

Engineering Encyclopedia

Saudi Aramco DeskTop Standards

Design Criteria For Cathodic Protection Systems

Note: The source of the technical material in this volume is the Professional Engineering Development Program (PEDP) of Engineering Services.

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OPERATIONS AND APPLICATIONS OF GALVANIC ANODE SYSTEMS

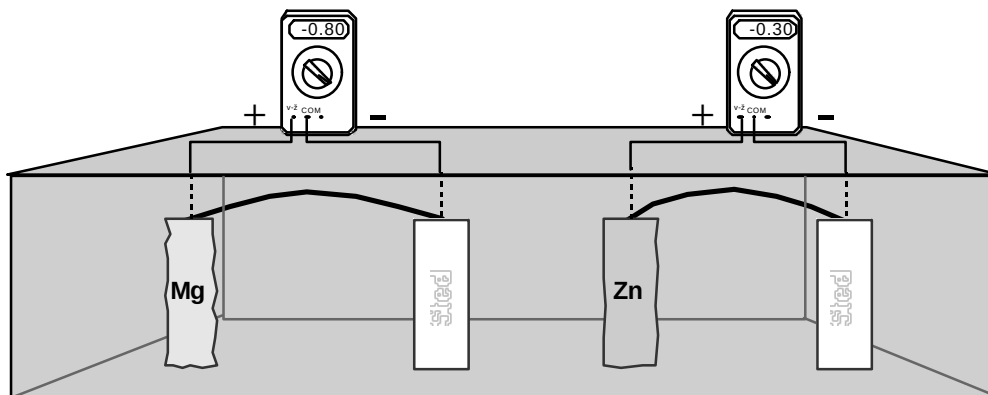
Operation of Galvanic Anode Systems

Galvanic anode systems are based on the principle of the galvanic corrosion cell. A galvanic corrosion cell is two dissimilar metals connected together in a common electrolyte. Corrosion current flows from the metal with the more negative potential to the metal with the least negative (more positive) potential. The metal with the least negative potential is protected from corrosion. For example, the Practical Galvanic Series below shows the potentials of metals in soil with respect to a Cu-CuSO₄ reference electrode. If two metals in the Series form a galvanic couple, the metal nearest the top will be anodic to any metal below it.

PRACTICAL GALVANIC SERIES IN NEUTRAL SOIL

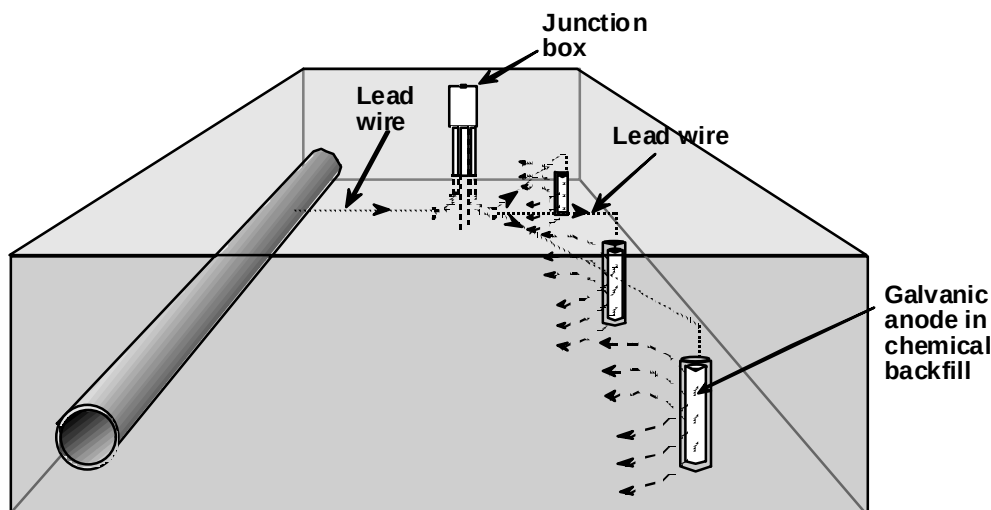
<u>Metal</u>	Normal Electrode Potential, volts vs. Cu-CuSO ₄	
Commercially pure magnesium	-1.75	More anodic
Magnesium alloy (contains Al, Zn, Mn)	-1.55	
Zinc	-1.10	
Aluminum alloy (Contains zinc)	-1.05	
Commercially pure aluminum	-0.80	
Mild steel	-0.50 to -0.80	
Cast iron	-0.50	
Brass, bronze, or copper	-0.20	
High silicon cast iron	-0.20	
Mill scale on steel	-0.20	
Carbon, coke, graphite	+0.30	More cathodic

Figure 1 shows two galvanic couples in soil. One couple contains magnesium and steel and the other couple contains zinc and steel. In each couple, the more negative metal (magnesium or zinc) corrodes and the steel is protected from corrosion. The rate of corrosion is greater in the magnesium-steel couple because the potential difference is greater.



Galvanic Couples in Soil
Figure 1

Galvanic anode systems work in the same manner. Galvanic anodes are usually made from materials near the top of the Galvanic Series (e.g., magnesium, aluminum, and zinc). When galvanic anodes are connected to a buried structure such as the steel pipeline, as illustrated in Figure 2, a galvanic corrosion cell develops. Electric current flows from the anodes, through the electrolyte, and to the pipeline. The pipeline becomes cathodically protected. To complete the circuit, current returns to the anodes through a lead wire.



Typical Vertical Galvanic Anode in Soil (arrows show the direction of current flow)

Figure 2

The components in a typical underground galvanic anode system include anodes, chemical backfill, lead wire, and a junction box. We will now describe these components in more detail.

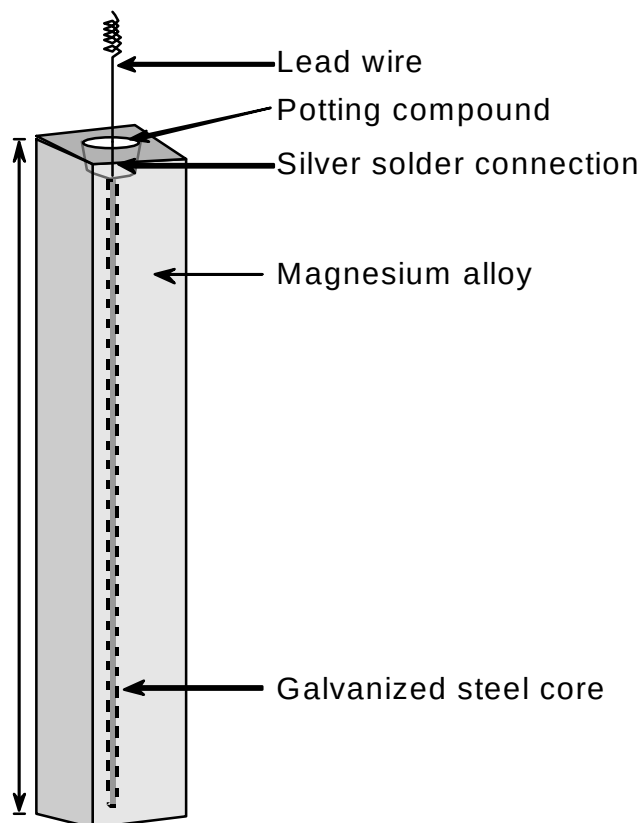
Galvanic Anodes

Galvanic anodes corrode and discharge current to protect the structure. When galvanic anodes corrode, all of their energy is not used to provide protective current. Local corrosion cells on the anode surface also use energy to produce corrosion current. The energy used by these local corrosion cells is not used to protect the structure. The ratio of the anode weight used to produce useful current to the total anode weight multiplied by 100 is called the anode efficiency.

A galvanic anode provides a given amount of electrical energy based on its composition and efficiency. Each anode material has a theoretical energy content given in ampere-hours per kg. An ampere-hour is any combination of amperage and time that equals 1.0 ampere flowing for 1 hour. For example, both 0.5 ampere flowing for 2 hours and 2.0 amperes flowing for 0.5 hour are the equivalent of 1 ampere-hour.

The three most common galvanic anode materials are magnesium, zinc, and aluminum. The typical characteristics of these anodes are discussed below.

Magnesium Anodes - Magnesium is the most widely used material for buried galvanic anodes. Saudi Aramco normally uses magnesium anodes on pipelines at road and fence crossings and at mainline valves. A typical 27.3 kg (60 lb) magnesium anode is shown in Figure 3.



Typical 27.3 kg (60 lb) Magnesium Galvanic Anode

Figure 3

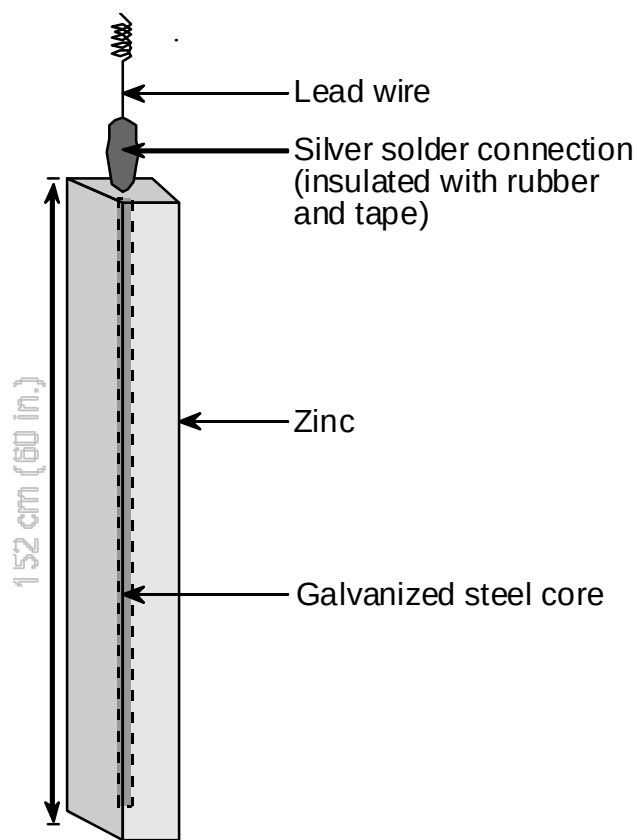
Two types of magnesium anodes are available--standard alloy and high-potential alloy. Both have a theoretical energy content of about 2,200 ampere-hours per kg and an efficiency of 50%. Therefore, the actual energy content available is 2,200 ampere-hours per kg x 0.50, or 1,100 ampere-hours per kg. The standard magnesium anode has a solution potential of -1.55 volts versus Cu-CuSO₄. High-potential magnesium anodes have a solution potential of -1.80 volts. Saudi Aramco uses high-potential magnesium anodes almost exclusively.

NOTE: Magnesium anodes are susceptible to polarization. For this reason, their solution potential is reduced by 0.10 volt.

Zinc Anodes are most often used in soil resistivities below 700 ohm-cm or in vessel interiors. Occasionally they are used in soils up to 2,500 ohm-cm. Pure zinc has a theoretical energy content of 820 ampere-hours per kg. Zinc anodes typically operate at about 95% efficiency. Therefore, the actual energy content available is 820 ampere-hours per kg $\times$ 0.95, or 779 ampere-hours per kg. Zinc anodes have a potential of -1.10 volts versus a Cu-CuSO₄ half-cell.

Zinc galvanic anodes have long slender shapes to achieve low resistance to earth. Their shape also provides practical current output despite their low driving voltages. Zinc anodes are not subject to significant polarization when they are used in suitable backfill.

CAUTION: Do not use zinc anodes when the temperature will exceed 49° C. This temperature may cause the polarity of zinc anodes to reverse and result in corrosion of the structure.



Typical 13.6 kg (30 lb) Zinc Anode

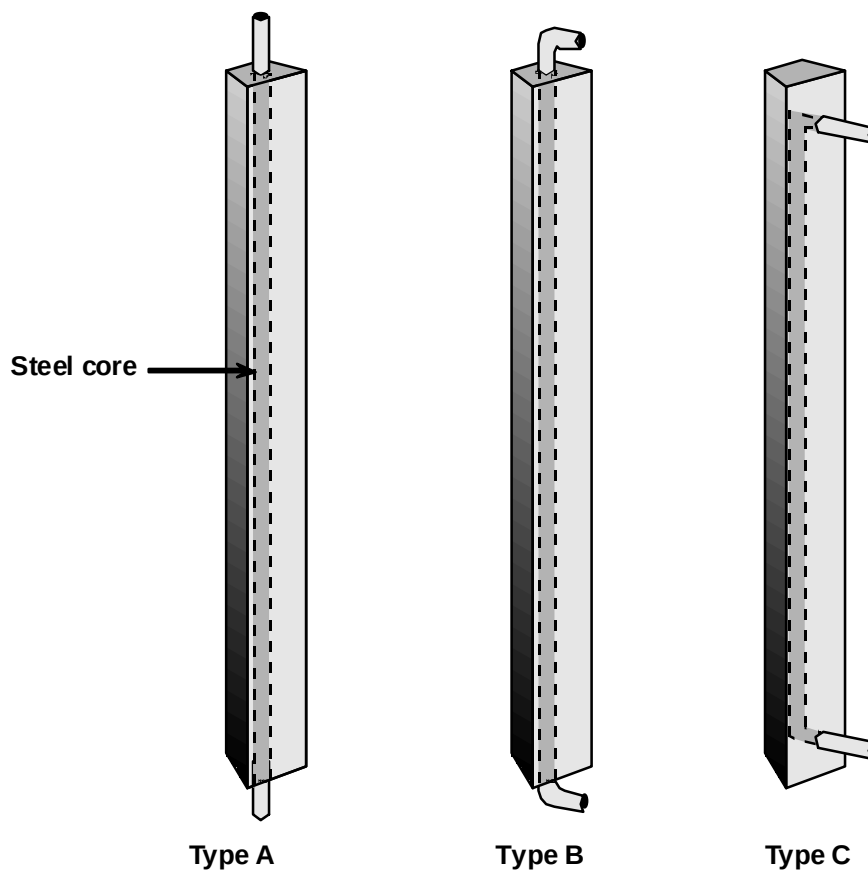
Figure 4

Aluminum Anodes are used in offshore applications or for protecting vessel and tank interiors. There are generally three types of aluminum anodes as follows:

- Heat-treated aluminum zinc-tin alloy
- Aluminum-zinc-mercury alloy
- Aluminum-zinc-indium alloy

All of these alloys have slightly different theoretical energy contents, but they average 2,700 ampere-hours per kg in seawater service. Aluminum anodes are effective in electrolyte resistivities less than 700 ohm-cm. The efficiencies of aluminum anodes range from 85% to 95% in seawater. The potentials of aluminum anodes range from -1.05 to -1.15 volt versus Cu-CuSO₄.

Aluminum galvanic anodes are manufactured so they can attach directly to an offshore structure. Three types of core arrangements are shown in Figure 5.



Aluminum Anodes for Offshore Structures

Figure 5

Function of Major Components of Galvanic Anode Systems

Anode chemical backfill is the special material that surrounds the buried anode (Figure 6A). A typical backfill mixture for magnesium anodes is 75% hydrated gypsum, 20% bentonite clay, and 5% sodium sulfate. Clays in the backfill absorb water from the soil and keep the anode moist for maximum current output. Chemical backfill also has low resistivity which reduces the anode to earth resistance. When backfill has a lower resistivity than the surrounding soil, the effective anode dimensions are increased to the dimensions of the backfill.

If an anode is buried in soil without backfill, variations in the soil's composition may start local corrosion cells on the anode surface. For example, chloride ions in soil increase the corrosion of magnesium anodes and lower their efficiency. Bicarbonates and carbonates in soil may react with magnesium and zinc anodes to form surface films with high electrical resistance. Surface films cause the anodes to "go passive" and cease to produce enough current to protect the structure.

Galvanic anodes are frequently pre-packaged in backfill material and buried directly in the soil. Figure 6B is a cutaway view of a pre-packaged 27.3 kg (60 lb) magnesium anode.

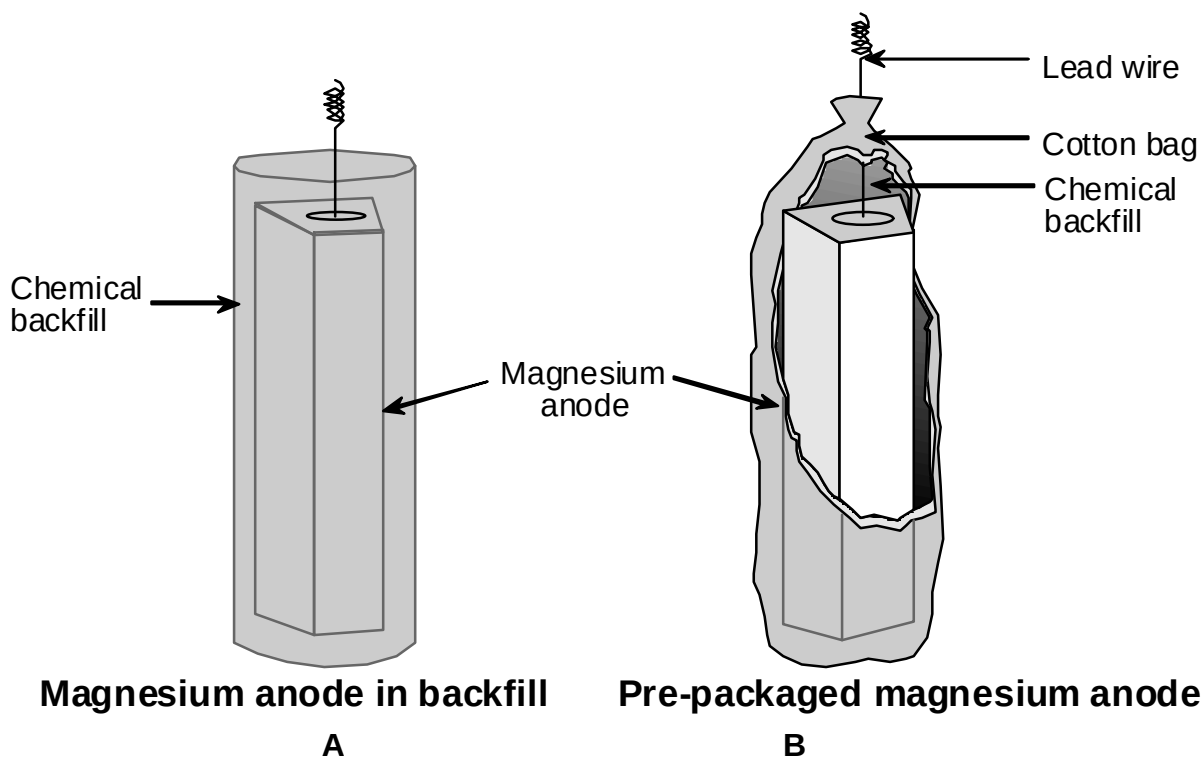
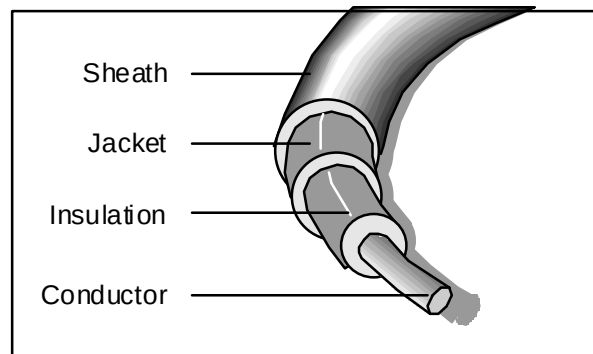


Figure 6

Conductors and Cables - A conductor is a metal wire that provides easy flow for electric current. Copper is the most common material used in standard electrical applications. An insulated conductor is surrounded with high resistance material like glass, rubber, and plastic. These insulators provide electrical and mechanical protection. Figure 7 shows an insulated conductor, or lead wire, with two extra protective layers--a jacket and a sheath.



