CHAPTER 5

CATHODIC PROTECTION

5.1 INTRODUCTION

Cathodic protection is a proven corrosion control method for protection of underground and undersea metallic structures, such as oil and gas pipelines, cables, utility lines and structural foundations. Cathodic protection is now widely applied in the protection of oil drilling platforms, dockyards, jetties, ships, submarines, condenser tubes in heat exchangers, bridges and decks, civil and military aircraft and ground transportation systems.

The designing of cathodic protection systems is rather complex, however, it is based on simple electrochemical principles described earlier in Chapter 2. Corrosion current flows between the local action anodes and cathodes due to the existence of a potential difference between the two (Fig. 5.1). As shown in Fig. 5.2, electrons released in an anodic reaction are consumed in the cathodic reaction. If we supply additional electrons to a metallic structure, more electrons would be available for a cathodic reaction which would cause the rate of cathodic reaction to increase and that of anodic reaction to decrease, which would eventually minimize or eliminate corrosion. This is basically the objective of cathodic protection. The additional electrons are supplied by direct electric current. On application of direct current, the potential of the cathode shifts to the potential of the anodic area. If sufficient direct current is applied, the potential difference between the anode and cathode is eliminated and corrosion would eventually cease to occur.

As the cathodic current increases (more transfer of electrons), the cathodic reaction polarizes in the direction of local action anode potential, thus reducing further the potential difference between the anodes and cathodes. Complete cathodic protection is achieved when the metallic structure becomes cathode (more negative). The severity of corrosion is directly proportional to the magnitude of the difference of potential between the anode and the cathode, hence by eliminating this difference, corrosion may be eliminated.

5.2 BASIS OF CATHODIC PROTECTION

Figure 5.3 illustrates the simple principle of cathodic protection. On application of an external current, the difference of potential between the cathodes and anodes on the structure decreases. Corrosion stops when potential of cathode becomes equal to the potential of anode. The anode would become more negative and the cathode more positive. Cathodic protection is, therefore, achieved by supplying an external negative current to the corroding metal to make the surface acquire the same potential to eliminate the anodic areas. The anodic areas are eliminated by transfer of electrons. After a sufficient current flow, the potential of anodic areas would become negative enough for corrosion to stop.

(a) There must be an anode, a cathode, an electrolyte and a metallic path for the transfer of electrons.
(b) A source of DC current to supply electrons.
(c) Sufficient direct current should be applied to eliminate the potential difference between the anode and the cathode.

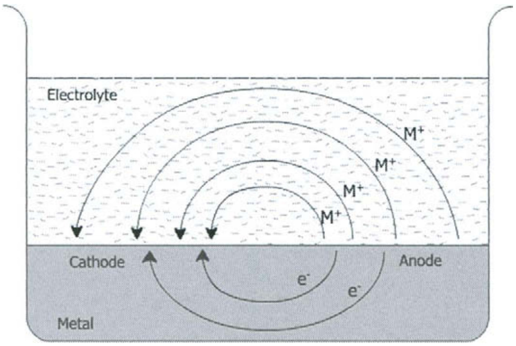


Figure 5.1 An electrochemical cell. Corrosion cell between two areas on single metal surface. Current flows because of a potential difference that exists between anode and cathode. Anions (e.g. Fe^{++}) leave at the anode which corrodes and are accepted at the cathode where corrosion is prevented. Electrons are insoluble in aqueous solutions and move only in the metal

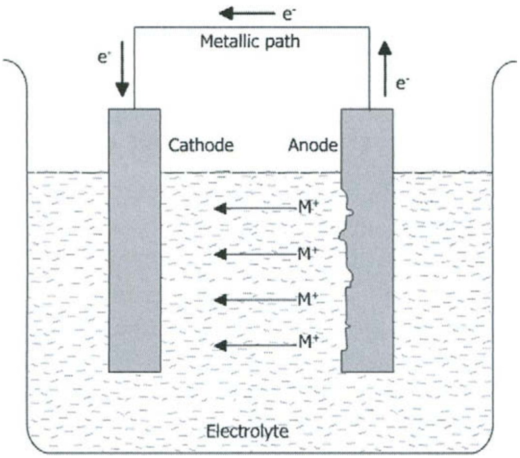


Figure 5.2 Simple electrochemical cell

5.3 WORKING OF CATHODIC PROTECTION SYSTEM

Figures 5.4a and b show how, in principle, a cathodic protection system works. Figure 5.4a shows a buried pipeline with anodic and cathodic areas prior to the application of the cathodic current. Figure 5.4b shows the same pipeline after the cathodic protection.

5.4 FACTORS LEADING TO CORROSION OF UNDERGROUND METALLIC STRUCTURES

The corrosion encountered by metals in aqueous solutions is always electrochemical in nature. It occurs because of the formation of anodic and cathodic areas and the flow of electrons through

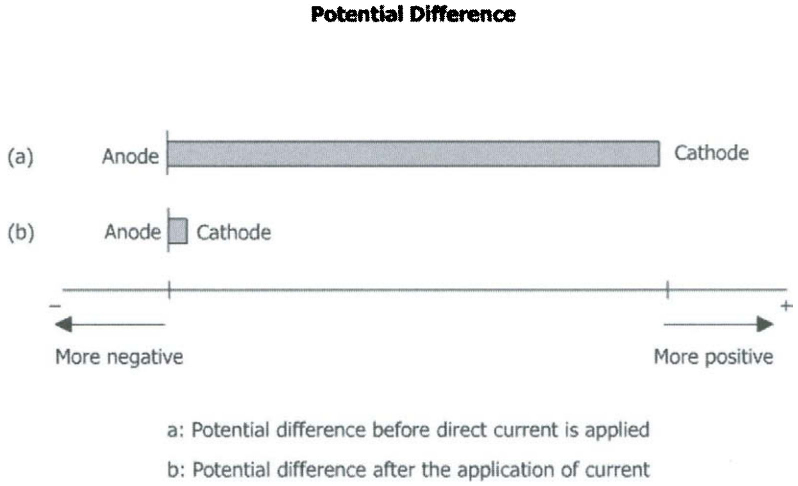


Figure 5.3 Effect of external current in the metallic structure

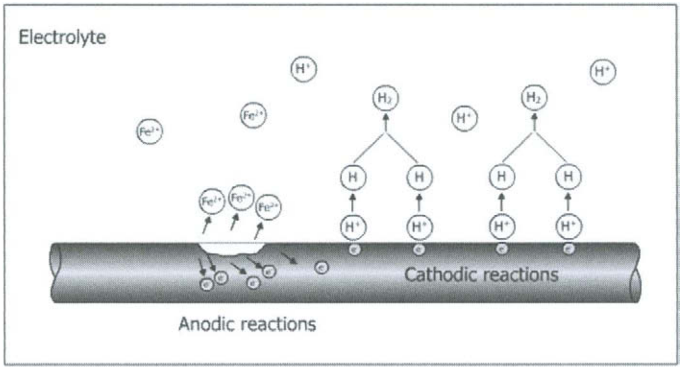


Figure 5.4a Anodic and cathodic reactions on a metal surface

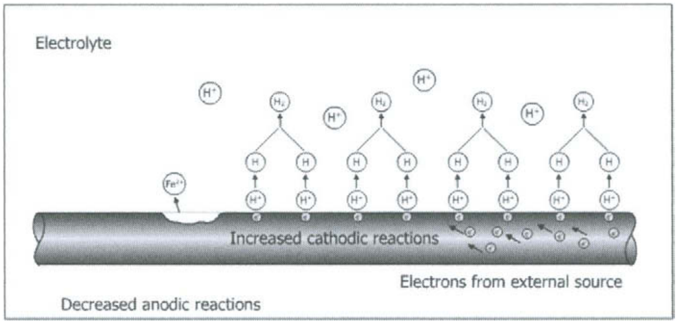


Figure 5.4b Increased cathodic reaction and decreased anodic reaction (insignificant) caused by introducing electrons from an external source

the metallic path. Structures, such as pipelines buried in the ground are affected by the presence of concentration cells, galvanic cells and stray currents. Some typical cells are described below.

(a) **Concentration cell**
A concentration cell is formed by the differences in concentration of salts, degree of aeration, soil resistivity and degree of stress to which the metals are subjected. The above differences cause the formation of anodic and cathodic areas on the surface which lead to corrosion.

(b) **Galvanic cell**
A galvanic cell is formed when two metals differing in potential are joined together. For instance, if copper is joined to aluminum, aluminum would corrode because it has a more negative potential (−1.66 V) than copper (+0.521 V). Copper being less active becomes the cathode and aluminum becomes the anode. But if iron is joined to aluminum, the iron corrodes (in seawater), due to the passive film on aluminum which causes it to behave like a nobler metal than iron (but not nobler than copper). The formation of such galvanic cells often leads to the corrosion of underground buried structures. A steel plate with copper rivets would form a galvanic cell. Several examples of galvanic cells are given in Chapter 4. A galvanic cell is basically a corrosion cell.

5.4.1 EXAMPLES OF CONCENTRATION CELLS

(a) Differential Aeration Cell

Suppose, a pipeline is buried in a completely uniform soil and that some areas of the line have a free supply of oxygen and other areas have a restricted supply. The part of the pipe buried in the soil with a free supply of oxygen (high oxygen content) would form the cathode and the part with a less supply of oxygen or poorly aerated forms that anode (Fig. 5.5). The current (Fe^{++} ions) would flow in the soil from anode to cathode resulting in the corrosion of the pipe end buried in poorly aerated soil. Such a cell is commonly called a *differential aeration cell.*

(b) Dissimilar Electrode Cells

Joining of a new pipe to an old pipe results in the corrosion of the new pipe, as the new pipe becomes anodic to the old pipe. The old pipe by virtue of film formation has a less active potential

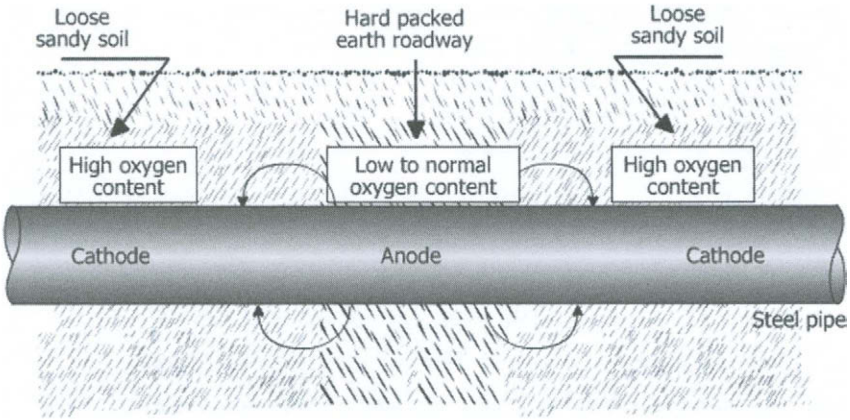


Figure 5.5 Formation of differential oxygen cells. (From CORRINTEC, USA, Presentation at KFUPM Dhahran, Saudi Arabia, March 5, 1982)

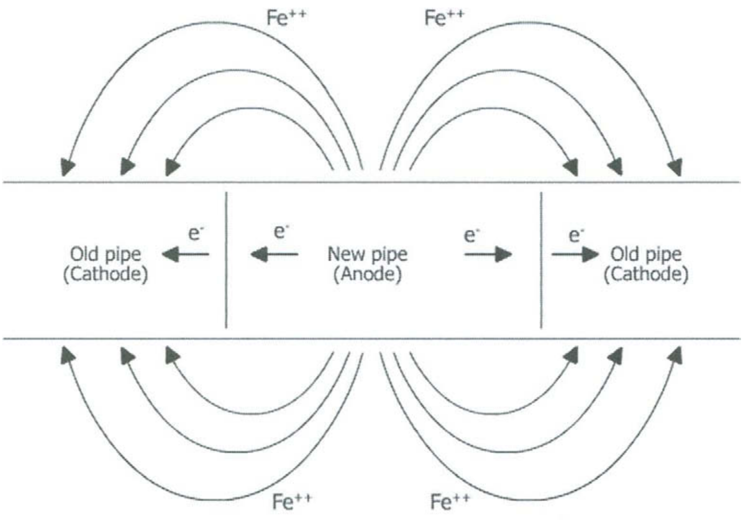


Figure 5.6 Dissimilar electrode cell formation by joining of an old pipe with a new pipe

than the new pipe and it, therefore, becomes the cathode (Fig. 5.6). Corrosion also occurs at the coating flaws when the new pipe is connected to the main with a bonded coupling.

(c) Stress Cells

Anodic areas may be formed in regions of high stresses and cathodic areas in regions of low stresses as shown in Fig. 5.7. Bright steel at threads and areas of stress at welds form the anode and corrosion occurs at these areas.

(d) Different Types of Soils

Suppose a pipeline is buried in two types of soils, one being a clay soil and the other sandy soil. The area of pipe buried in the clay soil would form the anode, whereas the area buried in the sandy soil would form the cathode, because of

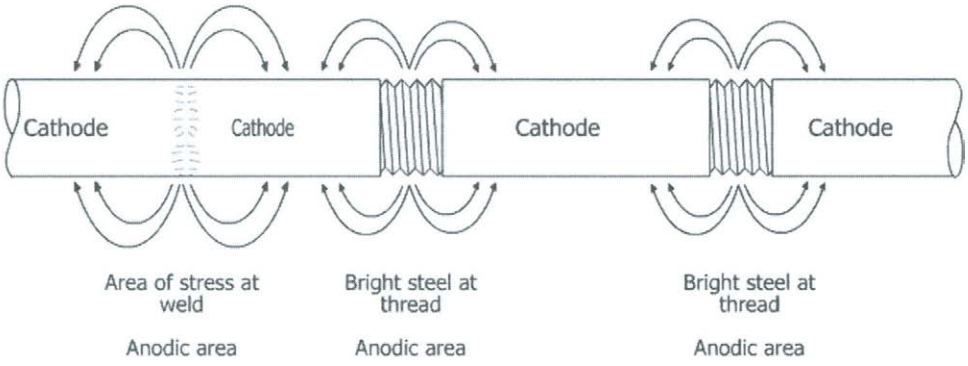


Figure 5.7 Stress cell. Corrosion caused by areas of stress and areas of bright steel on an underground pipeline

excess of oxygen and higher porosity. The pipe in the clay soil, therefore, corrodes. Corrosion caused by different types of soils is shown in Fig. 5.8.

(e) Different Moisture Contents

If a pipe is buried in two types of soil having different moisture contents, the area of the pipe in contact with wet soil (high moisture) would corrode, whereas the pipe in contact with the dry soil would not corrode. The area of the pipe in contact with the dry soil becomes the cathode and the area in contact with the wet soil, the anode. Differential concentration cell is shown in Fig. 5.9.

At the anode: $Fe \rightarrow Fe^{++} + 2e^-$

At the cathode: $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$

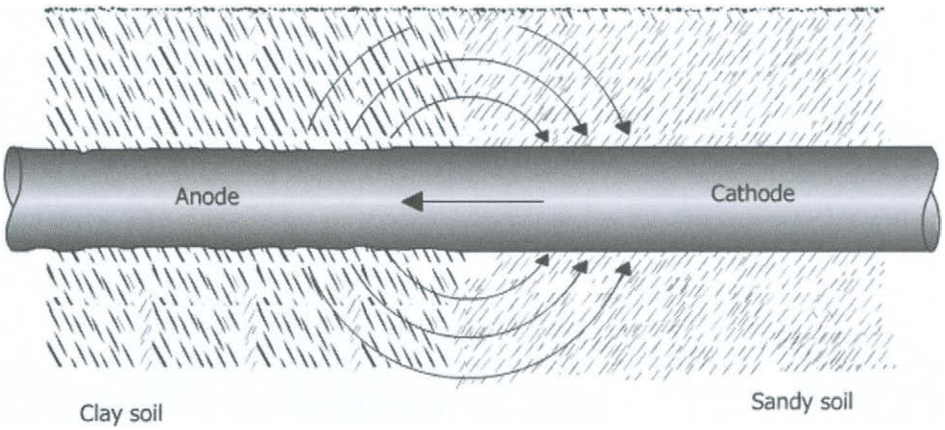


Figure 5.8 Corrosion caused by different types of soils

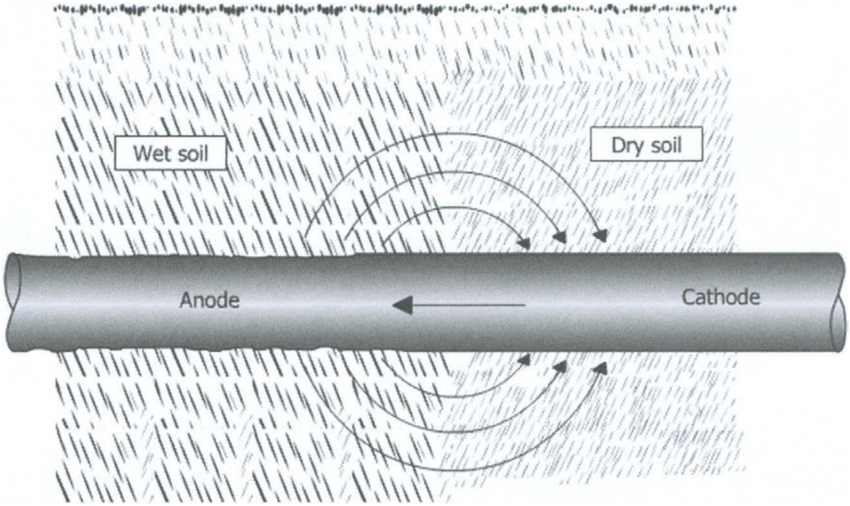


Figure 5.9 Differential concentration cell

5.4.2 GALVANIC CELLS

This type of corrosion arises by two dissimilar metals in contact with each other. In pipe lines it can occur when replacing an old section of the pipe by a new section. The same problem arises when the new lines are laid adjacent to the existing lines and connected across by means of branches. Any dissimilarity within the two metals would bring about this type of corrosion. The more active metal in this situation becomes the anode and the less active, the cathode. For example, if zinc is connected with steel, zinc would corrode as it would be anodic (more active potential), and by sending electrons to the cathode (steel) it would protect the steel. Any metal with a more active potential would always form the anode and the one with less active potential the cathode. The conventional current in the soil always flows from anode to cathode.

Figure 5.10 shows a cast iron box containing copper tubes. Electrons would flow in the metallic path from the cast iron box to the copper tubes as the cast iron has a more negative potential and so would be the anode, whereas copper has a noble potential would be the cathode. Eventually the box would be corroded and the copper tubes protected.

By installing a magnesium anode, a hot water steel tank may be protected against corrosion as shown in Fig. 5.11. In this case magnesium being very active would become the anode and corrode.

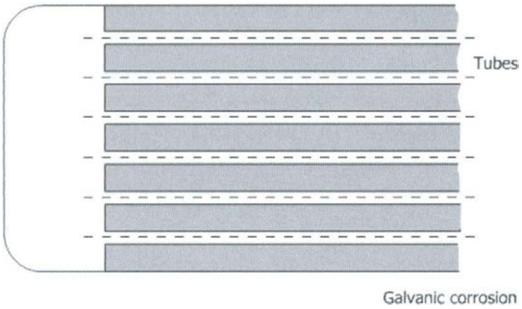


Figure 5.10 Current flows in the metallic path from case iron box into copper based tubes

5.5 ELECTRICAL BASIS OF CATHODIC PROTECTION

Let us suppose a pipe is buried in a soil. A difference of potential exists between the anode and the cathode, i.e.

$$\Delta E = (E_a - E_c)$$

ΔE is the difference in potential. If $R_a + R_c$ is controlling resistance, and $E_a - E_c$ has a finite value of circuit resistance, the corrosion current (I_c) would flow. If complete freedom from corrosion is desired, I_c must be made zero.

$$I_c = \frac{E_a - E_c}{R_a + R_c} = 0 \left(I = \frac{E}{R} \right) \quad \text{Ohms law}$$

where

I_c = corrosion current (A)
E_a = cathode potential
E_c = anode potential
R_a = anode resistance (ohms)
R_c = cathode resistance.

The corrosion current can be made zero by making $R_a + R_c$ equal to infinity, for example by pointing. This can also be achieved by equalizing the potential difference between E_c and E_a or making $(E_c - E_a)$ equal to zero. The structure can be made cathode (negative) by supplying an electric current from outside until its potential becomes equal to the potential of the anode, and the difference between E_c and E_a completely disappears.

To further illustrate the principle, the equivalent circuit (a) of a cathodically protected metal is shown in Fig. 5.12A. Complete cathodically protected metal is shown in Fig. 5.12B. Here

$$E_A - E_C = I_1 R_A + R_C(I_1 + I_2)$$

$$I_1 = \frac{E_A - (E_C + R_C I_2)}{R_A + R_C}$$

where

E_A = open circuit anode potential
E_C = open circuit cathode potential
R_A = effective anode resistance

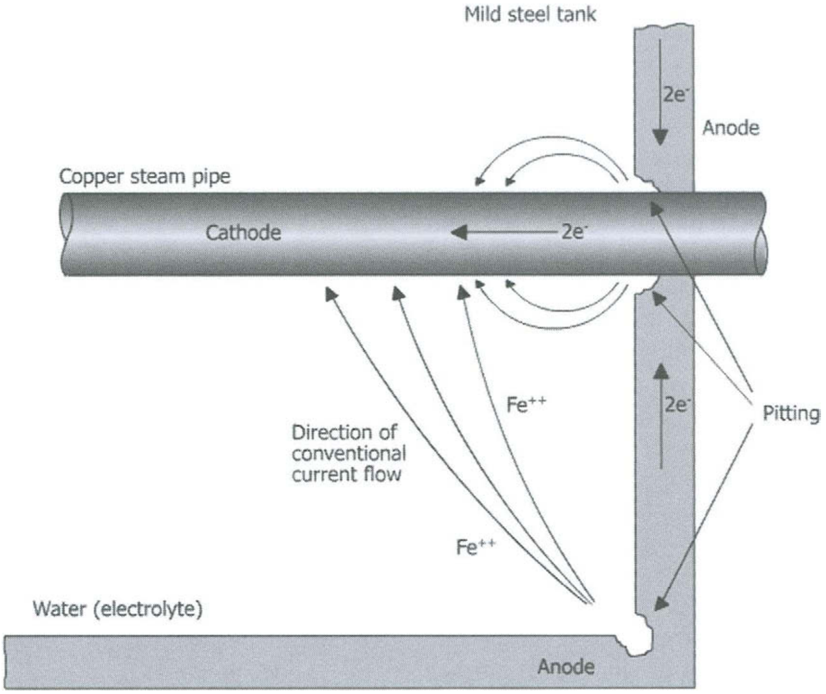


Figure 5.11 Galvanic corrosion in a hot water tank

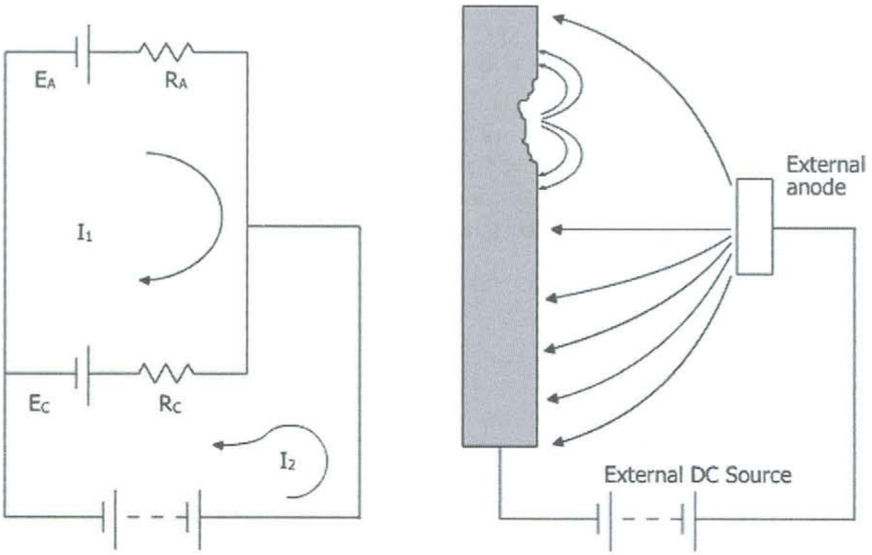
R_C = effective cathode resistance
I_1 = current from anodic area
I_2 = current from the external anode.

If corrosion is not to occur, I_1 must be zero, therefore, $(E_C + R_C I_2) = E_A$. It means that sufficient current must flow through R_C for the potential of the anode to be equal to the potential of the cathode (open circuit potential).

The above relationship suggests that enough current must be provided by an external anode to flow through the cathode resistance R_C to make the cathode potential (E_C) equal to the anode potential (E_A). When this condition, $E_A = (E_C + R_C I_2)$, is achieved, no corrosion would occur and the structure would be cathodically protected. Figure 5.12 illustrates the complete and incomplete protection. In part(b) current is not flowing to all anodic areas, whereas in part(c) current is supplied to all anodic areas. Figure 5.12A shows partial protection and Fig. 5.12B shows complete protection, $E_A = (E_C + R_C I_2)$.

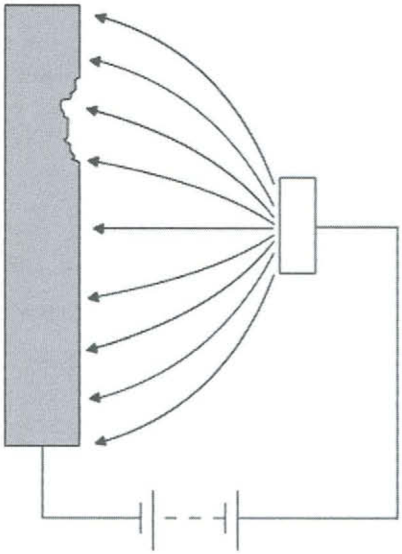
5.5.1 SOURCES OF CURRENT

It has been shown above that there must be a source of current to supply electrons to the areas of the metal which is corroding. In a metal buried in ground, anodic areas corrode by release of electrons and if an equal number of electrons are not introduced from an external source, the metal would continue to corrode. An external anode which supplies such current is called *auxiliary anode* in the electrochemical cell and referred to as anode in a cathodic protection system. Electrodes of graphite, cast iron, platinum and titanium act as conductors of electricity and supply the desired current to the structure to be protected. The conductors are energized by a DC source. The rate of consumption of anode electrodes



(a) Equivalent circuit ($I_1>0$) (b) Physical circuit

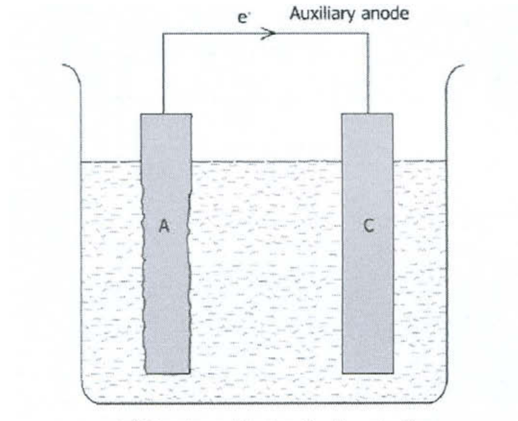
(A) Partial protection



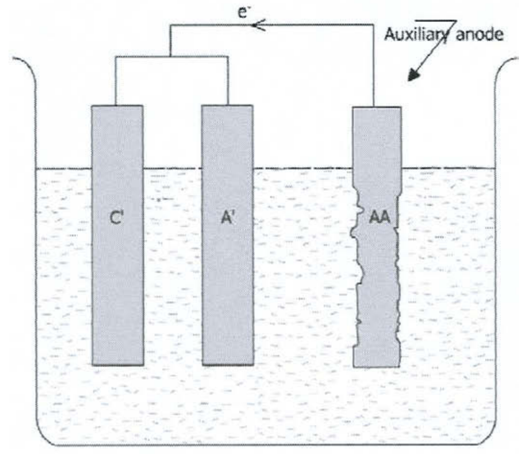
(c) Physical circuit

(B) Complete protection

Figure 5.12 Equivalent circuit of cathodically protected metals. (From Spencer, K.A. (1960). The Protection of Gas Plant and Equipment from Corrosion. *Joint Symp. Corrosion Group of the Society of Chemical Industry*, Sept 22–23) depends on the material used. The more expensive the anode, such as titanium, the lesser the rate of consumption. The above anodes are called *impressed current anodes.* The other types are *sacrificial anodes* which corrode in the soil and generate electric current required for protection of the structure. These anodes are not energized by an outside DC source. Details of galvanic and impressed current anodes are provided later in this chapter.



(a) Structure without cathodic protection
A = anodic area of structure
C = cathodic area of structure



(b) Structure with cathodic protection

Figure 5.13 Diagram illustrating the principle of cathodic protection

A structure without cathodic protection is analogous to an electrochemical cell, and is shown in Fig. 5.13a.

In a cathodic protection system, the current (electrons) leaves the anode and enters both the anodic and cathodic areas of the buried metal or by analogy to the electrochemical cell, the current from the auxiliary anode (AA) enters both the anodic and cathodic areas of corrosion, A and C, where A = anode and C = cathode, returning to the source of DC current (Fig. 5.13b). Naturally, when the cathodic areas are polarized to the open circuit potential of the anode, all the metal surface is at the same potential and the local active current would no longer flow. The metal does not corrode as long as the external current is maintained. The electrodes A and C would achieve the same potential if they are polarized by the external current supplied by AA. The potential of the cathode would shift close to the potential of the anode, and after some time both A and C would acquire the same potential, thus, by supplying an external current it is possible to prevent corrosion. As the two electrodes, A and C, become more negative, the method is called *cathodic protection.* Cathodic protection is, therefore, a method of preventing the corrosion of a metallic structure by making it a cathode with respect to the auxiliary anode (anode supplying the current).

