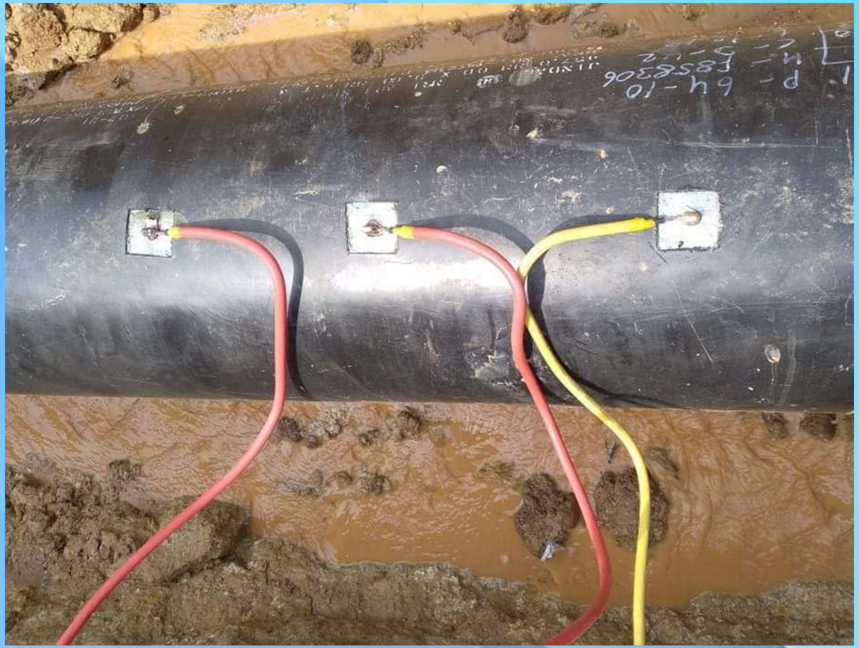
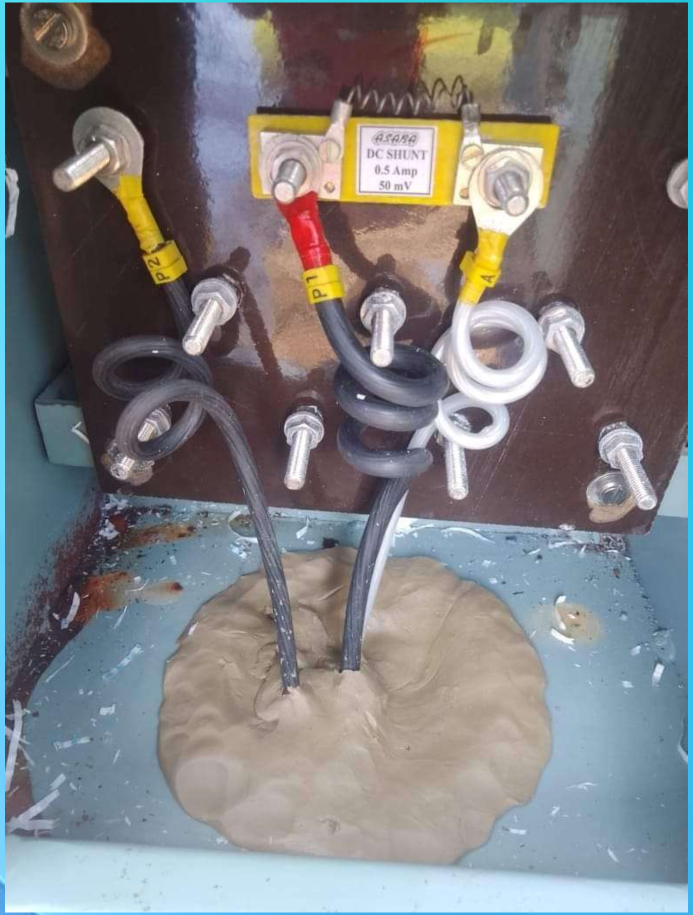
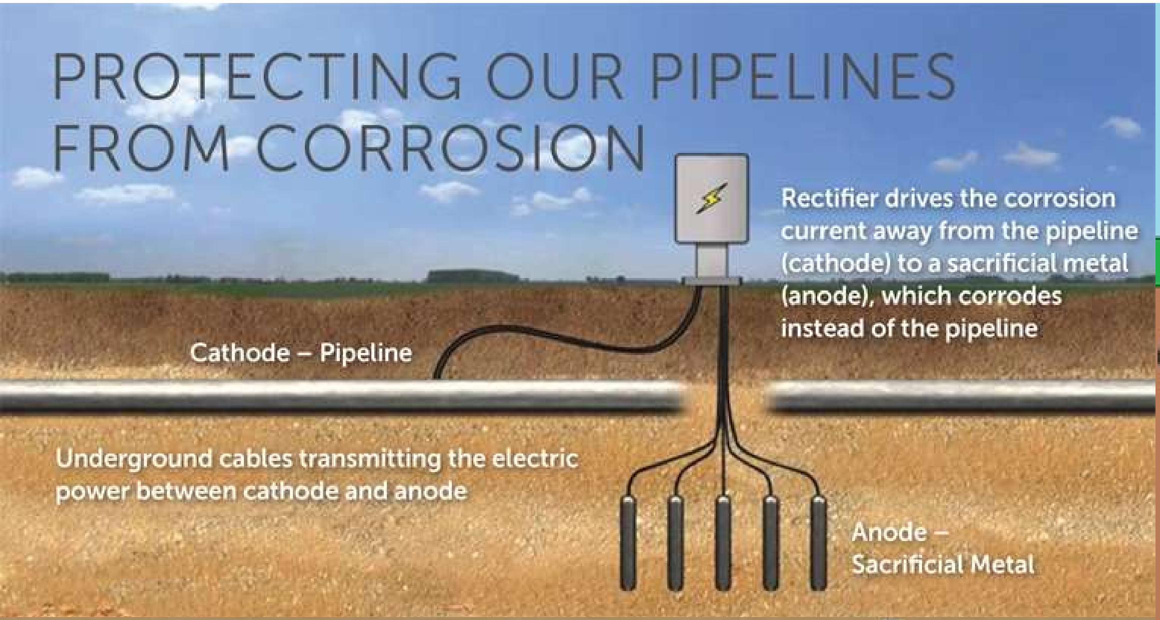
Galvanic cathodic protectio

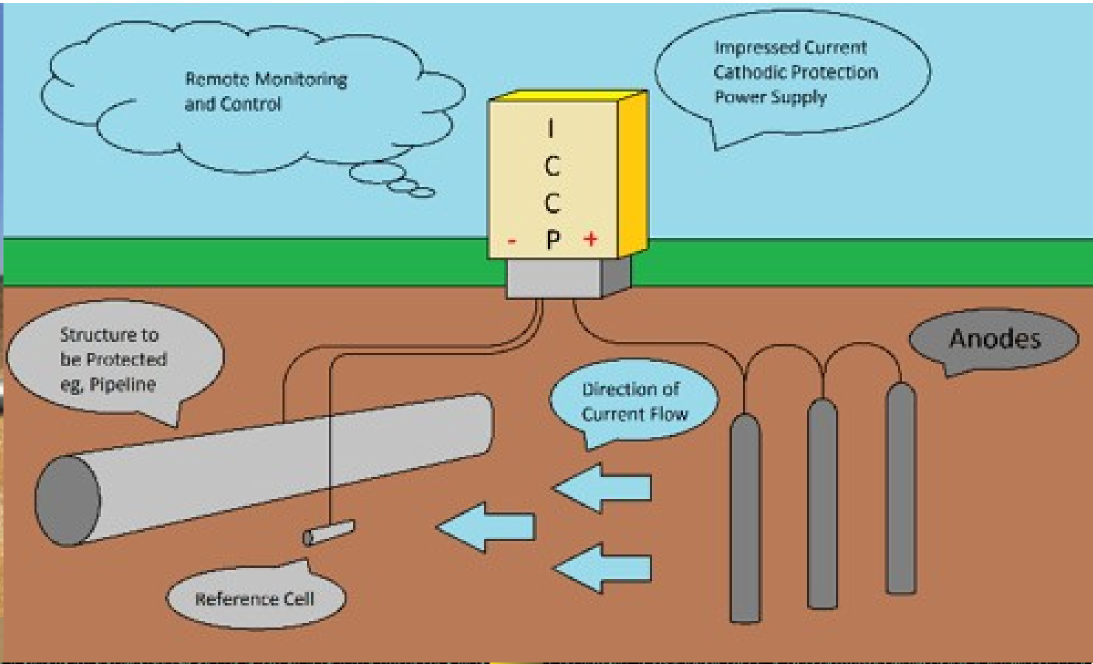


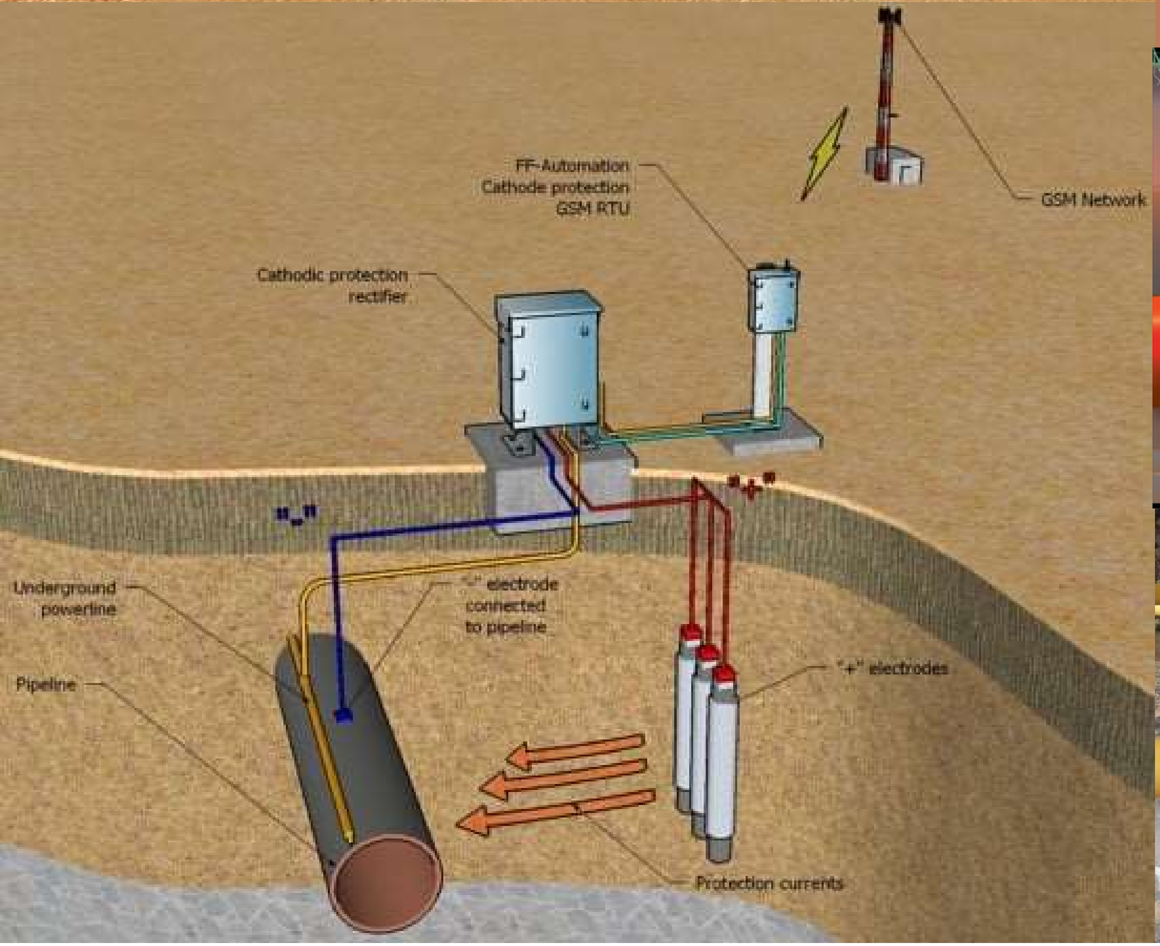


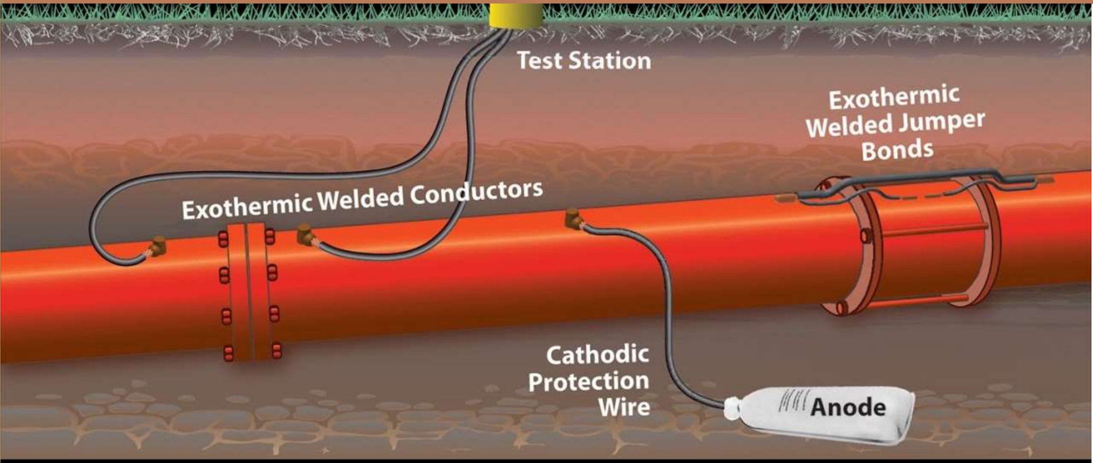
Prepared by: DSc PhD Dževad Hadžihafizović (DEng)

Sarajevo 2023


PROTECTING OUR PIPELINES FROM CORROSION
Rectifier drives the corrosion current away from the pipeline (cathode) to a sacrificial metal (anode), which corrodes instead of the pipeline
Cathode – Pipeline
Underground cables transmitting the electric power between cathode and anode
Anode – Sacrificial Metal


Remote Monitoring and Control
Impressed Current Cathodic Protection Power Supply
I C C P
-
+
Structure to be Protected eg, Pipeline
Direction of Current Flow
Anodes
Reference Cell


GSM Network
FF-Automation Cathode protection GSM RTU
Cathodic protection rectifier
"-"
"+"
Underground powerline
"-" electrode connected to pipeline
Pipeline
"+" electrodes
Protection currents


Test Station
Exothermic Welded Jumper Bonds
Exothermic Welded Conductors
Cathodic Protection Wire
Anode


2021.12.23 11:44

Basics of Corrosion

INTRODUCTION

Definition Of Corrosion:

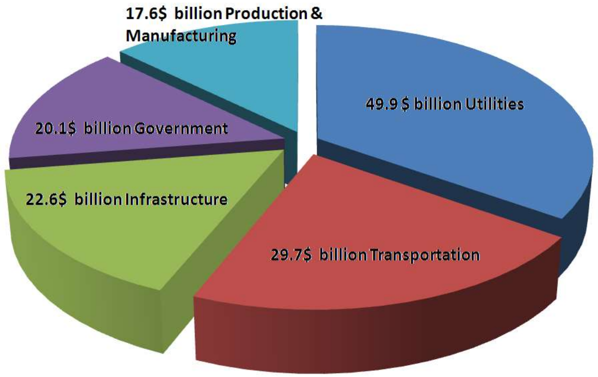
Destruction of materials due to interaction with environment:

Not necessarily to produce oxides

Corrosion and oxidation

Hot corrosion

Corrosion Cost (See Fig.)



1. Utilities
- Drinking water & sewer system
- Electrical utilities
- Gas distribution
- Telecommunication

2. Transportation
- Aircraft
- Hazardous materials transport
- Motor vehicles
- Rail road car
- Ships

3. Infrastructure
- Airports
- Gas and liquid transportation pipelines
- Hazardous materials storage
- Highway bridges
- Railroads
- Waterways and ports

4. Government
- Defense
- Nuclear waste storage

5. Production and production
- Agriculture
- Chemical and petrochemical pharmaceutical
- Electronics
- Food processing
- Home appliance
- Mining
- Oil and gas exploration production
- Petroleum refining
- Pulp and paper

Annual corrosion cost in the USA (The year 1998)

Historical Cases of Corrosion

The first recorded study of corrosion was in 1763. Copper sheathing on the timber hull of the HMS Alarm, a 32-gun frigate.

Industries that Suffer Corrosion Problems:

- Marine and Desalination
- Oil Industry
- Chemical and Petrochemical
- Metal Refining
- Transport
- General Engineering
- Food
- Building and Construction

Corrosion Environments:

- Air and Moisture
- Water: Fresh, Distilled, Brackish, Sea…etc.
- Industrial Environments: Steam, NH_3, SO_2, H_2S, flue gases……etc.
- Chemicals: Organic and Inorganic.
- Nuclear, High temperature and pressure conditions.

Corrosion rate Expressions:

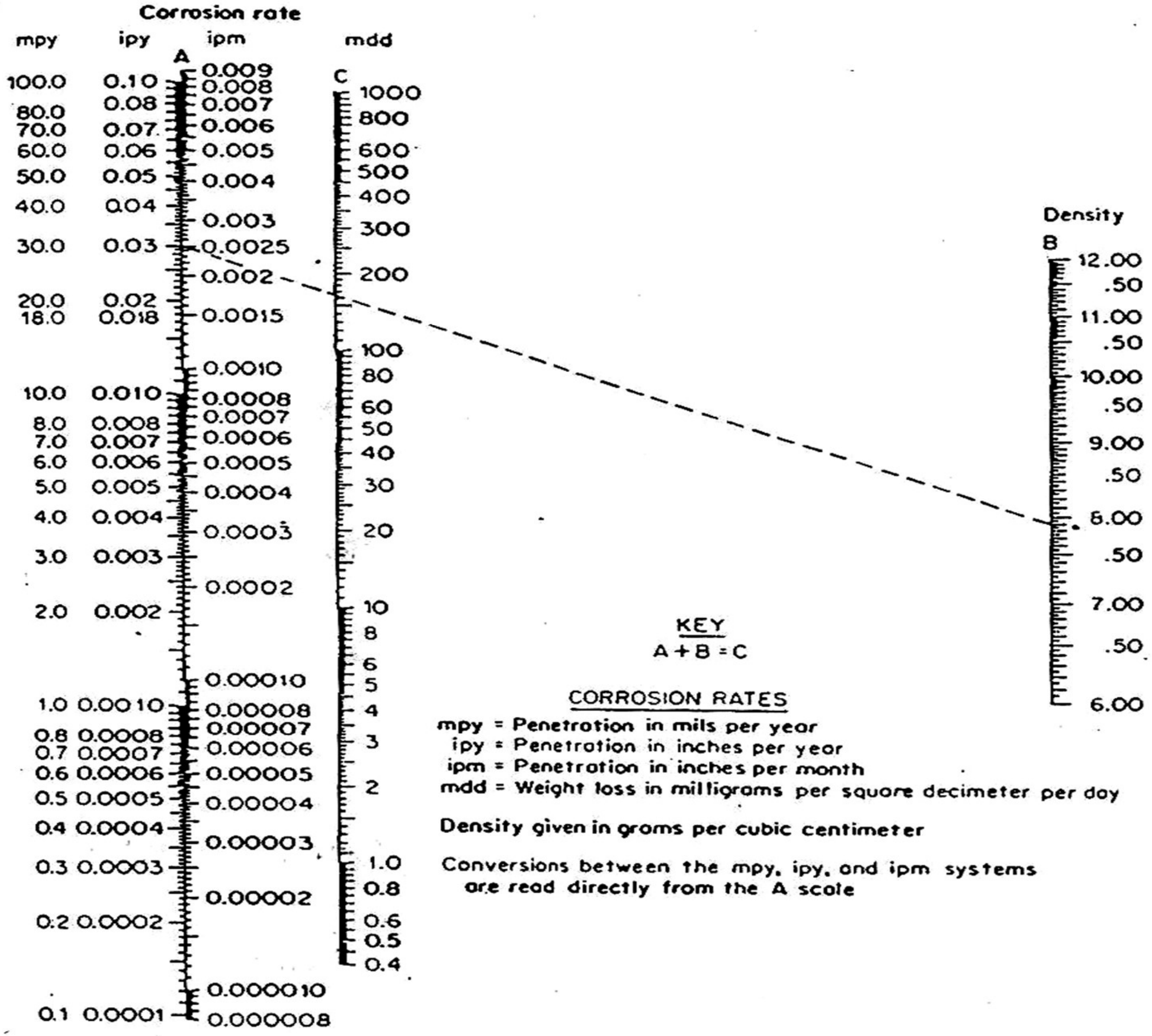
* **Weight loss or weight gain**

mg/ dm^2/day……mdd

mg/cm^2/day

* **Penetration**

mils per year	(mpy)
mms per year	(mmpy)
µms per year	(µmpy)



KEY
A + B = C

CORROSION RATES

mpy = Penetration in mils per year
ipy = Penetration in inches per year
ipm = Penetration in inches per month
mdd = Weight loss in milligrams per square decimeter per day

Density given in grams per cubic centimeter

Conversions between the mpy, ipy, and ipm systems are read directly from the A scale

Nomograph for mpy,ipy,ipm,and mdd

Conversion Table

from	To	Multiply by
In./yr	mils per year, mpy	1000
In./month	mils per year, mpy	12000
Mg/dm^2/day, (mdd)	mils per year, mpy	1.44/specific gravity

$$\frac{\mu m}{yr} = 87{,}600 \frac{W}{DAT}$$

$$\frac{mm}{yr} = 87.6 \frac{W}{DAT}$$

where W is the weight loss in milligrams, D is the density in g/cm^3, A is the area in cm^2, and T is the time of exposure in hours.

Comparison of Mils Penetration Per Year (mpy) with Equivalent Metric-rate Expressions

Relative Corrosion Resistance	Approximate metric equivalent		
	mpy	mm/yr	µm/yr
Outstanding	<1	<0.02	<25
Excellent	1-5	0.02-0.1	25-100
Good	2-20	0.1-0.5	100-500
Fair	20-50	0.5-1	500-1000
Poor	50-200	1-5	1000-5000
unacceptable	200+	5+	5000+

Basic Principles

Electrochemical Aspects

Electrochemical Reactions

The Electrochemical nature of corrosion can be illustrated by the attack on zinc by hydrochloric acid. Consider that HCl is air-free.

$$Zn + 2HCl \dashrightarrow Zn\,Cl_2 + H_2 \qquad (1)$$

This Means:

$$Zn + 2(H^+ + Cl) \dashrightarrow Zn^{++} + 2Cl + H_2 \qquad (2)$$

i.e. The net result of this reaction is:

$$Zn \dashrightarrow Zn^{++} + 2e \qquad (3)$$

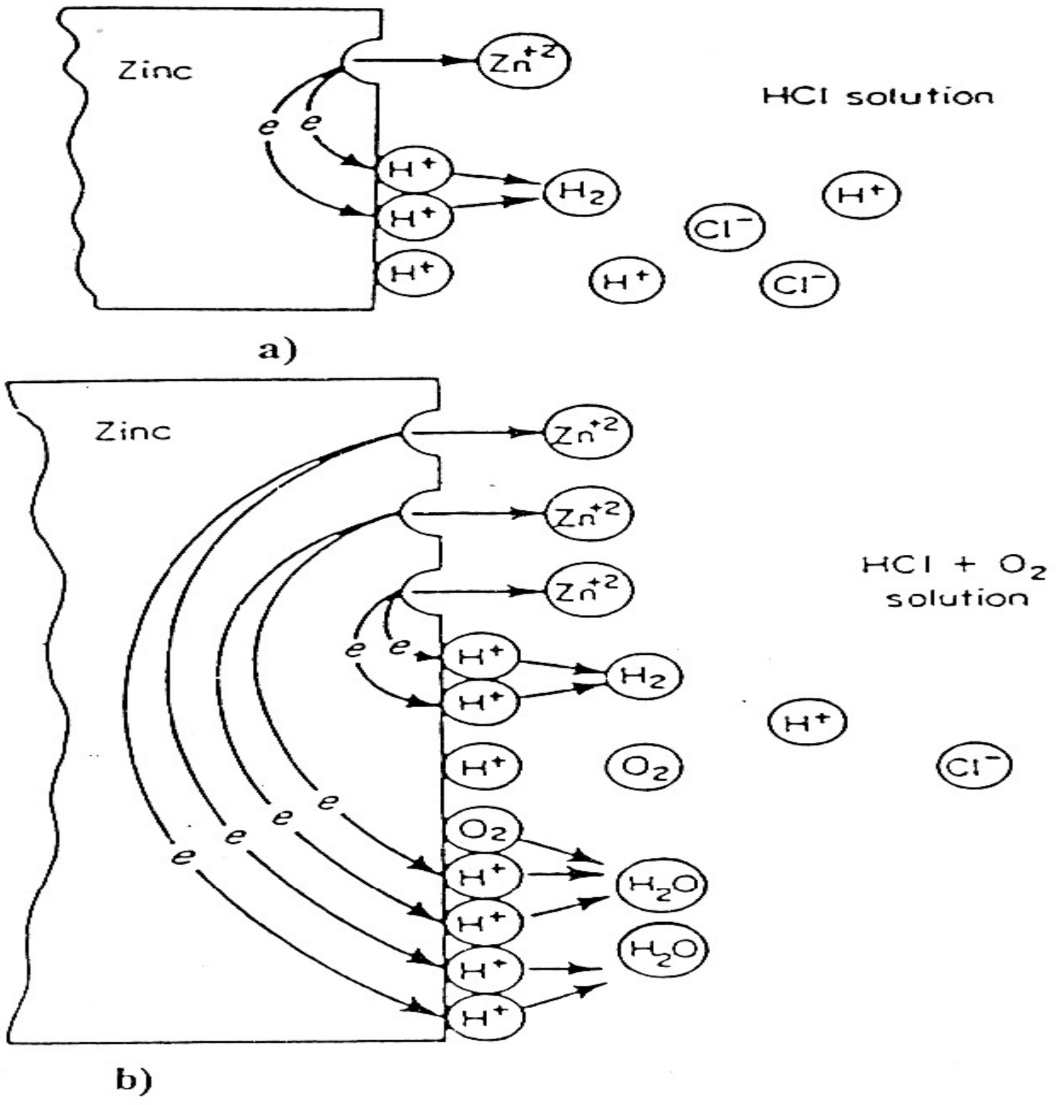
And $2H^+ + 2\,e \dashrightarrow 2\,H \qquad H_2 \qquad (4)$

- Reaction (3) is the change of Zn into the zinc ions (Zn++)

  i.e. <u>The production of electrons = Anodic Reaction = Oxidation Reaction</u>

- During metallic corrosion:

Rate of oxidation = Rate of reduction



Electrochemical reactions occurring during corrosion of zinc in:
a) Air-free hydrochloric acid
b) Aerated hydrochloric acid

- Corrosion reactions are divided into two partial types of reactions, anodic that is the Release of electrons, and cathodic, that is the Consumption of electrons.

For iron

$Fe \dashrightarrow Fe^{++} + 2e$ (anodic) (5)

For dissolved oxygen

$O_2 + 2H_2O + 4\,e \dashrightarrow 4\,OH^-$ (cathodic) (6)

- Zn corrosion in air-free & aerated HCl
- When Fe^{+++} ions are added to dilute aerated HCl.

$Fe^{+++} + e \dashrightarrow Fe^{++}$ (7)

- Typical anodic reactions:

$M \dashrightarrow M^{++} + 2\,e$ (8)

$M \dashrightarrow M^{+} + e$ (9)

- Typical cathodic reactions:

$M^{+} + e \dashrightarrow M$ (10)

$M^{++} + 2\,e \dashrightarrow M$ (11)

$2H^{+} + 2\,e \dashrightarrow H_2$ (12)

$O_2 + 2H_2O + 4\,e \dashrightarrow 4\,OH^-$ (13)

$O_2 + 4H^- + 4\,e \dashrightarrow 2H_2O$ (14)

Polarization:

- Activation polarization:
- Concentration polarization:

Thermodynamic Aspects

Free Energy Changes:

- The change in free energy "G" concept.
- Sign of □G is most important in corrosion reactions.
- In electrochemical reactions:

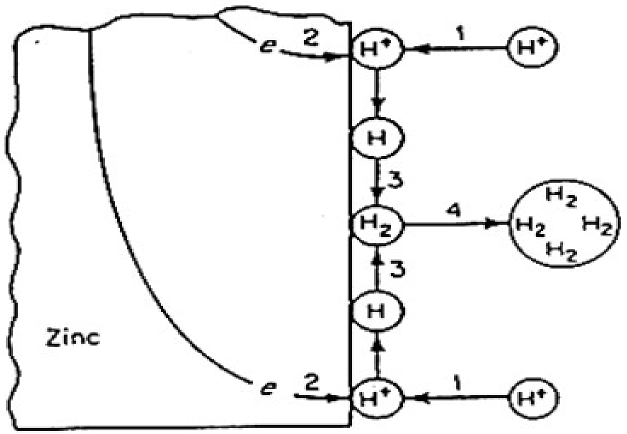
$$\Delta G = - nEF$$

Where: DG = Free energy change

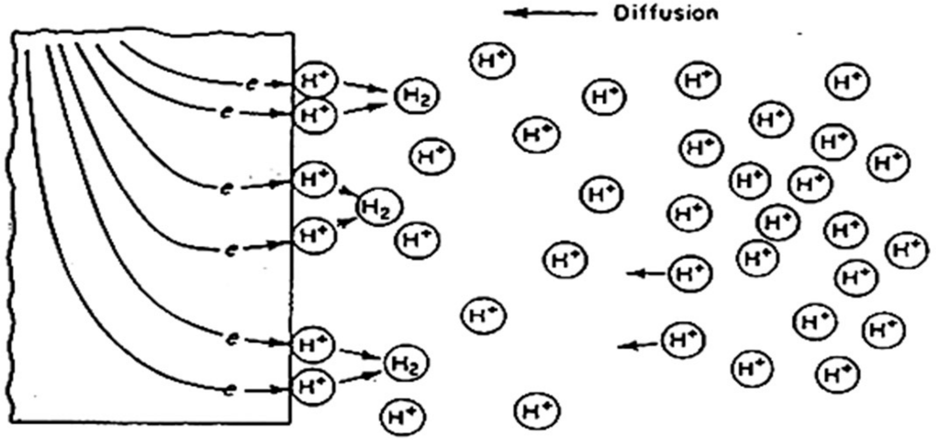
n = Number of electrons involved in the reaction

E = Cell potential

F = Faraday's constant



Hydrogen-reduction reaction under activation control



Concentration polarization during hydrogen reduction

Cell Potential and the EMF Series: (Redox Potential Series)

- Nernst equation : $E = E_o + \frac{2.3\ RT}{nF} \text{Log} \frac{a_{oxid}}{a_{red}}$

$$E_o + \frac{0.059}{n} \log C$$

Where E_o = Standard Electrode potential

C = Solution concentration of oxidized

ions in gm ion/liter.

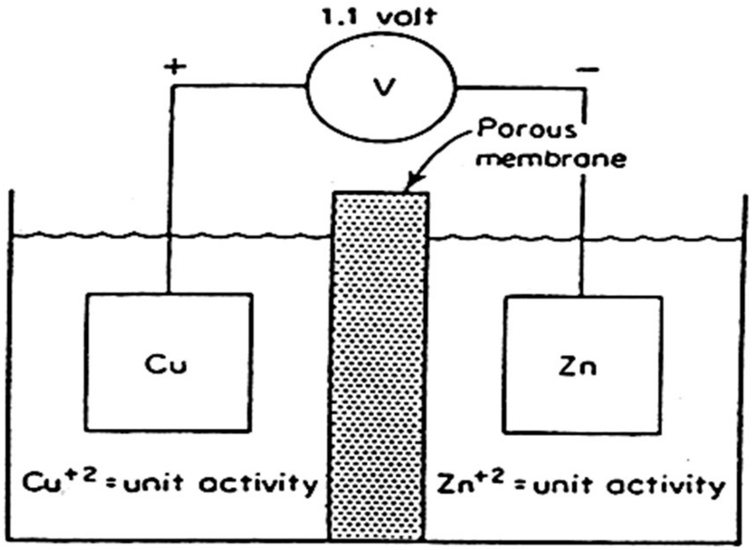
n = No. of transferred electrons.