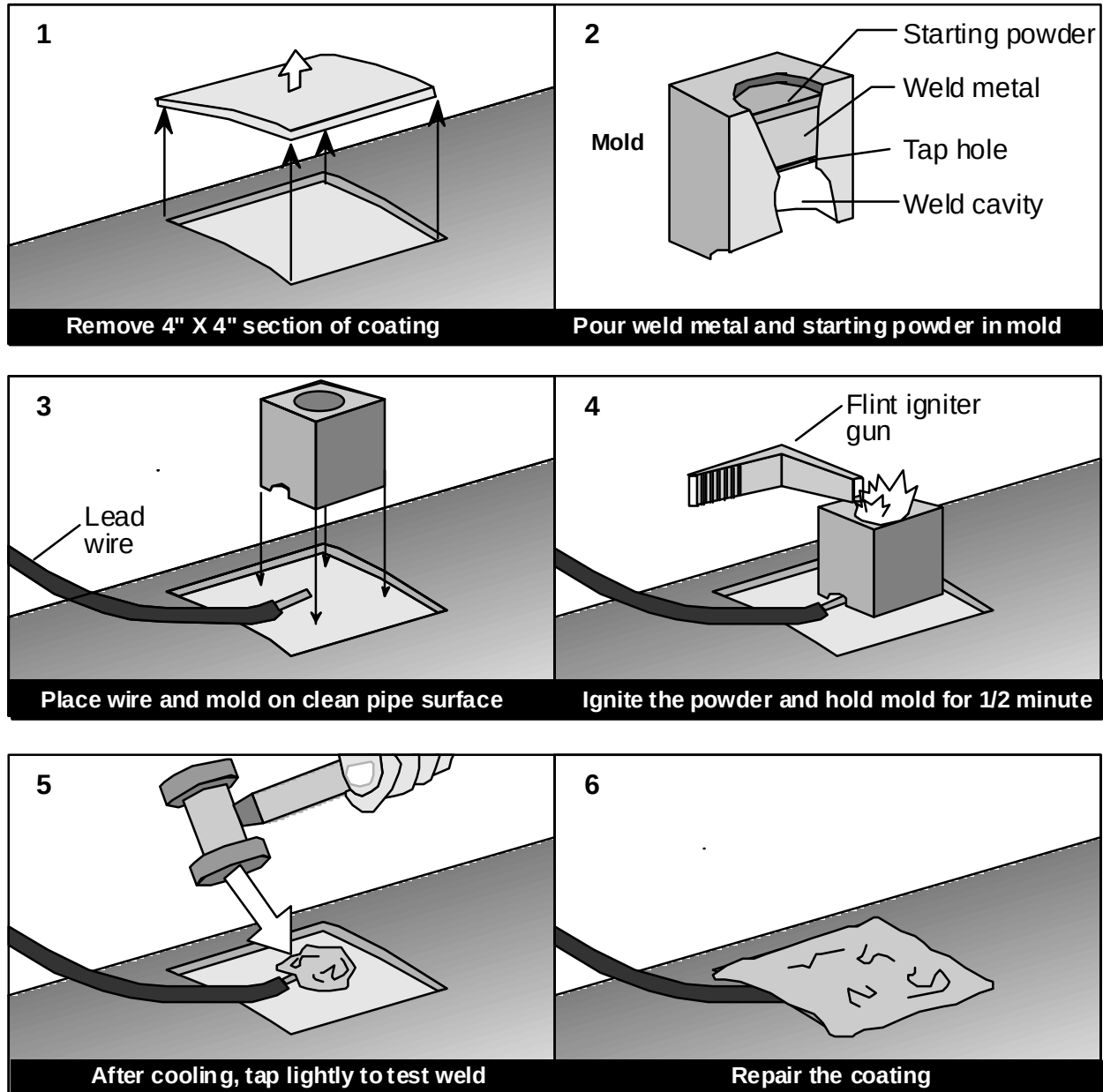
Lead Wire
Figure 7

Saudi Aramco uses cables and lead wires to:

- connect the anode to the structure
- connect the negative lead from the structure to the test station

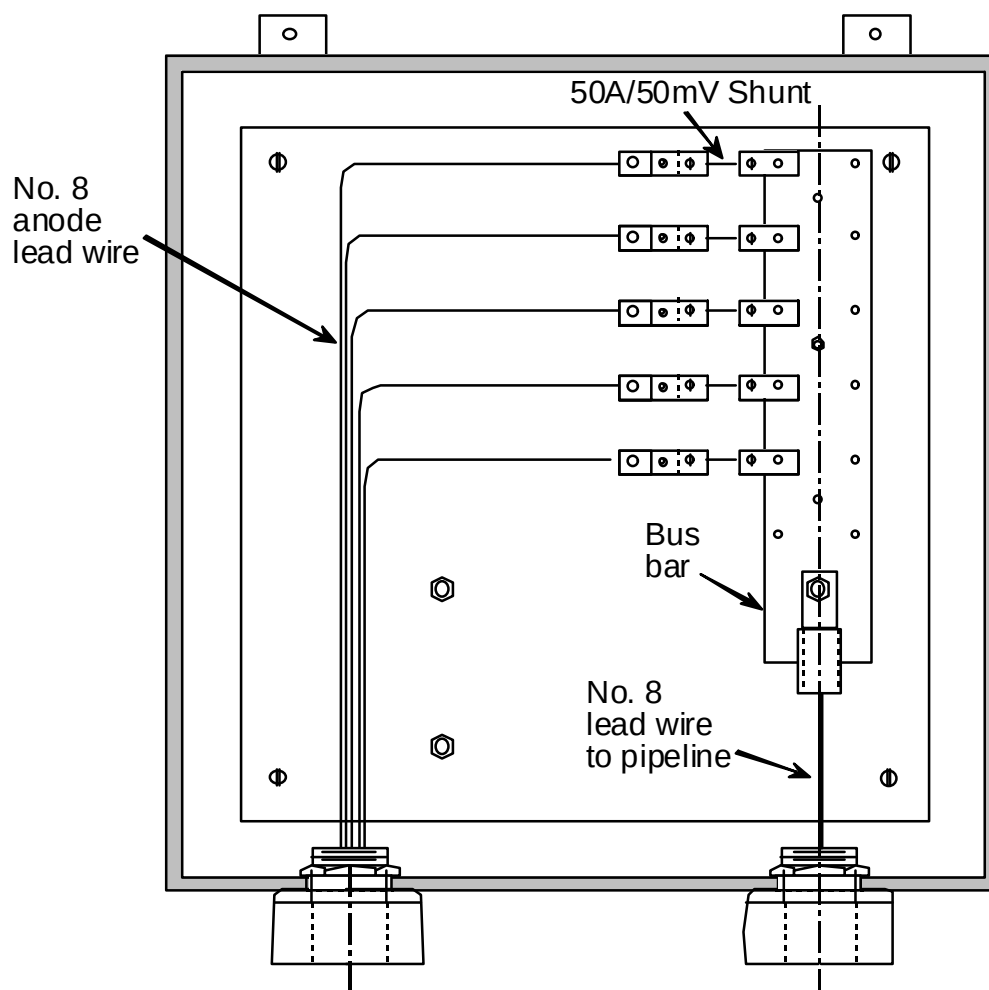
The amount of current a conductor can carry is determined by the type of metal and its size. Cables and conductors are available in different types and sizes. The National Electric Code (NEC) specifies the number and size of conductors in a cable. The number and size should be enough to dissipate heat and prevent damage during installation or withdrawal. Cable types and sizes are specified on standard Aramco engineering drawings. Saudi Aramco normally requires No. 8 AWG wire for test station connections.

Cables are usually thermite brazed to structures. Proper thermite brazing eliminates the expense of welding. Figure 8 summarizes the thermite welding procedure used by Saudi Aramco.



Graphic Summary of the Thermite Brazing Procedure
Figure 8

Junction Boxes - The anode lead wires go to a junction box as shown in Figure 9. A shunt is inserted in each anode lead wire inside the junction box. A common shunt resistance is 0.001 ohms. This allows the current output of each anode to be measured by determining the voltage drop across the shunt. For example, the current output of an anode with a voltage drop of 0.75 millivolts across a 0.001 ohm shunt is $0.00075 \text{ volt} / 0.001 \text{ ohm} = 0.75 \text{ amperes}$. A No. 8 AWG wire connects the anode lead wires in the junction box to the structure.

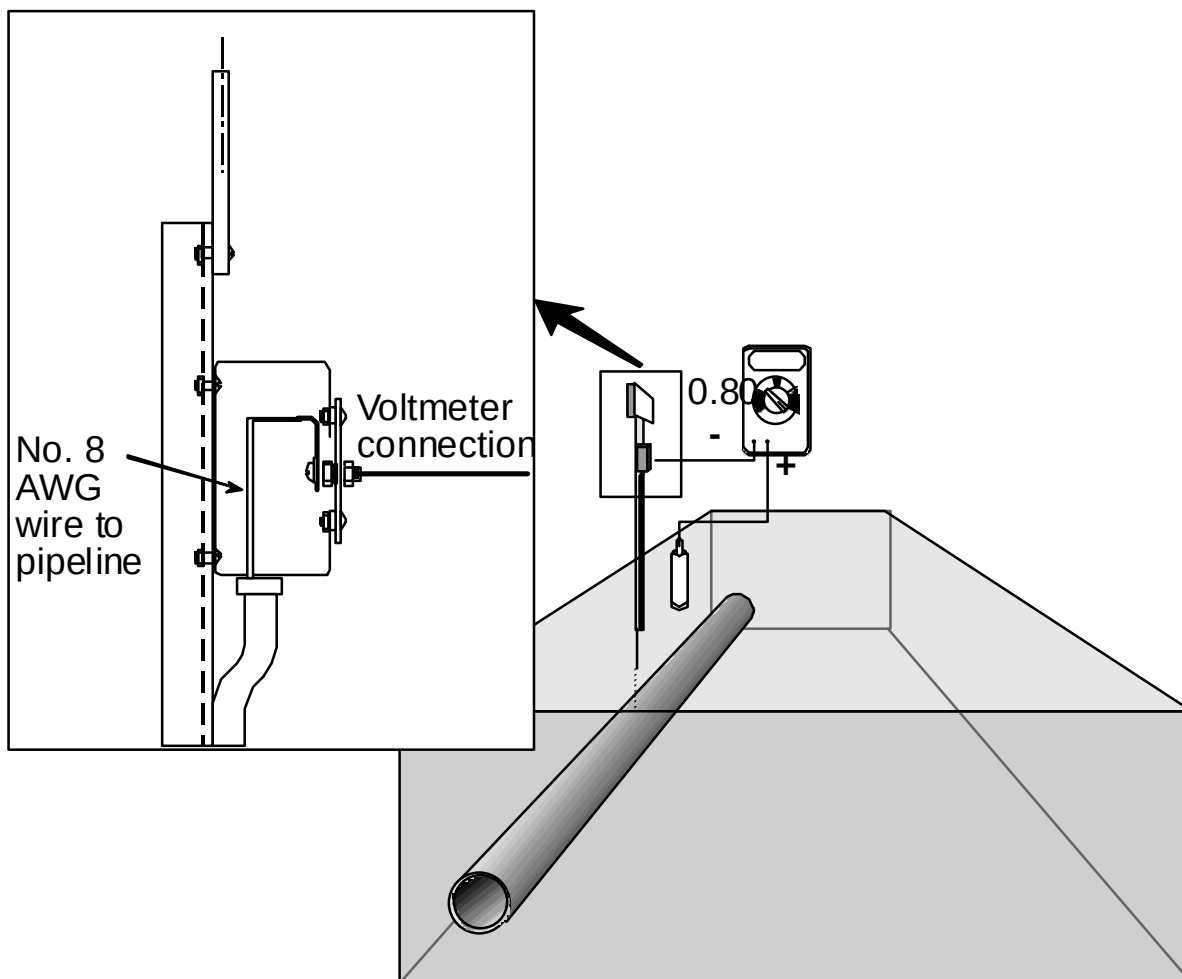


5-Terminal Junction Box, Standard Drawing AA-036274

Figure 9

Test Stations - A test station is a test point for measuring pipe-to-soil potential. It contains a lead wire which is thermite brazed to the pipeline. Saudi Aramco requires potential test stations at each kilometer marker of a pipeline, insulated cased crossing, major road crossing, and other locations as needed.

Figure 10 shows a typical one pin test station for a buried galvanic anode system. The pipe-to-soil potential is measured using a voltmeter and a Cu-CuSO₄ reference electrode.



Test Station Details, Standard Drawing AA-036907

Figure 10

Applications of Galvanic Anode Systems

Advantages and Disadvantages of Galvanic Anode Systems

Galvanic anode systems are used when current requirements are low. The main advantages of galvanic anode systems are as follows:

- An external power source is not required.
- Installation costs are low for new structures.
- Maintenance costs are low.
- Sacrificial anodes seldom cause interference problems with other structures.

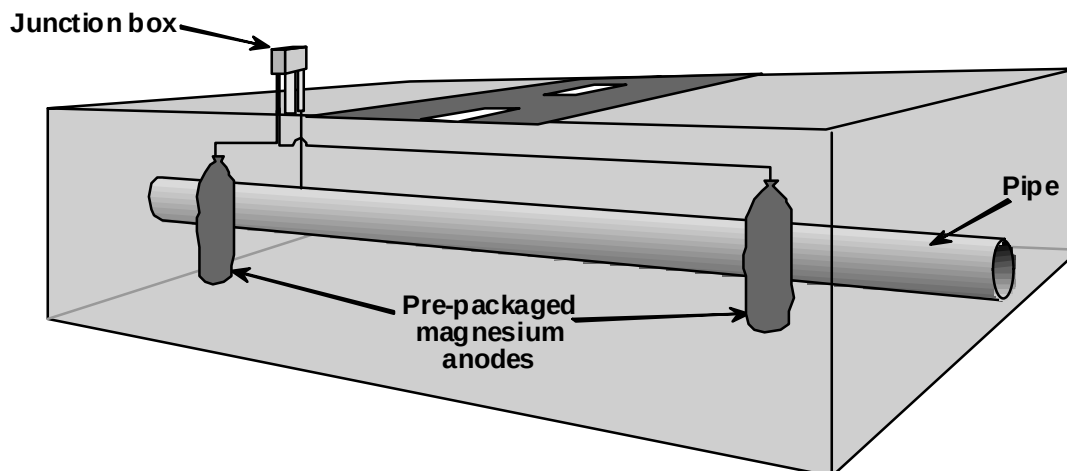
The main disadvantages are as follows:

- The driving potential is limited.
- The current output from individual anodes is low and limited.
- Sacrificial anodes are effective in a limited range of soil resistivities.

The following information discusses various applications of galvanic anode systems.

Buried Pipeline Applications

Saudi Aramco uses galvanic anodes to protect mainline valves, road and camel crossings, and short sections of pipelines that are not part of an impressed current system. Figure 11 shows how pre-packaged, 27.3 kg (60 lb) magnesium anodes are often used to protect pipelines under roads or camel crossings. In Subkha, bare 45.5 kg (100 lb) magnesium anodes are used. Except in Subkha, magnesium anodes are rarely effective beyond 10 meters.



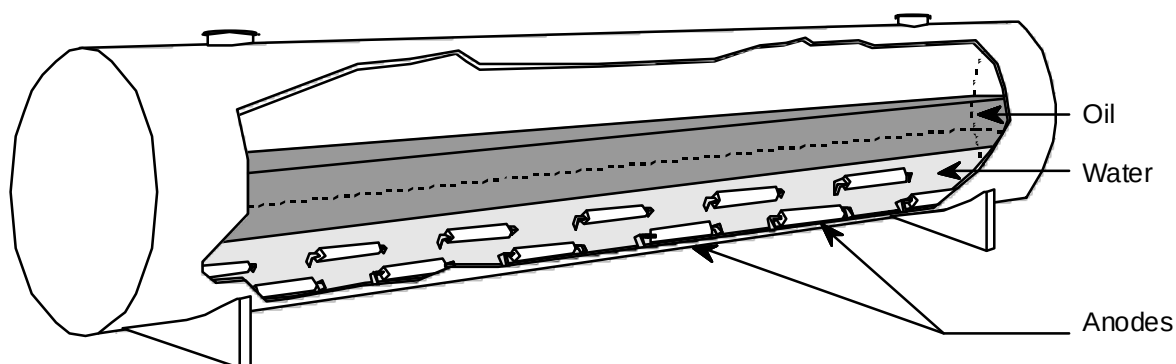
Magnesium Anodes at a Road Crossing, Standard Drawing AA-036352

Figure 11

Vessel and Tank Interior Applications

Produced brine can cause severe corrosion problems inside oil field production vessels such as free water knock outs, desalters, and separators. Cathodic protection can increase the service life of these vessels. Current density requirements range from 3 mA/m^2 for coated vessels to 30 mA/m^2 for uncoated vessels. An anode, however, can only protect the surfaces that it can "see." Consequently, the number of anodes required is usually determined more by vessel geometry and current distribution than by current requirements.

Saudi Aramco uses Hydral 2B galvanic anodes to protect water-wet areas inside production and process vessels. Figure 12 shows a low pressure production treater (LPPT) which contains several Hydral anodes in its water section. The anodes are attached to the vessel wall with brackets. The brackets also hold the anodes above any sludge that may settle on the bottom.

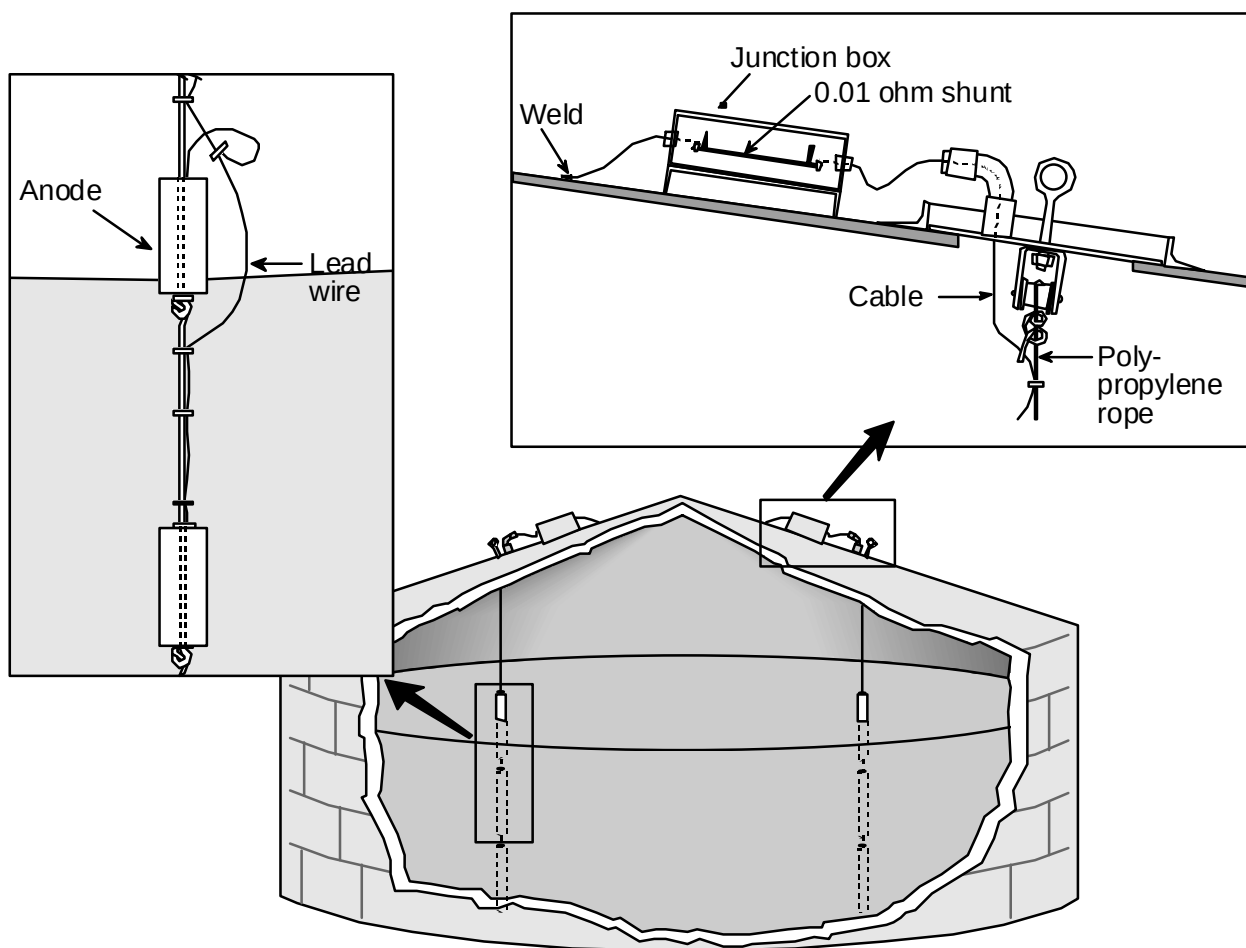


Galvanic Anodes in the Water Section of a LPPT

Figure 12

The efficiency of aluminum anodes in dehydrators is approximately 18%. In desalters, aluminum anode efficiency is less than 50%.