5.6 ELECTROCHEMICAL THEORY OF CATHODIC PROTECTION

In Fig. 5.14a, $E_{o,c}$ represents the reversible potential of the cathode and $E_{o,a}$ represents the reversible potential of the anode. β_a represents the Tafel slope of the linear portion of anodic curve (slope = 0.12 V/decade), and β_c the cathodic slope. E_{corr} represents the corrosion potential, where the rate of oxidation equals the rate of reduction. I_{corr} is the corrosion current corresponding to corrosion potential (100 μA/cm^2) (Figs 5.14a and b). Extrapolation of the linear portion of the anodic curve to the equilibrium potential of the anode, gives the exchange current density for the anodic reaction ($I_{o,c}$). I_o is defined

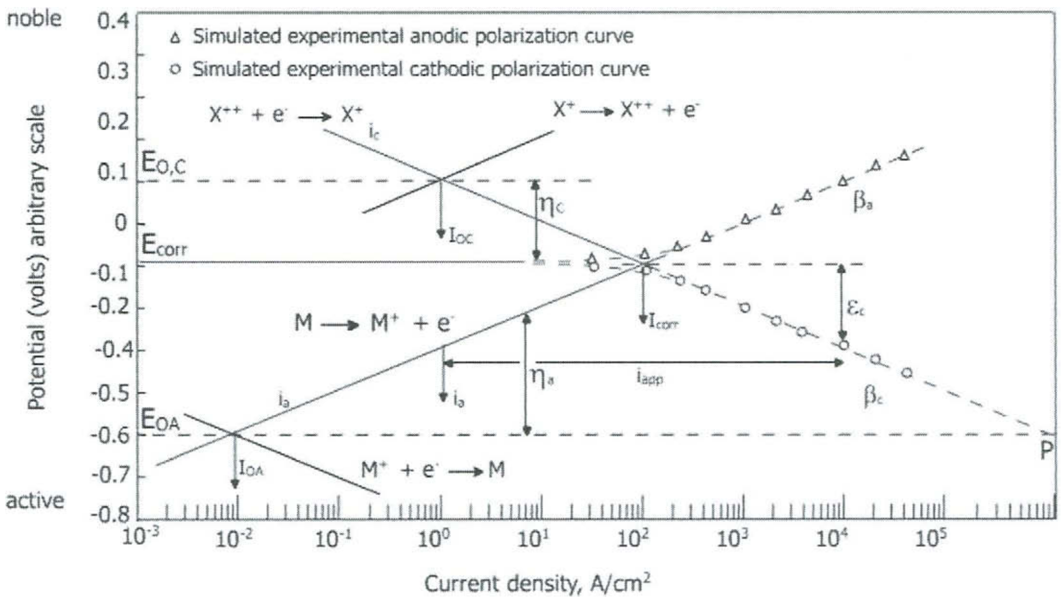


Figure 5.14 a Anodic and cathodic Tafel curves for corrosion of metal, M, showing the principle of cathodic protection. (From Jones, D.A. (1981). *Principles of Measurement and Prevention of Buried Metal Corrosion by Electrochemical Polarization.* In Underground Corrosion, STP 741, ASTM. Reproduced by the kind permission of ASTM, Philadelphia, PA, USA)

as equal and opposite ('exchange') current per unit area on a reversible electrode at equilibrium potential (reversible potential). I_o is a kinetic factor and has a significant influence on the rate of corrosion. For example, pure zinc has no reaction in reducing acids (e.g. H_2SO_4), whereas impure zinc evolves hydrogen. The I_o (H^+/H_2) on pure zinc is much lower than I_o (H^+/H_2) on commercial zinc. The values of $I_{o,a}$ and $I_{o,c}$ in the diagram are 10^{-2} and 1.0 $\mu A/cm^2$, respectively.

The relation between the current and overvoltage is given by the Tafel equation discussed in Chapter 3.

$$\eta = \pm\beta \log \frac{i}{i_o}$$

$$Mg \rightarrow Mg^{2+} + 2e \quad \text{(Tafel equation)}$$

$$M^+ + e \rightarrow M$$

Here η denotes the over-voltage of an anode (the difference between the actual potential of the electrode at certain value of applied current and the equilibrium potential E_o). If the cathode, for instance, is polarized by applying an external current, the cathodic process would be accelerated ($M^+ + e \rightarrow M$) and the anodic process ($M \rightarrow M^+ + e$) would be retarded. Similarly, an anodic process could be accelerated by supplying an external current to the anode and the cathodic process suppressed. In both cases, however, charge would be conserved and the current applied would be equal to the difference between the i_c and i_a. $i_{\text{applied}} = i_c - i_a$ (where i_c is current density at the cathode and i_a is current density at the anode).

If i_a is made smaller than i_c, i_{applied} would be equal to i_c and only the cathode would be polarized. Under such conditions, a linear Tafel behavior would be observed. On applying an electrical current (I_{applied}) equal to 10^4 $\mu A/cm^2$, and continuously polarizing the cathode, the corrosion current would be reduced from 100 $\mu A/cm^2$ at I_{corr} to 1 $\mu A/cm^2$ at I_a in Fig. 5.14a which is a 99% reduction in the rate of corrosion of *M* (Fig. 5.14a). By continuously increasing the

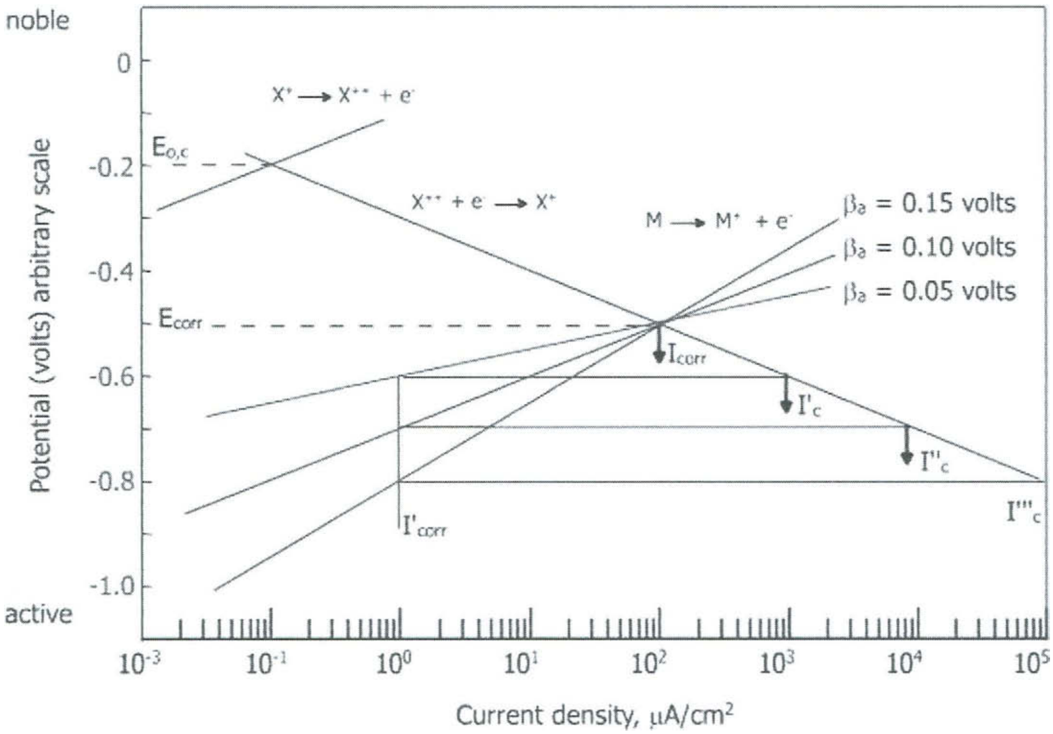


Figure 5.14 b Effect of anodic Tafel slope on polarization and current necessary for cathodic protection of three different metals with (hypothetically) identical E_{corr} and I_{corr}, but different Tafel β slopes. (From Jones, D.A. (1981). *Principles of Measurement and Prevention of Buried Metal Corrosion by Electrochemical Polarization.* In Underground Corrosion, STP 741, ASTM. Jones, D.A. (1971). *Corrosion Science.* **11**, 439. Reproduced by the kind permission of ASTM, Philadelphia, PA, USA)

applied current, the value of I_{corr} can be made negligible and corrosion can be stopped. In order to reduce the current density to zero, an applied current density of 10^6 μA/cm^2 would be required (point P in Fig. 5.14a).

Figure 5.14b (for three different metals) shows how the amount of corrosion is controlled by the anodic Tafel slope, β_a. The lower the value of β_a, the greater is the reduction in the rate of corrosion for a given cathodic polarization. Lower β_a means lower polarization required to achieve the required degree of protection. The Tafel slope β_a gives the measure of the amount of cathodic polarization required to reduce the anodic reaction by one order of magnitude. In order to reduce I_{corr} from 10^2 μA/cm^2 to 1 μA/cm^2, a potential change of 100 mV (0.1 V) is required for $\beta_a = 0.05$. To achieve the same amount of reduction in I_{corr} a potential change of 0.2 V and 0.3 V would be required, respectively, for $\beta_a = 0.1$ V and $\beta_a = 0.15$ V. Thus, lesser polarization is needed with a lower value of β_a. It is, however, not necessary to reduce the rate of corrosion to zero at $E_{\text{o,a}}$ (Fig. 5.14a) as this would require a large amount of current which might not be economically justified. It is only sufficient to reduce the corrosion to a negligible amount which would depend on the number of years the cathodic protection structure is to be designed for.

By cathodic polarization the potential of the cathode ($E_{\text{o,c}}$) becomes nearly equal to the equilibrium potential of anode ($E_{\text{o,a}}$) and the metal surface attains a uniform potential, hence, corrosion is prevented. As long as the value of E_{corr} is brought very close to the value of $E_{o,a}$ by applying an external current, corrosion is prevented, hence, it is not necessary to reduce the corrosion rate to zero completely.

5.7 ANODIC POLARIZATION

Imagine what would happen if the structure is now polarized in the opposite direction. It would amount to polarizing the potential of the anode to that of cathode in the positive direction. Theoretically, such a practice should result in creating corrosion rather than protection. But for some metals, positive polarization forms a protective oxide/hydroxide surface film and this phenomenon of passivation for a limited number of metals results in retardation of corrosion. By this method called *anodic protection*, it is possible to passivate active–passive metals. Metals, such as iron, chromium and nickel are passivated by anodic polarization, which leads to retardation of corrosion. The potential of this must, however, be maintained in the region of passivity by a potentiostat. Anodic protection is widely applied in transport of acids and corrosives in containers and other applications.

5.8 CATHODIC PROTECTION SYSTEMS

Two types of cathodic protection systems exist:

(a) Galvanic anode system or Sacrificial anode system.
(b) Impressed current anode system.

In the galvanic or impressed current system, the metallic structure is made the cathode (negative) by connecting it to galvanic anodes, which are more negative than the metallic structure to be protected. In this system, the current is generated by the corrosion of active metals, such as magnesium, zinc and also aluminum, which are galvanic anodes:

$$\mathrm{Al} \rightarrow \mathrm{Al}^{+++} + 3e$$
$$\mathrm{Mg} \rightarrow \mathrm{Mg}^{++} + 2e$$
$$\mathrm{Zn} \rightarrow \mathrm{Zn}^{++} + 2e$$

The anodes of the above materials are utilized as sources of electrons which are released when the anodes are buried in the soil corrode. The electrons released pass through the metallic connection between anode and steel, and thus enter the structure to be protected.

A suitable anode is buried adjacent to and level with the invert (lowest part) of a pipeline. A connection is made between the anode and the pipeline. The anode, generally magnesium or zinc, is connected to the pipeline or any buried metallic structure by an insulated cable. A schematic diagram of a galvanic anode cathodic protection system is shown in Fig. 5.15a. The figure shows a carbon steel pipe (A), magnesium anode (B), chemical backfill (C) surrounding the anode, wires connecting the carbon steel pipe to the anode, the soil (E) and test station (F). The details of test station are shown in Fig. 5.15b. The resistive component of a galvanic circuit is shown in Fig. 5.16.

The copper wire connection provides a passage for flow of electrons to the pipe to be protected. The electrons are released by the consumption of Mg anode in accordance with the anodic reaction, $\mathrm{Mg} \rightarrow \mathrm{Mg}^{++} + 2e$. The outer circuit is completed by the passage of electrons from the pipe (cathode) to the anode (Mg anode) through the copper wire (D). The pipe continues to be protected as long as it receives a regular supply of electrons from the anode. A typical anode installation in detail is shown in Fig. 5.17. The figure shows galvanic anodes (A) connected by a test station (F) and separated from each other by a distance of 8 feet. The test station provides a connection between the anode lead wire and the structure via the test panel. The details of the surface box housing test station are shown in the figure. The surface box is sometimes buried below the ground level. The anodes are connected to the pipe via a central control test panel. For measurement of pipe-to-soil potential and currents from the magnesium anode ground-bed, test stations

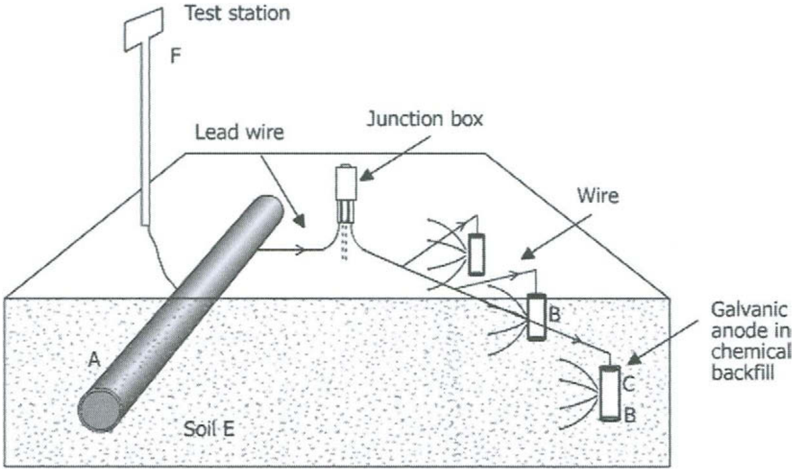


Figure 5.15 a Typical vertical galvanic anode in soil (arrows show the direction of convention positive current flow)

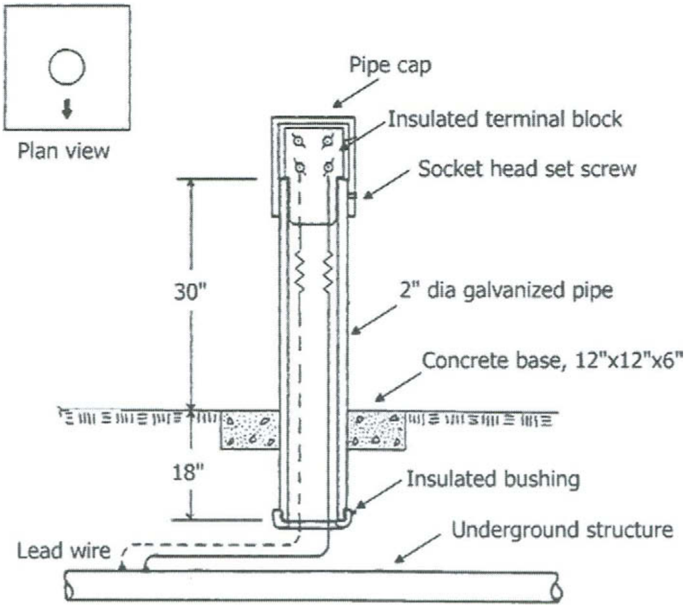
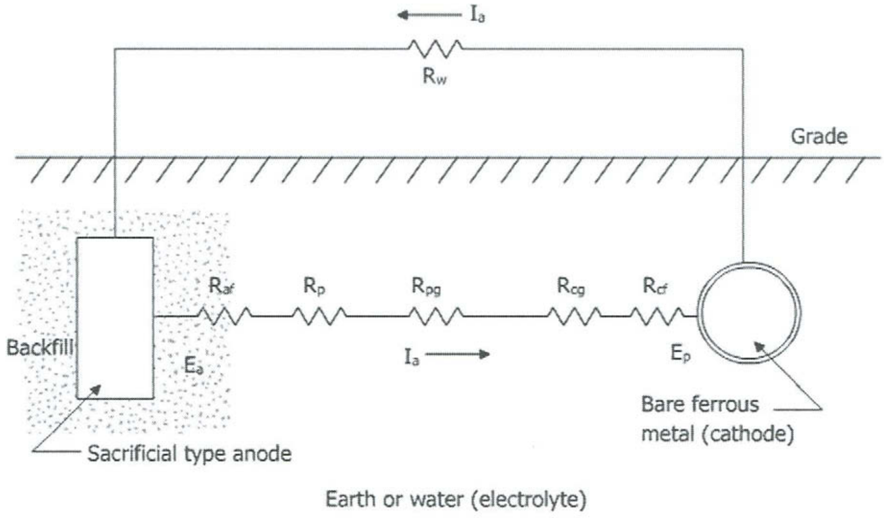


Figure 5.15 b Details of a test station



E_a = potential of anode (half cell potential)
E_p = potential of pipe (half cell potential)
R_w = resistance of connecting wire (metallic resistance)
R_{af} = anode film resistance
R_p = backfill resistance
R_{pg} = resistance of anode backfill to ground
R_{cg} = resistance of cathode to ground (this value can become the major component if pipe is coated
R_{cf} = cathodic film resistance
I_a = anode current

Figure 5.16 Resistive components of a galvanic circuit

are utilized. A special backfill, such as hydrated gypsum, bentonite and clay is placed around the anode, to ensure low resistance contact to the local soil.

The anodic installation is often designed for ten years but may last much longer if current demand is low. The potential of the pipe must be continuously monitored and the value should not be allowed to fall below −0.85 V ($CuSO_4$ reference electrode used). A 70 lb Mg anode practically gives a current of more than 300 mA in a soil of average resistivity of 2000 ohms-cm. Bare steel sometimes requires about 15 mA/ft^2. A single anode can protect about 2 square feet of the pipe. By applying a coating, the current requirement is reduced to 0.5 μA/cm^2, hence one Mg anode can protect up to 6000 square feet of the pipe surface. A potential value of 1.11 V is obtainable from the magnesium anode. This subject will be discussed in details later in this chapter.

The following are the advantages and the disadvantages of the galvanic anode system:

(a) Advantages

1. It requires no external source, which might fail.
2. It is economical.
3. It can be easily installed.
4. It can be easily maintained.
5. It can be used in areas where the soil resistivity is low.

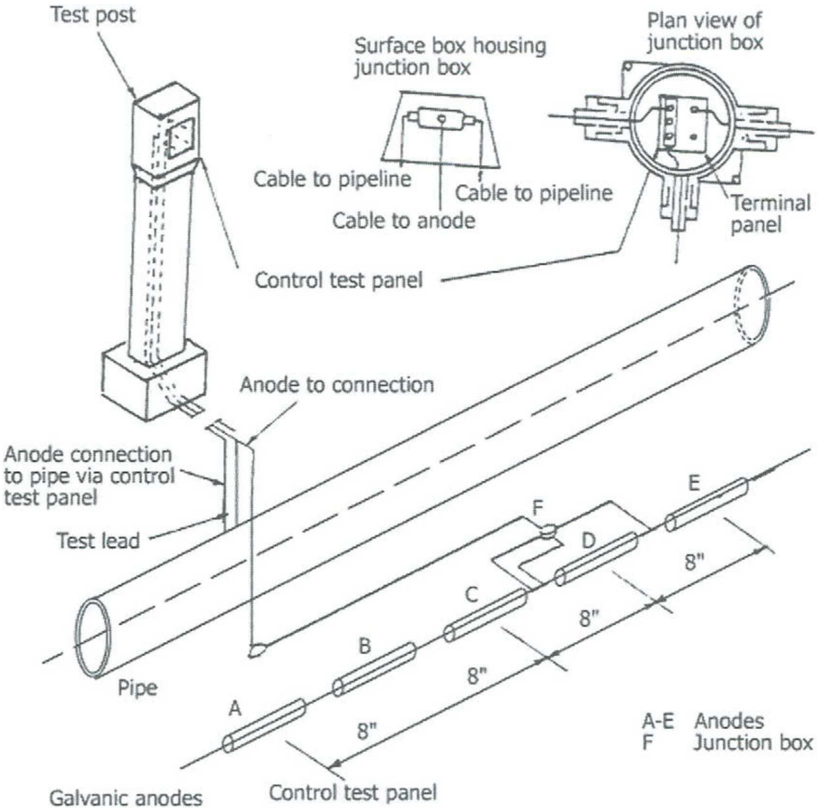


Figure 5.17 Typical galvanic anode installation layout and test points. (By kind permission of Cheveron Corp., USA)

6. Lesser interference with the other metallic structures is caused because of a relatively low current output.
7. The current is evenly distributed.

(b) Disadvantages

1. It has limited applications compared to impressed current.
2. Driving voltage is fixed and cannot be manipulated, except by selecting Mg instead of Zn for example.
3. The cost of protection is high for bare systems (uncoated structures).
4. As no above-ground equipment is used, it is difficult to trace the protected system, unless contact posts are provided.

The following are the advantages and disadvantages of impressed current anode systems:

(a) Advantages

1. Rectifiers available in unlimited current output.
2. May be designed for long lives.
3. More economical.
4. Possibility of variation of current to suit the changes in the system.

(b) Disadvantages

1. External power is essential.
2. More complicated system for installation.
3. Less economical for smaller jobs.
4. Limited to use below a soil resistivity of 3000 ohms-cm.

5.9 COMPONENTS OF GALVANIC SYSTEMS

5.9.1 ANODES

As mentioned earlier, magnesium and zinc anodes are customarily used in this system. The magnesium anodes are most popular because of their high current output. They have the following advantages:

(a) Favorable position in the emf series (very active).
(b) Non-polarizing.
(c) High current output. An average current output of 500–600 A-h/lb can be obtained assuming the efficiency to be 65%. Magnesium anodes are usually applied in soils of resistivity lower than 3000 ohms-cm. A standard 17 lb magnesium anode will produce 1 A of current for one year or 0.1 A for ten years, and so on. The current output, however, depends on the soil resistivity. With a resistivity of 1000 ohm-cm, the current produced would be 0.1 A. If the resistance is very high, the produced current would be lower. To obtain a maximum efficiency the anodes are surrounded with a mixture of gypsum and bentonite called as *backfill*. The composition of a typical backfill is given in Table 5.1.

The mixture must be 100% capable of passing through a 20 mesh screen and 50% through a 10 mesh screen.

5.9.2 MAGNESIUM ANODES

The details of a magnesium anode are shown in Fig. 5.18. The open circuit potential (no current draw) of a standard alloy magnesium anode is −1.55 V with respect to Cu–$CuSO_4$ reference electrode. The open circuit potential of a high manganese magnesium anode is −1.75 V with respect to a copper–copper sulfate half cell. If iron is polarized to −0.85 V, the driving potential of standard alloy magnesium would be (1.55 − 0.85 = 0.70 V) and that of a high manganese magnesium anode is (1.75 − 0.85 = 0.90 V). The composition of some magnesium anodes is shown in Tables 5.2a and 5.2b.

Table 5.1 Composition of backfill

Element	Percentage
Ground hydrated gypsum	75
Powdered wyoming bentonite (local brand)	20
Anhydrous sodium sulfate	5

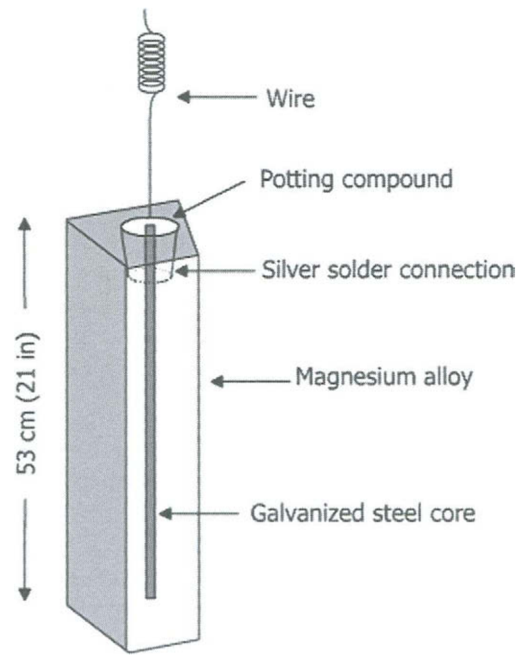


Figure 5.18 Typicl 14.5 kg magnesium galvanic anode

At 100% efficiency, the output is limited by local corrosion cells. To avoid this, magnesium is alloyed with Al and Zn. Practically, an efficiency of 60–70% can only be obtained. Galvomag anodes are used for seawater service. A typical composition is shown in Table 5.3a. The consumption rate is 17.52 lb/A-year. The compositions of high purity and Galvomag Mg anodes are also shown in Table 5.3a.

Table 5.2a Composition of standard magnesium anodes

Element	Percentage
Aluminum	5.30–6.7
Manganese	0.15–min
Zinc	2.50–3.5
Silicon	0.30–max
Copper	0.05–max
Nickel	0.003–max
Iron	0.003–max
Other impurities	0.300–max
Magnesium	Balance

Table 5.2b High manganese magnesium anodes

Element	Percentage
Aluminum	0.010–max
Manganese	0.50–1.31
Copper	0.02–max
Iron	0.03–max
Nickel	0.001–max
Other impurities	0.3–max
Magnesium	Balance

Table 5.3a Specifications of galvomag Mg anodes

Specification	Galvomag
Specifications	
Cu	0.02
Al	0.01 max
Si	–
Fe	0.03
Mn	0.5–1.3
Ni	0.001
Zn	–
Sn	0.01 max
Pb	0.01 max
Mg	Remainder
Efficiency	50%
Potential	−1.70 V Ag/AgCl
Capacity – Ampere hours	1230 per kg 560 per lb

AgCl is a reference electrode

5.9.3 ZINC ANODES

Zinc anodes are frequently used for protection of submarine pipelines. They are commercially available in weights from 5 to 60 lb. Prepared backfill should be used for anodes if they are to be installed in the earth. They have a driving potential of −1.10 V compared to a $Cu–CuSO_4$ reference electrode. The details of zinc anodes are shown in Fig. 5.19.

Specifications of some zinc anodes are given below. Suppliers specifications must, however, be consulted before application. Some commercial specifications and details of zinc anodes are appended to this chapter.

The composition and characteristics of zinc anodes are shown in Tables 5.3b and c.

(a) Characteristics of zinc anodes

(1) Corrosion products insulate the anodes and the anodes are, therefore, installed below the water table in soils with no free carbonate or phosphate so that passivity does not occur.

(2) Zinc is not generally polarized anodically and the theoretical current output can be as high as 372 A-h/lb for a 99.99% pure zinc.

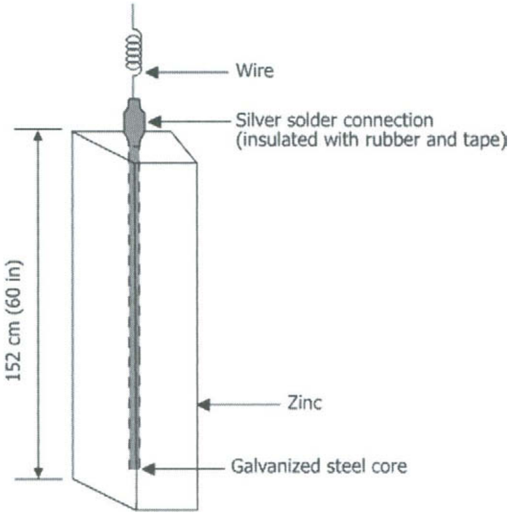


Figure 5.19 Typical 13.6 kg (30 lb) zinc anode

Table 5.3b Zinc anode for soil or fresh water use

Element	Percentage
Aluminum	None
Cadmium	0.004 min
Iron	0.0015 max
Lead	0.006 max
Copper	0.005 max
Impurities (Total)	0.010
Zinc	99.99

Table 5.3c Zinc anode for seawater use

Element	Percentage
Aluminum	0.3 max
Cadmium	0.06 max
Iron	0.003 max
Lead	0.006 max
Copper	0.005 max
Impurities (Total)	0.014
Zinc	Remainder

(3) Zinc can operate up to 95% efficiency and a current output of 335 A-h/lb can be obtained (0.90 × 372 = 335 A-h/lb).

(4) The open circuit potential of zinc is generally −1.10 V with respect to a copper–copper sulfate reference electrode.

(5) Based on a polarization potential of −0.85 V for steel, the driving potential of zinc is 0.25 V.

5.9.4 ALUMINUM ANODES

These are mostly employed for seawater applications. The base metal contains 98–99% of aluminum. Elements commonly added in different types of aluminum anodes are shown in Table 5.4a. Table 5.4b shows the solution potential of various classes of anodes.

Table 5.4a Elements added in various classes of aluminum anodes

Type	Additives
I	3.0–7.0% Zn
II	3.5–9.0% Zn, 0.10–0.5% Sn
III	7.0% Zn, 1% Sn
IV	0.5% Sn
V	0.45% Zn, 0.045% Hg
VI	0.1–0.40% Zn, 6.0–8.0% Mg and 0.08–0.15% Hg
VII	1–5% Zn, 0.1–0.05% Mn and 0.06–0.15% Hg

Table 5.4b Solution potential of aluminum anodes

Type	Open circuit potential ($E_{\mathrm{Cu-CuSO_4}}$)	Working potential (Driving potential)	Consumption rate (kg/A-year)
I	−1.06	−1.00	4.7–3.6
II	−1.10	−1.15–1.25	4.3–3.6
III	−1.35	−1.10	3.3–2.9
VI	−1.43	−0.93–1.30	–
VII	−1.10	−0.93–1.13	–

(a) Characteristics of aluminum anodes

(1) The cost is low and they are light in weight.

(2) The corrosion products do not contaminate the water.

(3) The rate of consumption varies between 7 and 9 lb/A-year. The efficiency varies between 87 and 95%.

(4) The anodes are easily passivated and must be rinsed with NaCl to reactivate. Backfill must be used with aluminum anodes.

(5) The consumption of Galvalum–Aluminum anodes (Fe = 0.08, Si = 0.11–0.21, Zn = 0.35–0.50 and Hg = 0.035–0.40) is 1285 A/h/lb (Table 5.4c). It is a very popular anode.

Table 5.4c Composition of galvalum–aluminum anodes

Galvalum*–aluminum	
Specification:	
Fe	0.08 max
Si	0.1 max
Zn	0.35–0.50
Al	Remainder
Efficiency	90%
Potential	−1.05 V, Ag/AgCl
Capacity – Ampere hours	2830 per kg 1285 per lb

*There are three types; Galvalum I, Galvalum II and Galvalum III

5.9.5 INSTALLATION OF GALVANIC ANODES

Galvanic anode installations are simple compared to impressed current installations. Figure 5.20 shows a single packaged anode installation. The common 17 pound packaged magnesium anodes are commonly used for a packaged installation. When several magnesium or zinc anodes are to be installed at a single location, the anodes are connected to a header wire which is directly connected to the pipeline. Packaged anodes in multiple may be installed as shown in Fig. 5.20. The anode line may be parallel or perpendicular to the pipeline. Zinc anodes are generally kept at a distance of 5 ft from the pipelines, if they are in parallel lines. Magnesium anodes are generally 15–20 ft from the pipelines.

