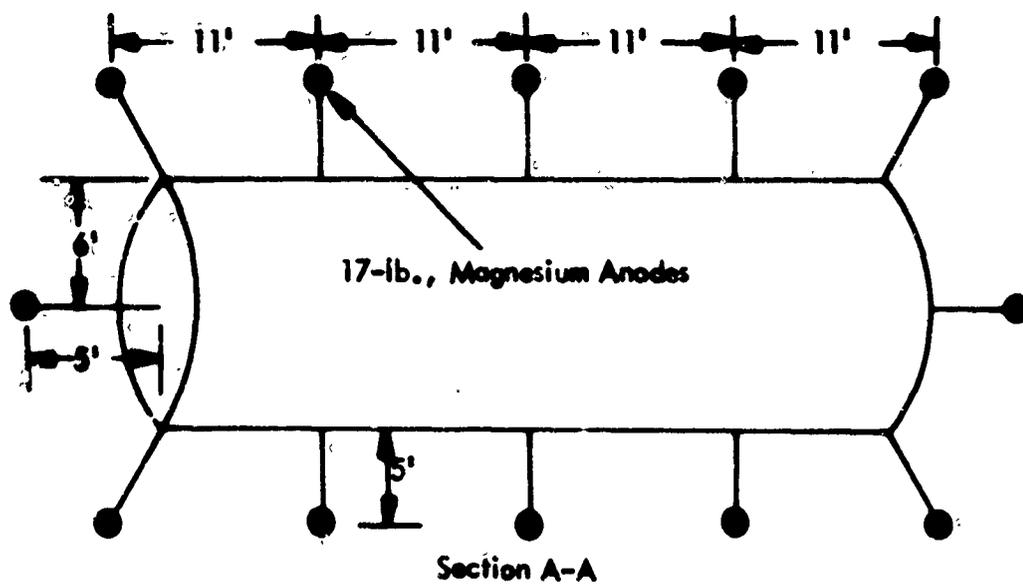
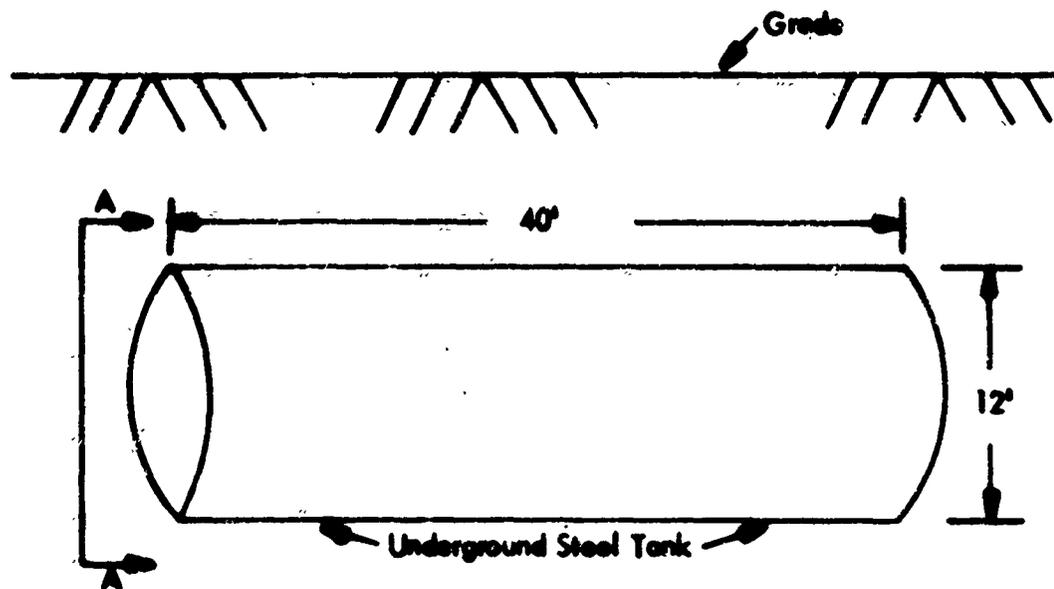


Figure 68
 GALVANIC ANODE CATHODIC PROTECTION
 OF UNDERGROUND STEEL STORAGE TANK

9 CORROSION COORDINATING COMMITTEE PARTICIPATION.

Corrosion coordinating committees have been organized to include areas of concentrated underground structures. Anyone designing and/or installing cathodic protection is expected to notify the committee in his area even though individual operating companies have been notified.

Coordinating committees are "clearinghouses" of information on operating cathodic protection, stray currents, and general corrosion problems. Membership is representative of all interested parties owning or operating underground structures. The committees have no authority to enforce procedures or regulations, but they do establish notification procedures, assist with testing schedules, and maintain records of conditions in their areas. Membership is voluntary and usually no cost is involved. Regular meetings are usually held three or four times per year. Some committees have monthly meetings.

Almost every metropolitan area of the United States and Canada now has a Coordinating Committee. Some of these cover entire states, or sections of states, to suit local needs. Most committees are affiliated with the National Association of Corrosion Engineers. A list of these, including names and addresses of current officers, can be obtained from NACE Headquarters, Houston.

10 INSTALLATION AND CONSTRUCTION PRACTICES.

Corrosion control must be justifiable, and also applied in the most economic manner. When all factors have been analyzed, total money to be spent on corrosion control is determined and broken down into specific allotments (coatings, cathodic protection, etc.). For example, little or nothing spent on coatings will mean high protective current requirements later on, if cathodic protection is to be used. In fact, the ratio of current requirements of a bare pipeline to those of a well-coated one is between 50 and 100 to one. Therefore, the corrosion engineer should be as much concerned with coating, insulating joints, casing insulation, and test stations as with cathodic protection.

For this reason, phases of both structure and cathodic protection installation are discussed here. Operational planning of construction can be as important as design itself. Money saved through concentration on details of construction practices will be evident in initial costs, longer life, and lower operating costs.

10.1 Coating Application (Pipeline). One area of great concern to the corrosion engineer during construction is application of the specified protective coating.

In many instances application is as or more important than materials used. This discussion covers important considerations in coating application, with the emphasis on pipelines. Coating application for other buried or submerged structures follows similar guidelines.

When discussing coating application, it is very difficult to generalize. The many coating materials available require a variety of application specifications. Hot-applied tars in conjunction with fiberglass and/or asbestos wrappers are in general use for major construction projects where pipelines of 6" and larger are laid. These may be applied in the mill, yard, or over the ditch. If coal tar is used, it is important that the grade of this material best suited for a particular job is available along with its compatible primer. As soon as coating material for a project begins to arrive, this should be verified since it is still not too late to make adjustments.

10.1.1 Over-the-Ditch Coating. Although location of coating application (stationary plant or over-the-ditch) is generally selected long before equipment is assembled for the job, a sudden change in weather conditions, right-of-way location, or delay in starting may make a change, even at this late date, well worth consideration. Over-the-ditch application is best used if the following conditions prevail:

- a. Long sections of welded pipe (few road crossings and foreign line crossings).
- b. A reasonably accessible, level, and firm terrain along the right-of-way.
- c. Mild weather conditions.

If any or all of these conditions appear to place satisfactory coating performance in jeopardy, mill-coating (usually performed indoors under ideal conditions) or yard-coating (performed either indoors or out) should be considered.

Structures with over-the-ditch applied coating may be lowered into the ditch directly behind the coating machine, or "skidded up" until the enamel has hardened and been electrically inspected. This decision depends upon:

- a. Time required for coating material to "set up", which in turn depends somewhat upon atmospheric temperature.
- b. Condition of ditch (is "cleaning out" necessary?).
- c. Type holiday detector used.

If it seems practical to lower directly into the ditch, the advantages of less handling, no skid marks to patch, and a better chance of having the coating inspector on hand to inspect ditch condition are worth remembering.

To insure coating performance, it is important to electrically inspect ("jeep") every length of coated pipe prior to backfilling. All holidays and breaks detected in this way must be repaired, by a method similar to field application of coating. The effectiveness of a well-applied, good-quality coating can be greatly hindered by damage done by handling, and not detected and repaired.

10.1.2 Stationary Plant (Mill or Yard). Pipe coating application at a stationary plant (yard or mill) is good practice when over-the-ditch coating would be ruled out for reasons mentioned, where pipe size is prohibitive, or where a material is used which cannot be applied in the field, such as asphalt mastic, special weighted coatings, or some epoxies.

Several additional advantages of stationary application are:

- a. Shot or grit blast machines not practical for over-the-ditch work can be used to clean pipe.
- b. Closer control of materials and equipment is possible.
- c. Final inspection is easier because materials and equipment are not spread over several miles of right-of-way. (However, several inspections are generally required: upon coating at mill (or yard), upon unloading at the site, and over-the-ditch.)

The greatest difficulty with yard- or mill-coated pipe lies with inspection of field patches. This includes repair of "skid marks", field welds, and shipping or handling damage. It is desirable to again use the electric holiday detector after pipe has been welded together and is ready to "lower in". However, it should be remembered that this device does not always indicate coating to steel surface bond trouble.

Various materials and "short-cut" methods are available specifically for coating field joints. It is important to select a material compatible with (if not the same as) the plant-applied coating. Of course, a dry, clean and/or primed surface is needed, as with any coating procedure.

The coating inspector should not depend too heavily upon the electric holiday detector. In addition, visual inspection of the coating material as it flows, occasional bond checks, continuous observation of coating thickness, and a view of lowering in operations should be maintained at all times. Also, the following should be watched as carefully as the actual coating application: cleaning and priming,

equipment condition and cleanliness, and material storage and handling. In general, any material haphazardly-applied will give poor performance while even a marginal one may serve exceptionally well when properly used.

10.2 Casing Installation.

Although casings should not be used over carrier pipes, they are sometimes required by codes, laws, or physical conditions. Where casings are used, they should be uncoated, and casing insulators, cradles, and end seals should be carefully inspected and electrically tested.

In addition to problems discussed in earlier sections, some precautions which inspectors should be aware of and/or could be incorporated in the contractor's specifications are as follows:

1. Keep casings, bell holes, and "false ditch" pumped out until carrier pipe has been installed in casing and annular space is sealed.

2. Be sure casing has been "swabbed" before carrier pipe is placed inside so that the possibility of coating damage from foreign material will be minimized.

3. As a further precaution against coating damage, rock shield or an extra thickness of coating can be applied to the carrier pipe between spacers.

4. Casing to pipe resistance should be measured. (At best this could mean observations both before and after "road section" is tied into line. At least it could mean a welding generator "test".)

Needless to say, it is advantageous to install test wires on casing and adjacent carrier pipe so that periodic internal resistance tests can be made.

10.3 Foreign Pipeline and Drainage Crossings.

It is usually standard practice for a newly constructed pipeline to pass under an older structure unless the latter is unusually deep. This is of some advantage to the party laying the new line in that maintenance work on the old line will not disturb the new one (coating damage, etc.). However, it is probably more a matter of courtesy because, in this way, the operator there first has the easiest access. Although not always possible in the more congested areas, one should strive for a structure-to-structure clearance of from 18" to 2'. Contacts between two structures should be avoided at almost any cost.

When a pipeline or other construction project is underway, it is good practice to contact the owner of any structures which will be crossed, or could later become involved in

mutual corrosion problems. This should be done well in advance of the time work forces actually arrive at the area, so that:

1. Arrangements can be made to install test leads on the lines.
2. Special coating applications, to increase internal resistance between structures, can be planned.
3. A general knowledge of any special problems peculiar to an area can be gained, and cooperative solutions sought.

Field drainage tile is a problem in some sections of the country - the flatlands of the Midwest, etc. The usual method of replacing displaced sections of tile across a pipeline ditch employs metal "tile supports". Here it is important to allow clearance between these supports and the line, so that even after settling, contact is not possible. This usually means that the pipeline ditch be deep enough, and that inspectors do not miss any drainage lines. While the ditch is being cut, close inspection should be maintained, and location of all field drainage recorded and marked. If some lines are missed completely, it may be necessary to lower long sections of the pipeline later on. This is only another opportunity for coating damage. If it is not possible to lower the line because of other obstructions, "catch basins" are sometimes built around pipelines. This is generally undesirable because moisture, silt, etc. can easily collect here.

10.4 Insulating Joints. Insulating material in the form of gaskets, sleeves, washers, special threaded couplings, unions, etc. is available for almost every size and type pipe connection in common usage today. This discussion will be limited to flange type joint. However, regardless of what type is needed to do a particular job, the engineer should always remember that his installation is most satisfactory when:

1. The material can be assembled in as "foolproof" a manner as possible.
2. It is assembled so that suitable tests can be made to ascertain its effectiveness.

In considering the flange type insulating joint, three suggestions to help achieve the above are:

1. Assemble the pair of flanges with insulating material inserted before welding either into the pipeline. (A short "spool" can be welded to each flange.) This minimizes the chance of damaging insulating material by prying or driving flange components together. It also lessens the chance of dirt or moisture damage since in-shop assembly is possible. At the same time, it is possible to get a positive test across the insulating joint while it is completely insulated from ground. (Resistance should be infinite, if joint

is good.)

2. Use insulating washers on both ends of studs, and sleeves which cover the studs from washer to washer. This practice makes possible a positive test of resistance between each individual stud and its flanges after the insulating joint assembly has been welded into the pipeline. (It must always be assumed that internal resistance between two sections of buried pipe is extremely low compared with infinitely high resistance through good insulating material.) Also, with this type assembly, the chances of a faulty joint when it is impossible or impractical to test are lessened.

3. Box coat insulating joint with coating material (2" minimum flange to outer edge of coating thickness.) This method of coating is somewhat expensive. However, it minimizes the possibility of voids between flange faces, studs, etc., and is fairly good insurance the the assembly bottom is covered.

When coating insulating joints, it is also important to remember that water, mud, dirt, etc. must be kept away from the insulating joint until it is finally coated. If the joint is shop-assembled, it is helpful to wrap tape around it during handling.

One number 12 test lead is attached to the line on each side of insulating flanges. **Two number 4 leads (one on each side of joint) will make future resistance bonding a simple matter, and make it possible to test internal resistance between the two sections of line without inclusion of test lead resistance.**

If an insulating joint is installed in a bare pipeline, it is more effective when the pipe on each side of it is coated. One recommended rule-of-thumb for this is 100 pipe diameters on each side of the joint.

When installing insulating joints, the engineer should always look for the unexpected which will render the entire installation ineffective. Scraps of metal, or any other conductor, can provide a short circuit across the flanges. Test leads connected to opposite sides of the joint could be in contact. If the joint is placed in the yard of a terminal, pump station, or compressor station, a "bypass" around it can be made up of fences, gauge lines, conduit runs, water lines, etc. It is somewhat risky to install and rely on the integrity of insulating material in valve flanges. When maintenance crews remove valves for repair, insulating material may not be replaced at all or only after it has absorbed moisture or become damaged. Also the common pressure leakage around valves may be somewhat hazardous in the presence of potential gradient across an insulating joint.

When insulating material is installed in ring joint flanges, foreign material can become lodged between flange faces in the space between insulating ring and inside pipe wall. (It is conceivable that much of this dirt, etc. is forced into the space during scraper runs.) If foreign material involved is conductive, the insulating joint will become ineffective. This can be controlled by placing a flat gasket in the space between flanges.

10.5 Test Stations. While test stations connected to a pipeline for future use in electrical measurements might be considered strictly part of the cathodic protection system, they are easily installed during construction of the structure to be protected. Therefore, their installation shall be considered a part of that phase.

Various configurations of test stations can be installed. Most of these are basically test leads (usually No. 12 insulated copper wires) thermit-welded to the structure and terminated in a junction box or conduit for easy access. In some cases, No. 4 insulated copper cables (for future bonding) are included. Wire insulation is color coded to designate its position on the structure.

Although test lead locations are usually selected prior to construction and incorporated in structure design, it is often necessary or desirable to move some of them, or to add additional ones. Selection of test lead locations is important. Test leads should always be installed where it is anticipated that periodic repetitive structure-to-electrolyte voltage and/or current readings will be taken. This would be necessary in detection of stray current, galvanic, or cathodic interference effects, coating conductance tests, and cathodic protection effectiveness tests. Test stations are also desirable where internal resistance tests are periodically required: at foreign structure crossings or proximity points, insulating joints, and cased sections of pipelines. Practical considerations for positioning test leads include:

1. Possible development or future use of land.
2. Future road or runway construction and repair.
3. Convenience and accessibility.

Soil test stations (test access holes) contain no test leads and are a means of contacting the electrolyte through black-top or concrete for structure-to-electrolyte potential measurements. They must be installed at the elevation of finished pavement in the area. Care must be taken that they are not inadvertently covered over during paving or construction operations.

10.6 Cathodic Protection Equipment. Installation considerations for magnesium and HSCBCI anode systems are given here.

10.6.1 Magnesium Anodes. Installation of a magnesium anode (Figure 69) usually consists of placing the anode vertically in an augered hole (3 to 10 feet from the structure to be protected), placing the anode lead wire in a trench, and connecting wire to protected structure. The top of the anode must be at least 3 feet below grade. The top also must be at least as deep as the protected structure.