Application of Thermodynamics to Corrosion:

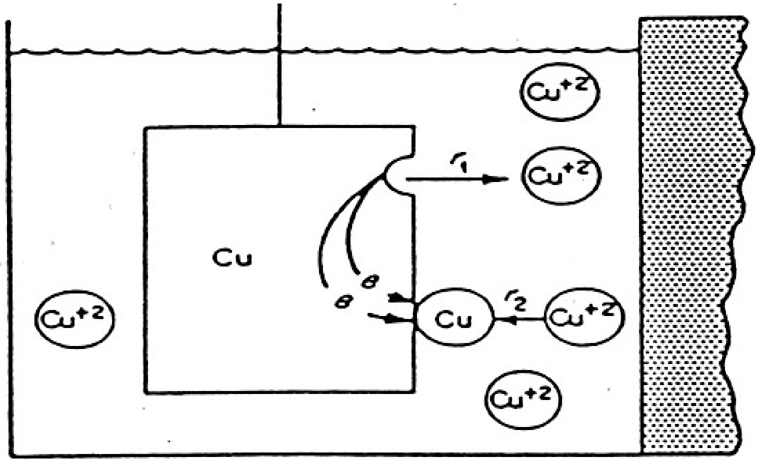
Sign of ΔG is most important

Magnitude of ΔG does not mean too much.

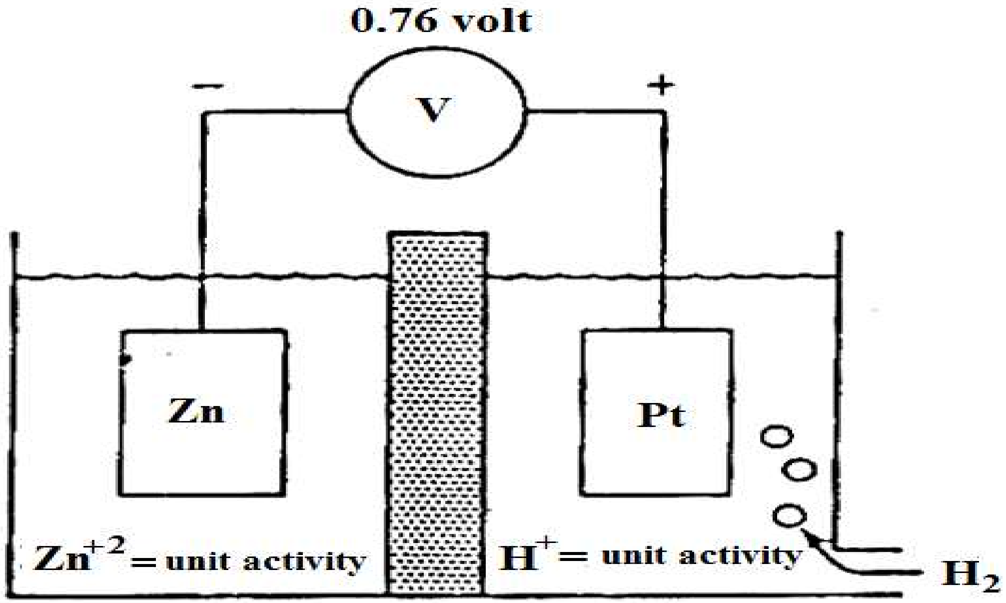
ΔG indicates possibility of corrosion, but not rate.



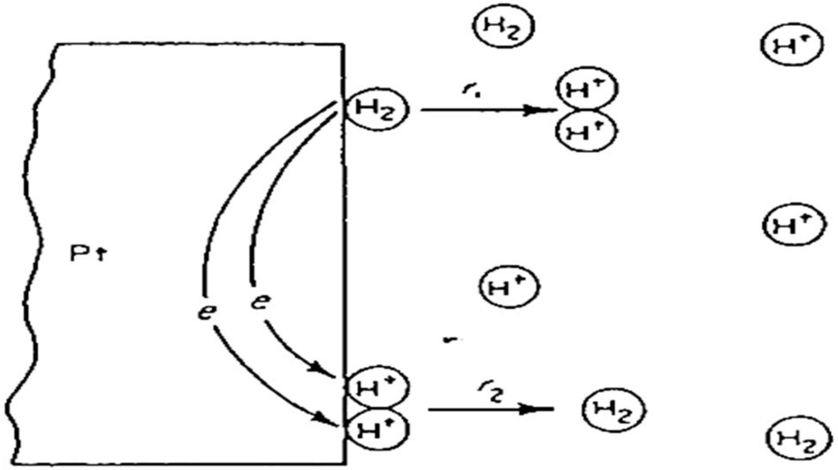
Reversible cell containing copper and zinc in equilibrium with their ions



Reversible copper electrode



Cell containing reversible zinc and hydrogen electrodes



Hydrogen electrode on platinum

Standard Oxidation Reduction (Redox) Potentials at 25^{o}C Volts vs. Normal Hydrogen Electrode

$Au = Au^{3+} + 3e$	+ 1.498
$O_2 + 4H^{+} + 4e = 2H_2O$	+ 1.229
$Pt = Pt^{2+} + 2e$	+ 1.2
$Pd = Pd^{2+} + 2e$	+ 0.987
$Ag = Ag^{+} + e$	+ 0.799
$2Hg = Hg^{2}_{2} + 2e$	+ 0.788
$Fe^{3+} + e = Fe^{2+}$	+ 0.771
$O_2 + 2H_2O + 4e = 4\ OH$	+ 0.401
$Cu = Cu^{2+} + 2e$	+ 0.337
$Sn^{4+} + 2e = Sn^{2+}$	+ 0.15
$2H^{+} + 2e = H_2$	0.000
$Pb = Pb^{2+} + 2e$	- 0.126
$Sn = Sn^{2+} + 2e$	- 0.136
$Ni = Ni^{2+} + 2e$	- 0.250
$Co = Co^{2+} + 2e$	- 0.277
$Cd = Cd^{2+} + 2e$	- 0.403
$Fe = Fe^{2+} + 2e$	- 0.440
$Cr = Cr^{3+} + 3e$	- 0.744
$Zn = Zn^{2+} + 2e$	- 0.763
$Al = Al^{3+} + 3e$	- 1.662
$Mg = Mg^{2+} + 2e$	- 2.363
$Na = Na^{+} + e$	- 2.714
$K = K^{+} + e$	- 2.925

Pourbaix Diagrams

- These illustrate thermodynamically stable corrosion products as a function of pH, and potential.
- Consider the main iron dissolution reaction

$$Fe \dashrightarrow Fe^{++} + 2e$$

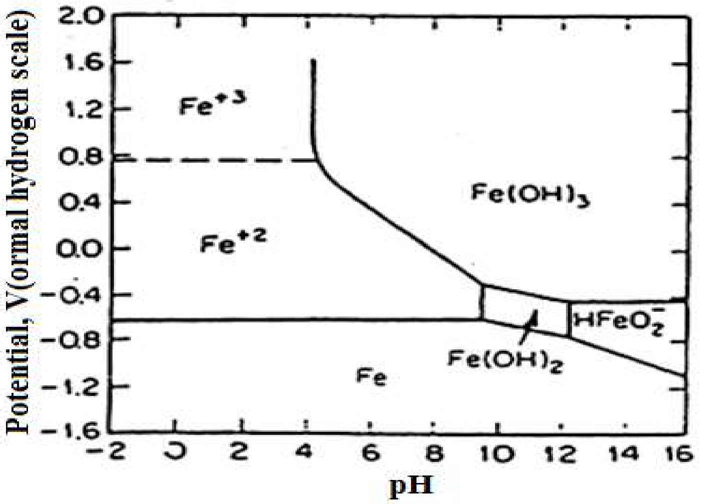
- Applying Nernst equation,(Fe^{++})should be:

10^{o} g-ion/1 at an applied potential = -0.44V
10^{-2} g-ion/1 at an applied potential = -0.50V
10^{-6} g-ion/1 at an applied potential = -0.62V

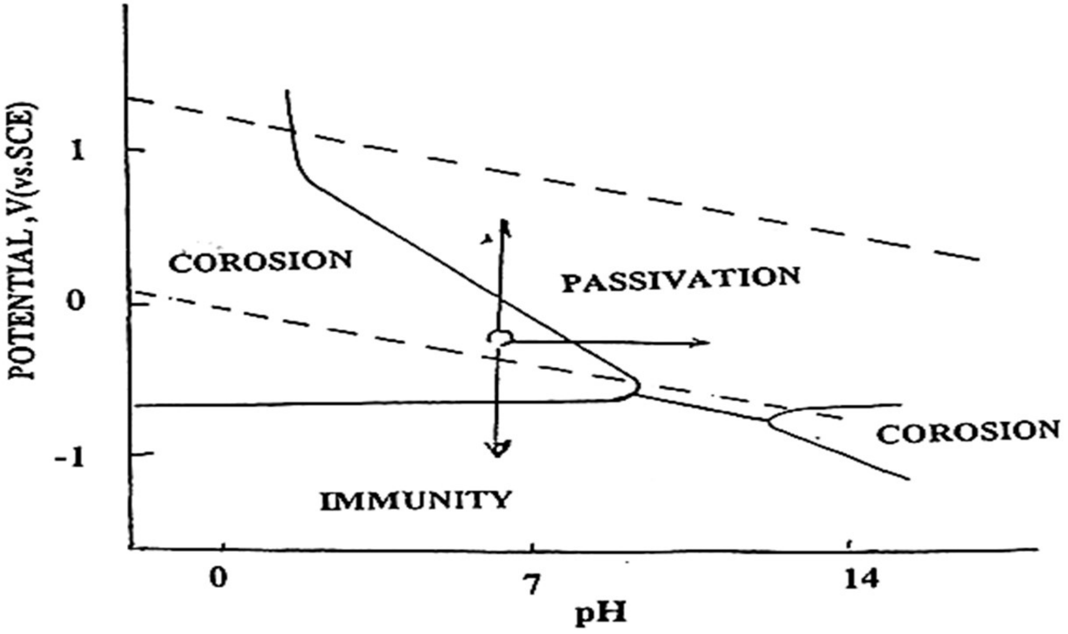
i.e. at cathodic applied potential of –0.62 V, Fe concentration = 10^{-6} g-ion/l. Below this cathodic potential, iron would thus practically be thermodynamically stable.

- Regions of corrosion, passivity and immunity

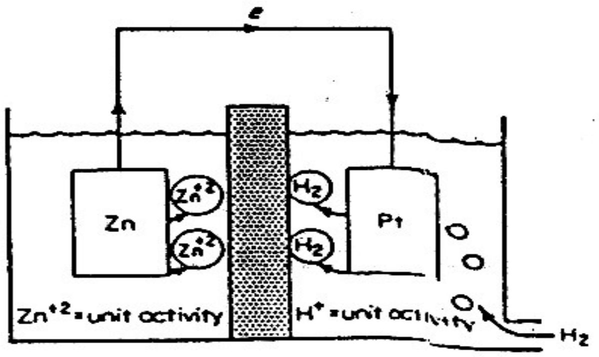
In corrosion region : corrosion can occur.
In passivity region : corrosion does not occur.
In immunity region: corrosion can not occur.



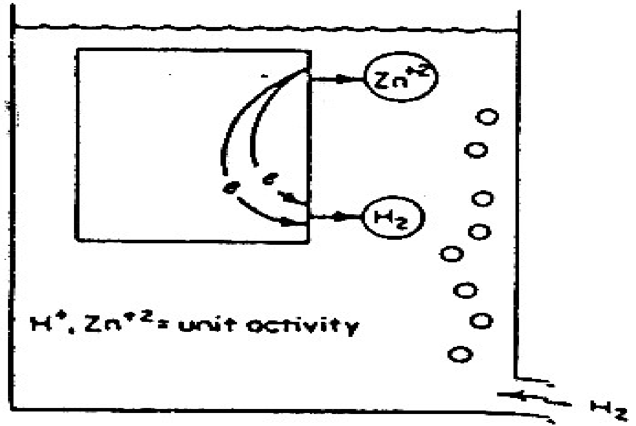
Simplified potential-pH diagram for the Fe-H_2O system



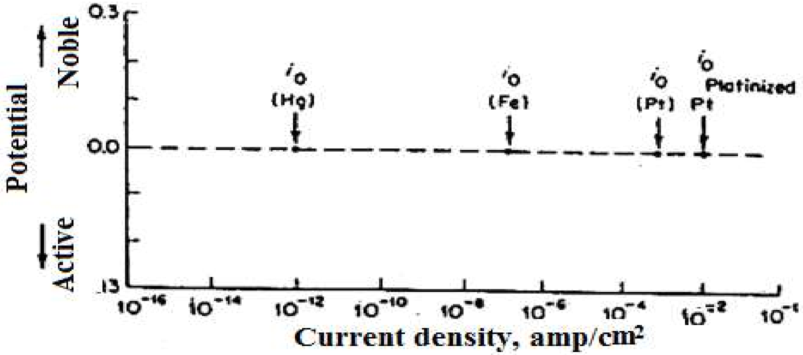
Pourbaix diagram for Fe in water (simplified)



Short circuited cell containing zinc and hydrogen electrodes



Corroding zinc, shown schematically



Hydrogen-hydrogen-ion exchange current densities

Electrode Kinetics

Introduction:

- From an engineering point of view, the major interest is the kinetics, or rate of corrosion.
- Thermodynamics describe the system at equilibrium, which is not the case for corrosion.
- Overvoltage is a measure of polarization with respect to the equilibrium potential of the electrode.
- Exchange current density

The Mixed – Potential Theory

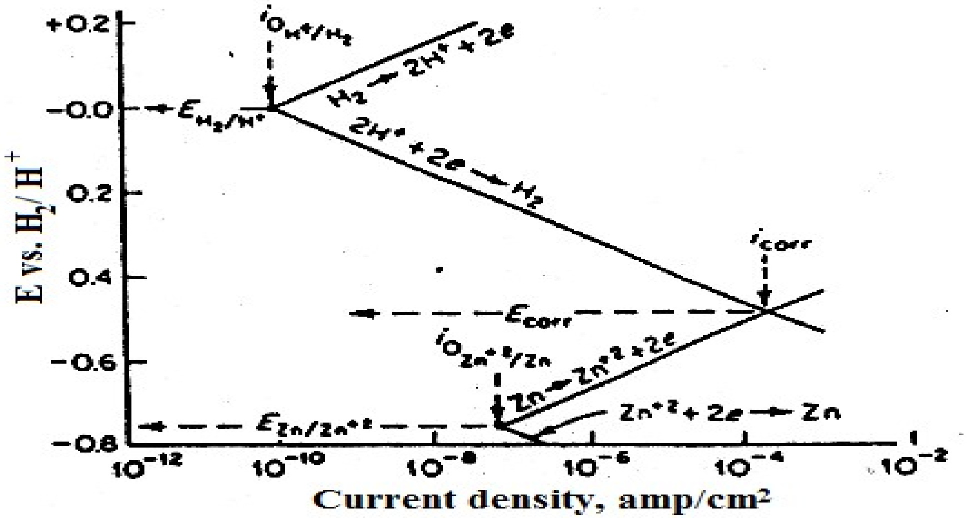
- Any electrochemical reaction can be divided into two or more partial oxidation and reduction reactions.
- No net accumulation of electric charge during an electrochemical reaction.
- The total rate oxidation must equal the total rate of reduction.

Mixed Electrodes

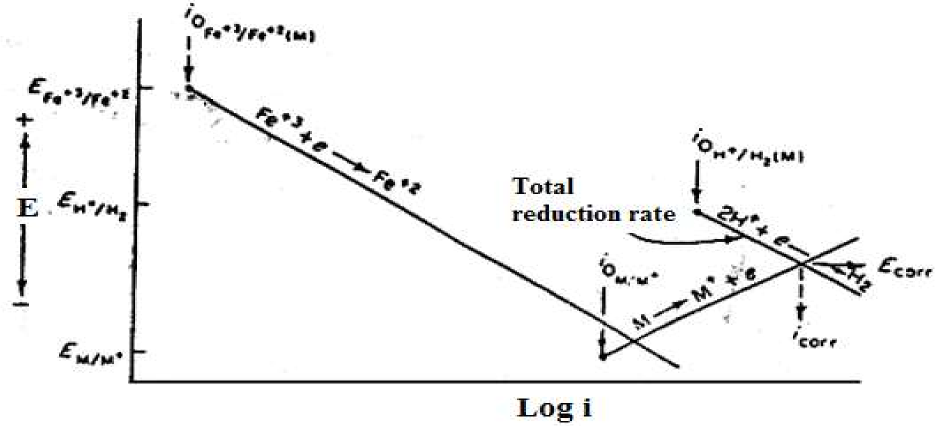
- A mixed electrode is an electrode or a metal sample that is in contact with two more oxidation-reduction systems.
- To illustrate, consider the case of zinc immersed in hydrochloric acid. This is represented graphically in Fig.

Note: Cathodic & Anodic reactions Zn/Zn^{++}

- Cathodic & Anodic reactions H_2 / H^+
- Single electrode potential E_Zn/Z_{n++} $E_{H^+/H2}$
- Tafel slopes.
- Exchange current densities:
- Mixed corrosion potential : E_{corr}
- Corrosion current i_{corr}



Electrode kinetic behaviour of pure zinc in acid solution, shown schematically



Behaviour of metal M in acid solution containing ferric salts showing effect of oxidizer exchange current density

The Evans Diagrams (Figures)

- **Passivity:**
- Loss of chemical reactivity experienced by some metals and alloys mostly due to the formation of a protective film.
- Metals including iron, nickel, chromium, titanium and their alloys.
- To some extent also in some environments: zinc, cadmium, tin, uranium, zirconium.

- Note:

* Ic	: critical current for passivation
* Epp	: Passivation potential

*Active range.

* Passive range, value of $I_{passive}$

* Transpassive range

- The relation of these parameters on the passivation behavior of materials.
- Passivity concept as a base for the principle of corrosion control by anodic protection.
- The concept of Flade potential, E_F:

  * The lower the potential at which a passivity metal become active (i.e. the lower E_F) the greater the stability of passivity.

  * Some typical value or E_F:

Titanium	- 0.24V
Chromium	- 0.22V
Steel	+ 0.15V
Nickel	+ 0.36V
Iron	+ 0.58V

Mixed-Electrodes Involving an Active-Passive Metal

(Fig .) illustrates 3 possible cases that may occur when an active-passive metal is exposed to a corrosive environment by an acid solution.

* The system represented d by case 1.

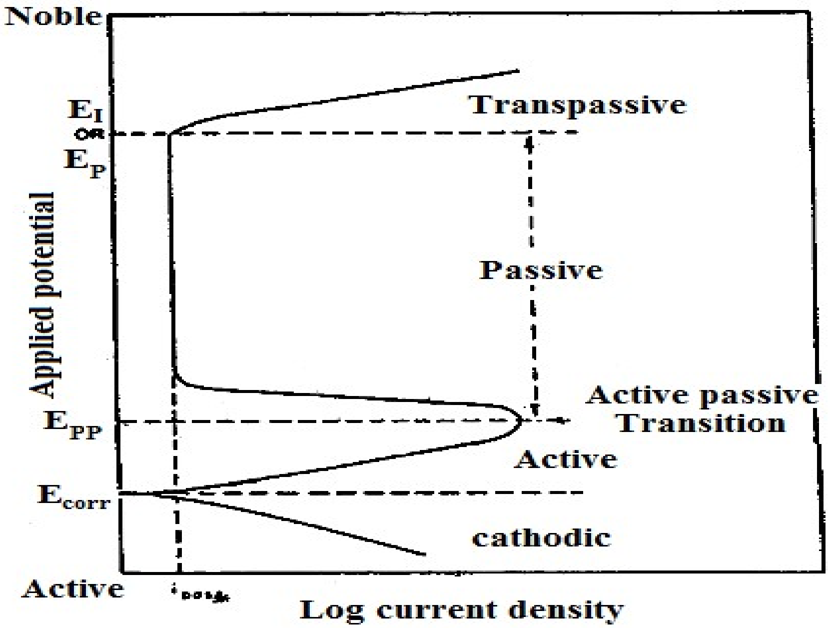
* The system represented by case 2.

* The system represented by case 3.

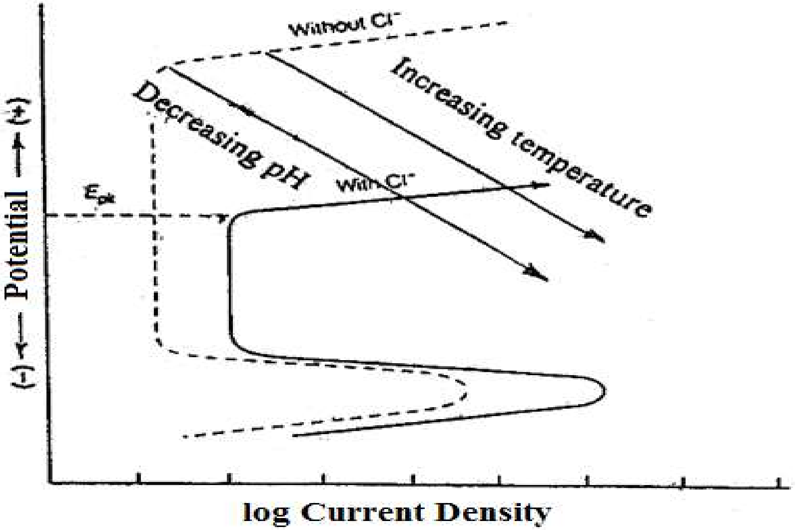
* Case 1, though not practically desirable, however, is better than case 2.

* Case 3, is the most desirable from the engineering point of view. This system will spontaneously passivate and crossed very slowly.

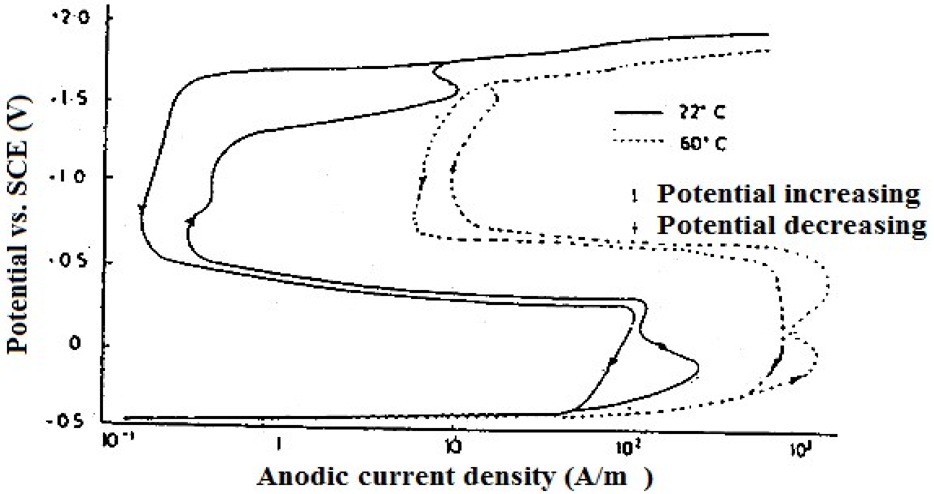
* Case 2, is the least desirable of the three cases.



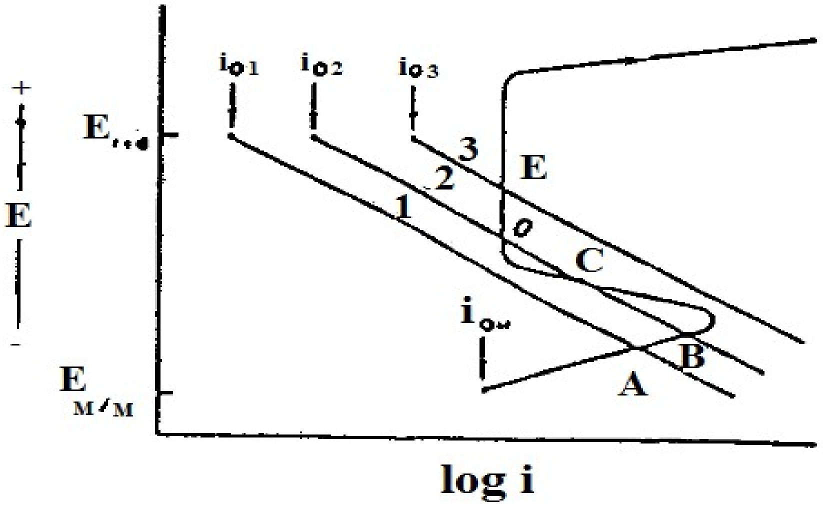
A schematic polarization curve for a stainless steel in a sulfuric acid solution



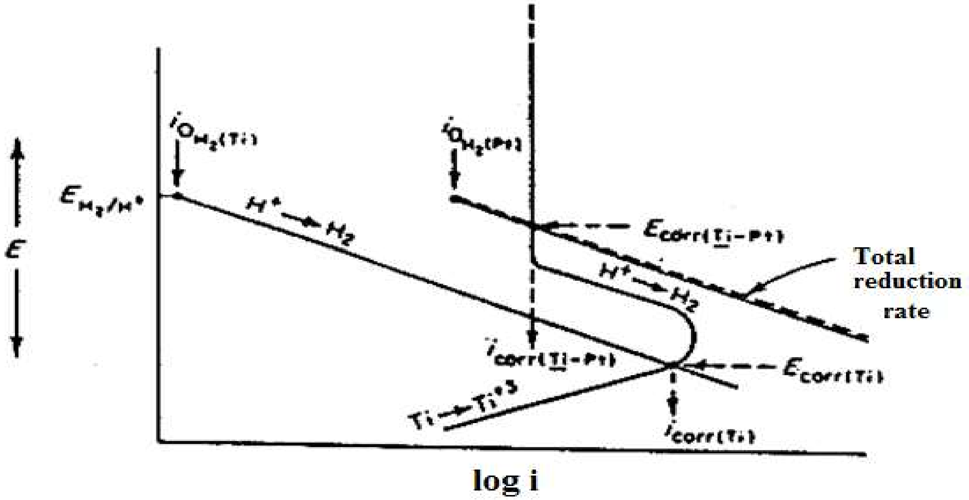
Schematic determination of critical pitting potential E_{pit}, from anodic polarization



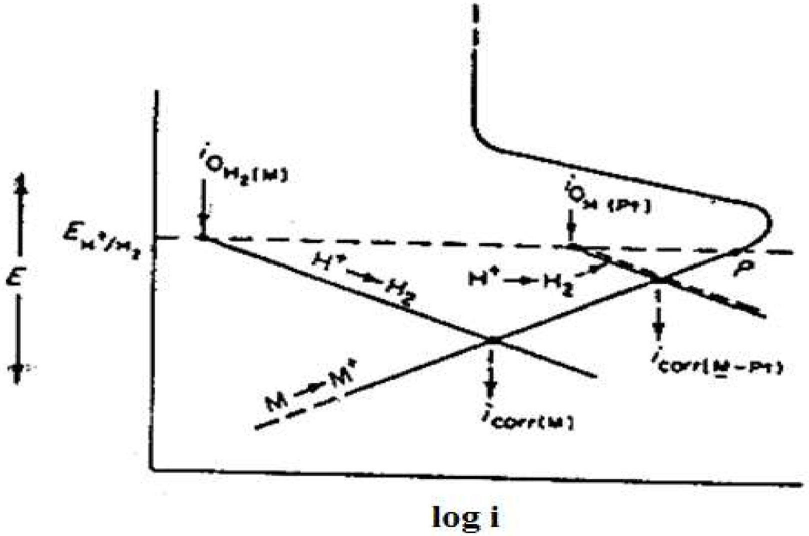
Potentiostatic anodic polarization curves for mild steel in 10% Sulfuric acid. (Note the magnitude or the critical current density which is 10^2 - 10^3 A/M^2, this creates a problem in practical anodic protection since very high currents are required to exceed I_{corr} and therefore to passivate the mild steel).



Behaviour of an active - passive metal under corrosive conditions



Spontaneous passivation of titanium by galvanically coupling of platinum



Galvanic couple between an active-passive metal and platinum in air-free acid solution

Active–Passive Alloy Evaluation and Noble Metal Alloying

Electrochemical Techniques for Corrosion Rate Measurement

Tafel Extrapolation

- **This method was to verify the mixed potential theory**
  - ⦿Data obtained from cathodic or anodic polarization measurements can be used. Cathodic polarization data is preferred.
  - ⦿Fig. () present a Tafel plot.
  - ⦿Practically, an applied cathodic polarization curve becomes linear (on a semi-log plot) at about 50mV more active than E_{corr}.

This Region of Linearity is called the Tafel Region

- To determine corrosion rate:

Extrapolate Tafel region to E_{corr}. At E_{corr}, the rate of hydrogen evolution equals the rate of metal dissolution. This point corrosion rate of the system expressed in terms of current density.

- This method has some limitations

Linear Polarization

- The disadvantages of Tafel extrapolation method can be over come by the linear polarization analysis.
- Within 10 mV more noble or more active than the corrosion potential, E_{corr}
- Note that the slope of the linear polarization graph is voltage over current, or resistance in ohms. It can be shown by electrochemical calculations that the slope is related to the corrosion rate by the following equation:

$$mpy = k / RA = \ldots\ldots\ldots\ldots$$

Where:

R is the resistance in ohms read from the linear polarization graph.

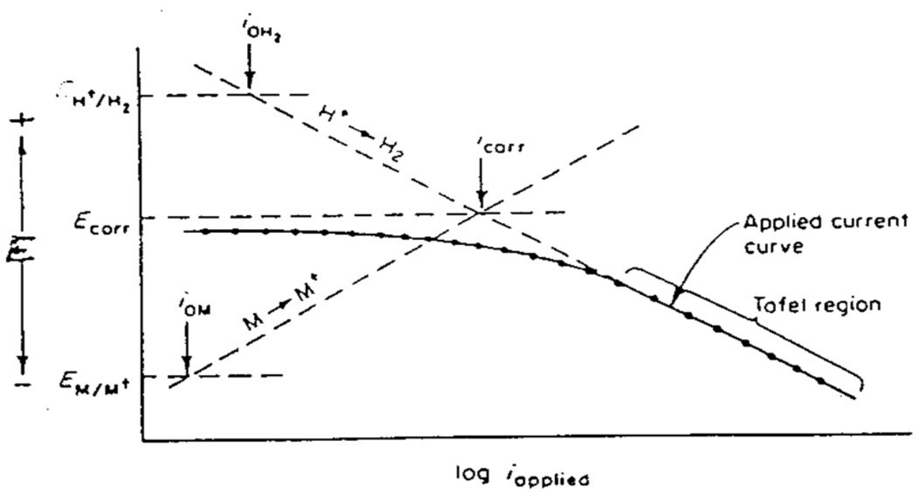
K is the electrochemical constant depending on the metal and the corrosive

A is the total area of the corroding specimen in square inches

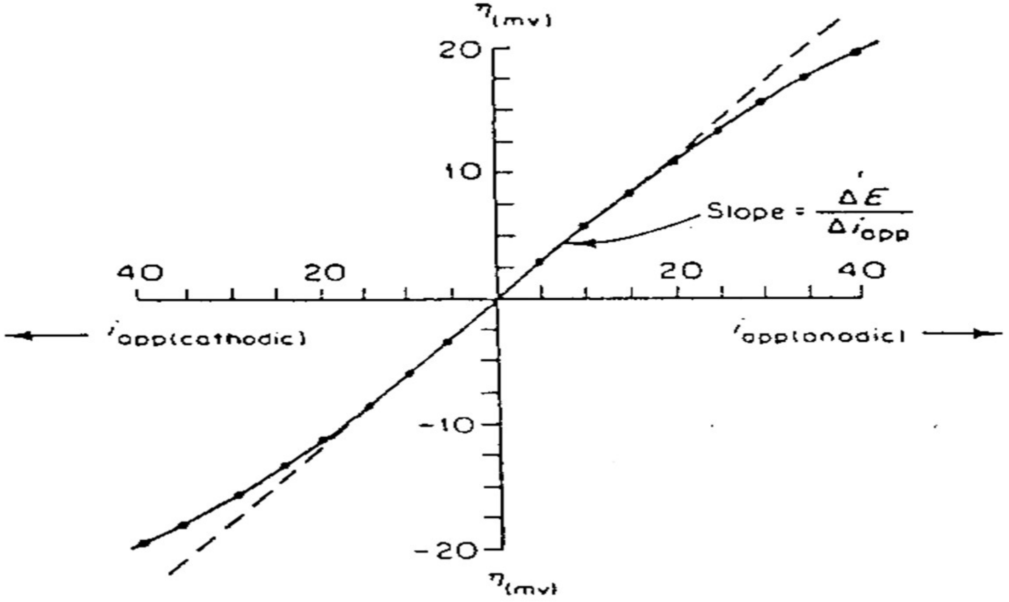
For iron, cobalt, nickel and alloys containing these elements

K is almost equal in most environments and

mpy= 2000 / RA=…………



Applied current cathodic polarization curve of a corroding metal showing Tafel extrapolation



Applied Current Linear Polarization Curve

PRINCIPLES OF CATHODIC PROTECTION

1. HISTORICAL

- Sir Humphrey Davy (1824): Zinc and iron anodes could be used to prevent the corrosion of copper sheathing on the wooden hulls of British naval vessels.
- The first 'full-hull' installation on a vessel in service was applied to the frigate HMS *Samarang* in 1824.
- Four groups of cast iron anodes were fitted and virtually perfect protection of the copper was achieved.