If space is not available and soil resistivity conditions are very low, galvanic anodes are

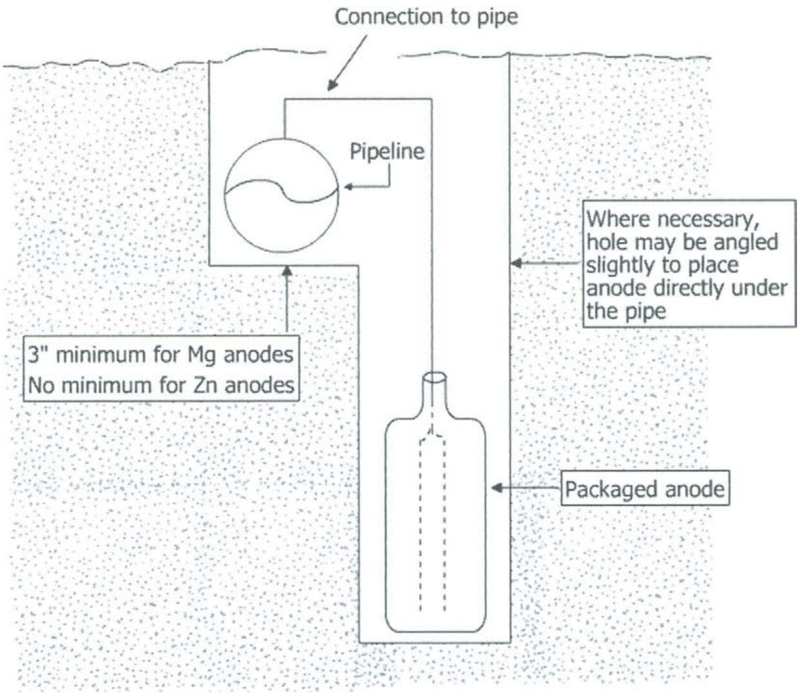


Figure 5.20 Galvanic anode installation for packaged anodes. (From Source: Peabody, A.W. *Control of Pipeline Corrosion*, NACE)

Table 5.5 Anode spacing factors

No. of anodes in parallel	Adjusting factors			
	Anode spacing (feet)			
	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

installed below the pipe. Very deep holes are required to place multiple anodes. The anodes are safer in deep soils as they are not affected by variation in the moisture contents and soil conditions. Due to seasonal changes, non-packaged anodes are frequently used. In this case, the anode and the backfill is not installed as single unit, but separately. Galvanic anode may also be installed horizontally. Table 5.5 shows the anode spacing factors.

5.9.6 CALCULATIONS OF CURRENT OUTPUT OF MAGNESIUM ANODES

The current output of galvanic anodes is affected by the resistivity of the soil. A higher current would be required for a low resistivity soil. The geometry of the anode is also important, for instance, the longer the length of the anode, the higher the current output would be. Lastly, the higher the potential of the alloy, the higher would be the current output. The efficiency of anodes is a major factor even under the best conditions. The Mg anodes, for instance, does not have an efficiency higher than 50%. The current output is an important information which must be known.

The current output of a magnesium alloy can be determined by the following relationship

$$I_{\mathrm{Mg}} = \frac{150\,000\,FY}{\rho} \quad \text{(for an uncoated pipeline)} \tag{5.1}$$

$$I_{\mathrm{Mg}} = \frac{120\,000\,FY}{\rho} \quad \text{(for a coated pipeline)} \tag{5.2}$$

where:

I_{Mg} = current output of magnesium anode

ρ = soil resistivity, ohm-cm

F = factor from Table 5.6

Y = correction factor for pipe-to-soil potential value (Table 5.7)

Example 1

Calculate the current output for a 32 pound packaged magnesium anode buried in a 1750 ohm-cm soil for the protection of a bare pipeline where the expected resultant pipe-to-soil potential is −0.85 V.

Solution:

The given data for a 32 pound anode is: $F = 1.06$ from Table 5.6. From Table 5.7, the Y factor for a pipe-to-soil potential of −0.85–1.00. Pipe-to-soil potential is the potential between the pipe and the surrounding soil.

Putting the data in equation (5.1), one obtains

$$I_{\mathrm{Mg}} = \frac{150\,000 \times 1.06 \times 1}{1750} = 90.9\,\mathrm{mA}$$

For multiple anodes, the current output obtained for a single anode should be multiplied by an adjusting factor (Table 5.5).

Extending the above example further for a 4 parallel anodes, 10 ft apart, one obtains:

3.455 (adjustment factor – Table 5.5) × 90.9 mA
= 310.50 mA

Similar calculations can be made for the output of magnesium anodes used with the coated pipelines. Equation (5.2) would be used under such conditions.

Table 5.6 '*F*' factor for different anode weights

Anode weight (pounds)	Details	Factor 'F'
Standard Anodes:		
3	(Packaged)	0.53
5	(Packaged)	0.60
9	(Packaged)	0.71
17	(Packaged)	1.00
32	(Packaged)	1.06
50	(Packaged – anode dimensions 8″ diam × 16″)	1.09
50	(Packaged – anode dimensions 5″ × 5″ × 3.1″)	1.29
Long Anodes:		
9	(2.75″ × 2.75″ × 26″ backfill 6″ × 31″)	1.01
10	(1.5″ × 1.5″ × 72″ backfill 4″ × 78″)	1.71
18	(2″ × 2″ × 72″ backfill 5″ × 78″)	1.81
20	(2.5″ × 2.5″ × 60″ backfill 5″ × 66″)	1.60
40	(3.75″ × 3.75″ × 60″ backfill 6.5″ × 66″)	1.72
42	(3″ × 3″ × 72″ backfill 6″ × 78″)	1.90
Extra Long Anodes:		
15	(1.6″ diam × 10′ backfilled to 6″ diam)	2.61
20	(1.3″ × 20′ backfilled to 6″ diam)	4.28
25	(2″ diam × 10′ backfilled to 8″ diam)	2.81

Table 5.7 '*Y*' correction factors

P/S	Magnesium	Zinc
−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

Example 2 – Current Output of Zn Anodes

A bare pipeline is to be protected by zinc anode. A 32 pound packaged is to be used for protection. The anode is buried in a 750 ohm-cm soil with an expected pipe-to-soil potential of −0.85 V. Determine the current output.

$$I_{\text{Zn}} = \frac{50\,000 \times F \times Y}{\rho}$$

Putting the data from the tables, as in the case of Mg anodes:

$$I_{\text{Zn}} = \frac{50\,000 \times 1.06 \times 1}{700} = 70.7\,\text{mA}$$

For a four parallel anodes, 10 ft apart, the estimated output would be: (*The factor for 4 parallel anodes, 10 ft apart is 3.445*) (Table 5.5)

$$I = 70.7 \times 3.455 = 243.92\,\text{mA}$$

5.9.7 CALCULATIONS OF NUMBER OF ANODES REQUIRED AND SPACING

The number of anodes required for a pipe or any bare structure can be conveniently estimated as per example given below.

Suppose 10 000 ft of a bare 4 inch pipeline is to be protected and if the resistance of soil is 1000 ohms per cubic centimeter, the pipe requires 1 mA/ft^2 for protection. The anode output curve shows 100 mA per anode in this type of soil. The number of anodes can be easily calculated as shown below.

Calculations

(a) First calculate the area of the pipe:

$$\text{Area} = \frac{4 \times 3.14 \times 10\,000}{12} = 10\,500\ \text{ft}^2$$

$$\text{Total current requirement} = 10\,500 \times 1.0 = 10\,500\ \text{mA}$$

Number of anodes required

$$= \frac{\text{Total current required}}{\text{Current output of a single anode}}$$

$$= \frac{10\,500\ \text{mA}}{100\ \text{mA/anode}} = 95\ \text{anodes}$$

(b) Total current requirement =

$$\text{Protected area (m}^2) \times \text{Current density (A/m}^2)$$

or

$$\text{Protected area (ft}^2) \times \text{Current density (mA/ft}^2)$$

(c) Total weight of anode material required:

$$\frac{\text{Current (A)} \times \text{Design life (years)} \times 8760}{\text{Capacity A-h/kg}}$$

5.10 IMPRESSED CURRENT SYSTEM

In contrast to the galvanic anode system, the flow of current from the anode to the cathode is forced from a DC source in the impressed current system. Thus, whereas the current is provided by the corrosion of the electrode in the anodic galvanic system, the electrode acts as a conductor and hardly corrodes in the impressed system and the AC input is transformed and rectified to a varying DC voltage. A transformer rectifier is the most important component of the system.

Figure 5.21 shows a schematic diagram of an impressed current cathodic protection system. The direct terminal supply is obtained from a transformer rectifier (T/R unit) designed to step down normal alternating mains voltage and then rectify this to the direct current. This output is adjustable over a wide range to suit requirements. An AC power supply with an ammeter is connected to the rectifier. A switch box is installed in the AC circuit which contains a magnetic or thermal circuit breaker to protect the rectifier against overloads. The AC goes to the rectifier unit. It passes through the primary coil (P), the resulting magnetic field continuously expands, contracts and reverses direction. The changing field induces AC in the secondary coil, that is proportional to the turns ratio between the two coils.

$$\frac{\text{Primary turns}}{\text{Secondary turns}} = \frac{\text{Primary volts}}{\text{Secondary volts}}$$

The rectifier cells are shown from B to E. Their function is to allow the current to flow in one direction and to block it in the opposite direction. When AC is applied to the AC terminal of the rectifier, DC appears at the output. The negative terminal of the rectifier assembly is connected to the pipeline (G) and the positive to the anode bed. The five anodes are represented by numbers 1 to 5. The anodes are surrounded by a mixture of coke breeze. The anodes are energized by the rectifier and they are made of silicon cast iron, steel scrap, platinized titanium, graphite or lead silver.

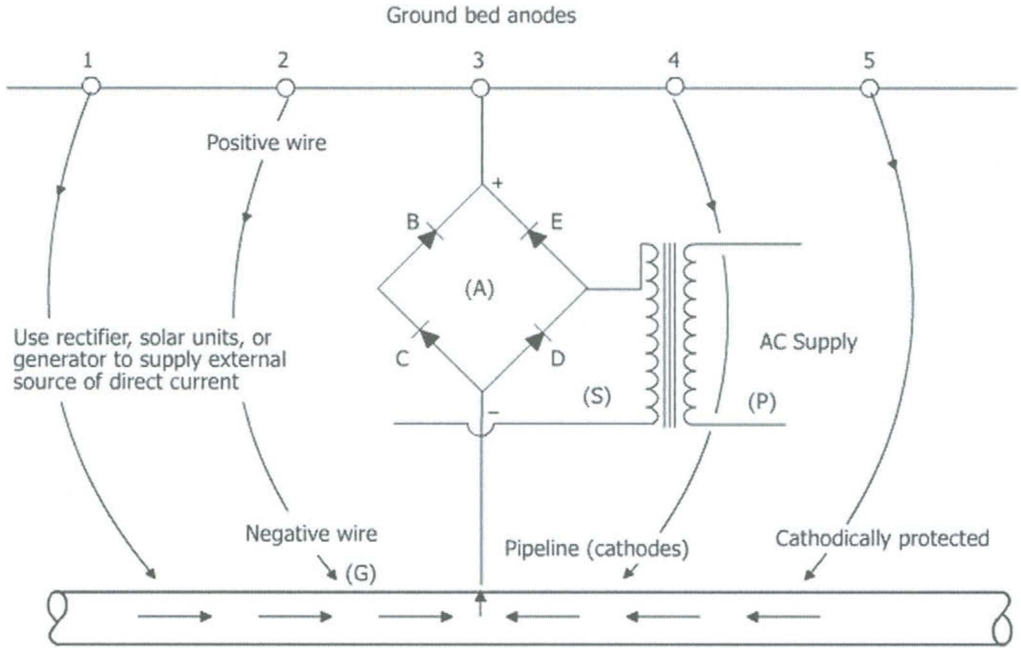


Figure 5.21 Schematic diagram of impressed current cathodic protection system

The electrons from the rectifier enter the pipe or any structure to be protected. The anodes are placed in a trench, which is termed a ground-bed. As a matter of practice, the anodes are placed in the lowest resistivity soil.

Details of a typical impressed current installation is shown in Fig. 5.22. The AC power unit is connected to the rectifier (R). The negative terminal is attached to the structure (S) and positive terminal to the ground-bed. The anodes are silicon cast iron and represented in the figure by A_1 to A_4. The individual anode leads are brought into a junction box (J) and a shunt is inserted in each anode lead. The junction box allows the measurement of current output of individual anodes by determining the IR drop. The anodes can be connected directly to the positive terminal of the rectifier by a ring main cable system shown in the figure or via a control box (direct connecting system) to monitor the current output above ground.

5.10.1 ADVANTAGES AND DISADVANTAGES OF IMPRESSED CURRENT SYSTEM

(a) Advantages

(a) One installation can protect a large area of metal.

(b) The system can be used for a wide variety of voltage and current requirement.

(c) Schemes can be designed for life in excess of 20 years, if required.

(d) Current requirements and potentials can be easily adjusted to the varying needs of protection.

(e) Can be applied to a wide range of structures.

(f) Requires generally a small total number of anodes.

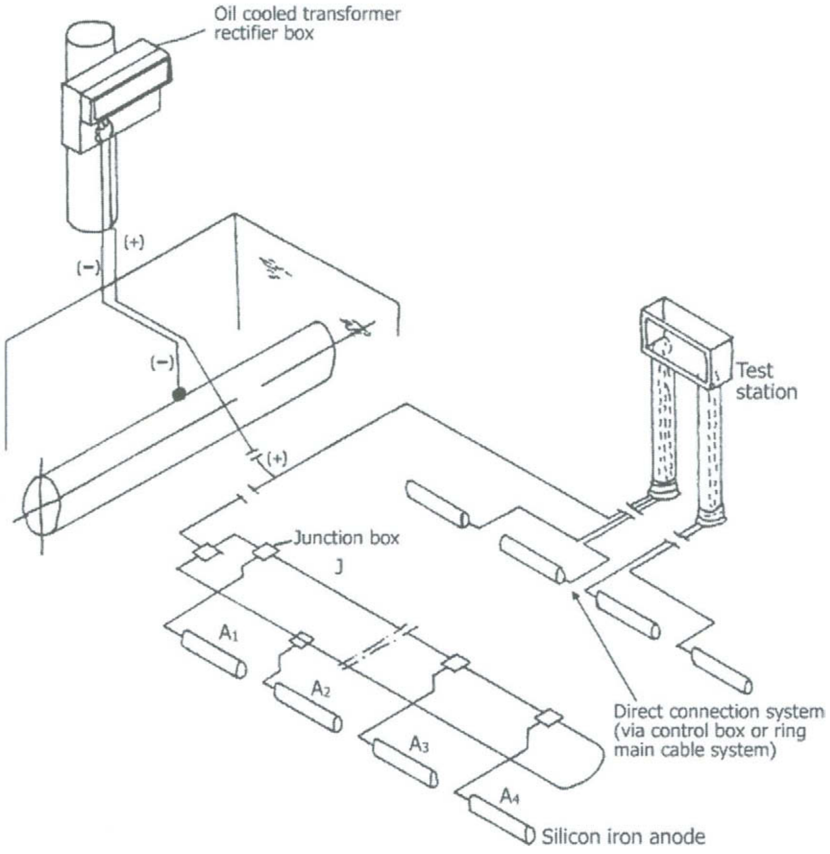


Figure 5.22 Details of typical power impressed ground-bed installation

(g) Requires simple controls which can be automated.
(h) The use is less restricted by soil resistivity.
(i) A large area can be protected by one installation.

(b) Disadvantages

(a) Possibility of interference effects on other buried structures.
(b) Regular maintenance is essential.
(c) Electrical power cost is high.
(d) Power failures can cause serious problems, and faults may go unnoticed for long times.

5.11 COMPONENTS OF IMPRESSED CURRENT SYSTEMS AND AC/DC SYSTEMS

5.11.1 POWER SOURCE

Rectifiers are commonly used as the source of power. Although rectifiers are most commonly used as a source of DC power for the impressed current systems, other external power sources, such as wind generators, thermoelectric generators and wind-driven generator units can also be employed if conventional AC power is not available.

5.11.2 RECTIFIERS

The rectifier units consist of a transformer, rectifier stacks, meter, switch and the transformer tap connections. The rectifiers convert AC to DC current. The transformer is used to step down the supply of voltage to that required for operation of the rectifier stacks. There are two types of rectifiers:

(a) Selenium (Oil and Air-cooled) Rectifier

The selenium air-cooled rectifiers have lower initial cost than the oil immersed units, but have poor ventilation. The oil immersed rectifiers are less vulnerable to air and dust than the air-cooled type. In either case, the structure to be protected is connected to the (–) negative terminal of the rectifier. The installation is normally at 8 miles interval for 36″ pipe and 12 miles for 24″ pipe.

(b) Silicon (Oil and Air-cooled) Rectifier

The silicon rectifiers (oil and water-cooled) have longer lives and higher efficiency compared to selenium rectifiers. The oil-cooled types are not susceptible to damage by dust and dirt. They are 20–50% smaller in size than the selenium rectifiers.

5.11.3 COMPONENTS OF A RECTIFIER

The three-phase bridge is the most common circuit for rectifiers operated from a three-phase AC power line. Each phase of a three-phase AC current is spaced 120 electrical degrees apart and therefore the voltage of each secondary winding reaches its peak at different times.

Figure 5.23 shows the operation of a single-phase bridge rectifier. The direction of flow reverses 60 times per second for 60 cycles AC. In a positive half-cycle (diagram A), current originates at T_1 on the secondary winding. It is blocked by D_3 (silicon diode). The current, therefore, flows through direction D_1, follows the path (3) and through diode D_4 it enters the negative terminal T_2. In the next half-cycle (1/120th) of a second later, polarities at T_1 and T_2 are reversed (see diagram B). The current is blocked by diode D_4 and flows through D_2, follows the path (3) through D_3 in the same direction as before. The load R_L thus receives energy in the form of pulses at 120 per second.

Although three-phase rectifiers are used as mentioned before, each single bridge shares a pair of diodes with one of the other bridges. The three-phase bridge is like three single-phase bridges, with each bridge sharing a pair of diodes with one of the other bridges.

A rectifier consists of three important components: circuit breaker, transformer and rectifying elements (stacks) (Fig. 5.24). Brief details are given below.

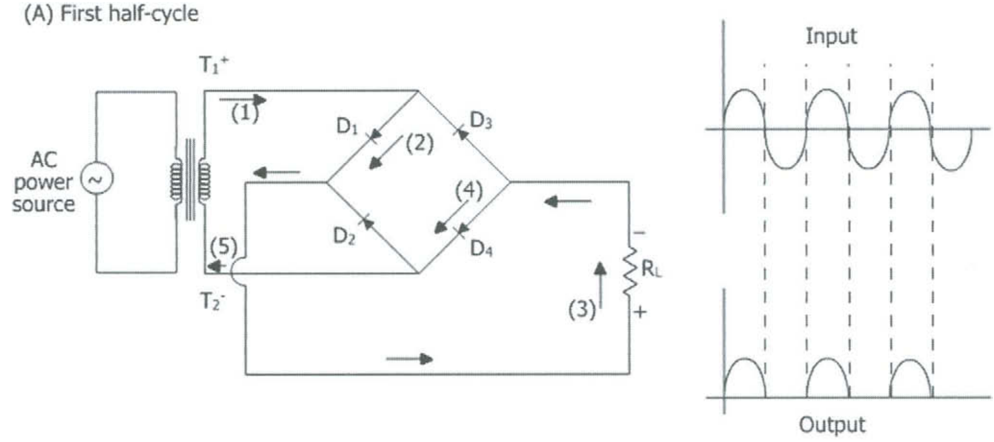
(a) Circuit breaker

These are basically switches with an internal mechanism which opens the switch when the current exceeds a prescribed designed limit. They also serve as 'on and off' switches. There are two types of switches: (1) magnetic and (2) thermal. The circuit breaker protects equipment from over loading.

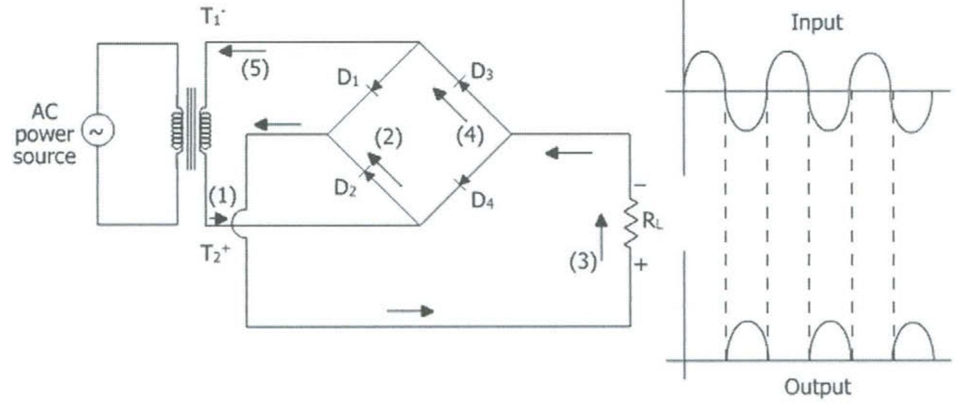
In the magnetic type, a coil is woven around a brass tube and a magnetic field is set up by a current flowing in the coil. The magnetic slug is held at one end of a tube by a spring. The magnetic field attracts the slug, but at or below the rated current the slug does not move. At overload, the magnetic field pulls the slug into the coil. When the slug is drawn to the opposite end of the tube, the circuit is completed for the trip mechanism and the breaker switch trips. The movement of the magnetic flux is slowed down and a time delay is provided. The breaker can trip on to 101–125% of the rated current. Overloads of ten times the rated currents can be sustained. The dropping is very fast when the overload is ten times.

In thermal magnetic breakers, the thermal tripping is caused by the flowing current through the resistor close to the bimetallic strip. When the current exceeds the rated value, the bimetallic element trips the

(A) First half-cycle



(B) Second half-cycle



(C) Final result

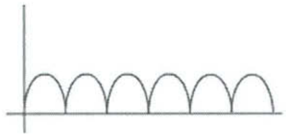


Figure 5.23 Operation of a single phase bridge rectifier. Arrows show conventional (postitive) current flow direction

breaker and a long time delay is involved before the breaker can be closed.

(b) Transformer

This consists of two coils of wire wound around an iron core. The coils are not connected electrically, but the core provides a magnetic link between them. AC voltage is applied to one coil (primary), the changing magnetic field crosses to the other coil (secondary) and induces a voltage in it. The changing field induces the AC voltage in the secondary coil that is proportional to the

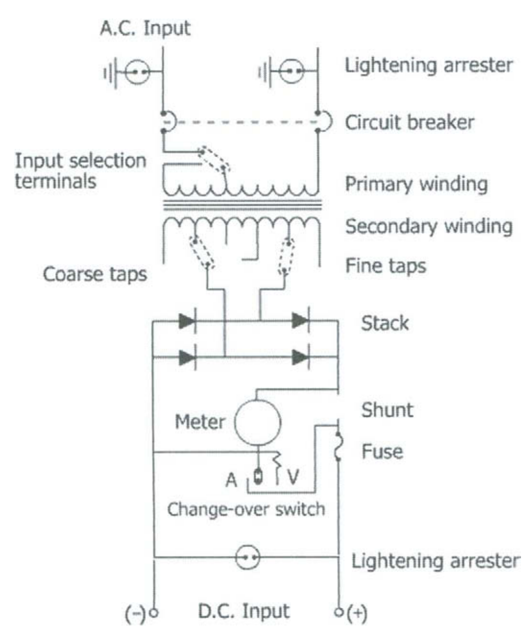


Figure 5.24 Components of a rectifier

turns ratio between the two coils.

$$\frac{\text{Primary turns}}{\text{Secondary turns}} = \frac{\text{Primary volts}}{\text{Secondary volts}}$$

(c) **Rectifier cells**
The change of AC power to DC is done by rectifying elements. They act like check valves by offering low resistance to current flow in one direction and high resistance in the other direction. The function of the rectifying element is to allow the current to flow readily in one direction and to block current flow in the opposite direction. The Selenium cell is the most common rectifier cell. Selenium is applied to one side of an aluminum base plate which has been nickel plated. A thin metallic layer is applied over the selenium layer. This layer acts as counter electrode. It collects the current and provides low resistance to the contact surface. These cells may be arranged in stacks or parallel to produce the desired voltage and current rating.

5.11.4 RECTIFIER EFFICIENCY

This is the ratio between the DC power output and AC power input. Rectifiers are used as a source of DC power. Rectifiers convert the AC current (60 cycles) to DC current through rectifier operated at maximum efficiency at the full rated loads.

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

An efficiency filter can be used to minimize the ripples.

5.11.5 CABLES

Cable conductors to the anodes are made from copper or aluminum. These conductors must, therefore, be insulated. High-density polyethylene has good properties with respect to abrasion and high-temperature while maintaining excellent dielectric properties. Technical information about cables is provided by the manufacturers.

5.11.6 INSULATION AND ELECTRICAL CONTINUITY

The structure to be protected must be free from all interconnected metal work in order to limit the flow of electric current on the structure. This is made possible by electrical insulation. It is the condition of being electrically isolated from other metallic structures. The term insulation is used interchangeably with isolation. The use of isolated flanges and joints is common in pipelines.

5.11.7 INSULATION OF INSULATING FLANGES

Insulating flanges are installed to isolate the cathodically protected buried pipelines from above-ground pipelines. An insulating kit consists of a non-conducting gasket separating the flange faces, an insulating sleeve and a washer for the bolt (Fig. 5.25a). Details of an insulated flange

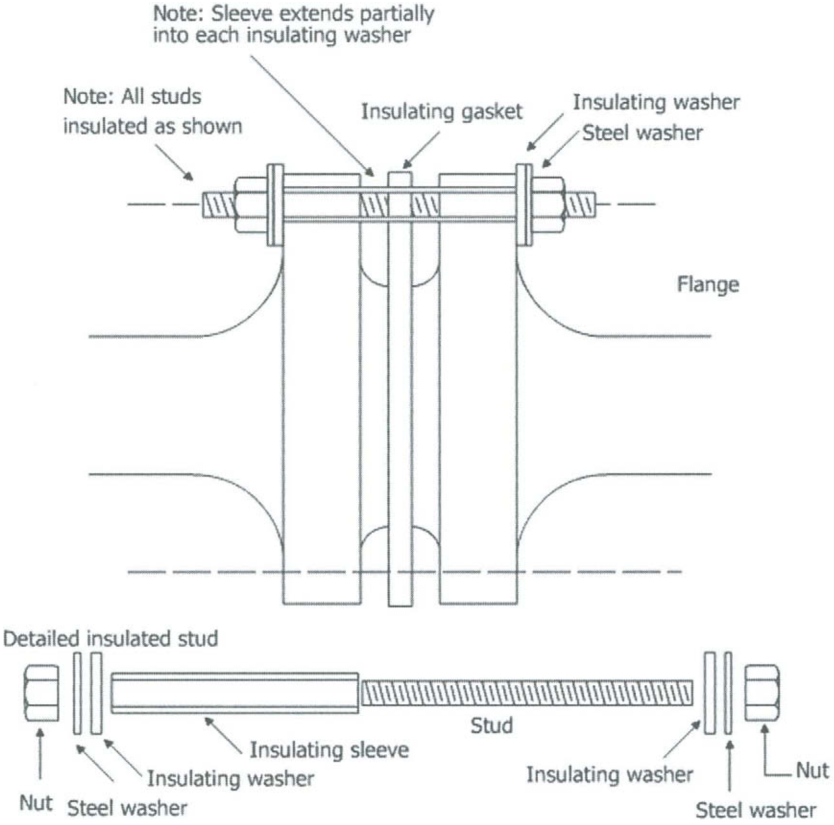


Figure 5.25a Insulating flange kit

are shown in Fig. 5.25b. Insulated flange sets are assembled prior to installation.

5.11.8 ISOLATION JOINT

It is a flangeless factory assembled pipe-length which incorporates an insulating coupling.

5.12 TYPES OF GROUND-BEDS

There are two types of ground-beds:

(1) Close ground-bed system (represented by distributed anode system)
(2) Remote ground-bed system.

5.12.1 CLOSE GROUND-BED SYSTEM

In a situation where only a limited amount of pipeline length is to be protected, distributed anodes are used. In congested areas, such as in tank farms, pipeline terminals or pump stations, close ground-beds or anodes have been used effectively. It is apparent that the density for the current flowing from the anode becomes less and less with distance. The highest potential drop is observed in the earth where the current density is highest. Most of the resistance to remote earth for an anode is, therefore, confined within the first few feet. In the close system, the positive potential gradient of the earth is used with advantage. The earth in the vicinity of the

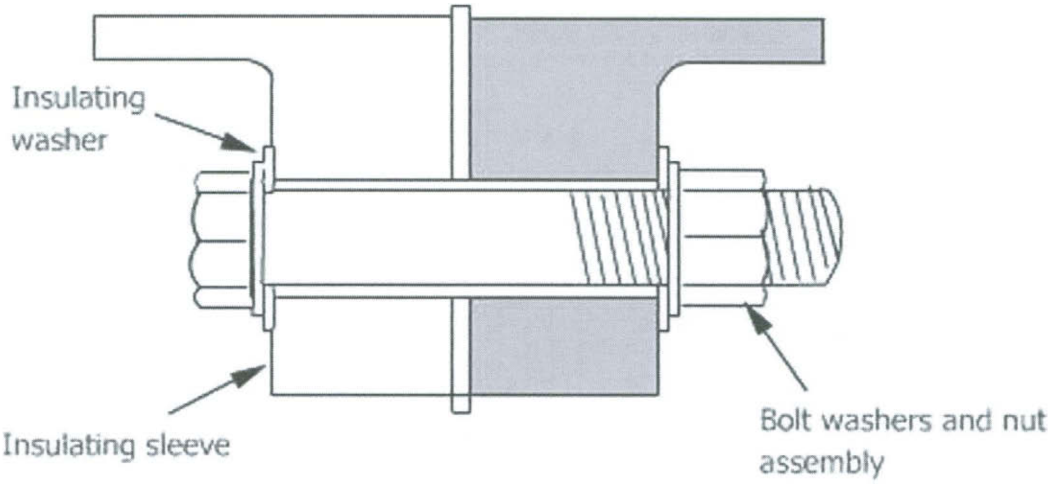


Figure 5.25b Details of insulated flange 12″ B.S.T.E.

anode is positive with respect to the remote earth. The positive earth is, therefore, very close to the anode, if the anodes are placed very close to the pipeline. The area of influence (area where voltage drop is caused by the pipeline) of the pipeline would pass through the earth which is at positive potential as compared to the remote earth (outside the area of influence with zero voltage drop). Consequently, a limited area nearest to the anode will attain cathodic protection because of the sufficient potential difference between the soil and the pipeline brought about by close anodes. In the above system, the potential of the local earth is changed rather than changing the potential of the pipe. The magnitude of the earth potential change depends on the voltage impressed on the anode and not on the current discharged from the anode. The potential to earth must be known so that the magnitude of earth potential change necessary to bring the potential of the pipe to −0.85 V is determined. The current requirements of the power source are designed after collecting information on the resistance of the parallel anodes and resistance of the cables and the back emf between pipeline and anode. In this system the anodes are required to be put close together. If the distance to be protected is very long, sufficient voltage for protection would not be obtained and, therefore, closer space between anodes may be required.