Saudi Aramco mainly uses magnesium and aluminum galvanic anode strings to protect the interior of water tanks (Figure 13). The lead wires from each string are connected to the exterior of the tank via a junction box. Each junction box contains a 0.01 ohm shunt which is used to measure the current output of the anode string. Magnesium anodes are not used if water resistivity is less than 500 ohm-cm. Aluminum anodes are not used if water resistivity is more than 1000 ohm-cm. Mercury-activated aluminum and zinc anodes are not used in potable water tanks because of health concerns. Firewater tanks in remote areas are generally regarded as potable because of local practice.



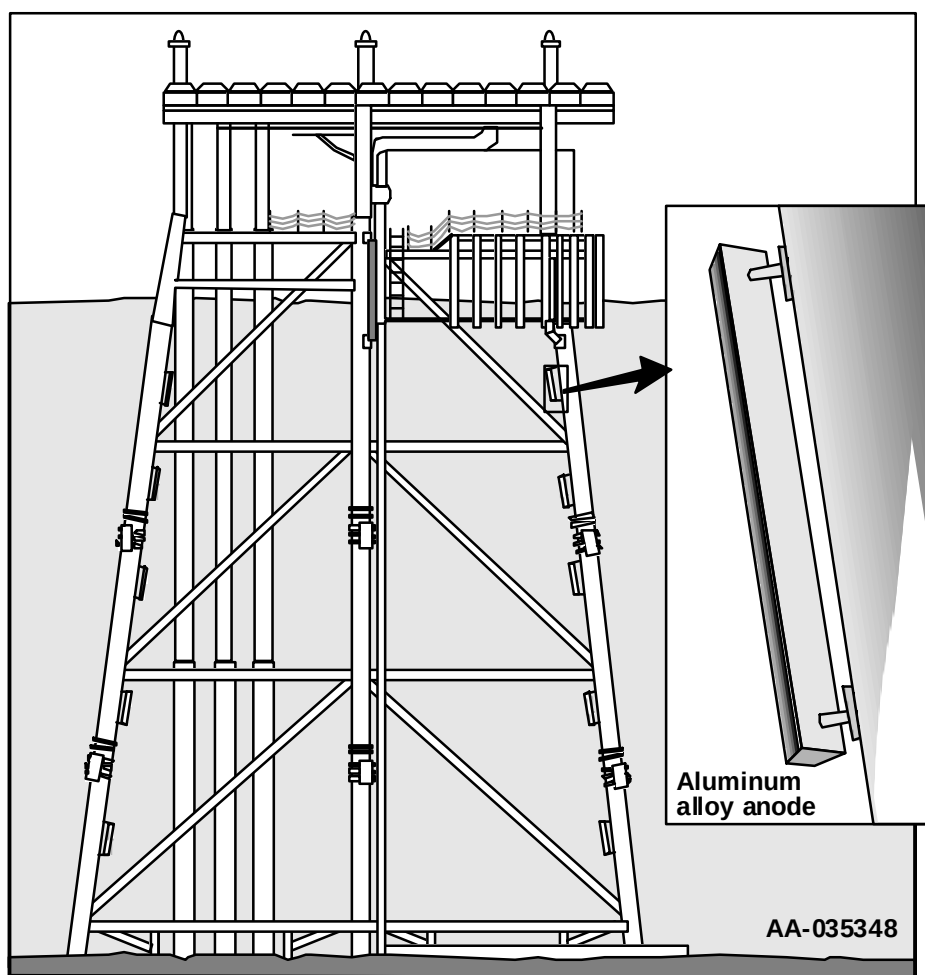
Galvanic Anodes in a Water Storage Tank, Standard Drawing AA-036354

Figure 13

Marine Applications

Saudi Aramco cathodically protects offshore platforms, subsea pipelines, breasting dolphins, and loading and mooring buoys. Galvanic systems are used on most marine structures. Marine galvanic anodes are usually indium doped aluminum alloys or zinc-tin doped aluminum alloys.

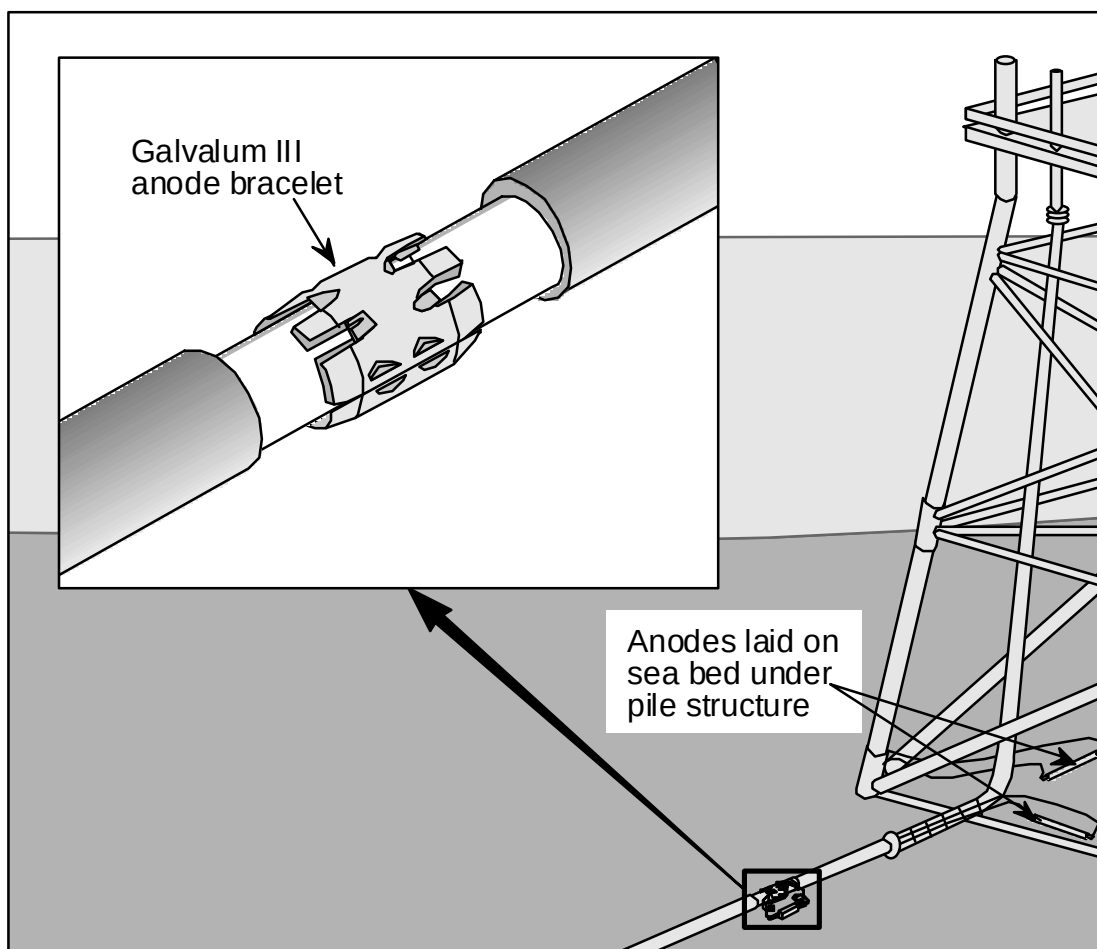
Saudi Aramco's objective is to quickly polarize offshore platforms to a minimum of 0.90 volt versus a silver/silver chloride half-cell. This has two advantages. First, little corrosion occurs. Second, chemical reactions at the cathode form a protective calcium carbonate scale. Scale reduces current requirements and allows current to reach metal surfaces further from the galvanic anode. Figure 14 shows aluminum alloy anodes on an offshore platform. Offshore platforms have several thousand meters of surface area and require many anodes. The anodes are positioned to completely protect the structure.



Marine Aluminum Alloy Galvanic Anodes, Standard Drawing AA-036348
Figure 14

There are two ways to cathodically protect a subsea pipeline. It can be electrically connected to a platform and share the platform's CP system, or it can be electrically isolated from the platform and have its own CP system. Saudi Aramco connects subsea pipelines to platforms so that they become part of the platforms' CP system. The purpose of this connection is to eliminate possible interference effects from impressed current systems.

Saudi Aramco also installs Galvalum III bracelet type anodes at intervals along subsea pipelines. This provides good current distribution along the pipeline and reduces the current requirements from the platform's CP system. Figure 15 shows a Galvalum III anode bracelet on a subsea pipeline. Normally, anode bracelets are installed on joints of pipe onshore and welded into the pipeline before going into the water from the lay barge.



Galvalum III Anode Bracelet on a Subsea Pipeline, Standard Drawing AA-036336

Figure 15

CALCULATING GALVANIC ANODE DRIVING POTENTIAL

Many galvanic anodes may be required to generate the amount of current needed to protect a portion of a structure. According to Ohm's Law, the amount of current generated by the galvanic anode system is determined by the following formula:

$$I = E/R_C$$

where -

E = the potential difference between the anode and structure
 R_C = the circuit resistance of the system

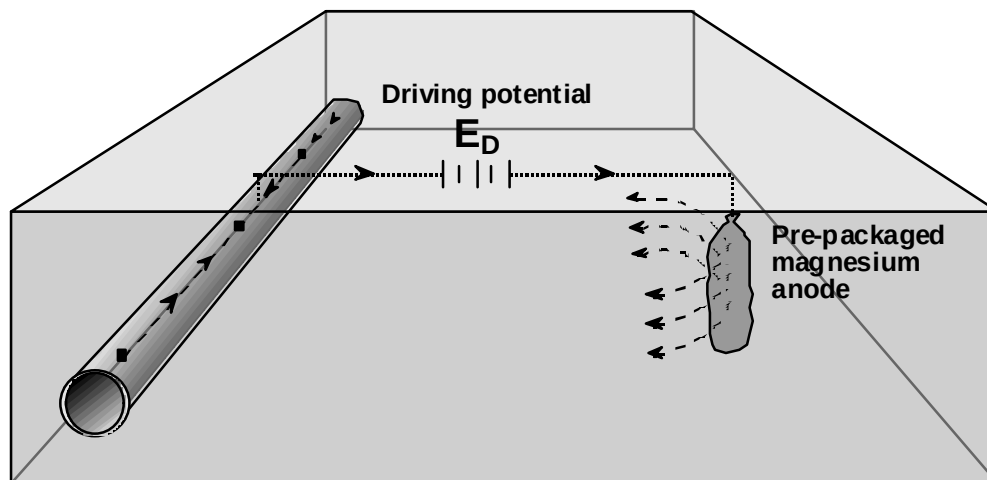
The potential difference between an anode and a structure is calculated as follows:

$$E = E_A - E_S$$

where -

E_A = the solution potential of the anode material
 E_S = the structure-to-electrolyte potential

For design purposes, we substitute the desired protected potential of the structure for E_S in the formula above. The anode's solution potential minus the protected potential of the structure is called the driving potential of the anode, E_D (Figure 16). The data and procedure used to calculate driving potential are provided in Work Aid 1.



Representation of the Driving Potential of a Galvanic Anode

Figure 16

$$E_D = E_A - E_p$$

where -

E_A	=	the solution potential of the anode material
E_p	=	the protected potential of the structure

Example

The following example will demonstrate how to calculate the driving potential of a standard magnesium galvanic anode that will protect a section of pipeline under a road crossing.

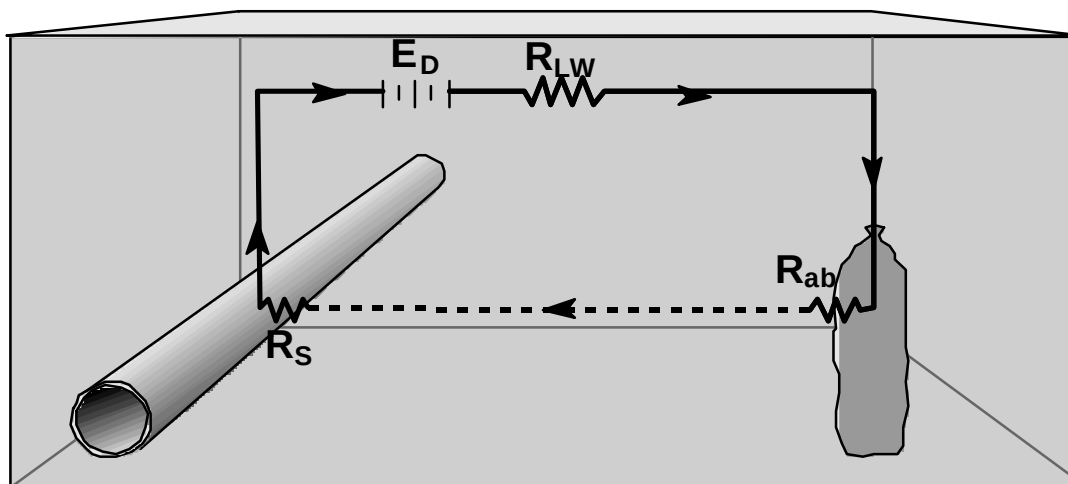
$E_D = E_A - E_p$ - magnesium polarization potential

$$E_D = -1.55 \text{ V} - (-1.20 \text{ V}) - (-0.10 \text{ V}) = -0.25 \text{ V versus Cu-CuSO}_4$$

For design calculations, we will use the absolute value, 0.25 V.

CALCULATING CIRCUIT RESISTANCES OF GALVANIC ANODE SYSTEMS

The anode current output is also a function of the resistance in the galvanic anode system. If we represent a galvanic anode system as an equivalent electrical circuit, we can determine the resistance in the circuit. Figure 17 is a representation of a galvanic anode system as an equivalent electrical circuit. The equivalent circuit includes the driving potential of the anode material, E_D , and the resistances of the circuit elements. For example, there is resistance in the anode lead wires. There is also resistance between the structure and the soil and resistance between the anode(s) and the soil.



Representation of a Galvanic Anode System as an Equivalent Circuit
Figure 17

We can calculate the total circuit resistance using the formula:

$$R_C = R_S + R_{LW} + R_{ab}$$

where -

- R_C = circuit resistance
- R_S = the resistance between the structure and the electrolyte
- R_{LW} = the resistance in the lead wire
- R_{ab} = the total anode bed resistance

The following information describes the circuit resistance elements above.

Circuit Resistance, R_C

The amount of current that flows from the anode bed is determined by the resistance of the system, or circuit resistance. For design purposes, the circuit resistance, R_C , must not exceed the maximum allowable circuit resistance. The maximum allowable circuit resistance is the anode driving potential, E_D , divided by the required current. The relationship between the circuit resistance and the maximum allowable circuit resistance is as follows:

$$R_C \leq R_{\max} = E_D / I$$

where -

E_D = the driving potential of the galvanic anode material (volts)
 I = the current required to protect the structure (amperes)

Structure-to-Electrolyte Resistance, R_S

The resistance to earth of the structure can be determined from current requirement test data. This resistance mainly depends on the quality of the coating. The better the coating, the higher the structure-to-electrolyte resistance. Calculate the structure-to-electrolyte resistance using the formula

$$R_S = (V_{\text{on}} - V_{\text{off}}) / I_{\text{on}}$$

where -

V_{on} = the structure-to-electrolyte potential with the current on
 V_{off} = the structure-to-electrolyte potential with the current off
 I_{on} = current applied to give the potential V_{on}

Lead Wire Resistance, R_{LW}

You can calculate lead wire resistance, R_{LW} , by multiplying the length of the conductor (in meters) by its characteristic resistance (in ohms per meter). A resistance table for copper conductors is provided in Work Aid 2. For a single anode that is close to a structure (less than 5 meters), the cable resistance can usually be ignored.

Total Anode Bed Resistance, R_{ab}

The total anode bed resistance, R_{ab} , depends on the soil resistivity, the dimensions of the anodes or backfill, and the orientation of the anodes. These design factors will be covered in detail in Module 107.03. At this point, it is easier to determine the allowable resistance for a galvanic anode bed, R_{aab} . The *allowable anode bed resistance* is the difference between the maximum allowable circuit resistance, R_{max} , and the sum of the remaining resistances. The relationship between R_{ab} and R_{aab} is as follows:

$$R_{ab} + R_{aab} = R_{max} - (R_s + R_{LW})$$

Example

The following example demonstrates how to calculate the allowable circuit resistance of ten high potential magnesium galvanic anodes that will protect 75 meters of 91.4 cm (36") diameter pipe. Assume that the current required to shift the pipeline potential from -0.75 V to -1.20 V versus Cu-CuSO₄ was determined to be 300 mA. Assume that No. 8 lead wire is used from the pipe to the junction box which is 15 meters away.