Permission to install magnesium anodes along a pipeline right-of-way (not on government property) is most often covered by the original pipeline easement. However, it is usually advisable to contact property owners before beginning work, and to exert every effort toward reduction of property damages which must always be paid. (These can be minimized through use of hand labor.)

The vertical hole in which a magnesium anode is placed will accommodate most of the common size packaged units if it is 10" in diameter. For pipelines, if anodes are placed on alternate sides, protective current distribution over the structure surface is generally somewhat improved, and mutual interference effects minimized. Occasionally, a layer of solid stone will be encountered. Here, it may be necessary to place anodes horizontally so that anode bottom is at least as deep as structure bottom (Figure 70). Anode-to-structure separation of 2 feet is recommended. If conditions along the right-of-way obstruct working area or limit anode-to-structure distance, anodes can be installed horizontally (Figure 71) under the pipe (using an "extra deep" augered hole so that sufficient anode-to-structure distance will be obtained). This is also worth consideration when anodes are to be installed on pipelines which are likely to be "looped" (possibility of construction damage will be reduced). An added bonus here is the more permanent moisture generally found at the greater depth.

Galvanic anodes protecting underground storage tanks are placed in augered holes about 5 feet from the tank surface. (Or possibly under the tank.) Holes should be approximately 5 feet deep.

Each anode may be attached to the protected structure individually, or several anodes may be connected together on a header wire (usually No. 10, solid) which is in turn connected back to the pipe through a test station. If a group is connected together, the number of pipe connections is reduced, and sometimes less excavation is required. However, any accidental break in the header wire disconnects several anodes. Chances of this can be reduced if header cables are

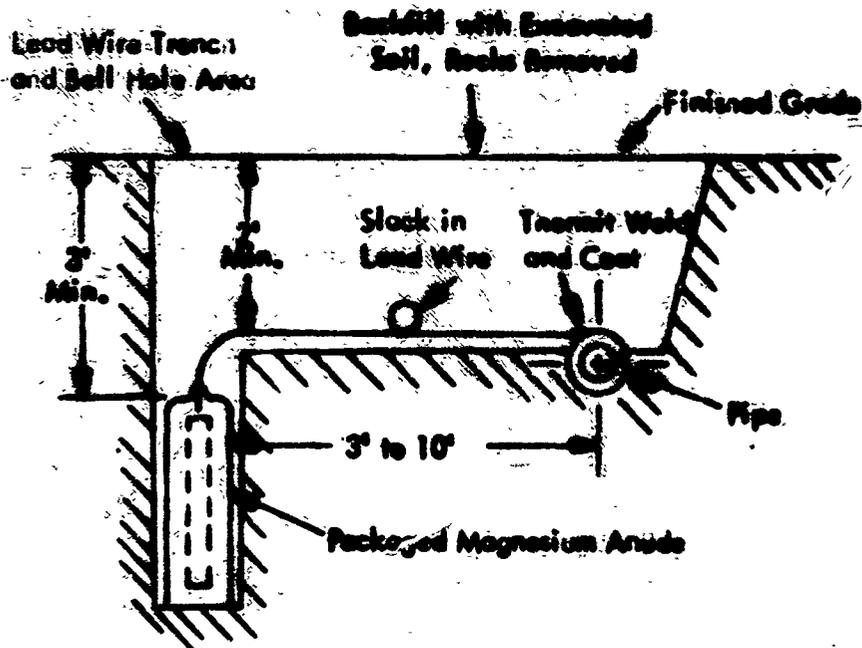


Figure 59
VERTICAL MAGNESIUM ANODE INSTALLATION

connected in at both ends of a pipeline, tank, etc. This is also useful for stream crossings and other locations where it is difficult or impractical to make a connection to the structure, even though usual practice may be the direct connection of individual anodes.

Damage to the cloth bag of prepackaged galvanic anodes resulting in loss of backfill will seriously reduce the effective current output. Each anode should be centered in its hole as it is being backfilled with earth. Pulling on anode leads to place the connection with the anode in tension cannot be tolerated as it may damage the crucial anode lead connection. Lowering a packaged anode into the hole by means of the lead wire is also potentially damaging. Anode leads should not contact sharp edges of tools and obstructions.

Backfilling holes for anodes is done with fine soil free of debris such as stone, brickbats, etc. (Sand should not be used.) Work must be done carefully to avoid injury to anodes and cables. Soil is moderately compacted in six-inch layers by hand to the top of the holes. Particular care

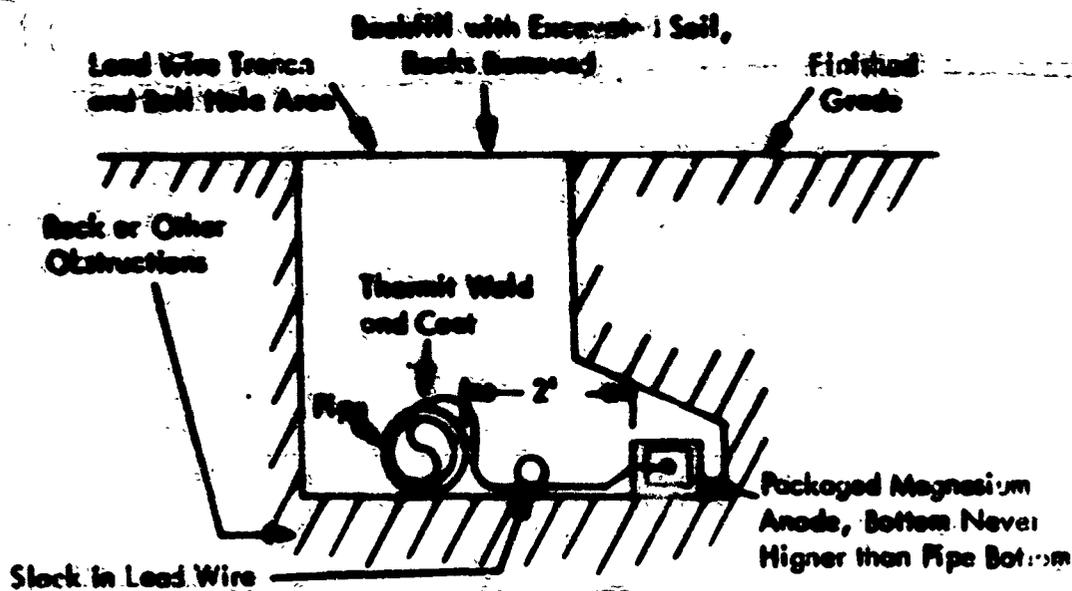


Figure 70

**HORIZONTAL MAGNESIUM ANODE INSTALLATION
WHERE OBSTRUCTIONS ARE ENCOUNTERED**

must be taken in placing and tamping soil around anodes to assure complete and intimate contact free from voids between anodes and backfill.

The most generally used method of connecting anode wires to steel surfaces is the thermit weld. It is important to use a sleeve of the correct size over the wire. Figure 72 is a cross-section of a thermit mold with charge in place. Connections should be coated. Cold-applied mastics are often used for this, and one convenient method of application is by filling paper cups with coating material, and then pressing them (inverted) over the welds. Molded plastic shields are also available to cover these connections.

When splicing anode wires together or connecting them to header cables, thermit welds, soldered U-belts, or compression connectors can be used. Here, the connection could be first covered with electrical putty, then plastic tape, and finally sealing compound.

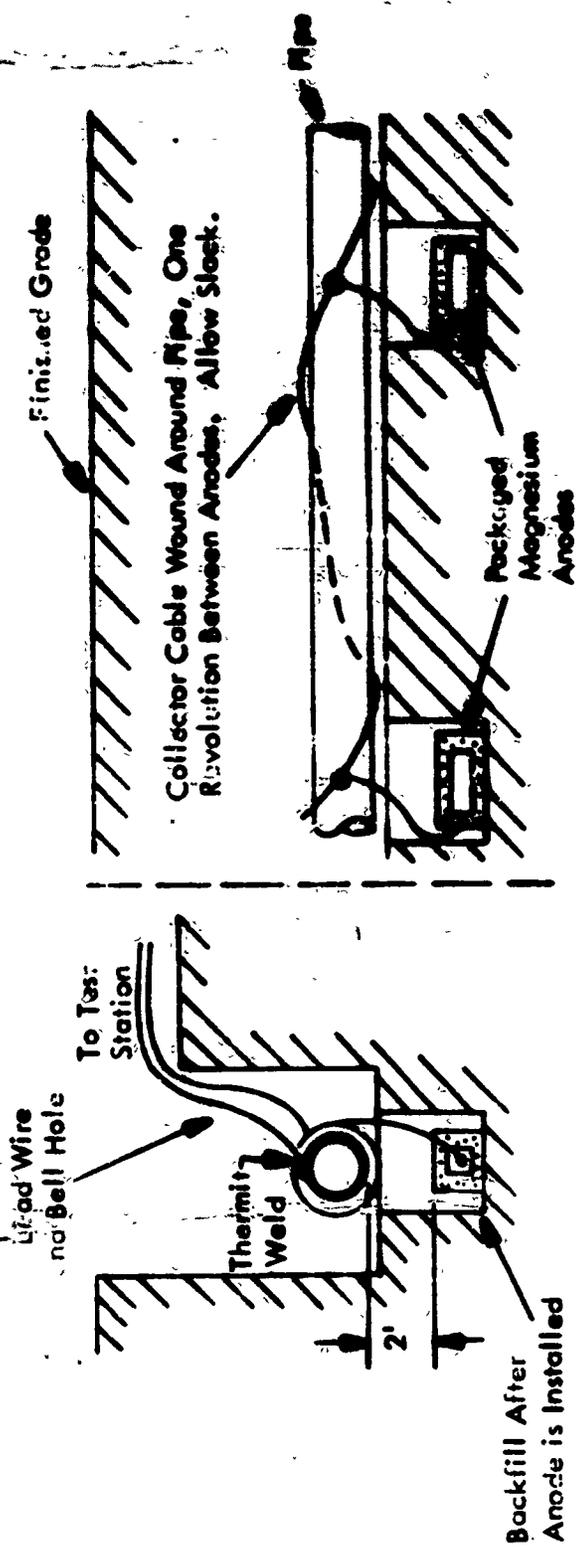


Figure 71
 HORIZONTAL MAGNESIUM ANODE INSTALLATION
 (BELOW STRUCTURE)

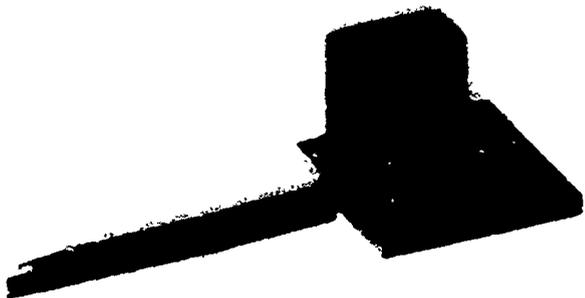


Figure 72
THERMIT WELD MOLD AND CHARGE

At least 25% of any galvanic anode installation cost is in the actual handling of material, and earthwork. This must be carefully planned, if a job is to be done efficiently, and property damages kept to a minimum. The type and quantity of mechanized equipment, and amount of labor best used for installation is determined by economics of cost vs. special right-of-way conditions (accessibility, etc.), and property owners' or base personnel's attitude toward a project. If base personnel are, in general, hostile toward excavation, fence cutting and the movement of heavy mechanized equipment through their area will certainly be prohibited or extremely expensive. Hand labor, in conjunction with small portable power tools, may be the solution. If lawns and cultivated fields cover a large percentage of the work area, the same is true. In "open" sections, rugged terrain and soil types may dictate the best construction practice. It is often advantageous to wait until after certain crops are harvested before installing anodes.

Power-driven earth augers vary in size and capacity from small hand-carried, two-man-operated, chain-saw-attachment type, to large, six-wheel-drive, truck-mounted units. The same is true for ditching machines and backhoes. However, there is seldom need for larger ditching machines unless special installation procedures are required. (Normally, a "Jeep"-mounted machine is large enough for cable trenching.) The usual backhoe might be mounted on a "Jeep" or farm tractor. If this equipment is to be used only occasionally, leasing what is needed for each particular job may be most economical.

When anode holes are augered, occasional "caving in" and "quick sand" will be encountered. If the holes are "cased", installation can be accomplished at some locations where it would otherwise be impossible. In other instances, greater depths can be reached and the material positioned better when casing is used. Common stovepipe is readily available and reasonably priced for this use.

Care should be taken in getting anodes and connecting wires to a depth below possible disturbance. In cultivated land, this will normally be in the neighborhood of 24" minimum. In some instances, it is most economical to punch or auger a small hole through the section of earth located between the bell hole and the augered anode hole.

When backfilling packaged galvanic anodes, it is good practice to fill the fine augered "chips" around the anode itself. This should lessen the chances of voids around it, and therefore give faster current output results. When working in lawns, water added as the soil is backfilled and care in replacing carefully cut sod, will minimize damages. In open fields, marmon boards or tractor blades can be best

for backfilling. If the work is done by hand, soil can be "raked" back into the ditches and holes with potato hoes.

After all earthwork has been completed, and one or two soaking rains have penetrated the ground (several weeks later), the backfill around all trenches and holes should be cleaned up and leveled off. Since this is actually the completion of the job, it is also a good time to settle any outstanding damage claims property owners may have submitted.

Magnesium anodes are available in almost any size or shape. Many are also obtainable in the packaged form. (A complete unit, ready to install - with lead wire attached and surrounded by especially prepared backfill material.) The advantages of these should always be carefully weighed against any special size anodes which might require field assembly and/or backfill. Currently, packaged anodes are widely used for underground applications.

If it is necessary to store packaged anodes out of doors, they should be kept skidded up, and under a waterproof cover. When unloaded, they should be piled with that side on bottom which had been on top during shipment. (This helps keep the anode centered in the backfill material.) As anodes are hauled out to the right-of-way and "strung", they should be kept away from livestock. (Farm animals will tear open the bags and eat the contents, if given an opportunity.) When cloth bags containing backfill around packaged anodes are broken, and this material lost, pure gypsum which is familiarly known to the building trade as "moulding plaster" can be substituted with satisfactory results.

If bare magnesium anodes are used, a package, or container for backfill material, may be improvised. However, generally the material is mixed in the field and poured into the hole at the time the anodes are installed. Standard galvanic anode backfill containing bentonite and gypsum will swell when wet and shrink when dry, thus reducing anode output because of poor soil contact. For this reason packaged anodes and anode backfill should always be installed dry and the soil tamped around and over the installed anode to insure tight contact with the surrounding soil.

Magnesium and zinc ribbon is usually installed without backfill. It can be placed in a trench or "plowed in" and connected to the structure at specified intervals.

It should be remembered that the main advantage of backfill around a magnesium anode is the gain in current output. Therefore, in the lower resistance soils, this material is unnecessary. Bare anodes of some forms can be driven.

Also, many types are available in the form of rods which can be welded together. Backfill should always be used with zinc.

10.6.2 Impressed Current Installations. The installation of impressed current cathodic protection (using rectifiers) can be divided into five phases which are:

- a. Site selection, right-of-way procurement, and coordination with power companies.
- b. Earthwork - installing groundbed, buried cables, and poles.
- c. Underground connections.
- d. Mounting and connecting rectifiers.
- e. Clean-up and damage settlement.

When considering possible rectifier sites, after current requirements and general area have been decided, it is good practice to diligently search the area for foreign buried structures. All operators of buried structures should also be contacted to be certain that none are overlooked. If a coordinating committee is active, any proposal should be discussed before its members. Preliminary tests, using a temporary groundbed, to determine effects on other buried structures may be necessary. Power availability must be kept in mind at all times. If an extension to existing service lines is necessary, one should determine whether or not the power company will pay any or all the cost. This may indicate deviation from optimum location, or additional expenditure.

When a tentative site is being selected, the ease of securing the right-of-way should receive serious consideration before placing the rectifier on a drawing. It is usually easier to obtain a groundbed easement along a property line road, or in a swampy wasteland than in the center of a cultivated field. Tracts of land likely to be subdivided in the near future should be given special consideration or avoided entirely.

If easements are difficult to obtain and/or soil resistivity extremely high, a "deep well" type groundbed may be considered. Distributed groundbeds have been used in areas where foreign structures are numerous. In some states, it is necessary to obtain an easement from both the township or county, as well as the property owner, when an installation lies within the bounds of a road right-of-way. It is a good idea to have drawings for one or two alternate rectifier installation sites available for each location. These can then be furnished the right-of-way agent on his first trip, possibly saving him several repeat calls.

The right-of-way agent can first purchase easement on an "option" basis. This can be done by having the property

accept sign easements on a retainer of one or two dollars. After the complete payment is made, the easement becomes binding. In the meantime, power companies can be contacted, and positive statements of service availability obtained as a prerequisite to the "firming up" of easements.

After easements have been purchased and arrangements made with power companies, earthwork (usually the major chore connected with impressed current installation) can begin. Here, the earthwork phase is construed as installation of groundbeds complete with all buried connecting cables.

Typical cylindrical anodes used for rectifier groundbeds are longer than galvanic anodes and therefore require deeper holes (if vertical) or longer ones (if horizontal). Also, more ditching for connecting cables is required. Power augers suitable for drilling vertical anode holes to the 9' to 12' depths usually required are sometimes difficult to locate. Long-handled hand tools such as post hole augers with pipe extensions, pole line digging bars, post hole diggers, spoons, spades, and wooden tampers are useful as auxiliary equipment or as a means of doing the entire job by hand.