5.12.2 REMOTE GROUND-BED

Basically, there are two types of anode ground-beds, close and remote. The terms, close and remote, are related to the area of influence in the electrolyte around the anode. In the case of a remote anode ground-bed surrounding the pipe, the pipeline is negative with respect to the remote earth as opposed to the close ground-bed system, where the local earth is made positive with respect to the pipe. The anode is so located that only a small area of structure is influenced by it. The length of pipeline that can be protected by close ground-bed anode depends on the voltage impressed by the anode. Only limited areas of structure are protected.

In the remote ground-bed, the current flowing to the pipeline from a DC source causes a voltage drop in the soil adjacent to the pipe. The ground-bed is considered remote if there is no overlapping between the area of influence surrounding the pipe and the area of influence surrounding the ground-bed (Fig. 5.26). The potential gradient readings continue to decrease

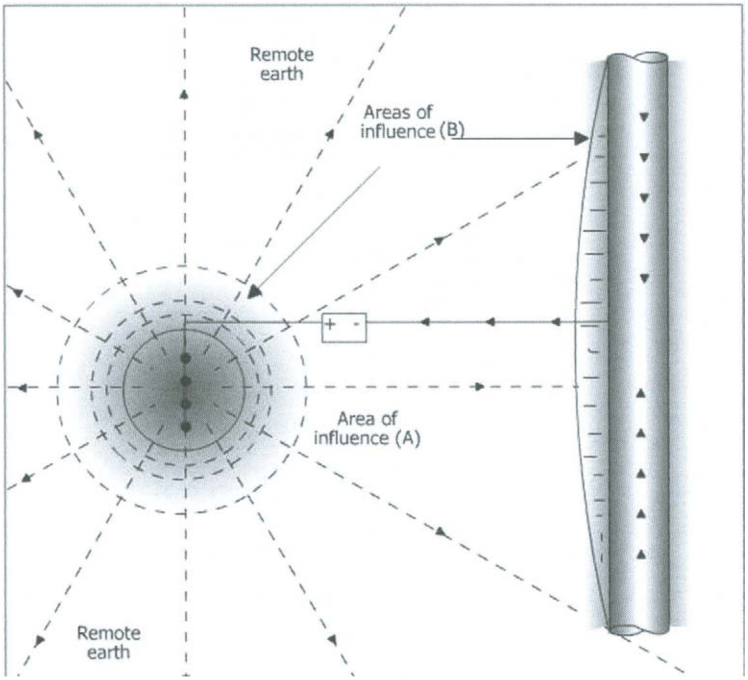


Figure 5.26 Two areas of influence caused by a remote ground-bed

until at a point of is no further decrease, which is the remote location. At this position, the current density and potential gradient approach zero. Large sections of structure may be protected, the only limiting factor being the resistance of the pipe itself (Fig. 5.26). The area of influence ends where there is no change in the soil potential. Beyond this point the earth is remote. When the current enters the remote earth there is no more resistance from the soil. Remote earth is considered as an infinite conductor for all practical purposes. Under such conditions, the current flows from the ground-bed, through the mass of the earth and then to the pipeline which is to be protected.

5.12.3 GROUND-BED DESIGN

The basic requirement of a good cathodic protected system is the protection of the structure at a minimal total annual cost over a protected period of life. It is not always the ground-bed with the least resistivity that is most suitable, but rather the ground-bed that fits into the economics of the design.

(a) Vertical Impressed Current Types

These are very commonly used for the impressed current system. A typical vertical anode installation is shown in Fig. 5.27. This type of ground-bed has a low resistivity which is an outstanding advantage. Almost all of the current flow is from the anode to the backfill by direct contact so the consumption of the material is mostly at the edge of the backfill. Vertical anodes are installed with a carbonaceous backfill.

(b) Horizontal Type

Anodes are installed in a continuous or non-continuous coke breeze bed in a horizontal ditch.

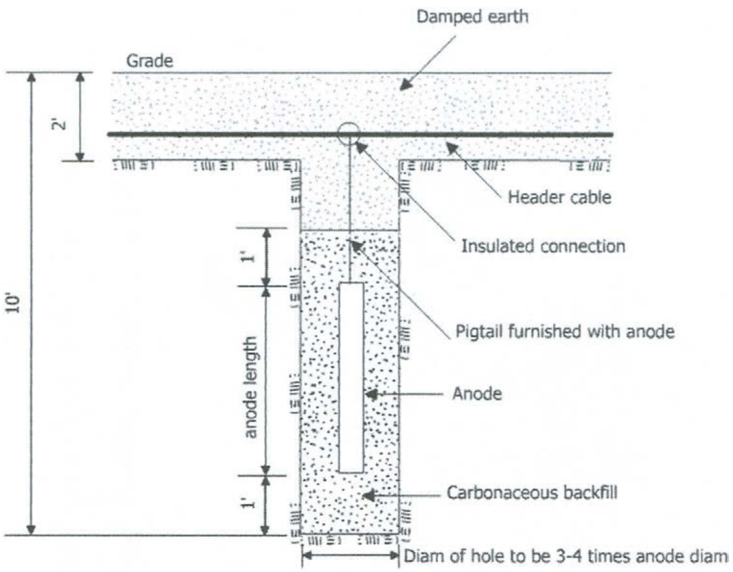


Figure 5.27 Typical vertical anode installation for impressed current cathodic protection system

These are used because of the near presence of the other structures and also because of the limitations of the soil depth. A typical installation is shown in Fig. 5.28. The anodes should always be placed in moist soil or in hygroscopic backfill so that it does not dry out during the dry season.

(c) Deep Vertical Anodes

A deep ground-bed is defined as a ground-bed in which the anodes are installed vertically in a drilled hole at a depth of 50 ft or more. A typical deep anode installation is shown in Fig. 5.29.

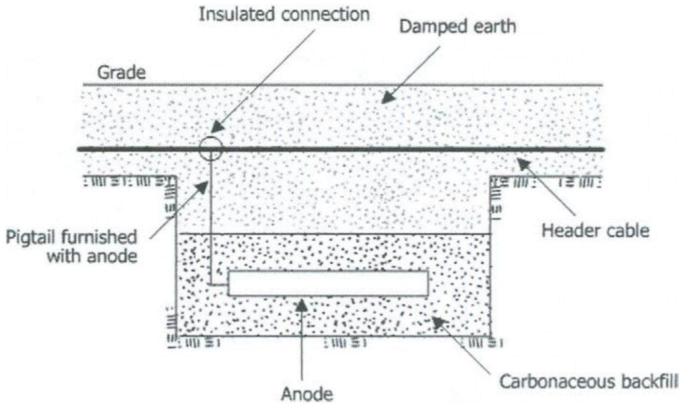


Figure 5.28 Typical horizontal anode installation for impressed current cathodic protection system

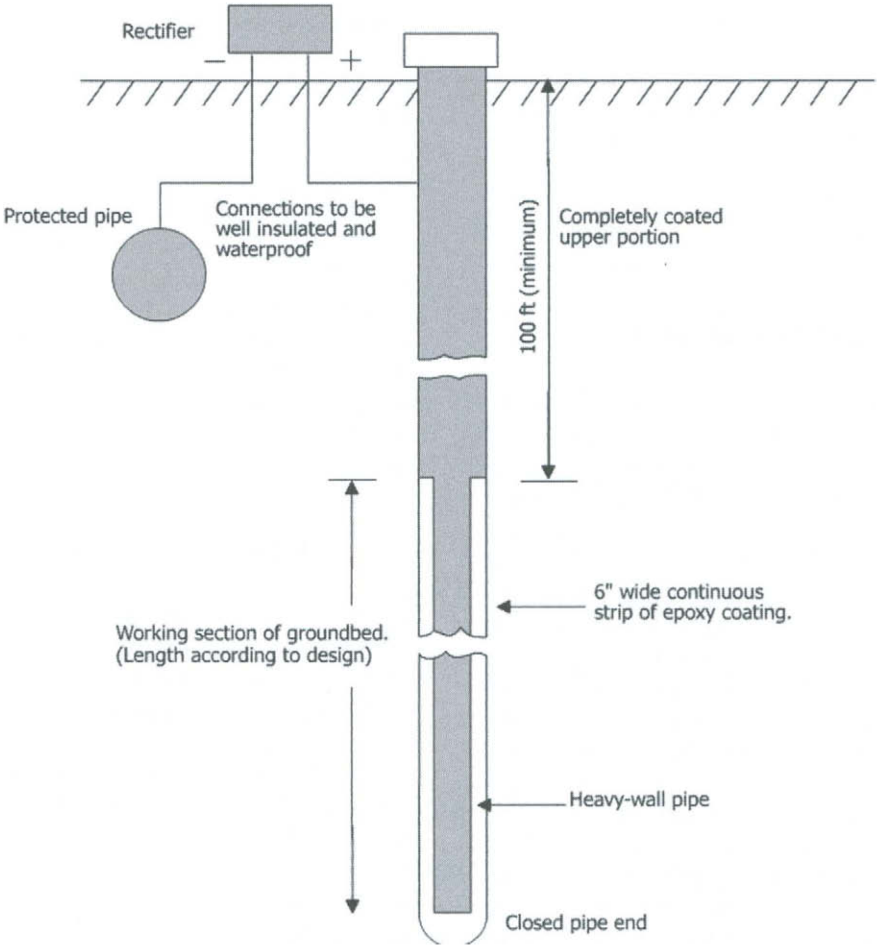


Figure 5.29 A heavy-wall deep impressed current anode ground-bed 'Casing method.' (From Peabody, *Control of Pipeline Corrosion*, NACE. Reproduced by kind permission of NACE, Int., Texas, USA)

Such anodes are used in areas where the resistivity of the soil is very high, such as in deserts. They are also suitable for areas where otherwise a large ground-bed electrically remote is required to keep the resistance to minimum. If the surrounding deep soil has a low resistivity, excellent distribution of current is obtained. The designs vary according to soil condition.

5.13 MAJOR IMPRESSED CURRENT ANODES

The following are the major impressed current anodes:

5.13.1 HIGH SILICON CAST IRON

Silicon iron anodes are composed of iron as the base metal with about 15% silicon and 1% carbon, additionally alloyed with chromium (5%), manganese (1%) and molybdenum (2%). The maximum current output is 50 A/m^2 and the rate of consumption is between 90 and 250 g/A/year. Anodes containing Mo are used in high-temperature media.

A typical analysis of high silicon cast iron anode is shown below in Table 5.8. It is generally used for onshore cathodic protection applications.

Table 5.8 Analysis of a typical silicon cast iron anode

Element	Percentage
Silicon	14.35 min
Carbon	0.85 max
Manganese	0.65 max
Iron	Remainder

5.13.2 METAL SCRAP

It has the advantage of being cheap and abundantly available. The rate of consumption of mild steel scrap pipes, rails and cast iron scrap castings varies. For mild steel scrap the rate of consumption is 6.6–9.0 kg/A/year, and for cast iron the rate is 0.9–9.0 kg/A/year. Steel in the form of old railroad line, pipes and structural sections is used. The rate of consumption of steel scrap is generally uniform. The material is mostly available in the form of long and thin section and depending whether these sections are installed horizontally or vertically, they may encounter soil strata with different resistivities resulting in non-uniform corrosion. Cast iron has the advantage of being thick in section and of such form that any one piece will be in soil of more or less uniform resistivity. Also, a graphite surface is left exposed as the outer iron is consumed. The remaining iron in the form of a graphite, therefore, acts as a graphite anode.

5.13.3 GRAPHITE ANODES

These have the advantages of long-life corrosion protection, low maintenance cost and high efficiency. The typical anode current density is between 10.8 and 40.0 A/m^2 (1.4 A/ft^2). The rate of consumption is between 0.225 and 0.45 kg (0.5 and 1.0 lb) per year. These are generally cylindrical in shape, although other forms are available.

5.13.4 PLATINIZED TITANIUM

These anodes are used for salt water or fresh water where the conductivity is very low. Titanium develops an adherent oxide layer of high electrical resistance. The oxide layer prevents corrosion by acting as a barrier. Titanium acts as an inert support for the platinum. Platinum can withstand very high current density and it is generally applied to a small area only. The platinum layer is normally 2.5 microns in thickness and it has an estimated life expectancy of 10 years. Titanium sheets, 1–2 mm thick with a platinum coating of 2.5–5.0 μm, can be loaded to 10 A/dm^2 or over a period of years. Rod anodes of 10–25 mm diameter are used frequently for protection of vessels, pipes, condensers, heat oil terminals, etc. Current densities up to 50 A/ft^2 (540 A/m^2) can be obtained. The anode should, however, be used at a low voltage.

5.13.5 LEAD ANODES

Lead anodes are made of various lead alloys, such as Pb–1Ag–6Sb and Pb–1Ag–5Sb–1Sn. The density of a lead anode is around 11.0 to 11.2 g/cm^3.

Pb-1Ag-6Sb has a capacity of 160–220 A/m^2 and a consumption rate of 90 g/A/year or 0.009 kg/A/year at a current density of 10 A/ft^2 (108 A/m^2). The other anode containing 10% Sn and 5% antimony has a capacity of 500 A/dm^2 and the rate of consumption 0.3 to 0.8 kg/year. This alloy has good mechanical properties, and can be extended to any shape. Lead–silver or lead–platinum anode with a diameter of 7.5 cm, length 75 cm and weighing 36 kg or with a diameter of 5 cm, length 180 cm and weighing about 45 kg are used in the form of round anodes to protect corrosion of marine structures. These are also used for protection of ships.

5.14 PROTECTION OF SUBMARINE PIPELINES

Pipelines in seawater are protected by so-called bracelets (annular anodes) as shown in Fig. 5.30. In marine structures, corrosion is at maximum at a small distance below the water line and decreases with depth. Corrosion is less severe in mud. For protection of bare steel in seawater, an initial current density of 15 mA/ft^2 (161 mA/m^2) is required, and this decreases after some time

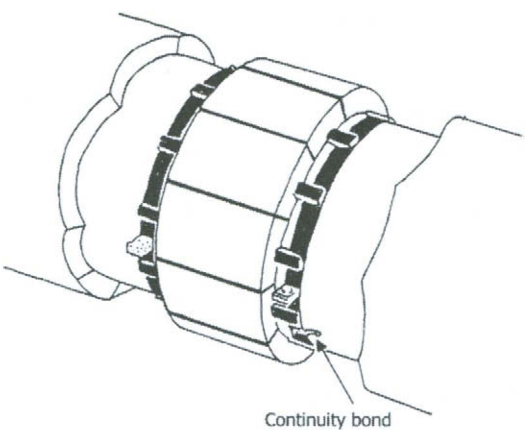


Figure 5.30 Bracelet type of anode for marine application. (From B.K.L. Cathodic Protection Division, Birmingham, England)

to 5 mA/ft^2 or (43 mA/m^2). In the impressed current system non-consumable graphite anodes are required, whereas in the galvanic system a magnesium anode is the best material. Zinc and aluminum anodes are also used as galvanic anodes, but the cost is high.

The protective current densities for steel structures in various seawaters are given in Table 5.9a. The current requirement of steel is affected by the degree of hardness as shown in Table 5.9b. The current required for protection of steels in various environments is shown in Table 5.9c.

Complete protection of buried steel or iron may require 0.75–5.0 mA of current per square foot of the surface. On a well-coated line, the current may be as low as 0.01–0.2 mA/ft^2.

Table 5.9a Protective current requirements in different seawater

Area	Protective current requirements (A/m^2)
Gulf of Mexico	80–150
Nigeria	85
Alaska	250
Arabian Gulf	65–85
North Sea	90–150
U.S. West Coast	24

Table 5.9b Degree of hardness *vs* the protective current density

Carbonate, hardness (Degree of hardness)	Protective current density (mA/m^2)
<2	250–320
2–10	100–150
>10	70–120

Table 5.9c Recommended current densities

Environment	Current density (mA/ft^2)	Current density (mA/m^2)
Soil	0.75–5.0	40–58
Fresh water	1–3	11–32
Seawater	4–5	43–64
Moving seawater	1–3	11–32
Sea mud	1–3	11–32

The potential necessary to protect buried steel is −0.85 V, however, in the presence of sulfates, reducing bacteria a minimum potential of −0.95 V with respect to copper sulfate electrode would be necessary. Approximately 15–100 mA/ft^2 current is needed for protection of bare steel in sluggish water. In rapidly moving water, 1–10 mA/ft^2 for bare steel in a soil would be necessary. Current requirements in various environments can be found abundantly in the literature as well as cathodic protection specifications. For submarine pipeline, a current density of 5 mA/ft^2 is required.

5.15 DESIGN PARAMETERS IN CATHODIC PROTECTION

The basic design requirement for cathodic protection is the choice of current density per square foot or square meter of the surface area to be protected. The choice of current density can vary from something in the order of 100 mA/ft^2 for a bare structure in water to as low as 0.0001 mA/ft^2 for well-coated pipes or structures of high resistivity. To estimate the current requirements, knowledge of soil resistivity is of a primary importance. The following are the major characteristics of soils:

(1) Sandy-type soils are less corrosive than non-homogeneous soils.
(2) Homogeneous soils are less corrosive than heterogeneous soils.
(3) Well aerated soils are less corrosive than sparsely aerated soils. The more aerated soils tend to be brown in color.
(4) Soils low in organic matter are less corrosive than soils with high amount of organic matter.
(5) High acid and high alkaline soils (high pH) are more corrosive.
(6) Soils containing sulfate reducing bacteria are more corrosive than soils free from this bacteria.
(7) Soils having low electrical resistivity are more corrosive than soils having high electrical resistivity.

The soils can be classified as below with respect to the corrosivity of steel and iron (Table 5.10).

5.16 CURRENT REQUIREMENTS

Generally, the quantity of current varies with the type of soil and the quality of coating. The current requirement for an uncoated structure may be seventy times the current requirement for a coated structure. For instance, 10 miles of well-coated pipelines (24″) may require about 8 A for protection compared to 560 A required by a non-coated line.

Table 5.10 Classification of soils according to corrosivity of steel and iron

Soil Resistivity	Tendency to Corrode
0–1000 ohm-cm	Very corrosive
1000–3000 ohm-cm	Corrosive
3000–5000 ohm-cm	Mildly corrosive
10 000 and above	Non-corrosive

It is necessary to experimentally conduct a current requirement test for the structures to establish the magnitude of power requirement for the system to be installed.

As a rough guide, the following current densities would be required to ensure anode life for 10 years in soils of different resistivities.

800 ohm-cm and below 300 mA
800–200 ohm-cm, 180 mA
2000–3000 ohm-cm, 90 mA

5.17 BACKFILL

Galvanic anodes are surrounded by a backfill which is usually a mixture of gypsum, bentonite, and clay. Table 5.11 shows a typical composition of a backfill.

The backfill for galvanic anodes serves the following purposes:

(1) It isolates the anode from the surrounding soil and protects the anode from the effect of chemicals contained in the soil.
(2) It provides a lower anode-to-earth resistance because of its low resistivity.
(3) It provides a higher current output because of the low resistivity of the surrounding soil.

For the impressed current anodes, the standard material is coke. The physical and chemical analysis of the coke breeze is given in Tables 5.12a and 5.12b, respectively.

Backfill should be installed very dry around the anodes except in desert conditions. The coke breeze provides a low resistance between anode and earth and a longer life for the impressed current anode. Because the greater part of the current passes from the anode to the backfill particles, the anode is consumed at a slower rate. Table 5.13 shows the amount of backfill required.

Table 5.11 Composition of backfill

Soil Resistivity (ohm-cm)	Gypsum (%)	Bentonite (%)
Below 3000	50	50
3000 and above	75	20

Table 5.12a Physical analysis of coke breeze

1% maximum to remain in No. 2 mesh screen	(0.525 in)
85% minimum to remain in No. 3 mesh screen	(0.263 in)
12% maximum to remain in No. 6 mesh screen	(0.131 in)

Table 5.12b Chemical analysis of coke breeze

Constituent	Percentage
Moisture	14.70
Volatile matter	3.14
Fixed carbon	76.66
Ash	1.50
Sulfur	4.00

Table 5.13 Amount of backfill required

Anode size (in)	Hole size (in)	Backfill (lb)
1 × 60	6 × 80	62
1.5 × 60	6 × 84	61
2 × 60	8 × 84	108
3 × 60	10 × 84	180

5.18 MEASUREMENTS IN CATHODIC PROTECTION

5.18.1 SOIL RESISTIVITY MEASUREMENTS

Soil resistivity measurement is the first important step in the design of a cathodic protection system as the current requirement would differ from one soil resistivity to another for the system. It may, however, be pointed out that there is no single method available to determine precisely the degree of corrosivity caused by soils. Soil resistivity only provides a rough guide to the corrosivity of the soils. There are several methods available to determine the soil resistivity and a few important methods are given below.

(a) Four-pin Direct Current Method (Wenner's Method)

On the site, four stainless steel pins are buried in the ground and spaced in a straight line. The spacing between the pins represents the depth to which the resistivity is measured. By increasing pin spacing, the resistivity to a greater depth is measured. The instruments used for measurement are easily available. Instruments, such as a Vibroground, are often employed for the measurement of soil resistivity (Fig. 5.31a). This method is based on voltage drop. Figure 5.31b shows two outside pins C_1 and C_2, and the two inside pins P_1 and P_2. The outer pins are connected to a DC source (12 V). In the meter all instruments, such as the power supply, the current meters, the switch, etc. are contained in one single case. A desired amount of current is made to flow in the earth between the two

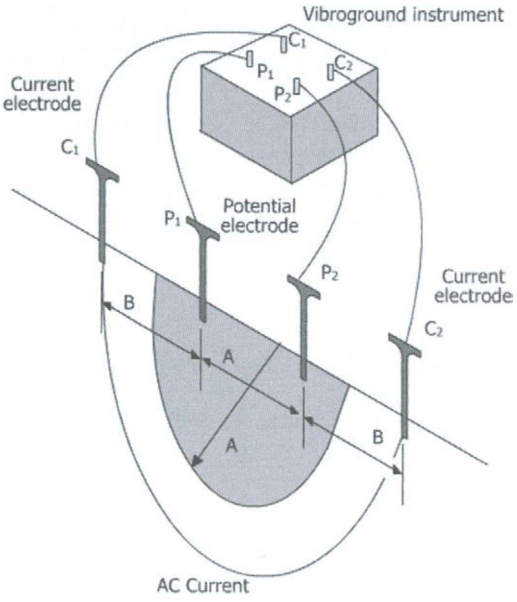


Figure 5.31a Vibroground method for determination of soil resistivity

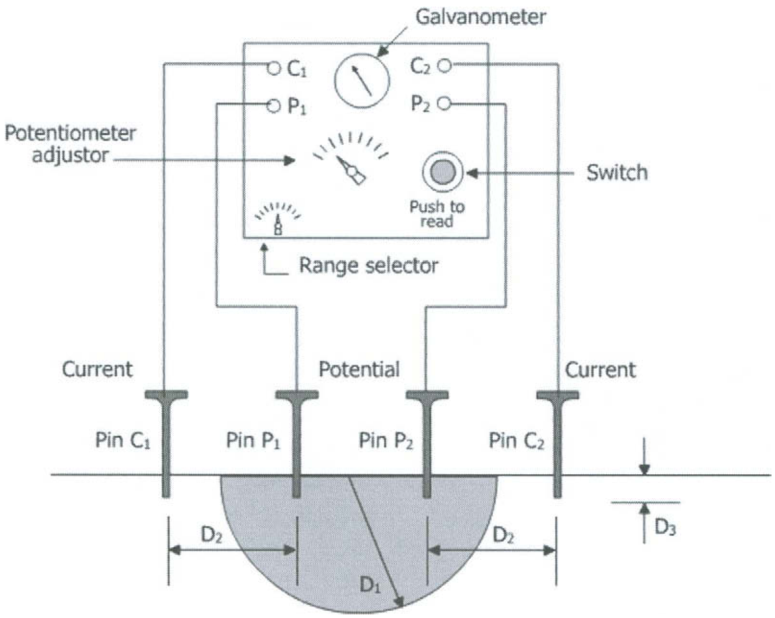


Figure 5.31b Four-pin (Wenner) resistivity measurement

outside pins C_1 and C_2, and the voltage drop is measured between the two inner pins P_1 and P_2. The millivoltmeter is used to measure the voltage drop in the earth between the inner pins P_1 and P_2, located along the current path between C_1 and C_2. The existing voltage between the two potential pins P_1 and P_2 is recorded before any current is applied. The test current is turned on and the voltage drop between the two potential pins is recorded. Resistivity is calculated by using the relationship

$$\rho = \frac{V_{\text{on}} - V_{\text{off}}}{I} \times \text{Spacing of pins (ft)} \times 191.5\,(\text{Factor})\,(\text{Voltage in mV})$$

Illustrative problem

Calculate soil resistivity from the following data given:

Pin spacing – 3 ft
Impressed voltage – 10 V
Current reading – 8 mA
Voltage across the inside pins – 50 mV with no current flowing
Voltage across the inside pins – 500 mV with current flowing.

Solution:

$$\rho = \frac{191.5 \times D \times \Delta V}{I}$$

$$\rightarrow \frac{191 \times 3 \times (500 - 50)}{8}$$

$$= 32\,231 \text{ ohm-cm}$$

where

D = distance between pins
ΔV = voltage drop

Similarly, if $D = 10'6''$

$$\Delta V = 412 \text{ mV}$$

$$I = 267 \text{ mA}$$

$$\rho = \frac{191 \times 10.5 \times 412}{267}$$

$$= 3094 \text{ ohm-cm}$$

(b) Soil Box Method

In the soil box method, no multiplying factor is necessary for calculation of resistivity as the dimensions are made such. A typical soil box has dimensions of 1″(*D*) × 1.5″(*W*) × 8.5″(*L*). It is constructed from a non-conducting material like plastic. The box contains the current terminals and potential terminals. The end plate of the box acts as current terminal and the inside contact plates as potential terminals. The box is filled with required soil which is packed firmly. The potential change is divided by the current to obtain the desired resistivity quickly. The resistivity of soil or water can also be measured by a soil box which has four terminals. The measurements can be conveniently made in the laboratory. The soil box method is a replica of a four pin method mentioned earlier. A typical soil box is shown in Fig. 5.32. In the figure shown, C_1 and C_2 are current terminals and P_1 and P_2 potential terminals. A DC source is connected to C_1 and C_2 terminals and the voltmeter is connected to the terminals P_1 and P_2 (potential terminals). A measured current is passed through the soil sample and the voltage drop is read across the P_1 and P_2 pins. Knowing the voltage drop and the current introduced, the resistivity of the soil can be conveniently measured.

The box can be used either with AC instrument, such as Nilssons or Vibroground or with Miller meter. When using Vibroground, the C_1 and C_2 terminals are connected to the end plates of the box and the P_1 and P_2 terminals to the intermediate terminals of the box.

5.18.2 SIGNIFICANCE OF SOIL RESISTIVITY

Soil resistivity gives an indication of the corrosivity of soil. Some typical approximations are given as below:

Soil resistivity (ohms-cm)	Corrosion
0–900	Severe corrosion
901–2300	Severe corrosion
2301–5000	Moderate corrosion
5000–10 000	Mild corrosion
10 000 and above	Very mild corrosion

The above is only a rough guide to predict corrosion. A soil resistivity survey is required to determine the current requirement for a given pipeline. Soil resistivity may be very high in cold areas, such as Alaska, and virtually no cathodic protection may be required for coated pipes. On the contrary, in tropical areas near the sea shores,

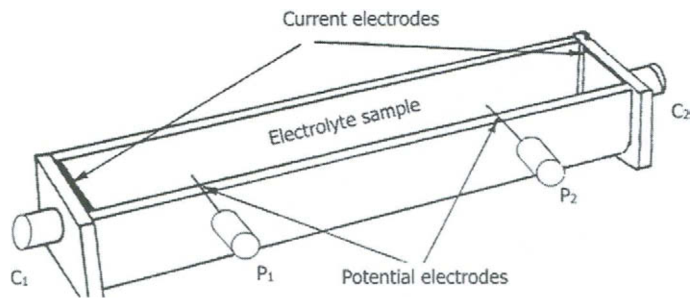


Figure 5.32 Typical soil box

Table 5.14 Characteristics of corrosive and non-corrosive soils

Corrosive	Non-corrosive
(1) Brackish water	Low moisture content
(2) Poorly aerated	Well aerated
(3) High acidity or alkaline pH	Low acidity or neutral pH or slightly acidic
(4) Sulfides present	Sulfates present
(5) Black or gray color	Red or brown color
(6) Anaerobic microorganism	Aerobic microorganism
(7) Soil with high salt contents	Dry soil

in particular, the soil resistivity may be low and cathodic protection for the pipes would be essential. Soil resistivity measurements will, however, depend upon dampness of soils and the prevalent weather conditions. The following are the characteristics of corrosive and non-corrosive soils (Table 5.14).

5.19 PIPE-TO-SOIL POTENTIAL

In order to determine the extent of corrosion of a buried pipe in soil, it is essential to determine its pipe-to-soil potential. It is to be realized that a potential difference existing on a pipe surface can cause corrosion, similar to the situation in a dry battery cell in which zinc is the anode and corrodes. The pipe-to-soil potential would indicate whether the pipe is corroding or it is fully protected.

The normal procedure for measurement of the structure-to-soil potential is to connect the negative terminal of a high resistance voltmeter (cm/V) to the pipe and the positive terminal to a standard copper/copper sulfate half cell (reference electrode) which is placed near the pipe (Fig. 5.33a). The Cu–$CuSO_4$ half cell acts as the cathode and the steel pipe as the anode. The difference of potential between the Cu–$CuSO_4$ half cell and the steel pipe is generally −0.55 V (pipe negative), when all connections have been made. The reading of the voltmeter indicates the structure-to-soil potential. The reference Cu–$CuSO_4$ is shown in Fig. 5.33b and connections are shown in Fig. 5.33c.