First, the structure-to-soil resistance is calculated as follows:

$$R_s = \frac{(-1.20 - (-0.75)) \text{ V}}{0.300 \text{ A}} = 1.5 \text{ ohms}$$

Next, calculate the lead wire resistance as follows:

$$R_{LW} = [15 \text{ m} + (10\%)(15 \text{ m})] [2.15 \times 10^{-3} \text{ ohm/m}] = 0.035 \text{ ohms}$$

The maximum circuit resistance is calculated as follows:

$$R_{max} = E_D/I = [-1.80 \text{ V} - (-1.20 \text{ V}) - (-0.10 \text{ V})]/0.300 \text{ A} = 1.67 \text{ ohms}$$

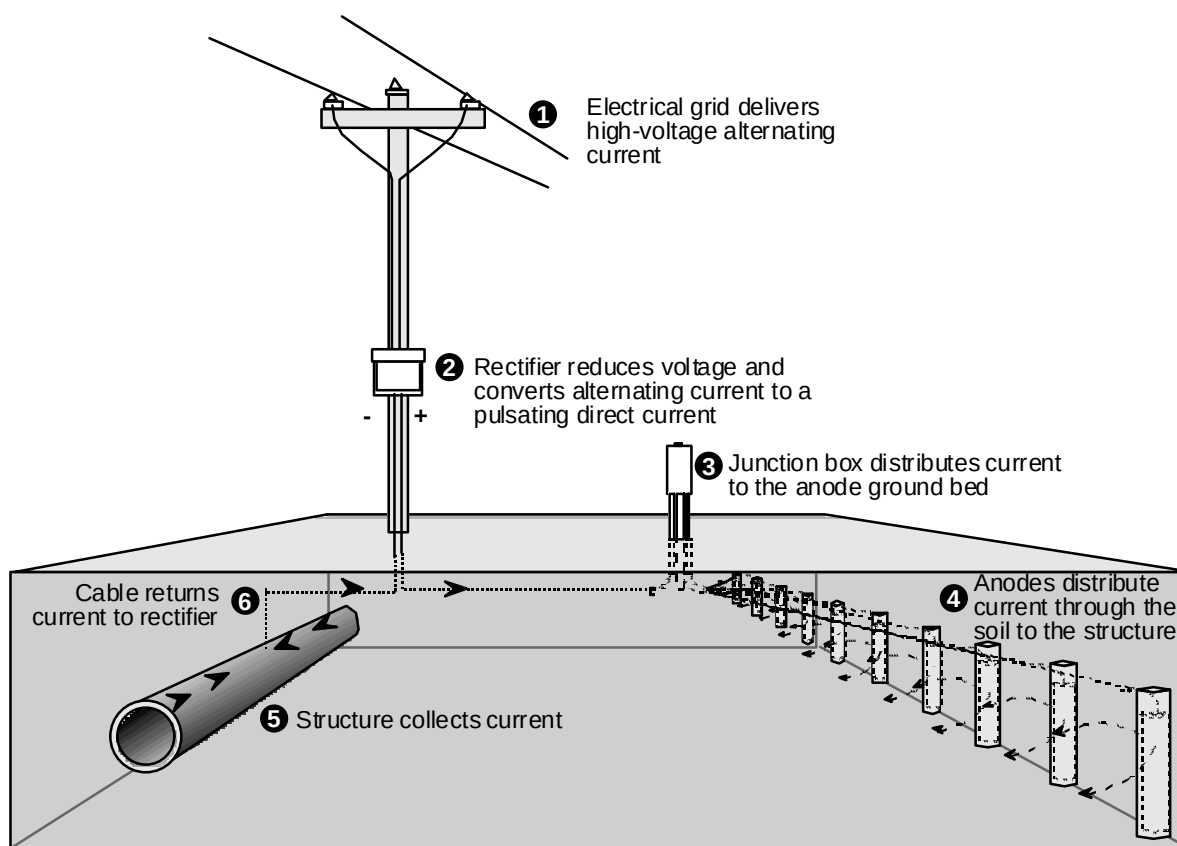
Therefore, the allowable anode bed resistance is

$$R_{aab} = R_{max} - (R_s + R_{LW}) = 1.67 - (1.5 + 0.035) = 0.135 \text{ ohm}$$

Operation and Applications of Impressed Current Systems

Operation of Impressed Current Systems

When current requirements are high, Saudi Aramco cathodically protects structures with impressed current (IC) systems. The operation of a typical IC system is shown in Figure 18. An electrical grid supplies high-voltage alternating current to a rectifier. The rectifier reduces the voltage of the alternating current and converts it to a pulsating direct current. The direct current goes from the positive terminal of the rectifier to a junction box. At the junction box, the current is distributed to an anode bed of impressed current anodes. The anodes drive, or impress, the current into the earth. The current migrates through the earth and enters the structure. The current returns to the negative terminal of the rectifier via a cable which is connected to the structure.



Typical Rectifier Impressed Current System

Figure 18

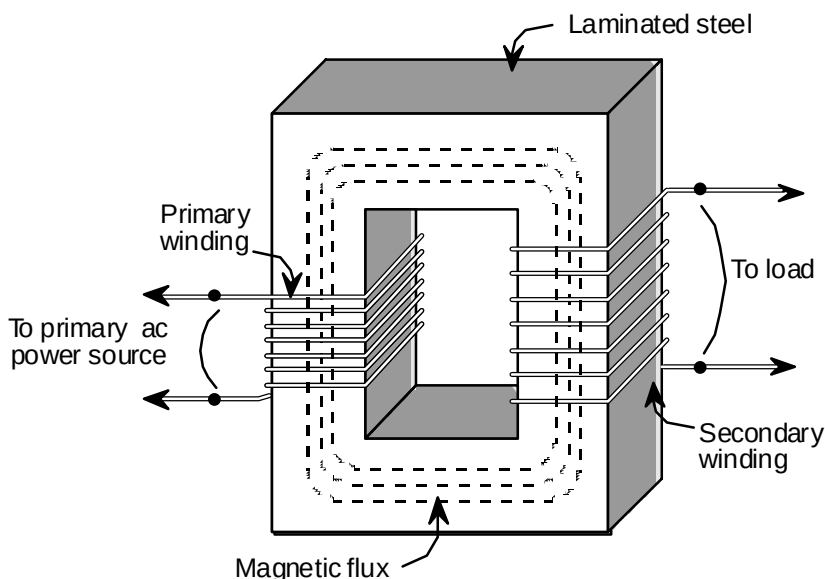
The following information describes the operation of impressed current system components in more detail.

Direct Current Power Sources

Saudi Aramco uses three types of direct current (dc) power sources--rectifiers, solar power systems, and engine generators. These dc power sources are described below.

Rectifiers - Electrical transmission systems supply high-voltage single phase or three-phase alternating current (ac). Rectifiers step down the voltage of the current and convert the alternating current to direct current.

A rectifier contains a transformer and several rectifying elements. The transformer steps down the voltage of the alternating current. A representation of a single phase transformer is shown in Figure 19. A single-phase transformer contains a primary winding and a secondary winding around a closed iron core. The primary winding receives voltage from the ac power source. This creates an alternating magnetic field, or flux, in the iron core. The amount of flux depends on the voltage and the number of turns in the winding.



Single-Phase Transformer

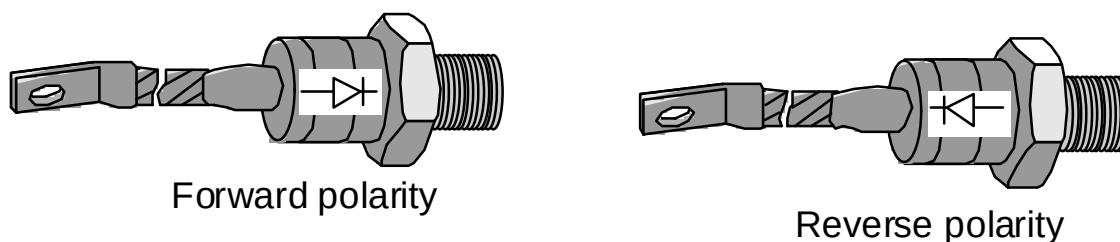
Figure 19

The magnetic flux induces a voltage in the secondary winding. The secondary winding is connected to the load. The load is the total resistance in the impressed current system.

The voltage in the secondary winding can be adjusted using connection points called "taps." Changing the tap connections changes the output voltage of the rectifier. Taps are used to make coarse and fine output voltage adjustments.

Alternating current from the secondary winding fluctuates between positive and negative values. The usual 60 cycle alternating current changes direction (reverses polarity) 120 times per second. Rectifying elements convert this alternating current to a pulsating direct current. Selenium cells and silicon diodes are both widely used as rectifying elements. Selenium cells are adversely affected by high ambient temperatures. Therefore, Saudi Aramco only uses silicon diodes.

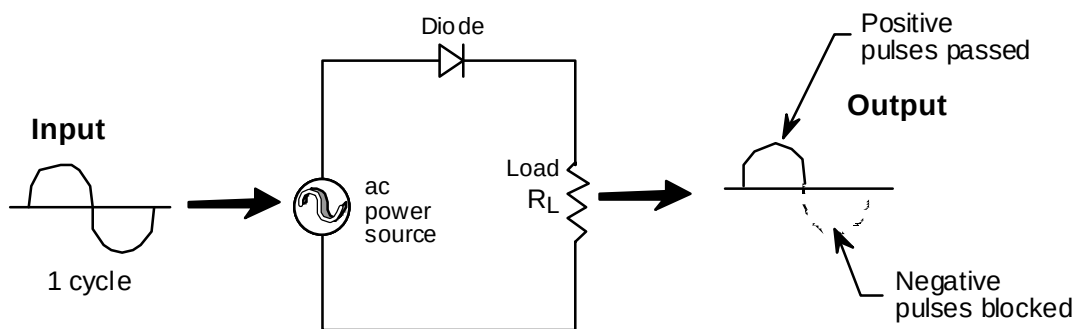
Figure 20 is a diagram of a silicon diode. Diodes have forward resistance that varies from 1 to 10 ohms and reverse resistance in hundreds of megohms. This allows current to flow smoothly in one direction but prevents current flow in the opposite direction. The arrowhead shows the direction in which positive current can easily flow.



Silicon Diodes

Figure 20

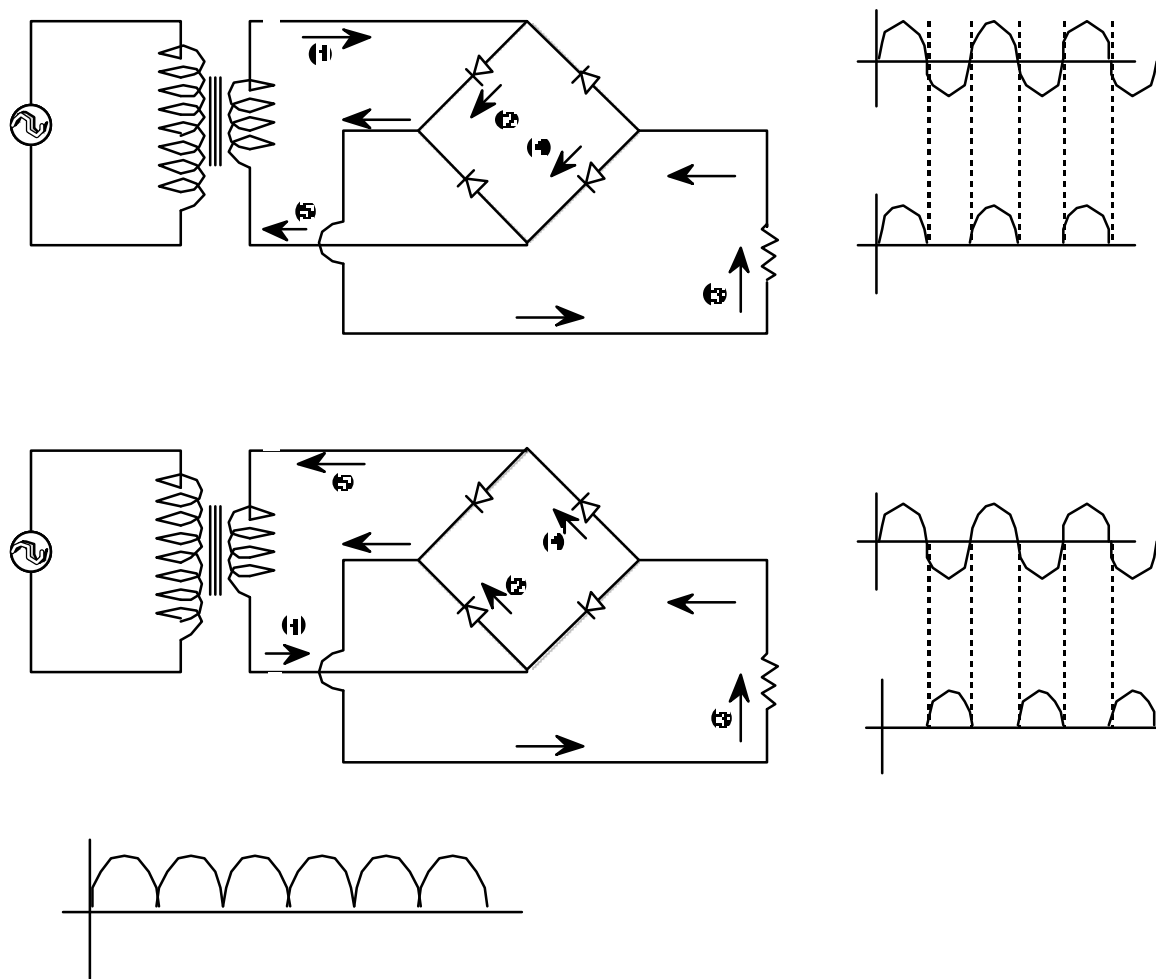
If a diode is connected in an ac circuit as shown in Figure 21, the diode allows only the positive fluctuations to pass to the load. The negative fluctuations are eliminated. The magnitude of the current varies from zero to some positive value and back to zero. The wave never goes negative so it is called pulsating dc.



A Silicon Diode in an AC Circuit

Figure 21

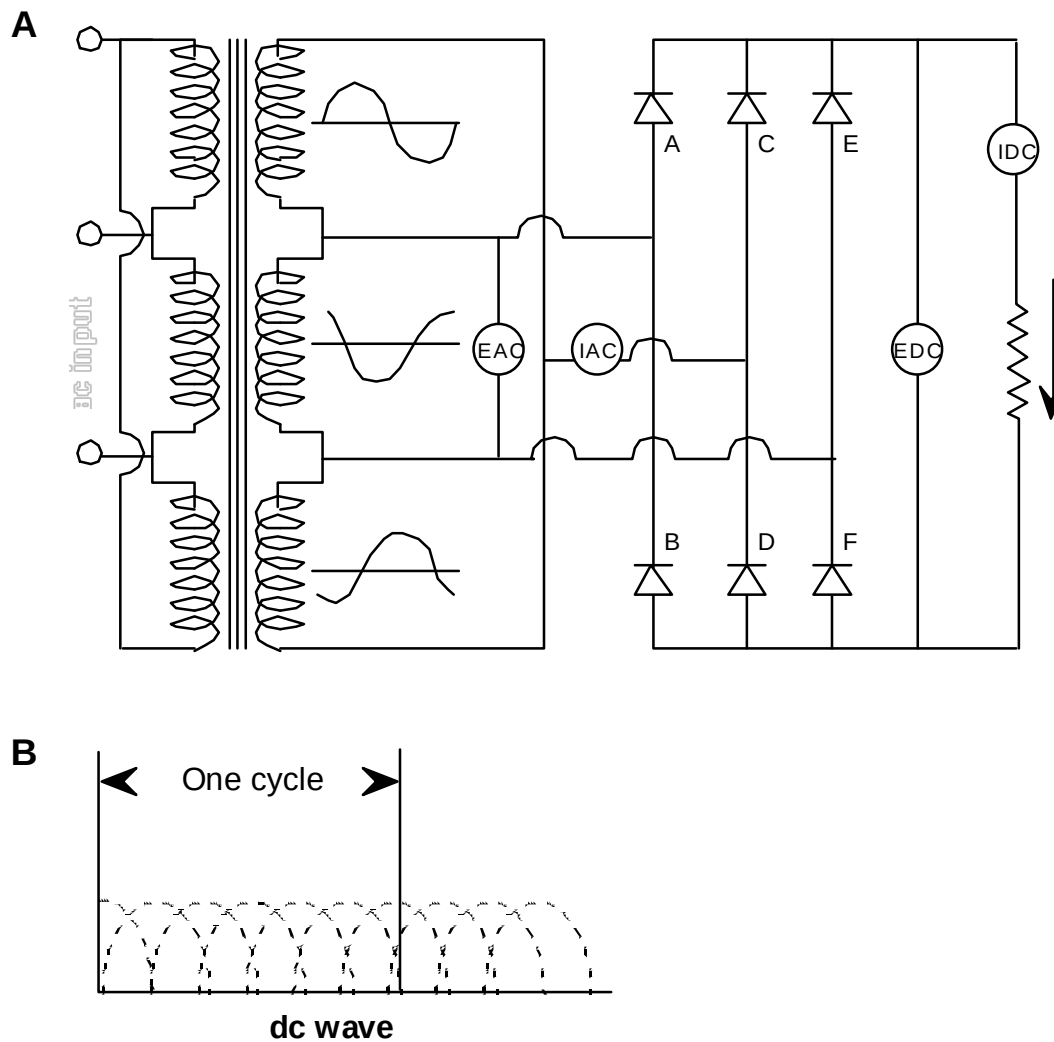
The diode in the previous figure only allowed half of the initial ac energy to reach the load. This is called half-wave rectification. The single-phase bridge rectifier in Figure 22 provides full-wave rectification. Figure 22A shows the first half cycle of the alternating current. Diodes D_1 and D_4 are in series and diodes D_2 and D_3 are reverse biased. The current originates at positive terminal T_1 on the secondary winding. D_3 blocks the current but the current flows through D_1 and through the load. Current then flows through D_4 and back to the negative transformer terminal T_2 . This results in a pulse across the load as shown on the right of Figure 22A. The frequency of pulses across the load is called the ripple frequency.



Operation of a Single-Phase Bridge Rectifier
Figure 22

During the next half cycle, the polarity of the secondary winding reverses (Figure 22B). Current originates at the positive terminal T_2 . Diode D_4 now blocks the current but diode D_2 lets current pass. The current flows through the load in the same direction as before. This allows the load to receive continuous pulses of energy over the whole cycle as shown in Figure 22C.

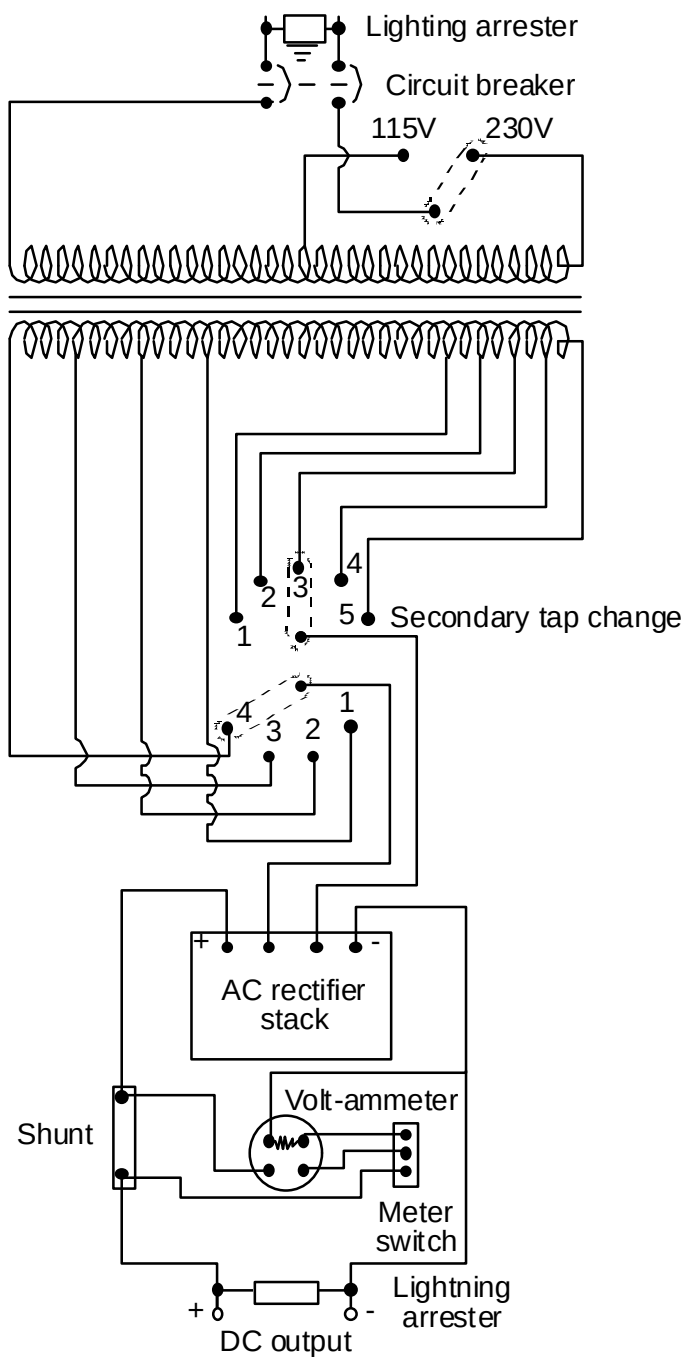
The three-phase bridge in Figure 23A is the most common rectifier circuit when three-phase power is available. Each phase of a three-phase alternating current is spaced 120 electrical degrees apart. Therefore, the voltage of each secondary winding reaches its peak at a different time.



Schematic of a Three-Phase Bridge Rectifier
Figure 23

The three-phase rectifier circuit contains three bridges. Each bridge shares a pair of diodes with one of the other bridges. Six times per second (twice for each bridge) current passes through the load. This results in a more constant direct current output from the rectifier (Figure 23B).