The graphite or HSCBCI ground anodes used are usually surrounded by carbonaceous backfill material. When these anodes are not packaged with their backfill, one construction problem is getting the backfill in place. This material can be tamped in, if the hole is dry. A long-handled wooden tamper, such as pole line crews use, is suitable for compacting the fill below vertical anodes. If large diameter holes (12" or 15") are augered, this tool is also suitable for tamping around the anodes. In smaller diameter holes, a 2" pole will work best. If augered holes are water-filled, it is helpful to pump them out before installing anodes. However, wet holes should be allowed to "settle" overnight. When this is done, it will be found that the carbonaceous material has seeped into the hole, making it necessary to add more. This should reduce the chances of backfill voids, which could result in anode failure. The backfill should be filled to above the anodes to within a few inches of grade, unless a loose material such as gravel can be placed on top of it. This is to allow for venting. It is a good idea to test samples from each shipment of coke breeze backfill for resistivity, particle size, and ash content.

If it is necessary to install ground anodes in a horizontal position because of special soil conditions, a continuous ditch can be cut. This can then be filled from end to end with backfill material, with the anodes centered in it.

If holes are difficult to auger because of caving-in soil, stovepipe casing can be used. HSCBCI anodes are also

sometimes installed without backfill, and satisfactory service is reported. These can be "jetted" in, using water pressure.

"Deep well" type groundbeds require well-drilling equipment, and special procedures for positioning anodes.

HSCBCI anodes are more fragile than graphite (at least partially due to the fact that smaller diameter rods are often substituted for thicker graphite anodes). Therefore, they must be padded when hauled. Coke breeze or other carbonaceous backfill material is much easier to use when packaged in sacks. Even though it costs more when purchased this way, savings in handling labor, waste, and special equipment often will be the deciding factor. It should be remembered, however, that sacks (especially burlap) deteriorate rapidly when stored with coke breeze in them. Furthermore, there seems to be no advantage to covering this material if it is kept outside, but "skidding up" is advisable.

All buried cables and connections should be deep enough below ground (usually 2' minimum) so that the possibility of damage from farming, etc. will be minimized. It is also necessary to exercise extreme caution when backfilling in rocky ground, and in avoiding damage to the cables with tools and/or machinery.

Generally, connections in the buried wiring of a rectifier installation must be made at:

1. Pipeline to negative return lead.
2. Header wire to each individual anode lead.
3. Any point where cable size changes.

As previously mentioned in the magnesium anode discussion, cables and lead wires can be joined by thermit weld, solder, U-bolt, or compression connectors although thermit weld is preferred.

Where a pole-mounted rectifier is to be used, it is usually economical to install the rectifier pole and the pipeline negative return lead at the same time the other earthwork is done. A 25" pole, heavy enough to support the size rectifier used, is usually sufficient. However, more height will be required if the distance to the closest power company pole is unusually great. This should be determined before beginning construction, so that pole extensions will not be necessary. If the direction from which service drops will come is known at that time, guy anchors and cables can also be installed.

a. HSCBCI Anodes.

Cylindrical HSCBCI anodes may be installed horizontally or vertically. Type "K" (Button) anodes are bolted to the protected structure. Groundbed anodes (buried in soil) may be

surrounded by either carbonaceous or soil backfill. When backfill is used, the ditch or hole is first excavated. The anodes are centered in the excavation, while backfill is carefully tamped around them. In some types of soil, such as swampy areas and quicksand, it may not be possible to use carbonaceous backfill. Packaged anodes containing carbonaceous backfill may then be used and the complete package (anode surrounded by backfill) placed in an excavation. Large "duct" or "sausage" anodes are often pulled into empty cable ducts. In this way, they are in position to supply cathodic protection to buried cable sheaths in adjacent ducts.

ASBCI anodes must be handled with care because they are extremely brittle. They must not be thrown, dropped or pulled. The anode-to-cable connection is critical. Pulling an anode leads to place this connection in tension cannot be tolerated. Anode leads and connecting cables cannot be allowed to contact sharp edges of tools or obstructions. Any connections or seals which seem to be damaged should not be used before consulting the supplier.

(1) Vertical Soil Installations. For typical installation, a vertical hole 10" in diameter is bored into the soil. For 60" anodes this should be at least nine or ten feet deep. Backfill (soil or carbonaceous material) is then carefully placed around centered anodes, and tamped in six-inch layers. This material can be filled into the tops of the holes if right-of-way conditions permit. If not, a few inches of top soil may be placed over anodes.

Power equipment or hand tools can be used to auger vertical anode holes.

A long-handled wooden tamper, such as used by pole line crews, is suitable for compacting fill around vertical anodes if holes are not more than 10' to 12' deep. In smaller diameter holes, a 2" pole works best for tamping.

If augered holes are water-filled, it is helpful to pump them out before installing anodes. However, the backfill can be mixed into a slurry with water and poured in. Wet holes should be allowed to settle overnight. When this is done, the carbonaceous material (usually coke) descends into the hole, making it necessary to add more. This should reduce the possibility of backfill voids. It is good practice to test samples from each shipment of coke breeze backfill, to be sure that it meets specifications. (Resistivity can be tested in a soil box.)

A high-velocity water-jetting method for introducing anodes into the ground has been used. This method is most adaptable to sand soil, but it has also been successfully applied to much more compact soil containing clay and shale.

Typical vertical anode installation in soil is shown in Figure 73. This method, using unpackaged anodes, is preferred for most installations. However, in swampy areas and quicksand where it may be impossible to use backfill, packaged anodes may be used (Figure 74).

(2) Horizontal Soil Installations. HSCBCI anodes are often installed horizontally even though anode-to-soil resistance is somewhat higher in this position (Figure 75). In this manner they can be placed in a low-resistance soil, and/or rock formations can be avoided. Strings of "duct" anodes can be placed in trenches to form distributed anode systems when ducts are not available for them.

If horizontal anodes are spaced fairly close (approximately 5' to 10'), the entire trench may be filled with carbonaceous backfill. When trenching for distributed anodes, all connecting cables and anodes should be buried at least two feet below grade so as to minimize physical damage. Treated boards or concrete slabs are sometimes placed over cables for further protection. Trenches can be cut somewhat deeper at anode locations to allow extra space for carbonaceous backfill (if used).

Horizontal metal pipes, or porous tile ducts can be installed under large tank bottoms or other structures placed in contact with soil. This is easiest to do during construction of the structure. Then anodes can be pulled through at any time in the future.

Backfill (soil or carbonaceous material) should be carefully tamped around anodes. If soil is used, every effort should be made to obtain a low-resistivity grade of uniform quality.

(3) Deep Anode Installation. Anodes which are placed fifty feet or deeper below the earth's surface are commonly called "Deep groundbeds". A complete deep anode installation can be made on a plot of ground no larger than five feet square. For typical installation, see Figures 76 and 77.

A six-inch hole is recommended, and either rotary or cable tool drilling rig may be used. Drilling with a cable tool usually takes longer than the rotary drill. However, the rotary drill, with the drilling mud used, usually results in a cleaner and drier hole. The more available and economical means should be selected, however. Because deep well groundbeds are usually less than 300 feet deep, most local water well drillers are capable of drilling the well.

A dry hole is not needed, so no more casing than absolutely necessary to prevent caving during installation should be used. Deep metal casings will transmit protective current to the surface. The resultant surface discharge will nullify many advantages of the deep well groundbed. If it is

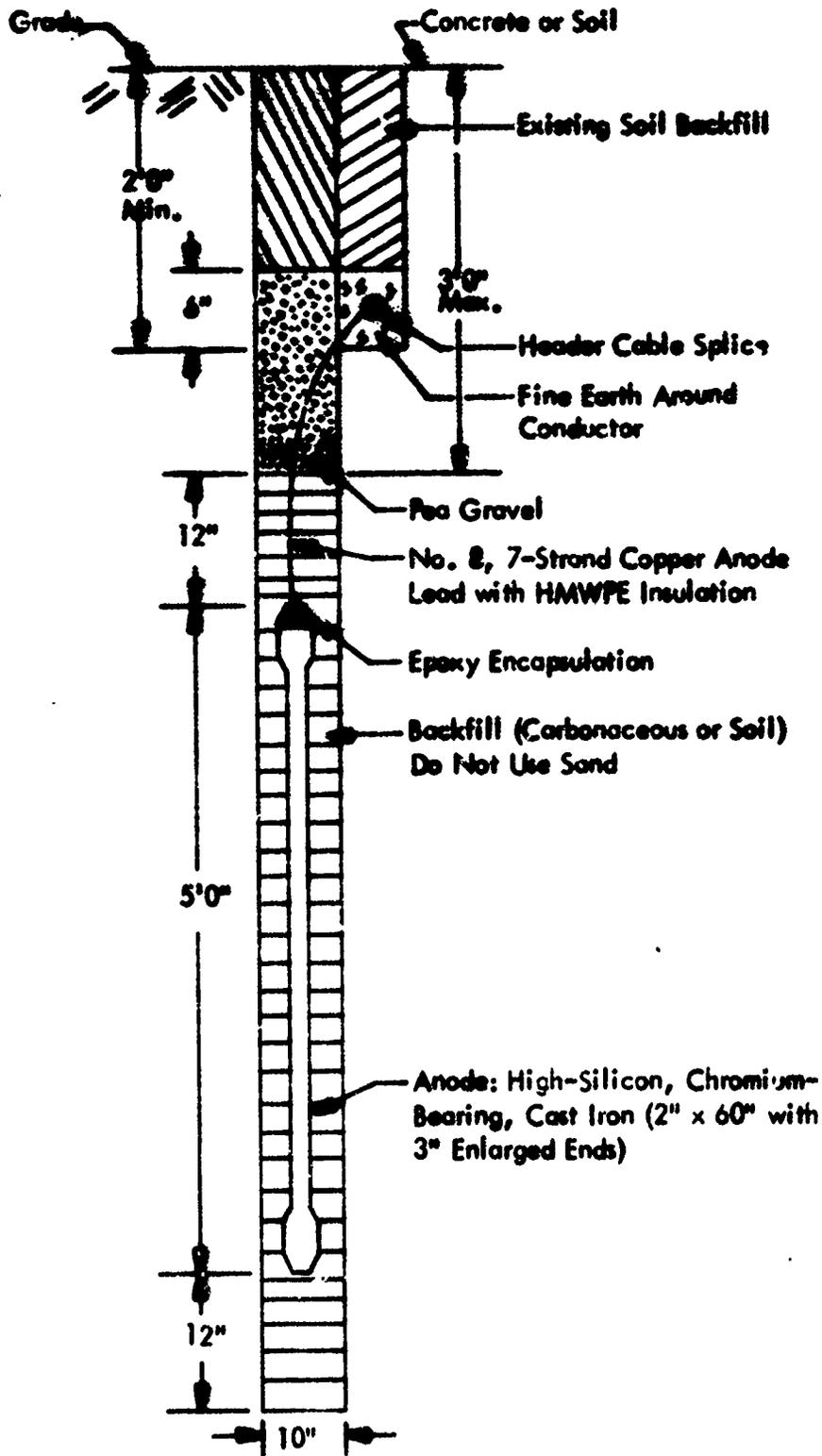


Figure 73
TYPICAL VERTICAL INSTALLATION - HSCBCI ANODE

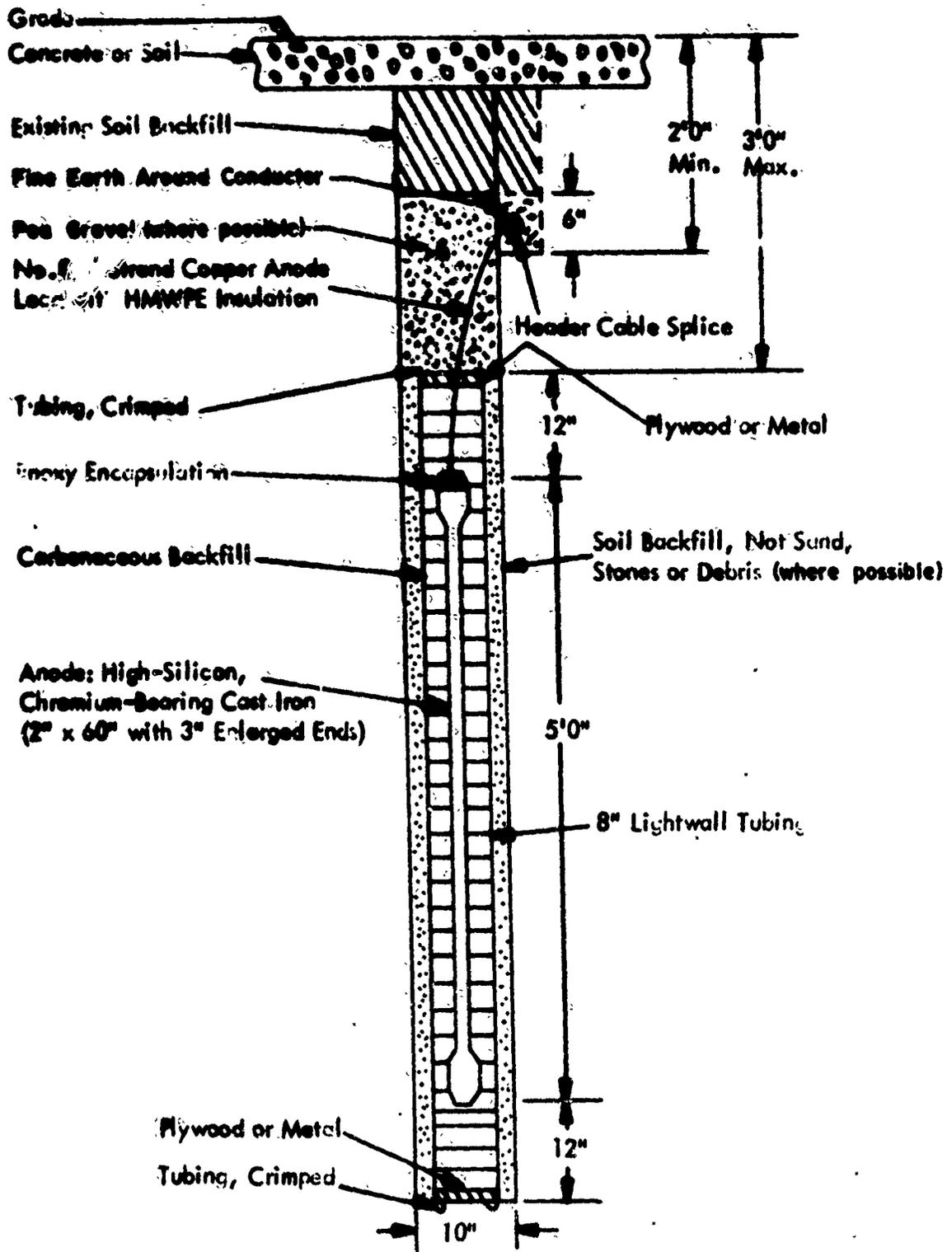


Figure 74
 TYPICAL VERTICAL INSTALLATION FOR
 IMPRESSED CURRENT PACKAGED ANODE

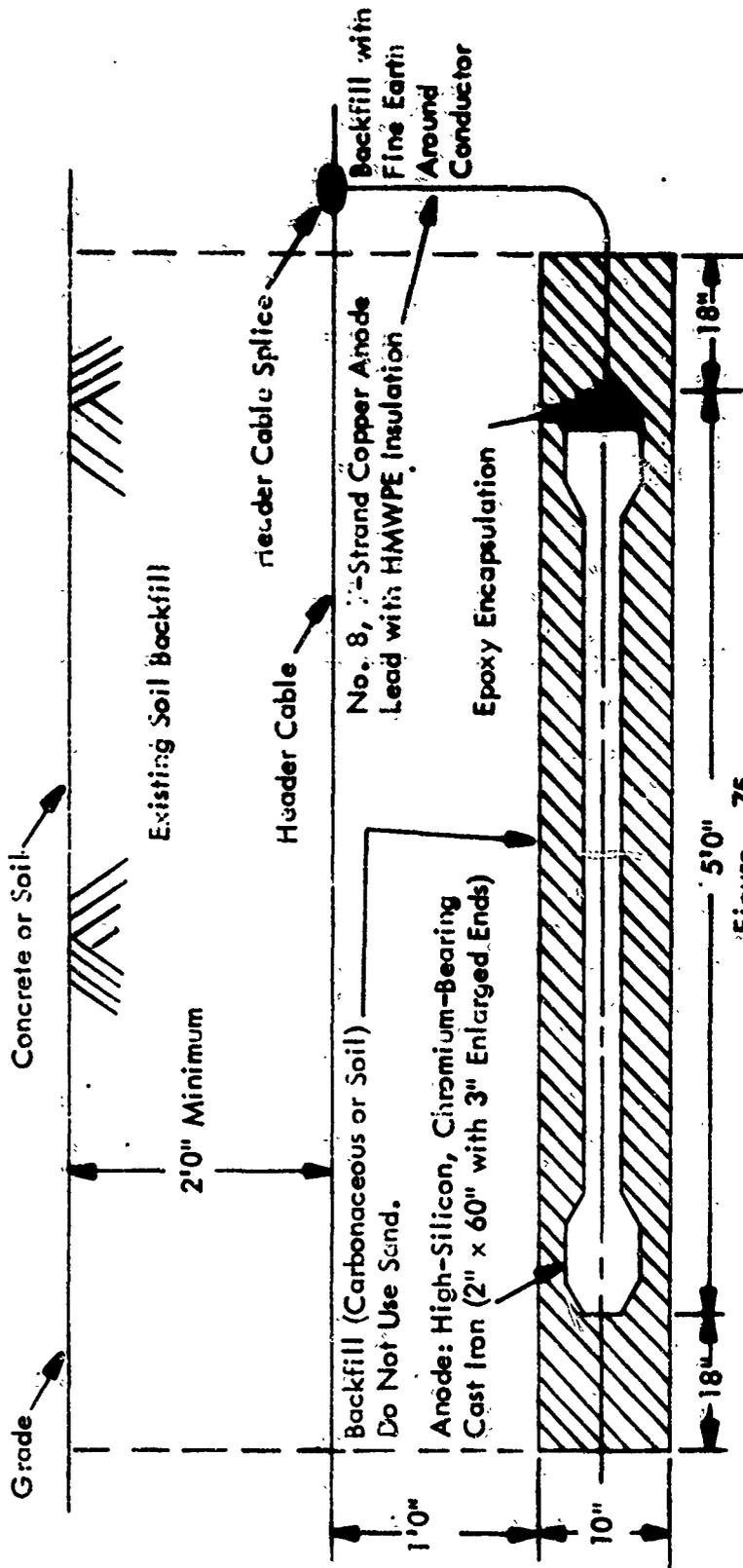


Figure 75
TYPICAL HORIZONTAL INSTALLATION - HSCBCI ANODE

necessary to extend the casing beyond fifty feet below the surface, every effort should be made to pull at least the top fifty feet of the casing out. If this is not possible, the casing above the anode string can be coated to reduce current discharge. Plastic casing can also be used for this upper portion. Finally, prior to the installation of the anodes, the casing can be separated at the fifty-foot level with casing cutters or dynamite. When the well is ready, the drilling rig is used to lower in the anode string.