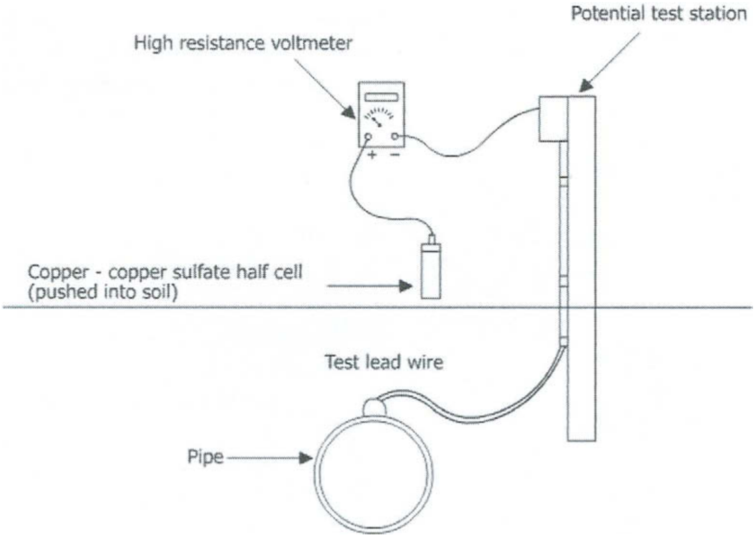


Figure 5.33a Typical pipe-to-soil potential measurement

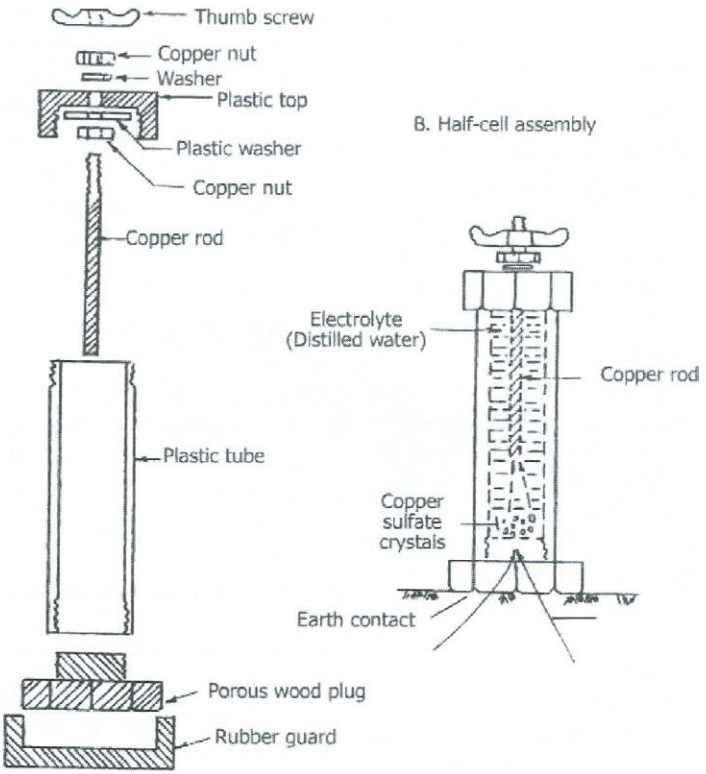


Figure 5.33b Copper–Copper sulfate half cell components

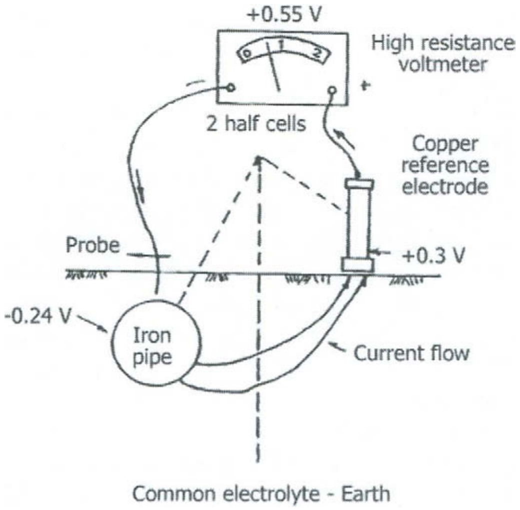


Figure 5.33c Copper–Copper sulfate half cell used as a reference electrode

5.20 FACTORS AFFECTING PIPE-TO-SOIL POTENTIAL

5.20.1 PLACEMENT OF REFERENCE ELECTRODE FOR MEASUREMENT OF PIPE-TO-SOIL POTENTIAL

One of the important points in the measurement of pipe-to-soil potential is the placement of the reference Cu–$CuSO_4$ electrode. Two locations are normally used, one near the structure and the other electrically remote. As a matter of principle, the reference electrode should be placed in such a way that the circuit resistance remains at the minimum. If a pipe is fully coated, the reference electrode may be placed in either remote or on the pipe position and it would not make any difference as the coating resistance makes up most of the resistance between the pipe and the soil. The potential of a cathodically protected pipe is measured by placing the reference electrode at least five or six pipe diameters away from the structure along the surface of the earth. In the case of an unprotected system, it may be essential to take measurements of pipe-to-soil potential with the reference electrode directly over the pipe and also at a position remote to the pipe. At the close position the potential of a small segment of the pipe is only indicated. Suppose an electrode is placed at a distance of 3 feet from a 12 inches diameter uncoated pipe, it would only survey a segment of six feet long as the electrode surveys a distance equal to twice its distance from the pipe. For a pipe length of 100 feet, the electrode must be placed at a distance of at least 50 feet. As a rule of thumb, the circuit resistance must be kept to minimum. For a bare structure, the reference electrode must be placed at a position electrically remote from the test section. This can be done by continuously increasing the distance and observing the readings in the voltmeter which becomes more and more negative. When the successive reading becomes more negative, the electrode is not outside the structure-to-earth resistance. Once, a point is reached at which there is no further increase in the negative reading, the remote position is reached which implies that the electrode is outside the influence of the structure-to-earth resistance. This is the desired location for placing the reference electrode. At this position, there is no further change in IR drop (potential drop). The remote earth does not offer any resistance to current flow. A remote location is outside the potential gradient of the anode bed and the pipe.

5.20.2 ELECTRICAL CONTACTS

Extreme caution must be taken to maintain a good electrical contact between the probe and the structure, and between the soil and the reference electrode.

5.20.3 INSTRUMENTS

Only high resistance voltmeters must be used to avoid errors in reading of potential. The voltmeter should have a minimum sensitivity of 50 000 ohms/V.

5.21 POTENTIAL SURVEY

It has been stated earlier that the tendency for a metal to corrode can be predicted by its potential in a particular environment. The potential surveys are made to assess the magnitude of corrosion of pipelines and detect special areas and spots where the degree of corrosion is severe; the later being termed as a hot spot. A general idea of corrosion of a pipeline can be obtained from the average pipe/soil potential. Newer pipelines show generally a lower negative potential than the older and coated pipelines. For example, a new pipeline may show an average potential of −1.65 V when compared to a potential of −1.2 V shown by an older pipeline. It is, however, important to detect the areas on the pipelines which are subjected to severe corrosion (hot spots).

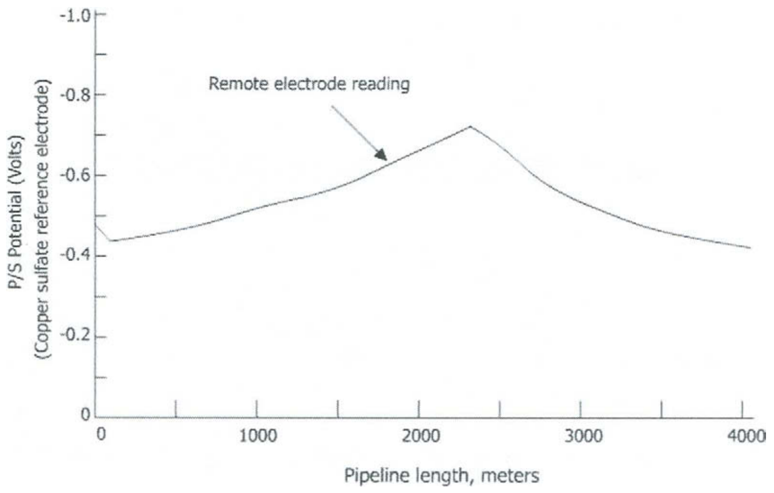


Figure 5.34 Potential survey – remote electrode

Figure 5.34 shows a plot of pipeline length *vs* pipe-to-soil potentials taken with the electrode in the remote position. The peak in the curve indicates the points towards which current is flowing to the pipe and discharging to the soil. It should be noted that the higher the value of *P/S* potential, the more would be the magnitude of corrosion. The peak, therefore, represent the hot spot or the areas where corrosion is active.

5.21.1 POTENTIAL SURVEY MEASUREMENTS

The distribution of potential along the survey of earth above the pipeline indicates the location of corroding areas. Different types of soil encountered by the pipe affect the potential of the pipe. The changes in soil resistivity also induce potential differences. The surface potential surveys are made to determine the anodic and cathodic areas on the pipe. The structure-to-soil potentials do not give a qualitative measurement of corrosion, however, they are very useful in prediction of corrosion when used in conjunction with other data, such as soil resistivity. Several methods are used for potential measurement, such as the one electrode and the two electrodes methods. The two electrodes method is described below.

The two electrodes method for measuring the surface potential is shown in Fig. 5.35. Two $Cu/CuSO_4$ electrodes (a) and (b) are placed on a wooden clipboard and connected to each other through a resistance voltmeter. One of the electrodes is in rear position and the other in the forward. The figure also shows the positions along which the electrodes are marked 1, 2 and 3. The anodic and cathodic areas are also shown in the figure. The IR (potential) drops at each location is measured between the two electrodes. The two electrodes leap-frog method is shown in Fig. 5.36. The survey is started at position 1 and the potential is recorded. Electrode 'A' is left at position 1 and electrode 'B' is moved at position 2. The potential difference is recorded and also the polarity of electrode is noted. This procedure is continued along the whole length of the pipeline. For instance, consider the potential at position 1 to be −0.72 V. If the potential drop at position 2 is 0.065 V

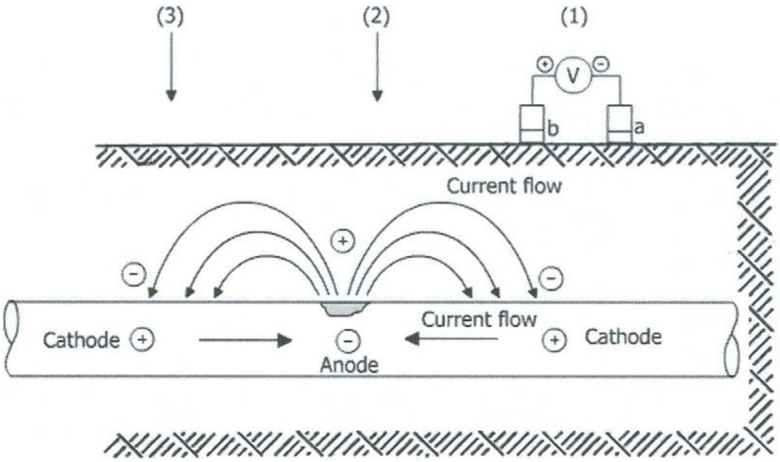


Figure 5.35 Surface potential method for determining corrosion involves electrodes (a) and (b) connected through a voltmeter (V). Potential is measured between the two electrodes

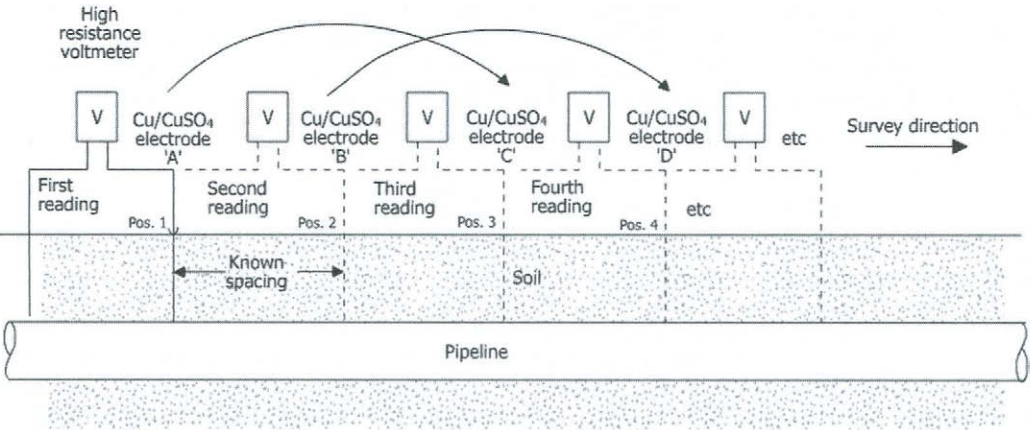


Figure 5.36 Two electrodes method of measurement of potential. (By kind permission of Cheveron, USA)

and the polarity is positive, then the pipe-to-soil potential would be −0.785 V. If the polarity of forward electrode is negative, the potential drop would be subtracted to get the final pipe-soil potential.

5.22 MEASUREMENT OF CURRENT FLOW

It is possible to measure the current flow in a pipeline or any buried structure by determining the voltage drop for a given length, if the resistance is known. Take, for instance, the current flow in a 6″ OD steel pipeline. Assume the length to be 500 feet. As the voltage drops are often small, low resistance voltmeters may be used. For example, a voltmeter with an internal resistance of 100 ohms/V on a 2 mV scale and external resistance of 2 ohm would be suitable for this measurement. Refer to Fig. 5.37 for the measurement technique.

Before determination of current flow, the true voltage between the tests points A and B and the resistance of the steel must be known. The latter information can be determined from standard tables for steel pipes.

Voltage drop

= Voltmeter reading between A and B

$= 1.5\,\mathrm{mV}$

True voltage between A and B =

Voltmeter reading

$$= \frac{\text{Voltmeter resistance} + \text{External resistance}}{\text{Voltmeter resistance}}$$

$$= \frac{1.5(2.0 + 2.0)}{2.0} = 3.0\,\mathrm{mV}$$

Thus the true voltage is 3 mV ($Cu\text{–}CuSO_4$).

The next step is to determine the resistances of the pipe. The resistance of a standard weight pipe is obtained by substituting in a simple equation:

$$R = \frac{215.8\,L}{1\,000\,000\,W}$$

where

R = resistance of the pipe per given length in ohms

W = weight of pipe per linear foot (consult tables)

L = length of the test pipe in feet (given)

The weight of a 6 inch steel pipe is 19 pounds per linear feet. The test length is 500 feet. The resistance of the pipe is, therefore,

$$R = \frac{215.8 \times 500}{19 \times 1\,000\,000}$$

$$= \frac{0.000216 \times 500}{19}$$

$$= 0.0005684\ \text{ohms}$$

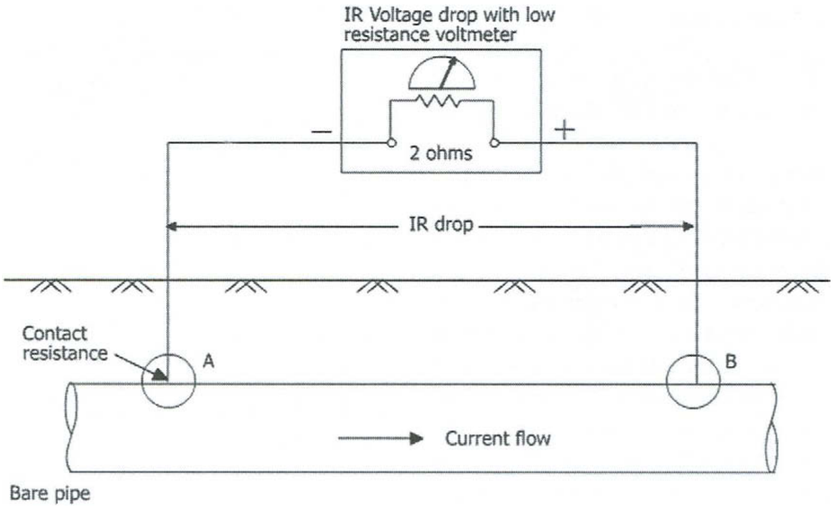


Figure 5.37 Measurement of current flow

By applying Ohm's law, $I = E/R$, the magnitude of current flow can be determined:

$$I = \frac{3.0}{0.0005684} = 0.5275\,\text{A}$$

As shown in the figure, the polarity indicates that the flow of current is from left to right. In the previous example, the magnitude of the current already flowing in a pipeline is determined. The amount of current flow may also be determined by passing a known amount of battery current and measuring the voltage drop between two points. The current is determined from Ohm's law ($E = 1/R$).

5.22.1 ZERO RESISTANCE AMMETER

The zero resistance ammeter can be used to determine the exact amount of current that would flow between two points of different voltages in a given circuit.

The zero resistance ammeter is useful for measurement of current flow in low resistance and low current circuits. If an ordinary ammeter is used to read current in such a circuit, an appreciable margin of error would be introduced by its internal resistance, the true voltage would not be shown. The basic advantage of this instrument is its ability to read test current accurately without introducing any resistance. For instance, if the circuit has a total resistance of 0.1 ohm, and an ammeter of 0.2 ohm resistance is introduced, the current flow would be reduced by 67% by a 0.2 ohm ammeter. Thus, the margin of error would be 67%. By not introducing any resistance in the circuit the meter is able to read true current. It is designed to work on a null principle.

The arrangement for measurement of current by zero resistance ammeter (ZRA) is shown in principle in Fig. 5.38. According to the arrangement, the open circuit potential between the pipe and the anode balanced by a potentiometer circuit. Sufficient current is allowed to flow from a battery through a variable resistor, until the IR drop balances the open circuit potential. At this point, the galvanometer registers zero current. The true current between the pipe and anode when bridged is then shown by the ammeter. The modern method employs using AC audio frequency energy for measurement.

5.23 REFERENCE ELECTRODE

The emf of a cell is comprised of its two half cells. For instance, the emf of a Daniel cell is the sum of the two half cells, i.e. Zn in $ZnSO_4$ and Cu in $CuSO_4$. The resulting emf is 1.1 V. In order to determine the half cell potential of zinc in any media, zinc is connected to the negative end of a voltmeter and a reference electrode of a known potential to the positive end. The difference of potential is directly read from the voltmeter.

The protective potentials for steel in seawater at 25°C and soils with respect to commonly used reference electrodes are shown in Table 5.15. Several reference electrodes can be used for measurement of half cell potential as shown in Chapter 2.

The most common electrode used for cathodic protection measurements is the copper–copper sulfate electrode. It contains a copper rod, a saturated solution of $CuSO_4$ containing the copper rod and a porous plug for contact with the electrolyte. The container is non-conducting. The space within the tube is filled with a saturated solution of copper sulfate and should contain an excess of crystals to insure that the solution would be saturated all the time. A rubber cap may be placed over the wooden plug when the electrode is not in use.

An increase in the temperature causes an increase in concentration of the solution and a decrease in temperature causes a decrease in concentration of the solution. The temperature correction is 0.5 millivolts per degree change (°F). Temperature potential correction charts may be used for correction.

Example

Determine the true half cell potential of a steel structure to a copper–copper sulfate reference electrode when the outside temperature is 90°F.

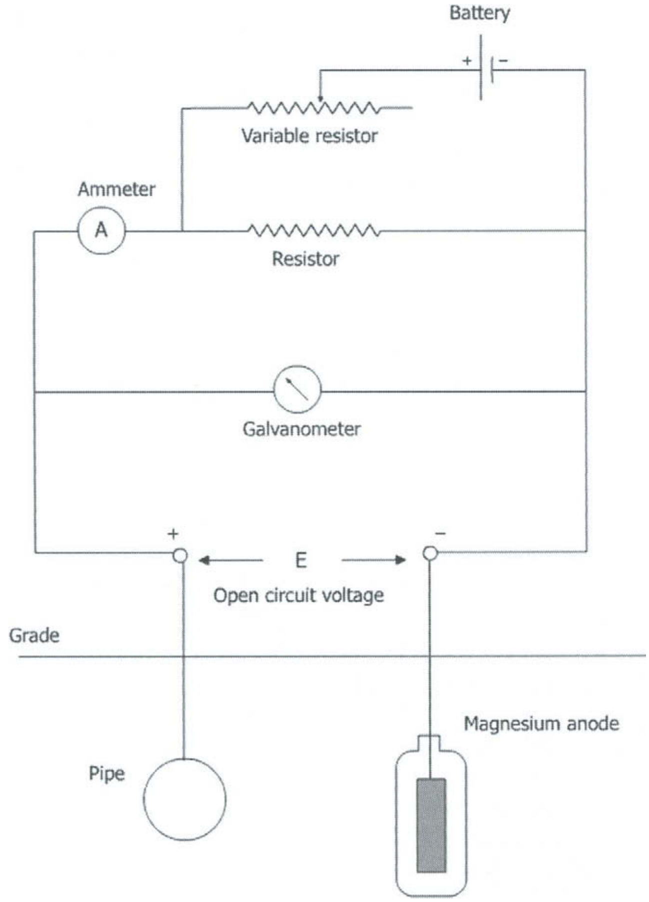


Figure 5.38 Measurement of current flow by the zero resistance ammeter method

The pipe-to-soil resistance potential reading is −0.70 V.

(a) Temperature correction +0.316 + (+0.007) = +0.323 V (Correction factor from the chart).

(b) Half cell potential of the steel structure without correction:

$$= -0.70 - (+0.316) = 0.384\,\text{V}$$

(0.316 V is the potential of Cu–$CuSO_4$ electrode.)

And with correction:

$$= -0.70 - (+0.323) = -1.023\,\text{V}.$$

5.24 COATING RESISTANCE TESTS

Suppose the coating resistance is to be measured on coated 24″ diameter steel pipe, the procedure is simple. Pass a known amount of current in the given section of the test pipe and note the voltage drop. By applying Ohm's law, determine the resistance (R) of coating. An experimental setup is shown in Fig. 5.39. Between the insulated flanges, three voltmeters are fixed at a predetermined spacing. A is the test section of a pipe, B is the on and off switch, C is the power source, D is an ammeter and E, F, G are the voltmeters. H is a copper–copper sulfate reference electrode.

Table 5.15 Protective potentials for steel in seawater and soils (aerated)

Reference electrode	Value for E_{prot} Fe in aerated soil or seawater
Copper/Copper sulfate (CSE) $Cu/CuSO_4$	−0.85 V
Saturated calomel (SCE) $Hg/Hg_2Cl_2(s)/KCl$ (Saturated)	−0.80 V
Silver chloride Ag/AgCl/Seawater	−0.80 V
Standard hydrogen electrode (SHE) Pt, $H_2/H^+(a_H^+ = 1)$	−0.53 V
Zinc Zn/Seawater	+0.20 V

A known amount of current is passed and the values of potential 'on' and 'off' are obtained by opening and closing the switch which controls the circuitry. The value of ΔV is obtained from V(on) and V(off). The amount of current passed is already known. The ΔV values of the voltmeters are averaged. By applying Ohm's law, the coating resistance is determined. Here is an example.

Example

(a) Length of the pipe = 2 miles, area = πDL, OD = 24″, soil resistivity = 10 000 ohms

The amount of current passed = 0.096 A, $\Delta V_E = 0.77$ V, $\Delta V_F = 0.75$, $\Delta V_G = 0.77$

Average voltage drop $(\Delta V_E + \Delta V_F + \Delta V_G)$ $\Delta = 0.75$ V.

The resistance by Ohm's law is $R = \frac{E}{I} = \frac{0.75\text{ V}}{0.096\text{ A}} = 7.8125$ ohms

The area of the above pipe = $24 \times \pi \times 2 \times 5280 = 66\,316\ \text{ft}^2$

The effective coating resistance would, therefore, be

$$7.8125\ \text{ohms} \times 66\,316$$

$$= 51\,792.7\ \text{ohms} \quad \text{per average square foot (approximately)}$$

The soil resistivity affects the coating resistance significantly. The pipeline resistance is the combined resistance of coating and the resistance of the pipeline to remote earth.

In the example shown above, the resistance was determined in 1000 ohm-cm soil. The resistance can be changed from one soil resistivity to another soil resistivity. For instance, if a resistance of 0.4 ohms obtained in a soil resistivity of 10 000 ohms, the resistance is 10 000 ohm, would be 10 000/1000 × 0.4 = 4 ohms.

(b) If now it is assumed that the test section was bare and in 1000 ohm-cm soil, the resistances to earth of the above line would be lower. Let us assume it is found to be 0.0040 ohm in a soil having a resistivity of 1000 ohm-cm. If the average soil resistivity is 100 000 ohm, the resistance would be

$$0.0040 \times \frac{100\,000}{1000}$$

$$= 0.40\ \text{ohms} \quad \text{(This is the resistance of the bare pipe)}$$

The difference between the resistance of the bare and coated pipe is 0.40 ohm. The difference is added to the resistance obtained above, i.e. 7.8125 and multiplied by the area of the pipe to obtain the effective coating resistance of the pipe per average square foot. In the example above, the effective average coating resistance would be 7.8125 + 3.60 = 11.412 × 66 316 = 756 002 ohm per average square foot. Area of pipe = 518 093 ohms per average square foot. The resistance of the steel pipes of various dimensions can be estimated from Table 5.16. It is based on the relationship

$$R = \frac{16.061 \times \text{Resistivity in micro-ohms}}{\text{Weight per foot}}$$

= Resistance of one foot of pipe in micro-ohms

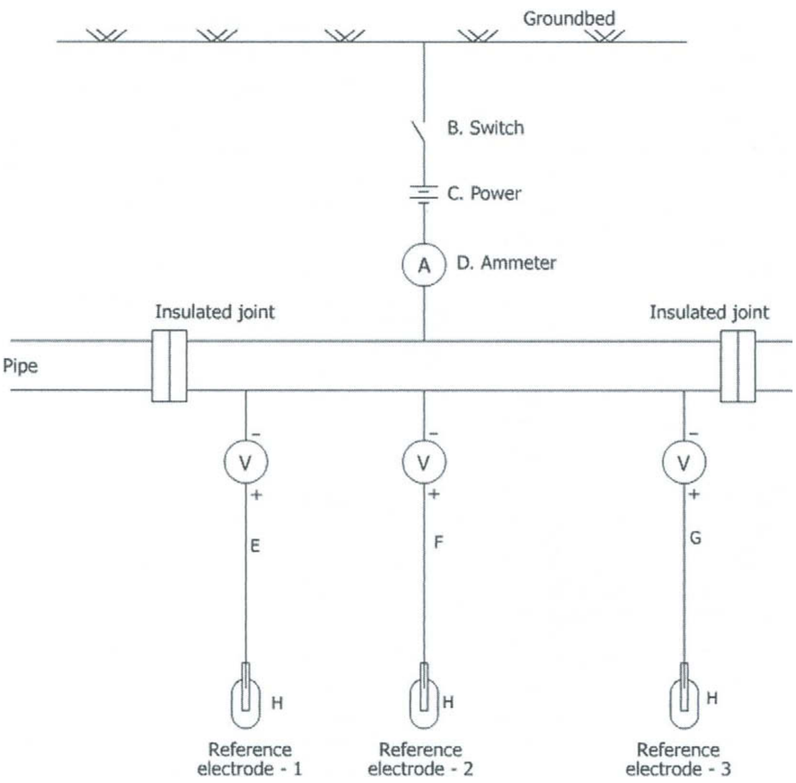


Figure 5.39 Determination of coating resistance. (From TEXACO Cathodic Protection – Design and application school, Texaco Houston Research Center, Training Manual. Reproduced by kind permission of Cheveron, Houston Research Center, USA)

5.25 CURRENT REQUIREMENT TESTS

Basically sufficient current is supplied from a power source to lower the potential of a structure to −0.85 V. At this potential all cathodic areas are polarized to the open circuit potential of the anodic areas, hence no corrosion would occur. A temporary ground-bed is made and a known amount of current is forced in the structure to determine the total current required for cathodic protection.

Protection of steel in an aggressive soil is achieved if the metal–soil potential is more negative than −0.85 V or –0.95 V for anaerobic soil conditions. In a bare pipeline or a structure, sufficient current is introduced in the system until a protective potential is achieved. To protect a structure from corrosion, say, a pipeline, a current requirement test is crucial, because if the required current to achieve a pipe-to-soil potential of −0.85 V is not provided, the pipe would not be protected as desired. If a bare pipe is buried in a soil of known resistivity and its characteristics are well-known, a selected current density can be given to the structure, without the necessity of current requirement test. In such instances experience is the best guide. In areas where experience lacks, the situation is different and current density required for protection can be determined experimentally by applying a range of current densities and selecting the most desirable current density to achieve cathodic protection.

The '*current drain*' test is commonly employed to determine the current requirement for a coated pipeline. A temporary drain point is set to

Table 5.16 Steel pipe resistance(1)

Pipe size (inches)	Outside diameter (inches)	Wall thickness (inches)	Weight per foot (pounds)	Resistance of one foot (2) in (ohms × 10^6) (millionths of an ohm)
2	2.375	0.154	3.65	79.2
4	4.5	0.237	10.8	26.8
6	6.625	0.280	19.0	15.2
8	8.625	0.322	28.6	10.1
10	10.75	0.365	40.5	7.13
12	12.75	0.375	49.6	5.82
14	14.00	0.375	54.6	5.29
16	16.00	0.375	62.6	4.61
18	18.00	0.375	70.6	4.09
20	20.00	0.375	78.6	3.68
22	22.00	0.375	86.6	3.34
24	24.00	0.375	94.6	3.06
26	26.00	0.375	102.6	2.82
28	28.00	0.375	110.6	2.62
30	30.00	0.375	118.7	2.44
32	32.00	0.375	126.6	2.28
34	34.00	0.375	134.6	2.15
36	36.00	0.375	142.6	2.03

(1) Based on steel density of 489 pounds per cubic foot and steel resistivity of 18 micro-ohm-cm as stated in the text

(2) $R = \dfrac{16.061 \times \text{Resistivity in micro-ohm-cm}}{\text{Weight per foot}}$ resistance of one foot of pipe in micro-ohms

determine how much current would be required to protect the line. The site must be selected where the pipeline is exposed or a valve box is located so that a connection may be made. The test current can be supplied either by a storage battery (100 A) or a welding machine. A machine with an output voltage of 40 V is sufficient for the test. The temporary ground-bed usually consists of scrap length of pipes, driven steel rods or aluminum foil. If desired, actual anode could be used instead of scrap length of pipes and left on the location. They can be later utilized in the permanent ground-bed. For final installation, currents from 2–3 A up to full ratings of the machine can be utilized. The procedure is continued until the quantity of current required to protect the entire line of test section is determined. The ground-bed must be between 100 and 50 ft of the pipeline. If the temporary installation (pipeline + ground-bed) is operated, for instance, at 25 A and a sufficient protection is obtained, it signifies that a rectifier, when set at this value, would also protect the pipeline. It is to be remembered that the temporary ground-bed described above has a high resistance, therefore, a high voltage is required from the welding machine. When a rectifier is installed with a proper ground-bed (low resistance), the voltage used would not be as high. The temporary ground-bed also would be consumed in a few days under test conditions because of high power consumption, however, it has no bearing on the protective current density determined for the protection of the pipe by the above test method. The method is illustrated in Fig. 5.40. Current is drained at point A by the welding machine. Two points, such as B and C are located on the pipeline test section after a polarization run of 3 or 4 hours. The two points should

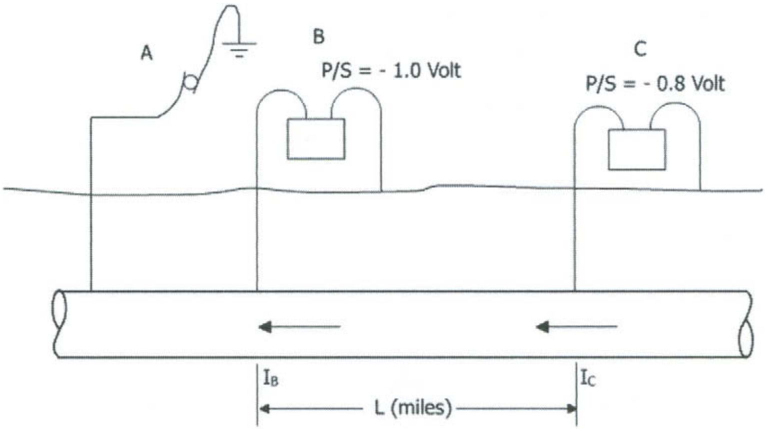


Figure 5.40 Current drainage method

have potentials of 1.0 and 0.8 V, respectively. The section between the two points will be at a potential of about 0.9 V, which is the potential required for protecting the line. The line current is measured between each of these points. The difference between the line currents at the two points would be the current picked up. If two points having *P/S* of −1.0 V and −0.8 V are not located, readings are taken which approximate the above values. Potential and current are adjusted to obtain the desired quantity. A static potential of −0.6 V is assumed. On the above basis, *P/S* and current curves are drawn as straight lines, and the points where the values are −1.0 and −0.8 are located in Fig. 5.41. If the distance between the two points is L miles, the average current required to bring them to 0.9 V line $I_B - I_C$, and $(I_B - I_C)/L$ would be average current, in amperes per mile. Once the two points are located, the current value at those points is determined. The total current requirement to raise the potential in a range −1.0 to −0.8 V can, therefore, be estimated.