Figure 24 shows other useful components inside rectifiers. Lightning arrestors are installed on the input and output. They protect sensitive components, especially diodes, from high voltage surges caused by lightning. Circuit breakers are placed on the ac power inlet for overload protection and to allow a person to turn the unit on and off.

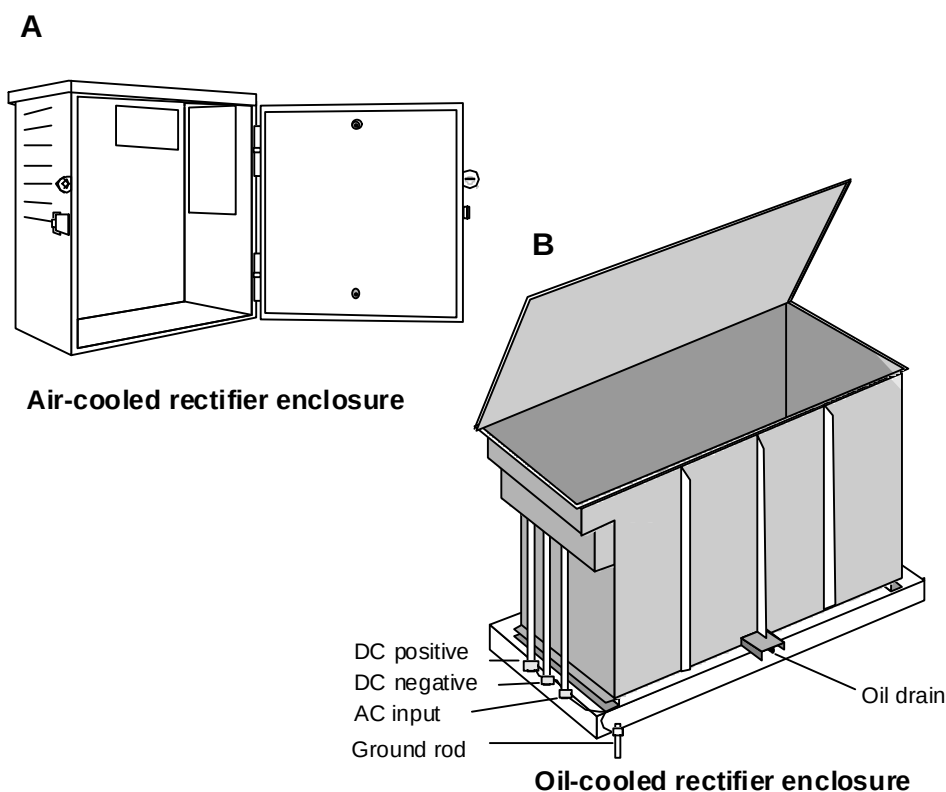


Schematic of a Typical Single-Phase Rectifier

Figure 24

The transformer and rectifier elements generate heat inside a rectifier cabinet. This heat must be dissipated for the rectifier to work properly. Two methods are used to cool rectifiers--air cooling and oil immersion.

In air-cooled rectifiers, the transformer windings and diode heat sinks are surrounded by ambient air. Heat is removed by natural convection of the surrounding air through holes and louvers in the metal housing (Figure 25A). Heat also radiates from different parts of the rectifier. Air-cooled rectifiers are usually mounted on a pole. They are cheaper than similarly rated oil-cooled units.



Air-Cooled and Oil-Cooled Rectifier Enclosures

Figure 25

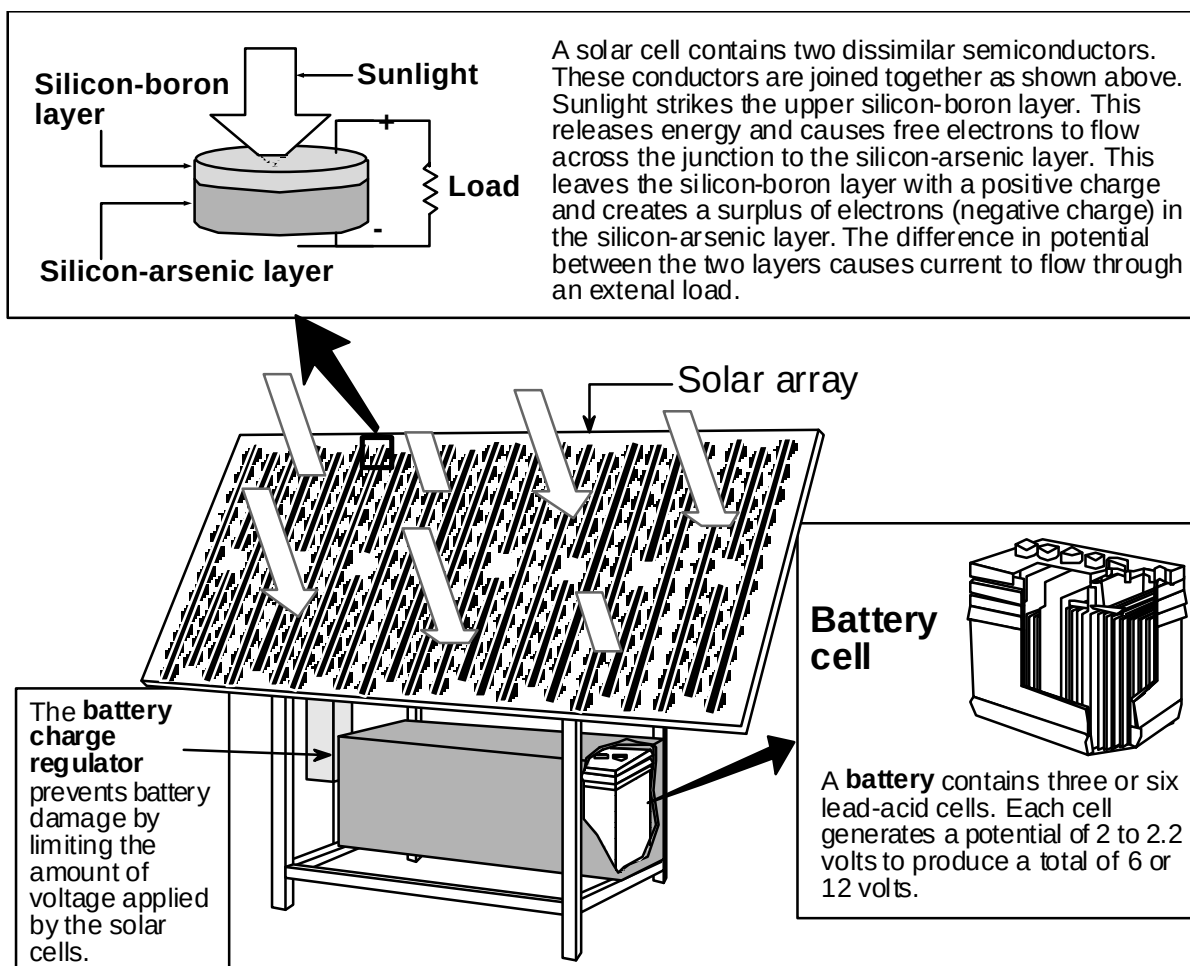
Oil-immersed rectifiers (Figure 25B) are used if corrosive or explosive vapors are present. Oil-immersed rectifiers are often required for dusty areas, marine environments, and plant locations. Mineral oil is widely used in oil-immersed rectifiers. The oil transfers heat from interior elements to the exterior surface of the rectifier. Temperature differences cause oil to circulate in the cabinet by natural convection. The warm oil expands and becomes lighter. It rises to the top and releases excess heat. As the oil cools, it becomes heavier and sinks to the bottom of the cabinet. Then the heat exchange cycle begins again. Oil also insulates the transformer windings from each other and from the core material.

Constant Current Rectifiers - Saudi Aramco uses constant current rectifiers when the circuit resistance varies significantly. This can occur when an environment is subject to wide variations (e.g., wet to dry). A constant current rectifier maintains the output current at a desired level regardless of changes in the circuit resistance.

Constant Potential Rectifiers - The current requirements of structures may change over time. For example, a newly installed well-coated pipeline may require a small amount of current initially. However, it may require much more current as the coating deteriorates. Constant potential rectifiers may be used in such situations. A constant potential rectifier changes its output to match the current requirements of the structure. This change in output allows the rectifier to maintain a constant protective potential on the structure.

Typically, this change is accomplished in the following manner. A reference electrode is buried at a point on the structure where constant potential is required. Leads from the reference electrode and structure are connected to a magnetic amplifier or equivalent circuitry. The amplifier sends a signal to a device that adjusts the output voltage of the rectifier. Initially, the rectifier is set for the desired structure-to-electrolyte potential. Any increase or decrease in this potential will cause the reactor to adjust the current output of the rectifier.

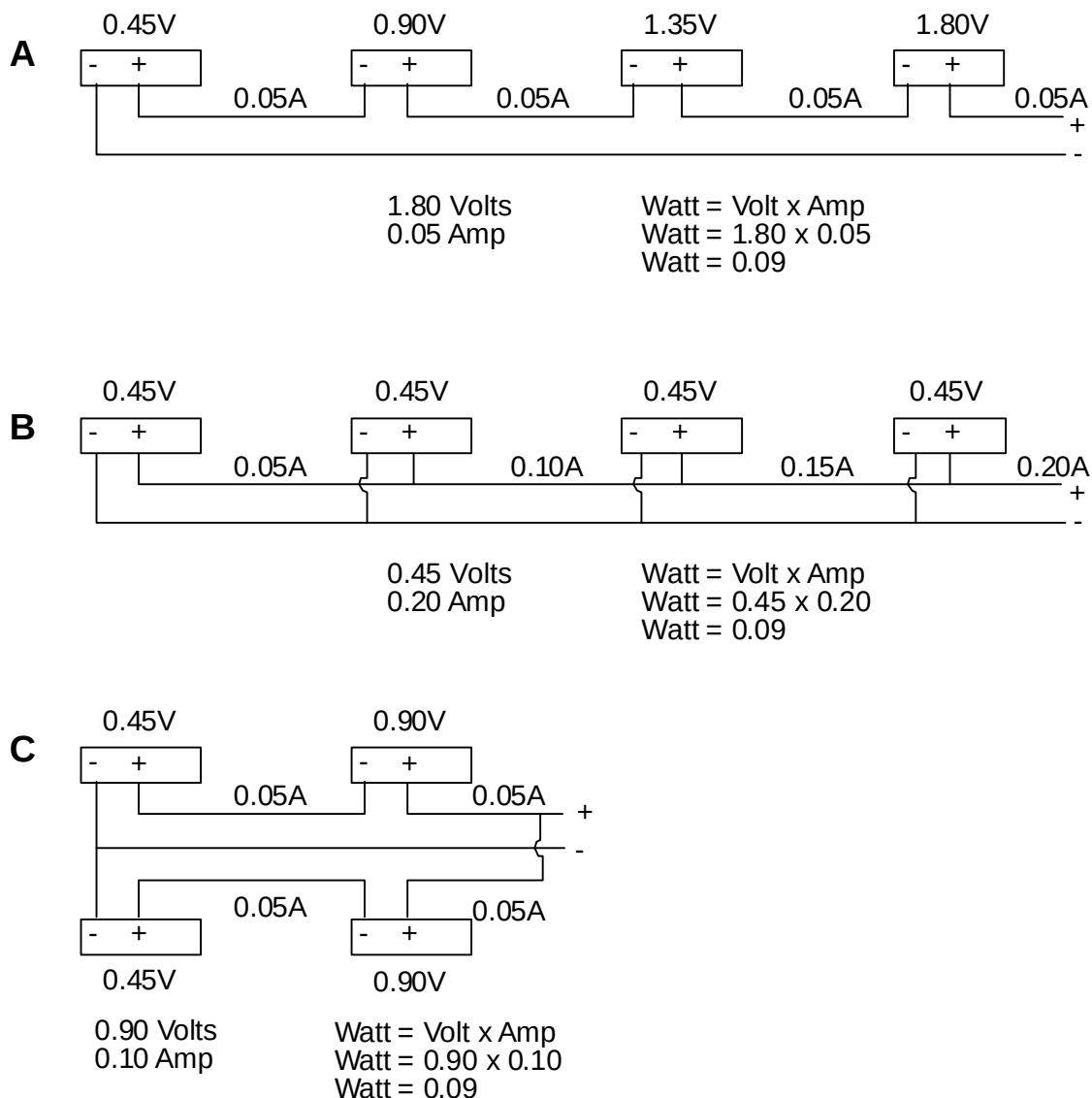
Solar Power Systems - There are many remote areas where alternating current is not available. Saudi Aramco uses solar power systems in these areas when it is more economical than extending power lines and installing rectifiers. Saudi Aramco sizes CP solar systems by using solar modules (Figure 26). Each module contains solar panels, rechargeable storage batteries, and a battery charge regulator. Each module can continuously deliver 10 amps of current at 6 volts dc.



Solar Module
Figure 26

Saudi Aramco uses rechargeable lead-acid storage batteries which are similar to automobile batteries. The batteries in each module can supply 1200 ampere-hours of current to the anodes. This is sufficient for five days without recharging. Batteries supply current to the impressed current anodes at night, during shamals, and on cloudy days. While the batteries are being charged, the solar panels apply current to the anodes.

The electrical output of a single solar cell depends on the intensity of the sunlight and the exposed area of the silicon-boron layer. Silicon crystals are usually three to four inches in diameter because it is very difficult to produce large crystals. The solar cells are connected in series to obtain the proper voltage or they are connected in parallel to obtain the needed current. This is shown graphically in Figure 27.



Series and Parallel Connection of Solar Cells

Figure 27

Engine Generators - Saudi Aramco also uses engine driven generators to provide power to impressed current anode beds. Remote areas of the East-West Pipeline and the QQ Pipeline are protected with engine driven impressed current systems.

Impressed Current Anodes

Saudi Aramco normally uses four types of impressed current anodes. These anodes are discussed below.

High silicon chromium cast iron anodes contain 14% to 15% silicon and about 5% chromium. High silicon cast chromium iron loses weight at a rate of 1.0 kg /A-year. It forms a stable amorphous hydrated oxide film that protects the anode surface and conducts electricity. High silicon chromium cast iron anodes are rated at a maximum current density of 1.0 mA/cm² in soils.

Scrap steel is sometimes used as impressed current anode material because it is abundant and inexpensive. Ordinary steel loses weight at the rate of 9.1 kg/A-year. However, the current discharge is seldom uniform. The area around the cable connection often corrodes rapidly; consequently, several cable connections are used. Scrap steel anodes perform erratically, and the anode bed life is fairly unpredictable. The suggested maximum current density of scrap steel is 0.5 mA/cm² in soil.

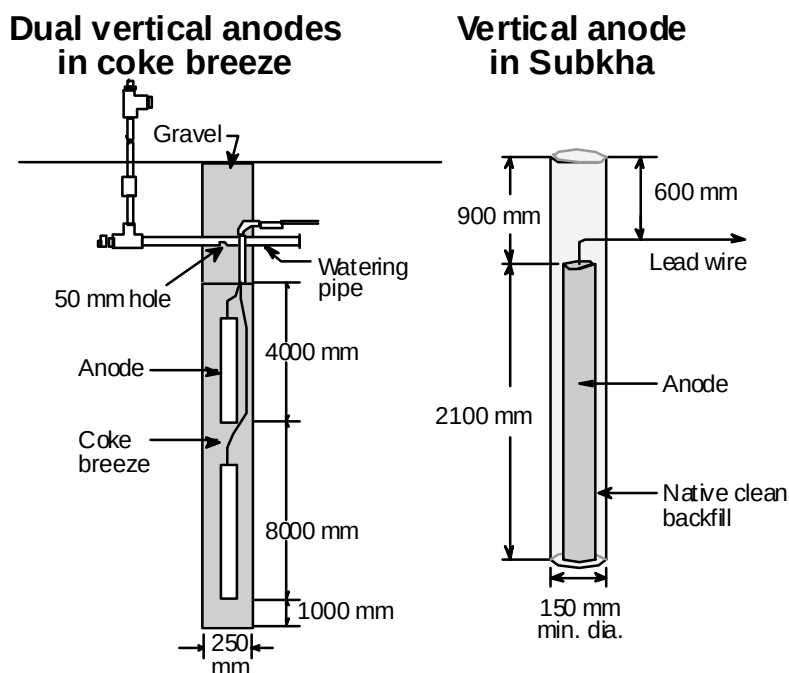
Mixed Metal Oxide Composite Anodes are used in soil and marine environments. Their major advantage is their small size and high current output compared to other impressed current anode materials. The consumption rate of mixed metal oxide composite anodes in soils is low (7 g/A-year). Their suggested current density is 10 mA/cm² in soils and 12.5 mA/cm² in seawater.

Platinized niobium anodes are used to protect offshore structures with high current requirements. Niobium alone is unsuitable as an anode material. Niobium forms very stable oxide films on its surface. These films have high chemical and electrical resistance. Therefore, niobium is plated with platinum or platinum alloys which form conductive oxide films. The niobium substrate maintains excellent chemical resistance while the platinum layer allows high current output with low consumption rates (8.63 x 10⁻⁶ kg/A-yr). The result is a more satisfactory anode.

Saudi Aramco no longer uses graphite anodes.

Functions of Major Components of Impressed Current Systems

Carbonaceous Backfill - Except for scrap steel, impressed current anodes in soil are usually surrounded with carbonaceous backfill. The carbonaceous backfill is usually calcined petroleum coke. It is sometimes called coke breeze. The particle size and resistivity of coke breeze are important factors. The maximum particle size should be 3/8 inch and the maximum dust content should be 10%. The resistivity should not exceed 50 ohm-cm. In Subkha soil, coke breeze does not improve anode output. The anode may be installed without coke breeze. However, the backfill must be oil-free. Oil has a very high resistivity so it may cause the anode to be consumed unevenly. Figure 28 is a diagram of dual vertical anodes in coke breeze backfill and a vertical anode in Subkha.



Dual Vertical Anodes in Coke Breeze Backfill and Vertical Anode in Subkha,
Standard Drawing AA-036346

Figure 28

Coke breeze serves two purposes.

1. It increases the effective size of the anode and lowers the anode-to-earth resistance.
2. It extends the life of the anode. Most of the current is transmitted from the anode to the coke. Most of the material consumed is at the outer edge of the backfill column.

Coke breeze consumption depends on good electrical contact between the anode and the backfill. The backfill must be packed solidly around the anode or much of the current will discharge directly from the anode. This reduces the life of the anode.