1-2 ELECTROCHEMICAL PRINCIPLES
AQUEOUS CORROSION

- The aqueous corrosion of iron under conditions of air access can be written:

$$2Fe + O_2 + 2H_2O \rightarrow 2Fe(OH)$$

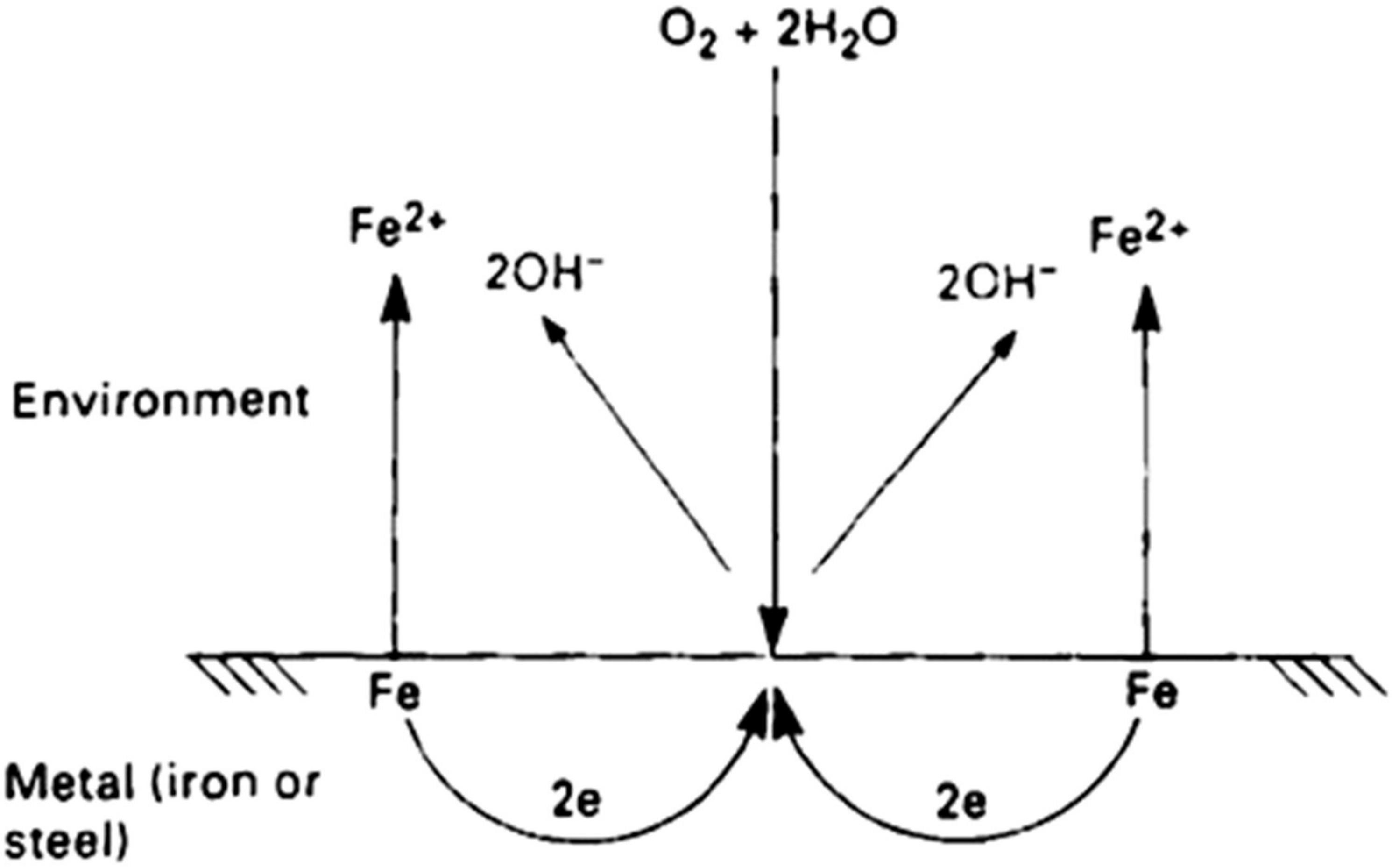
- It is convenient to consider separately the metallic and non-metallic reactions in equations:

$$2Fe \rightarrow 2Fe^{2+} + 4e^{-}$$

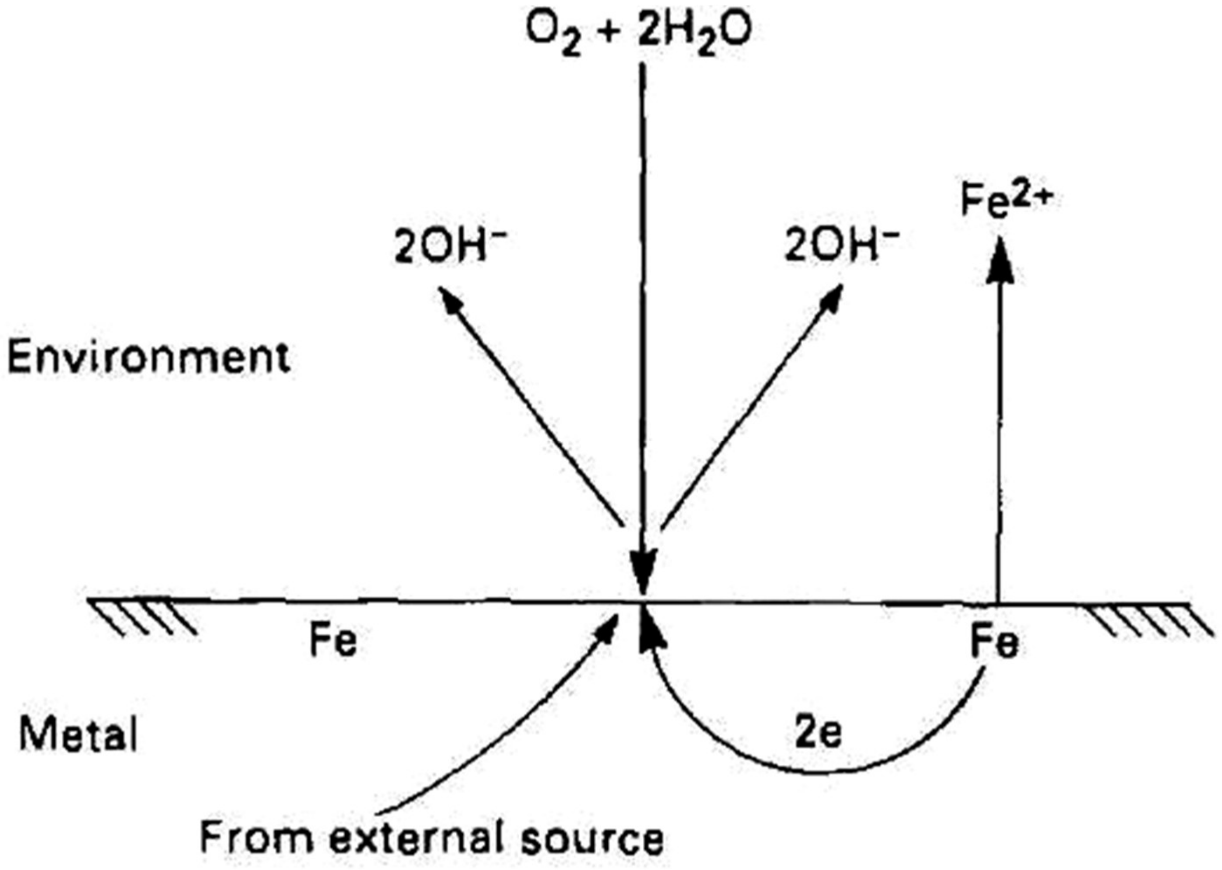
$$O_2 + 2H_2O + 4e^{-} \rightarrow 4OH^{-}$$

- The electrode potential, often called the corrosion or mixed potential (E_{corr}).

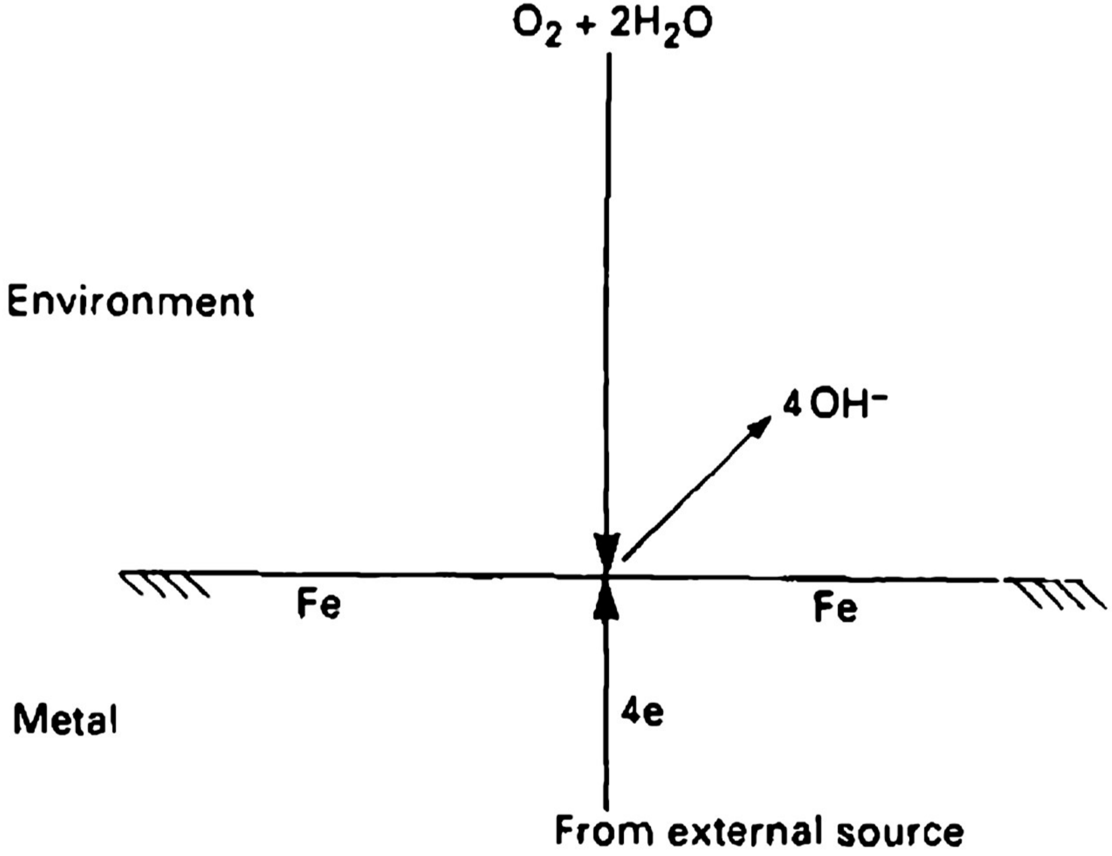
- Figure 1 is a schematic representation of aqueous corrosion occurring at a metal surface.



- Figure 2 shows the effect on the corrosion reaction shown in Fig.1 of providing a limited supply of electrons to the surface. The rate of dissolution slows down because the external source rather than an iron atom provides two of the electrons.

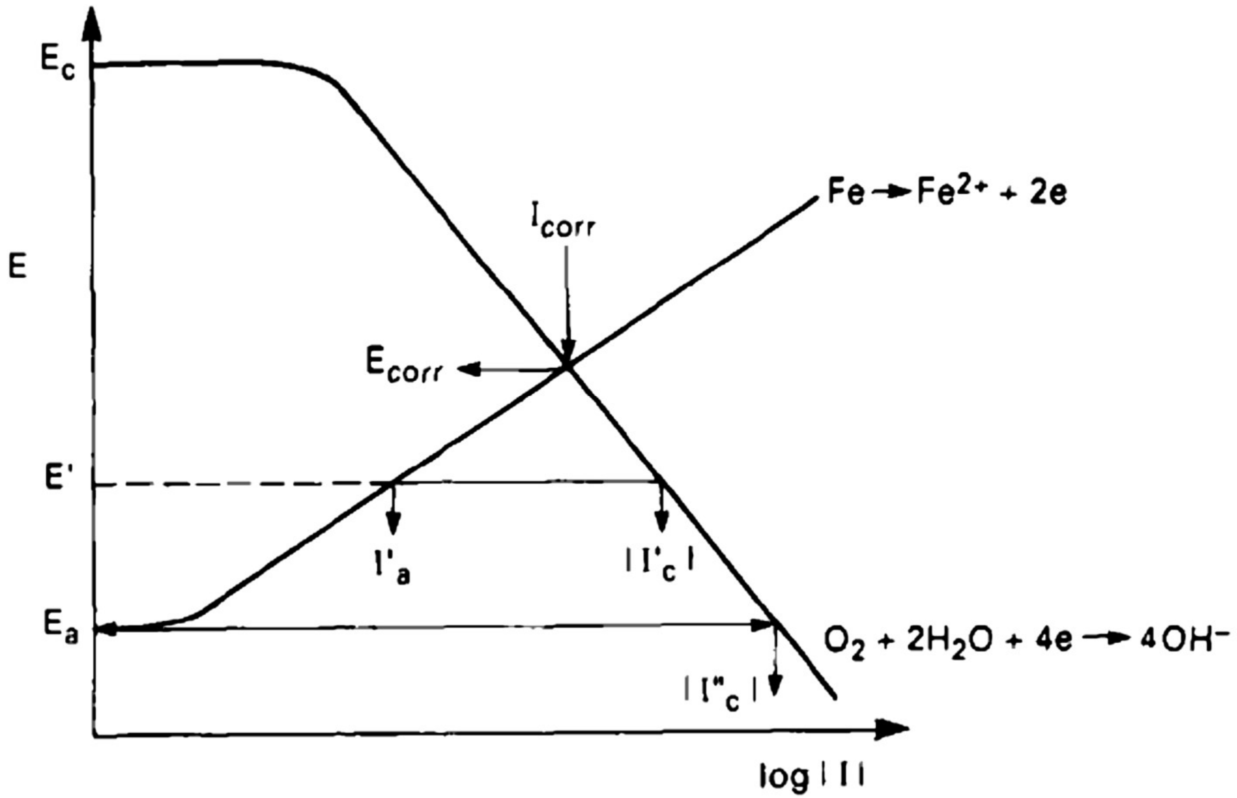


- Figure 3 shows the effect of a greater electron supply; corrosion ceases since the external source provides all the required electrons. No reason for further electrons

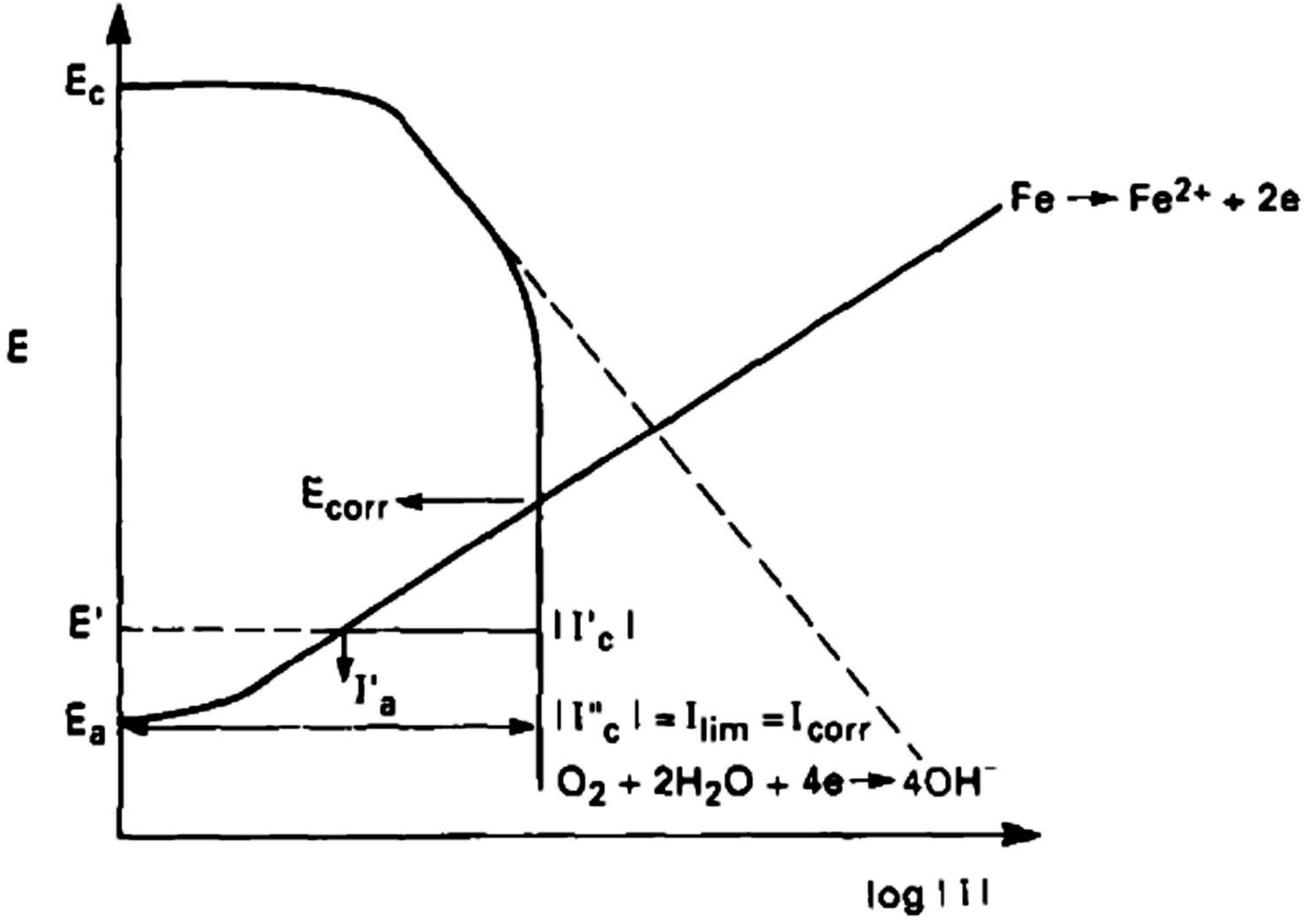


OXYGEN REDUCTION

- When corrosion occurs, if the cathodic reactant is in plentiful supply, the cathodic kinetics are semi-logarithmic, as shown in Fig.4. The rate of the cathodic reaction is governed by the rate at which electrical charge can be transferred at the metal surface. Such a process responds to changes in electrode potential giving rise to the semi-logarithmic behavior.



- Figure 5 shows that the corrosion rate approximates to the limiting current for oxygen reduction (I_{lim}) and the current required for protection is substantially lower than when semi-logarithm cathodic behaviour prevails.



Methods of Applying Cathodic Protection

- Two principal methods: The impressed current technique and the use of sacrificial anodes.
- Figure 6 illustrates the concept of the impressed current method
- The electrode and the structure must be in both electrolytic and electronic contact.
- The power supply is usually a transformer / rectifier that converts A. C. power to D. C.

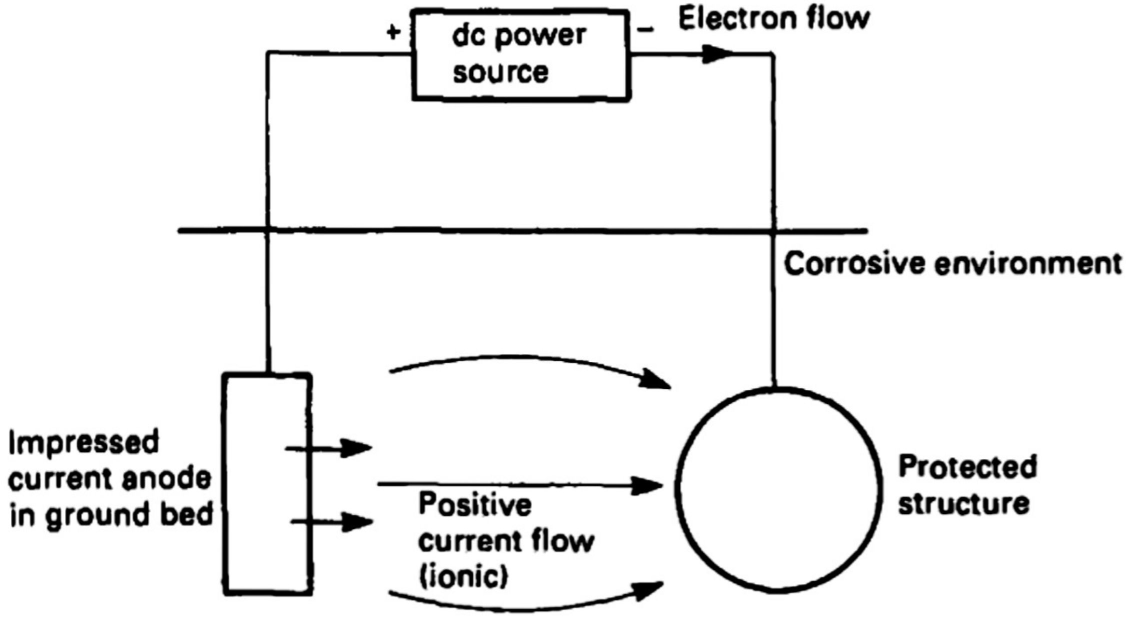


Fig. 6:Schematic diagram of cathodic protection using the impressed-current technique

- Three generic types of anodes:
    - consumable,
    - non-consumable and
    - semi-consumable.
- The consumable electrodes undergo an anodic reaction that involves their consumption.

- In practice the loss for an iron anode is approximately 9kg/Ay.
- Non-consumable anodes sustain an anodic reaction that decomposes the aqueous environment rather than dissolves the anode metal. In aqueous solutions the reaction may be:

$$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$$

- Or in the presence of chloride ions:

$$2Cl^{-} \rightarrow Cl_2 + 2e^{-}$$

- Examples: platinised titanium or niobium.
- The platinised electrodes can operate at a high current density (>100A/m^2), but will then produce high levels of acidity (pH<2) and large volumes of gas.
- The consumption rate of platinized electrodes about 8 mgs/Ay
- Semi-consumable electrodes:
  - silicon-iron,
  - chromium-silicon-iron and
  - graphite fall into this category.

Table 1: Impressed current anode material

Material	Consumption rate or operating current density	Notes
Consumable: Scrap iron	9 kg/Ay	Cheap: suitable for buried or immersed use
Cast iron	> 9 kg/Ay	Cheap: buried or immersed use carbon Skelton reduces consummation (<1kg/Ay) Mo reduces consumption in seawater
Simi- consumable: Silicon Cast iron (Fe- 14Si-(3Mo)	5-50 A/m^2 In fresh water or soil	buried or immersed use consumption
Graphite	2-5 A/m^2	
Non- consumable: Lead alloys: 1. Pb-6sb-1Ag 2. Pt-activated Platinised Ti, Ta or Nb	<50-200 A/m^2 (in seawater) <50-500 A/m^2 (in seawater) <1000 Am/ m^2 (consumption)	Consumption rate very much less than steel or cast iron(>1kg/Ay), chloride ions reduce consumption

Sacrificial Anodes

- The sacrificial anode technique uses the natural potential difference that exists between the structure and a second metal in the same environment to provide the driving voltage.
- In principle, zinc, aluminum or magnesium could be used to protect steel, and iron used to protect copper. Figure 7 illustrates the use of a sacrificial anode for cathodic protection.
- In practice pure metals are never used as sacrificial anodes.

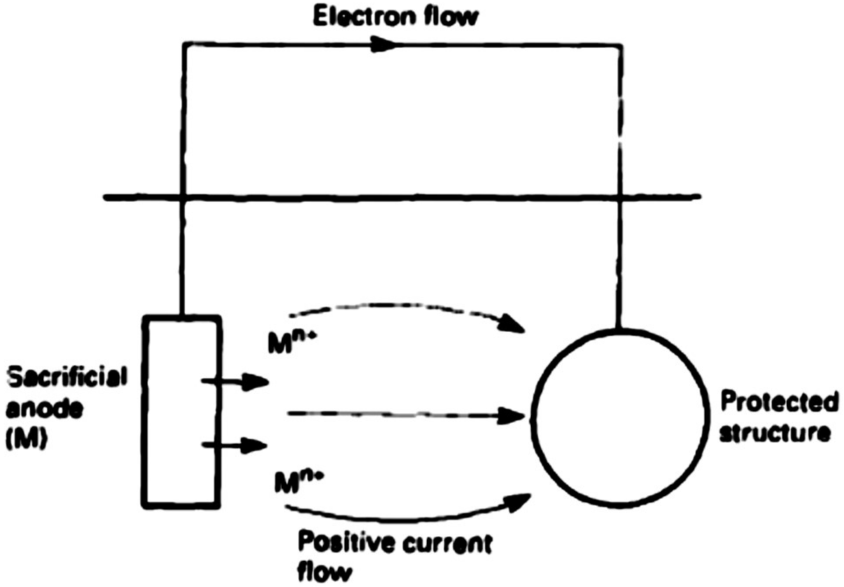


Fig. 7: Schematic diagram of cathodic protection using sacrificial anodes. In practice the anode, which will be mounted on a steel core, can be attached directly to the structure

Table 2: Typical sacrificial anode compositions and operating parameters

Alloy	Environment	Operating voltage vs. Ag/AgCl/ Seawater (V)	Driving voltage [a] (V)	Capacity (Ah/kg)
Al-Zn-Hg	Seawater	-1.0 to -1.05	0.20 to 0.25	2600-2850
Al-Zn-In	Seawater	-1.0 to -1.10	0.20 to 0.30	2300-2650
Al-Zn-In	Marine sediments	-0.95 to -1.05	0.15 to 0.25	1300-2300
Al-Zn-Sn	Seawater	-1.0 to -1.05	0.20 to 0.25	925-2600
Zn[b]	Seawater	-0.95 to -1.03	0.15- to 0.23	760-780
Zn[b]	Marine sediments	-0.95 to -1.03	0.15- to 0.23	750-780
Mg-Al-Zn	Seawater	-1.5	0.7	1230
Mg-Mn	Seawater	-1.7	0.9	1230

[a] The driving voltage to bare steel. i. e. protection potential of steel- anode operating potential

[b] US Military Specification

Note: It is often important to control impurities and specially Fe, Cu, Ni and Si although a controlled Si to some aluminum alloy

Proof of Protection

Steel

Table 3 Cathodic protection criteria [a]

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1. ≤-0.85 v w.r.t Cu/$CuSO_4$ with current applying but minimizing IR error
2. Negative shift ≥ 300 mV when current applied
3. Positive shift ≥100 mV when current interrupted
4. More negative than beginning of Tafel segment of cathodic polarization (E-log I) curve
5. A net protective current in the structure at former anodic points
6. Polarize all cathodic areas to open circuit potential at most active anode areas

N. B. Only the first three are useful in real practice

---

[a] **After British Standard code and NACE recommended practice**

- The most widely accepted criteria for protection of steel at room temperature (the protection potential) in aerobic conditions is -0.85V with respect to a $Cu/CuSO_4$ reference electrode. In anaerobic conditions -0.95V (vs. $Cu/CuSO_4$) is the preferred protection potential because of the possible presence of active sulphate-reducing bacteria (SRB).
- The standard equilibrium potential *(E^o)* for iron/ferrous-ion is -0.440V (vs. the standard hydrogen electrode). If the interfacial ferrous ion concentration when corrosion ceases is approximately 10^{-6}g ions/1 then, according to the Nernst equation, the equilibrium potential *(E_a)* is given by:

$$E_a = E^o + \frac{0.059}{2}\log a_{Fe^{2+}}$$

Where, $a_{Fe^{2+}}$ is the activity or thermodynamic concentration of the ferrous cation. Thus E_a= -0.62 V vs. the standard hydrogen electrode or 0.93V vs. $Cu/CuSO_4$. This is a value substantially more negative than the accepted protection potential (-0.85 V).

Other Metals

- Copper-base alloys will corrode in aerated conditions. It is; therefore, sometimes appropriate to consider cathodic protection.
- It is possible to forestall pitting, or to stop it once started, using cathodic protection. A negative shift of 100mV from the natural corrosion potential in the environment will often be sufficient. This technique has been applied to various stainless steels and to aluminum.
- Cathodic protection can often be used to prevent initiation of crevice corrosion. A 100mV cathodic polarization will usually prove sufficient.
- Table 4.

Table 4: Recommended protection potentials for other metals [a]

Metal	Protection potentials (V vs. Cu/$CuSo_4$)
Lead	-0.6
Copper-base alloys	-0.5 to -0.65
Aluminum	-0.95
+ve limit	-1.2
-ve limit	

[a] **After British Standard code of practice CP 1021:1973)**[12]

STEEL IN CONCRETE

- Concrete is a very benign environment for steel so long as its natural pH remains high and no aggressive species enters.
- When chloride ions reach the reinforcing bar (rebar) they may cause localized corrosion damage to it, with consequent cracking, even spalling, of the concrete. Impressed current cathodic protection has been used to overcome the problem.

POTENTIAL MEASUREMENTS

- The protection potential for a given metal is numerically different according to the reference electrode used. Thus the protection potential for iron in aerobic environments is:
  - -0.85V vs. $Cu/CuSO_4$.
  - -0.80V vs. Ag/AgCl/seawater.
  - -0.77V vs. Ag/AgCl/1M KCl.
  - -0.84V vs. Ag/AgCl/0.1M KCl.
  - -0.55V vs. standard hydrogen electrode.

- It is fundamental that a reference electrode should have a stable and reproducible potential.
- Ag/AgCl/seawater electrode should only be used in seawater.
- Calomel electrodes (and more especially hydrogen electrodes) are not suitable for field measurements.
- When the reference electrode is placed remote from the metal surface, the measured potential comprises the true electrode potential of the metal and the potential difference in the environment between the metal and the reference electrode due to the electric field.
- Deviation from the correct potential value by inclusion of the field gradient in the measurement is often called the *IR* error and it must be minimized in assessing the state of polarization of a cathodically protected structure

- It is desirable to measure the potential of a structure without an *IR* error. It is not always possible to place the reference electrode close to the structure to minimize the *IR* error but it can be achieved using the so-called instant-off technique.
- This technique relies on the fact that when the current is interrupted, the *IR* effect, being ohmic, dissipates immediately but the polarization decays much more slowly.
- Thus, if the current is switched off and the potential is measured immediately, the *IR*-free polarized potential of the structure can be measured.
- By contrast a cathodic protection system based on sacrificial anodes is designed from the outset to achieve the required protection potential.

Table 5: Estimates of the current density required to protect bare steel in various corrosive environments

Environment	Current density (A/m^2)
Sulphuric acid (hot, concentrated, stationary	350-500
Soils	0.01-0.5
Fast-flowing seawater	0.3[a]
Air-saturated hot water	0.1- 0.15
Flowing fresh water	0.05-0.1

[a] This value will decay to less than 0.05 A/m^2 if the calcareous deposit forms.

COATINGS AND CATHODIC PROTECTION

- Large structures, even in near-neutral pH environments, require a considerable current for cathodic protection. As a result structure coatings are an almost mandatory requirement when cathodic protection is contemplated.
- The cathodic protection system must only deliver a fraction (often less than 1%) of the current that would be required to protect a bare structure. Figure 8 shows schematically that there is an optimum combination of coating quality and cathodic protection which minimizes the cost of protecting structure.