It also possible to obtain data that would give information on the current requirement while the coating resistance tests are being made. Such a setup is shown in Fig. 5.42. In the setup a current interrupter is provided (automatic switch). The switch is 'on' position for 30 seconds and in 'off' position for 15 seconds. The data is taken at every specified length's interval for calculation of coating resistance.

The values of ΔV (voltage 'on' and voltage 'off') and ΔI (current 'on' and current 'off') are measured. The average pipe potential change, which is mostly the voltage drop across the pipe coating due to the current increment (arithmetic difference between ΔI value) is determined. From the data, the current required to protect the coated pipe as well as the resistance of the coating is estimated. The estimate is preliminary only.

5.26 CURRENT DENSITY REQUIREMENT FOR A BARE STRUCTURE

In case of a bare structure, or a pipe, a current requirement test is made by placing the electrode at a position remote to the structure. The setup for a current requirement test of a bare structure is shown in Fig. 5.43. The most important condition is that the structure must be fully polarized to a potential −0.85 V for complete cathodic protection. It is to be noted on the current off position, the potential must show −0.85 V immediately. This value should not be reached gradually on

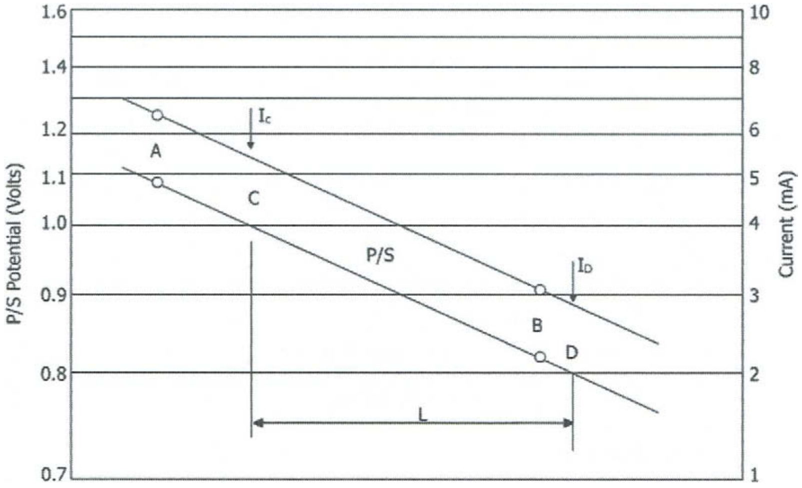


Figure 5.41 Measurement of pipe-to-soil *P/S* potential and line current. The difference in the current values for the two points gives the current demand for the distance *L*

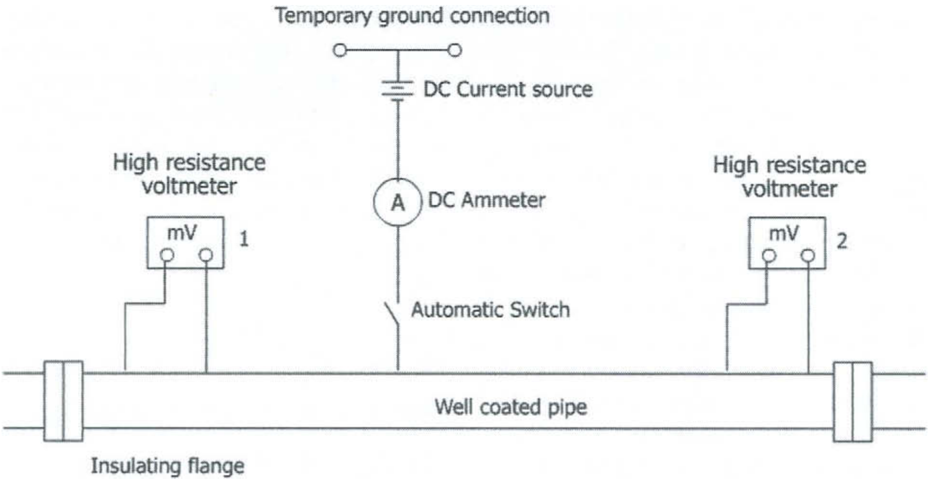


Figure 5.42 Current requirement test using close Cu/CuSO4 electrodes. (From TEXACO Cathodic Protection – Design and application school, Texaco Houston Research Center, Training Manual. Reproduced by kind permission of Cheveron, USA)

opening the '*current on*' switch. It may take a very long time in several instances to achieve polarization. To shorten the waiting period for achievement of complete polarization (−0.85 V), the curve can be extrapolated. Figure 5.44 shows a polarization curve. It is a plot of pipe potential to remote earth *vs* time. The immediate objective is to determine the amount of current for the test section to achieve a potential of −0.85 V.

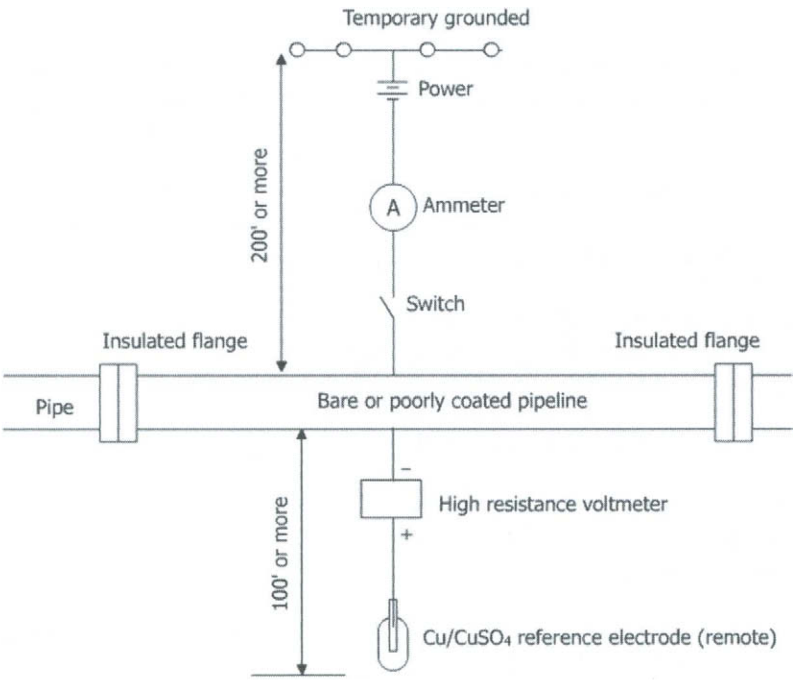


Figure 5.43 Cathodic protection of a bare structure. (From TEXACO Cathodic Protection – Design and application school, Texaco Houston Research Center, Training Manual. Reproduced by kind permission of Cheveron, USA)

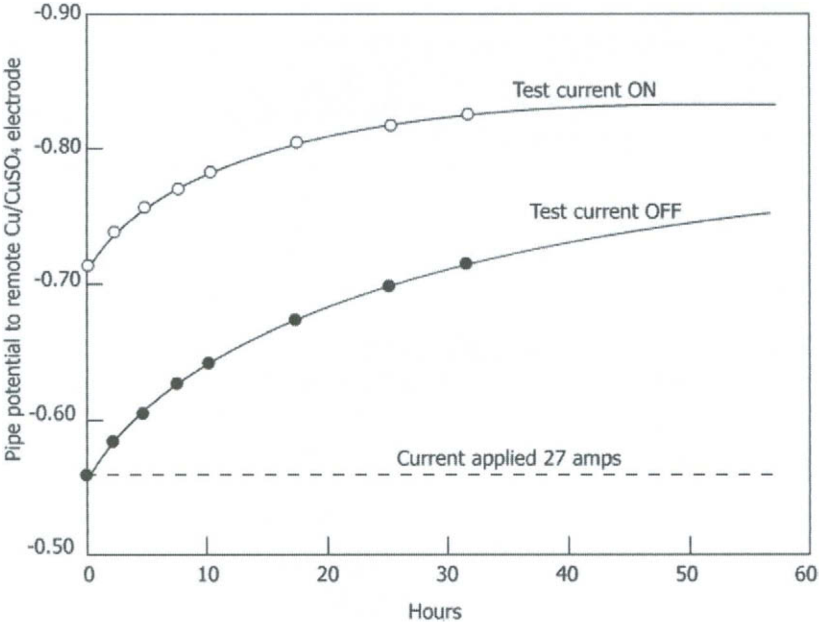


Figure 5.44 Polarization curve. (From TEXACO Cathodic Protection – Design and application school, Texaco Houston Research Center, Training Manual. Reproduced by kind permission of Cheveron, USA)

Referring to the polarization plot shown in Fig. 5.44, the following are the salient characteristics:

(1) The broken line in the plot shows the pipe-to-soil potential before the application of cathodic protection, in the diagram it is shown as 0.560 V.
(2) Variation of pipe potential with time read in current 'off' position (curve II).
(3) Variation of pipe potential with time read in current 'on' position (curve III). The curve extrapolated to read maximum potential, −0.838 V.
(4) The value of current recorded to achieve maximum potential is recorded. Assume the current value as 25 A (I_A).

Example
Assume that the test section of bare pipe, 1 mile long, 6–5/8″ OD, is to be protected, and the approximate current requirement is 25 A. An approximate quantity of current is introduced in this pipe or buried structure. This approximate value is based on the experience of cathodic protection engineer. Later this approximate quantity is modified on the basis of the results obtained from the polarization plot. The following steps show clearly, how the exact current requirement is worked out:

(a) Determine the total change of voltage (ΔE) from the original value of pipe potential (−0.560 V)

$$\Delta E = -0.838 - (-0.560) = -0.278\,\text{V}$$

(b) Calculate the average potential change per ampere for the test section

$$\frac{\Delta E}{I} = \frac{0.278}{25} = 0.0112\,\frac{\text{V}}{\text{A}}$$

(c) The additional current required to raise the potential from −0.838 to −0.850 is

$$-\,0.850\,\text{V} - (-0.838) = -0.01\,\text{V}$$

$$\frac{0.01}{0.0112} = 0.822\,\frac{\text{V}}{\text{A}}$$

(d) The total current required would, therefore, be 25 + 0.822 = 25.822, or say 26.0 A.
The field test data can be modified by this method.
(e) The current approximation for a temporary DC power source on the basis of 2.50 mA/ft is calculated as below for a bare line

$$= \left[\frac{6-5/8\,\text{in}}{12}\right](\pi)\left[5280\,\frac{\text{ft}}{\text{mile}}\right]\left(0.0025\,\frac{\text{A}}{\text{ft}^2}\right)$$

$$= \left[\frac{0.552}{12}\right](3.41\pi)\left[5280\,\frac{\text{ft}}{\text{mile}}\right]\left(0.0025\,\frac{\text{A}}{\text{ft}^2}\right)$$

$$= 0.25\,\text{A}$$

5.26.1 CURRENT DENSITY REQUIREMENTS

Table 5.17 shows typical current requirements of uncoated steel in various environments.

Table 5.17 Typical current density requirements for cathodic protection of uncoated steel

Environment	Current density, (mA/ft^2)	
	AFM 88–9	Gerrard
Neutral soil	0.4 to 1.5	0.4 to 1.5
Well-aerated neutral soil	2 to 3	2 to 3
Wet soil	1 to 6	2.5 to 6
Highly acidic soil	3 to 15	5 to 15
Soil supporting active sulfate reducing bacteria	6 to 42	up to 42
Heated soil	3 to 25	5 to 25
Stationary fresh water	1 to 6	5
Moving fresh water	9 to 25	5 to 6
Turbulent fresh water containing dissolved oxygen	5 to 15	5 to 15
Seawater	3 to 10	5 to 25

5.27 STRAY CURRENT CORROSION

5.27.1 INTRODUCTION

In a cathodic protection system, the conventional current (e.g. Zn^{++} ions) flows from the ground-bed through the earth towards the metallic structure. If a current encounters a metallic structure on its way it is picked up by the metallic structure, transmitted to other parts of the structure and finally discharged from the structure through the earth and returns to the cathode. The following are the two routes:

(a) Ground-bed (Anode) – Earth – Metallic structure – Earth – Cathode
(b) Ground-bed (Anode) – Earth – Cathode.

If an underground metallic structure is present, the point at which the current is discharged from the metallic structure to the ground becomes the anode and, therefore, corrodes (forming Fe^{++} ions). The undesired current which enters the metallic structure on its way to the cathode is called stray current and the corrosion caused by stray current is called *stray current corrosion.* This type of corrosion is associated with DC transit systems, such as in the case of electric trains on super-grid contacts which cross the electrical lines. There are numerous other sources of stray currents, such as welding machines, elevators, electroplating machines, etc. Speaking simply, stray currents are uncontrolled currents which originate mostly from DC systems and cause corrosion at the point of leakage from the system (site of exit of Fe^{++} ions). There are two main categories into which these currents can be divided:

(A) Static type

  (1) Cathodic protection rectifier
  (2) Railroad signal batteries

(B) Dynamic type

  (1) DC equipment in mines
  (2) Electric railway generating equipment.

The part of the pipe receiving the current from the rails becomes the cathode and the part of the pipe from which the current leaves the pipe becomes the anode. It has been shown earlier that anode is the area of exit of Fe^{++} ions (corrosion site).

5.27.2 MAJOR SOURCES OF STRAY CURRENTS

(a) DC Transmit Systems, such as Electric Trains

Stray currents create a great source of difficulty in DC transit systems. In such transit systems, the overhead feeder is connected to the positive bus of DC substations. The load current which is required to operate the trains is expected to return via the tracks connected to the negative bus. For illustration, one train and a substation of a transit system is shown in Fig. 5.45. A part of the load current may enter the earth as the tracks are not completely insulated from the earth. Load current would enter where the tracks are positive and take a path back to the substation. In the current pick areas, any underground bare pipes or other metallic structures would pick up the current and they would be cathodically protected at no cost to the other. The current after being picked up by a pipeline would be carried in the neighborhood of the DC substation where it would be discharged as Fe^{++} ions to the earth. The discharge area of the pipe would, therefore, become the anode and the pipe would seriously corrode. Thus, in a current pickup area the pipe would be protected and in a current discharge area it would corrode. If all negative return was to be carried by the tracks completely insulated, this problem would not exist. In DC systems, the negative side of the generator is grounded because of the contact of rails or structures with the earth. In the example given of an electric railway system the positive side of the generator is connected to the trolley contact wire through the feeder cables and the negative side to the rail.

The return path of the current is shown in Fig. 5.45. The current flows back to the generator, either through the rails or an earth path parallel to rails. There is strong possibility of such current

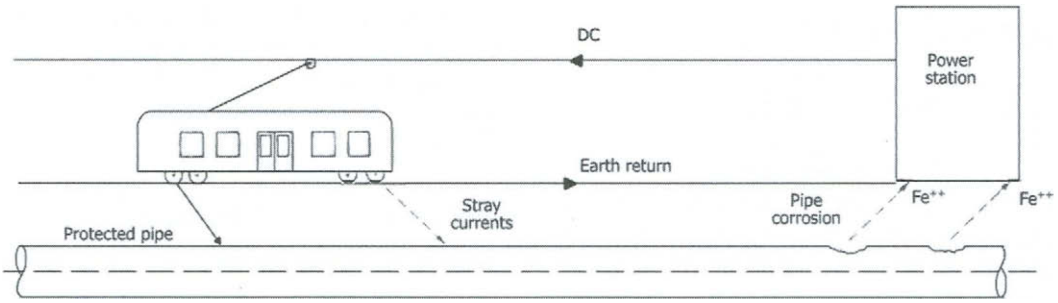


Figure 5.45 Showing how a current flowing between a train and the distant generating station tends to split itself between the track and a pipeline

being picked up by a nearby metallic structures. From the structure the current would discharge to the earth, returning to the rails and finally to the negative terminal of the generator. The underground metallic structure would corrode at the point where the current discharges back to the ground before its entry to the rail and its return to negative terminal of the generator.

Any underground metallic structure would corrode at the point of exit of Fe^{++} ions. To prevent this undesirable stray current corrosion a metallic bond, such as a bond cable between the pipeline and the negative bus of the DC substation, is installed as shown in Fig. 5.46. The current is then drained off by the metallic bond and all the surface of the secondary pipes becomes completely cathodic. The situation here is rather over-simplified, as there may be hundreds of substations serving the system depending on the traffic load and the load may vary during the 24 hours period. In certain instances, a bond connected may not be useful as the direction of flow of current in the bond may reverse and the current may flow to the pipelines rather than to the negative return. In order to handle this problem, rectifier discs may be inserted in the circuit so as to prevent the reversal of the current flow.

(b) Welding Generators

During the electric arc welding of ships and fabrication of large structures, large currents are involved and they escape to earth where they are picked up by the buried metallic structures. While the ships are being repaired in the dock basin, welding generators are placed on shore and the ground DC lines are taken to the ship. Any current returning from welding electrode through the water to the shore would destroy paint work and cause damage to the hull of the ship. This happens particularly where the earth circuit is closed. The stray current on the ground would be picked up by underground metallic structures and cause corrosion at the point of exit. In such instances, the DC generator should be placed on ship rather than on the shore to minimize the magnitude of stray currents.

5.28 CATHODIC PROTECTION INTERFERENCES

For cathodic protection of an underground structure, current is directly injected into the soil in the neighborhood of the pipe or structure to be protected. High current density, therefore, exists close to the ground-bed. If another metallic structure, such as a water pipe or a cable, happens to be present in the immediate neighborhood of the cathodically protected structure, it would pick up some current at one point and discharge it via the soil at other point on the metallic structure.

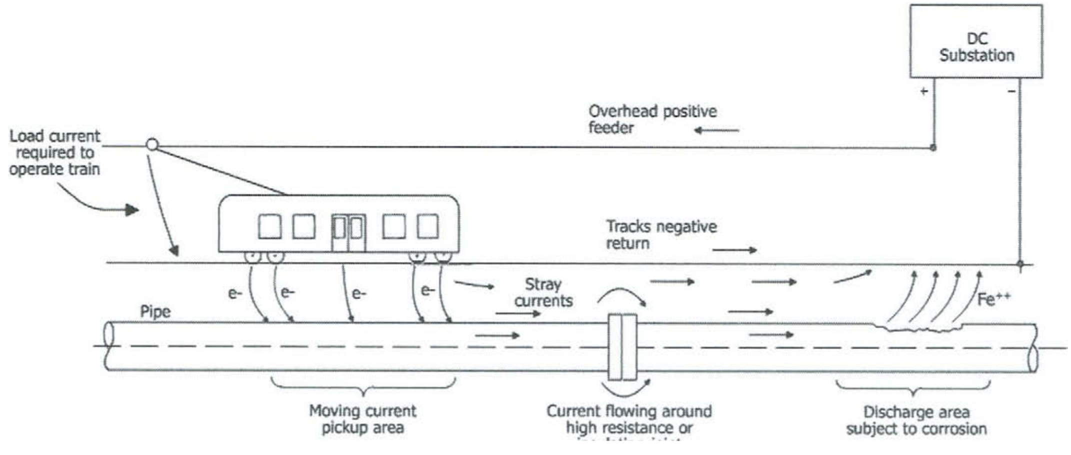


Figure 5.46 Stray current corrosion caused by DC transit system. (From Peabody, A.W. (1967). *Control of Pipeline Corrosion*, NACE. Reproduced by kind permission of NACE, Int., USA)

Any water pipe or cable in the vicinity would corrode as a result of discharge of positive current from it (Fe^{++} ions). This is an unwanted corrosion and is referred to as cathodic protection interference. It refers to an undesirable current discharge from a pipeline or structure in the vicinity of a cathodically protected pipeline or structure.

5.28.1 EXAMPLES OF INTERFERENCE

A foreign (unprotected) pipeline may either cross a protected pipeline or passes close to the ground-bed of the protected line. Such situations cause varying degrees of interference. Suppose a foreign pipeline does not cross the cathodically protected line but passes very close to a ground-bed of cathodically protected line. This is an example of interference caused by radial current flow. When a foreign pipeline lies across the normal flow lines of current, there would be a little difference in the potential between the path nearest to the anode and nearest to the cathode as only small amount of current would be interrupted. If, however, the foreign pipeline runs parallel to flow lines of current, there would be a large amount of current pickup which would be discharged to the protected structure. This is because current prefers a low resistance path (metal path) rather than higher resistance (via soil). A tank close to an anode bed may pickup current at one point and discharges it as Fe^{++} ions from another point (Fig. 5.47). The discharge area would undergo heavy damage and corrode due to the consequent loss of Fe.

In areas of positive soil potential, the foreign pipeline would pickup the current. This current would leave the foreign pipeline in remote areas in order to reach the protected pipeline and flow back to the rectifier to complete the circuit. Because of several areas of Fe^{++} current discharge, the foreign pipeline would corrode.

However, if a foreign pipeline is coated, it would not be affected to the same degree as a bare pipeline or structure, although it may be in the region of potential gradients. To ascertain the damage, potential readings can be taken at the points of crossing of the pipes. If the potential of the foreign pipeline becomes positive, it would indicate corrosion caused by Fe^{++} current discharge. In order to prevent this, the bare pipelines may be coated in the region of crossing or a metallic bonding may be introduced between the two as illustrated in Fig. 5.48.

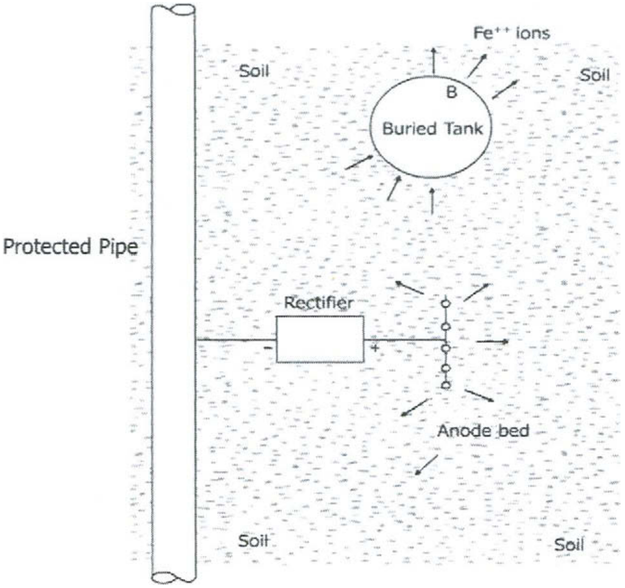


Figure 5.47 Damage caused by current flow. Corrosion occurs at position 2 due to discharge of Fe^{++} ions

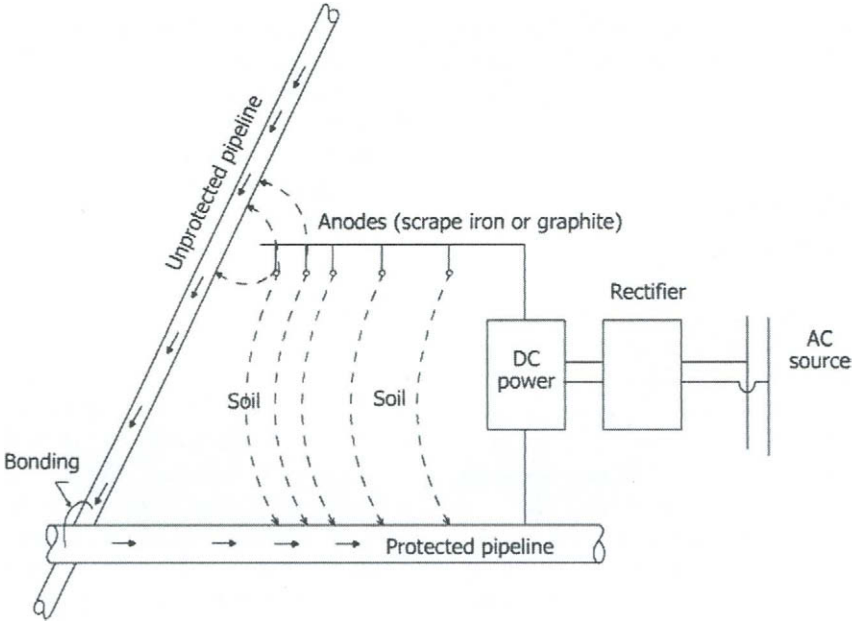


Figure 5.48 Showing current impressed by a DC source being picked up by an unprotected line and returning to the protected line via a bonding link

The following is a summary of preventive methods which could be used to minimize the interference:

(1) The current output of the main rectifier may be reduced.
(2) The ground-bed may be re-sited, if necessary. This is applicable if a foreign pipeline passes close to the ground-bed.
(3) Installation of a crossing bond between the pipes. A bond between the two points of crossing is installed and the amount of current flow is controlled by a resistor.
(4) Installation of magnesium anodes on the corroding structure.
(5) Isolation of the anodic section of the structures and installation of continuity bonds across the anodic section.
(6) Coating the metal/electrolyte interface, or the contact surfaces. In cases of corrosion involving a foreign line, the foreign line must be coated.

5.29 DESIGN CHARTS

Figure 5.49 shows a typical horizontal anode design chart where the number of anodes is shown on the abscissa and the resistance of the anode at different spacings on the ordinate axis. The following basic information is required for the construction of a design chart:

(a) Anode size
(b) Size of coke breeze column
(c) Resistivity of coke breeze
(d) Anode spacing
(e) Soil resistivity

The resistance of a given number of anodes in a soil of 100 ohm-cm at a specified spacing can

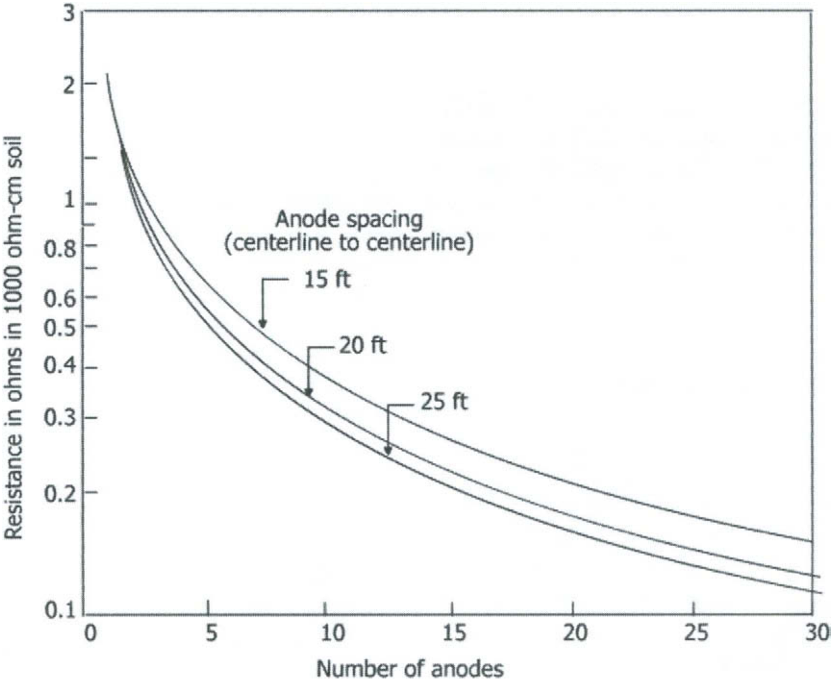


Figure 5.49 Typical horizontal anode design chart for impressed current ground beds. (From TEXACO Cathodic Protection – Design and application school, Texaco Houston Research Center, Training Manual. Reproduced by kind permission of Cheveron, USA)

be directly noted from the chart. It is to be noted that separate charts need preparing for each anode size, size of coke breeze column and resistivity of the coke breeze. Resistance can be conveniently converted from one soil resistivity to another soil resistivity.

Suppose it is desired to obtain resistance of 20 anodes in parallel at 20 ft spacing in a soil of 3000 ohm-cm, the following is a step-wise procedure.

(1) Obtain the parallel resistance of 20 anodes at 20 ft spacing in 1000 ohm soil directly from the chart.
(2) Determine the resistance in a soil of 3000 ohm by conversion. Suppose the anode resistance determined is 0.50 ohm. It would be

$$0.50 \times \left(\frac{3000}{1000}\right) = 1.5\,\text{ohm-cm}$$

(3) Add to this resistance (1.5 ohm-cm) the internal resistance of the anode and divide by the number of anodes in parallel (twenty in this case).

The above procedure can be used to determine the anode to earth resistance. Design charts can be constructed for vertical anodes and horizontal anode ground-beds for both impressed and galvanic anode systems. The development of design curves is discussed in Section 5.31.2.

5.30 GROUND-BED DESIGN

The ground-bed design is an essential component of a cathodic protection system. The following are the salient points which need consideration while selecting a site for the ground-bed installation:

(1) Presence of metallic structures in the vicinity of the ground-bed.
(2) Location of the site with respect to the pipeline.
(3) Source of power.
(4) Ready access.