Type M HSCBCI anode, 2" x 60" with enlarged heads and epoxy cap, is most suitable for deep groundbeds. Because of the inaccessibility of the anodes, individual anode leads should extend to the surface. Thus, difficulty with one lead or anode connection would not lead to failure of the entire groundbed. When more than ten anodes are used, the wire bundle becomes rather bulky. In this case, not more than two anodes may be spliced to a single header. To reduce the number of wires, No. 8, stranded copper wire with HMWPE insulation is suggested.

Anodes should not be suspended from lead wires as prolonged stress may lead to difficulties. Instead, anodes should be fastened to a 1" support pipe as shown in Figure 77 using steel banding or large hose clamps. Not more than three anodes should be attached to each section of support pipe. Sections are joined together with pipe unions.

Gases liberated by electrolysis of the electrolyte in the groundbed should be vented. They form an insulating barrier and decrease anode current output. Gas blocking results in a gradually increasing resistance that eventually can cause the groundbed to become ineffective.

One or more plastic vent pipes from the bottom anode to the surface will aid in dissipating gases to the atmosphere. A combined vent and support pipe system is shown in Figures 76 and 77. This method of support is only temporary in nature (the metal section will corrode) and therefore can be used only with backfill. For a permanent type support-vent pipe system that can be used in backfill or water-filled deep groundbeds, the total system of brackets and pipe should be made of plastic.

Before lowering anodes, the well should be bailed as dry as possible to facilitate backfilling. Anode sections are lowered in one at a time. Anodes must be lined up when sections are joined. Wires and the plastic tubing should be taped to each succeeding section to prevent fouling. Plastic tubing must not become bent or kinked. When the last anode section is ready for lowering, wires and tubing should be bundled and bound with tape at five-foot intervals. The completed anode string is then lowered down the well by one of two

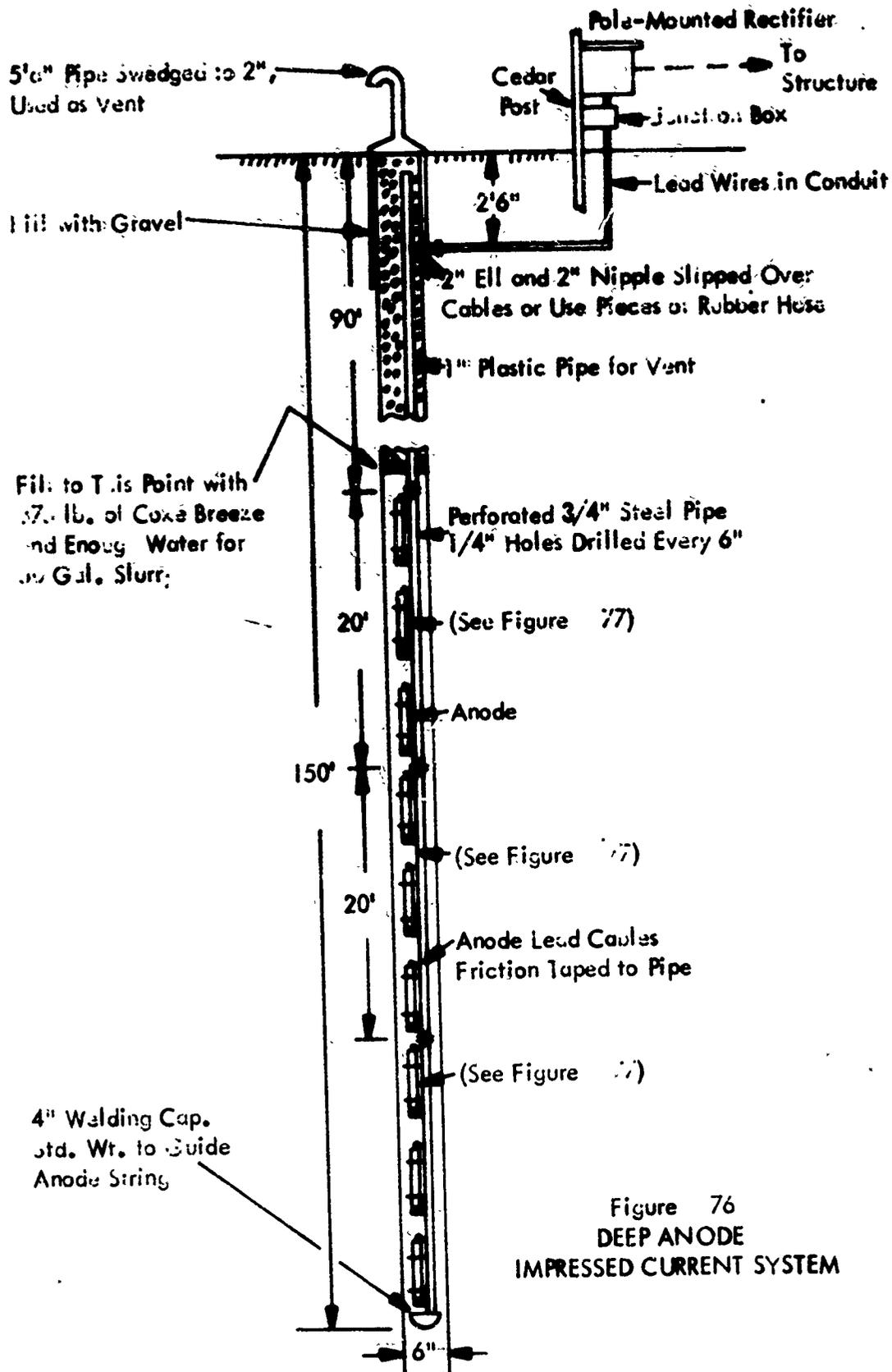


Figure 76
DEEP ANODE
IMPRESSED CURRENT SYSTEM

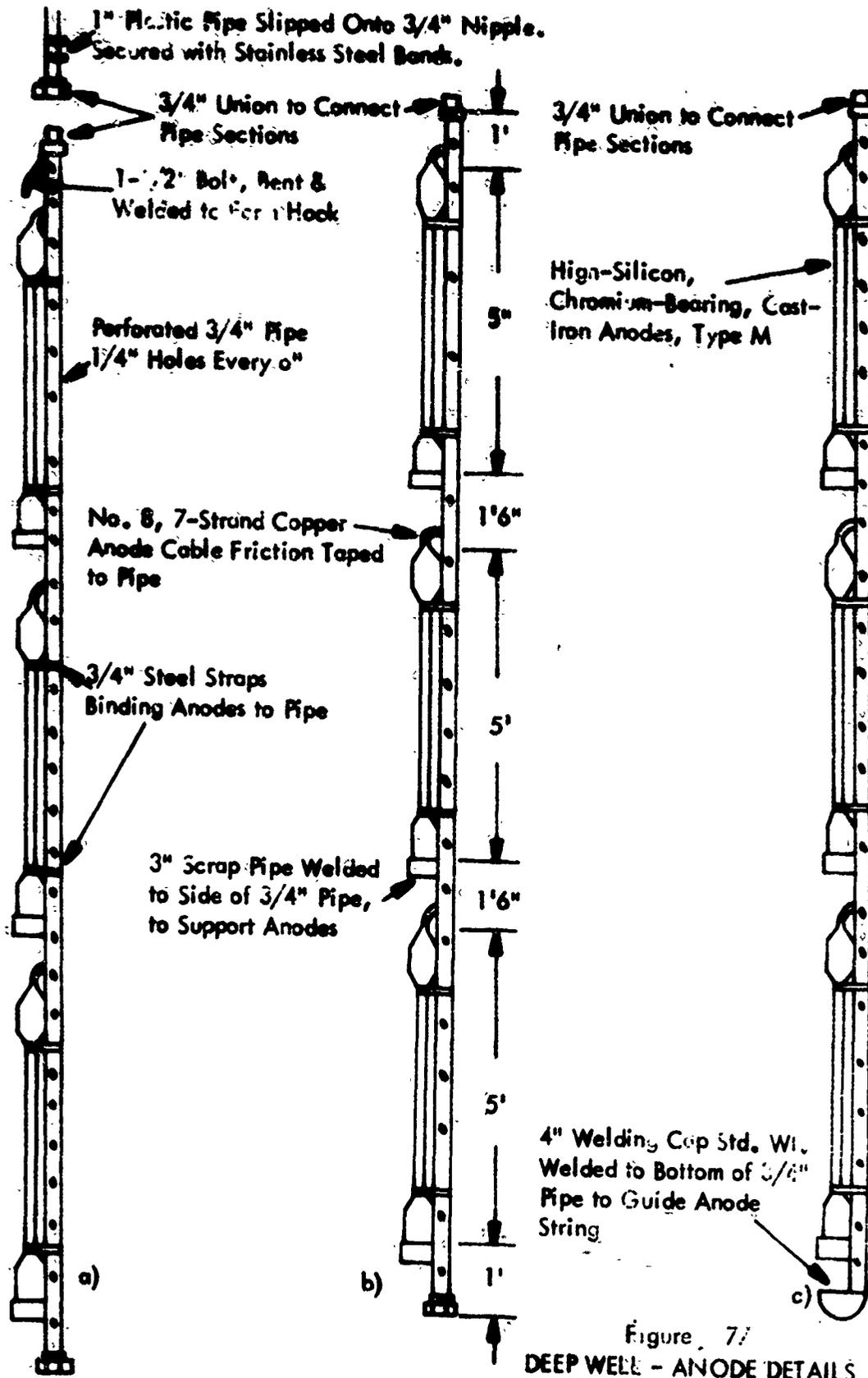


Figure 7/
DEEP WELL - ANODE DETAILS

methods.

1. Joints of 1" pipe are attached to the string and the entire assembly lowered. After the string has reached bottom, the lowering pipe is removed joint by joint. To insure removal of the lowering pipe from the anode string, the connection should be made with a left-hand thread or a hand-tight right-hand thread.

2. It is also possible to attach a pulley to the top of the anode string and lower the string with the driller's boiler cable. Clothesline is then attached to the end of the cable, and the cable retrieved. The lowering pipe, however, makes it possible to turn or manipulate the anode string, should it become fouled on the way down.

Backfilling is recommended to lower anode to ground resistance. A slurry of flake graphite has proven the most workable. Water in the hole will not affect backfilling because graphite will settle through the water and surround the anodes. About a cup of liquid household detergent should be mixed with the slurry to increase the wetting action. If backfill is mixed in a slightly elevated tank, it may easily be piped into the top of the hole.

The well head may terminate above or below ground. For above ground termination, four feet of casing should protrude above the surface. A vented cap should be screwed onto the top of the casing, for access. Anode leads should terminate in a box at the top of the well head. For below ground termination, place a steel cap over the well to prevent earth settling above it. Anode leads should be run through an underground conduit to a terminal box at some convenient location.

Install the rectifier as close as possible to the well head. Often, utility pole can be located next to it; if necessary, the rectifier can be installed on the well head itself. An insulated copper cable is then run from the positive terminal of the rectifier to the anode lead terminal box.

(4) Marine, Water Tank, and Process Equipment Installation. In most marine, water tank and process equipment installations, HSCBCI anodes are suspended in the solution at some distance from the cathodically protected structure. However, button anodes are bolted onto the plates of metal. Here it is necessary to apply coating and/or a dielectric pad between anode and structure metal.

Suspended anodes should never be supported by connecting cables; a nylon rope or net bag is suggested.

b. Cables. Every effort must be made to avoid damage to cable insulation. Small breaks will result in early failure when positive cable is suspended or buried in electrolyte. When cables are placed in trenches, sand or soft earth padding should be provided to minimize the chance of insulation damage by rocks and/or other debris.

Buried cables and connections must be placed deep enough below grade so that the possibility of damage from construction, farming, etc., will be minimized. Two feet is usually satisfactory. Further protection from physical damage to buried cables can be provided by placing treated boards or concrete slabs over and/or around them.

Insulated cables, suspended in water or chemicals, must be provided with brackets to prevent wear failure of insulation due to movement. They must be securely fastened in turbulent areas, and kept out of slow streams where trash could foul them.

c. Rectifiers. Rectifiers can be attached to poles with through bolts for large units, and lag screws for smaller ones. Units must be installed to standards of local power companies and/or electrical inspectors. It is best to get information on this before beginning to wire up a unit. Meter sockets are usually furnished by the power company, but must be wired in by the electrician connecting the rectifier. Sometimes the power company wires down the pole to the meter socket, and in other cases to the top of the pole only. In some localities, all wiring must be contained in conduit, while exposed wiring is permissible in others. The following are advantages to using conduit which point toward long life and trouble-free operation:

(1) Possibility of damage from vandalism or animals minimized.

(2) Safety - reduces the chances of children being hurt when tampering with exposed wires, and provides connection to ground for switch boxes, meter case, and rectifier case.

(3) Reduced possibility of weathering damage to cable insulation.

"Light wall" conduit is easy to bend in the field and gives satisfactory service. A separated fused switch at the A.C. inlet side of the rectifier should also be included, for additional overload and fault protection. (See Figure 78, showing rectifier, fused switch and electric meter.)

When installation work has been completed at a rectifier site, it is important to thoroughly clean up the area. Trash must be removed, backfill smoothed up, loose stone removed, etc. It is good practice to "mound up" loose backfill soil over trenches, if it has not been tamped. Most of the fill will then settle back down into the ditch. It is helpful to contact property owners upon completion, to be certain they are satisfied with the appearance of the job. Final clean-up will be necessary after the soil has settled. Any damage claims should also be paid at the same time.

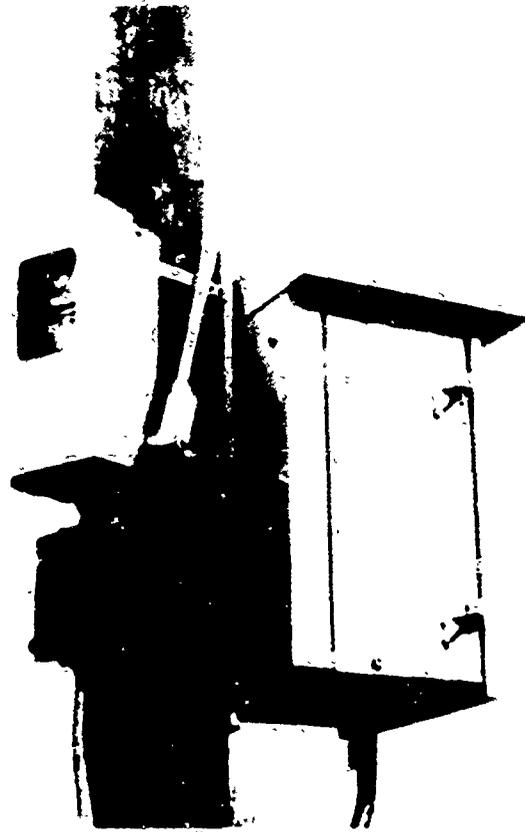


Figure 78
POLE-MOUNTED RECTIFIER AND FUSED SWITCH

Scheduling rectifier installation is important, especially where large numbers of rectifiers are involved. When pole-mounted units are used, as soon as possible after final easement payments have been made, a crew of three to four men sets out to install rectifier poles and negative return leads. This has the dual advantage of beginning work on the property owners' land while their agreement and reimbursement is still fresh in mind, and also pinpointing the location for power company personnel so that they may promptly proceed with any necessary or unforeseen problems.