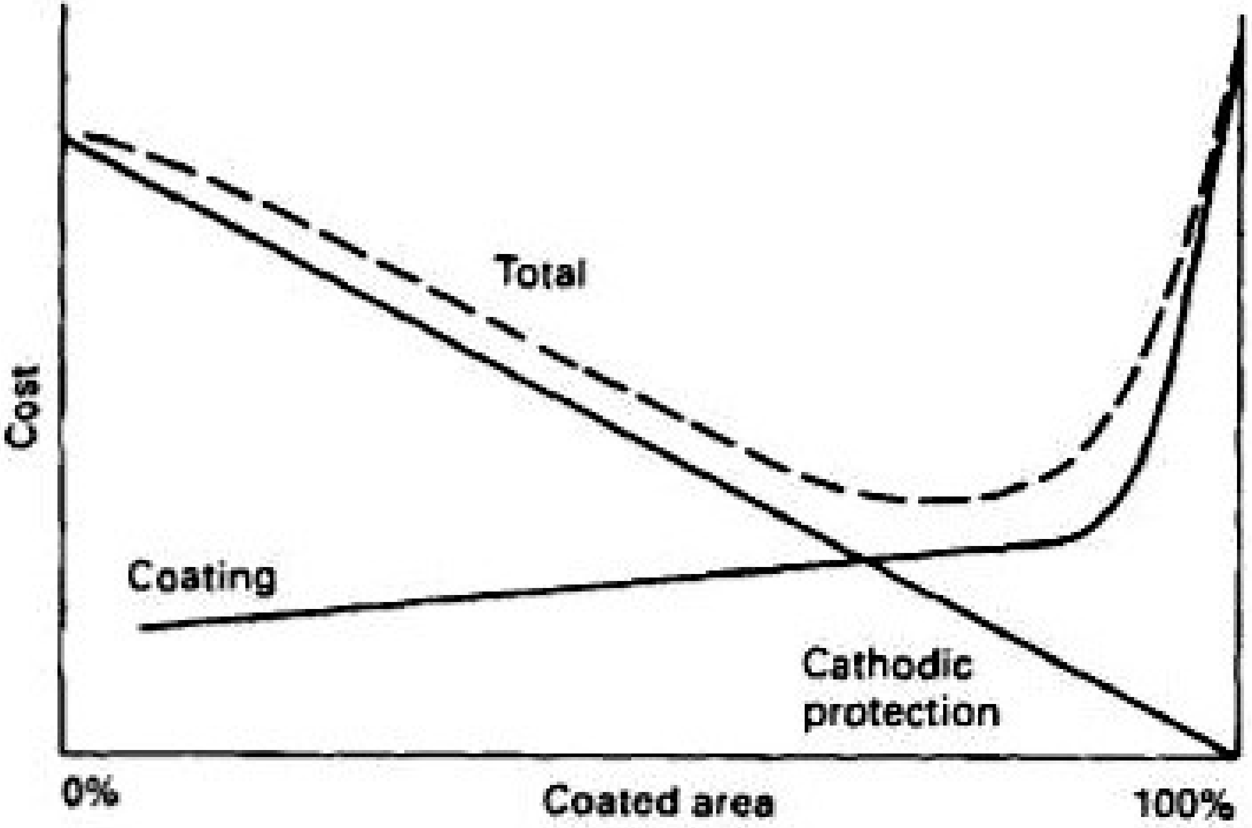


Fig. 8: Schematic diagram illustrating the economic benefit of the conjoint use of coating and cathodic protection.

- Coating deteriorates chemically and mechanically during its lifetime. This means that the cathodic protection system as installed must have sufficient reserve to provide this necessary extra current.
- Ships, many piers and jetties and virtually all buried pipelines are coated when cathodic protection is applied. Liquid storage tanks standing on sand or bitumen sand often have the underside of their base plate under cathodic protection.
- Only offshore oil production platforms, particularly in the North Sea, are cathodically protected but often deliberately uncoated.
- There are two reasons for this.
    - First, these structures are almost all protected using sacrificial anodes and it is easier to design for a more or less constant current demand than for an increasing current demand in these systems.
    - Second, the construction of the platforms is made against a tight schedule; any weather conditions that prevented completion of coating would involve launching a platform with an incomplete coating and insufficient anodes to protect the now partially coated structure.

CALCAREOUS DEPOSIT

- During cathodic protection the dissolved oxygen is reduced to produce hydroxyl ion:

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

- Seawater contains carbonate and bicarbonate ions that are in a pH-dependent equilibrium with one another:

$$HCO_3^- \overset{\leftarrow}{\rightarrow} CO_3^{2-} + H^+$$

- The higher the pH of the seawater the greater will the proportion of carbonate ions present (since as the pH increases, so the H^+ concentration decreases, thereby moving the equilibrium to the right). It follows that at a surface under cathodic protection, the hydroxyl ion produced has effect of increasing the local carbonate ion concentration.
- Seawater also contains calcium ions which form an insoluble carbonate with carbonate ions:

$$Ca^{2+} + CO_3^{2-} \overset{\leftarrow}{\rightarrow} CaCO_3$$

- Similarly, the seawater contains magnesium ions which can react with the hydroxyl ion directly to form magnesium hydroxide:

$$Mg^{2+} + 2OH^{-} \rightarrow Mg(OH)_2$$

- Once the calcareous film has formed, a cathodic current density at least an order of magnitude lower than that required to protect bare steel is needed to maintain protection.

Attenuation

In a pipe line of infinite length:

$$\Delta E_x = \Delta E_o e^{-\alpha x} \qquad \text{(Fig. 9)}$$

Where

DE_o is the change in potential at the drainage point

DE_x is the change of potential at a distance from the point

$\therefore x$ = half protected distance:

The attenuation constant is defined by:

$\alpha = \frac{Rs}{Rk}$

R_s = Longitudinal resistance of the pipe (Ω - unit length)

R_k = Characteristic resistance of the line, and is given by $R_K = (R_S R_L)^{½}$

R_L = Leakage resistance to remote earth of the line (Ω-unit length) at the drainage point = $\frac{\Delta Eo}{\Delta Io}$

- Assuming the protection potential at the drainage Point = 1.25V

and at a distance x = 0.85V,
and the structure soil potential = 0.55V

Then:

DE_O = 1.25 – 0.55V = 0.7V
ΔE_x = 0.85 – 0.55V = 0.3V

$$X = \text{Log}\ \frac{\Delta E_O}{\Delta E_X}$$

$$= \frac{2.3}{\alpha}\ \text{Log}\ \frac{0.7}{0.3}$$

$$\simeq \frac{2.3}{\alpha}\ \text{Log}\ 2.3$$

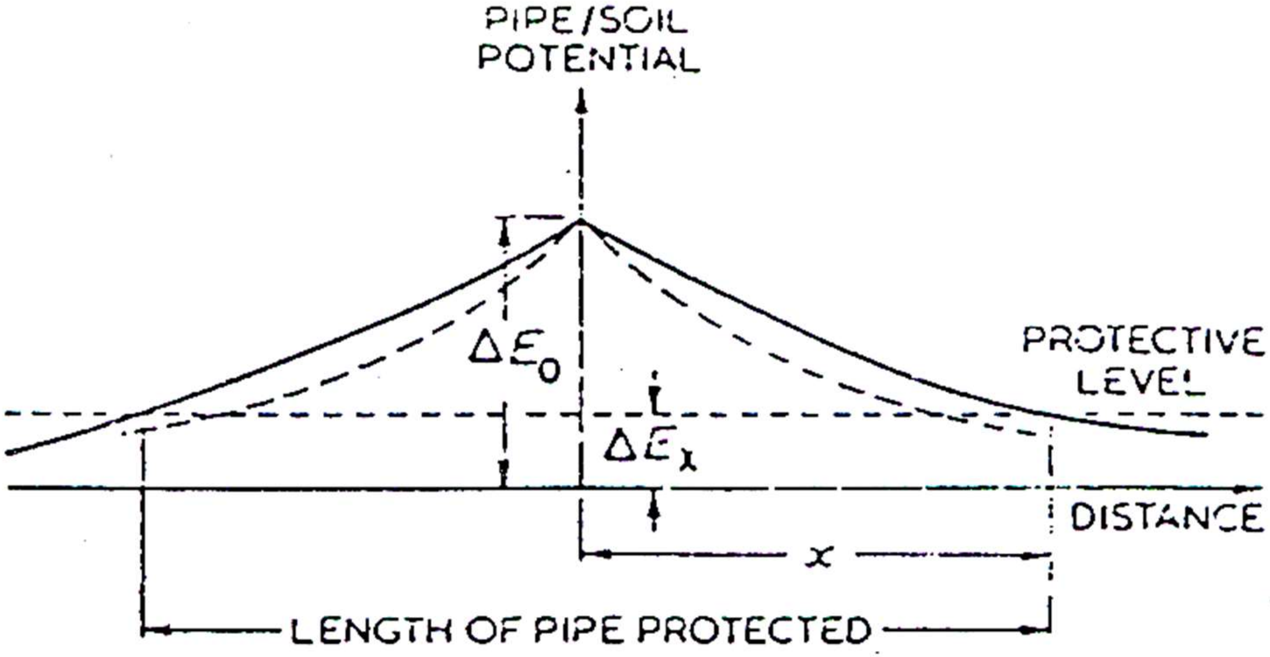


Fig. 9: Theoretical distribution of pipe/soil potential on infinite line

Sacrificial Anodes

GENERAL

- The sacrificial anode is a material that has an open circuit potential that is more negative than the structure to be protected.
- Well known materials used in practice: Zinc, Aluminum, and Magnesium (or alloys)

Sacrificial Anode basics

- **Anode operating potential**:

It's potential when coupled with a structure.

- **Protection potential:** The potential at which experience shows corrosion of a metal will cease (Table 1)
- **The driving potential:** The difference between the anode operating potential and the potential of the polarized structure to which it is connected.
- **Anode capacity:** Total columbic charge produced by unit mass as a result of electrochemical dissolution (normally expressed Ah/Kg). The inverse of the capacity i.e. the consumption rate (Kg/Ay) is sometime used.
- Anode efficiency =

$$\frac{\text{Anode Capacity}}{\text{Theoretical Capacity}} \times 100$$

Table 1: Protection potentials of metals in seawater (V vs. Ag/AgCl/ seawater)

Iron and steel	
Aerobic environment	**-0.8**
Anaerobic environment	**-0.9**
Lead	**-0.55**
Copper alloys	**-0.45 to 0-0.60**

Anode Requirements

- A sufficiently large driving voltage.
- Anode to have a more or less constant operating potential.
- Must have a high, reproducible and available capacity.
- Production of anode materials in large quantities, with the desired mechanical properties.

Table 2: Anode potentials of various alloys used for cathodic protection

Alloy	Anode potential (V vs. Ag/AgCl/ Seawater (V)	Capacity (Ah/kg)
Al-Zn-Hg	-1.0 to -1.05	2830
Al-Zn-Sn	-1.0 to -1.10	2600
Al-Zn-In	-1.0 to -1.15	2700
Zn-Al-Cd	-1.05	780
Mg-Mn	-1.5	1230
Mg-Al-Zn	-1.7	1230

Factors Affecting Anode Performance

- Alloy composition: Generally anode alloys formulations are proprietary and covered by patents.
- Impurities:
  - Anode alloy should dissolve with a capacity approaching the theoretical value.
  - The presence of iron is deleterious. When the solid solubility of iron in zinc is exceeded the anode operating potential becomes more positive. Both silicon and aluminum are added to zinc to control the adverse effects of iron.
  - Other heavy metal impurities (especially copper and nickel) have similar adverse effects.
  - Table 3

Table 3: Suitable primary material quality requirements

99.90% Magnesium			99.99% Zinc		
Cu	0,02	max	Pb	0.003	max
Mn	0,01	max	Cu	0.003	max
Sn	0.01	max	Cd	0.003	max
Ni	0.001	max	Fe	0.002	max
Pb	0.01	max	Sn	0.001	max
Others	0.05	max	Zn	99.99	min
Mg	99.90	min			
99.80 % Aluminum			**99.99% Aluminum**		
Fe	0.12	max	Pb	0.003	max
Si	0.08	max	Cu	0.002	max
Cu	0.03	max	Cd	0.003	max
Zn	0.03	max	Fe	0.003	max
Mn	0.02	max	Sn	0.002	max
Mg	0.02	max	Al	99.99	min
Al	99.80	min			

ALLOY ADDITIONS:

- Additions are made to improve the performance of the anode. **This includes:**
  - Lowering the anode operating potential to increase the driving voltage
  - Avoiding passivation
  - Increasing the anode capacity.
  - Improve the dissolution morphology.
  - Modifying the mechanical properties of the dissolution product to promote detachment.
  - Improving the mechanical properties of the anode.

- **Common zinc anode alloys (Table 4)**
  - Aluminum is added in some cases to improve the uniformity of dissolution.
  - Cadmium: to encourage the formation of soft corrosion product that readily falls away.

Table 4: Standard zinc alloys

Alloy Component (wt. %)	ASTM B418-88 Type I	ASTM B418-88 Type II	US Mit[12] Spec. A 18001 J	Dn V recomm[13] for elevated temp.
Al	0.10-0.5	0.005 max	0.10-0.5	0.10-0.20
Cd	0.025-0.07	0.003 max	0.025-0.07	0.03-0.06
Fe	0.005 max	0.0014 max	0.005 max	0.002 max
Cu	0.005 max	0.002 max	0.005 max	0.005 max
Pb	0.006 max	0.003 max	0.006 max	0.006 max
Si	-	-	-	0.125 max
Others (total)	0.1	-	0.1	-
Zn	Reminder	Reminder	Reminder	Reminder
Operating potential (V vs. Ag/AgCl/Seawater)	-1.05	-1.05	-1.05	-1.05
Capacity (Ah/kg)	780	780	780	780

- **Most common commercial aluminum alloys (Table 5)**

Table 5: Proprietary aluminum anode materials

Alloy Component (wt. %)	Al-Zn-In	Al-Zn-In*	Al-Zn-Sn	Al-Zn-Hg
Fe	0.12 max	0.18 max	0.13 max	0.08 max
Si	0.05-0.20	0.01-0.02	-	0.11-0.21
Zn	2.8-6.5	2.0-6.0	4.0-5.0	0.35-0.50
Hg	-	-	-	0.35-0.50
In	0.01-0.02	0.01-0.03	-	-
Sn	-	-	0.1	-
Mg	-	0.1-2.0	-	-
Cu	0.006 max	0.01 max	-	0.006 max
Mn	-	0.1-2.0	0.1	-
Ti	-	0.02 max	-	-
Others (each)	0.006 max	-	0.01 max	-
Al	Reminder	Reminder	Reminder	Reminder
Operating potential (V vs. Ag/AgCl/Seawater)	-1.10	-1.10	-1.10	-1.05
Capacity (Ah/kg)	2700 max	2700 max	variable	2830 max

Table 6: Proprietary magnesium alloys

Alloy Component (wt. %)	Mg-Mn No.1	Mg-Mn No.2	Mg-Al-Zn
Cu	0.02	0.02 max	0.08 max
Al	0,01 max	0.05 max	5.3-6.7
Si	-	0.05 max	0.3 max
Fe	0.03	0.03 max	0.005 max
Mn	0.5-1.3	0.5-1.5	0.25 min
Nj	0.001	-	0.003 max
Zn	-	0.03 max	2.5-3.5
Others (each)	0.01 max	0.03 max	0.03 max
Mg	Reminder	Reminder	Reminder
Operating potential (V vs. Ag/AgCl/Seawater)	-1.7	-1.7	-1.5
Capacity (Ah/kg)	1230	1230	1230

Metallurgical Factors:

- Porosity within the anode is detrimental.
- Cracking of the anodes during casting is in many cases unavoidable: longitudinal cracks can not be accepted.
- Anode material must stay firmly attached to the steel insert.
- The method of casting: undesirable to permit segregation, as this may lead to preferential attack at grain boundaries.

Environmental Factors

- The presence of H_2S (from bacterial activity) in anaerobic saline mud can result in significant decrease in capacity and loss of operating potential for Al-Zn-In anodes.

- Aluminum alloy anodes require the presence of chloride ions to prevent passivation; consequently aluminum alloy anodes only find application in saline environments.
- The capacity and operating potential of aluminum alloy anodes are dependent on the degree of salinity .

Selecting the Appropriate Anode Material

Choice basis: Desirable to be the lowest cost per Amp. hour of current supplied, however it is governed by other constraints.

Zinc

- Most reliable electrochemical performance.
- Lowest driving voltage of generic alloy types, thus, unsuitable for high resistivity soils and low salinity waters.
- An operating potential of -1.05 V vs. Ag/AgCl/sea water can not lead to overprotection, which is an advantage where concern for coating disbandment or hydrogen damage of high strength steel (>700 MPa) exist.
- Zinc has a poor capacity (780 Ah/Kg) compared with aluminum (>2500 Ah/Kg).

Aluminum

- Attraction: very high capacity.
- Three generic types: Al-Zn-In, Al-Zn-Hg and Al-Zn-Sn (last one has been superseded).
- Indium and Mercury are added to overcome the natural passivation of aluminum. However aluminum anodes are not suitable for low chloride environments, which would lead to passivation, hence they are not used for land-based applications.
- Al-Zn-In may be preferred in sea bed mud (where an additional driving voltage is required) to ensure adequate structure polarization.
- Al anodes are less constant in their electrochemical characteristics than zinc.
- Al alloys are susceptible to thermite sparking when dropped to rusty surfaces.
- Aluminum anodes based on Al-Zn-In and Al-Zn-Hg are now the work – horse materials for sea water service.

Magnesium

- Two generic types: Mg-Mn and Mg-Al-Zn, both have a high driving voltage, hence find applications in high resistivety environments.
- Mg-Mn alloy is useful in environments up to 60Ωm. (200 mV driving voltage greater then Mg-Al-Zn). However the high driving voltage may result in over-protection.
- Magnesium rarely finds application in subsea environments; mainly due to:
  - Possibility of over-protection.
  - High unit cost.
  - Poor capacity.
- However Mg-Al-Zn anodes (in ribbon form) have been used in seabed for rapid polarization of structures.
- Susceptibility to theremite sparking precludes consideration for applications involving a spark hazard (e.g. tankers carrying inflammable petroleum products).
- Magnesium is the predominant sacrificial anode material for onshore use.

Anode Testing

- Anode testing involves: screening ranking, performance information and quality control.
- *Screening tests*: for rapid selection of materials as potential candidates for the given application, and are normally carried for a short duration (hours).
- *Performance testing*: (months or years) to produce detailed data an anode performance and behaviour under the anticipated exposure conditions. Tests should mirror as closely as possible the expected operating conditions.
- *Quality control* tests: to detect deviation from manufacture specifications. This involves spectrographic analysis as a primary quality control check. Corrosion test conditions may involve using artificial sea water to simulate marine environment…etc. Corrosion test methods include free corrosion, galvan-static, potentiostatic tests…etc.

Cathodic Protection Design

- Important design parameters
  - The area of the steelwork to be protected;
  - The type of coating, if any that is to be used;
  - The cathodic current density;
  - Cathodic protection system life.
- Steel structures are normally coated. The % breakdown area needs to be protected; this area varies with time (Table 7).

Table 7: Guide to coating breakdown for offshore structures

Lifetime (years)	Coating breakdown (%)		
	Initial	Mean	Final
10	2	7	10
20	2	15	30
30	2	25	60
40	2	40	90

- Current density requirements to achieve protection of steel in offshore structures (to achieve -0.8V vs. Ag/AgCl/sea water) are given (Tables 8)

Table 8: Guidance on minimum design current densities for cathodic protection of bare steel

Area	Current density (mA/m^2)		
	Initial	Mean	Final
North Sea (northern sector, 57-62N)	180	90	120
North Sea (southern sector, up to 57N)	150	90	100
Arabian Gulf	130	70	90
India	130	70	90
Australia	130	70	90
Brazil	130	70	90
West Africa	130	70	90
Gulf of Mexico	110	60	80
Indonesia	110	60	80
Pipelines burial specified)	50	40	40
Saline mud (ambient temperature)	25	20	15

System Life

- The system may be designed for a life of up to 40 years.
- Intermittent exposure to be taken into account (e.g. ballast or storage taken, effect of tidal and seasonal variation on wetted area in offshore structure)…etc.

Calculating the Weight and Number of Individual Anodes

$$W = \frac{i_{av} A l \, 8760}{C}$$

- The total weight of anode required to protect the structure for its project life is calculated. This is given by:

Where W= total mass of anode material (Kg)

A= structure area to be protected (m^2)

i_{av}= mean structure current density demand (A/m^2)

l= design life in years (1 year = 8760 h)

C= anode capacity (Ah/Kg)

- The total weight of the anode material must be equal to or greater than the total weight, W, calculated above. Similarly each anode must be of sufficient size to supply current for the design life of the cathodic protection system.

◉ **Anode Size and Shape**

- Choice of shape and size of the anode is often limited. Economics may dictate an 'off-the-shelf' choice from a manufacturer.
- Current output from an anode depends on its surface area.
- Anodes of the same weight but different shape can have different outputs.

Anode Output (I)

•That is the current of available from the anode under the design conditions.

•It depends on the:

- Anode shape
- Resistivity of the environment.
- Protection potential of the structure.
- Anode operating potential.

$$I = \frac{[E_2 - E_1]}{R}$$

Where I= anode output (A)

E_1= operating potential of the anode (V)

E_2= protection potential (V)

R= anode resistance (ohm)

The protection potential of steel in aerobic environments is taken as -0.80V (vs. Ag/AgCl/seawater).

Anode Life

- Having calculated the resistance, and hence current output the anode life L, is checked by calculation:

$$L = \frac{MU}{IE}$$

Where L= effective life of anode (years)

M= mass of single anode (Kg)

U = utilization factor, e.g. 0.75-0.80 for bracelet anode

E= consumption rate of the anode (Kg/Ay)

(inverse of capacity in suitable units)

I= anode output (A)

U is purely a function of anodic geometry and is the fraction of anode material consumed when the remaining anode material cannot deliver the current required.

NUMBER OF ANODES

- The total number of anodes, *N*, is calculated from:

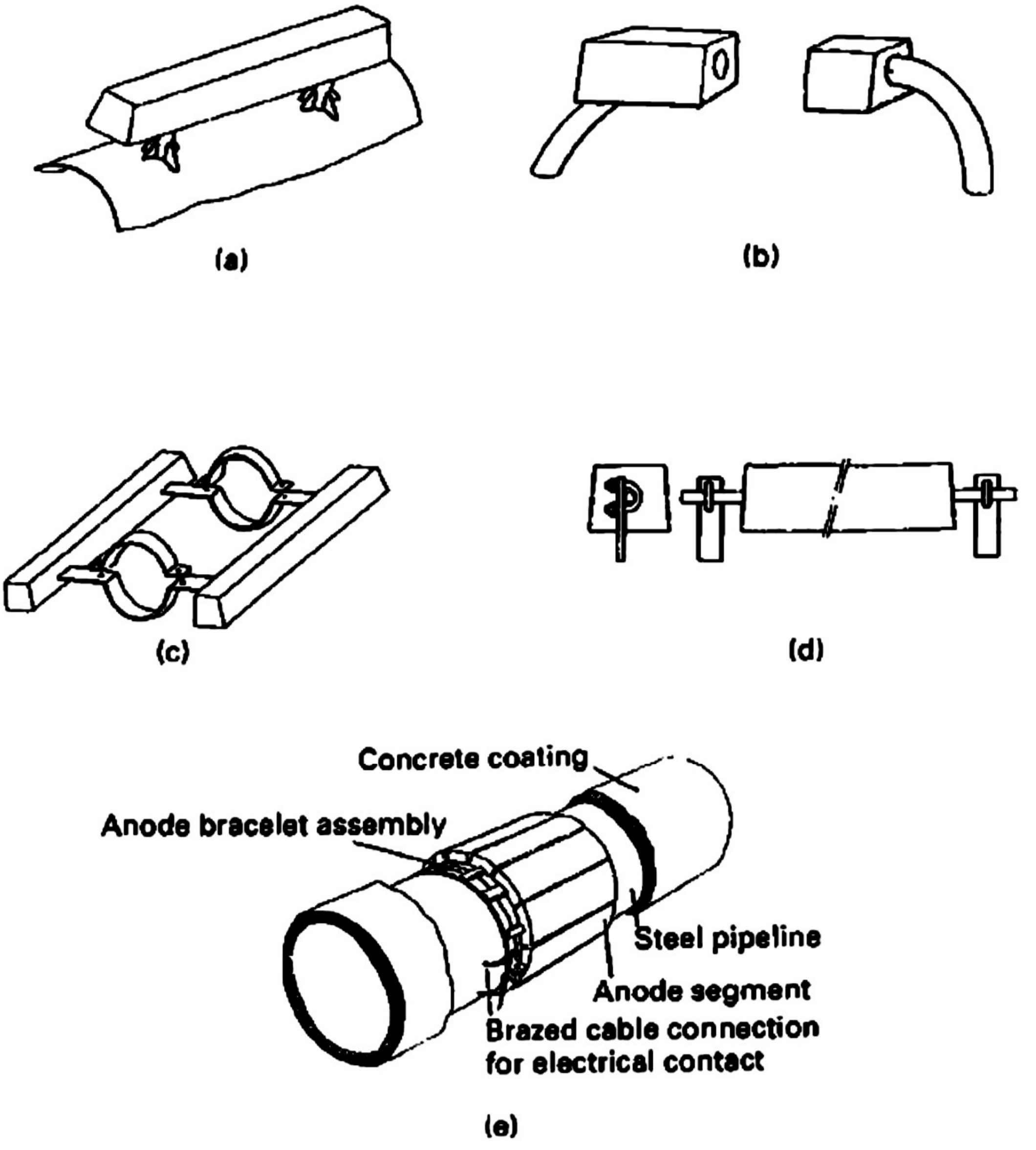
$$N = \frac{A \quad i_{av}}{I}$$

- *N* x *M* must be equal to or greater than the total weight of the anode material.
- Difficult to achieve both the exact current output and the precise weight of the anode material simultaneously. Hence, a compromise is reached, but both must at least match design requirements.
- A check to ensure that the anodes will deliver sufficient current to protect the structure at the end of the design life should be conducted.
- Generally the output is calculated using a modified resistance based on an anode that is 90% consumed.

Anodes (and Current) Distribution

- A greater number of anodes distributed over the structure improve current distribution (But: cost).
- The anode must continue to function throughout the life of the structure. However very large number of heavy anodes is impracticable and uneconomic.
- Adequate protection is essential and overprotection should be avoided.
- Some flexibility in the output to weight ratio of the anode can be achieved by varying anode shape.
- Proximity of the anode to the structure is important (e.g. in a steel pipe-work).

THE ANODES INSERT:



Typical anode shapes and fixing methods, (*a)* Offshore stand-off anode; *(b)* Stand-off anode - types of bowed core; (c) Stand-off anode, damp finings; (*d)* Typical tank fixing for shipping: (e) Bracelet anode assembly

BACKFILLS FOR ANODES

- Zinc and magnesium anodes used in onshore cathodic protection are usually surrounded by a backfill which decreases the resistance of the anode.
- Bag backfills are used for small anodes and loose backfills are used for large anodes.
- Backfill lowers the circuit resistance and reduce potential loss.
- For high resistivity soils the most common mixture for backfills is 75% gypsum, 20% bentonite 5% sodium sulphate.
- Carbonaceous backfills are relevant to impressed current systems and must not be used with sacrificial anodes. This is an electronic conductor which is noble to both sacrificial anode and material.

Other Considerations

Calcareous Scale

- Increased local pH at the steel surface caused by hydroxyl production favors the deposition of a mixed scale of $CaCO_3$ and $Mg(OH)_2$.
- This scale is beneficial as it reduces the cathodic current density.
- Increased current densities in the early stages of operation encourage scale deposition.

Combined Alloy Anodes for Rapid Structure Polarization

- New binary alloy sacrificial anodes have been developed.
- A short life supplementary magnesium anode or anodes may be attached to an aluminum anode for quick polarization of the structure.

Impressed Current Anodes

GENERAL

- Many electronic conducting materials may be utilized as impressed current anodes.
- Important: their cost per unit of energy emitted, their electrochemical inertness and mechanical durability and the cathodic protection system.
- Choice of a material which does not pollute potable water for example may add cost (chromium containing or lead – based alloys are typical pollutants).

Materials used:

1. Precious metals and oxides: platinised titanium, platinised niobium, platinised tantalum, platinised silver, solid platinum metals, mixed metal oxide-coated titanium, titanium oxide-based ceramics,
2. Ferrous materials: steel, cast iron, iron, stainless steel, high-silicon iron, high-silicon molybdenum iron, high-silicon chromium iron, magnetite, ferrite.
3. Lead materials: lead-antimony-silver, lead with platinum alloy micro-electrodes, lead/magnetite, lead dioxide/titanium, lead dioxide/ graphite.
4. Carbonaceous materials: graphite, carbon, graphite chips, coke breeze, conductive polymer, conductive paint.
5. Consumable non-ferrous metals: aluminium, zinc.

Combination Anodes

- These may be:
  - Canister anodes: a spirally wound galvanized steel outer casing containing a carbonaceous based extender surrounding the primary anode (graphite, silicon iron titanium, Platinized titanium …etc).
  - Groundbeds: carbonaceous extender, generally coke breeze and graphite, silicon – iron scrap steel, platinized titanium or niobium anodes.
  - Co-axial anodes: copper – cored anodes of lead – silver, platinized titanium and platinized niobium.
- For long lengths of anodes it may be sometimes necessary to extrude one material over another, e.g. titanium over copper to improve longitudinal conductivity and current attenuation characteristics of titanium.
- Tubular, rather than solid rod cantilever anodes may be used in flowing water environments to resist fatigue failure.

Platinum and Platinized – Coated Anodes

- A small mass of platinum can give a very large surface area, and platinum can operate at very high current densities.
- Typical consumption rates of precious metals and their alloys are in the range of 6-7 $mgA^{-1}y^{-1}$ or slightly higher, These are the results of test for several months in sea water at current densities ranging from 540 – 5400 Am^{-2}.

Platinized Titanium

- The anodes are mainly produced by electro-deposition of a thin coating of Pt from aqueous solution on roughened titanium
- Mechanically bonded coatings may also be produced. These have the advantage that thick, low porosity, ductile platinum coatings can be produced.
- Pt coatings can also be thermally sprayed or sputtered onto the titanium to provide uniform well – bonded coatings.

Operational Characteristics of Platinized – Titanium Anodes

- The protective passive film can breakdown in certain solutions (Table 1).
- These anodes may be operated at current densities as high as 5400 Am^{-2}.
- Consumption rates in sea water over the current density range 300-5000 Am^{-2} is in the range 8.7 – 17.4 mg $A^{-1}y^{-1}$.
    - Formation of deposits leading to anode degradation.
    - Organic impurities in the electrolyte can lead to an increased consumption rate of Pt dissolution.
- Platinized – titanium anodes are in use for about 30 years for jetties, ships and submarines, and may be used in soils when surrounded by a carbonaceous backfill.

Table 1: Breakdown potentials of commercially pure titanium in various environments

Electrolyte and conditions	Breakdown potentials of commercially pure titanium (V)
Tests in pure seawater at ambient temperatures	8.5-15
Tests in NaCl from 5 g / l to saturated below 60°C	8.5-15
Sea water	9-14
Sulphuric acid	80-100
Chloride	8
Sulphate	60
Carbonate	60
Phosphate	60
Fluoride	50
Bromide	2-3
Iodide	2-3
Sulphate	>80
Phosphate	>80
Ratio of sulphate plus carbonate to chloride ions, 4:1	>35
River water	50
Tap water	80

Platinized Niobium and Platinized Tantalum (Table 2)

- Platinized niobium and tantalum have found use in applications where high breakdown potentials and hence higher operational current densities can be utilized.
- Examples:

  - Ships and cooling system anodes.
  - Offshore structures where high reliability in service is required.
  - Domestic water tanks
  - Deep well groundbeds

- The consumption rate of platinized niobium in sea water over the range 5000 – 10000 Am^{-2} is similar to platinized titanium i.e. $\simeq$ 7.8 mg $A^{-1}y^{-1}$.

Table 2: Comparison of breakdown potential

Solutions	Ti	Nb	Ta
Seawater	9	120	120
Sulphate/carbonate	60	255	280
Phosphate/borate	80	250	280
Drinking water	37.5	250	280
Bromides	2-3		

Platinized Silver

- Used only in sea water or similar chloride – containing electrolytes.
- An anode consisting of Pt-10 Pd on Ag was tried as substitute for rapidly consumed aluminum for use as a trailing wire anode for the cathodic protection of ship hulls, and has been operated at 1900 Am^{-2}.
- With the advent of hull mounted anodes this material has been replaced by the superior platinized titanium and niobium anodes.

Mixed Metal Oxide Coated Titanium

- The anode consists of a thin film of valve and precious metal oxides baked onto a titanium substrate.
- When first developed it was given the proprietary name of Dimensionally Stable Anode (DSA).
- The precise composition of the alloy coating is generally considered proprietary information.
- These anodes, like platinized titanium, may be supplied in different forms e.g. rod, tube, mesh, wire, etc.

Conductive Titanium Oxide Based Ceramics

- An electrically conductive titanium oxide based ceramic material has been developed recently, and is marketed under the trade name "Ebonex". This material consists principally of Ti_4O_7 but may also contain some higher oxides.

Ferrous Materials

Steel

- One of the earliest materials to be used in power-impressed cathodic protection was steel. Its economy lies in situations where steel scrap is available in suitable quantities and geometry and it is only in such situations where its use would now be considered.
- It is necessary to ensure the integrity of anode cable connections and to give consideration to the number of such connections related to longitudinal resistance of the anode and current attenuation, if early failure is to be avoided.

Cast Iron

- Cast iron may be used under similar circumstances, but has inferior mechanical properties. It has been used, although not in current practice.

Stainless Steel

- Stainless steel has been tried as an inert anode, mainly under laboratory conditions and with only partial success.
- At practical current densities, the presence of chloride ions, deposits on the anode or crevice corrosion at the anode support lead to rapid failure.

High Silicon Iron (HSI)

- These are iron alloys that contain 14-18% Si.
- The only practical method of machining is by grinding, and to obviate machining it is cast into fairly standard sizes to suit the general requirements of industry.
- HSI has a long successful history as a corrosion-resistant material in the chemical industry for such items as acid storage vessels and has been used in this application for more than 60 years. A typical analysis for HSI anodes is 14.5% Si, 0.75% Mn, 0.95%C, remainder Fe.
- The consumption rate of HSI anodes buried directly in soils will vary depending upon the soil composition and will be excessive in chloride-containing soils.