Once the current requirement of a structure is established, the ground-bed is designed to keep the resistances as low as possible. Such an arrangement allows a small voltage for the purpose of driving the required protective current. By lowering the resistances, the cost of power consumption is also reduced. The simplified relation given below can be used to determine the resistance of a single or vertical anode to earth.

$$R_V = 0.00521\frac{\rho}{L} \times \left[2.3\log\frac{8L}{d} - 1\right]$$

It is known as D'Wights equation for single vertical anode, where

R_V = resistance of vertical anode (ohms) to earth
L = anode length in feet
ρ = soil resistivity (ohm-cm)
d = anode diameter (in feet)

A more common form of equation for multiple vertical anodes is:

$$R_V = 0.0052\frac{\rho}{NL}\left[\left(2.303\log\frac{8L}{d} - 1\right) + \left(\frac{2L}{S} \times 2.303\log 656N\right)\right]$$

It is called Sundae equation.

H. B. D'Wights equation can also be used to determine the resistance to earth for a single horizontal anode.

$$R_h = \frac{0.00521\rho}{L}\left(2.303\log\frac{4L}{D} + 2.303\log\frac{L}{H} + \frac{2h}{L} - 2\right)$$

where

L = anode length in feet
R_h = resistance of horizontal anode
d = anode diameter (including the backfill)
h = depth from surface to center of the anode (ft).

For multiple anodes, multiply R_h by the adjusting factors for the parallel anodes given in standard tables.

The following relationship is widely used to determine the resistances of the anode backfill:

$$R_V = \frac{0.0171\rho}{L}\left(2.303\log\frac{8L}{d} - 1\right)$$

Illustrative Examples

Calculate the resistance to earth of a 3 in × 60 in long vertical anode in 1000 ohm soil. The anode length is 5 ft and diameter is 0.25 in. What would be its resistance in a 5000 ohm-cm soil?

Solution:

Using the formula mentioned above (D'Wights equation)

$$R = \frac{0.00521\rho}{L}\left(2.303\log\frac{8L}{d} - 1\right)$$

and inserting the appropriate values

$$R = \frac{0.00521 \times 1000}{5}\left(2.303\log 8 \times \frac{5}{0.25} - 1\right)$$

$$= 4.24 \text{ ohms}$$

In a soil of 5000 ohm-cm, the resistance would be

$$4.24 \times \frac{5000}{1000} = 21.20 \text{ ohms}$$

With the help of the above formula, it can also be shown that a long slender anode has a lower resistance than a short square anode, given the same weight.

5.31 SOIL RESISTIVITY AND PIPE-TO-SOIL POTENTIAL SURVEY

5.31.1 SOIL RESISTIVITY SURVEY

Conducting soil resistivity surveys is a primary step in designing of a cathodic protection system for pipelines. The methods of determination of soil resistivity have been described in an entire section. Pipelines in low resistivity soils would require a greater amount of current for protection than pipelines in a high resistivity soils, because of a higher magnitude of corrosion in the former. Hence, low soil resistivity areas are selected to install the anode ground-bed.

Figure 5.50 shows a typical plot of soil resistivity survey. The peaks in the plot indicate the areas of high soil resistivity and the valleys, the

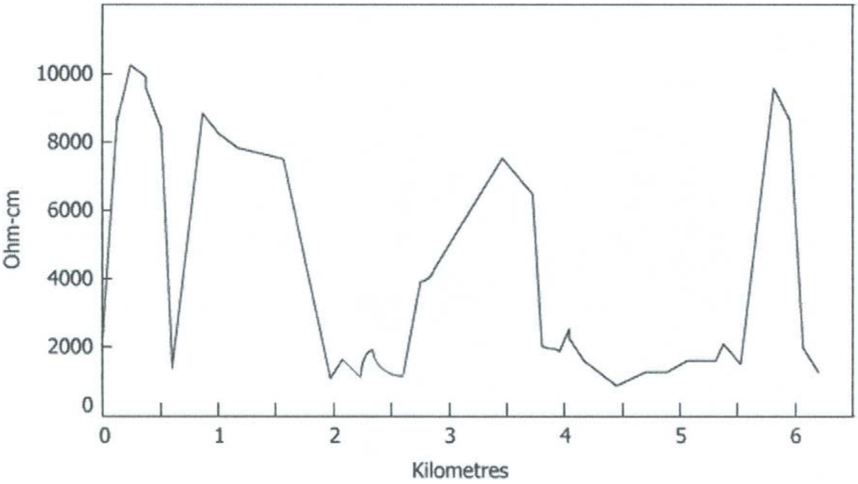


Figure 5.50 Soil resistivity data

areas of low soil resistivity, the preferred areas for installation of anode ground-beds.

The basic idea of the survey is to detect anodic and cathodic areas on the pipe for cathodic protection. The potential readings differ for coated and uncoated pipelines and are influenced by galvanic corrosion and external current. Therefore, no generalized statement can be made on the value of potentials above which the areas are anodic and below which are cathodic. More negative potentials indicate the anodic areas in general and these areas need to be protected. The following are the guidelines for determining the pipe-soil potential:

1. Potentials for newer pipelines are more negative than the other ones.
2. Potentials are more negative in neutral and acidic soils than those in alkaline environments.
3. Regions of more negative potential correspond to locations of low soil resistivity (anodic areas) in uncoated pipelines.
4. Typical values of potentials along uncoated pipelines are, in general, in the range of −0.5 V – −0.6 V and −0.65 V – −0.75 V along wet coated pipelines. The peaks in the potential profile represent locations liable to corrode.

Determining the degree of cathodic protection: A reading less negative than −1.2 V *vs* $Cu/CuSO_4$ would indicate adequate C. P. and a reading more positive than −1.2 V would indicate inadequate C. P.

5.31.2 COMBINED PLOTS (COMPOSITE PLOTS)

Composite plots of pipe-to-soil potential and soil resistivity surveys can be constructed to identify the hot spots (corroding areas determined by both soil resistivity and pipe-to-soil potential surveys). The corrosive areas in the composite figure are shown by shaded areas where the peaks in the pipe-to-soil correspond with the valleys in the soil resistivity survey (Figs 5.50–5.52). A low soil resistivity (say, 1000 ohm-cm) and a high negative value of pipe-to-soil potential (say, −1.3 V) would constitute a corrosion area.

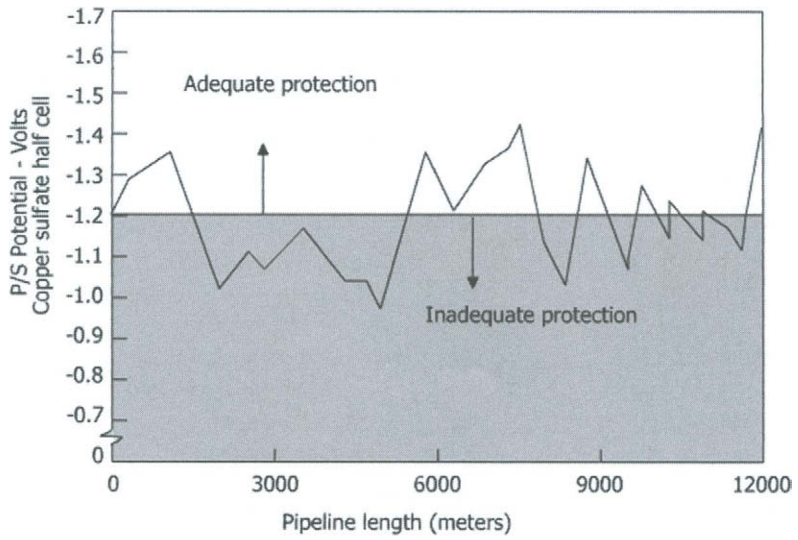


Figure 5.51 Pipe-to-soil potential survey. (From TEXACO Cathodic Protection – Design and application school, Texaco Houston Research Center, Training Manual. Reproduced by kind permission of Texaco, Houston, USA)

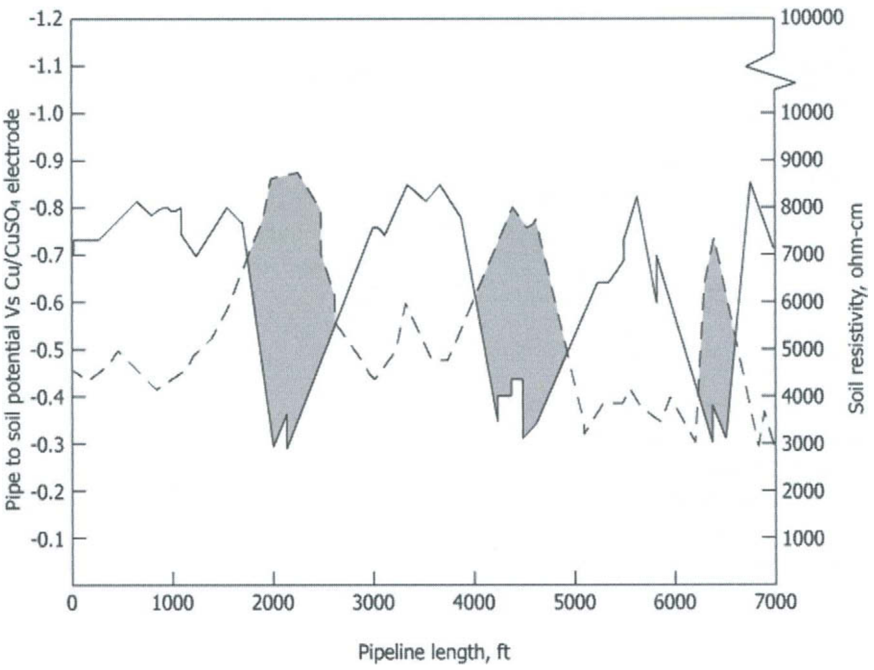


Figure 5.52 Composite data – pipe-to-soil potential and soil resistivity surveys. Shaded areas represent hot areas which need protection. (From TEXACO Cathodic Protection – Design and application school, Texaco Houston Research Center, Training Manual. Reproduced by kind permission of Texaco, Houston, USA)

5.32 CALCULATIONS IN CATHODIC PROTECTION DESIGN

5.32.1 DESIGN CURVE CALCULATIONS

It has been stated earlier that the resistance of a number of anodes can be determined from design charts. The design charts are made for definite sizes of anodes, in a known soil resistivity. The following calculations show how the design curves are constructed.

(A) Determination of resistance of the anodes to outer edge of the backfill (internal resistance)

In order to determine the internal resistance, the following data would be required:

(a) Resistivity of the backfill
(b) Dimensions of anode
(c) Dimensions of the backfill

Suppose the following data is given:

$a = 40$ ohm-cm (backfill resistivity)
$b = 3'' \times 5'$ (anode dimensions)
$c = 6'' \times 7'$ (backfill dimensions)

Solution:
Applying Sundae equation, determine first the resistance of vertical anode to outer edges of the backfill (R_1).

$$R_{V_a} = \frac{0.00521}{L}\rho\left(2.3\log\frac{8L}{d} - 1\right)$$

$$R_{V_a} = \frac{(0.00521)(40)}{5}\left[2.3\log\frac{40}{0.25} - 1\right]$$

$$= 0.166 \text{ ohms}$$

(use anode dimensions and backfill resistivity)

$$R_{V_{\mathrm{bf}}} = \frac{(0.00521)(40)}{7}\left[2.3\log\frac{56}{0.5} - 1\right]$$

$$= 0.107\ \text{ohms}$$

$$R_1 = R_{V_\mathrm{a}} - R_{V_{\mathrm{bf}}}$$

$$= 0.166 - 0.107\ \text{ohms}$$

$$= 0.059\ \text{ohms}$$

(B) Calculation of total resistance of one anode to earth
Data required:

R_I = resistance of anode to outer edge of backfill (internal resistance)
ρ = resistivity of soil (1000 ohm-cm)
d = dimension of backfill column ($6'' \times 7'$) as in (A)
R_2 = resistance of backfill column to soil

Solution:
$R_{V(\mathrm{total})} = R_1 + R_2$ (internal resistance + backfill to soil)

R_1 – has already been determined in (A) to be 0.059 ohms

R_2 – resistance of backfill to soil is now to be determined, which is

$$R_2 = \frac{(0.00521)(1000)}{7}\left(2.3\log\frac{56}{0.5} - 1\right)$$

$$= (0.74)(2.3\log 112 - 1)$$

$$= (0.74)(2.3 \times 2.04 - 1)$$

$$= (0.74)(3.692)$$

$$= 2.76\ \text{ohms}$$

R_1 – has already been determined in (A) to be 0.059 ohms

As $R_{V(\mathrm{total})} = R_1 + R_2 = R_\mathrm{T}$

$$R_\mathrm{T} = R_{V(\mathrm{total})} = 0.059 + 0.76$$

$$= 2.822\ \text{ohms}$$

(C) A design curve is to be developed for 10, 15, 25 and 30 anode beds at a 10 ft spacing in 1000 ohm-cm soil resistivity.
Required data:

(1) $\rho = 1000$ ohm-cm (soil resistivity)
(2) $N = 10, 15, 20, 25, 30$ (number of anodes)
(3) $S = 10$ ft (anode spacing)
(4) $d = 6'' \times 7'$ (backfill dimensions)

$$R = \frac{0.00521}{NL}\rho\left\{\left(2.3\log\frac{8L}{d} - 1\right) + \left(\frac{2L}{S}\,2.3\log 0.656\,N\right)\right\}$$

Workout R for 10, 15, 20, 25 and 30 anodes from the given data.

(1) For $N = 10$

$$R = \frac{(0.00521)(1000)}{10(7)}\left\{\left(2.3\log\frac{8\times 7}{0.50} - 1\right) + \left(\frac{2\times 7}{10}\,2.3\log 0.656(10)\right)\right\}$$

$$= 0.47216$$

(2) For $N = 15$

$$R = \frac{(0.00521)(1000)}{15(7)}\left\{\left(2.3\log\frac{8\times 7}{0.50} - 1\right) + \left(\frac{2\times 7}{10}\,2.3\log 0.656(15)\right)\right\}$$

$$= 0.343$$

(3) For $N = 20$

$$R = \frac{(0.00521)(1000)}{20(7)}\left\{\left(2.3\log\frac{8\times 7}{0.50} - 1\right) + \left(\frac{2\times 7}{10}\,2.3\log 0.656(20)\right)\right\}$$

$$= 0.272$$

(4) For $N = 25$

$$R = \frac{(0.00521)(1000)}{(25)(7)}\left\{\left(2.3\log\frac{8\times 7}{0.50} - 1\right) + \left(\frac{2\times 7}{10}2.3\log 0.656(25)\right)\right\}$$

$$= 0.227$$

(5) For $N = 30$

$$R = \frac{(0.00521)(1000)}{(30)(7)}\left\{\left(2.3\log\frac{8\times 7}{0.50} - 1\right) + \left(\frac{2\times 7}{10}2.3\log 0.656(30)\right)\right\}$$

$$= 0.1955$$

From the above calculations tabulate the results as below:

Number of anodes	R (ohms)
10	0.47216
15	0.343
20	0.272
25	0.227
30	0.1955

Repeat the calculations for the following anode spacing

$S = 10$
$S = 15$
$S = 20$
$S = 25$

For $S = 15, N = 10$

(1) R_{10} for $S = 10$

$$\frac{(0.00521)(1000)}{10(7)}\left\{\left(2.3\log\frac{8\times 7}{0.5} - 1\right) + \left(\frac{2\times 7}{10}2.3\log 0.656(10)\right)\right\}$$

$$= 0.471\,\Omega$$

(2) R_{10} for $S = 15$

$$\frac{(0.00521)(1000)}{10(7)}\left\{\left(2.3\log\frac{8\times 7}{0.5} - 1\right) + \left(\frac{2\times 7}{15}2.3\log 0.656(10)\right)\right\}$$

$$= 0.471\,\Omega$$

(3) R_{10} for $S = 20$

$$\frac{(0.00521)(1000)}{10(7)}\left\{\left(2.3\log\frac{8\times 7}{0.5} - 1\right) + \left(\frac{2\times 7}{20}2.3\log 0.656(10)\right)\right\}$$

$$= 0.3742\,\Omega$$

(4) R_{10} for $S = 25$

$$\frac{(0.00521)(1000)}{10(7)}\left\{\left(2.3\log\frac{8\times 7}{0.5} - 1\right) + \left(\frac{2\times 7}{25}2.3\log 0.656(10)\right)\right\}$$

$$= 0.355\,\Omega$$

(5) R_{15} for $S = 10$

$$\frac{(0.00521)(1000)}{10(7)}\left\{\left(2.3\log\frac{8\times 7}{0.5} - 1\right) + \left(\frac{2\times 7}{10}2.3\log 0.656(15)\right)\right\}$$

$$= 0.343\,\Omega$$

(6) R_{15} for $S = 15$

$$\frac{(0.00521)(1000)}{15(7)}\left\{\left(2.3\log\frac{8\times 7}{0.5} - 1\right) + \left(\frac{2\times 7}{15}2.3\log 0.656(15)\right)\right\}$$

$$= 0.290\,\Omega$$

(7) R_{15} for $S = 20$

$$\frac{(0.00521)(1000)}{15(7)}\left\{\left(2.3\log\frac{8\times 7}{0.5} - 1\right) + \left(\frac{2\times 7}{20}2.3\log 0.656(15)\right)\right\}$$

$$= 0.2635\,\Omega$$

(8) R_{15} for $S = 25$

$$\frac{(0.00521)(1000)}{15(7)}\left\{\left(2.3\log\frac{8\times 7}{0.5}-1\right)+\left(\frac{2\times 7}{25}2.3\log 0.656(15)\right)\right\}$$

$$=0.248\,\Omega$$

(9) R_{20} for $S = 10$

$$\frac{(0.00521)(1000)}{20(7)}\left\{\left(2.3\log\frac{8\times 7}{0.5}-1\right)+\left(\frac{2\times 7}{10}2.3\log 0.656(20)\right)\right\}$$

$$=0.272\,\Omega$$

(10) R_{20} for $S = 15$

$$\frac{(0.00521)(1000)}{20(7)}\left\{\left(2.3\log\frac{8\times 7}{0.5}-1\right)+\left(\frac{2\times 7}{15}2.3\log 0.656(20)\right)\right\}$$

$$=0.2275\,\Omega$$

(11) R_{20} for $S = 20$

$$\frac{(0.00521)(1000)}{20(7)}\left\{\left(2.3\log\frac{8\times 7}{0.5}-1\right)+\left(\frac{2\times 7}{20}2.3\log 0.656(20)\right)\right\}$$

$$=0.205\,\Omega$$

(12) R_{20} for $S = 25$

$$\frac{(0.00521)(1000)}{20(7)}\left\{\left(2.3\log\frac{8\times 7}{0.5}-1\right)+\left(\frac{2\times 7}{25}2.3\log 0.656(20)\right)\right\}$$

$$=0.192\,\Omega$$

For R = 25 and S = 10, 15, 20 and 25:

(13) R_{25} for $S = 10$

$$\frac{(0.00521)(1000)}{25(7)}\left\{\left(2.3\log\frac{8\times 7}{0.5}-1\right)+\left(\frac{2\times 7}{10}2.3\log 0.656(25)\right)\right\}$$

$$=0.229\,\Omega$$

(14) R_{25} for $S = 15$

$$\frac{(0.00521)(1000)}{25(7)}\left\{\left(2.3\log\frac{8\times 7}{0.5}-1\right)+\left(\frac{2\times 7}{15}2.3\log 0.656(25)\right)\right\}$$

$$=0.19\,\Omega$$

(15) R_{25} for $S = 20$

$$\frac{(0.00521)(1000)}{25(7)}\left\{\left(2.3\log\frac{8\times 7}{0.5}-1\right)+\left(\frac{2\times 7}{20}2.3\log 0.656(25)\right)\right\}$$

$$=0.17\,\Omega$$

(16) R_{25} for $S = 25$

$$\frac{(0.00521)(1000)}{25(7)}\left\{\left(2.3\log\frac{8\times 7}{0.5}-1\right)+\left(\frac{2\times 7}{25}2.3\log 0.656(25)\right)\right\}$$

$$=0.158\,\Omega$$

From the above results tabulate the calculations in the following form:

No. of anodes	Anode spacing			
	10	15	20	25
R_{10}	0.472	0.407	0.37428	0.355
R_{15}	0.343	0.29	0.2635	0.248
R_{20}	0.272	0.2275	0.205	0.192
R_{25}	0.229	0.19	0.17	0.158

Plot the data and obtain the number of anodes (*N*) *vs* resistance curves for a soil of 1000 ohm-cm resistivity and backfill dimensions of 0.5 ft diameter and 7 ft long.

The following example shows how the design curve can be used to obtain the resistance of impressed current and galvanic anodes. Separate charts are constructed for impressed current ground-beds and horizontal ground-beds. With each chart the following design information is provided:

(1) Anode dimensions
(2) Backfill dimensions
(3) Anode resistance
(4) Soil resistivity
(5) Spacing of anodes
(6) Internal resistance of anode
(7) Type of anode

The charts can be prepared for special applications by utilizing the data and working out the resistance according to the method given above.

5.32.2 CURRENT REQUIREMENTS

Example to illustrate the total current requirements for a bare 1 mile section of a 10(3/4″) OD pipe. The current density required to protect the pipe is 50 mA/ft^2.

Solution:
For a bare steel structure, a potential of −0.85 V on it provides a reasonable degree of cathodic protection. The structure is polarized by a known amount of current until a potential of −0.85 $V_{Cu-CuSO_4}$ is acquired by the pipe.

Step 1 – Estimation of current requirement

$$\left[\frac{10.75}{12}\right] \times (3.14) \times 5280\,\frac{\text{ft}}{\text{mile}}\left(0.005\,\frac{\text{A}}{\text{ft}^2}\right)$$
$$= 0.895 \times 3.14 \times 5280 \times 0.005\,\text{A}$$
$$= 74.2\,\text{A}$$

(An approximate current density on the basis of experience is first selected.)

Apply a current of approximately 74.2 A to the pipe. In order to ensure the accuracy of the estimation, a pipe potential *vs* time polarization curve is plotted as shown in Fig. 5.52. By extrapolation of the polarization curve, the maximum potential achieved by the predetermined current is noted. If, for instance, by applying 74.2 A of current, the potential achieved is −0.8386, the additional current needed to achieve −0.85 is worked out and added to the approximated current to obtain an accurate value of current requirements. For example, the amount of current approximated raised the potential of the structure to −0.838 rather than −0.85 V, which is the required potential to achieve cathodic protection. If the voltage before cathodic protection is applied is −0.6 V, then the total voltage change is

$$\Delta E = -0.838 - (-0.6) = -0.238\,\text{V}$$

The average potential change per ampere is

$$\frac{\Delta E}{\Delta I} = \frac{0.238}{74.2} = 0.0032\frac{\text{V}}{\text{A}}$$

Amount of current required to raise the potential from −0.85 − (−0.838) = 0.01 V.

Therefore, additional amount of current required:

$$= \frac{0.01\text{V}}{0.0032\text{V/A}} = 3.125\,\text{A}$$

Total current = 74.2 + 3.125 = 77.325 A.

Additional current needed to raise the potential from −0.838 V to −0.85 V is 0.892 A. The total current required is, therefore,

$$74.2\,\text{A} + 0.892\,\text{A} = 75.092\,\text{A}$$

which is not too far away from the approximation (74.2 A).

5.32.3 DETERMINATION OF COATING RESISTANCE OF A PIPE

Determine the coating resistance of 4(6/8)″ OD pipe, 4 miles long.

Solution:

Data provided:

Location	Volts (ON)	Volts (OFF)	DF
1	−1.10	−0.83	0.27
2	−1.45	−1.19	0.26
3	−1.30	−1.00	0.30

The current measured is 0.05 A.

(A) Calculate the average value of ΔE

$$\Delta E = \frac{0.27 + 0.26 + 0.30}{3} = \frac{0.83}{3} = 0.276\,\text{V}$$

(B) Calculate the area of the pipe

$$\text{Area} = \pi DL = \frac{4.625}{12} \times (\pi)(4)(5280) = 25559.6\,\text{ft}^2$$

(C) Calculate the resistance, R

$$R = \frac{\Delta E}{I} = \frac{0.276\,\text{V}}{0.05\,\text{A}} = 5.52\,\text{ohms}$$

The resistance of the coating for one average square feet is (5.52 ohms)(25559.6) = 141088.99 ohms·ft^2.

Illustrative Problem 1

From the design chart for 3″ diam × 5′ long anode, determine the resistance of 25 graphite anodes at 10 ft spacing in a 3000 ohms-cm soil.

Solution:

(1) Suppose the resistance of 25 anodes at 10 ft spacing in 1000 ohm-cm soil is 0.26 ohms from a design chart.

(2) The resistance in 3000 ohm-cm soil

$$R_{(3000)} = 0.26 \times \frac{3000}{1000} = 0.78\,\text{ohms}$$

Illustrative Problem 2

Design an impressed current system to protect a coated pipeline 4 mile long, 6(5/8)″ OD in a soil of 2000 ohm-cm resistivity. Graphite anodes 3″ × 5′ are to be used. The back voltage between the pipeline and ground-bed is 3.0 V.

Data

(1) In order to cause a potential shift (ΔV) of 0.2 V, (−0.65 to −0.85), 0.13 A of current is applied as required by the current requirement test (extrapolation method).
(2) The coating has 2% holidays.
(3) A current density of 3 mA/ft^2 is to be applied.
(4) Resistivity of anode bed = 2000 ohm-cm.

The following values are to be calculated:

(1) Current requirement.
(2) Pipe-soil resistance.
(3) Maximum allowed circuit resistance.
(4) Wire resistance.
(5) Anode bed resistance.
(6) Anode bed size.
(7) Weight of the backfill and its volume.

Solution:

Current required

(1) From the data given above, surface area of the pipe

$$= \left[\frac{6.6}{12}\right](\pi)(4)(5280) = 36\,474\,\text{ft}^2$$

(2) Percentage of uncoated pipeline = 2%.
(3) Current density required, 0.003 A/ft^2. Total current needed = 36474 × 0.02 × 0.003 = 2.188 A. A rectifier, possibly 12 V, 4 A may be installed. However, an 18 V, 6 A rectifier is recommended to make allowances for future requirements.
(4) Pipe-to-soil resistance from the given data:

I = current applied for voltage drop = 0.13 A

ΔE = voltage drop = 0.2 V

$$R = \frac{\Delta E}{I} = \frac{0.2}{0.13} = 1.5\,\text{ohms}.$$

(5) Calculations of maximum allowable circuit resistance in this case

Back voltage
= 3.0 V (provided in the data)
Rectifier voltage
= 18 V (available from the rectifier)
$\Delta E = 18 - 3$
= 15 V (maximum rectifier output)
$I = 6$ A (maximum current output)
Maximum allowable circuit resistance:

$$R = \frac{\Delta E}{I} = \frac{15}{6} = 2.5 \text{ ohms.}$$

(6) Calculation of resistance of wire

Wire selected (gauge of wire) = 6
Resistance of the wire
= 0.410×10^{-3} ohms (from tables)
Length = 60 ft
Additional length for safety
= 10% of the original = 6 ft
Total length of wire = 66 ft
Resistance of the wire
= 0.259×10^{-3} ohms

$$(0.259 \times 10^{-3})66 \text{ ft} = 0.017 \text{ ohms.}$$

(7) Anode bed resistance

Maximum circuit resistance = 2.5 ohms
Pipeline-soil resistance = 1.5 ohms
Wire resistance = 0.017 ohms
$R_{(\text{anode bed})}$ = maximum circuit resistance − pipe to soil resistance − wire resistance
= 2.5 − 1.5 − 0.017 = 0.983 ohm

in a soil of 2000 ohm-cm.

The resistance in a soil of 1000 ohm-cm shall be

$$0.983 \times \frac{1000}{2000} = 0.491 \text{ ohms.}$$

(8) Calculation of the anode bed size
Suppose 25 anodes are placed at 10 feet spacing.

The resistance of 25 anodes from the design chart (suppose) = 0.26 ohms in 1000 ohm-cm soil.

The resistance of 25 anodes (anode bed) in a soil of 2000 ohm-cm

$$= 0.26 \times \frac{2000}{1000} = 0.520 \text{ ohms.}$$

Internal resistance (from data)
= 0.520 ohm/25 = 0.020 ohm.

The header cable resistance (assume)
= 0.017 ohm

Total anode bed resistance = Resistance of 25 anodes bed + internal resistance + header wire resistance.

Total anode bed resistance:

$$= 0.52 + \underset{\substack{\text{(internal}\\ \text{resistance)}}}{0.020} + \underset{\substack{\text{(header-wire}\\ \text{resistance)}}}{0.017}$$

= 0.557 ohms

(9) Total resistance of circuit

Pipe-to-soil resistance
= 1.5 ohms (given in data)
Anode bed resistance = 0.557 (Step 8)
Lead wire resistance = 0.017 (Step 6)
Total = 1.5 + 0.557 + 0.017 = 2.077 ohms
It is obviously less than the maximum permissible resistance of 2.5 ohms (as shown in Step 5).

(10) Weight of backfill

Anode dimension (given) = $3'' \times 5'$
= 0.245 ft^3
Backfill dimension = $8'' \times 7'$ = 2.446 ft^3
Number of anodes is 25 at a spacing of 15 ft

$$\begin{aligned}\text{Backfill volume} &= 25\,(2.45 - 0.246)\\ &= 55.1 + 20\%\ \text{for over-design}\\ &= 66.12\ \text{ft}^3\end{aligned}$$

Weight of backfill at 70 lb/ft^3

$$= 70 \times 66.12 = 4628\ \text{lb/ft}^3$$

Illustrative Problem 3

Calculate the expected current output of a single 48 lb Galvamog magnesium alloy anode. The size of the backfill package is 10″ × 40″. The steel has been polarized to a potential of −0.85 V. The resistivity of soil is 2000 ohm-cm. The solution potential of Galvamog is −1.75 V. Calculate the life of 48 lb magnesium anode.

Solution:

(a) First determine the resistance of the anode from the given data:

$$d = 10'' = \frac{10}{12}\ \text{ft} = 0.83\ \text{ft}$$

$$L = 40'' = \frac{40}{12}\ \text{ft} = 3.33\ \text{ft}$$

$$R = \left[\frac{0.00521}{L} \times \rho\right]\left[\ln\frac{8L}{d} - 1\right]$$

$$= \frac{0.00521}{3.33}(2000)\left[\ln\frac{8 \times 3.33}{0.83} - 1\right]$$

$$= 7.72\ \text{ohms}$$

(b) The driving potential $= -1.75 - (-0.85) - (-0.10) = 0.8\ \text{V}$.