After poles have been set, the same crew now strengthened by additional manpower, tools, and/or other equipment may begin installation of groundbeds with their associated cables and connections. One crew should be able to complete a 25 to 35 anode groundbed in a working day. Upon completion of groundbeds, a test of pipe-to-groundbed resistance will make it possible to size rectifiers and have them shipped promptly. At this time, power companies can also be given a reasonably accurate estimate of the electrical load.

Upon receipt of rectifier units, a crew of two or three men can mount and connect rectifiers. If large rectifier units are being used, it may be best to divide this work between two groups of people - one of which simply hangs units on the poles, while the other actually does the electrical work.

Typical installations are shown in Figures 79 and 80.

Pole-mounted rectifiers are also typical of those mounted on building walls. In less stable areas and/or for extremely heavy units, floor-mounted (or slab-mounted) rectifiers may be used. A diagram of a mounting slab is given in Figure 81.

10.7 Bonds Between Structures. In almost any cathodic protection system, it is necessary to make connections between isolated structures. These may be:

1. Sections of line separated by insulating joints.
2. Completely separate piping systems.
3. Separate pipelines, or piping systems, connected to a common cathodic protection unit.

The basic components of such bonds should be:

1. Cables from structures involved.
2. Resistor for the control of current flow (if cables have a lower resistance value than that required for current drainage).
3. Calibrated shunt, ammeter, or other current flow measuring device.

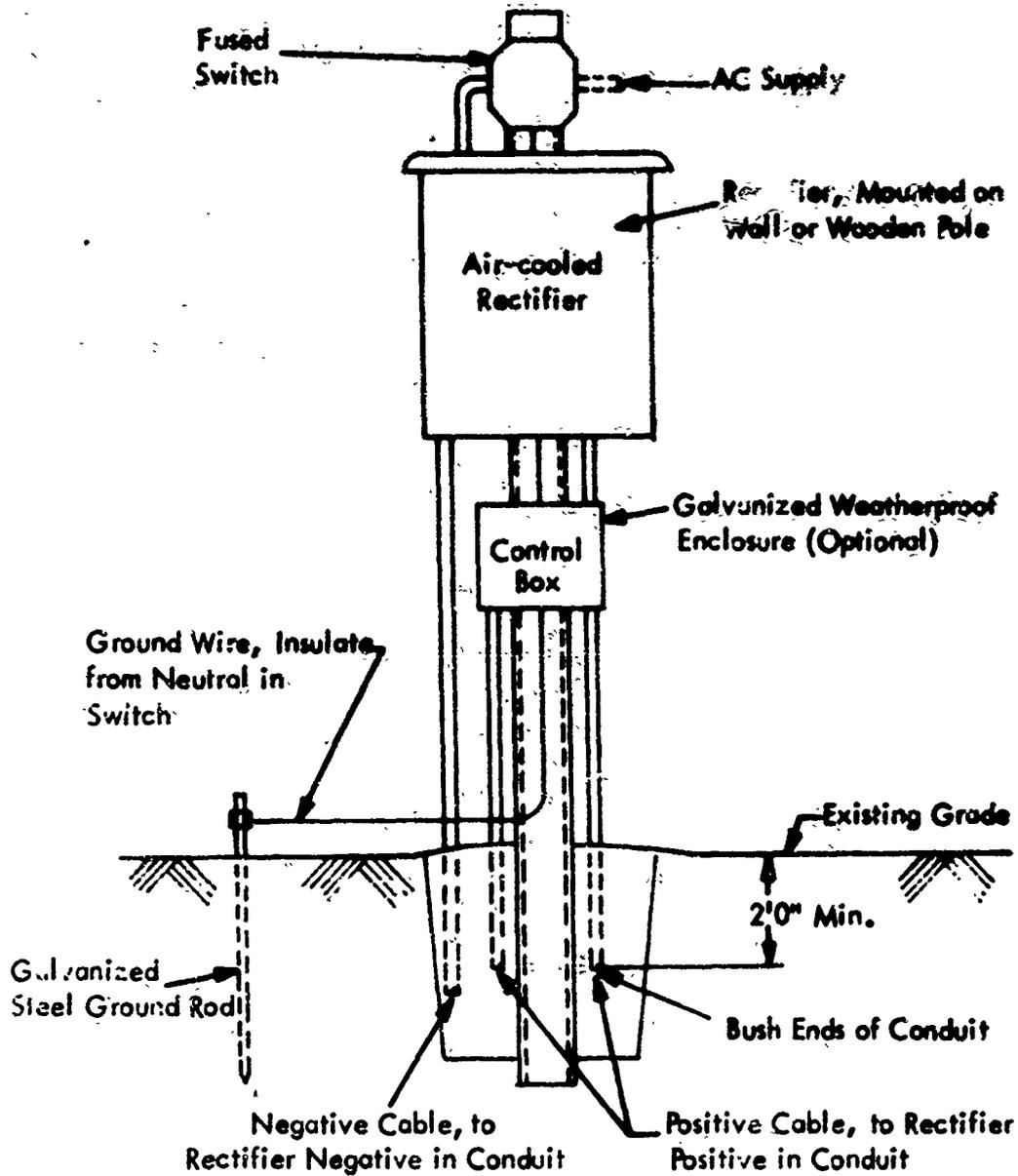
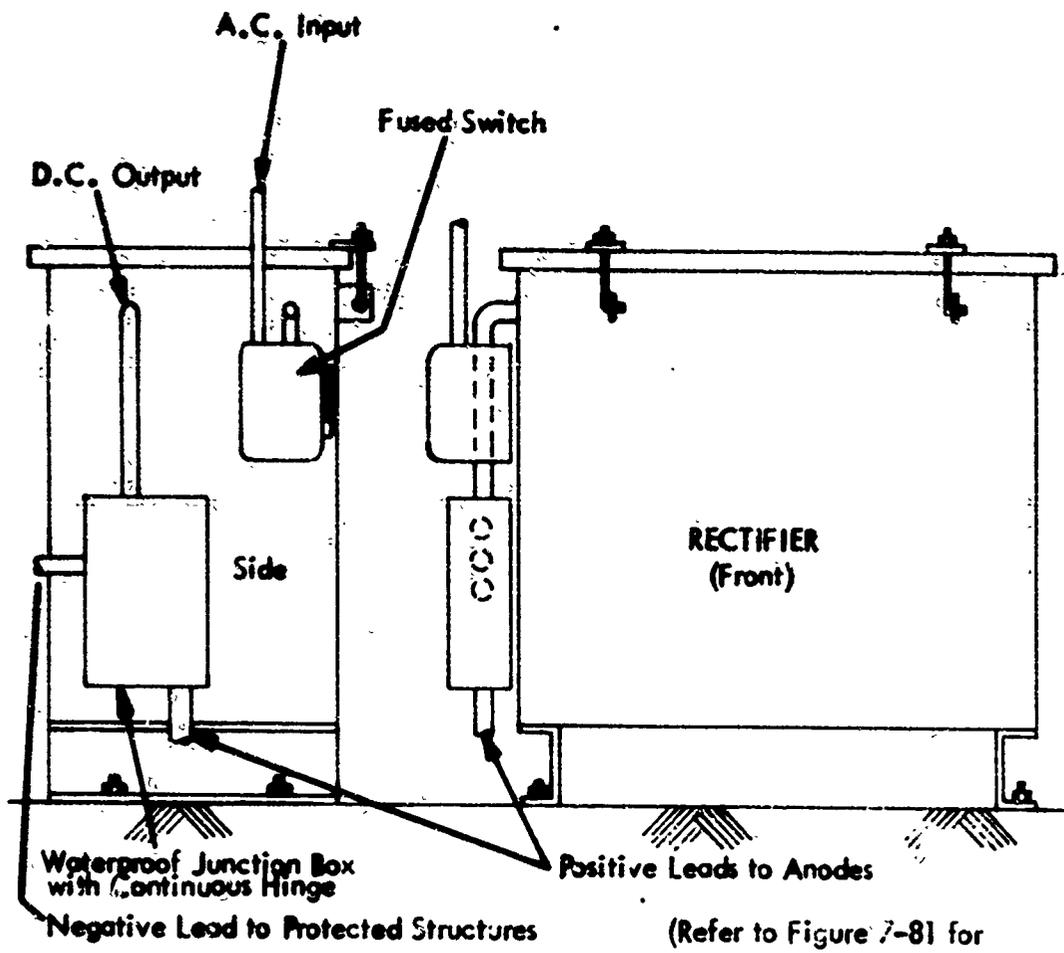
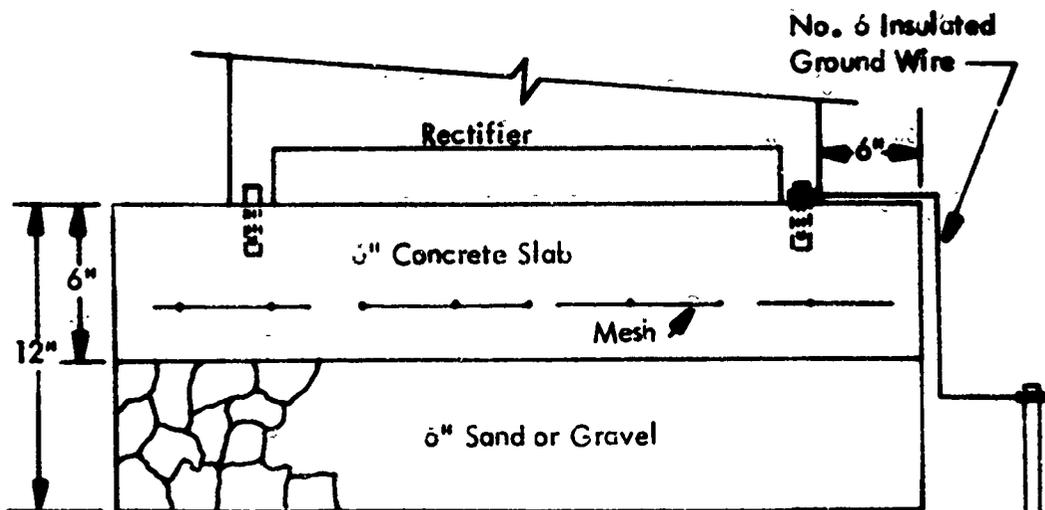
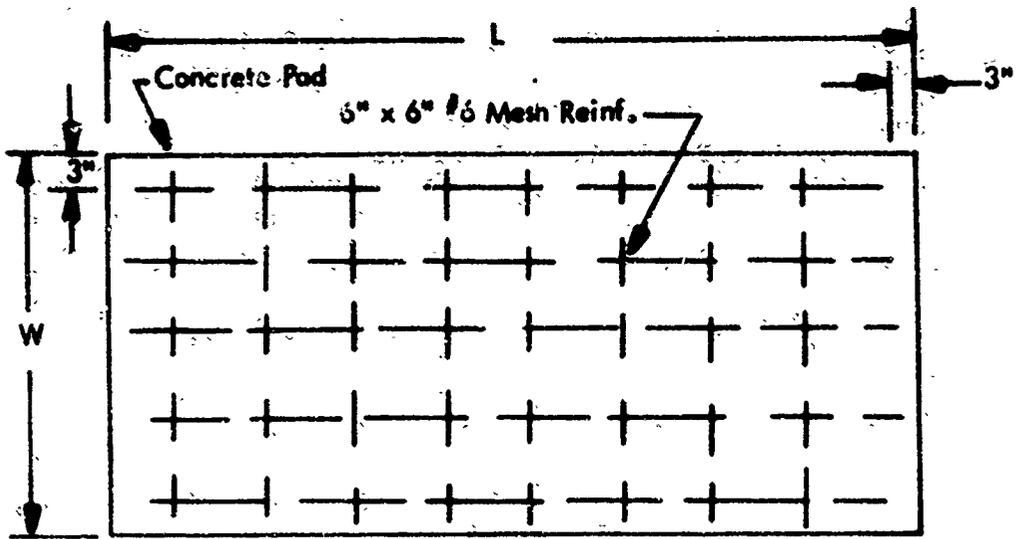


Figure 79
TYPICAL POLE OR WALL MOUNTED RECTIFIER



(Refer to Figure 7-81 for
Mounting on Concrete Pad)

Figure 80
FLOOR-MOUNTED RECTIFIER



Note:
L and W to
Suit Rectifier

Ground Rod 3/4" x 8"
Galvanized Steel or
Stainless Steel

Figure 81
RECTIFIER CONCRETE PAD

When installing bonds, it is advantageous to use cables heavier than the number 10 through 14 commonly employed as test leads, even though resistance or current-carrying capacity may not be critical. This is because larger size cables are less susceptible to physical damage during excavation and other routing maintenance. Also, they are usually very important factors in maintaining protective potentials, while at the same time not numerous enough to noticeably affect installation costs. No. 4 cables are recommended for military use. Bonding cables should always be marked immediately, as they are installed, to avoid confusion and unnecessary testing later on. This can be done by color coding, metal tags attached to the wires, marks on the test box panel, or combinations of these.

Components of a bond test station are generally installed in a weathertight, galvanized box mounted conveniently above ground (with joint lock, if required). This may be wall- or pole-mounted as with a rectifier. Typically, a 4" cedar post 6 feet long (2 feet below grade, 4 feet above) is used for a mounting pole where no convenient wall, fence post, etc. is available. This provides relatively convenient access, when required. Where such a bond station is impractical or not allowed, such as in a farmer's field, the bond test components can be installed in a curb box buried 18" below grade. This provides limited access, since it must be located and dug up whenever testing is required.

11 MAINTENANCE. All corrosion control systems must be maintained. This established cost goes with them and should be accepted as such. If maintenance is neglected, the usefulness of any corrosion control system will soon end. Part of maintenance is replacement and repair of coatings, electrical components, anodes, chemical feeders, etc.

In corrosion prevention, another facet of maintenance must be considered. This is the fact that the corrosion environment of most facilities changes over the years, generally slowly but occasionally radically and rapidly. Factors which commonly change are addition of new structures, alteration of existing ones, and chemical composition of the electrolyte.

Maintenance is especially important in cathodic protection systems. These electrical systems require the same care as any other electrical installation. Their effectiveness is especially responsive to alterations or additions to structures in the area. These structures may shield or channel protective current flow.

A guide for maintaining cathodic protection systems is AFM 85-5 - "Maintenance and Operation of Cathodic Protection Systems" (1 November 1965). An effective maintenance schedule should be established for all cathodic protection installations, based on this manual. A recommended schedule, after the initial installation checks, and six-month inspections, is:

1. Keep a record of all rectifier outputs (volts, amperes) monthly, and report any variations because these may indicate system malfunctions.
2. Once a year, base personnel should make a cathodic protection base survey, taking structure-to-electrolyte and any other necessary measurements (e.g. current output of galvanic anodes). Rectifiers should be adjusted as needed at this time.

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APPENDIX A.

GLOSSARY OF CORROSION TERMS (*Definitions from NACE Standard RP-01-69)

Adsorption. The taking up of one substance at the surface of another. The tendency of all solids to condense upon their surfaces a layer of any gas or solute which contact such solids.

Aeration cell (oxygen cell). An electrolytic cell in which a difference in oxygen concentration at the electrodes exists, producing corrosion.

Amphoterics. Materials subject to attack by both acid and alkaline environments. Aluminum, zinc, and lead, commonly used in construction, are examples.

Anaerobic. Free of air or uncombined oxygen; an aerobic bacteria are those which do not use oxygen in their life cycle.

Anion. A negatively charged ion which migrates toward the anode under influence of a potential gradient.

*Anode. An electrode at which oxidation of its surface or some component of the solution is occurring. Antonym:cathode.

*Bell hole. An excavation to expose a buried structure.

Cathode. An electrode at which reduction of its surface or some component of the solution is occurring. Antonym:anode

Cathodic corrosion. Corrosion resulting from a cathodic condition of a structure, usually caused by the reaction of alkaline products of electrolysis with an amphoteric metal.

*Cathodic Protection. A technique to prevent the corrosion of a metal surface by making that surface the cathode of an electrochemical cell.

Cation. A positively charged ion of an electrolyte which migrates toward the cathode under the influence of a potential gradient.

Concentration cell. An electrolytic cell in which a difference in electrolyte concentration exists between anode and cathode, producing corrosion.

*Continuity bond. A metallic connection that provides electrical continuity.

*Corrosion. The deterioration of a material, usually a metal, because of a reaction with its environment.

*Current density. The current per unit area.

*Electrical isolation. The condition of being electrically separated from other metallic structures or the environment.

*Electro-osmotic effect. Passage of a charged particle through a membrane under the influence of a voltage. Soil may act as the membrane.

*Electrode potential. The potential of an electrode as measured against a reference electrode. The electrode potential does not include any loss of potential in the solution due to current passing to or from the electrodes, i.e. it represents the reversible work required to move a unit charge from the electrode surface through the solution to the reference electrode.

Electrolyte. A chemical substance or mixture, usually liquid, containing ions that migrate in an electric field. Examples are soil and seawater.