High Silicon / Molybdenum Iron

- The addition of 1-3% Mo to HSI results in an improvement in maintaining a conducting oxide film in chloride-containing solutions above 200 p.p.m. or at temperatures of 38°C or above.

High Silicon / Chromium Iron (HSCI)

- A typical analysis is 14.5% Si, 0.75% Mn, 1.0% C, 4.5% Cr, and remainder Fe.
- Comparative tests between HSI and HSCI in seawater at 93°C and 10.8 Am^{-2} showed consumption rates of 8.4kg $A^{-1}y^{-1}$ and 0.43kg $A^{-1}y^{-1}$, respectively.
- HSCI anodes cannot be used in potable waters because of the possibility of chromium contamination.
- Improvements in anode construction have also been carried out to reduce the non-uniform material loss along the length of the HSCI anode, the so-called 'end effect' phenomenon. This involves the use of hollow, centrifugally cast anodes of uniform wall thickness with a centrally located interior electrical connection.

Magnetite Anodes

- The anodes are constructed from a cast alloyed magnetite shell, the centre of which is hollow. The internal surfaces of the magnetite shell are then lined with an electronic conductor so as to ensure a uniform distribution of current density over the external surface.
- Magnetite anodes exhibit a relatively low consumption rate when compared with other anode materials, namely graphite, silicon iron and lead and can be used in seawater.
- Magnetite anodes can be operated at elevated temperatures up to 90°C
- The main disadvantage of magnetite anodes is that they are brittle, and susceptible to high-impact shocks.

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Ferrite Anodes

- Sintered and sprayed ceramic anodes have been developed for cathodic protection applications. The ceramic anodes are composed of a group of materials classified as ferrites with iron oxide as the principal component.
- Ceramic anodes based on a plasma-sprayed ferrite coating on a titanium or niobium substrate have also been developed. These consist of plasma-sprayed lithium, nickel or cobalt ferrite on a machined Ti or Nb button shaped substrate fitted into a plastic electrode holder.

Lead Materials

- The Pb-6Sb-1Ag alloy is commonly used where Pb-Ag anodes are specified. The results of tests on Pb-6Sb-lAg given in Table 3 are of interest in recognizing the scope of practical lead alloys in waters of differing resistivities.
- A minimum current density is necessary to ensure passivation of the anode and anodes operating below this current density may experience rapid consumption rates. A minimum value of 32.3 Am^{-2} is required.
- Recent experience with Pb-6Sb-1Ag and Pb/Pt anodes operating in seawater at depths greater than 25m has revealed a marked increase in consumption rate compared with that found on the surface.
- It is therefore recommended that lead anodes are not used at depths below 25m.

Table 3: Behavior of Pb-6Sb-IAg anodes

Resistivity of electrolyte at 35°C (ohm m)	Average wastage rate at 108 Am^{-2} Kg A^{-1} y^{-1}	Length of trial (days)
0.163 (sea)	0.086	236
0.163 (NaCl)	1.99	1.75
0.5 (sea)	0.0145	234
0.5 (NaCl)	0.654	1.75
10 (sea)	23.80	5.75
10 (NaCl)	23.70	1.75
50 (sea)	0.10	236
50 (NaCl)	11.64	1.75

Lead / Platinum Bi-Electrodes

- A typical anode for practical use would be in the order of 25 to 48mm in diameter, with hard platinum alloy pin, of 0.50mm diameter by 10mm length, spaced every 150 to 300mm and progressively positioned around the circumference.

Lead / Magnetite Composites

- It has been demonstrated that particles of conducting Fe_3O_4 in a Pb matrix can produce results similar to that of platinum, in acting as stable nucleation sites for PbO_2 formation.
- These anodes were found to operate successfully in both artificial seawater, resistivity 0.25 Ω m and in this water diluted with distilled water to give a higher resistivity of 10 Ω m.

Lead Dioxide on Other Substrates

- Lead dioxide on a titanium substrate has also been tested for use in the cathodic protection of heat exchangers and in seawater may be operated at current densities up to 1000 Am^{-2}.

Graphite

- Graphite is a denser crystalline form of carbon Graphite anodes are prepared by heating calcined petroleum coke particles with a coal tar pitch binder.
- Graphite is immune to chlorine and has a long history in the chemical industry in this and similar applications.
- The anode is not recommended for use in water at above 50°C, where the consumption rate increases rapidly.
- Table 4 gives some results obtained with graphite under different conditions.
- Graphite anodes when used in soils are invariably placed in a carbonaceous backfill. This helps to compensate for the lower electrical resistivity of graphite when compared with silicon iron.

Table 4: Performance of graphite

Environment	Wastage rate Kg A $^{-1}$ y^{-1}	Current density (Am^{-2})
Backfill	0.9	10.8
Hot Water	0.9	-
Sea water	0.045	4.5-115
Sea water	Little	10.8
Fresh water	0.45	3.5
Fresh water	0.45	2.7
Mud	0.91-1.36	71

Conductive Polymers

- The anode, marketed under the trade name Anodeflex, consists of a continuous stranded copper conductor (6AWG) which is encased in a thick jacket of carbon loaded polymer, overall diameter 12.5mm.
- The major applications for this material are tank protection, internal protection, mitigation of poor current distribution and hot spot protection, i.e. to supplement conventional cathodic protection systems and provide increased levels of cathodic protection in areas that exhibit low levels of protection.

Carbonaceous Backfills

- Coke breeze is used as an anode extender thus producing an anode with an enormous surface area, its main component being carbon.
- The grading of the coke is of some importance in that too large a grade offers large local contact resistance, leading to uneven consumption, whilst an excessively fine coke leads to over-tight compaction and gas blocking (gaseous polarization).
- Some typical properties of coke breeze and similar materials are shown in Tables 5 to 7.
- The usual main object in using coke breeze is to lower the resistance of the anode to remote earth with the coke cross -section, in a typical groundbed, normally about 300 x 300 mm.
- Calcined petroleum coke breeze with a high fixed carbon content of 99% is used in deep well applications. The material has a low particle size and, with suitable additives, may be converted into slurry and pumped into a borehole.

Table 5: Densities of backfill

Back fill in bulk	Density range kg m^{-3}	Typical density kgm^{-3}
Coal coke breeze	650-800	690
Calcined petroleum coke granules	700-1100	720-850
Natural graphite granules	1100-1300	-
Man-made graphite, crushed	1100-1300	-

Table 6: Typical coal coke specification for cathodic protect

To pass 16 mm screen	100%
To pass between 16 mm and 8 mm screen	8.9-9.8%
To pass between 8 mm and I mm screen	78-90%
To pass I mm screen	1-14
Fixed Number	82.7min to91% max
Volatile matter	0.1%
Ash	8.6%
Moisture	5% max, typically 4%
Sulphur	1.2 max , typically
Phosphorus	0.42-0.7%
Resistivity (uncompacted)	0.55 ohm max, (typically 0.35 ohm)
Specific gravity	1.4

Table 7: Resistivities of carbonaceous backfills (ohm meter)

Material	Dry	Tempered	Wet
Coal coke	**0.55**	**0.45**	**0.15**
Graphite granules	**1.5**	**1.2**	**0.20**

Anodes Used for the Cathodic Protection of Reinforced Concrete Structures

- Reinforced concrete structures that are fully immersed or buried in a corrosive environment may generally be protected using conventional cathodic protection ground-bed design.
- However, for the cathodic protection of above-ground reinforced concrete structures, e.g. bridge decks, jetties, tunnel parking garages, and certain concrete buildings, a number of specific anode systems have been developed. These are applied directly onto the concrete surface and often consist of a primary and secondary anode. Theses include the following:

- **Conductive Overlay Systems**
- **Conductive Polymers**
- **Slotted Anode Systems**
- **Conductive Paints**
- **Mixed Metal Oxide Coated Titanium Mesh**

Practical Applications of Cathodic Protection

GENERAL

- The practical application of C. P. remains more of an art than a science. Why?
- Both the structure to be protected and the anode used for protection must be in both metallic and electrolytic contact.
- Forms of corrosion which can be controlled by cathodic protection include all forms of general corrosion, pitting corrosion, graphitic corrosion, crevice corrosion, stress-corrosion cracking, corrosion fatigue, cavitations corrosion, bacterial corrosion, etc.

- **Structures that are Cathodically Protected**
  - Underground and underwater.
  - Above ground (internal surfaces only).
  - Floating structures.

Type of System

- The use of an impressed-current system or sacrificial anodes will both provide satisfactory cathodic protection, but each has advantages and disadvantages with respect to the other (Table 1).
- The main anodic reactions may be summarized as follows:
  - Sacrificial anodes $M \rightarrow M^{2+} + 2e$

    Primary reactions

    Secondary reaction $M^{z+} + zH_2O \rightarrow M(OH)_z + zH^+$
  - Impressed-current anodes

$$3H_2O \rightarrow 2H_3O^+ + 2e + \tfrac{1}{2}O_2$$

and / or

$$2Cl^- \rightarrow Cl_2 + 2e$$

$$C + O_2 \rightarrow CO_2$$

or, in the case of graphite anodes:

- Sacrificial anodes are normally restricted to environments having a resistivity of <6000Ω cm there is no similar limitation in the use of power impressed system.
- In the protection of pipelines or other underground structures the actual anode is the carbonaceous backfill, and graphite or silicon-iron anodes are used primarily to make electrical contact between the cable and the backfill.

SACRIFICIAL ANODE SYSTEMS

Advantages:

- No external source of power is required;
- Installation is relatively simple;
- The danger of cathodic protection interaction is minimized;
- More economic for small schemes;
- The danger of over-protection is alleviated;
- Even current distribution can be easily achieved;
- Maintenance is not required apart from routine potential checks;
- Replacement of anodes at the end of their useful life.
- No running costs.

Disadvantages:

- Maximum anode output when first installed decreasing with time when additional current may be required to overcome coating deterioration;
- Current output in high resistivity electrolytes might be too low and render anodes ineffective;
- Large numbers of anodes may be required to protect large structures resulting in high anode installation; and replacement costs;
- Anodes may require replacement at frequent intervals when current output is high.

IMPRESSED-CURRENT SYSTEMS

- **Advantages:**
  - One installation can protect a large area of metal;
  - Systems can be designed with a reserve voltage and amperage to cater for increasing current requirement due to coating deterioration;
  - Current output can be easily varied to suit requirements;
  - Schemes can be designed for a life in excess of 20 years;
  - Current requirements can be readily monitored on the transformer-rectifier or other d.c. source;
  - Automatic control of current output or of the structure potential can be achieved.

- **Disadvantages:**
  - Possible interaction effects on other buried structures;
  - Subject to the availability of a suitable a.c. supply source or other source of d.c.;
- Regular electrical maintenance checks and inspection required; running costs for electrical supply (usually not very high except in the case of bare marine structures and in power stations where structures are often bare and include bimetallic couples);
  - Subject to power shutdown and failures.

  - Hybrid Systems
  - Offshore structures are often protected by hybrid systems using both sacrificial anodes and impressed-current.

- **Comparison of cathodic protection systems are given in Table 1**

Table 1: Methods of application of cathodic protection

	Sacrificial anode	Impressed current (power impressed)	Stray current (drained current)
Characteristics	Metal protected by sacrificial wastage of more electronegative metal	Impressed currents using transformer rectifiers or any other D.C. source	Buried structures bonded into traction system in such a way as lo receive impressed -current protect ion
Anode Materials	Magnesium, aluminum or zinc (iron for copper and copper alloys)	Carbon, silicon iron, lead-platinum, platinum platinised Titanium Platinised, niobium, scrap iron. platinum metal oxides deposited on titanium substrate	Bonded directly into stray d.c. supply
Current source	Faradic equivalent of sacrificial metal in practice the efficiency is seldom 100%	Source of low-Voltage d.c. This may be generated or drawn from transformer-rectifier fed from main supply	Drained from d.c. traction or stray-current supply
Installation	Extremely simple	More complex	Simple
Possibilities of secondary interaction in foreign structures	very improbable providing anodes properly located with respect to surface being protected	Very significant especially in built-up areas	Stray current effects are basically associated with primary power supply

Table 1 (cont.): Methods of application of cathodic protection

	Sacrificial anode	Impressed current (power impressed)	Stray current (drained current)
Application for which scheme economical	Small land based schemes and for avoidance of interaction problems. Marine structure e.g. offshore plat forms	Especially suited to large schemes	Applicable only in proximity to stray d.c. areas
Major limitation	High soil/water resistivity's and small driving e,m,f. may require a large number of anodes	Impracticable for small schemes on account of high installation costs Requires an external power source	
Potential distribution	Reasonably uniform	Varies-maximum at drainage point falling towards remote points, but not below the optimum potentials for protection, i.e. in most cases the potential -0-85 V	
Current limitation	Cannot be applied m high resistivity environments	Can be used in high-resistivity environment	

Stray Current Protection or Forced Drainage

- A metallic bond between the pipeline and the negative bus of the railway substation. (Fig. 1).

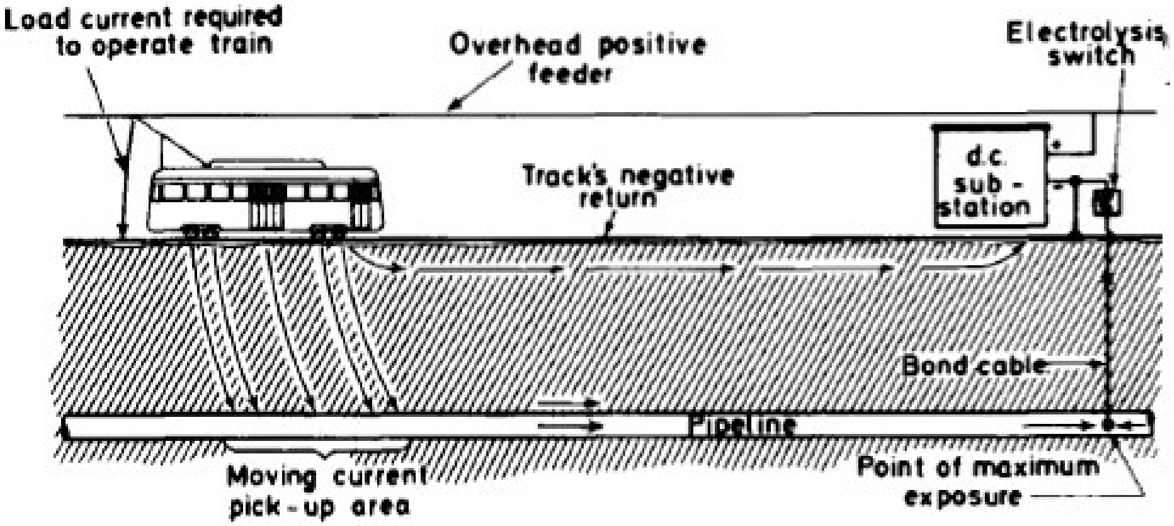


Fig.1: Bond between pipeline and d.c.

- A reverse-current prevention device or electrolyses switch is normally used at the bond.

Design of a Cathodic-Protection System

To enable an engineer to design a cathodic-protection scheme, consideration should be given to the following points (Table 2).

- Good coating

The current density required for a bare steel pipeline in average soil conditions could be up to 30 mA/m^2 whereas a well coated-pipeline would require only 0.01 mA/m^2

- **Surface Area** should include any off-takes and other metal structures in electrical contact with the main line.

- **Electrical Continuity**
- **Estimation of Current Required** (Table 3)
- Application of a temporary cathodic-protection system may be necessary to determine the amount of current required for protection, as established by the potential.
- Establishing Electrolyte Resistivity
- Economics

Table 2: Steps in design of cathodic protection installation

Sacrificial and impressed-current anodes
1. Establish soil or water resistivity
2. Estimate total current requirements which will depend on aggressiveness of like environment nature of protective coating, area of structure, materials of construction.
3. Establish electrical continuity of structure.
4. Consider requirements for electrical isolation in order to restrict the spread of protective current. Alternatively assess extra current allowance for unrestricted spread.

Sacrificial	impressed-current
5. Selected suitable anode metal; calculate total mass of metal for required life.	5. Consider the number and disposition of anodes/ground beds bearing in mind: (i) Uniformity of current distribution (ii) Proximity to available power supplies (iii) Avoidance of interaction (iv) Avoidance of mechanical damage (v) Desirability of low resistivity environment
6. Select individual anode shape to satisfy total current distribution requirements.	6. Select suitable anode martial
7. Check that total anode weight as determined by (6) will satisfy the requirements of (5).	7. Calculate anode/ground bed size shape, configuration.
8. Consider facilities for monitoring performance	8. Calculate circuit, resistance and system d.c. volts, 9. Consider facilities required for control/ monitoring

Table 3: Typical values of current requirements for steel Free from adverse galvanic influences in various environments

Environment	Current density required or adequate cathodic protection* based on superficial area (mA/m^2)
Bare steel	
Sterile, neutral soil	4.3-16.1
Well-aerated natural soil	21.5-32.3
Dry, well-aerated soil	5.4-16.1
Wet soil, moderate/severe conditions	26.9-64.6
Highly acid soil	53.8-161.4
Soil supporting active sulphate-reducing bacteria	451.9
Heated in soil (e.g. hoi-water discharge (me)	53.8-269.0
Dry concrete	5.4-16.1
Moist concrete	53.8-269.0
Stationary fresh water	53.8
Moving fresh water	
Fresh water highly turbulent and containing	53.8-64.6
dissolved oxygen	53.8-I61.4
Hot water	53.8-161.4
Polluted estuarine water	538.0-1614.0
Sea-water	53.8-269.0
Chemicals, acid or alkaline solution in process tanks	53.8-269.0
Heat-exchanger water boxes with non-ferrous tube plates and tubes	1345.0 overall
Well coated steels (pipelines)	
Soils	0.01

Impressed-Current Systems (Table 4)

- Cathodic-protection schemes utilizing the impressed-current method fall into two basic groups, dictated by the anode material:

  Group 1

  - Graphite, silicon-iron and scrap-steel anodes used for buried structures and landward faces of jetties, wharves, etc.

  Group 2

  - Platinized-titanium, platinized-niobium, lead and lead-platinum anodes used for submerged structures, ships and power stations.

Table 4 Impressed-current anodes

Material	Max working capacity A/m^{-2}		Approx. consumption (kg/A year)	
	Soil	Sea water	Soil	Sea water
Scrap steel	5.4	5.4	8.0	10.0
Silicon cast iron	5.4	5.4	6.0	8.0
Silicon iron	32	32-43	<0.1	0.1
Graphaite	11	21.5	0.25	0.5
Lead	-	107-215	-	-
Lead-platinum	-	1080	-	-
Platinum-titanium	-	<10800	-	-
Platinum		<10800	-	-
Platinum-tantalum	-	<10800	-	-
Aluminium	-	21.5	-	4.0

Soil or Water Resistivity Survey

- Soil resistivity measurements are carried out by the Wenner technique using commercially available instruments.
- In the case of a pipeline route, variations in soil resistivity may stimulate localized corrosion , the area in the soil of lower resistivity is usually anodic (more negative) compared to that in the soil of higher resistivity.
- A typical soil resistivity survey is shown in Fig. 2. It may, as a result of the survey, be considered desirable to apply protection to the whole line or to limit protection to certain areas of low soil resistivity or 'hot spots.

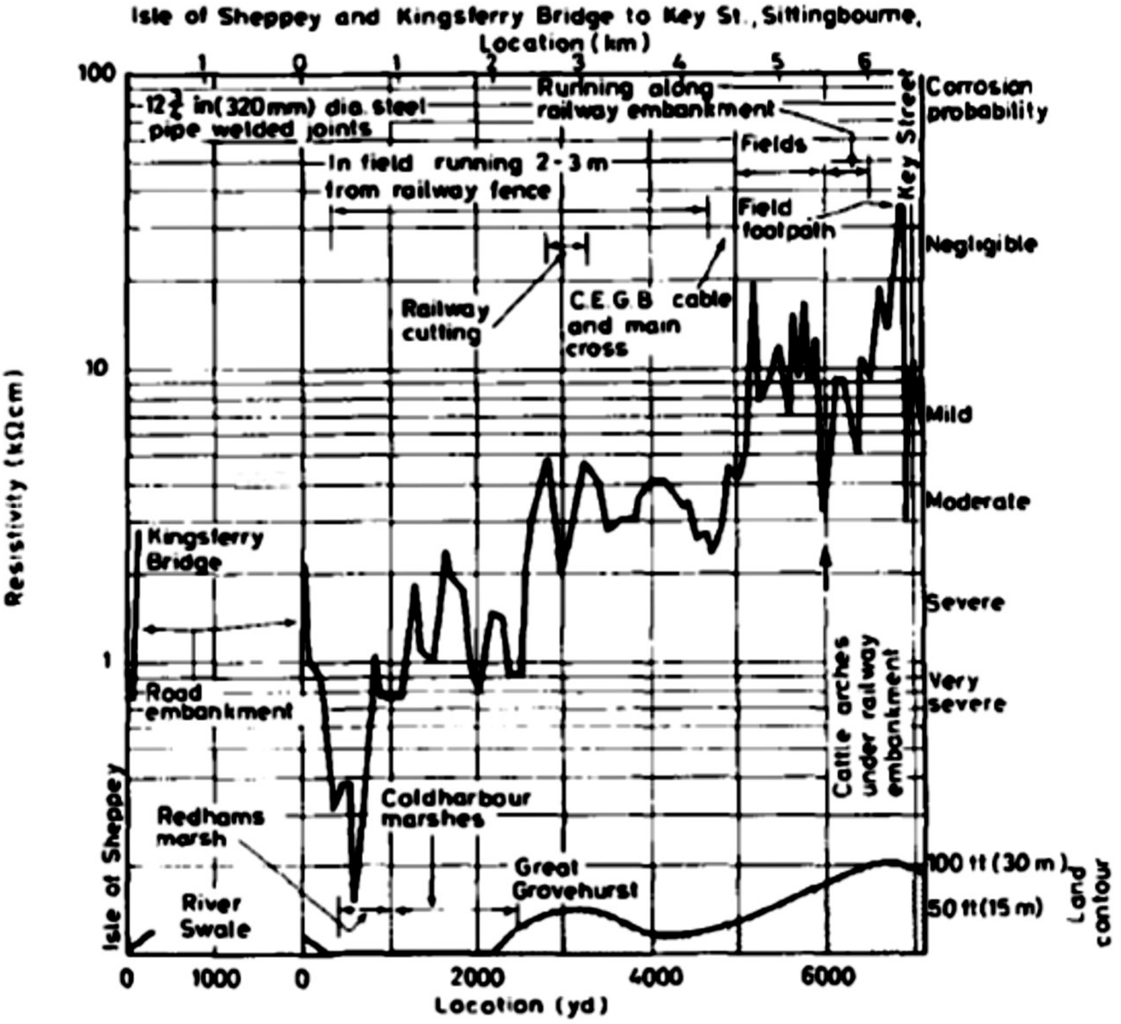


Fig. 2: Typical resistivity survey

- The cost of protecting uncoated structures is relatively high and expense may prohibit complete protection.
- In the case of high-pressure gas and oil lines, it is common practice to apply cathodic protection irrespective of the soil resistivity or coating condition.
- Soil resistivity survey is often impractical in built-up areas. In such areas impressed-current cathodic protection is usually avoided on account of the danger of interaction.

Impressed-current Design

Design steps:

- Select the current density to be applied from the results of cathodic protection tests and from any available data.
- Compute the total current requirement to achieve the required current density (total current = current density x superficial surface area).
- Design the groundbed system in accordance with procedures outlined.

- Design the d.c. wiring system for the most economical cable size in accordance with standard electrical practices and then calculate the total IR drop in the circuit.
- Select rectifier voltage and current outputs.
- Design the electrical circuits, fittings and switchgears in accordance with standard electrical practice.
- Select the location of cathodic-protection test stations.
- Prepare project drawings and specifications.

A typical installation (Fig. 5.3)

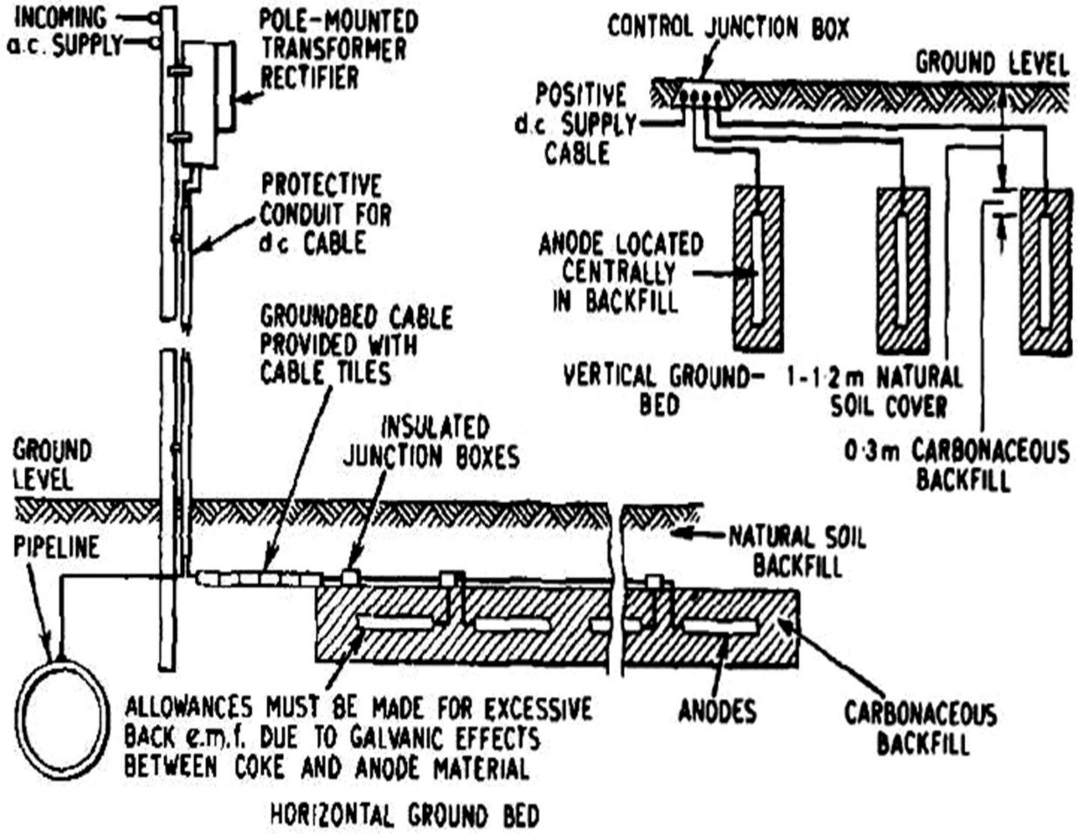


Fig. 3: Groundbeds for buried pipes using impressed current

Anode Backfill

- The carbonaceous backfill surrounding an anode is essential and serves a number of functions, e.g.:
  - Being of low resistivity it has the effect of increasing the anode size with resulting reduction in resistance to earth.
  - Most of the current is transmitted to the backfill from the anode by direct contact, so that the greater part of material consumption is on the outer edges of the backfill column enabling the anodes themselves to have an increased life.
- The backfill composition may be of several types varying from coke breeze to man-made graphite particles.

RESISTANCE OF GROUNDBEDS

- Calculated in accordance with the formula originally developed by Dwight.

Resistance of a single horizontal rod anode

$$R_H = \frac{\rho}{2\pi L}\left(\ell n\frac{4L}{d} - 1\right)$$

and

$$R_v = \frac{\rho}{2\pi L}\left(\ell n\frac{8L}{d} - 1\right)$$

Resistance of a single vertical rod anode

Where R_H is the resistance of a single horizontal anode (Ω), R_v is the resistance of a single vertical anode (Ω), ρ is the resistivity (Ωcm) of soil or backfill, L is the length of rod (cm) and d is the diameter of the rod (cm).

Where anodes are installed in special backfill, two series resistances are present – anode to backfill and backfill to soil. In practice, and with coke breeze backfill, a single calculation based upon the dimensions of the backfill column and soil resistivity is satisfactory.

$$R = \frac{\rho}{2\pi NL}\left(\ell n\frac{8L}{d} - 1 + \frac{2L}{S}\ell_n \ 0.656\ N\right)$$

Where *R*= resistance to earth (Ω) of the vertical anodes in parallel, ρ = soil resistivity (Ωcm), *N*= number of anodes in parallel, *L* = length of anode (cm), *d* = diameter of anode (cm) and *S* = anode spacing (cm).

Deep Well Ground-beds

This type of groundbed is illustrated in Fig. 4 and is normally employed where the surface soil resistivities are very high, e.g. in desert areas.

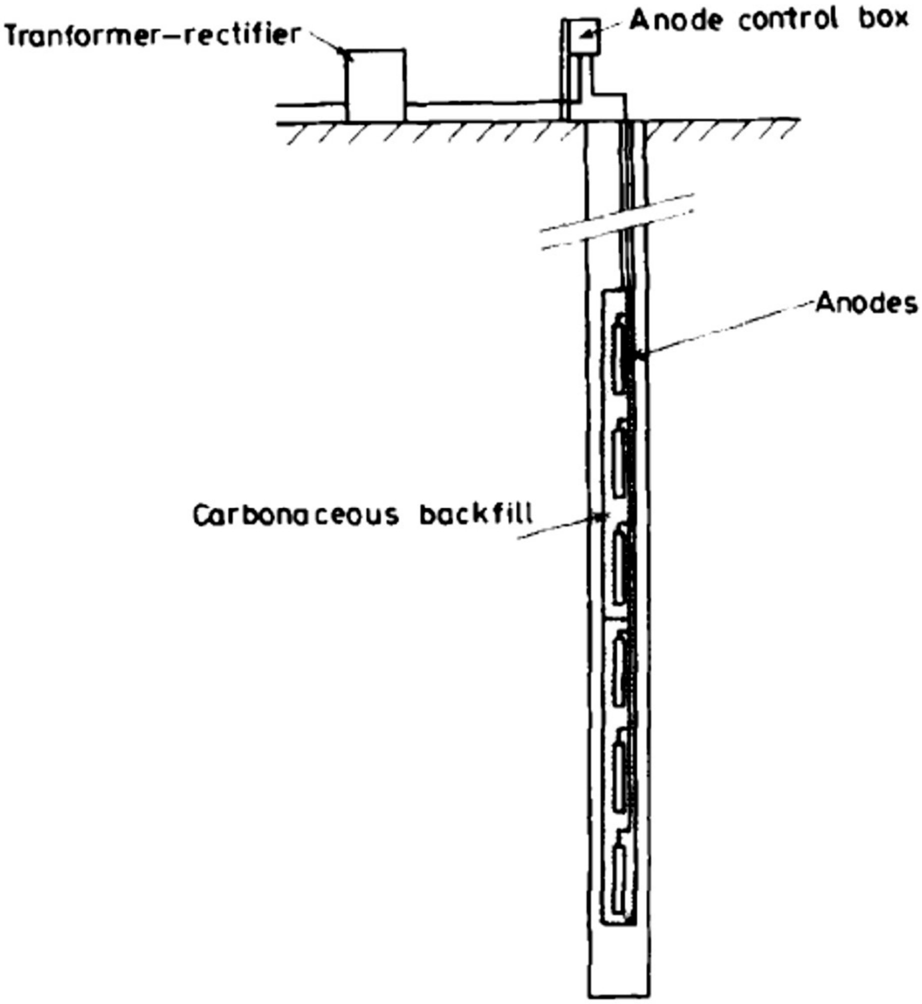


Fig. 4: Deep well installation

- **Determining Rectifier Voltage**

In determining the rectifier voltage, the following must be taken into consideration:

- Voltage drop caused by groundbed resistance, as previously explained.
- Back voltage polarization between groundbed and pipeline.
- Resistance to earth of the pipeline at the groundbed location.
- Resistance of the cable from the pipeline to the power source and from the power source to and along the comprising the groundbed.

Attenuation

- When cathodic protection is applied to an underground metal structure the greatest effect on the pipe to soil potential is at drainage point. This effect decreases, or attenuates, as the distance from the drainage point increase.

Field Measurements of Attenuation

- In order to obtain the actual field attenuation characteristics, a pipeline can be placed under temporary cathodic protection and measurements made under different cathodic-protection current conditions.
- A 'natural' pipe to soil potential survey should be made over the length of the line to which cathodic protection is to be applied.
- Fig. 5.