Cables and Lead Wires - Impressed current systems contain cables and lead wires. Cables electrically connect the following:

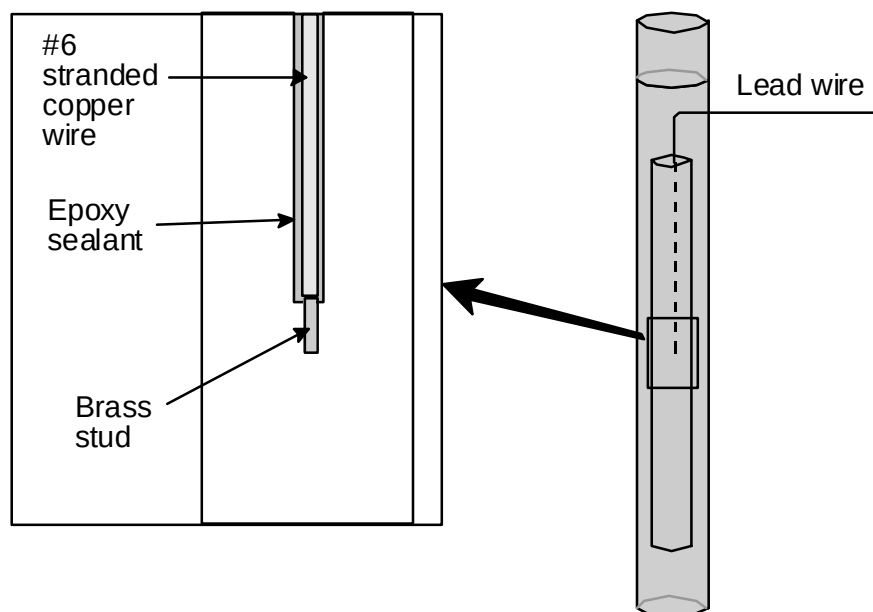
- the positive terminal of the dc power source to the anode junction box
- the junction box to the anode header cable or to additional junction boxes
- the structure to the negative terminal of the dc power source
- the structure to other protected or unprotected structures (bonding)

Lead wires electrically connect the following:

- individual anodes to the junction box or header cable
- pipelines to test stations

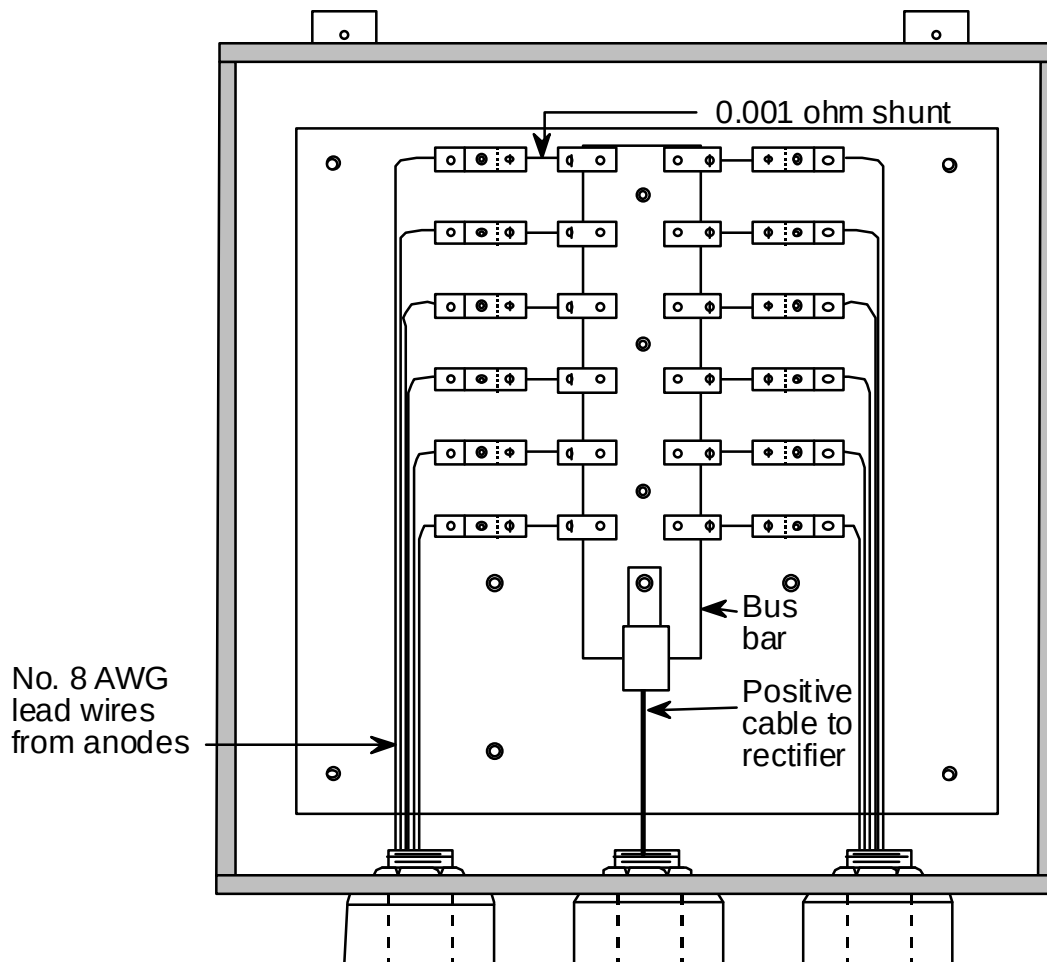
Anode lead wire and header cables have a positive potential with respect to the soil. If there are imperfections in their insulation, they will discharge current and be severed by corrosion. This will cut off current from all or part of the anode bed. All cables and wires should be surrounded with high quality insulation that has a minimum 600-volt rating. Saudi Aramco holiday tests all (+) cable before burial.

Lead wire is mechanically connected to the impressed current anode. Insulating materials are used to protect the connection from moisture penetration. Figure 29 shows a typical center-tapped graphite anode. Center-connections reduce the accelerated consumption of anode material usually seen at the ends of anode with end-type connections.



Center-Tapped Graphite Anode
Figure 29

Junction Boxes - A single cable goes from the positive terminal of the dc power source to a junction box as shown in Figure 30. The junction box is connected to the individual anode lead wires. A shunt is inserted in each anode lead wire inside the junction box. Saudi Aramco commonly uses 0.001 ohm (50 mV-50A) shunts. This allows the current output of each anode to be measured by determining the voltage drop across the shunt. For example, the current output of an anode with a voltage drop of 10 millivolts across a 0.001 ohm shunt is $0.01 \text{ volt} / 0.001 \text{ ohm} = 10 \text{ amperes}$.



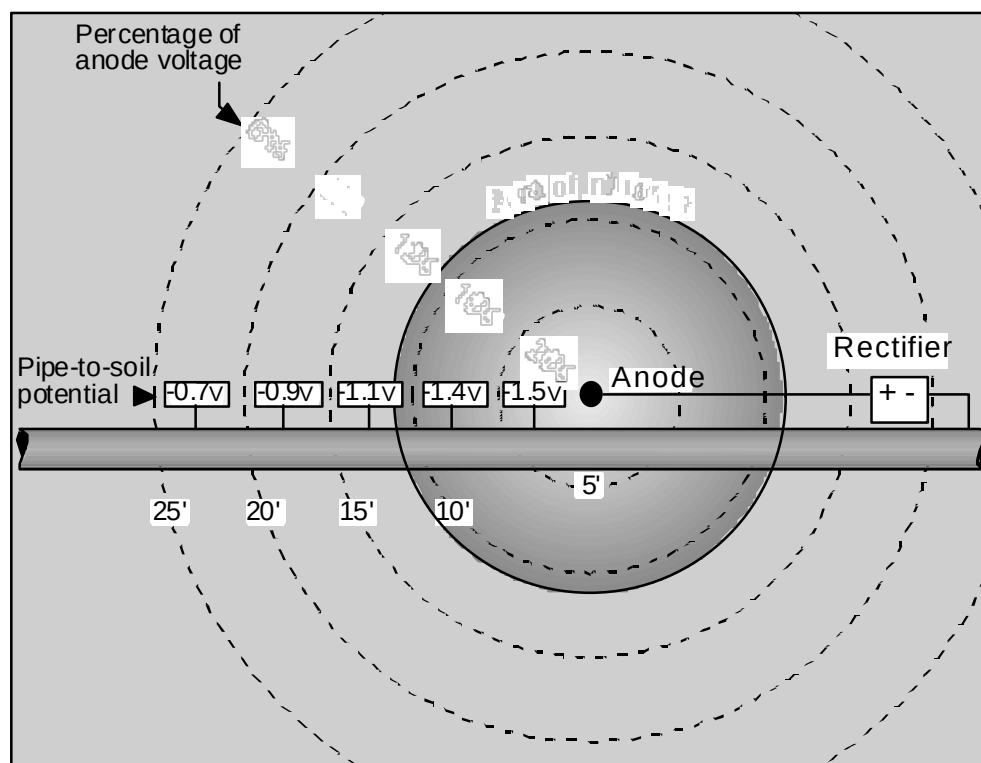
12-Terminal Junction Box, Standard Drawing AA-036275

Figure 30

Anode Beds

There are basically two types of anode beds--close and remote. The terms close and remote relate to the area of influence in the electrolyte around the anodes. The area of influence is the area in which cathodic protection is achieved.

Close anode beds are used to cathodically protect limited areas of metal structures (e.g., congested pipe in plants where metallic isolation cannot be achieved or is not allowed). A single close anode provides protection by making the earth positive with respect to the structure. Figure 31 shows a close anode next to a buried pipeline. The anode is located so that a small area of the structure is in the anode's area of influence.



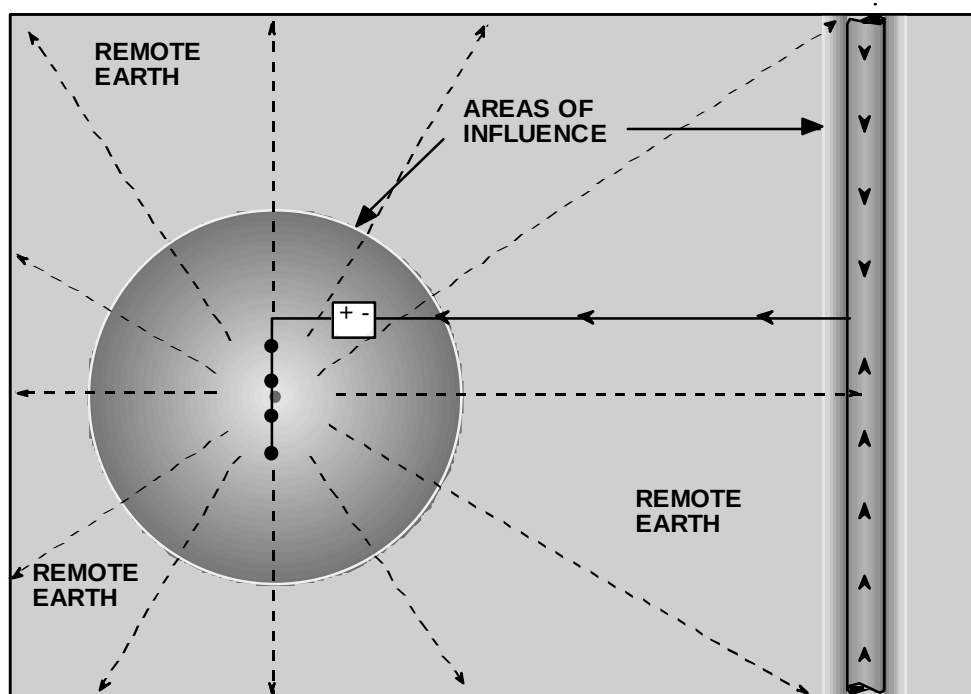
Area of Influence of a Close Anode (top view)

Figure 31

For a close anode, the amount of potential shift (and the length of pipeline that can be protected) is a function of the voltage impressed on the structure by the anode. The shaded area shows the area of influence in which the pipe-to-soil potential exceeds -1.2 volts versus Cu-CuSO₄. Close anode beds are also called distributed anode beds. Distributed anode beds are installed as surface anodes that are physically close to the structure.

Remote anode beds cathodically protect large areas of a structure. Both close and remote anode beds cause a change in the potential of the soil around them. This change in soil potential decreases with distance from the anode beds. The areas of influence of close and remote anode beds end where there is no longer a measurable change in the soil potential. Beyond this point is remote earth.

When current enters remote earth, there is no more resistance from the soil and no limit to how far the current can travel (Figure 32). When current travels through remote earth and enters a pipeline, it causes the potential of the pipeline to decrease. As the pipeline becomes more negative, cathodic protection results. This creates a second area of influence surrounding the pipeline as shown in the figure. If the area of influence around the anode bed does not significantly overlap the area of influence of the pipeline, the anode bed is said to be remote from the pipeline.



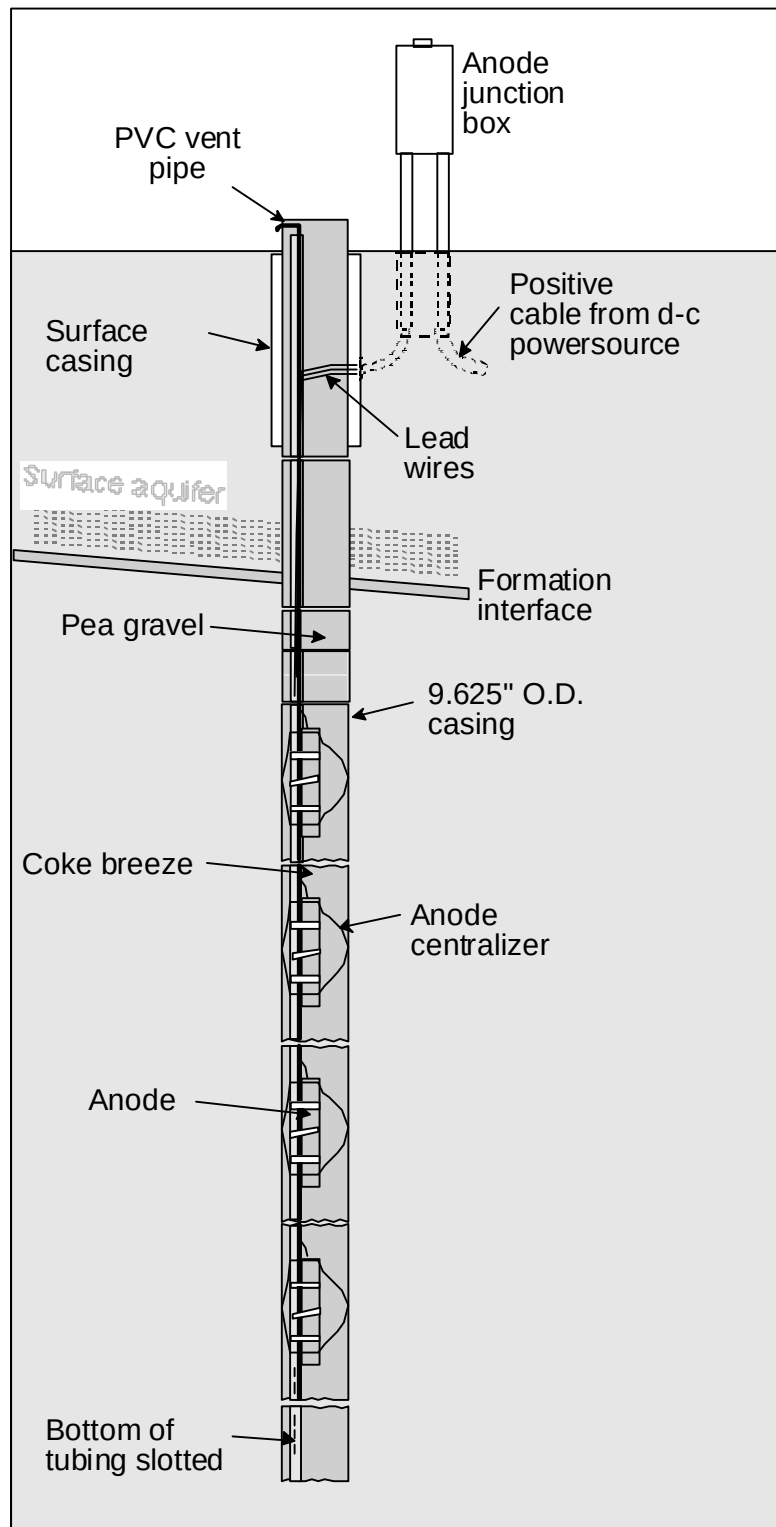
Two Areas of Influence Caused by a Remote Anode Bed

Figure 32

Although there is no limit to how far current can travel in remote earth, there is a limit to the length of pipeline that can be cathodically protected by the current. This length depends on the resistance in the structure during the current's return to the rectifier. The length of pipeline that is protected also depends on the quality of the pipeline's coating. For example, one impressed current system can protect 100 km of 60", fusion bonded epoxy coated-pipeline. However, the same system can only protect 10 km of 8" tape wrapped pipeline.

Remote anode beds are surface or deep anode beds that are installed in strata with low resistivity. Remote anode beds are usually located at least 50 m from the structure to be protected. In a deep anode bed, the anodes are placed vertically in a hole with a diameter of 25 to 30 cm and a depth of 70 to 400 m. Deep anode beds are used when surface soil resistivity is too high for normal anode bed design. Resistivity generally decreases with depth, especially below the water table.

The two most common types of deep anode beds are aquifer penetrating and non-aquifer penetrating. An aquifer penetrating deep anode bed is shown in Figure 33. The anodes and a PVC vent pipe are strapped to 2-3/4" steel tubing and installed inside 9-5/8" casing. A non-aquifer penetrating deep anode bed is similar except that it does not contain casing.



Typical Aquifer Penetrating Deep Anode Bed, Standard Drawing AA-036356

Figure 33

Advantages and Disadvantages of Impressed Current Systems

Impressed current systems have the following advantages:

- greater driving voltages
- higher current outputs
- adjustable current output

Impressed current systems have the following disadvantages:

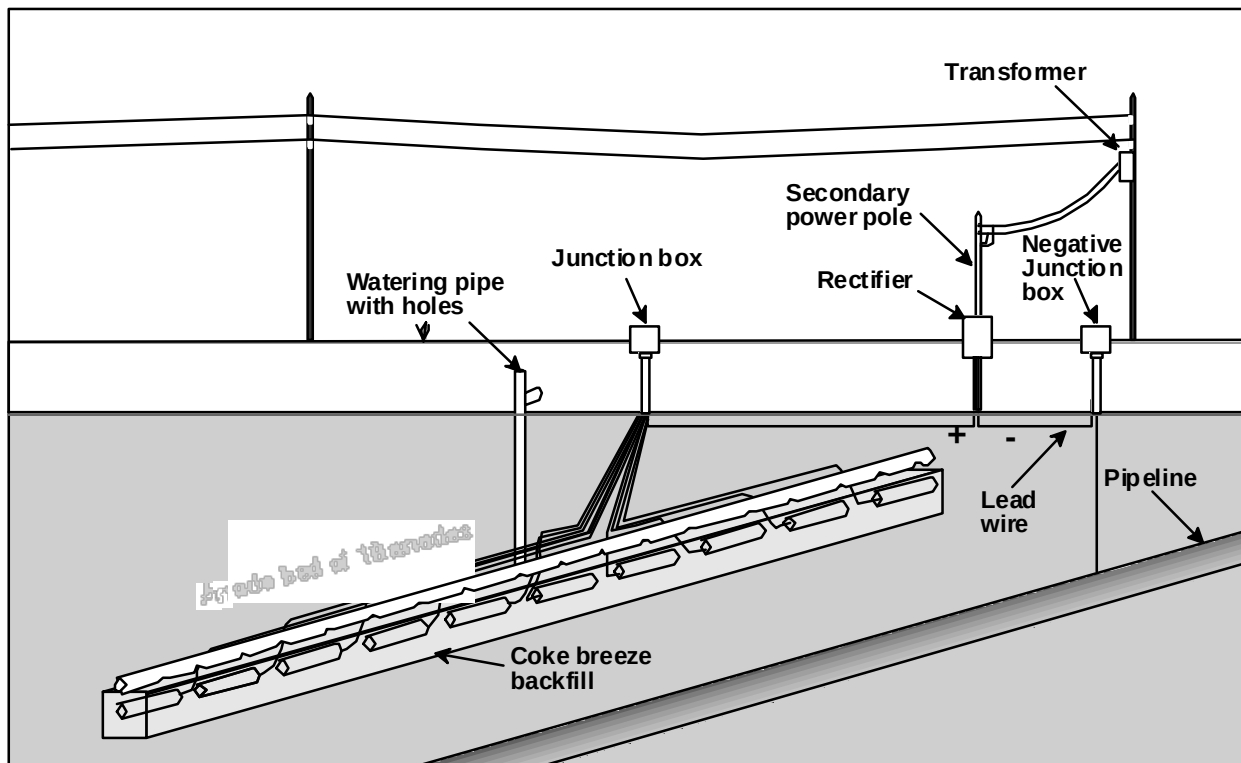
- higher equipment and installation costs
- higher maintenance costs
- possible interference problems with foreign structures

Saudi Aramco uses impressed current systems for the following:

- buried pipelines
- offshore pipelines within the area of influence of offshore platforms
- offshore structures
- piers
- external storage tank bottoms
- interiors of water tanks
- well casings
- seawater intake systems
- ship hulls (if galvanic anode systems are not used)

Buried Pipeline Applications

Saudi Aramco usually protects buried pipelines with remote surface anode beds. It is sometimes advantageous to install anodes horizontally rather than vertically. This is usually done in low resistivity surface strata. Figure 34 shows a typical impressed current system with an anode bed of ten horizontal anodes.