Electromotive force series (EMF series). A list of elements arranged according to their standard electrode potentials, the sign being positive for elements having potentials that are cathodic to hydrogen and negative for those elements having potentials that are anodic to hydrogen.

*Foreign structure. Any structure that is not intended as a part of the system of interest.

*Galvanic anode. A metal which, because of its relative position in the galvanic series, provides sacrificial protection to metal or metals that are more noble in the series, when coupled in an electrolyte. These anodes are the current source in one type of cathodic protection.

Galvanic cell. A corrosion cell in which anode and cathode are dissimilar conductors, producing corrosion because of their innate difference in potential.

*Galvanic series. A list of metals and alloys arranged according to their relative potentials in a given environment.

*Holiday. A discontinuity of coating that exposes the metal surface to the environment.

Hydrogen overvoltage. Voltage characteristic for each metal-environment combination above which hydrogen gas is liberated.

*Impressed current. Direct current supplied by a power source external to the electrode system.

*Insulating coating system. All components comprising the protective coating, the sum of which provides effective electrical insulation of the coated structure.

*Interference bond. A metallic connection designed to control electrical current interchange between metallic systems.

Ion. Electrically charged atom or molecule.

*IR drop. The voltage across a resistance in accordance with Ohm's Law.

*Line current. The direct current flowing on a pipeline.

Local action. Corrosion caused by local cells on a metal surface.

Mill scale. The heavy oxide layer formed during hot fabrication or heat-treatment of metals. The term is applied chiefly to iron and steel.

Molality. Concentration of a solution expressed as the number of gram molecules of the dissolved substance per 1000 grams of solvent.

pH. A measure of hydrogen ion activity defined by $\text{pH} = \log_{10} (1/a\text{H}^+)$ where $a\text{H}^+$ = hydrogen ion activity = molal concentration of hydrogen ions multiplied by the mean ion activity coefficient (= 1 for simplified calculations).

Polarization. The deviation from the open circuit potential of an electrode resulting from the passage of current.

*Reference electrode. A device whose open circuit potential is constant under similar conditions of measurement.

*Reverse-current switch. A device that prevents the reversal of direct current through a metallic conductor.

*Stray current. Current flowing through paths other than the intended circuit.

*Stray current corrosion. Corrosion resulting from direct current flow through paths other than the intended circuit.

*Structure-to-electrolyte voltage. (also structure-to-soil potential or pipe-to-soil potential). The voltage difference between a buried metallic structure and the electrolyte which is measured with a reference electrode in contact with the electrolyte.

*Structure-to-structure voltage. (also structure-to-structure potential). The difference in voltage between metallic structures in a common electrolyte.

*Voltage. An electromotive force, or a difference in electrode potentials expressed in volts.

APPENDIX B.

**DEPARTMENT OF TRANSPORTATION
REGULATIONS**

Title 49 - Transportation

**Chapter 1-Hazardous Materials Regulations Board, Department of Transportation.
(Docket No. OPS-5; Amdt. 192-4)**

Part 192-Transportation of Natural and other gas by pipeline: Minimum Federal safety standards

**Subpart 1-Requirements for
Corrosion Control**

192.451 Scope.

This subpart prescribes minimum requirements for the protection of metallic pipelines from external, internal, and atmospheric corrosion.

192.453 General.

Each operator shall establish procedures to implement the requirements of this subpart. These procedures, including those for the design, installation, operation and maintenance of cathodic protection systems, must be carried out by, or under the direction of, a person qualified by experience and training in pipeline corrosion control methods.

192.455 External corrosion control: buried or submerged pipelines installed after July 31, 1971.

(a) Except as provided in paragraphs (b) and (c) of this section, each buried or submerged pipeline installed after July 31, 1971 must be protected against external corrosion, including the following:

(1) It must have an external protective coating meeting the requirements of 192.46.

(2) It must have a cathodic protection system designed to protect the pipeline in its entirety in accordance with this subpart, installed and placed in operation within one year after completion of construction.

(b) An operator need not comply with paragraph (a) of this section, if the operator can demonstrate by tests, investigation, or experience in the area of application, in-

cluding, as a minimum, soil resistivity measurements and tests for corrosion accelerating bacteria, that a corrosive environment does not exist. However, within 6 months after an installation made pursuant to the preceding sentence, the operator shall conduct tests, including pipe-to-soil potential measurements with respect to either a continuous reference electrode or an electrode using close spacing, not to exceed 20 feet, and soil resistivity measurements at potential profile peak locations, to adequately evaluate the potential profile along the entire pipeline. If the tests made indicate that a corrosive condition exists, the pipeline must be cathodically protected in accordance with paragraph (a) (2) of this section.

(c) An operator need not comply with paragraph (a) of this section, if the operator can demonstrate by tests, investigation, or experience

(1) For a copper pipeline, a corrosive environment does not exist; or

(2) For a temporary pipeline with an operating period of service not to exceed 5 years beyond installation, corrosion during the 5-year period of service of the pipeline will not be detrimental to public safety.

(d) Notwithstanding the provisions of paragraph (b) or (c) of this section, if a pipeline is externally coated, it must be cathodically protected in accordance with paragraph (a) (2) of this section.

(e) Aluminum may not be installed in a buried or submerged pipeline if that aluminum is exposed to an environment with a natural pH in excess of 8, unless tests or experience indicate its suitability in the particular environment involved.

192.457 External corrosion control: buried or submerged pipelines installed before August 1, 1971.

(a) Except for buried piping at compressor, regulator, and measuring stations, each buried or submerged transmission line installed before August 1, 1971, that has an effective external coating must, not later than August 1, 1974, be cathodically protected along the entire area that is effectively coated, in accordance with this subpart. For the purposes of this subpart, a pipeline does not have an effective external coating if its cathodic protection current requirements are substantially the same as if it were bare. The operator shall make tests to determine the cathodic protection current requirements.

(b) Except for cast iron or ductile iron, each of the following buried or submerged pipelines installed before August 1, 1971, must, not later than August 1, 1976, be cathodically protected in accordance with this subpart in areas in which active corrosion is found:

- (1) Bare or ineffectively coated transmission lines.
 - (2) Bare or coated pipes at compressor, regulator, and measuring stations.
 - (3) Bare or coated distribution lines. The operator shall determine the areas of active corrosion by electrical survey, or where electrical survey is impractical, by the study of corrosion and leak history records, by leak detection survey, or by other means.
- (c) For the purpose of this subpart, active corrosion means continuing corrosion which, unless controlled, could result in a condition that is detrimental to public safety.

192.454 External corrosion control: examination of buried pipeline when exposed.

Whenever an operator has knowledge that any portion of a buried pipeline is exposed, the exposed portion must be examined for evidence of external corrosion if the pipe is bare, or if the coating is deteriorated. If external corrosion is found, remedial action must be taken to the extent required by 192.483 and the applicable paragraphs of 192.485, 192.487, or 192.489.

192.461 External corrosion control: protective coating.

- (a) Each external protective coating, whether conductive or insulating, applied for the purpose of external corrosion control must-
- (1) Be applied on a properly prepared surface;
 - (2) Have sufficient adhesion to the metal surface to effectively resist under-film migration of moisture;
 - (3) Be sufficiently ductile to resist cracking;
 - (4) Have sufficient strength to resist damage due to handling and soil stress; and
 - (5) Have properties compatible with any supplemental cathodic protection.
- (b) Each external protective coating which is an electrically insulating type must also have low moisture absorption and high electrical resistance.
- (c) Each external protective coating must be inspected just prior to lowering the pipe into the ditch and back-filling, and any damage detrimental to effective corrosion control must be repaired.
- (d) Each external protective coating must be protected from damage resulting from adverse ditch conditions or damage from supporting blocks.
- (e) If coated pipe is installed by boring, driving, or other similar method, precautions must be taken to minimize damage to the coating during installation.

192.463 External corrosion control: cathodic protection.

(a) Each cathodic protection system required by this subpart must provide a level of cathodic protection that complies with one or more of the applicable criteria contained in Appendix D of this subpart. If none of these criteria is applicable, the cathodic protection system must provide a level of cathodic protection at least equal to that provided by compliance with one or more of these criteria.

(b) If amphoteric metals are included in a buried or submerged pipeline containing a metal of different anodic potential-

(1) The amphoteric metals must be electrically isolated from the remainder of the pipeline and cathodically protected; or

(2) The entire buried or submerged pipeline must be cathodically protected at a cathodic potential that meets the requirements of Appendix D of this part for amphoteric metals.

(c) The amount of cathodic protection must be controlled so as not to damage the protective coating or the pipe.

192.465 External corrosion control: monitoring.

(a) Except where impractical on off-shore pipelines, each pipeline that is under cathodic protection must be tested at least once each calendar year, but with intervals not exceeding 15 months, to determine whether the cathodic protection meets the requirements of 192.463. However, if tests at those intervals are impractical for separately protected service lines or short sections of protected mains, not in excess of 100 feet, these service lines and mains may be surveyed on a sampling basis. At least 10 percent of these protected structures, distributed over the entire system must be surveyed each calendar year, with a different 10 percent checked each subsequent year, so that the entire system is tested in each 10-year period.

(b) At intervals not exceeding 2 months, each cathodic protection rectifier or other impressed current power source must be inspected to ensure that it is operating.

(c) At intervals not exceeding 2 months, each reverse current switch, each diode, and each interference bond whose failure would jeopardize structure protection, must be electrically checked for proper performance. Each other interference bond must be checked at least once each calendar year, but with intervals not exceeding 15 months.

(d) Each operator shall take prompt remedial action to correct any deficiencies indicated by the monitoring.

(e) After the initial evaluation required by paragraphs (b) and (c) of 192.455 and paragraph (b) of 192.457, each operator shall, at intervals not exceeding 3 years, reevaluate its unprotected pipelines and cathodically protect them

in accordance with this subpart in areas in which active corrosion is found. The operator shall determine the areas of active corrosion by electrical survey, or where electrical survey is impractical, by the study of corrosion and leak history records, by leak detection survey, or by other means.

192.467 External corrosion control: electrical isolation.

(a) Each buried or submerged pipeline must be electrically isolated from other underground metallic structures, unless the pipeline and the other structures are electrically interconnected and cathodically protected as a single unit.

(b) An insulating device must be installed where electrical isolation of a portion of a pipeline is necessary to facilitate the application of corrosion control.

(c) Except for unprotected copper inserted in ferrous pipe, each pipeline must be electrically isolated from metallic casings that are a part of the underground system. However, if isolation is not achieved because it is impractical, other measures must be taken to minimize corrosion of the pipeline inside the casing.

(d) Inspection and electrical tests must be made to assure that electrical isolation is adequate.

(e) An insulating device may not be installed in an area where a combustible atmosphere is anticipated unless precautions are taken to prevent arcing.

(f) Where a pipeline is located in close proximity to electrical transmission tower footings, ground cables or counter-poise, or in other areas where fault currents or unusual risk of lightning may be anticipated, it must be provided with protection against damage due to fault currents or lightning, and protective measures must also be taken at insulating devices.

192.469 External corrosion control: test stations.

Except where impractical on offshore and wet marsh area pipelines, each pipeline under cathodic protection required by this subpart must have sufficient test stations or other contact points for electrical measurement to determine the adequacy of cathodic protection.

192.471 External corrosion control: test leads.

(a) Each test lead wire must be connected to the pipeline so as to remain mechanically secure and electrically conductive.

(b) Each test lead wire must be attached to the pipeline so as to minimize stress concentration on the pipe.

(c) Each bared test lead wire and bared metallic area at point of connection to the pipeline must be coated with an electrical insulating material compatible with the pipe coating and the insulation on the wire.

192.473 External corrosion control: interference currents.

(a) After July 31, 1973, each operator whose pipeline system is subjected to stray currents shall have in effect a continuing program to minimize the detrimental effects of such currents.

(b) Each impressed current type cathodic protection system or galvanic anode system must be designed and installed so as to minimize any adverse effects on existing adjacent underground metallic structures.

192.475 Internal corrosion control: general.

(a) After July 31, 1972, corrosive gas may not be transported by pipeline, unless the corrosive effect of the gas on the pipeline has been investigated and steps have been taken to minimize internal corrosion.

(b) Whenever any pipe is removed from a pipeline for any reason, the internal surface must be inspected for evidence of corrosion. If internal corrosion is found-

(1) The adjacent pipe must be investigated to determine the extent of internal corrosion;

(2) Replacement must be made to the extent required by the applicable paragraphs of 192.485, 192.487, or 192.489; and

(3) Steps must be taken to minimize the internal corrosion.

(c) Gas containing more than 0.1 grain of hydrogen sulfide per 100 standard cubic feet may not be stored in pipe-type or bottle-type holders.

192.477 Internal corrosion control: monitoring.

If corrosive gas is being transported, coupons or other suitable means must be used to determine the effectiveness of the steps taken to minimize internal corrosion. After July 31, 1972, each coupon or other means of monitoring internal corrosion must be checked at intervals not exceeding 6 months.

192.479 Atmospheric corrosion control: general.

(a) Pipelines installed after July 31, 1971. Each above-ground pipelines or portion of a pipeline installed after July 31, 1971 that is exposed to the atmosphere must be cleaned and either coated or jacketed with a material suit-

able for the prevention of atmospheric corrosion. An operator need not comply with this paragraph, if the operator can demonstrate by test, investigation, or experience in the area of application, that a corrosive atmosphere does not exist.

(b) Pipelines installed before August 1, 1971. Not later than August 1, 1974, each operator having an above-ground pipeline or portion of a pipeline installed before August 1, 1971 that is exposed to the atmosphere, shall-

(1) Determine the areas of atmospheric corrosion on the pipeline;

(2) If atmospheric corrosion is found, take remedial measures to the extent required by the applicable paragraphs of 192.485, 192.487, or 192.489; and

(3) Clean and either coat or jacket the areas of atmospheric corrosion on the pipeline with a material suitable for the prevention of atmospheric corrosion.

192.481 Atmospheric corrosion control: monitoring.

After meeting the requirements of paragraphs (a) and (b) of 192.479, each operator shall, at intervals not exceeding 3 years, reevaluate its above-ground pipelines or portions of pipelines that are exposed to the atmosphere and take remedial action wherever necessary to maintain protection against atmospheric corrosion.

192.483 Remedial measures: general.

(a) Each segment of metallic pipe that replaces pipe removed from a buried or submerged pipeline because of external corrosion must have a properly prepared surface and must be provided with an external protective coating that meets the requirements of 192.461.

(b) Each segment of metallic pipe that replaces pipe removed from a buried or submerged pipeline because of external corrosion must be cathodically protected in accordance with this subpart.

(c) Except for cast iron or ductile iron pipe, each segment of buried or submerged pipe that is required to be repaired because of external corrosion must be cathodically protected in accordance with this subpart.

192.485 Remedial measures: transmission lines.

(a) General corrosion. Each segment of transmission line pipe with general corrosion and with a remaining wall thickness less than that required for the maximum allowable operating pressure of the pipeline, must be replaced or the operating pressure reduced commensurate with the actual remaining wall thickness. However, if the area of

general corrosion is small, the corroded pipe may be repaired. Corrosion pitting so closely grouped as to affect the overall strength of the pipe is considered general corrosion for the purpose of this paragraph.

(b) Localized corrosion pitting. Each segment of transmission line pipe with localized corrosion pitting to a degree where leakage might result must be replaced or repaired, or the operating pressure must be reduced commensurate with the strength of the pipe, based on the actual remaining wall thickness in the pits.

192.487 Remedial measures: distribution lines other than cast iron or ductile iron lines.

(a) General corrosion. Except for cast iron or ductile iron pipe, each segment of generally corroded distribution line pipe with a remaining wall thickness less than that required for the maximum allowable operating pressure of the pipeline, or a remaining wall thickness less than 30 percent of the nominal wall thickness, must be replaced. However, if the area of general corrosion is small, the corroded pipe may be repaired. Corrosion pitting so closely grouped as to affect the overall strength of the pipe is considered general corrosion for the purpose of this paragraph.

(b) Localized corrosion pitting. Except for cast iron or ductile iron pipe, each segment of distribution line pipe with localized corrosion pitting to a degree where leakage might result must be replaced or repaired.

192.489 Remedial measures: cast iron and ductile iron pipelines.

(a) General graphitization. Each segment of cast iron or ductile iron pipe on which general graphitization is found to a degree where a fracture or any leakage might result, must be replaced.

(b) Localized graphitization. Each segment of cast iron or ductile iron pipe on which localized graphitization is found to a degree where any leakage might result, must be replaced or repaired, or sealed by internal sealing methods adequate to prevent or arrest any leakage.

192.491 Corrosion control records.

(a) After July 31, 1972, each operator shall maintain records or maps to show the location of cathodically protected piping, cathodic protection facilities, other than unrecorded galvanic anodes installed before August 1, 1971, and neighboring structures bonded to the cathodic protection system.

(b) Each of the following records must be retained for as long as the pipeline remains in service:

(1) Each record or map required by paragraph (a) of this section.

(2) Records of each test, survey, or inspection required by this subpart, in sufficient detail to demonstrate the adequacy of corrosion control measures or that a corrosive condition does not exist.