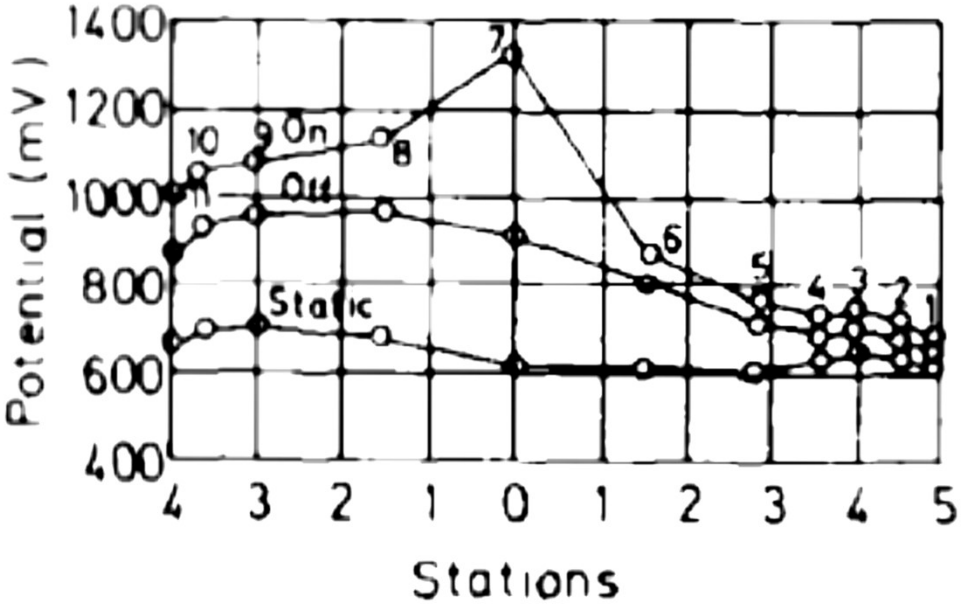


Fig. 5: Longitudinal distribution potential on pipeline

- The polarization potential and the driving voltage are then plotted on semi-logarithmic paper using the same horizontal scale (Fig. 6). Attenuation is more rapid in low resistivity soils than in high resistivity soils.

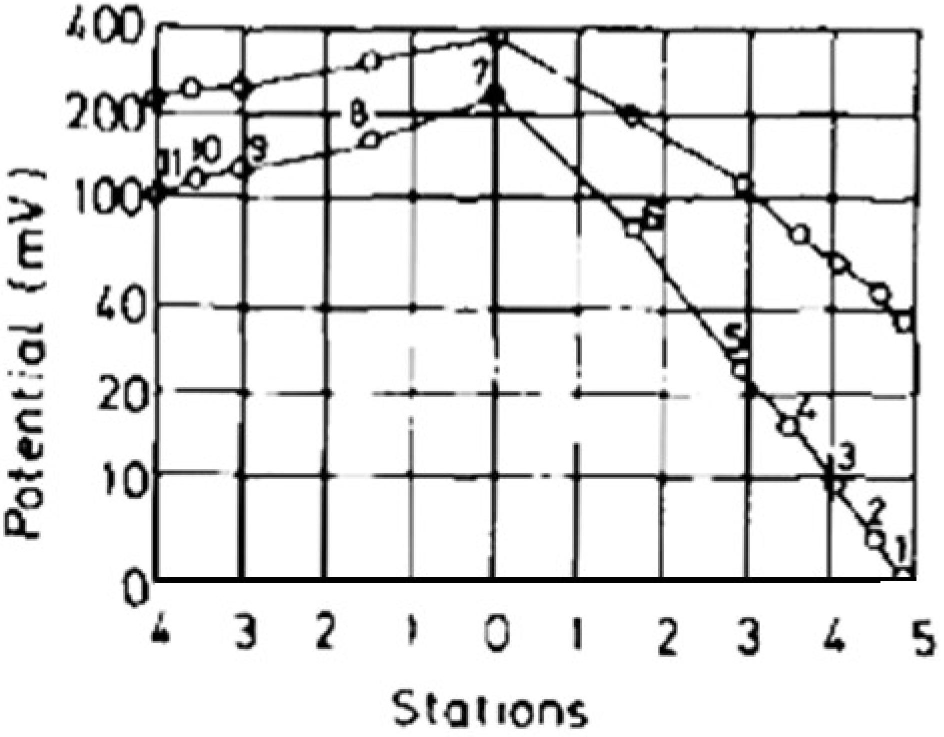


Fig. 6: Attenuation curve on pipeline shown in Fig. 5.4 Upper curve shows driving voltage lower curve the pipe/soil potential

Measurement between Drainage Points

- Figure 7 shows typical curves for a bare pipe and poorly coated pipe in similar soils, and it can be seen that the former has a much steeper attenuation curve than the latter.

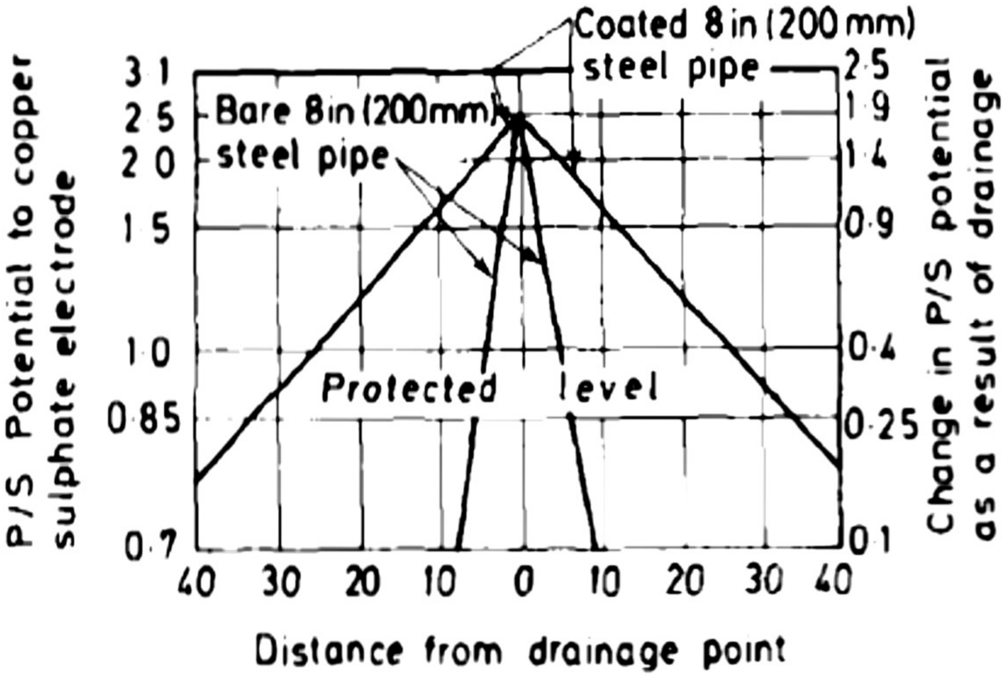


Fig. 7: Attenuation curves for bare pipe and poorly coated pipe in similar soils

- Figure 8 shows how the desired protection level of potential has been attained between widely spaced drainage points.

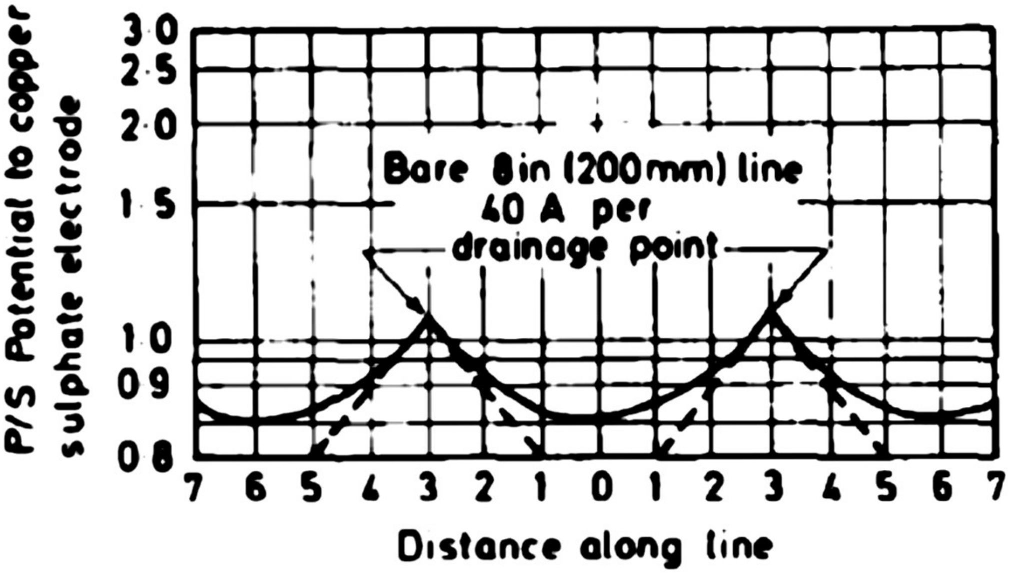


Fig. 8: Attenuation curve for multiple drainage points of moderate size

Coating Resistance

- The leakage resistance of given section of pipeline can be determined by the following procedure:
  - Applying temporary cathodic protection to the pipeline and measuring the pipe-to-soil potential for a given driving voltage of various test points spaced along the pipeline from the drainage point. The drainage current should also be measured.
  - Calculating the attenuation constant.
  - Measuring or calculating the longitudinal resistance of the pipeline. The resistance can be calculated from:

$$R = \frac{2 \rho 1}{dt}$$

Where ρ is the specific resistivity, *l* is the length of the pipeline, *d* is the diameter and *t* is the thickness in appropriate and consistent units.

- If it has been evaluated for 1000 ft of pipeline leakage resistance of the coating R_c is given by:

$$R_c = 262dR_L$$

- Where R_c is in Ω ft and d is the external diameter of the pipe (in), and R_L is the leaking resistance.

Types of Cables for Anode Installations

- Cables used for anode groundbeds must be well insulated and suited to operational conditions. Mechanical damage from sharp coke particles and chemical attack from generated gases (e.g. chlorine) may be prevented by the use of PTFE additional sleeving or a similar material.

Power sources for cathodic protection

- Where a.c. supplies exist, transformer-rectifiers are the most economical source of d.c. for cathodic protection system. They range in size from 5A, 5V for small systems to 100A, 48V for major pipeline schemes.
- Where a.c. supplies do not exist, other sources of power can be used such as d.c. generators, and either diesel or gas driven.
- Thermoelectric generators may be considered if the power requirement is relatively low.

- **Table 5**

Table 5: Thermo electric generators

Electrical characteristics				Fuel consumption		
Power (W)	Load voltage (V)	Load current (A)	Power range (W)	Propane		Natural
				Kg/h	liter/h	
9	1	9.0	8.5-10.0	0.033	0.077	0.035
15	2	7.5	14-18	0.059	0.105	0.054
28	3.8	7.3	26-32	0.082	0.191	0.1
50	6	8.3	46-60	0.136	0.322	0.2
100	12	8.3	92-120	0.272	0.636	0.4
200	6	33	188-420	0.544	1.273	0.8

Protection of Power Station or Refinery Seawater-Cooled Circulating Water Systems

a) Sacrificial Anodes

- The use of sacrificial anodes in circulating water systems is limited to the application of cathodic protection to stop gates, coarse screens and other parts that are readily accessible so that the anodes can be replaced when they are consumed.

- Such anodes are not normally used in condensers, pumps and auxiliary coolers for the following reasons:
    - Frequent replacement required with consequent shut-down of the plant concerned.
    - Anodes required to be very large to provide the current density necessary.
    - Anodes can interfere with the water flow.
    - Corrosion products from anodes can cause tube blockage and subsequent failure.

b) Impressed – Current Anodes

Anodes for the internal protection of plant are normally of platinised titanium.

1- **Continuous Anodes:** considerable lengths of relatively flexible copper-cored material contoured to suit restricted spaces or to distribute current in a localized fashion.

2- **Rod Anodes** These consist of solid or copper-cored titanium rod, portions of which can be platinised.

3- **Tubular Anodes** Tubular anodes are used where water conditions on the plant under protection are known to be turbulent.

Impressed – Current - Systems

- Impressed–current systems for power stations are somewhat more sophisticated than those required for pipelines or marine structures
- Each section of every water box in order to provide even current distribution requires one or more anodes.
- In the case of a large circulating water pump as many as 30 anodes may be required to provide the current distribution necessary. These types of system should be considered as follows:
    - Manually controlled.
    - Automatically thyristor controlled.
    - Automatically controlled modular.

- **Manually Controlled System** A manually controlled system comprises one or more transformer – rectifiers each with its associated control panels which supply the d.c. to the various anodes installed in the water box spaces.
- When coolers or condensers are shut-down but remain full of water, the amount of current required to maintain satisfactory cathodic protection is considerably reduced.
- If the current is not reduced over-protection occurs and excessive amount of chlorine can be generated causing considerable corrosion to the water boxes and possibly to the tubes.
- To ensure against this a standby condition should be included on the control panel which effectively reduces the current required under shut-down conditions.

- **Automatically – Thyristor-Controlled System** This method is basically the same as the manual system. However, the current output of the transformer – rectifier is automatically maintained at a level to ensure satisfactory cathodic protection under all operating conditions. It is also usual to fit reference (monitoring) electrodes as an independent check on the performance of sensing electrodes.
- **Automatically Controlled Modular System** This method employs one large manually controlled transformer – rectifier used in conjunction with a number of modular cabinets located adjacent to each item of plant requiring protection.

◉ Marine Structures

The method of applying cathodic protection to immersed structures will depend on several factors including:

- Size of the project.
- Availability of power supply.
- Possibility of problems from interaction.
- Necessity for safety from spark hazard.
- Expected economic life of the system.
- Fig. 9

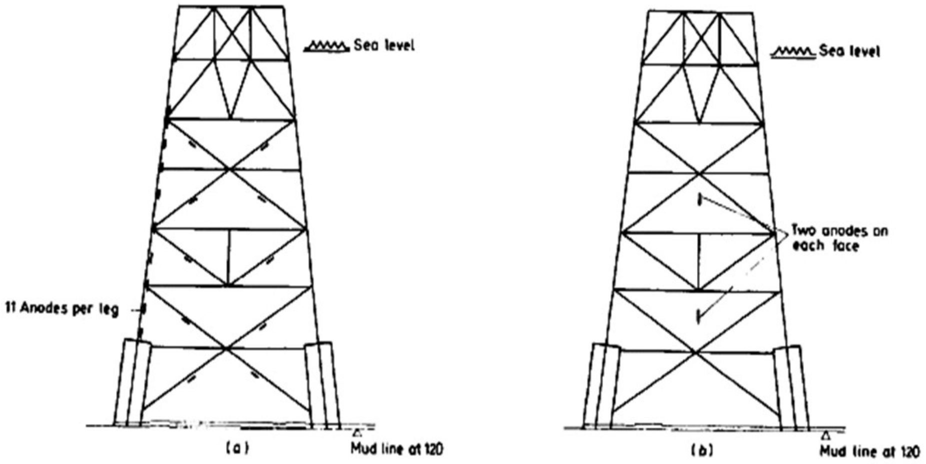


Fig. 9: Protection of offshore marine oil-drilling rig, (*a)* with external zinc (or aluminum) anodes and (b) with impressed current using platinised titanium or platinised niobium.

- Current density requirements depend on the environment, galvanic effects, velocities and other factors influencing polarization.
- Groundbeds remote from the structure can be considered but usually with this type of installation problems arise due to damage to the connecting cable by ships' anchors.

Sheet Steel Piles

- For protection of sheet-steel piling, the anodes are normally mounted within the re-entrants of the piles to prevent mechanical damage by berthing ships, dredging, etc….. (Fig. 10).

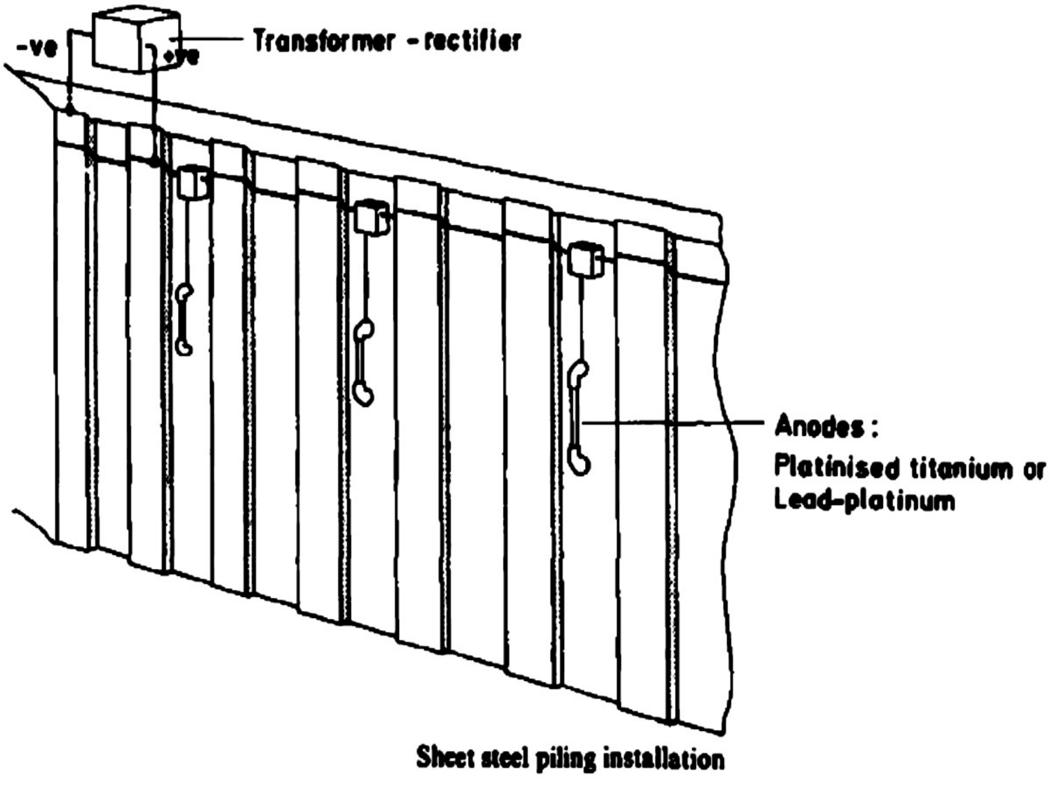


Fig. 10: Sheet steel piling installation

•Water Storage Tanks

Sacrificial anodes are of limited application due to accumulation of anode corrosion product and also in many cases, to high water resistivity.

Impressed current systems are normally based upon anodes of silicon iron, platinised titanium or platinised niobium.

Coatings are normally employed for water storage tanks which result in relatively low total current requirements in association with the current densities given in Table 3.

- **Ships**
  - Cathodic protection is effectively supplied to ships' hulls and also to the tanks of oil tankers and other vessels where seawater is used for ballast or other purposes.
  - For internal protection sacrificial anodes are normally employed of the zinc or aluminum type.
  - Impressed current is not normally used because of the potential fire hazard and also because of the anodic generation of chlorine inside closed water spaces.

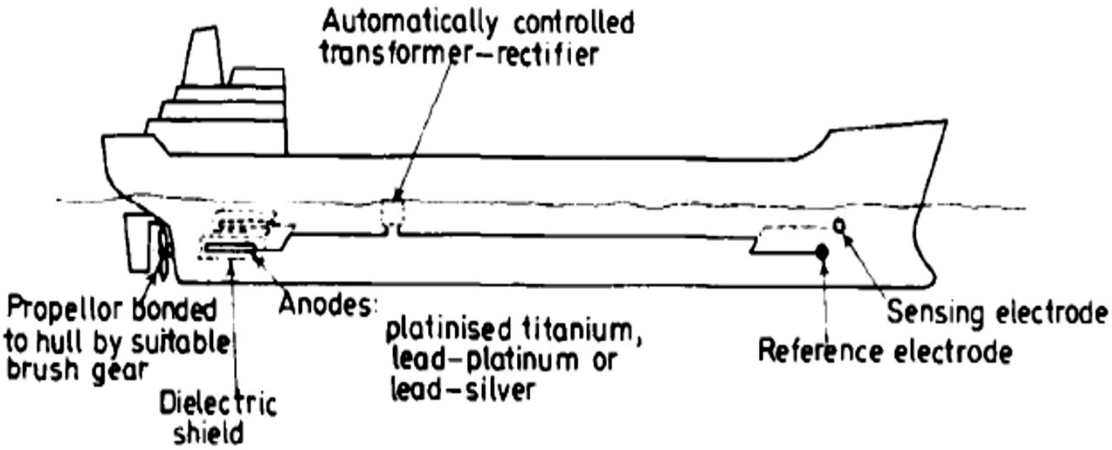


Fig. 11: Impressed current system for ships

- External hulls can be protected either by sacrificial or impressed-current methods, although impressed current is now preferred (Fig. 11).
- Anodes of platinised titanium, lead-platinum or lead, are mounted on the hull below the water line and can be designed to have current outputs of up to 200A.

Internal Protection of Pipelines

- The current spread from an internally immersed anode is directly related to pipe size and the resistivity and temperature of the water; (Fig. 12). Small bore or high resistivities and velocities further reduce the anode spacing.
- Cathodic protection is normally practicable only in large bore pipes currying salt water.

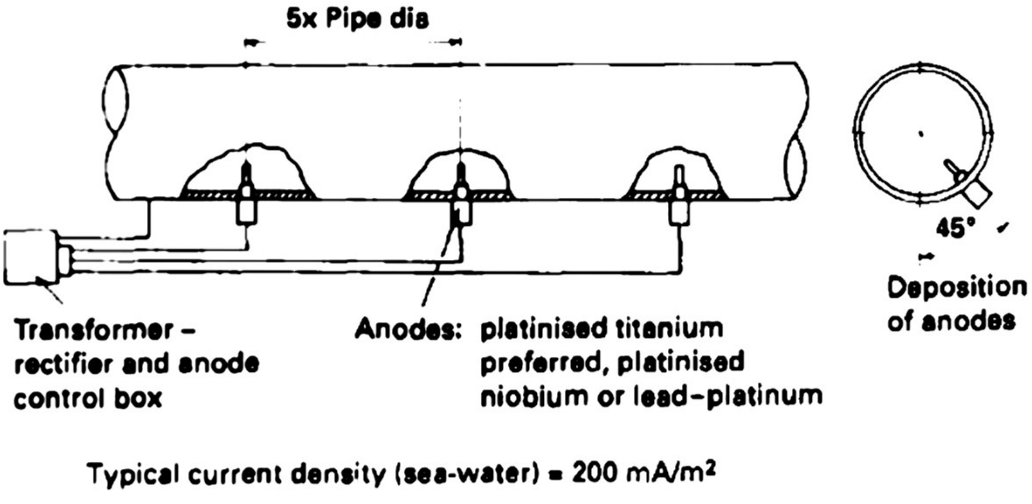


Fig. 12: Internal Protection of pipe lines

- **Economics**
- Typical cost curves plotted on a cost versus the number of anodes in a groundbed for an assumed set of conditions are shown in Fig. 13 and 14. Figure 13 is based on installation costs only, whereas Fig. 14 indicates the minimum annual cost.

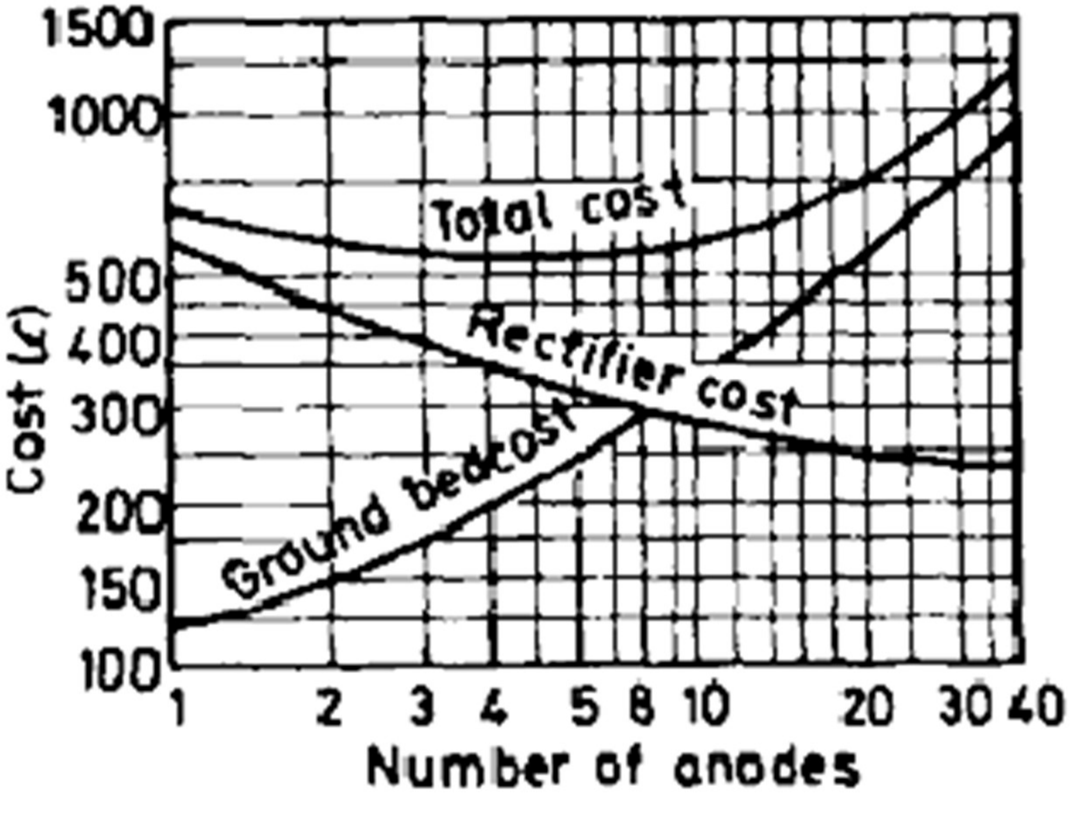


Fig. 13: Total cost in relation to number of anodes installed

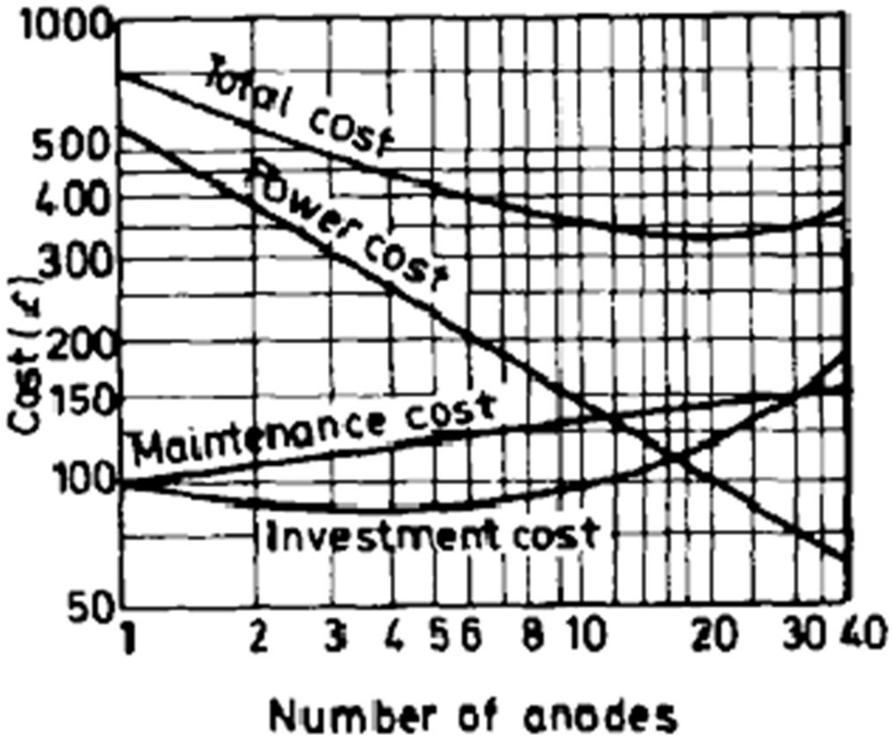


Fig. 14: Variation of minimum annual cost with number of anodes installed

STRAY- CURRENT CORRSION

If a continuous metallic structure is immersed in an electrolyte (e.g. placed in the sea or sea – bed or buried in the soil) stray direct current from nearby electronic installations, of which parts are not insulated from the soil, may flow to and from the structure

- At points where stray current enters such structure, the potential will be electrically (catholically) protected partially or completely.
- At points where stray current leaves the structure, the potential will be more positive and corrosion will occur with serious consequences.

- In practice, buried metallic pipeline or cable sheaths are liable to corrosion when direct current flows from equipment associated with electric railway traction systems; trolley vehicles or tramway systems, electricity supply systems or electric welding machines
- This type of attack is known as stray current corrosion.

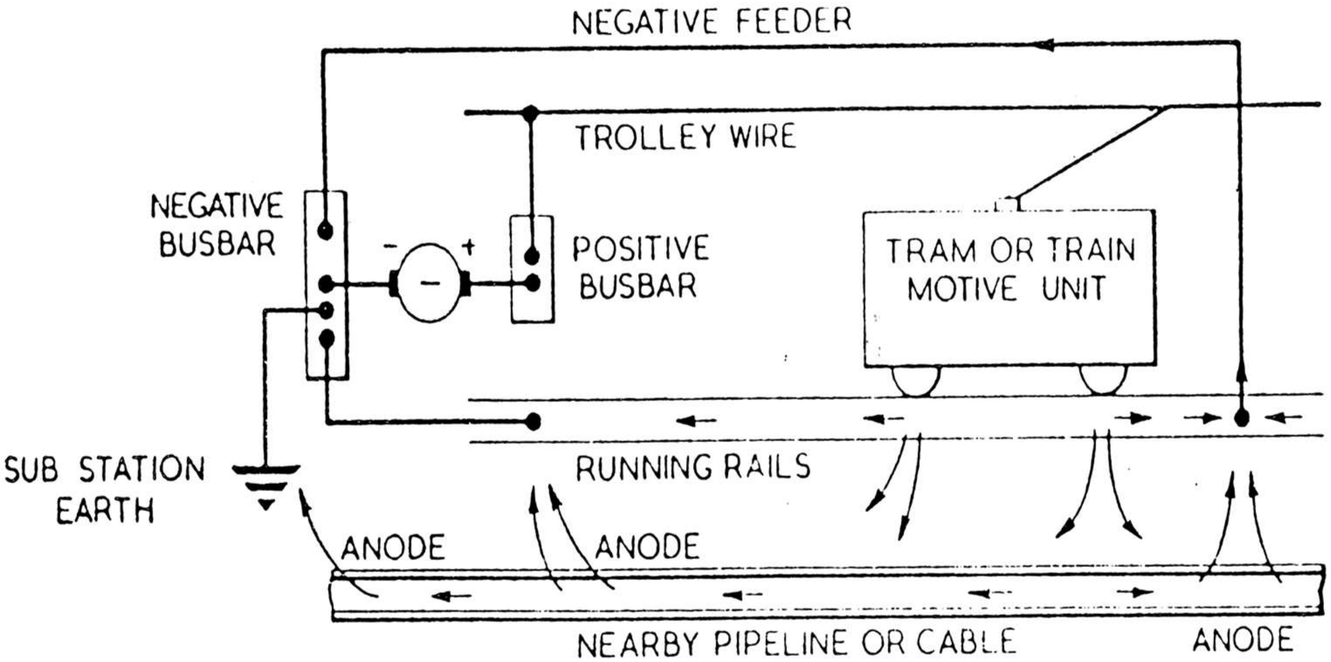


Fig.1 Stray current from d.c.traction system

Fig. 1: Stray current from d.c. traction system

Mechanism of d.c. stray current corrosion

When one vehicle of an electric train or tram is in service, there will be rapid changes in potentials and currents as the tram or train moves along the running rails.

Corrosion of the burned structure will occur at points near the substation or near the negative feeder where the stray current leaves the structure to return to the negative busbar at the substation.

- In some cases buried cables or pipes have been severely pitted by stray current corrosion in less than one year after installation.
- The potential of the soil immediately beneath the wheel may rise 10 or more volts above the normal rail potential.

There will be fluctuating potential changes in the surrounding soil. Tests in such circumstances have shown that, the potential difference between 2 reference electrodes placed in the soil about 100 meters apart near the railway will vary rapidly in amplitude and polarity and may reach peak values of 3 or 4 volts .

The most common method of estimating the order of magnitude of the current density flowing from the buried structure to the adjacent soil is to measure the potential of the pipe to nearby earth by means of a high-resistance recording voltmeter connected between the buried structure and the reference (Cu/Cu-SO_4) electrode buried in the soil close to the structure.

The natural structure / soil potential (the shutdown potential) is obtained by recording the steady – state potential attained after the system has been de-energized for at least one hour.