(c) According to Ohm's law:

$$I = \frac{E}{R}$$

$$I = \frac{0.8}{7.72} = 0.103\ \text{A}$$

The life expectancy is determined by

$$\frac{(\text{Weight of anode})(0.116)(0.50^{*})(0.85^{**})}{0.103}$$

$$= \frac{(48)(0.116)(0.50)(0.85)}{0.103}$$

$$= 22.97\ \text{years}$$

*consumption rate = A/year/lb (inverse of theoretical consumption rate)

**efficiency of anode

Illustrative Example 4

The interior of a tank is to be protected. The tank contains 5000 barrels of salt water. The following data is provided:

(1) Water level = 25.0 ft
(2) Height of tank = 30.0 ft
(3) Diameter of tank = 40 ft
(4) Water level is maintained at 25 ft
(5) Current density = 4 mA/ft^2
(6) Resistivity of water = 10 ohm-cm
(7) Length of 2 AWG wire = 130 ft

Resistance = 0.162×10^{-3} ohms/ft

From the above data, calculate the following:

(1) Current requirement.
(2) Current output per anode if 3″ × 5′ graphite anodes are used and the anode current density is 2.0 A/ft^2.
(3) Number of anodes required.
(4) Anode to electrolyte resistance.
(5) Resistance of lead wire (R_w) 130 ft long.
(6) Resistance of anode.
(7) Potential drop in the circuit.
(8) Size of the rectifier to be selected.

Solution:

(1) Firstly, the area of the tank in contact with water is calculated (wetted area, A_w)

$$\begin{aligned}A_w &= \frac{\pi d^2}{4} = \pi d L\\ &= \frac{\pi(40)^2}{4} + \pi(40)(25)\\ &= 1256 + 3140\\ &= 4396\ \text{ft}^2\end{aligned}$$

The current requirement is:

$$I = 4396 \times 0.004 = 17.6\ \text{A}.$$

(2) Current output of each anode.
From the previous calculation we have observed that the current requirement is 13.2 A.
The area of the anode surface is (A_a)

$$A_a = \frac{d\pi L}{12} = \frac{3\pi}{12} \times 5$$
$$= 3.92\,\text{ft}^2 (\sim 4\,\text{ft}^2)$$

The current output is, therefore,

$$C_a = Cd_a \times A_a \; (C_a = \text{current output of anode, } A_a = \text{area of anode})$$

$$Cd_a = 2.0\,\frac{\text{A}}{\text{ft}^2} \times 3.92$$
$$= -8.0\,\frac{\text{A}}{\text{anode}} \; (Cd_a = \text{current density of anode})$$

As the total current requirement is 17.6 A, the number of anodes required is:

$$\frac{17.6}{8} \simeq 2 \text{ anodes}$$

(3) Anode to electrolyte resistance use D'Wight equation as before:

$$R = \frac{0.00521}{L}\rho\left[\ln\frac{8L}{d} - 1\right]$$
$$= \frac{0.00521}{5}(10)\left[\ln\frac{40}{0.25} - 1\right]$$
$$= 0.0425 \text{ ohms}$$

(4) Calculation of resistance of lead wires
The resistance of the lead wires is the estimated average length × resistance of 2 AWG wire. The known resistance is 0.162×10^{-3} ohms/ft.

$$\text{Resistance} = 130 \times 0.162 \times 10^{-3} \text{ ohms}$$
$$= 0.021 \text{ ohms.}$$

(5) The resistance of the anode. We have now all the necessary information to calculate the resistance of the two anodes.

The resistance of the circuit is given by

$$\frac{1}{R} = \frac{4}{R_w + R_a}$$

Here

R_w = resistance of the wire which is calculated to be 0.02 ohms
R_a = resistance of the anode to electrolyte which has been determined to be 0.0425 ohms

Therefore,

$$\frac{1}{R} = \frac{4}{0.021 + 0.0425}$$
$$= \frac{4}{0.0635}$$
$$= 62.992$$
$$R = 0.016 \text{ ohms}$$

(6) The potential drop is determined by Ohms' law:

$$E = I \times R$$
$$= 17.6 \times 0.016$$
$$= 0.282 \text{ V}$$

The size of the rectifier to be used must be a 30 V–30 A circuit rectifier would be quite suitable.

Illustrative Example 5

Calculate the current output and life expectancy of a Galvomag anode from the following data:

Backfill package size
= 8″ × 32.5″ (0.65′ × 2.71′)
Potential of the polarized structure = −0.95 V
Soil resistivity = 2000 ohm-cm
Solution potential of Galvomag anode
= −1.75 V
Weight = 48 lbs
Polarization potential = −0.10 V

Solution:

Apply the following relationship to obtain the resistance:

$$R = \frac{0.00521}{L}\rho\left[\ln\frac{8L}{d} - 1\right]$$

Inserting the value

$$R = \frac{0.00521}{2.71}(2000)\left[\ln\frac{21.7}{0.67} - 1\right]$$

$$= 9.53\text{ ohms}$$

The driving potential (E_D)

$$E_D = -1.75 - (-0.95) - (-0.1)$$

$$E_D = 0.7\text{ V}$$

Determine the current *I*, by using $E = IR$

$$I = \frac{0.700}{9.53} = 0.073\text{ A}$$

$$\text{Life expectancy} = \frac{(48)(0.116)(0.50)(0.85)}{0.73}$$

$$= 32\text{ years}$$

5.33 IMPORTANT FORMULAE IN CATHODIC PROTECTION CALCULATIONS

(1) Series Circuit

$$R = R_1 + R_2$$

(2) Parallel Circuit

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{R_1 + R_2}{(R_1)(R_2)}$$

(3) $\rho = \dfrac{RA}{L}$

where

ρ = resistivity in ohm-cm
R = resistance
L = length between two points
A = area

(4) $\rho = \dfrac{RA}{L}$

where L = length between two points in the soil or metal surface.

(5) Four Pin, DC Method for soil resistivity

$\rho = 2\pi AR$
A = distance between two points, in cm
R = resistance between two points

(6) Four Pin, AC Method for soil resistivity

$\rho = 191DR$
D = pin spacing, feet
R = instrument (potentiometer reading)
ρ = resistivity

(7) Life of Mg anode (years)

$$L_{Mg} = \frac{57.08 \times W}{I}, \quad L_{Zn} = \frac{38.24 \times W}{I}$$

where

L_{Mg} = life of magnesium anode
L_{Zn} = life of zinc anode
W = anode weight (lb)
I = current (mA)

(8) Driving potential of an anode

= Solution potential − Potential of polarized structure − Polarization potential (−0.100)

(9) Current output of Mg anode and Zinc anode (coated)

$$I_{Mg} = \frac{150\,000 fY}{\rho}, \quad I_{Zn} = \frac{50\,000 fY}{\rho}$$

where

I_{Mg} = current output of Mg anode (mA)
I_{Zn} = current output of Zn anode (mA)

ρ = soil resistivity, ohm-cm
f = factor from Table I
Y = factor from Table II

(Condition: The above equations apply if the soil resistivity is above 500 ohm-cm and the distance between the anode and structure is not more than 10 ft.)

(10) E. D. Sundae equation for resistance to earth.

(a) Using multiple vertical anodes

$$R_V = \frac{\rho}{191.5\,NL}\left[2.303\log_{10}\frac{4L}{d} - 1 + \frac{2L}{s}\times 2.303\log_{10} 656\,N\right]$$

(b) H. E. D'Wight equation for resistance to earth for a single anode (horizontal)

$$R_h = \frac{0.00521}{L}(\rho)\left[2.303\log_{10}\frac{4L}{10} + 2.303\log_{10}\frac{L}{h} + \frac{2h}{L} - 2\right]$$

where

R_V = resistance of vertical anode
R_h = resistance of horizontal anode
L = length (ft)
S = anode spacing, ft
h = depth from surface to center

(c) D'Wight equation for single vertical anode

$$R_V = \frac{0.00521}{L}(\rho)\left[2.3\log\frac{8L}{d} - 1\right]$$

(d) Sundae's equation for multiple vertical anodes

$$R = \frac{0.00521}{NL}(\rho)\left[\left(2.3\log\frac{8L}{d} - 1\right) + \left(\frac{2L}{S}2.3\log 0.656N\right)\right]$$

where N is the number of anodes

(e) R_V (Total resistance of vertical anode) = R_1 (Resistance to vertical anode-to-backfill) + R_2 (Resistance of vertical anode to earth)

(f) Working diameter of magnesium anode

$$\text{Area} = \frac{\pi d^2}{4}$$

(g) Internal resistance of the anode to backfill

$$R_I = R_{V(\text{anode})} - R_{\text{backfill column}}$$

(h) Resistance of a single graphite high silicon cast iron anode installed vertically (no backfill)

$$R_I = \frac{K_\rho}{1000}$$

where

K = constant
ρ = soil resistivity

(i) Resistance of graphite of high silicon cast iron anode with and without backfill

$$R = \frac{K_\rho}{1000}\times NY$$

where

ρ = soil resistivity
N = number of anodes
Y = spacing factor from the curve
R = resistance in ohms

(11) Current requirement on a coated pipe

A_s × % uncoated pipe × current density
A_s = surface area of pipe
% uncoated pipeline current density

(12) Wire resistance

Length of wires + 10% safety factor + resistance of wire ohms/ft

(13) Total volume of backfill needed

= (Number of anodes) (Volume of backfill − Anode volume) + 20%

(14) (a) Induced emf

$$= \frac{\text{Secondary winding} \times \text{Applied voltage}}{\text{Primary winding}}$$

(b) Efficiency of rectifier

$$= \frac{\text{DC volts} \times \text{DC amps} \times \text{Seconds} \times 100}{Kh \times 3600 \times \text{Revolutions}}$$

where

Kh = meter constants

$$\text{or } \frac{\text{DCV} \times \text{DCA}}{\text{Input watts}} \times 100$$

Input Watts = $K \times N \times 12$

(N = number of dial revolutions in a 5 min period)

(15) Number of anodes (N)

$$= \frac{\text{Total current requirement}}{\text{Current output of one anode (A)}}$$

(16) Rectifier current rating AC

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

where

I_{ac} = AC current (A)
E_{dc} = DC volts
I_{dc} = DC current (A)
F = rectifier efficiency
E_{ac} = AC volts

(17) (a) Number of anodes required based on the anode consumption rate

$$N = \left(\frac{Y \times I \times C}{W}\right)$$

where

N = number of impressed current anodes
Y = impressed current system design life, years
I = total current required in A
C = anode consumption rate in kg/A-yr
W = weight of anode in kg

(b) Number of anodes based on weight (lb) Number of anodes (lb)

$$= \frac{\text{Total weight of anode material}}{\text{Weight of one anode}}$$

(c) Number of anodes based on current output, N

$$N = \frac{\text{Total current output (A)}}{\text{Output of one anode (A)}}$$

(use manufacturer's data)

(d) Current output of one anode (A)

$$= \frac{\text{Driving potential of the anode (V)}}{\text{Resistance of the anode (ohms)}}$$

(18) Structure to electrolyte resistance

$$R_s = \frac{V_{on} - V_{off}}{I_{on}}$$

where

V_{on} = potential (on)
V_{off} = potential (off)
I_{on} = current applied to give V_{on}

(19) Maximum circuit resistance

$$R_{max} = \frac{E_D}{I}$$

where

E_D = driving potential of anode
I = current requirement

(20) Allowable ground-bed resistance

$$R_{agb} = R_{max}(R_s + R_{Lw})$$

where

R_s = structure to electrolyte resistance
R_{Lw} = lead wire resistance

QUESTIONS

A. MULTIPLE CHOICE QUESTIONS

Select one correct answer for the following questions:

1. A bare structure requires more current than a coated structure because

   [ ] the coated structure corrodes rapidly
   [ ] the bare structure has a more negative potential than a coated structure
   [ ] a coated structure is more rapidly polarized than a non-coated structure
   [ ] the bare structure takes a very long time to polarize than a coated structure

2. A backfill is used *around* an anode

   [ ] to provide a uniform environment around the anode
   [ ] to accelerate the rate of consumption of the galvanic anode
   [ ] to increase the anode-to-earth resistance
   [ ] to increase the magnitude of the current which is to be provided to the structure

3. Cathodic protection in a metallic structure is achieved by

   [ ] polarizing the cathode to the open circuit potential of the anode
   [ ] polarizing the anode to the open circuit potential of cathode
   [ ] shifting the potential of the structure to less negative values
   [ ] producing a film of oxide on the surface of the metallic structure to be protected

4. The following is the criteria for cathodic protection:

   [ ] A shift in the pipe-to-soil potential in the negative direction by 0.40 to 0.50 V from the initial potential for bare structures
   [ ] To achieve a pipe-to-soil potential of 0.85 V with respect to Ag–AgCl electrode
   [ ] To achieve a potential of −0.85 V with respect to a copper sulfate electrode
   [ ] To polarize the whole structure to the cathodic potential of the structure

5. In the *impressed* current *cathodic protection* system

   [ ] the pulsating direct current goes from the positive (+) terminal of the rectifier to the ground-bed
   [ ] the pipeline is the positive return or external circuit of the electrolytic cell
   [ ] AC current is directed to a rectifier where a step-down transformer increases the voltage
   [ ] it is not necessary to install a magnetic circuit breaker in the AC circuit

6. The following are the disadvantages of the rectifier ground-beds:

   [ ] Larger driving voltages
   [ ] Higher current outputs
   [ ] Protection of larger and more expensive structures
   [ ] High installation costs

7. The following is the H. B. D'Wight equation for resistance to earth of a single vertical anode:

   [ ] $$R_V = \frac{\rho}{191.5\,NL}\left[2.303\log_{10}\frac{4L}{d} - 1 + \frac{2L}{S}\,2.3\log_{10}0.656N\right]$$

   [ ] $$R_V = \frac{0.00522\,\rho}{L}\left[32.303\log_{10}\frac{4L}{d} + 2.303\log_{10}\frac{L}{h} + \frac{2h}{L} - 2\right]$$

   [ ] $$R_V = \frac{0.00521}{L}\rho\left\{2.3\log\frac{8L}{d} - 1\right\}$$

   [ ] None of the above

8. The pipe-to-soil potential of a pipe is −1.35 V and the potential of the polarized structure −0.90 V. The resistance of the anode-to-earth has been found to be 0.150 ohm. The anode output would be

   - [ ] 5 A
   - [ ] 4 A
   - [ ] 3 A
   - [ ] 1.15 A

9. Cathodic protection systems can be described as

   - [ ] transferring corrosion from the protected structure to the anodes
   - [ ] transferring corrosion from the protected structure to the soil
   - [ ] effective when all current has stopped flowing in the system
   - [ ] effective when all piping is made sufficiently negative

10. The surface potential survey requires

    - [ ] the use of a high resistance voltmeter or potentiometer connected to the copper–copper sulfate reference electrode
    - [ ] the use of a rectifier
    - [ ] the use of a low resistance voltmeter
    - [ ] a strip-chart recorder

11. Which one of the following is a good indicator to ensure that the structure is receiving current?

    - [ ] The achievement of $-850\ \mathrm{mV}_{\mathrm{Cu-CuSO_4}}$ with C. P. applied
    - [ ] A change of 200 mV from the original potential
    - [ ] The structure become passive
    - [ ] Polarized potential of $-600\ \mathrm{mV}_{\mathrm{Cu-CuSO_4}}$

12. While determining the current requirements for a bare structure, it is essential to

    - [ ] place the electrode over the structure directly
    - [ ] place the electrode 100 ft from the structure
    - [ ] place the electrode contacts far enough until there is *no* increase in the negative reading
    - [ ] place the electrode always 50 ft away from the structure

13. The driving potential is the

    - [ ] difference between the 'on' value and the 'off' value of potentials
    - [ ] difference between the 'on potential' and 'static potential'
    - [ ] difference between the solution potential and polarization voltage
    - [ ] None of the above

14. The total resistance of the vertical anode to earth is

    - [ ] resistance of the anode to backfill + resistance of the backfill to the soil
    - [ ] resistance of the anode to backfill − resistance of the backfill to soil
    - [ ] resistance of the backfill to soil + resistance of the pipe
    - [ ] None of the above

15. A low resistance backfill is specified in anode bed design, because it

    - [ ] increases the area of contact between anode and the soil
    - [ ] decreases the area of contact between the anode and the soil
    - [ ] provides a lower anode to earth resistance
    - [ ] has a higher current output

16. A deep well anode bed design is selected because

    - [ ] the soil has a higher resistance at a greater depth
    - [ ] the soil is more aerated at a higher depth compared to a lower depth

[ ] the soil has a high resistance near the surface and a low resistance at a greater depth
[ ] it can be useful in congested areas and will

17. Which of the following is true?

[ ] A remote ground-bed protects a smaller area of pipe than a close ground-bed
[ ] A remote ground-bed protects a larger area of the pipe
[ ] Soil nearest to the anode is most negatively charged
[ ] The further is the soil away from the anode, the more positively charged it becomes

18. Which of the following is true for current originating from a rectifier?

[ ] Return to the rectifier through the pipeline
[ ] Travel to the metallic structure and to get discharged from the metallic structure to the ground
[ ] The current flow reverses 240 times per second
[ ] None of the above

19. When the current enters the remote earth

[ ] the resistance of the soil increases
[ ] the resistance of the soil decreases
[ ] the soil offers no resistance at all
[ ] there is an increase in the potential of the pipe

20. A stray current is indicated if

[ ] a positive potential is indicated at the point of corrosion
[ ] a positive potential is indicated at the point of protection
[ ] the current flows from the electrolyte, like soil, into the metal
[ ] very small magnitude of current flows between the anode and the protected structure

21. The best remedy to minimize stray current corrosion is to

[ ] relocate the metallic structure
[ ] coat the metallic structure
[ ] bury the metallic structure deeper in the ground
[ ] install a metallic bond between the structure and the source of stray current

22. In measurement of soil resistivity by four-pin method

[ ] an alternate current is passed between the outer electrode and the resulting voltage drop is measured between these two electrodes
[ ] the galvanometer is adjusted to read zero by means of a potentiometer which is calibrated to read directly in ohms
[ ] a direct current is passed between the two outer electrodes and the voltage drop is measured between the inner electrode
[ ] the depth of pins is made to be the same as the distance between two electrodes

B. HOW AND WHY QUESTIONS

Explain why (very briefly) the following:

1) A bare structure requires approximately 10 000 times more current than a coated structure.
2) The resistivity of soil decreases with higher salt content.
3) The reference Cu–$CuSO_4$ electrode is placed directly over a coated pipe and away from the pipe if it is not coated.
4) Stray currents cause the uncontrolled corrosion of underground pipes.
5) Well-coated structures polarize more rapidly than bare structures, when cathodic protection is applied.
6) Long slender anodes are preferable over short squat anodes for high resistivity soils.
7) Cathodic current protects the outside of the pipes only.

8) The lowest resistivity soil is often the best location for placement of galvanic anode.
9) High resistance voltmeter must be used to make accurate measurement of pipe-to-soil potential.
10) Over-protection causes damage to the pipeline.

C. PROBLEMS

1. Calculate the current output of a single anode bed and its life. Assume a pipe-to-soil potential of 0.4 ohm. The following data is given:

   Driving potential = 0.5 V
   Resistance = 7.18 ohms
   Weight of Mg per bed = 128 lbs
   Consumption rate = 0.116 A-year/lb
   Efficiency = 0.5
   Utilization factor = 0.81

2. The open circuit potential of a magnesium anode is $-1.55\,\mathrm{V_{Cu-CuSO_4}}$. It protects a steel tank polarized to a potential of $-0.950\,\mathrm{V_{Cu-CuSO_4}}$. Estimate the driving potential of magnesium anode.
3. The open circuit potential of a single 48 lb Galvomag magnesium alloy anode is −1.75 V. The surrounding backfill has dimensions of 8″ × 30″. The anode has polarized the steel in a soil of resistivity 3000 ohms-cm to −0.85 V. Estimate the current output of the anode.
4. Calculate the life of the anode given in Problem (3), if it has an efficiency of 50% and a utilization factor of 0.85.
5. Calculate the expected current output of a 725 lb Galvalum anode, from the data given below:

   Resistivity of seawater = 30 ohms-cm
   Anode length = 96″
   Anode width = 10″ × 10″
   Anode core = 4″*d*
   Steel polarized to −0.900 V
   Open circuit potential of anode = $-1.15\,\mathrm{V_{Cu-CuSO_4}}$

   Estimate anode radius from $c = 3.14 \times d$
   Hint: $c = \pi d$

   $$\text{Working diameter} = \text{Core diameter} + \frac{\text{Anode diameter}}{2}$$

   $$R = \frac{0.00521\,\rho}{L}\left[2.3\log\frac{8L}{d} - 1\right]$$

6. From the following data calculate the life of a magnesium anode:

   Weight of magnesium anode = 50 lb
   Number of available ampere hour per pound = 500
   Current output = 35 mA
   (8760 h in one year)

7. Find the number of 17 lb magnesium anodes and the spacing between the anode to protect a 10 000 ft of a bare 4″ diameter pipeline in a corrosive soil having a resistivity of 800 ohms-cm. Assume a current requirement of 2 mA/ft^2 and an anode output of 100 mA per anode.
8. Determine the internal resistance from the anode to the outer edge of the backfill column (R_1) from the following data:

   Resistivity of backfill = 8000 Ω-cm
   Anode dimension = 3″ × 5′
   Backfill column dimension = 8″ × 11′

9. In Problem (8), R_1 is to be determined. The total resistance of a vertical anode-to-earth $R_v = R_1 + R_2$, where R_1 is the resistance of the backfill column to earth. If the soil resistivity is 2000 ohms-cm and the dimension of the backfill column are 0.50′ × 8′, determine the total resistance of the anode-to-earth.
10. Calculate the total resistivity of the anode bed from the following data:

    Soil resistivity = 1000 ohms-cm
    Backfill resistivity = 70 ohms-cm
    Backfill dimensions = 5″ × 7′

Anode weight = 16 lbs
Anode dimensions = 15″ × 5′

Hint: Use D'Wight's equation to determine the resistance of a single anode.

11. Determine the amount of current needed to protect a bare pipe, 3 miles long, 6″ OD. The estimated current density required for protection is 2 mA/ft^2.
12. From the data provided below, determine the coating resistance of a 5 mile, 10¾ OD pipe:

    a) Current output as recorded by ammeter = 0.50 A
    b) The following volts (on) and volts (off) reading were taken at three different locations:

Location	*Volts (on)*	*Volts (off)*
A	−1.10	−0.83
B	−1.45	−1.17
C	−1.28	−0.99

13. Calculate the surface area of a 10 mile long, 4–5 ft diameter, 2% uncoated pipeline, if the current density required for protection is 2 mA/ft^2.
14. Calculate the life of an anode bed and its current output from the following data:

Driving potential of Mg anode = 6 V
Resistance = 5.18 ohms
Weight of Mg per anode
= 5 × 32 = 120 lbs (5 anodes to a bed)
Consumption rate = 0.116 A-year/lb
Efficiency of Mg anode = 0.6
Utilization factor = 0.85

15. In DC four-pin method, a direct current of 221 mA is passed between the two outer electrodes and a voltage drop of 191.8 mV is observed between the two inner electrodes. The pin spacing and anode depth is 7.5 inch. Determine the soil resistivity.
16. If $\rho = 2\,\pi\, AR$ and $A = 30.48\ D$, prove that $\rho = 191\ DE/I$.

D = distance between electrode, E = volts,
I = mA

17. An appropriate rectifier is to be selected for designing an impressed current system. The minimum current required has been estimated to be 2.36 A and the total circuit resistance is determined to be 2.54 ohms. Specify the nearest commercial size of the rectifier. (*Hint:* $E = I \times R$)
18. Calculate the minimum potential *vs* Cu–CuSO$_4$ reference electrode to which cadmium must be polarized for complete protection.

$$\left(K_{\mathrm{sp;Cd(OH)_2}} = 2 \times 10^{-14},\ \text{where } K_{\mathrm{sp}} \text{ is solubility product}\right)$$

19. Iron corrodes at a rate of 3 mdd in Arabian Gulf water. Calculate the minimum initial current density (A/m^2) necessary for complete cathodic protection.

RECOMMENDED LITERATURE ON CATHODIC PROTECTION

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KEYWORDS

Anode It is the electrode in a corrosion cell which corrodes by passage of electrical current into the electrolyte.
Anode bed (ground-bed) The specific area where anodes are buried in soil and a backfill is placed around them.
Anode life The number of years taken by an anode to be consumed at a certain current output.
Anodic polarization That portion of polarization which takes place at the anode. The potential becomes more noble as anodic polarization proceeds.
Attenuation curves Curves obtained by plotting driving voltage (ΔE) and polarization potential (ΔV_P) on semi-log paper against distance are called attenuation curves.
Backfill The special soil placed around the anodes to provide uniform resistivity. The material used as backfill in an impressed current system is generally coke breeze whereas in the galvanic system the backfill is composed of a mixture of gypsum, bentonite and clay, the composition being dependent on soil resistivity.
Bond An electrical connection between two metallic structures.
Casing voltage profile A plot of the voltage *vs* the depth of an oil well casing.
Cathode The electrode in a corrosion cell through which conventional (positive) direct current leaves the electrolyte. Reduction takes place at the cathode processes, for example, oxygen reduction and hydrogen reduction takes place at the cathode. Electrons from the cathode are consumed at the cathode surface by $O_2 + H_2O$ forming OH^- ions, or by H^+ ions forming H_2.
Cathodic polarization That portion of polarization which takes place at the cathode. The potential becomes more negative as cathodic polarization proceeds.
Cathodic protection Elimination or reduction of corrosion of a metal surface by making it the cathode (negative), using either a galvanic or an impressed current.
Cell An anode and a cathode is an electrolyte.
Close ground-bed In this arrangement series of anodes are used. The length of the pipeline protected by a single closed anode depends on changing the potential of earth around the pipeline with respect to earth. The earth is made more positive in areas where protection is needed.
Coating resistance The electrical resistance of a coating to the flow of current.
Concentration cell An electrolyte cell in which the emf is the result of a difference in concentration of the electrolyte or active metal at the anode and the cathode.
Copper sulfate half-cell A reference electrode consisting of copper rod in a tube containing a saturated solution of copper sulfate. It is used for measurement of potential of buried structures.
Current density The amount of current required to protect a metallic structure. The magnitude of current varies with the environment.
Depolarization The reduction of a counter emf by removing or diminishing the cause of polarization.
Diode An electrical device with two electrodes, which allows electrons to pass through it in one direction only, hence converting AC to DC.
Drainage Conduction of positive electricity from an underground metallic structure by means of a metallic conductor.
Drainage (forced) Drainage applied to an underground metallic structure by impressed current or by sacrificial anode.
Drain point The point of connection between a cable and protected structure.
Efficiency of rectifier

$$\frac{\text{DC volts} \times \text{DC ampere}}{\text{Input watts}}$$

Electronic current Charge flow by electrons.
Energy content Maximum capability of current output of an anode expressed in either Ah/lb or lbs/A-year. For instance, the energy content of a standard magnesium anode is 1230 Ah/kg or 559 Ah/lb.
Faraday Faraday = 96 400 Coulombs per gram equivalent.
Forward bias The current proceeds in the forward direction and is blocked in the backward direction.
Full-wave rectification Rectification producing both AC waves in the DC output.
Galvanic anode A sacrificial anode that cause a spontaneous current flow.
Galvanic cell A corrosion cell formed by combination of metals differing in potential.
Ground-bed Anodes (impressed current or galvanic) buried in a soil with special backfill and connected to the positive terminal of a current source.
Impressed current anode Electrodes, such as scrap iron, titanium, lead-silver and silicon cast iron which provide current to an underground structure under cathodic protection.
Impressed current system A cathodic protection system which receives the required current for protection from a transformer–rectifier.
Insulation flanges Flanges employed to electrically isolate the over-ground pipeline from the underground pipeline.
Internal resistance of anode Resistance of anode to backfill – Resistance of backfill to earth.
Interrupter-current It is a device which momentarily stops current.
Ion current Charge transfer taking place by ions.
IR drop Voltage drop caused by a current flow (I) through the conductor of resistance R.
Isolating joint A joint or coupling between two lengths of pipe inserted to provide electrical discontinuity (insulation).
Junction boxes Connect electrical cables used in cathodic protection system.
Microampere 0.000001 ampere.

Mote earth A position in earth which offers no resistance to the flow of electrical current.

Overload protection It is a device which protects an electronic component from destruction by excess current.

Over-protection Current in excess of that required for protection.

Pipe-to-soil potential It is the potential of a pipe measured in a soil which acts as an electrolyte. Also, the corrosion potential of a metal in soil.

Polarization A shift in the potential of a metal in an electrolyte by passage of current flow.

Positive current Current flow of cations (e.g. Fe^{++} ions) or hypothetical positron (electron holes).

Potential criteria Attainment of a potential of −0.85 V *vs* $Cu–CuSO_4$ for steel structure in soil, such as steel pipe.

Potential decay (attenuation) The drop in the potential of a pipeline with increasing distance. For instance, the pipe-to-soil potential is at maximum near the area of influence where the soil is positive and decreases with the distance.

Potential gradient Potential difference per unit distance.

Potential 'on' Pipe-to-soil potential with switch on. It includes also IR drop.

Potential 'off' Pipe-to-soil potential without any IR drop. Varies with time.

Potential shift criterion Shift of potential required to completely protect a structure. A shift of 200–300 mV negative from the original value of potential brought about by external current to the structure to be protected is considered safe for protection.

Potential survey Survey of the potential of a pipeline with respect to soil over a defined distance. A plot of potential with respect of $Cu–CuSO_4$ electrode *vs* the distance is called a potential profile.

Rectifier An electrical device which converts AC to DC. A diode.

Resistance bond A metallic connection between the point of drainage of current from a structure to the origin of the current to avoid interferences.

Resistivity (soil) Resistance in ohms of a cm^3 of a material, measured across opposite faces

$$\left[\rho = R\,(l/a)\,,\text{where } l = \text{length};\, a = \text{area}\right].$$

The unit is ohms-cm.

Reverse bias diode It has extremely high resistance and blocks all current flows.

Silicon diode Silicon anode is positive with respect to cathode.

Stray current Current flowing in the soil or water environment of a structure and arising mainly from electric power or traction installation. It is the uncontrolled current.

Structure-to-soil potential Potential in a buried structure and a non-polarizable electrode placed in soil.

Surface potential survey Survey of pipe-to-soil potential by two copper sulfate electrodes.

Tap transformer. A connection brought out of a winding at some point between its extremities to permit changing voltage or current ratio.

Test stations Special devices installed above in cathodic protection systems. They are used to measure pipe-to-soil potential, line current and current flow of a bond, to monitor potential measurements and also to measure stray current corrosion.

Transformer It is a device which makes it possible to transfer power from one circuit to another by mutual induction. In a step-up transformer, the energy transferred is from a lower voltage circuit to a higher voltage circuit. In a step-down transformer, the transfer of energy is the reverse of the step-up transformer.