Appendix D-Criteria for Cathodic Protection and Determination of Measurements

I. Criteria for cathodic protection-A. Steel, cast iron, and ductile iron structures.

(1) A negative (cathodic) voltage of at least 0.85 volt, with reference to a saturated copper-copper sulfate half cell. Determination of this voltage must be made with the protective current applied, and in accordance with sections II and IV of this appendix.

(2) A negative (cathodic) voltage shift of at least 300 millivolts. Determination of this voltage shift must be made with the protective current applied, and in accordance with sections II and IV of this appendix. This criterion of voltage shift applies to structures not in contact with metals of different anodic potentials.

(3) A minimum negative (cathodic) polarization voltage shift of 100 millivolts. This polarization voltage shift must be determined in accordance with sections III and IV of this appendix.

(4) A voltage at least as negative (cathodic) as that originally established at the beginning of the Tafel segment of the E-log-I curve. This voltage must be measured in accordance with section IV of this appendix.

(5) A net protective current from the electrolyte into the structure surface as measured by an earth current technique applied at predetermined current discharge (anodic) points of the structure.

B. Aluminum structures. (1) Except as provided in subparagraphs (3) and (4) of this paragraph, a minimum negative (cathodic) voltage shift of 150 millivolts, produced by the application of protective current. The voltage shift must be determined in accordance with sections II and IV of this appendix.

(2) Except as provided in subparagraphs (3) and (4) of this paragraph, a minimum negative (cathodic) polarization voltage shift of 100 millivolts. This polarization voltage shift must be determined in accordance with sections III and IV of this appendix.

(3) Notwithstanding the alternative minimum criteria in subparagraphs (1) and (2) of this paragraph, aluminum, if cathodically protected at voltages in excess of 1.20 volts as measured with reference to a copper-copper sulfate half

cell, in accordance with section IV of this appendix, and compensated for the voltage (IR) drops other than those across the structure-electrolyte boundary, may suffer corrosion resulting from the build-up of alkali on the metal surface. A voltage in excess of 1.20 volts may not be used unless previous test results indicate no appreciable corrosion will occur in the particular environment.

(4) Since aluminum may suffer from corrosion under high pH conditions, and since application of cathodic protection tends to increase the pH at the metal surface, careful investigation or testing must be made before applying cathodic protection to stop pitting attack on aluminum structures in environments with a natural pH in excess of 8.

C. Copper structures. A minimum negative (cathodic) polarization voltage shift of 100 millivolts. This polarization voltage shift must be determined in accordance with sections III and IV of this appendix.

D. Metals of different anodic potentials. A negative (cathodic) voltage, measured in accordance with section IV of this appendix, equal to that required for the most anodic metal in the system must be maintained. If amphoteric structures are involved that could be damaged by high alkalinity covered by subparagraphs (3) and (4) of paragraph B of this section, they must be electrically isolated with insulating flanges, or the equivalent.

II. Interpretation of voltage measurement. Voltage (IR) drops other than those across the structure-electrolyte boundary must be considered for valid interpretation of the voltage measurement in paragraph A(1) and (2) and paragraph B(1) of section 1 of this appendix.

III. Determination of polarization voltage shift. The polarization voltage shift must be determined by interrupting the protective current and measuring the polarization decay. When the current is initially interrupted, an immediate voltage shift occurs. The voltage reading after the immediate shift must be used as the base reading from which to measure polarization decay in paragraphs A(3), B(2), and C of section 1 of this appendix.

IV. Reference half cells. A. Except as provided in paragraphs B and C of this section, negative (cathodic) voltage must be measured between the structure surface and a saturated copper-copper sulfate half cell contacting the electrolyte.

B. Other standard reference half cells may be substituted for the saturated copper-copper sulfate half cell. Two commonly used reference half cells are listed below along with their voltage equivalent to -0.85 volt as referred to a saturated copper-copper sulfate half cell:

- (1) Saturated KCl calomel half cell: -0.78 volt.
- (2) Silver-silver chloride half cell used in sea water: -0.80 volt.

C. In addition to the standard reference half cells, an alternate metallic material or structure may be used in place of the saturated copper-copper sulfate half cell if its potential stability is assured and if its voltage equivalent referred to a saturated copper-copper sulfate half cell is established.
(FR Doc. 71-9221 Filed 6-29-71; 8:48 am)

TRANSPORTATION OF LIQUIDS BY PIPELINE*

SUBPART A -- GENERAL

AFFECTED FACILITIES

195.1 Scope.

(a) Except as provided in paragraph (b) of this section, this part prescribes rules governing the transportation by pipeline in interstate and foreign commerce of hazardous materials that are subject to Parts 172 and 173 of this chapter, petroleum, and petroleum products.

(b) This part does not apply to-

(1) Transportation of water or any commodity that is transported in a gaseous state;

(2) Transportation through a pipeline by gravity;

(3) Transportation through pipelines that operate at a stress level of 20 percent or less of the specified minimum yield strength of the line pipe in the system; and

(4) Except for Subpart B of this part, transportation of petroleum in rural areas between a production facility and the point where the petroleum is received by a carrier.

SUBPART D -- CONSTRUCTION

REQUIRED PROTECTIVE MEASURES

195.236 External corrosion protection.

Each component in the pipeline system must be provided with protection against external corrosion.

195.238 External coating.

(a) No pipeline system component may be buried unless that component has an external protective coating that-

(1) Is designed to mitigate corrosion on the buried component;

(2) Has sufficient adhesion to the metal surface to prevent underfilm migration of moisture;

(3) Is sufficiently ductile to resist cracking;

(4) Has enough strength to resist damage due to handling

and soil stress; and

(5) Supports any supplemental cathodic protection. In addition, if an insulating-type coating is used it must have low moisture absorption and provide high electrical resistance.

(b) All pipe coating must be inspected just prior to lowering the pipe into the ditch and any damage discovered must be repaired.

195.242 Cathodic protection system.

(a) A cathodic protection system must be installed for all buried facilities to mitigate corrosion deterioration that might result in structural failure. A test procedure must be developed to determine whether adequate cathodic protection has been achieved.

(b) A cathodic protection system must be installed not later than 1 year after completing the construction.

195.244 Test leads.

(a) Except for offshore pipelines, electrical test leads used for corrosion control or electrolysis testing must be installed at intervals frequent enough to obtain electrical measurements indicating the adequacy of the cathodic protection.

(1) Test leads must be installed as follows:

(1) Enough looping or slack must be provided to prevent test leads from being unduly stressed or broken during back filling.

(2) Each lead must be attached to the pipe so as to prevent stress concentration on the pipe.

(3) Each lead installed in a conduit must be suitably insulated from the conduit.

SUBPART F -- OPERATION AND MAINTENANCE

CATHODIC PROTECTION REQUIREMENTS

195.414 Cathodic protection.

(a) After March 31, 1973, no carrier may operate a pipeline that has an external surface coating material, unless that pipeline is cathodically protected. This paragraph does not apply to tank farms and buried pumping station piping.

(b) Each carrier shall electrically inspect each bare pipeline before April 1, 1975, to determine any areas in which active corrosion is taking place. The carrier may not increase its established maximum operating pressure on a section of bare pipeline until the section has been so electrically inspected. In any areas where active corrosion is found, the carrier shall provide cathodic protection.

Section 195.416 (f) and (g) applies to all corroded pipe that is found.

(c) Each carrier shall electrically inspect all tank farms and buried pumping station piping before April 1, 1973, as to the need for cathodic protection, and cathodic protection shall be provided where necessary.

EXTERNAL CORROSION CONTROL

TESTING AND INSPECTION

195.416 External corrosion control.

(a) Each carrier shall, at intervals not exceeding 12 months, conduct tests on each underground facility in its pipeline systems that is under cathodic protection to determine whether the protection is adequate.

(b) Each carrier shall maintain the test leads required for cathodic protection in such a condition that electrical measurements can be obtained to ensure adequate protection.

(c) Each carrier shall, at intervals not exceeding 2 months, inspect each of its cathodic protection rectifiers.

(d) Each carrier shall, at intervals not exceeding 5 years, electrically inspect the bare pipe in its pipeline system that is not cathodically protected and must study leak records for that pipe to determine if additional protection is needed.

(e) Whenever any buried pipe is exposed for any reason, the carrier shall examine the pipe for evidence of external corrosion. If the carrier finds that there is active corrosion, that the surface of the pipe is generally pitted, or that corrosion has caused a leak, it shall investigate further to determine the extent of the corrosion.

(f) Any pipe that is found to be generally corroded so that the remaining wall thickness is less than the minimum thickness required by the pipe specification tolerances must either be replaced with coated pipe that meets the requirements of this part or, if the area is small, must be repaired. However, the carrier need not replace generally corroded pipe if the operating pressure is reduced to be commensurate with the limits on operating pressure specified in this subpart, based on the actual remaining wall thickness.

(g) If isolated corrosion pitting is found, the carrier shall repair or replace the pipe unless-

(1) The diameter of the corrosion pits, as measured at the surface of the pipe, is less than the nominal wall thickness of the pipe; and

(2) The remaining wall thickness at the bottom of the pits is at least 70 percent of the nominal wall thickness.

(h) Each carrier shall clean, coat with material suitable for the prevention of atmospheric corrosion, and, maintain

this protection for, each component in its pipeline system that is exposed to the atmosphere.

INTERNAL CORROSION CONTROL

195.418 Internal corrosion control.

(a) No carrier may transport any commodity that would corrode the pipe or other components of its pipeline system, unless it has investigated the corrosive effect of the commodity on the system and has taken adequate steps to mitigate corrosion.

(b) If corrosion inhibitors are used to mitigate internal corrosion the carrier shall use inhibitors in sufficient quantity to protect the entire part of the system that the inhibitors are designed to protect and shall also use coupons or other monitoring equipment to determine their effectiveness.

(c) The carrier shall, at intervals not exceeding 6 months, examine coupons or other types of monitoring equipment to determine the effectiveness of the inhibitors or the extent of any corrosion.

(d) Whenever any pipe is removed from the pipeline for any reason, the carrier must inspect the internal surface for evidence of corrosion. If the pipe is generally corroded such that the remaining wall thickness is less than the minimum thickness required by the pipe specification tolerances, the carrier shall investigate adjacent pipe to determine the extent of the corrosion. The corroded pipe must be replaced with pipe that meets the requirements of this part.

(*) Excerpt from Federal Register, October 4, 1969, Title 49 - Transportation, Part 195 - Transportation of Liquids by Pipeline.

APPENDIX C.

ELECTROMOTIVE FORCE SERIES

<u>Electrode Reaction</u>	<u>Standard Electrode Potential E° (volts), 25°C.</u>
Potassium = $K^+ + e^-$	-2.922
Calcium = $Ca^{++} + 2e^-$	-2.87
Sodium = $Na^+ + e^-$	-2.712
Magnesium = $Mg^{++} + 2e^-$	-2.34
Beryllium = $Be^{++} + 2e^-$	-1.70
Aluminum = $Al^{+++} + 3e^-$	-1.67
Manganese = $Mn^{++} + 2e^-$	-1.05
Zinc = $Zn^{++} + 2e^-$	-0.762
Chromium = $Cr^{+++} + 3e^-$	-0.71
Gallium = $Ga^{+++} + 3e^-$	-0.52
Iron = $Fe^{++} + 2e^-$	-0.440
Cadmium = $Cd^{++} + 2e^-$	-0.402
Indium = $In^{+++} + 3e^-$	-0.340
Thallium = $Tl^+ + e^-$	-0.336
Cobalt = $Co^{++} + 2e^-$	-0.277
Nickel = $Ni^{++} + 2e^-$	-0.250
Tin = $Sn^{++} + 2e^-$	-0.136
Lead = $Pb^{++} + 2e^-$	-0.126
Hydrogen = $2H^+ + 2e^-$	0.000
Copper = $Cu^{++} + 2e^-$	0.345
Copper = $Cu^+ + e^-$	0.522
Mercury = $Hg^{2++} + 2e^-$	0.799
Silver = $Ag^+ + e^-$	0.800
Palladium = $Pd^{++} + 2e^-$	0.83
Mercury = $Hg^{++} + 2e^-$	0.854
Platinum = $Pt^{++} + 2e^-$	1.2
Gold = $Au^{+++} + 3e^-$	1.42
Gold = $Au^+ + e^-$	1.68

APPENDIX D.

TABLE D-1

GALVANIC SERIES WITH RESPECT
TO SATURATED CALOMEL ELECTRODE¹

Metal	Negative Potential to Saturated Calomel Electrode, volts ¹
Mercury	1.03
Aluminum (Al-1) (PS)	0.94
Aluminum (Al-2) (PS-H)	0.79
Aluminum (Al-3) (PS-T)	0.76
Aluminum (Al-4) (PS-H)	0.74
Lead	0.61
Lead (Pb-1)	0.61
Lead (Pb-2) (type 47)	
17% Cr (passive)	0.57
Cast iron, 20% Ni	0.54
Stainless steel type 304	
18% Cr, 8% Ni (passive)	0.53
Stainless steel type 410,	
17% Cr (passive)	0.52
Cast iron, 30% Ni	0.49
Cast iron, 30% Ni + Cu	0.46
Cast rolled brass	0.40
Yellow brass	0.36
Copper	0.36
Red brass	0.33
Composition of bronze	0.31
Admiralty brass	0.29
90-10 Cupro nickel, 0.8% iron	0.28
90-30 Cupro nickel, 0.06% iron	0.27
90-30 Cupro nickel, 0.47% iron	0.25
Stainless steel type 430,	
17% Cr (passive)	0.22

¹ Based on potential measurements in sea water; velocity of flow, 13 ft. per sec.; temperature 25°C. (77°F).

TABLE D-1 (Continued)

GALVANIC SERIES WITH RESPECT
TO SATURATED CALOMEL ELECTRODE¹

Metal	Negative Potential to Saturated Calomel Electrode, volts ¹
Nickel	0.20
Stainless steel type 316, 18% Cr, 12% Ni, 3% Mo (active)	0.18
Inconel	0.17
Stainless steel type 410, 13% Cr (passive)	0.15
Titanium (commercial)	0.15
Silver	0.13
Titanium (high purity from iodide)	0.10
Stainless steel type 304, 18% Cr, 8% Ni (passive)	0.08
Hastelloy C	0.08
Monel	0.08
Stainless steel type 316, 18% Cr, 12% Ni, 3% Mo (passive)	0.05

¹ Based on potential measurements in sea water; velocity of flow, 13 ft. per sec.; temperature 25°C. (77°F.).

TABLE D-2

GALVANIC SERIES WITH RESPECT TO
SATURATED COPPER-COPPER SULFATE ELECTRODE¹

Metal	Negative Potential to Saturated Copper-Copper Sulfate electrode
Magnesium (Galvomag alloy) ²	1.75
Magnesium (- alloy) ^a	1.55
Zinc	1.10
Aluminum (Al-100 3S)	1.01
Carbon steel	0.68
Stainless steel type 430, 17% Cr ^b	0.64
Stainless steel type 304, 18% Cr, 8% Ni	0.61
Stainless steel type 304, 18% Cr, 8% Ni ^b	0.60
Stainless steel type 410, 13% Cr ^b	0.59
Cast iron, 30% Ni	0.56
Cast iron, 20% Ni + Cu	0.53
Yellow brass	0.47
Red brass	0.43
Copper	0.43
Nickel	0.40
Brass, composition G	0.38
Admiralty brass	0.36
Steel-Cr-Ni + 0.8% Fe	0.35
Steel-Cr-Ni + 0.06% Fe	0.34
Steel-Cr-Ni + 0.47% Fe	0.32
Stainless steel type 430, 17% Cr ^b	0.29
Stainless steel type 316, 18% Cr, 10% Ni, 2% Mo ^b	0.27
Stainless steel type 316, 18% Cr, 10% Ni, 2% Mo ^b	0.25
Stainless steel type 410, 13% Cr ^b	0.24
Stainless steel type 410, 13% Cr ^b	0.22
Titanium (commercial)	0.22
Silver	0.20
Titanium (high purity from iodide)	0.17
Stainless steel type 304, 18% Cr, 8% Ni ^b	0.15
Stainless steel type 304, 18% Cr, 8% Ni ^b	0.15
Stainless steel type 316, 18% Cr, 10% Ni, 2% Mo ^b	0.15
Stainless steel type 316, 18% Cr, 10% Ni, 2% Mo ^b	0.12

¹ Based on potential measurements in sea water; velocity 100 ft./min., 15 ft. per sec.; temperature 25°C. (77°F).

² Data based on data by The Dow Chemical Company.

^b The stainless steels as a class exhibited erratic potential depending on the incidence of pitting and corrosion in the electrolyte formed around the specimen supports. The values listed represent the extremes observed and, due to their erratic nature, should not be considered as representing an important potential reaction among the alloys which are covered.

APPENDIX E.

TYPICAL GOVERNMENT REGULATIONS FOR SELECTION OF PIPE

1. Scope.

This subpart prescribes minimum requirements for the selection and qualification of pipe and components for use in pipelines.

2. General.

Materials for pipe and components must be--

(a) Able to maintain the structural integrity of the pipeline under temperature and other environmental conditions that may be anticipated;

(b) Chemically compatible with any gas that they transport and with any other material in the pipeline with which they are in contact; and

(c) Qualified in accordance with the applicable requirements of this subpart.