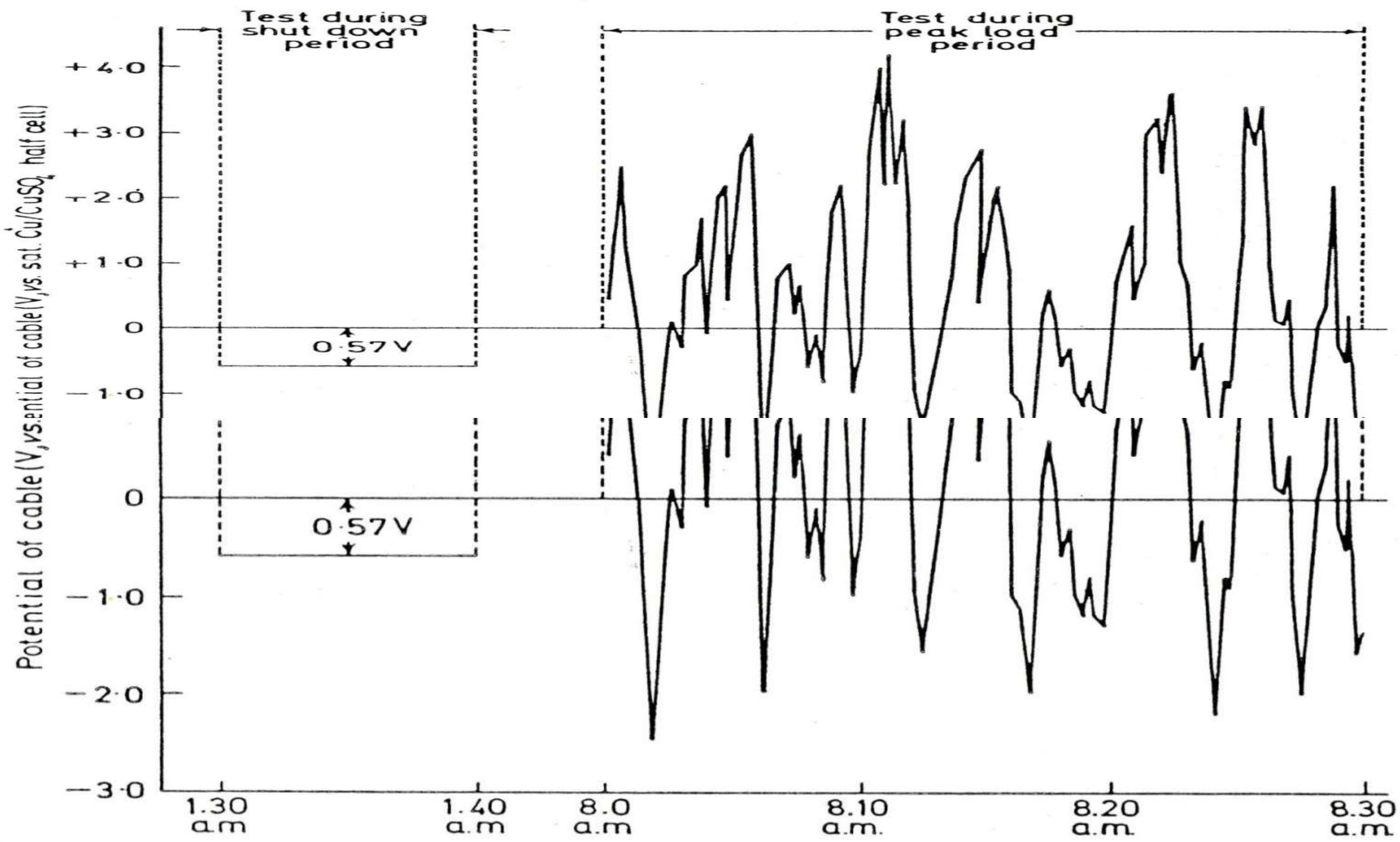


Fig. 2: variation of cable sheath potential due to stay d.c. traction currents

A.C. Stray Current Corrosion

In nearly all known cases of stray current corrosion the damage is caused by direct current, but; leakages of alternating currents at industrial frequencies have been suspected of causing corrosion of buried metallic structures.

The mechanism of corrosion caused by a.c is not yet clearly understood. The corrosion caused by a.c is much less severe compared to d.c. stray-current corrosion. At 50 Hz the corrosion caused by a.c stray current is less than 1% of that caused by equivalent d.c. stray current.

Methods of Control

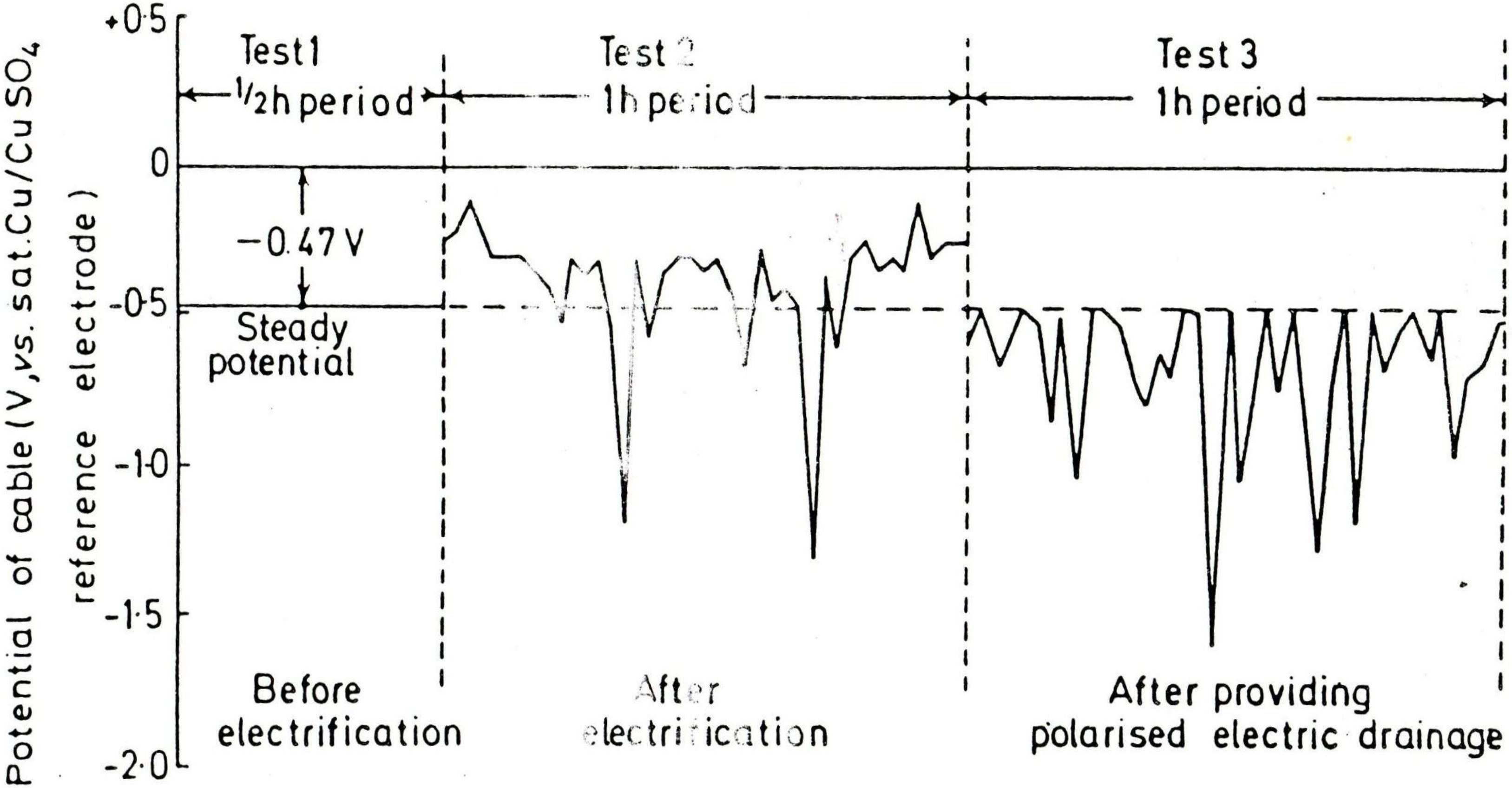
The amount of stray current from running rails should be controlled by limiting the average difference in potential between any point on the running rails and the nearest substation negative feeder bus – bar.

- Attention should be given to reducing the amount of stray current by improving the conductivity of the running rails.
- Provision for additional negative feeders and increasing the resistance to earth of running rails whenever possible (e.g. by embedding rails in bituminous materials, etc.)
- The most satisfactory way of preventing corrosion of nearby buried metallic structure is by means of drainage bonds.

Drainage bonds

- The structure is made cathodic to the surrounding soil by being connected to the negative feeders or to suitable point on the running rails.
- The connection may be direct through a resistance or similar current collecting device or through a suitable rectifying device.

The rectifier must be capable of passing a current of 1A when the potential of the structure rises about ¼ V relative to the adjacent rail e.g. lead – sheathed telephone cable.



Improvement effected by the provision of polarized electric drainage

Interrupting the longitudinal conductivity of the buried pipe or cable by means of insulating gaps or joints substantially reduces the amount of stray current picked up by the buried structure. Gaps should be located at positions where current tends to enter the structure and at points on each side of the track where the pipe or cable crosses under the rails.

- **Protection against stray current corrosion may be achieved through applying protective coating.**
- **Pipes are dipped in bituminous compounds and wrapped with glass-fiber or similar materials.**

- At pinholes or discontinuities of the coating, stray-current corrosion may take place.
- Additional protection must be applied. This includes drainage bonds or direct cathodic protection.

Cathodic protection interaction

Stray currents are produced in the electrolyte during operation of cathodic protection systems. Part of the protection current may traverse nearby immersed structures, which are not being cathodically protected.

The resultant corrosion produced on the unprotected structure is referred to as cathodic protection interaction.

The cathodically protected primary structures may be hulls of ships, jetties, pipes, etc. immersed in water or pipes, cables or tanks buried in the soil.

The nearby unprotected secondary structures subjected to interaction may be the hulls of adjacent ships, unbonded parts of ship’s hull such as the propeller blades or pipes and cables laid close to the primary structure or to the cathodic protection anode system or groundbed.

Methods of Estimating Interaction.

Two sources of interaction are considered;

a) Interaction caused by current flowing from the groundbed (the anode effect).

- A structure buried near the groundbed of a C.P system will pick up current. The current will flow in the structure in each direction away from a point close to the groundbed.

b)Interaction caused by the protection current flowing to and from the unprotected structure buried in the vicinity (structure effect).

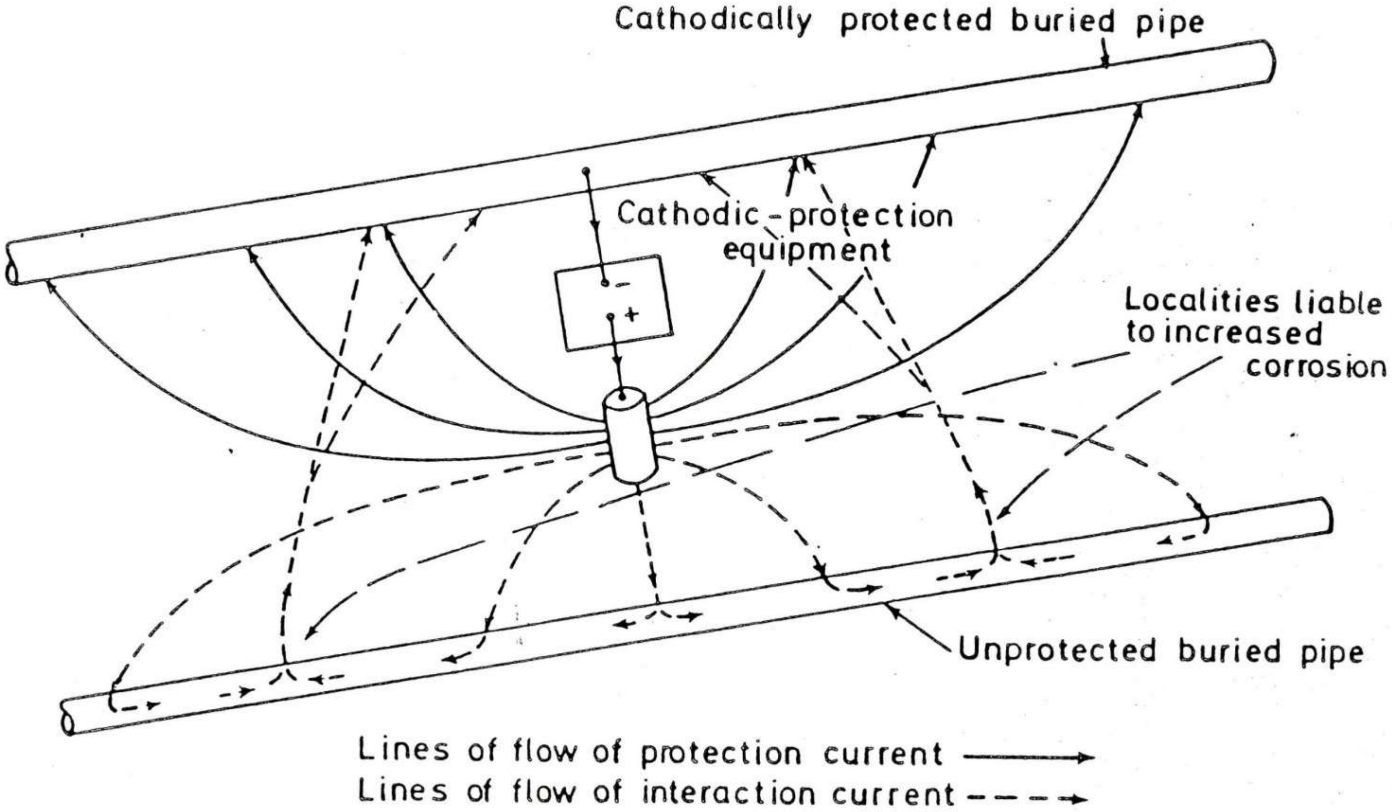


Fig. 3: Cathodic protection and interaction current with parallel pipelines.

Due to leakage of protection current through the soil between the protected structure and a nearby unprotected structure, part of the protection current may flow in a direction towards the point of connection to the C.P. equipment

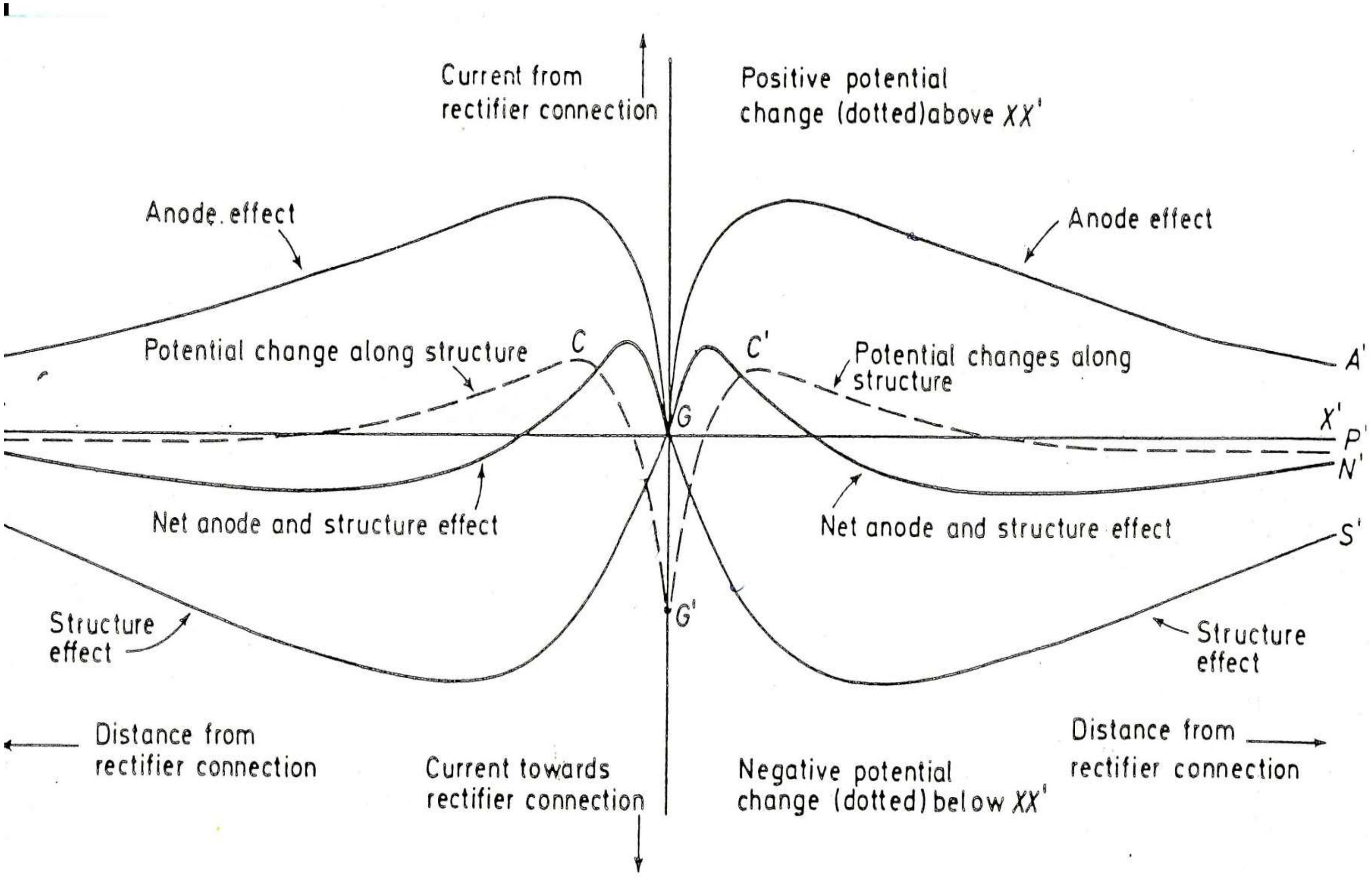


Fig. 5: Change of current and potential of an unconnected structure near a groundbed due to cathodic-protection interaction

The net effect at any point on the unprotected structure is obtained by adding together the 2 currents due to (a) and (b).

The rate at which the net current is picked up or discharged by the secondary structure will be proportional to the changes in structure / soil potential along the this structure.

- At points where current is picked up the potential change is negative and the natural rate of corrosion is decreased.
- The structure to soil potential is made more positive when the interaction current is discharged and the rate of corrosion at such points is increased.

- The maximum positive structure / soil potential occurs where the gradient of the net current curve is steepest (points – c,c’ on fig).
- If the groundbed is installed near the unprotected structure, large negative potential changes may occur on the structure at points close to the anode.

The amount of interaction caused by a protection system using galvanic anodes will be much less than that involved in case of impressed current protection system, because of the low current output from each anode. However, significant positive potential changes have been measured when the galvanic anodes are closely spaced and the distance between structures is small.

The severity of corrosion interaction will depend on the density of stray current discharged at any point on the secondary structure. This may be assessed by measuring the changes in structure/soil potential due to the application of protection current.

Potential tests should be concentrated on the portions of pipe or cable which are close to the structure to be cathodically protected where the potential change is likely to be more positive.

Experiments showed that in conditions simulating corrosion of mild steel burried in soil, a positive potential change of 20 mv produces a 2 to 3 – fold increase in corrosion rate.

Therefore, when cathodic protection is applied to a buried structure, the maximum permissible change in potential in the positive direction on a nearby structure is 20 mv. But, if there is a history of corrosion on the unprotected structure, no detectable positive change in potential is allowed. (British Standard Code of Practice for C.P).

In practice, potential change of +20 mv does not appear to cause noticeable corrosion damage even after the passage of many years, and in some countries a potential change of + 100 mv is acceptable.

In practice, potential change of +20 mv does not appear to cause noticeable corrosion damage even after the passage of many years, and in some countries a potential change of + 100 mv is acceptable.

The rate of corrosion depends on the density of the current exchanged between the structure and electrolyte. Pipe coating, cable wrapping and resistivity of the soil should be considered.

Methods of Preventing or Reducing Interaction

Interaction tests should be made on all unprotected structures in the vicinity of a proposed C.P. installation, and should be repeated annually or at any other suitable intervals.

It is most convenient if tests are made on all unprotected pipes or cables at the same time. The potential measurements should be synchronized with the regular switching on or off the protection current.

- A number of methods may be used to reduce the interaction on neighboring structures;

1) In some circumstances, it may be practicable to reduce the protection current or to resite the groundbed so that the anode effect on an unprotected structure is altered as required.
2) Increasing the physical separation between the groundbed and the buried structure (the groundbed can be installed at the bottom of deep- driven shafts).

3) The electrical resistance between structures can be increased by applying insulating wrappings.

- If the wrapping is to be applied only to sections of the unprotected pipes or cables where positive change in potential is measured, the wrapping must ensure uniformly high insulation in order to avoid localizing the corrosion attack at pinholes or similar discontinuities.

4) If the positive potential changes are very small and are confined to a few points on a small unprotected structure, it may be practicable to reduce the potential at these points by installing reactive anodes. The anodes will be most effective if they can be buried between the structures. In some circumstances, screes of Zn, Al or steel may be installed between the structures; the screen must be electrically connected to the unprotected structure.

5) If both structures have been subjected to corrosion damage, the best solution may be to install a joint cathodic protection scheme with sufficient current output to provide adequate protection for both structures.

The application of separate cathodic protection schemes for structures buried close to each other is liable to cause interaction damage because of variations in the current output on the two systems. This may be avoided by connecting the two structures together at several points.

6) In the U.K. the most convenient method of reducing interaction is to connect the unprotected and the protected structures together by means of metallic bonds. Care should be taken to ensure electrical continuity of the unprotected structure. Bonds should be connected to points on the unprotected structure where positive potential changes are maximum.

If one of the structures to be bonded is the sheath or metallic armoring of an electric cable supply, precautions should be made to ensure that the potential rise on the bond in case of instantaneous earth fault will not endanger personnel or equipment associated with other buried structures. The bond should be suitably insulated.

7) Interaction due to the use of reactive anodes can best be avoided by careful sitting of each anode during installation e.g.:

- Anodes should not be buried close to a point where the protected structure crosses an unprotected structure.
- Anodes should not be placed where unprotected structure passes between the anode and the protected structure.

Worked Examples

CATHODIC PROTECTION OF A PIPELINE

1. Cathodic Protection of a Pipeline

The cathodic protection parameters of a pipeline could be studied by using simulated model, an electrical analogue, which possesses the same electrical characteristics as an actual pipeline.

These series represent lumped parameters which are determined by pipeline diameter, wall thickness, coating resistance and soil resistivity. If these parameters could be simulated, a pipeline several hundred kilometers long could be represented by a model less than a meter long.

Calculations:

R_S is the longitudinal resistance of the pipe (Ω unit length).

R_L is the leakage resistance to remote earth of the line (Ω unit length) at the drain point

$$R_L - \frac{\Delta Eo}{\Delta Io}$$

$$\alpha - \sqrt{\frac{R_S}{R_L}}$$

α = Cathodic protection coefficient

$$R_S - \frac{\rho_S}{\pi (D - t) \quad t} \quad \Omega / m$$

r_s = Resistivity of steel.
t = Thickness of the pipeline, m.
D = Diameter of the pipeline, m.
R_K (equivalent) = $\sqrt{R_S . R_L}$

L Spread of protection = $\frac{4.6}{\alpha}\log\frac{\Delta Eo}{\Delta Em}$

$I_{prot.}$ (Protection current) = $\dfrac{\Delta Eo}{R_K + \dfrac{\rho_g}{2\pi . y}}$

ρ_g = resistivity of soil.
y = distance between anode and pipe.
$V_{prot} = I_{prot.} (R_X + R_A + R_P)$

R_P = Electrical connection resistance

Example 1

Cathodic Protection of Underground Pipeline
Pipe line length = 24.6 Km
Diameter D = 0.72 m
Thickness t = 0.011 m
ρ Steel = $1.35 \times 10^{-7}\ \Omega.m$
ρ_g (soil) = 12 Ω *m*
R_L (leaking resistance) = 442 Ω.*m*
R_P: cable resistance = 0.4 Ω
Anode Resistance (R_A) is calculated utilizing this formula =

$$\frac{0.16\,\rho_g}{nl}\left(2.3\lg\frac{4l}{r} - 1 + \frac{2l}{m}2.3\lg 0.656n\right)$$

Where:

n = number of anodes = 2
l = anode length = 1.2 m
r = anode radius = 0.15 m
m = anode spacing = 10 m

Distance between anode and pipeline y = 250m

Calculations

$$R_S = \frac{\rho_S}{\pi(D-t)\,t} = \frac{1.35 \times 10^{-7}}{3.14(0.72-0.011)\,0.011} = 0.55 \times 10^{-5}\ \Omega/\text{m.}$$

$$\alpha = \sqrt{\frac{R_S}{R_L}} = \frac{0.55 \times 10^{-5}}{442} = 1.12 \times 10^{-4}$$

$$R_K = \sqrt{R_S.R_L} = \tfrac{1}{2}\sqrt{0.55 \times 10^{-5} \times 442} = 0.025\Omega$$

R_A is calculated through applying equation 7

≅ 2Ω

$$L = \frac{4.6}{\alpha}\log\frac{\Delta Eo}{\Delta Em} = \frac{4.6}{1.2\,x\,10^{-4}}\log\frac{-0.55-(-1.2)}{-.55-(-0.85)} = 13800\ m.\ (1^{st}\ station).$$

$$I_{prot.} = \frac{\Delta Eo}{R_K + \frac{\rho_g}{2\pi y}} = \frac{-0.55-(-1.2)}{0.025 + \frac{12}{2\,x\,3.14\,x\,250}} = \quad 20\text{A}$$

Potential (V) = 20 (0.055 + 2 + 0.4) = 49 Volt.

Power (W) = IV = 20 x 48 = 960 W ≃ 1 KW.

Anode: Pb – 2% Ag.

Required System:

2 Stations, each one: 60 V, 25 A, 1500 W

Other Case Histories

1. Resistance Calculations

- The resistance of impressed current anodes buried in soil can be lowered by surrounding them with carbonaceous backfill material such as coke breeze or flake graphite. This is particularly beneficial in high resistance soils
- If the soil resistance is 10 or more times the backfill (resistivity - 500 to 1000 Ωcm), the voltage drop of anode current passing through the backfill may become negligible with respect to the voltage drop through the soil.
- Increasing the diameter and/or the length of a cylindrical anode will decrease the anode - to -"electrolyte resistance. Changes in length have greater effects than changes in diameter. Thus, the resistance of a backfilled anode is lower than that of a non-backfilled anode.
- Many engineers first measure structure - to - anode resistance by actually impressing current into installed anodes. In this way, a rectifier can be sized to fit the circuit resistance without relying on questionable test and empirical data.

1.2. Single Anodes;

$$R_v = \frac{0.0052\rho}{L}\left(2.3\log\frac{8L}{d}-1\right)$$

$$R_h = \frac{0.0052\rho}{L}\left(2.3\log\frac{4L^2+4L\sqrt{S_/^2+L^2}}{dS_/}+\frac{S}{L}-\frac{\sqrt{S^2+L^2}}{L}-1\right)$$

Where:

R_v = electrolyte - to - anode resistance (vertical)

R_h = electrolyte - to - anode resistance (horizontal)

r = electrolyte resistivity, ohm cm

L = anode length, ft
d = anode 'diameter, ft
S = twice the depth of anode, ft

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

K is the shape function representing the anode length to diameter ratio. (Table 1).

1.3. One-row vertical anode group

For group of vertical parallel anodes equally spaced:

Where:

R_n is the total anode - to - electrolyte resistance, ohms
n is the number of anodes.

rr is the soil resistivity, Ω cm.
P is the paralleling factor, (Table 2).
For more than "one row

1.4. Vertical and Horizontal Anode Groups - Simplified

These formulae are used:

$$R_v = \frac{\rho F}{537}, \; R_h \frac{\rho F}{483}$$

R_v, is the electrolyte - to - anode resistance, any number of anodes to a remote reference, Ω.

R_h, is the electrolyte - to - anode resistance, any number of horizontal anodes to a remote reference, Ω.

r: electrolyte resistivity Ω cm.

F: adjusting factor for groups of anodes (Table 3).

Example 2: Cathodic Protection System for Steel Storage Tanks.

An impressed current c.p. system is being designed to stop corrosion on the bottoms of several large diameter steel tanks in contact with the soil:

Given the following information:

* 17 high silicon C. I. anodes (1.5 inch diameter, 60 inch long) shall be installed vertically in coke breeze backfill.

* Anode spacing: 20 ft apart.

* Backfill: 8 ft length, 10 inch diameter.

* Average soil resistivity (ρ) = 4500 Ω Cm at anode depth.

Calculate the soil to anode resistance after installation.

Solution:

As the anodes are to be installed around the periphery of tanks, a single row configuration is assumed, consult Table 1 for the shape function K.

$$\frac{L}{D} = \frac{8}{10/12} = 9.604$$

Then from (Table 1), K for $\left(\frac{L}{D} = 9.604\right) = 0.0175$

$$R_v = \frac{\rho}{L} K = \frac{4500}{8} \, x \;\; 0.0175 = 9.844 \, \Omega$$

Then for the total of one – row of 17 anodes

$$R_n = \frac{1}{n} R_v + \rho \rho \frac{P}{S} = \frac{1}{17} \, x \, 9.844 + 4500 \, x \, \frac{0.00150}{20}$$

= 0.579 + 0.338 = 0.917 Ω

= Total resistance between all anodes and soil

Example 3 Cathodic Protection of a Pipeline

- Impressed current C.P. system.
- Anodes are 1.5 in diam. , 60 in. Long, (Space permits 3 anodes only)
- Horizontally arranged, backfield with coke breeze, 10 Ft length X 1 ft^2 C.S., 6 ft below ground, 10 ft apart
- C.P. unit must supply a current of 5 A to protect the pipeline.
- Soil resistivity = 12000 Ω cm. at a depth of 6 ft.

Calculate rectifier voltage.

SOLUTION

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

As F (From Table 9.3) = 0.460

$$R_h = \frac{1200 \ x \ 0.460}{483} = 11.4252$$

∴ From Ohm's Law

E = IR = 5 x 11.42 = 57.10 v

∴**The rectifier must produce 58 V**

Example 4: Use of Zinc Sacrificial Anodes to Protect a Pipe Pile Structure

- A pier structure 20 ft. wide extending 150 ft. from shore consists of 16 in diam. steel pipe piles that support the pier deck. The piles will be driven so that 14 ft. Will be in the soil zone, 18 ft. In the submerged zone, 3 ft in the tidal zone and 5 ft in the atmospheric/splash zone (Fig-9.1).
- The salt water resistivity = 25 Ω cm. and the steel piles are coated with 16 mil dry-film of coal tar epoxy. Cathodic protection is applied in the form of sacrificial anodes.

Solution

- Calculation of steel areas exposed to specific zones:

area = p DLh

D = diameter of pile (ft)

L = length of pile in specified zone

h = number of piles

* In atmospheric/splash zone:

$$= \pi \text{ x} \frac{16}{12} \text{x } 5 \text{ x } 16 = 335 \text{ ft}^2$$

* *In* tidal zone:

$$= p \text{ x} \frac{16}{12} \text{x } 3 \text{ x } 16 = 201 \text{ ft}^2$$

* *In* submerged zone:

$$= p \text{ x} \frac{16}{12} \text{x } 18 \text{ x } 16 = 1206 \text{ ft}^2$$

- *In* soil zone: $= p \text{ x} \frac{16}{12} \text{x } 14 \text{ x } 16 = 938 \text{ ft}^2$
  - Current requirements for calculation (Table 4).

- Tidal Zone :

Assuming 10% coating damage during installation:

Area of bare steel = 0.1 x 201 = 20 ft^2.

Current required polarizing bare and coated steel

= 20 x 35 + 181 x 5= 1.6 A

- **Submerged Zone**

Assume 15% damage during installation.

Current requirements:

To polarize: = 1206x0.15x 35+120 x 0.85 x 5= 11.4 A

To Maintain = 1206 x 0.15 x 10 + 120 x 0.85 x 1.5 =3.3 A

- **Soil Zone**

Assume 50%. Coat damage pile driving operations

Current requirements:

To polarize = 938 (0.5 x 5 + 0.5 x 1 = 2.8 A

To Maintain =938(0.5 x 1.5 + 0.5 x 0.5) = 0.9 A

Total Current Requirements for the Entire Structure

To Polarize = 1.6 + 11.4 + 2.8 = 15.8 A

To Maintain =1.6+3.3+0. = 5. 8 A

The Total Current Required Maintaining Protection as Coating Deteriorates:

Calculate the expected current requirements after 20 years service, assuming coating deterioration at a rate of 2% per year.