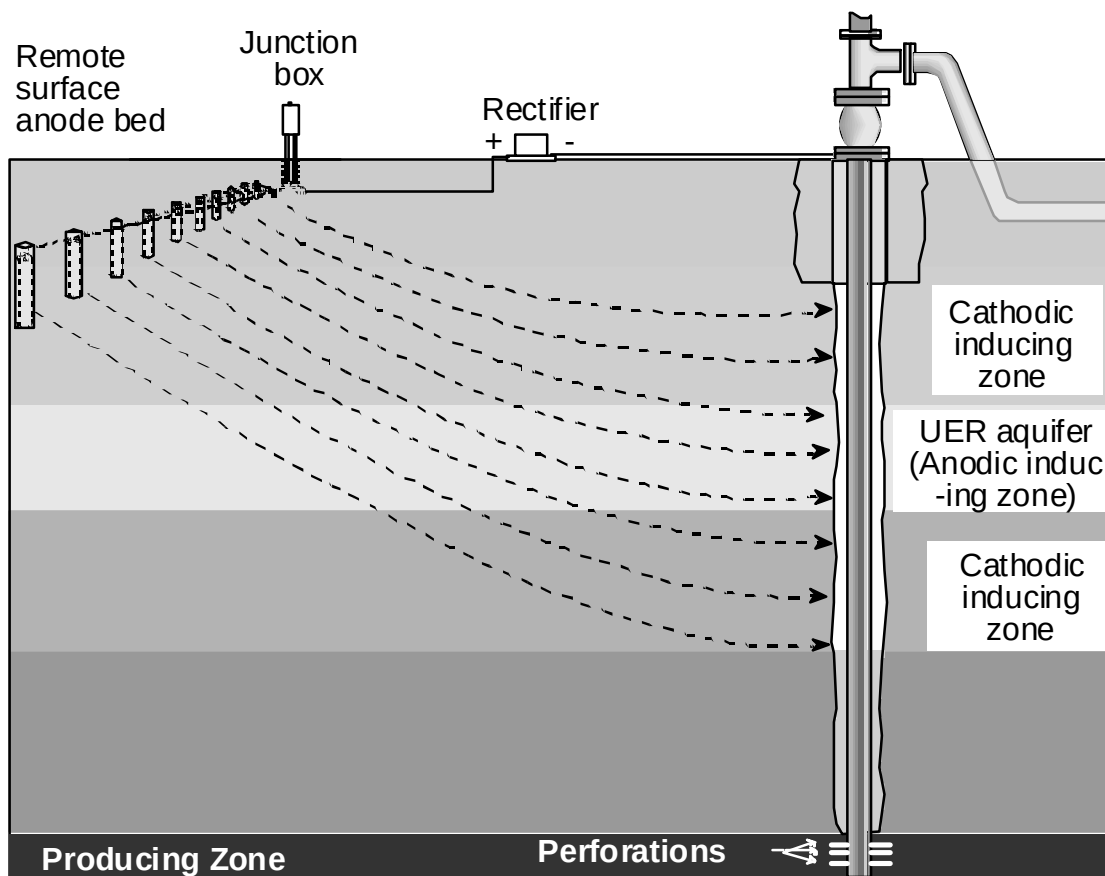


Anode Bed of 10 Horizontal Anodes, Standard Drawing AA-036346

Figure 34

Onshore Well Casing Applications

External casing corrosion may be caused by a metallic difference in the structure or an electrolyte difference in the surrounding environment. Saudi Aramco requires impressed current systems on all onshore well casings if the wells will not be plugged within five years. Figure 35 shows how cathodic protection can be accomplished using a surface anode bed. Well casing cathodic protection requires anodes to be installed at least 150 meters from the well head to ensure adequate downhole current distribution.



Surface Anode Bed Cathodically Protecting a Well Casing

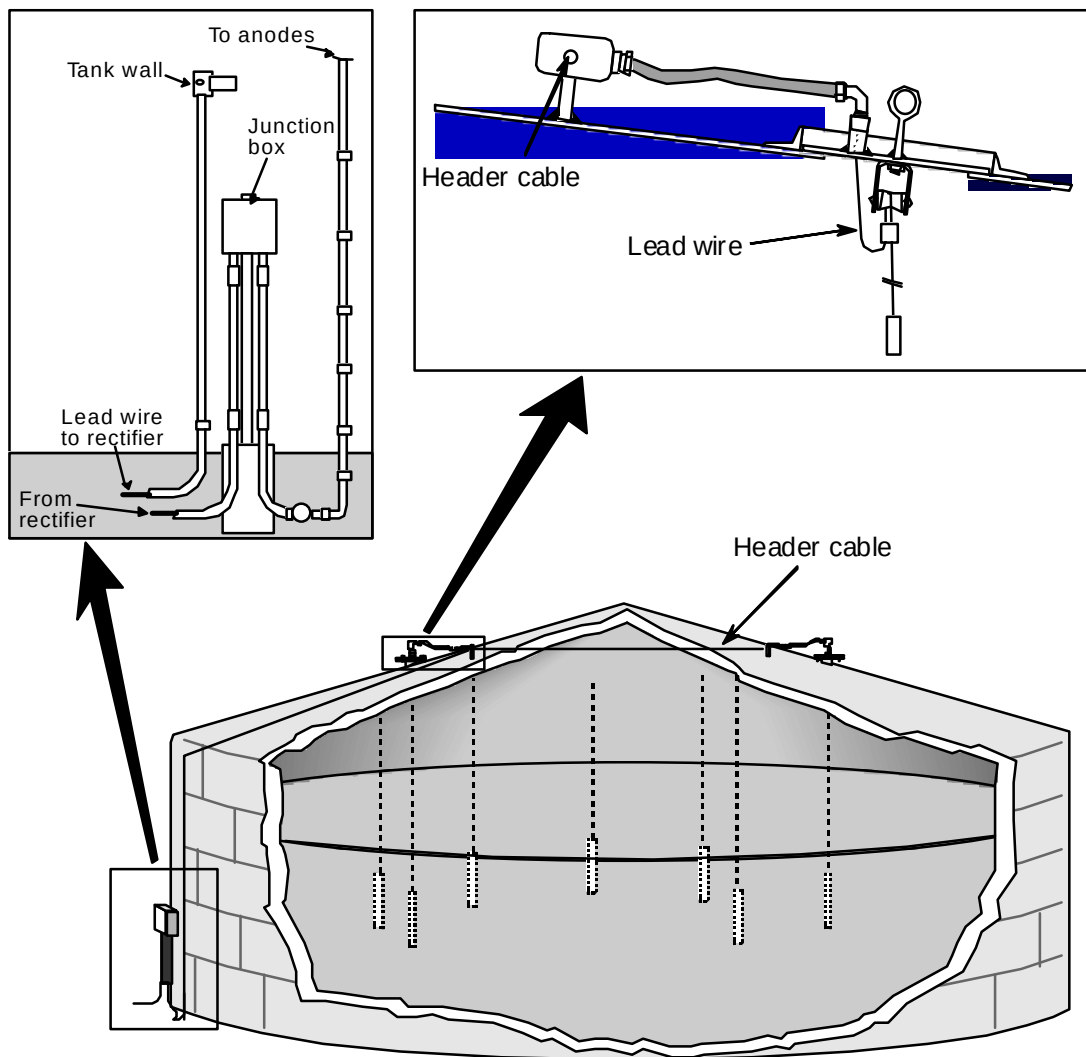
Figure 35

Impressed current systems can be designed to protect more than one well; however, the following factors must be considered:

- well spacing
- other cathodic protection systems
- buried pipelines and flowlines
- plant structures that may be affected

Vessel and Tank Interior Applications

The interior of vessels and tanks may be protected by galvanic or impressed current systems. Impressed current systems are used mainly in large bare tanks (Figure 36). The internal parts of vessels are usually protected with a combination of coatings and galvanic anodes.



Impressed Current Anodes Inside a Water Tank, Standard Drawing AA-036353

Figure 36

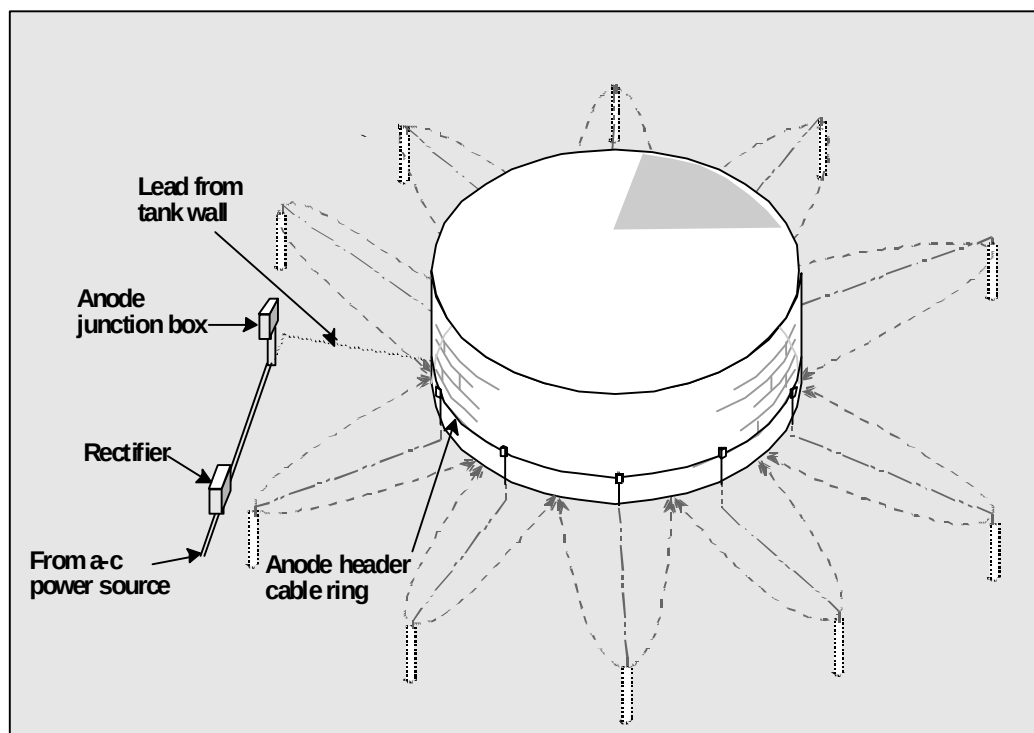
In-Plant Facility Applications

Saudi Aramco requires cathodic protection for buried and submerged in-plant facilities. These facilities include the following:

- pressurized steel hydrocarbon pipelines
- bottoms or soil side of above ground storage tanks
- buried tanks containing hydrocarbons
- sea walls and associated anchors

Cathodic protection can be provided by galvanic anodes, impressed current systems or a combination of both. Structures protected by impressed current systems must be bonded together for electrical continuity. Oil-immersed rectifiers must be used inside the plant fence, within 30 meters outside the plant fence, and within 1 km of a coast line.

Above ground storage tanks are protected with distributed impressed current systems (Figure 37). Saudi Aramco requires anodes to be no more than 20 meters apart and between 3 and 10 meters from the tank wall.



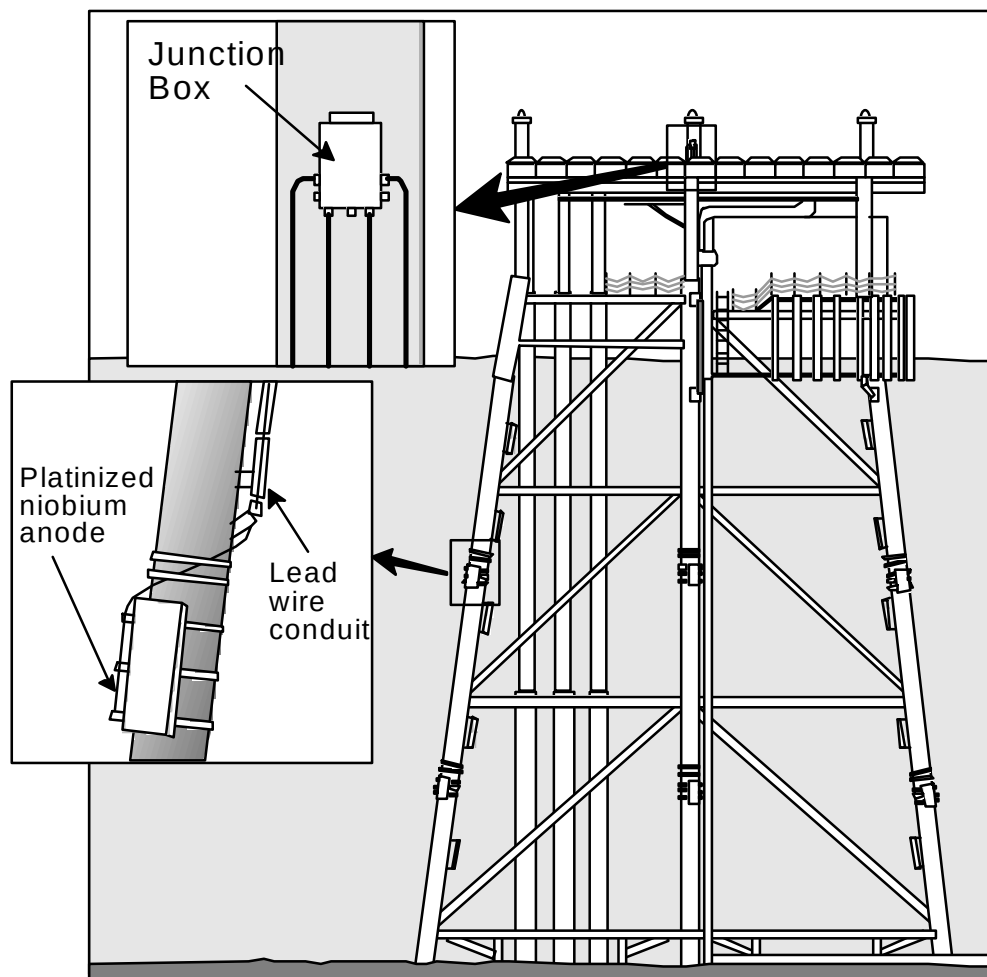
Impressed Current Anodes Protecting the Exterior Bottom of a Storage Tank,
Standard Drawing AA-036355

Figure 37

Marine Applications

Saudi Aramco protects all marine structures with galvanic anodes. Impressed current systems are installed when they are economically justifiable. Impressed current systems provide greater current output and weigh a lot less than galvanic anode systems. Impressed current systems cost less initially, but they require continuous operation and maintenance. They cannot be commissioned until power is available on the platform, and they are frequently turned off during well workovers.

Figure 38 is a diagram of an impressed current system on an offshore platform. If the rectifier is located outside, oil-immersed rectifiers are required. Air-cooled rectifiers may be used indoors in suitable environments. Saudi Aramco uses platinized niobium or mixed metal oxide impressed current anodes.



Impressed Current System on an Offshore Platform, Standard Drawing AA-036348

Figure 38

Selecting Impressed Current Anode Bed Sites

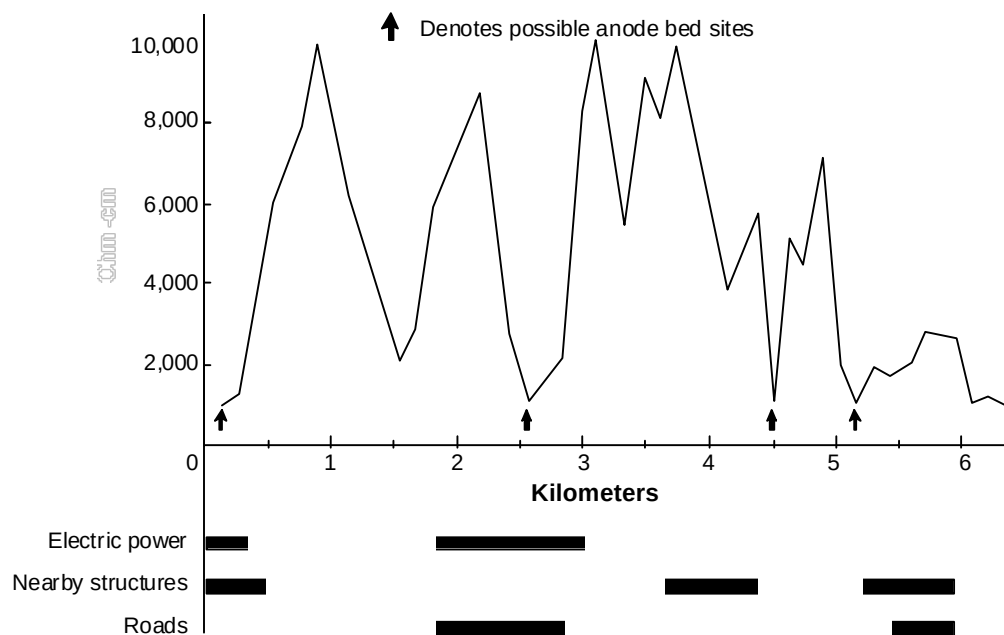
The locations of impressed current anode beds are primarily determined using soil resistivity data. Soil resistivity may change over relatively short distances. Anode beds that are rather long can cross areas of varying resistance. For example, an anode bed of 10 impressed current anodes that are spaced by 9 meters can be over 80 meters long. Therefore, you must select the best soil conditions possible.

You must consider more than soil resistivity when you select an anode bed site. Other considerations include the following:

- the availability of electric power
- accessibility for construction and maintenance personnel
- interference from other structures
- * optimum current distribution

Example

Figure 39 shows a graph of data from a soil resistivity survey along a 6 km section of pipeline. The most favorable anode bed locations are areas that have the lowest effective soil resistivity. These areas are designated with arrows in the figure. However, when available power, nearby structures, and accessibility are considered, the 2.5 km site is best.



Soil Resistivity Survey Along a 6 km-Section of Pipeline

Figure 39

Calculating Maximum Driving voltages for DC Power Sources

The output rating of the dc power source is determined by (1) the amount of current required for cathodic protection and (2) the voltage required to force the current through the resistance in the impressed current system.

You can determine the actual amount of current needed with a current requirement test. Alternatively, you can estimate the amount of current needed using Saudi Aramco's current density requirements.

The rated output voltage of the dc power source should be greater than the minimum voltage needed to force adequate current through the circuit resistance. This is because the circuit resistance typically changes with time. Circuit resistance is a function of the anode bed resistance. The anode bed resistance increases as the anodes deteriorate with age.

Most impressed current anodes are surrounded by granular carbonaceous backfill. The use of backfill material results in additional resistance. Usually, the additional circuit resistance due to carbonaceous backfill is compensated for by reducing the useful output of a rectifier by two volts. This reduction of useful rectifier output, resulting from the use of carbonaceous backfill, is often called back voltage.

The back voltage must be overcome by the dc power source before current can be discharged from the anode bed. Therefore, you must compensate for back voltage when calculating the maximum driving voltage of the power source. For design purposes, Saudi Aramco usually uses a back voltage of 2 volts. This back voltage is subtracted from the rated voltage capacity of the dc power source when calculating the useful driving voltage of the source. The procedure to calculate the maximum driving voltages of dc power sources is provided in Work Aid 4.

Example

Calculate the useful driving voltage of a three-phase rectifier that can protect a well casing requiring 12 amperes of current. Assume that the well casing is in a hazardous area.