3. Steel Pipe.

(a) New steel pipe is qualified for use under this part if--

(1) It was manufactured in accordance with a listed specification;

(2) It meets the requirements of paragraphs II-A through II-D of this part; or

(3) It is used in accordance with paragraph (c) or (d) of this section.

(b) Used steel pipe is qualified for use under this part if--

(1) It was manufactured in accordance with a listed specification and it meets the requirements of paragraph II-C of this part;

(2) It meets the requirements of II-A through II-D of this part.

(3) It has been used in an existing line of the same or higher pressure and meets the requirements of paragraph II-C of this part; or

(4) It is used in accordance with paragraph (c) of this section.

(c) New or used steel pipe may be used at a pressure resulting in a hoop stress of less than 6,000 p.s.i. where no close coiling or close bending is to be done, if visual ex-

amination indicates that the pipe is in good condition and that it is free of split seams and other defects that would cause leakage. If it is to be welded, steel pipe that has not been manufactured to a listed specification must also pass the weldability tests prescribed in paragraph II-B of this part.

(d) Steel pipe that has not been previously used may be used as replacement pipe in a segment of pipeline if it has been manufactured prior to November 12, 1970, in accordance with the same specification as the pipe used in constructing that segment of pipeline.

(e) New steel pipe that has been cold expanded must comply with the mandatory provisions of API Standard 5LX.

4. Cast Iron or Ductile Iron Pipe.

(a) New cast iron or new ductile iron pipe is qualified for use under this part if it has been manufactured in accordance with a listed specification.

(b) Used cast iron or used ductile iron pipe is qualified for use under this part if inspection shows that the pipe is sound and allows the makeup of tight joints and--

(1) It has been removed from an existing pipeline that operated at the same or higher pressure; or

(2) It was manufactured in accordance with a listed specification.

5. Plastic Pipe.

(a) New plastic pipe is qualified for use under this part if--

(1) It is manufactured in accordance with a list specification; and

(2) It is resistant to chemicals with which contact may be anticipated.

(b) Used plastic pipe is qualified for use under this part if--

(1) It meets the requirements of a listed specification;

(2) It is resistant to chemicals with which contact may be anticipated;

(3) It has been used only in natural gas service;

(4) Its dimensions are still within the tolerances of the specification to which it was manufactured; and

(5) It is free of visible defects.

6. Copper Pipe.

Copper pipe is qualified for use under this part if it has been manufactured in accordance with a listed specification.

7. Qualification of Pipe.

I. Listed Pipe Specifications. Numbers in parentheses indicate applicable editions.

API 5L--Steel and iron pipe (1967, 1970).
API 5LS--Steel pipe (1967, 1970).
API 5LX--Steel pipe (1967, 1970).
ASTM A53--Steel pipe (1965, 1968).
ASTM A106--Steel pipe (1966, 1968).
ASTM A134--Steel pipe (1964, 1968).
ASTM A135--Steel pipe (1963T, 1968).
ASTM A139--Steel pipe (1964, 1968).
ASTM A155--Steel pipe (1965, 1968).
ASTM A211--Steel and iron pipe (1963, 1968).
ASTM A333--Steel pipe (1964, 1967).
ASTM A377--Cast iron pipe (1966).
ASTM A381--Steel pipe (1966, 1968).
ASTM A539--Steel tubing (1965).
ANSI A21.3--Cast iron pipe (1953).
ANSI A21.7--Cast iron pipe (1962).
ANSI A21.9--Cast iron pipe (1962).
ANSI A21.52--Ductile iron pipe (1965).
ASTM A72--wrought iron pipe (1964T, 1968).
ASTM B42--Copper pipe (1962, 1966).
ASTM B68--Copper tubing (1965, 1968).
ASTM B75--Copper tubing (1965, 1968).
ASTM B88--Copper tubing (1966).
ASTM B251--Copper pipe and tubing (1966, 1968).
ASTM D2513--Thermoplastic pipe and tubing, (1966T, 1968).
ASTM D2517--Thermosetting plastic pipe and tubing (1966T, 1967).

II. Steel pipe of unknown or unlisted specification.

A. Bending Properties. For pipe 2 inches or less in diameter, a length of pipe must be cold bent through at least 90 degrees around a cylindrical mandrel that has a diameter 12 times the diameter of the pipe, without developing cracks at any portion and without opening the longitudinal weld.

For pipe more than 2 inches in diameter, the pipe must meet the requirements of the flattening tests set forth in ASTM A53, except that the number of tests must be at least equal to the minimum required in paragraph II-D of this appendix to determine yield strength.

B. Weldability. A girth weld must be made in the pipe by a welder who is qualified under Subpart E of this part. The weld must be made under the most severe conditions under which welding will be allowed in the field and by means of the same procedure that will be used in the field. On pipe more than 4 inches in diameter, at least one test weld

must be made for each 100 lengths of pipe. On pipe 4 inches or less in diameter, at least one test weld must be made for each 400 lengths of pipe. The weld must be tested in accordance with API Standard 1104. If the requirements of API Standard 1104 cannot be met, weldability may be established by making chemical tests for carbon and manganese, and proceeding in accordance with section IX of the ASME Boiler and Pressure Vessel Code. The same number of chemical tests must be made as are required for testing a girth weld.

C. Inspection. The pipe must be clean enough to permit adequate inspection. It must be visually inspected to ensure that it is reasonably round and straight and there are no defects which might impair the strength or tightness of the pipe.

D. Tensile Properties. If the tensile properties of the pipe are not known, the minimum yield strength may be taken as 24,000 p.s.i.g. or less, or the tensile properties may be established by performing tensile tests as set forth in API Standard 5LX. All test specimens shall be selected at random and the following number of tests must be performed.

Number of Tensile Tests--All Sizes

10 lengths or less.....	1 set of tests for each length.
11 to 100 lengths.....	1 set of tests for each 5 lengths, but not less than 10 tests.
Over 100 lengths.....	1 set of tests for each 10 lengths, but not less than 20 tests.

If the yield-tensile ratio, based on the properties determined by those tests, exceeds 0.85, the pipe may be used only as provided in 3 (c).

APPENDIX F.

UNDERGROUND CORROSION SURVEY CHECK LIST

New Construction

- I. Meeting with A/E or owner.
- A. Description of facilities to be constructed.
 1. What is included?
 - a. Gas
 - b. Water
 - c. Buried electrical and grounding system
 - d. Buried communications or signal
 - e. Tanks
 - f. Piling
 - g. Bulkheads
 - h. Building structural members
 - i. Other
 2. Materials to be used and where?
 - a. Steel
 - b. Cast Iron
 - c. Lead
 - d. Concrete
 - e. Copper
 - f. Aluminum
 - g. Other
 3. Construction methods specified.
 - a. Coatings - Types?
 - b. Insulation between structures?
 - c. Are special fills being used?
 - d. Road and railroad casings?
Are they insulated?
 - e. Type pipe joints - weld, flange, dresser, other?
 - f. Type grounding connecting cables?
 - g. Layout of structures (distance between those of varying materials, etc.)?
 - h. Roadways - Will deicing salts leach down into buried structures?
 - i. Lawns - Their location. Is it objectionable to install above grade test stations, etc. in or near them?
 - j. Pavement - Its location and type. What buried facilities will be placed under it?
- B. Get complete drawings of all facilities.
 1. The following are usually included:
 - a. Electrical
 - b. Mechanical
 - c. Communications
 - d. Fire Protection
 - e. Piling
 - f. Fuel systems

- g. Storage tanks
 - 2. Be sure they are the latest.
 - 3. Ask to be kept advised of any changes.
- C. Ownership of Facilities.
 - 1. Gas, water, power, telephone, etc. - Which are to be included in project? Which are "utility owned"?
 - 2. Where does utility's ownership and plant's jurisdiction begin?
 - 3. Will the utility install insulation?
- D. What life does the owner expect from his facilities? How many years?
- E. What does a corrosion failure cost? (Each type facility)
- F. Are any facilities extremely critical? (no failures of any kind to be tolerated because of cost or hazard.)
- G. Is direct current being used anywhere in this plant or nearby?
 - 1. Get complete information on where and why.
 - 2. Wiring diagrams and schematics.
 - 3. Method of grounding.
- H. Are any abandoned facilities located in the vicinity? (Metal pipes, etc. might be used as groundbeds.) Are they connected or to be connected to anything else?

II. Field Tests

- A. Soil Resistivity

If site is uniform, take 5' and 10' (usual depth of buried structures) readings at suitably spaced grid. (20' to 100' readings may be required.) Do not exceed 100' spacing with Vibroground instrument. If route of piping or structure known, follow route. Take readings of fill, if any.
- B. Soil pH

Take pH at same places resistivity, if soil is moist.
- C. Soil Samples and/or Water (steam riser, etc.)

Take samples for sulfides and sulfate (and pH) at representative grid locations. (Min. = 6)
- D. Stray Currents

Using 2 copper sulfate cells, take soil potential profile reading in a rosette pattern as necessary.

III. Consulting

- A. Contact Corrosion/Maintenance Engineers of operators in area.
 - 1. Oil Transmission Pipelines
 - 2. Gas Transmission Pipelines
 - 3. Gas Distribution Company
 - 4. Telephone Company

5. Water Department
6. Electrical Power Company
7. Manufacturing Plants in area
8. Corrosion Coordinating Committee
9. Railroad (do nearby railroads have signal systems?
Electrical Propulsion - AC or DC?)
- B. Data to get from those contacted in A.
 1. Failure and corrosion experience.
 2. Is cathodic protection being used?
Type?
Rectifier locations?
 3. Personnel to contact for coordination tests-
names, addresses and telephone numbers.
 4. Place and time of Coordinating Committee meeting.
 5. Is stray current a problem? Its source?
What structures have been affected?
 6. Are deicing salts used in streets?
 7. Are underground structures coated?
Which ones?
Type Coating?
 8. Get drawings and/or other location information on
all structures in the area.
Mark those protected and locations of rectifiers.
 9. Are other new facilities planned for this area?
Utilities, pipelines, etc.
 10. Will these new facilities be coated and/or cathod-
ically protected?
 11. Is it objectionable to use impressed current cath-
odic protection?

Existing Structures

1. Meeting with A/E or owner.
 - A. Find out what facilities are to be covered by this
investigation. Also get data on all others in area.
 1. Look for the following:
 - a. Gas
 - b. Water
 - c. Buried electrical and grounding system
 - d. Buried communications or signal
 - e. Tanks
 - f. Piling
 - g. Bulkheads
 - h. Building structural members
 - i. Other
 2. What materials have been used and where?
 - a. Steel
 - b. Cast iron
 - c. Lead
 - d. Concrete
 - e. Copper

- f. Aluminum
- g. Other
- 3. Construction methods used.
 - a. Coatings - Types?
 - b. Insulation between structures?
 - e. Are special fills being used?
 - d. Road and railroad casings?
Are they insulated?
 - e. Type pipe joints - weld, flange, dresser, other?
 - f. Type grounding connecting cables?
 - e. Layout of structures (distance between those of varying materials, etc.)?
 - h. Roadways - Will deicing salts leach down into buried structures?
 - i. Lawns - Their location. Is it objectionable to install above grade test stations, etc. in or near them?
 - j. Pavement - Its location and type. What buried facilities will be placed under it?
 - k. Have test wires been installed on buried structures?
 - l. Where can connections to buried structures be made? Exposed valves, sections of pipe, etc.
- B. Get complete drawings of all facilities.
 - 1. The following are usually included:
 - a. Electrical
 - b. Mechanical
 - c. Communications
 - d. Fire protection
 - e. Filing
 - f. Fuel systems
 - g. Storage tanks
 - 2. Be sure they are the latest.
 - 3. Ask to be kept advised of any changes.
 - 4. Test station locations.
 - 5. Test station wiring diagrams.
 - 6. Insulation joint locations.
 - 7. Insulation joint types.
- C. Ownership of Facilities.
 - 1. Gas, water, power, telephone, etc. -Which are to be included in project?
Which are "utility owned"?
 - 2. Where does utility's ownership end and plant's jurisdiction begin?
 - 3. Will the utility install insulation?
 - 4. Are utility companies using cathodic protection?
 - 5. Have the utility company's made any tests or investigations on the systems covered by this survey?
- D. What life does the owner expect from his facilities?
How many years?

- E. What does a corrosion failure cost? (Each type facility)
- F. Are any facilities extremely critical? (No failures of any kind to be tolerated because of cost or hazard.)
- G. Have any corrosion failures been experienced?
 - 1. How many?
 - 2. When (dates)?
 - 3. Where? (Mark on drawings)
 - 4. What was their appearance?
- H. Have other failures occurred? (investigate to be sure they were not really corrosion.)
- I. Is direct current being used anywhere in this plant or nearby?
 - 1. Get complete information on where and why.
 - 2. Wiring diagrams and schematics.
 - 3. Method of grounding.
- J. Are any abandoned facilities located in the vicinity? (Metal pipes, etc. might be used as groundbeds.) Are they connected or to be connected to anything else?
- K. Are additional facilities planned? (Immediate or long range) If so, get information.
 - 1. Type and methods of construction.
 - 2. Probable location.
 - 3. How will they be connected to existing facilities?
 - 4. Will direct current be used?

II. Field Tests

- A. Soil Resistivity

If site is uniform, take 5' and 10' (usual depth of buried structures) readings at suitably spaced grid. (20' and 100' readings may be required.) Do not exceed 100' spacing with Vibroground instrument. If route of piping or structure known, follow route. Take readings of fill, if any.
- B. Soil pH

Take pH at same places resistivity, if soil is moist.
- C. Soil Samples and/or Water (steam riser, etc.)

Take samples for sulfides and sulfate (and pH) at representative grid locations. (Min. = 6)
- D. Structure-to-Soil Voltage (at discretion of engineer).
 - 1. Thorough test of bare structure requires one over structure and one on each side every 25'.
 - 2. Coated Structure-less frequent.
- E. I.R. Drop (get at least one on every structure.)
 - 1. Always test external circuit resistance.
 - 2. Correct readings if necessary.
 - 3. Be sure to indicate polarity of all readings.
- F. Voltage between structures. Test voltage between all metallic structures. (Be sure to indicate polarity

- of each reading.)
- G. Insulating Joint- Test resistance of all known and look for others.
1. Use four connections (two on each side of joint) with D. C. Method.
- H. Mechanical pipe Joints.
1. Test each piping system to find if mechanical joints exist.
 2. Test representative number of mechanical joints to determine quantitative resistance per joint.
 3. Be sure to use four point contact method with direct current.
- I. Electrical and communications cables in duct.
1. All electrical tests at each manhole.
 - a. As in D, E, and F (above).
 - b. Be sure to test voltage between all cables in multiple run duct systems.
 2. Visually inspect all hardware in each manhole.
 - a. Brackets
 - b. Bonds
 - c. Condition of cables
 - d. Note material of each component and its condition
 - e. Note fastening methods and insulation between components.
- J. Stray Current Investigation
1. Stray currents will be indicated by abnormal structure-to-soil voltages and/or IR drop. (Either steady or fluctuating.)
 2. If stray current is suspected, investigate:
 - a. Any possible source of direct current in area.
 - b. Operating cathodic protection.
 3. Have suspected source turned off and on to establish its affect on any structure.
 4. Get additional IR and voltage readings to establish circuit.
- K. Current requirement tests (for cathodic protection). At least cursory current requirement tests should usually be conducted if there is any chance of using cathodic protection at the site.
1. Test using artificial groundbed for both magnesium anode and impressed current design.
 2. Extent of testing will be determined by scope of work laid out by client. (Is all design data to be included with this survey?)
- L. Existing cathodic protection.
1. Visually inspect all equipment.
 2. Test to determine protection being afforded and possible interference to other structures.
 3. Get operating record.
 4. Find out when installed and turned on.
- M. Miscellaneous - Note any other corrosion problems (chemical, water, atmospheric, etc.) which could use

further detailed study.

III. Consulting

- A. Contact all plant personnel who have knowledge of structures being studied and get all possible information from them.
- B. Contact Corrosion/Maintenance Engineers of operators in area.

- 1. Oil Transmission Pipelines
- 2. Gas Transmission Pipelines
- 3. Gas Distribution Company
- 4. Telephone Company
- 5. Water Department
- 6. Electrical Power Company
- 7. Manufacturing Plants in area
- 8. Corrosion Coordinating Committee
- 9. Railroad (Do nearby railroads have signal systems? Electrical Propulsion - AC or DC?)

C. Data to get from those contacted in B.

- 1. Failure and corrosion experience.
- 2. Is cathodic protection being used? Type? Rectifier Locations?
- 3. Personnel to contact for coordination tests - names, addresses and telephone numbers.
- 4. Place and time of Coordinating Committee meeting.
- 5. Is stray current a problem?
Its source?
What structures have been affected?
- 6. Are deicing salts used in streets?
- 7. Are underground structures coated?
Which ones?
Type coating?
- 8. Get drawings and/or other location information on all structures in the area. Mark those protected and locations of rectifiers.
- 9. Are other new facilities planned for this area?
Utilities, pipelines, etc.
- 10. Will these new facilities be coated and/or cathodically protected?
- 11. Is it objectionable to use impressed current cathodic protection.

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