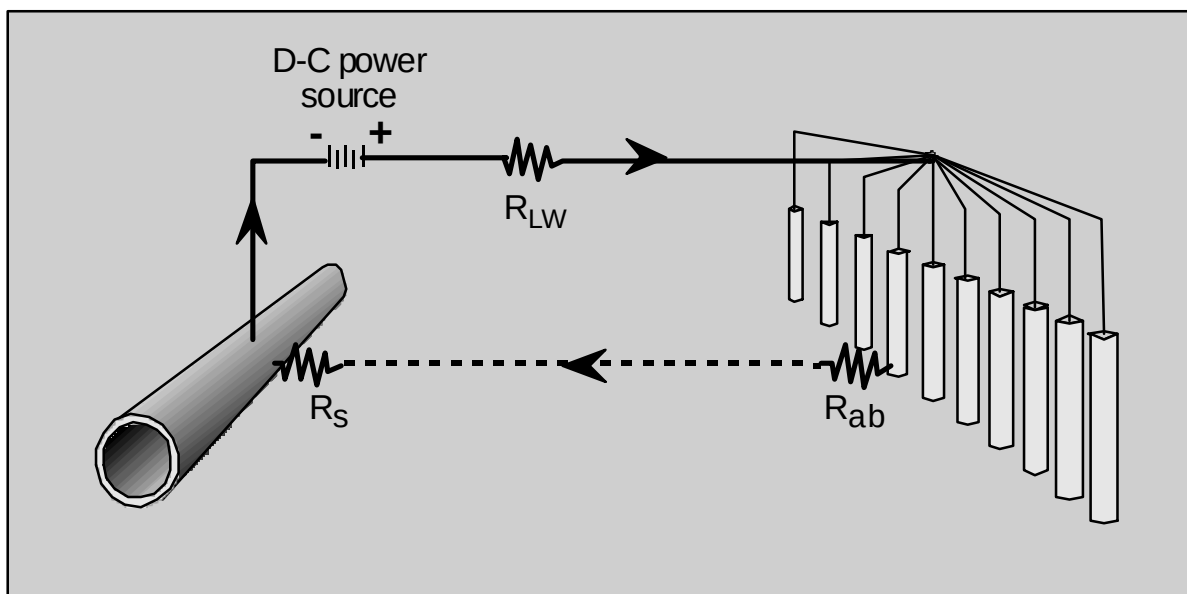
From the list of rectifiers in Work Aid 4, the smallest oil cooled rectifier available is rated at 50 V and 50 A. The driving voltage of the rectifier is calculated as follows:

$$50 \text{ V} - 2 \text{ V} = 48 \text{ V}$$

Calculating Circuit Resistances of Impressed Current Systems

The current and voltage output of the dc power source is only part of the design criteria for an impressed current system. Saudi Aramco Engineering Standards require that anode beds be designed to discharge 120% of the rated current output of the dc power source. The circuit resistance of the impressed current system determines how much current is discharged by the anode bed. Circuit resistance is a function of the anode bed resistance.

To determine the allowable anode bed resistance, we represent the buried impressed current system as an equivalent electrical circuit (Figure 40).



Representation of a Buried Impressed Current System as an Equivalent Circuit

Figure 40

The electrical circuit includes the driving voltage of the dc power source, E_D , and the resistances in the impressed current system circuit. We calculate the circuit resistance using the following equation:

$$R_C = R_S + R_{LW} + R_{ab}$$

where -

- R_C = circuit resistance
- R_S = structure-to-electrolyte resistance
- R_{LW} = total lead wire cable resistance
- R_{ab} = the anode bed resistance

Structure-to-Electrolyte Resistance

The structure-to-electrolyte resistance, R_S , is usually low. The resistance to earth of the structure can be determined from current requirement test data. This resistance mainly depends on the quality of the coating. The better the coating, the higher the structure-to-electrolyte resistance. Calculate the structure-to-electrolyte resistance using the formula

$$R_S = (V_{on} - V_{off}) / I_{on}$$

where -

- V_{on} = the structure-to-electrolyte potential with the current on
- V_{off} = the structure-to-electrolyte potential with the current off
- I_{on} = current applied to give the potential V_{on}

Lead Wire Resistance

Lead wire electrically connects the structure to the negative terminal of the rectifier and the positive terminal of the rectifier to the junction box. Anodes are individually connected to the junction box via lead wires. Lead wires are sized by current rating and/or allowable voltage drop. The types and sizes of lead wires are specified in Saudi Aramco standard drawings and by engineers. To calculate the resistance of a lead wire, its length (in meters) is multiplied by its resistance per unit length (ohm-m).

Maximum Allowable Circuit Resistance

The circuit resistance must not be greater than the maximum allowable circuit resistance, R_{max} . You can calculate the maximum allowable circuit resistance by using the following equation:

$$R_{max} = V_{max} / I_{max}$$

where -

- V_{max} = the maximum driving voltage of the dc power source
- I_{max} = the maximum current output of the dc power source

Allowable Anode Bed Resistance

For design purposes, the maximum allowable anode bed resistance, R_{aab} , must not exceed the difference between the maximum allowable circuit resistance, R_{max} , and the lead wire resistance, R_{LW} .

$$R_{aab} = R_{max} - (R_{LW} + R_S)$$

Work Aid 5 provides a procedure for calculating the allowable anode bed resistance. The actual anode bed resistance is a function of the number and spacing of anodes and resistivity between the anode bed and the electrolyte. This is part of the design procedure which will be covered in Module 107.03.

Example

Calculate the allowable anode bed resistance of an impressed current system with a 50V, 35A rectifier. The rectifier is 3 meters from the structure and 12 meters from the junction box. Assume that No. 4 AWG lead wire is used for the positive and negative rectifier leads. Neglect the structure-to-electrolyte resistance ($R_S = 0$).

From the Conductor Resistance Table in Work Aid 5, the resistance per unit length of No. 4 AWG lead wire is 0.85×10^{-3} ohm/m. The resistances in the rectifier negative lead (R_{RNL}) and rectifier positive lead (R_{RPL}) are calculated as follows:

$$R_{RNL} = [3 \text{ m} + (0.10)(3 \text{ m})] [0.85 \times 10^{-3} \text{ ohm/m}] = .003 \text{ ohm}$$

$$R_{RPL} = [12 \text{ m} + (0.10)(12 \text{ m})] [0.85 \times 10^{-3} \text{ ohm/m}] = 0.011 \text{ ohm}$$

$$R_{LW} = 0.003 + 0.011 = 0.014 \text{ ohm}$$

The maximum allowable circuit resistance for an impressed current system with a rectifier rated at 50 volts and 35 amperes is:

$$R_{max} = (50 - 2)V/35 \text{ A} = 48V/35A = 1.37 \text{ ohms}$$

The allowable anode bed resistance is calculated as follows:

$$R_{aab} = R_{max} - R_{LW} = 1.37 - 0.014 = 1.36 \text{ ohms}$$

Work Aid 1: Data Base and Procedure for Calculating Galvanic Anode Driving Potential**Work Aid 1A: Data Base For Calculating Galvanic Anode Driving Potential**

This Work Aid provides galvanic anode solution potentials and Saudi Aramco's required potentials for various structures.

	<u>Standard Magnesium</u>	<u>High Potential Magnesium</u>	<u>Zinc</u>	<u>Zinc-Tin Al-alloy</u>
Solution potential (V) to Cu-CuSO ₄	-1.55	-1.80	-1.10	-1.10
Solution potential (V) to Ag-AgCl	-1.50	-1.74	-1.02	-1.12
Anode polarization potential (V)	-0.10	-0.10	--	--

Structure	Required Potential
Current On	
Buried cross-country pipeline	-1.20 volts or more negative versus CuSO ₄
Buried plant piping	-0.85 volt or more negative versus CuSO ₄ electrode +0.25 volt or less positive versus Zn
Tank bottom external	-1.00 volt or more negative versus CuSO ₄ at periphery -0.85 volt or more negative versus permanent CuSO ₄ +0.20 volt or less positive versus permanent Zn -0.35 volt change in structure potentials vs CuSO ₄
Tank interior	-0.90 volt or more negative versus AgCl electrode +0.15 volt or less positive versus Zn
Marine structures	-0.90 volt or more negative versus AgCl electrode
Current Off	
Well casings	-1.00 volt or more negative versus CuSO ₄ (G.I. 428.003)

Saudi Aramco's Required Potentials for Various Structures
Figure 42

Work Aid 1B: Procedure for Calculating Galvanic Anode Driving Potential

This Work Aid contains a procedure to calculate the driving potentials of galvanic anodes.

To calculate the galvanic anode driving potential, E_D , subtract the required potential of the structure (in Figure 42) from the solution potential of the anode material.

$$E_D = E_A - E_P$$

where -

E_A = the solution potential of the anode material

E_P = the protected potential of the structure

NOTE: Reduce to solution potential of a magnesium galvanic anode by 0.10 volt because of polarization.

Work Aid 2: Formulas and Procedure for Calculating Circuit Resistances of Galvanic Anode Systems

This Work Aid provides equations and procedures for calculating the circuit resistance of galvanic anode systems.

Formulas

Circuit Resistance

$$R_C = R_S + R_{LW} + R_{ab}$$

where -

R_C	=	circuit resistance
R_S	=	structure-to-electrolyte resistance
R_{LW}	=	total lead wire resistance
R_{ab}	=	anode bed resistance

Structure-to-Electrolyte Resistance

$$R_S = (V_{on} - V_{off}) / I_{on}$$

Where -

V_{on}	=	the structure-to-electrolyte potential with the current on
V_{off}	=	the structure-to-electrolyte potential with the current off
I_{on}	=	current applied to give the potential V_{on}

Maximum Allowable Circuit Resistance

$$R_{max} = E_D / I$$

where -

E_D	=	driving potential of the galvanic anode
I	=	current requirement of structure

Galvanic Anode Driving Potential

$$E_D = E_A - E_p$$

where -

E_A	=	the solution potential of the anode material
E_p	=	the protected potential of the structure

Allowable Anode Bed Resistance

$$R_{aab} = R_{max} - (R_S + R_{LW})$$

where -

R_{aab}	=	allowable anode bed resistance
R_{max}	=	maximum allowable circuit resistance
R_S	=	structure-to-electrolyte resistance
R_{LW}	=	total lead wire resistance

Procedure

- 1.0 Calculate structure-to-electrolyte resistance.
 - 1.1 Determine the amount of current required to shift the structure to the protected potential required by the appropriate Saudi Aramco SAES-X Engineering Standard.
 - 1.2 Subtract the potential of the structure before current was applied from the protected potential of the structure.
 - 1.3 Divide the potential shift from Step 1.2 (volts) by the current from Step 1.1 (amperes).
- 2.0 Calculate total lead wire resistance.
 - 2.1 Determine the length of the lead wire from the structure to the junction box. Add 10% to the length of the lead wire for slack and the junction box connection.
 - 2.2 Multiply the lead wire length by its resistance in the table on the following page.
 - 2.3 If the operating temperature is not 25°C, multiply the resistance from 2.2 by the appropriate correction factor shown below the table.
 - 2.4 Repeat Steps 2.1 to 2.3 for any other lead wires.
 - 2.5 Add the resistances of all lead wires to calculate the total cable resistance.
- 3.0 Calculate allowable anode bed resistance.
 - 3.1 Calculate the maximum allowable circuit resistance by dividing the galvanic anode driving potential by the current required to protect the structure.
 - 3.2 Subtract the sum of the resistances calculated in Steps 1.0 and 2.0 from the maximum allowable circuit resistance to obtain the allowable anode bed resistance.

Conductor Resistance Table

The table below provides cable resistances and recommended cable sizes for various cathodic protection applications.

	Conductor (AWG)	Size	Resistance of Stranded Copper Conductors in ohm/m x 10 ⁻³ at 25°C
Test Current and Leads	4/0	Impure Steel	0.167
	3/0	Galv. Steel	0.211
	2/0		0.268
	1/0		0.335
			0.423
Anode and Pipeline Joints	1		0.531
	2		0.850
	4		1.35
	6		2.15
	8		3.41
Instrument Test Leads	10	Galvanic	5.41
	12	Install	8.60
	14	Test	13.71
	16		21.85
	18		34.78
	20		55.77
	22		

Use the following table to correct the resistances above for temperatures other than 25°C.

Correction Factors for Other Temperatures

Temperature (°C)	Multiply resistance at 25°C by
0	0.901
5	0.921
10	0.941
15	0.961
20	0.980
30	1.020
35	1.040
40	1.059

Source: Control of Pipeline Corrosion, A.W. Peabody

Work Aid 3: Procedure for Selecting Impressed Current Anode Beds Sites

This Work Aid provides a procedure to select sites for impressed current anode beds.

Procedure

- 1.0 Locate low resistivity areas along the pipeline.
 - 1.1 Plot the resistivity data on a chart that shows resistivity versus location of the pipe line markers.
 - 1.2 Identify areas of low resistivity that are large enough for an anode bed installation (at least 80 to 100 meters long).
- 2.0 Determine the location of roads and utilities.
 - 2.1 Plot the locations of roads, electric power, and buried structures.
 - 2.2 Identify areas that are close to roads and/or electric power but away from buried structures that may cause interference.

Work Aid 4: Properties of Impressed Current Anodes

This Work Aid lists the material properties of impressed current anodes approved by Saudi Aramco.

Procedure

1. If current requirement test data is available, determine the amount of current required to shift the structure to its protected potential as required by the appropriate SAES-X Engineering Standard. Go to Step 3.
2. If current requirement test data is not available, refer to Saudi Aramco's current density requirements in the appropriate SAES-X standard and estimate the current required.
3. Select the smallest capacity rectifier that provides the required amount of cathodic protection current.
4. To calculate the maximum driving voltage, subtract a back voltage of 2 volts from the output voltage of the rectifier.

Ratings of Rectifiers Used by Saudi Aramco

<u>Max. Rated Input Voltage</u>	<u>Cooling</u>	<u>Max. Rated Output DC Volts</u>	<u>Max. Rated Output DC Amps.</u>	<u>No. of Phases</u>
115/240V	Oil	18V	40A	1
115/240V	Oil	50V	300A	1
240/480V	Air	10V	25A	1
240/480V	Oil	25V	100A	1
240/480V	Air	50V	35A	1
240/480V	Air	50V	50A	1
240/480V	Oil	50V	50A	1
240/480V	Oil	50V	150A	1
240/480V	Oil	50V	250A	1
240/480V	Oil	50V	400A	1
240/480V	Oil	100V	250A	1
480V	Oil	25V	300A	3
480V	Oil	50V	50A	3
480V	Oil	50V	150A	3
480V	Oil	50V	300A	3
480V	Oil	100V	150A	3
480V	Oil	100V	250A	3
480V	Oil	100V	400A	3

Work Aid 5: Formulas and Procedure for Calculating Circuit Resistances of Impressed Current Systems

This Work Aid provides formulas and procedures for calculating the allowable anode bed and lead wire resistances for impressed current systems.

Formulas

Driving Potential of DC Power Source

$$E_D = \text{Output voltage} - 2 \text{ volts (Back voltage)}$$

Circuit Resistance

$$R_C = R_S + R_{LW} + R_{ab}$$

where -

R_C	=	circuit resistance
R_S	=	structure-to-electrolyte resistance
R_{LW}	=	total lead wire resistance
R_{ab}	=	the anode bed resistance

Structure-to-Electrolyte Resistance

$$R_S = (V_{on} - V_{off}) / I_{on}$$

Where -

V_{on}	=	the structure-to-electrolyte potential with the current on
V_{off}	=	the structure-to-electrolyte potential with the current off
I_{on}	=	current applied to give the potential V_{on}

Allowable Anode Bed Resistance

$$R_{aab} = R_{max} - (R_S + R_{LW})$$

where -

R_{aab}	=	allowable anode bed resistance
R_{max}	=	maximum allowable circuit resistance
R_S	=	structure-to-electrolyte resistance
R_{LW}	=	total lead wire resistance

Procedure

- 1.0 Calculate structure-to-electrolyte resistance.
 - 1.1 Determine the amount of current required to shift the structure to the protected potential required by the appropriate SAES-X Engineering Standard.
 - 1.2 Subtract the potential of the structure (before current was applied) from the protected potential of the structure.
 - 1.3 Divide the potential shift from Step 1.2 (volts) by the current from Step 1.1 (amperes).
- 2.0 Calculate total lead wire resistance.
 - 2.1 Determine the length of the lead wire from the structure to the junction box. Add 10% to the length of the lead wire for slack and the junction box connection.
 - 2.2 Multiply the lead wire length by its resistance in the table in the conductor resistance table on the following page.
 - 2.3 If the operating temperature is not 25°C, multiply the resistance from 2.2 by the appropriate correction factor shown below the table.
 - 2.4 Repeat Steps 2.1 to 2.3 for any other lead wires.
 - 2.5 Add the resistances of all lead wires to calculate the total cable resistance.
- 3.0 Calculate allowable anode bed resistance.
 - 3.1 Calculate the maximum allowable circuit resistance by dividing the driving potential of the d-c power source by its d-c current output rating.
 - 3.2 Subtract the sum of the resistances calculated in Steps 1.0 and 2.0 from the maximum allowable circuit resistance to obtain the allowable resistance for the anode bed.

Conductor Resistance Table

The table below provides cable resistances and recommended cable sizes for various cathodic protection applications.

	Conductor (AWG)	General Use	Size	Resistance of Stranded Copper Conductors in $\text{ohm/m} \times 10^{-3}$ at 25°C
Lead Current and leads	4/0	Impre		0.167
	3/0	Cable		0.211
	2/0			0.268
	1/0			0.335
				0.423
Anode cables and Pipeline joints	1			0.531
	2			0.850
	4			1.35
	6			2.15
	8	Galvanic		3.41
Instrument Test Leads	10	Installs		5.41
	12	Test		8.60
	14			13.71
	16			21.85
	18			34.78
	20			55.77
	22			

Use the following table to correct the resistances above for temperatures other than 25°C.

Correction Factors for Other Temperatures

Temperature (°C)	Multiply resistance at 25°C by
0	0.901
5	0.921
10	0.941
15	0.961
20	0.980
30	1.020
35	1.040
40	1.059

Source: Control of Pipeline Corrosion, A.W. Peabody

GLOSSARY

allowable anode bed resistance

The difference between the maximum allowable circuit resistance, $R_{\max}$, and the sum of the structure-to-electrolyte resistance, R_s , and the lead wire resistance, R_{LW} . The allowable anode bed resistance, R_{aab} , is calculated as follows:

$$R_{aab} = R_{\max} - (R_s + R_{LW})$$

area of influence

The area in which the potential of a structure exceeds the minimum potential required for protection.

AWG

The American Wire Gauge is based on a constant ratio between diameters of successive gage numbers. The ratio of any diameter to the next smallest diameter is approximately 1.12.

back voltage

The reduction of useful rectifier output by 2 volts due to the use of carbonaceous backfill around impressed current anodes.

circular mil (CM)

The area of a circle with a diameter of one mil (0.001 inch). For example, the area of a wire that is one mil in diameter is 1 cm.

close anode bed

Anodes that protect a local area of a structure by making the earth more positive with respect to the structure.

deep anode bed

An anode bed where the anodes are installed vertically in a single 25 to 30 cm dia. hole, 70 to 400 meters deep.

distributed anode bed

Surface anodes that are located physically close to a structure.

interference

Corrosion damage to an underground structure caused by a cathodic protection system on another structure.

MCM

Thousands of circular mils.

remote anode bed

Anodes that protect a large area of a structure by making the structure more negative with respect to remote earth. A remote anode bed consists of anodes installed 50-150 meters (or more) from the pipeline so that the pipeline is outside the influence of the anodes' IR gradient.

remote earth	The point at which there is no longer a measurable change in potential.
shunt	A low, calibrated, resistance connected between two points in an electrical circuit. A shunt is used to measure current.
three-phase current	Current that is delivered through three "hot" wires. The phases of the three current components differ by one-third of a cycle or 120 electrical degrees. Each wire serves as a return for the other two. A fourth neutral wire is usually present; however, it does not carry current.