- **Tidal Zone**

Intact coating after '20 years

= 90% initial - 40% deterioration = 50%

Maintenance current requirements

= 201 (0.5 x 35 + 0.5 x 5) = 4.0 A

- Submerged Zone

Intact coating after 20 years = 85% - 40% = 45%

Maintenance current requirements

= 1206 (0.55 x 10 + 0.45 x 1.5) = 7.4 A

- Soil Zone

- **Soil Zone**

Assume no coating deterioration, current requirements remain the same

$$= 0.9A$$

Total current requirements to maintain protection of entire structure in the tidal, submerged and soil zones after 20 years

$$=4+7.4+0.9 \qquad = 12.3A$$

Anode Design Calculations:

Average total current to maintain protection of the entire structure for 20 - year life:

$$= \frac{\text{initial current (after polarization)} + \text{final current}}{2} = \frac{2.8+12.3}{2} = 9.1A$$

Total weight of high purity zinc anode material required for 20 year life expectancy:

Where $W = \dfrac{CR\ x\ L\ x\ ATC}{E\ x\ U}$

W = Total weight in pounds

CR = Consumption rate, lb/Ay

L = Life, years

ATC = Average Total Current, A

E is the efficiency factor, U is the utilization factor

$$W = \frac{23.585\ x\ 20\ x\ 9.1}{0.9\ x\ 0.85} = 5611\ Ib$$

- Based on the structure description and the amount of zinc required, it can be determined that for this structure: 8 Strings of *2* (390 lb each) Anodes (10 x 10 x 15 in) zinc anodes (6240 lb).
- Suspended at locations shown in (Fig. 11) should afford adequate protection for 20 - year life expectancy
- The other factor to consider: is the amount of current that can be discharged from anodes:
  - ⊙ Resistance of the Anode System:

The diameter of cylindrical objects whose circumference = 40 In. is 12.73 In. or 1.06 ft.

anode spacing = 25 ft

The resistance of one 390-Ib anode is:

The resistance of one 390-Ib anode is:

$$R_v = \frac{0.0052\rho}{L}\left(2.3\log\frac{8L}{d}-1\right) = \frac{0.0052\, x\, 25}{(15/12)}\left(2.3\log\frac{8\, x\,(15/12)}{1.06}-1\right) = 0.129\Omega$$

The resistance of the anode system, R_S

$$R_S = \frac{0.0052\rho}{L}\left(2.3\log\frac{8L}{d}-1+\frac{2L}{S}\, x\, 2.3\log 0.656n\right) = \frac{0.0052\, x\, 25}{8\, x 2x(15/12)} x25$$

$$\left(2.3\log\frac{8\, x\, 2\, x\,(15/12)}{1.06}-1+\frac{2\, x\, 2\, x\,(15/12)}{25}\, x\, 2.3\log 0.656\, x\, 8\right) = 0.0147\,\Omega$$

Anode output = $\frac{E}{R}$

Where

E is the driving potential and R is the resistance of the anode system to the electrolyte.

Driving voltage of galvanic zinc anode to <u>Polarized Coated</u> steel is of the order of 0.0 V.

Driving potential = 1.1 - 1.0 = 0.1 V

Current available after polarization: I = 0.10 / 0.0147 = 6.8 <u>A</u>

The 6.8 A output after polarization is greater than the 5.8 A required for the total current requirements given above. Therefore the current requirement is satisfied

To verify, that life expectancy is met:

Average total current output for 20 year life= $\frac{6.8+12.3}{2}$

= 9.6A

Total weight of anode material required:

$$W = \frac{23.585\, x\, 20\, x\, 9.6}{0.90\, x\, 0.85} = 5919\ 1b$$

The total weight of the anode material used is

8 x 2 x 390 = 6420 1b

Therefore, the life expectancy is satisfied.

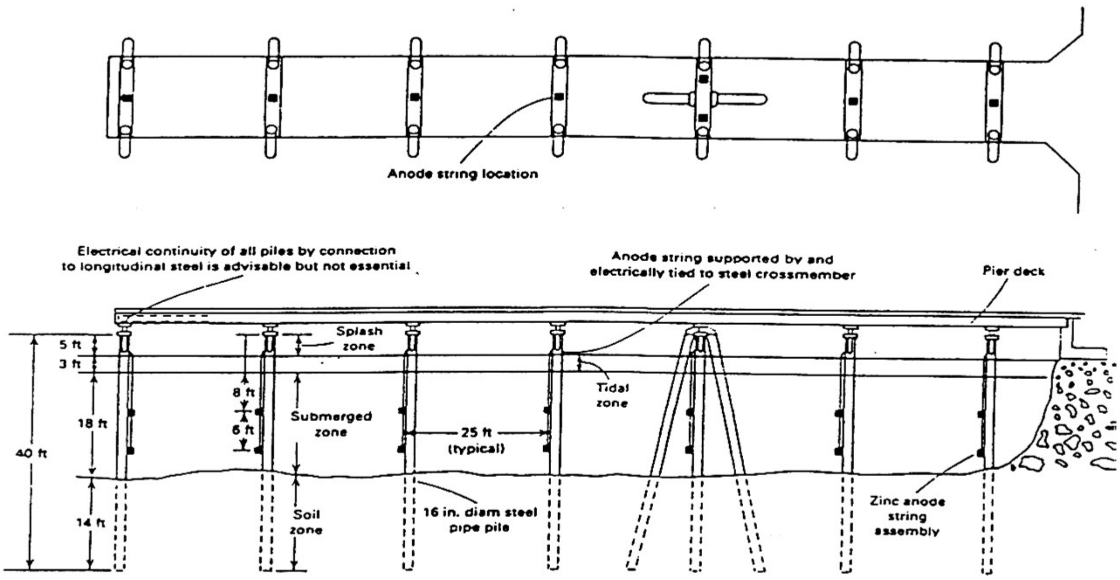


Fig. 1: Protection of a steel pipe pile pier with a protective coating and zinc sacrificial anodes

Table 4: Current Densities Required for Coated and Uncoated Steel in Moving and Stagnant Sea Water and Soil Areas

Environment	Current Density, mA/ft^2			
	Bare Steel		Coated Steel	
	To Polarize	After Polarization	To Polarize	After Polarization
Moving Sea Water	30 - 35	7 - 10.0	3 – 5.0	1.0 – 1.5
Stagnant Sea Water	15 - 25	4 - 07.0	1 – 3.0	0.5 – 1.0
Soil Zone	4 - 5	1 - 1.5	0.5 – 1.0	0.1 – 0.5

Example 5: Use of Impressed - Current Anodes to Protect an H-Pile Structure

- A 30 - ft. wide pier structure that extends 200 ft. from shore is supported by 20 H - piles 'that are 92 ft. long. The H - piles are connected in four - pile clusters by W shapes. The piles are to be driven so that 50 ft. will be below the dredged mud line, 30 ft. in the submerged zone, 4 ft. in the tidal zone and 8 ft. in the atmospheric/splash zone (Fig…..).
- The pier is located in a saltwater bay in a highly commercial and industrial area. There are commercial, industrial, chemical, and sewage pollutants'. The average resistivity is 30 Ω cm. The H-piles (coated 'with I0-mil dry film) is to be cathodically protected, for a life expectancy of 20 years.

Solution

- Calculation of Steel Areas

The 10 cross braces and the 20 vertical H- piles have a surface area of 8 ft^2, per linear foot.

*** Area in atmospheric splash zone:**

= L n A

= 8 x 20 x 8 = 1280 ft^2

*** In tidal zone:**

= 4 x 20 x 8 = 640 ft^2

*** In submerged zone:**

Piles = 30 x 20 x 8 = 4800 ft^2

Cross braces= 30 x 10 x 8 = 2400 ft^2

Total = 4800 + 2400 = 7200 ft^2

*** In soil zone: = 50 x 20 x 8** = 8000 ft^2

- **Current Requirement Calculations :**
- Table 4 shows that a greater amount of current is initial required to polarize the structure and bring it to protect levels than is required to maintain these levels.

- Tidal Zone

- Assume 5% coating damage during installation, the current required:

To polarize=640 (0.05 x 35 + 0.95 x 5) =4.1A

Which is the current required for maintaining protection.

•Submerged Zone

Assume 5% coating damage, then the current required:

To polarize 7200 (0.05 x 35 + 0.95 x 5) = 46.8A

To maintain = 7200 (0.05 x 10 + 0.95 x 1.5) = 13.9A

- **Soil Zone**
  - Assume coat is 40% intact
  - Current required:

To polarize = 8000 (0.6 x 5 + 0.4 x 1.0) = 27. 2 A
To maintain = 8000 (0.6x1.5+0.4 x 0.5) = 8.8 A
Total current requirements
I pol. =4.1+46.8+27.2 = 78.1A
I prot. =4.1+13.9+8.8 = 26.8 A

The final current requirements are calculated for the 20 - year life expectancy assuming: 2% per year coating deterioration in the tidal zone, 1% in the submerged zone, and 0.5% in the soil zone.

Then, the final current requirement after 20 years would be:

Tidal Zone :
= 640 (0.45 x 35 + 0.55 x 5) = 11.9 A
Submerged Zone ;
= 7200 (0.25 x 10 + 0.75 x 1.5) = 26.1 A
Soil Zone :
= 8000 (0.7x1.5 + 0.3x0.5) = 9.6 A

Then, total current required to maintain protection of the entire structure at the end of the 20 - year period:

= 11.9 + 26.1 + 9.6 =47 .6 A

Anode Design Calculations

The anode material is high silicon cast iron, consumption rate = 0.75 Ib/AY.
Average total current required for 20 - year life:

$$= \frac{\text{initial current} + \text{Final Current}}{2} = \frac{26.8 + 47.6}{2} = 37.2\text{A}$$

Total weight of anode material $W = \frac{CR\ x\ L\ ATC}{E\ x\ U}$

In impressed current systems, the efficiency factor E = 100% compared to 90% for sacrificial anodes.

$$W = \frac{0.75\ x\ 20\ x\ 37.2}{0.50} = 1116\ Ib$$

The total number of anodes will be determined by taking into consideration the water depth, number and spacing of piles, amount of current available from each anode for a uniform consumption and current distribution to the structure. For this structure, twenty 2-in. diam. x 60 in. long anodes with enlarged heads have seen chosen, the anodes are to be hung in ten strings of two anodes each. The top of the upper anode is to be 5 ft. below the mean low/water level (MLW) and the top of the lower anode will be 15 ft. below MLW (Fig.2).

Resistance of anodes (ground bed resistance):

The resistance of one vertical anode (anode-to-electrolyte) **is:**

The resistance of the anode system:

(Vertical anodes in parallel) is:-

$$R_v = \frac{0.0052\rho}{L}\left(2.3\log\frac{8L}{d} - 1\right) = \frac{0.0052x30}{60/12}\left(2.3\log\frac{8x(60/12)}{2/12} - 1\right) = 0.140\Omega$$

$$R_S = \frac{0.0052\rho}{nL}\left(2.3\log\frac{8L}{d} - 1 + \frac{2L}{S}x2.3\log 0.656n\right) = \frac{0.0052x30}{10x120/12}\left(2.3\log\frac{8x(120/12)}{2/12} - 1 + \frac{2x(120/12)}{20}x2.3\log\right) = 0.011\Omega$$

DC Circuit Cable Resistance:

The circuit of a rectifier system consists of one or more anode header cables that run from the rectifier positive terminal to the anodes. Current from the anodes flows from the electrolyte and is collected on the structure. A negative return cable then returns this current to the rectifier negative terminal. The cable size must be large enough to carry the current to avoid excessive voltage drop.

- For this installation a no. 4 A.W.G. (American Wire Guage) copper wire is adequate.

Cable resistance =

- The voltage drop in this wire, with the rectifier at the shore end of the pier will be as follows:
- Voltage drop = wire resistance x current

Where:-

$$\text{Cable resistance} = \left(\frac{\text{header cable length}}{2} + \text{neaative return length Cable resist} \right)$$

The header cable length is divided by 2 because the total current is not flowing through the entire length of cable. The current is being dropped off in equal amounts at equal distances. The wire unit resistance is 0.000254W / ft

$$\text{Circuit cable resistance} = \left(\frac{200}{2} + 20 \right) x\ 0.000245 = 0.0305\ \Omega$$

Voltage drop = 0.0305 x 78.1 A
= 2.38V

Total DC Circuit Resistance;

This is the total of the following:

- anode-to-electrolyte resistance
- circuit cable resistance
- structure-to-electrolyte resistance (negligible)

Total resistance = 0.011 + 0.0305 = 0.0415 W
Voltage required = 78.1 x 0.0415 = 3.24 V
Add V for anode back voltage = 5.24 V
Allow 20% for stack aging = 1.05V
Rectifier voltage required = 6.29 V
Rectifier output required = 6.29 V, 78.1A
Closest available rectifier = 8 V dc 80 A dc

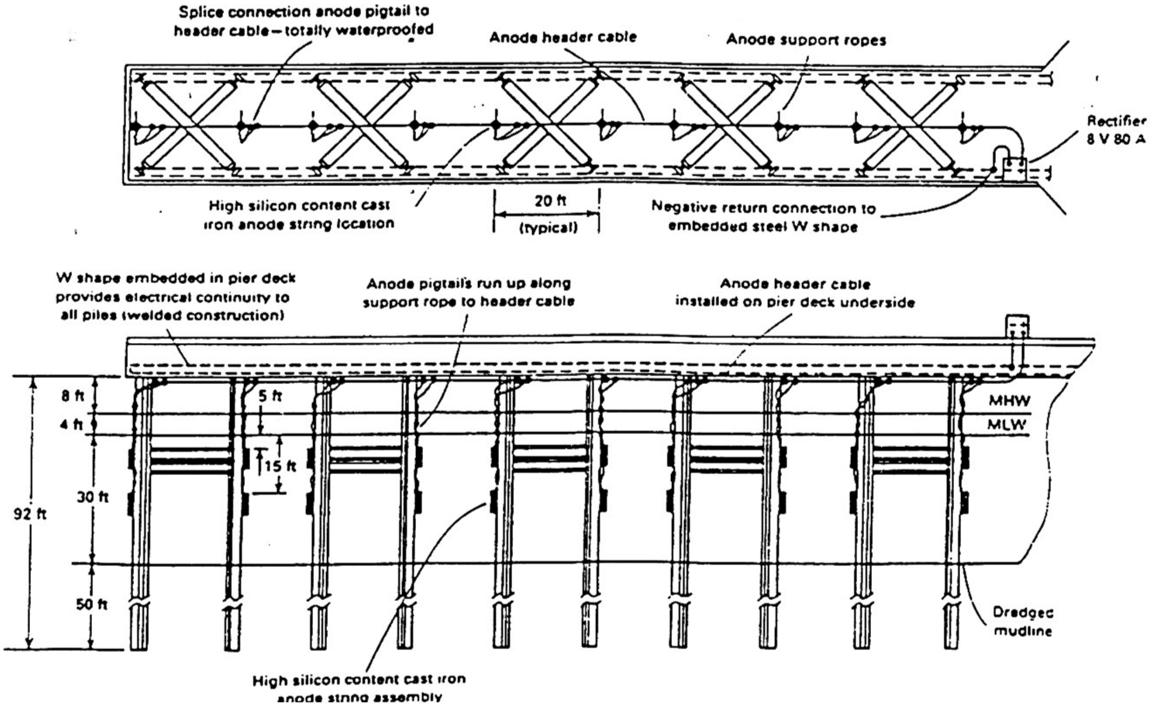


Fig. 2: Protection of H-pile steel pier structure using a protective coating and high-silicon cast iron impressed-current anodes

Example 6: System Design for an Offshore Platform

- ***The following is a sample of an offshore cathodic protection design procedure. The platform is in the Gulf of Mexico, and the design parameters, which are similar to other Gulf platforms, include the following:***
- Maintenance current density: 5 mA/ft^2
- Design life: 20 years.
- Calculated surface area: 33.484 ft^2 (water zone) and 47.984 ft^2 (mud zone).
- Anode capacity: 1280 A h/lb
- Safety factor: 25%
- Water resistivity: 20 Ω cm
- Assumed anode parameters: 725-lb net aluminum weight; 8ft long; 90.25 in^2 cross-sectional area.

Given these numbers, the total current in the water zone and the mud zone can then be calculated:

$$Current_{water} = \frac{(5\ mA/\ ft^2)\,(33\,484\ ft^2)}{1000} = 167.4\ A$$

$$Current_{mud} = \frac{(5\ mA\ /\ ft^2)\,(47\,984\ ft^2)}{1000} = 239.9\ A$$

The next step is to evaluate the total weight, TW, of the anode material required:

$$TW_{water} = \frac{(167.4\ A)\ (8760\ h/yr)\ (20\ yr)\ (1.25)}{(1280\ A\ h/bl)} = 28\,461\ lb$$

$$TW_{mud} = \frac{(239.9\ A)\ (8760\ h/yr)\ (20\ yr)\ (1.25)}{(1280\ A\ h/lb)} = 41\,045\ lb$$

At this stage, the number of anodes needed in each section, N can be evaluated:

$$N_{water} = \frac{28\,641\ lb}{725\ lb\ /\ anode} = 39.5$$

$$N_{mud} = \frac{41\,045\ lb}{725\ lb\ /\ anode} = 56.6$$

$$N_{total} = 40\ + 57 = 97\ anodes$$

A total number of 97 anodes are needed to pre-polarize the steel or to provide the initial current density. The initial current density must be at least 160 mA/ft^2) to ensure the buildup of an adequate calcareous deposit on the steel members. The total initial current output per anode is calculated by using a potential of 0.45V between bare, un-polarized steel (-0.60 V) and aluminum (-1.05 V) and anode resistance calculated from Dwight's equation (Eq. 1) for a single cylindrical anode, because experience show no significant interference between the various numbers of multiple anode design:

Where *L* is the anode length in inches, p is 3.14159, *p* is water resistivity in Ω cm, and *R* is equivalent radius in inches.

For anode shapes other than cylindrical:

$$R = \sqrt{\frac{cross - \mathrm{sec}tional\ area}{\pi}}$$

In this case, the anode has a trapezoidal cross section, and the equivalent radius is calculated by using Eq 2, as follows:

$$R = \sqrt{\frac{90.25}{\pi}} = 5.36\ in.$$

Equation 1 can now be used to calculate the anode resistance:

$$= \frac{20\,\Omega\,cm}{2\,\pi\,(96\,in.)}\left[\ln\left(\frac{4\,(96\,in.)}{5.36\,in.}\right)-1\right]\left(\frac{1\,in.}{2.54\,cm}\right)=0.0427\,\Omega$$

Next, the initial current output, I, of the anode is determined:

$$I\ =\frac{\Delta E}{\text{Resistance}}$$

Where, DE is the potential difference (0.45 V), and the resistance=0.0427 Ω

$$I=\frac{0.45\,V}{0.0427\,\Omega}=10.54\,A$$

The initial structure current density is determined as follows:

$$Current\ density=\frac{(10.54\ A/anode)\,(97\ anodes)}{33\,484\ ft^2}=0.0305\ A/ft^2\ =30.5\ mA/ft^2$$

A current of 328 mA/m^2 (30.5 mA/ft^2) is considered to be an adequate current density for the buildup of a calcareous deposit, which leads to a satisfactory polarization of steel.

Fully polarized steel develops a potential more negative than -0.80 V versus the Ag/AgCl reference electrode and will therefore establish a potential drop of 0.20 to 0.25 V versus aluminum anodes. Use of the 0.20 to 0.25 V potential drop for Ohm's law and calculation of the anode resistance with Dwight's equation (Eq.1) based on anode dimension at 40 to 50% consumption will then result in a maintenance current density that is roughly one-half the value of the calculated initial current density. Therefore, if the steel is polarized to -0.80 V versus Ag/AgCl, the current output of the anode is (according to Eq. 3).

$$I\ =\frac{\Delta E}{\text{Resistance}}$$

Where DE = 1.05 V -0.8 V = 0.25 V, and resistance = 0.0441 Ω (The derated anode radius based on a 10% reduction of the initial radius).

$$I=\frac{0.25\,V}{0.0441\,\Omega}=5.6\,A$$

The actual potential drop between structural steel cathodic and aluminum anodes at some time after launching of the platform is estimated as the difference between the given aluminum versus Ag/AgCl potential and the average of polarized steel potentials as measured with Ag/AgCl reference electrodes at various locations of the structure. The true current output per anode is therefore available for predicting the life of the cathodic protection system given the capacity of 330 kg (725-lb) ***aluminum anodes, namely:***

$$Life = \frac{(1280\ A\ h/lb)\ (725\ lb/anode)}{(8760\ \text{h/yr})\ (\text{I A/anode})}$$

Which leads to the life in years for I amps of current output per anode as follows:

$$Life = \frac{106}{\text{I (A/anode)}}$$

Based on a current output per anode of 5.6 A, the design life of the cathodic protection system is:

$$Life = \frac{106}{5.6} = 18.9\ years$$

The required design life is 20 years, so another anode geometry should be chosen. Suppose that the new anode has the following anode characteristics: length = 10 ft (120 in.), radius = 6 in., weight = 1135 lb, and anode capacity = 1280 A h/lb. ***The total number of anodes needed, based on the surface areas of the water and mud sections, is:***

$$N_{water} = \frac{28\,641\,lb}{1135\,lb/anode} = 25.2$$

$$N_{mud} = \frac{41\,045\,lb}{1135\,lb/anode} = 36.2$$

$$N_{total} = 26 + 37 = 63\ anodes$$

The resistance of one anode using Dwight's equation (Eq-1) is:

$$= \frac{20\,\Omega\,cm}{2\,\pi\,(120)}\left[\ln\left(\frac{(4)\,(120)}{(6)}\right) - 1\right]\left(\frac{1\,in.}{2.54\,cm}\right) = 0.03532\,\Omega$$

$$I = \frac{0.45\ V}{0.03532\ \Omega} = 12.74\ A$$

The structure initial current density is now evaluated and is equal to:

$$Current\ density\ = \frac{(12.74\ A/anode)\ (63\ anodes)}{33\,484\ ft^2} = 0.0239\ A/ft^2 = 23.9\ mA/ft^2$$

The initial total current output / based on a potential drop of 0.45 V and using Eq 3 is:

An initial structure current density of 257 mA/m^2 (23.9 mA/ft^2) is acceptable. A more conservative design will allow for a higher number. Next, the anode resistance is calculated using Eq 12 and based on a de-rated radius of 5.4 in. (a 10% reduction).

$$\text{Resistance} = \frac{20\,\Omega\,cm}{2\,\pi\,(120)}\left[\ln\left(\frac{(4)\,(120)}{(5.4)}\right) - 1\right]\left(\frac{1\,in.}{2.54\,cm}\right) = 0.03642\,\Omega$$

Using potential on a current of 6.86 A, A the design life in years of the cathodic protection system is:

$$Life\ = \frac{(1280\ A\,h/lb)\ (1135\ lb/anode)}{(8760\ \text{h/yr})\ (6.86\ \ \text{A/anode})} = 24.2\ years$$

Therefore, the design is acceptable.

Type of System

- The use of an impressed-current system or sacrificial anodes will both provide satisfactory cathodic protection, but each has advantages and disadvantages with respect to the other (Table 1).
- The main anodic reactions may be summarized as follows:
  - Sacrificial anodes

    Primary reactions $M \rightarrow M^{Z+} + ze$

    Secondary reaction $M^{z+} + zH_2O \rightarrow M(OH)_z + zH^+$
  - **Impressed-current anodes** $3H_2O \rightarrow 2H_3O^+ + 2e + \frac{1}{2}O_2$

and / or

$$2Cl^- \rightarrow Cl_2 + 2e$$

or, in the case of graphite anodes:

$$C + O_2 \rightarrow CO_2$$

- Whereas sacrificial anodes are normally restricted to environments having a resistivity of <6000Ω cm there is no similar limitation in the use of power impressed system.
- In the protection of pipelines or other underground structures the anode reaction is dependent on diffusion of water to the anode surface and oxygen and CO_2 away from it, and since these processes do not occur with the same mobility as in water it is necessary to use a very large surface area of anode and a corresponding low current density. For this reason the actual anode is the carbonaceous backfill, and graphite or silicon-iron anodes are used primarily to make electrical contact between the cable and the backfill.

Table 1: The shape function, k, obtained by dividing the anode length by the anode diameter

L/d	K
5	0.0140
6	0.0150
7	0.158
8	0.0165
9	0.0171
10	0.0177
12	0.0186
14	0.0194
16	0.0201
18	0.0207
20	0.0213
25	0.0224
30	0.0234
35	0.0242
40	0.0249
45	0.0255
50	0.0266
55	0.0270
60	0.0270

Table 2: Paralleling Factor Used for Determining Anode Resistance

n	p
2	0.00261
3	0.00289
4	0.00283
5	0.00268
6	0.00252
7	0.00237
8	0.00224
9	0.00212
10	0.00201
12	0.00182
14	0.00186
16	0.00155
18	0.00145
29	0.00135
22	0.00128
24	0.00121
26	0.00114
28	0.00109
30	0.00104

Table 3: Adjusting Factor, F, for Parallel Anodes

Number of Anode in Parallel	Adjusting Factor,			Anode Spacing ft	
	5	**10**	**15**	**20**	**25**
2	0.652	0.576	0.551	0.538	0.530
3	0.586	0.460	0.418	0.397	0.384
4	0.520	0.385	0.340	0.318	0.304
5	0.466	0.333	0.289	0.267	0.253
6	0.423	0.295	0.252	0.231	0.218
7	0.387	0.265	0.224	0.204	0.192
8	0.361	0.243	0.204	0.184	0.172
9	0.332	0.222	0.185	0.166	0.155
10	0.311	0.205	0.170	0.153	0.142
11	0.292	0.192	0.158	0.141	0.131
12	0.276	0.180	0.143	0.132	0.122
13	0.262	0.169	0.139	0.123	0.114
14	0.249	0.160	0.131	0.116	0.107
15	0.238	0.152	0.124	0.109	0.101
16	0.226	0.144	0.117	0.103	0.095
17	0.218	0.138	0.112	0.099	0.091
18	0.209	0.132	0.107	0.094	0.086
19	0.202	0.127	0.102	0.090	0.082
20	0.194	0.122	0.098	0.86	0.079
22	0.182	0.114	0.091	0.079	0.073
24	0.171	0.106	0.085	0.074	0.067
26	0.161	0.100	0.079	0.069	0.063
28	0.152	0.094	0.075	0.065	0.059
30	0.145	0.089	0.070	0.061	0.056

Reference electrodes used for cathodic protection system in offshore structures

Type of Electrode	Protection potential of steel, V
Ag/AgCl	-0.80 (or more negative)
Cu/CuSO4	-0.85 (or more negative)
Zinc	+0.25 (or more positive)

Energy characteristics of materials used for sacrificial anodes

Material	Energy capacity; Ay/Kg	Consumption rate Kg/Ay
Al-Zn-Hg	2750-2840	3.1-3.2
Al-Zn-In	1670-2400	3.6-5.2
Al-Zn-Sn	925 - 2600	3.4-9.4
Zinc	81	10.8
Magnesium	1100	7.9

Consumption rates of impressed-current anode materials

Material	Typical Anode Current Density		Consumption Rate Per AY	
	A/m^2	A/ft^2		
Pb-6Sb-1Ag	160-200	15-20	0.045-0.09 kg	(0.1-0.2 1b)
Pt (plated on substrate)	450-1080	50-100	0.006 g	
Pt (wire or clad)	1080-4500	100-500	0.01 g	
Graphite	10.8-40	1-4	0.225-0.45kg	(0.5-1.0 1b)
Fe-14Si-4Cr	10.8-40	1-4	0.225-0.45kg	(0.5-1.0 1b)

CASE STUDY(1)

Cathodic Protection Design for 1,900 Miles (3,050 Km) of High-Pressure Natural Gas Pipeline

General

The main pipeline runs from northwest Alberta, Canada to just south of Chicago, Illinois. Pipelines from British Columbia and Alberta feed gas into the main pipeline. A systematic approach to the design was undertaken. A computer analysis of the Cathodic Protection (CP) attenuation and voltage gradients was made. An analysis of subsurface geology was conducted for deep-anode groundbeds. This article discusses the systematic design process used for the CP application.

Project Start:

A route survey: soil conditions, subsurface geology, locations of electrical transmission lines…etc

Pipeline runs parallel (20m) to another cathodically protected line for most of the route.

Concerns over parallel high voltage (HVAC) transmission line were approached.

Attenuation and voltage gradient calculations were made: rectifier spacing and distance between pipelines and anodes.

Pipeline Route (Fig.1)

Extends from Fort St. John, British Colombia Canada to south of Chicago, Illinois (USA).

In Canada ~ 1559 km.

In USA: 1499 km.

Facility: high pressure line (12 MPa) ~35.4 million cubic meters per day.

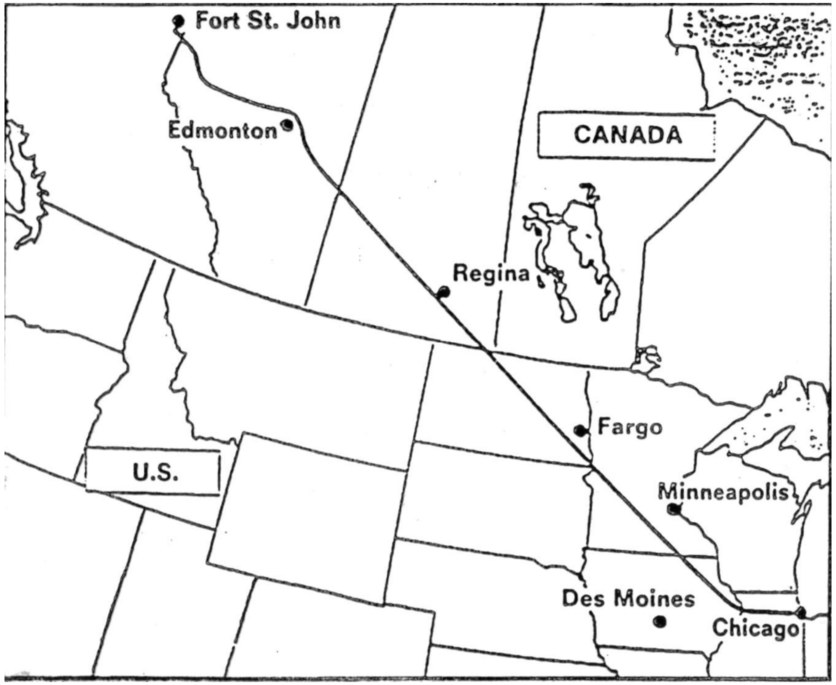


Fig. 1: Pipeline Route

Initial Evaluation

Design Phase Concerns

- Close proximity to parallel pipelines.
- Crossing of foreign pipelines.
- Crossing of two HVDC transmission lines in the US.
- Effect of HVAC line in Canada and the US.
- Soil conditioning along pipeline route.
- Subsurface geology along route (deep anode beds).

Paralleling and Crossing Pipelines

The parallel line (20m away) runs for 2285 km and other parallel lines run for short distances.

Discussions with representatives of the other pipelines, so as cathodic interference would be minimal.

HVDC Transmission Line Crossings

The pipeline crosses two bipolar HVDC lines.

Earth return only occurs in cases of pole breakdown or during maintenance.

The closest pipeline comes to any earth electrode at ~80 km.

Previous tests showed that at this offset distance, even at full earth return of ~1000 A, effects on buried pipeline would be minimal.

Soil Conditions

Soil data taken at 1.6 km intervals in the US (resistivity, pH, chlorides and sulphates).

In Canada: resistivity taken adjacent to proposed groundbeds, power line crossings and existing foreign groundbeds.

In Canada resistivity 1000-2000 □ cm.

In the US: 8000-10000 □ cm.

Surface Geology (Lithology)

As there was insufficient space at compressor stations and mainline block valve sites for surface groundbeds, deep anode groundbeds were needed.

Data bases that designate state were accessible in the US and Canada.

Design Analysis

- Good quality coating and high soil resistivity decrease attenuation.
- From the beginning of the pipeline to the Mississippi river, low soil resistivities make attenuation a significant factor.
- In the high resistivity soil of Illinois attenuation becomes less significant.
- Main pipeline is coated with Fusion Bonded Epoxy (FBE) and the long term coating resistance was taken as 20% of the initial coating resistance to allow for coating deterioration.
- The analysis led to selecting a current requirement of ~39.1 mA/km for the new pipeline and~197 mA/km, for long term requirement.
- Verification on the coat quality and current requirement was made through tests 151 km of newly installed, 610 mm diameter line in Canada.
- Voltage attenuation graphs indicated that placing a rectifier every 32 km would provide a reasonably smooth voltage profile. *This would*:
    - ❖Minimize over protection and stresses on the coating near the rectifiers.
    - ❖Minimize stray current effects on nearby foreign pipelines.
- Initial DC output of each block valve rectifier ~1.5 A.

Voltage Gradient Analysis

- A maximum of P/S potential of 1.2V is decided with permissible excursions of 1.5V where unavoidable.
- Voltage gradient calculations (Fig. 2) with groundbed located. 63.5 m from pipeline, an anode gradient of 0.2V would occur in a 1000 □-cm soil, and a 0.4V for 2000 □-cm soil.
- These values were considered suitable to minimize the impact on the P/S potentials, so deep groundbeds were designed to be 70 m from the pipeline.
- At compressor stations, there were sufficient rooms for groundbeds to be at the desired distance from the piping, still be situated on-site. As a result, the anode bed could install closer to the ground surface than at block valves.
- The main line block valve sites were small, so deep groundbeds (70m) could be used.

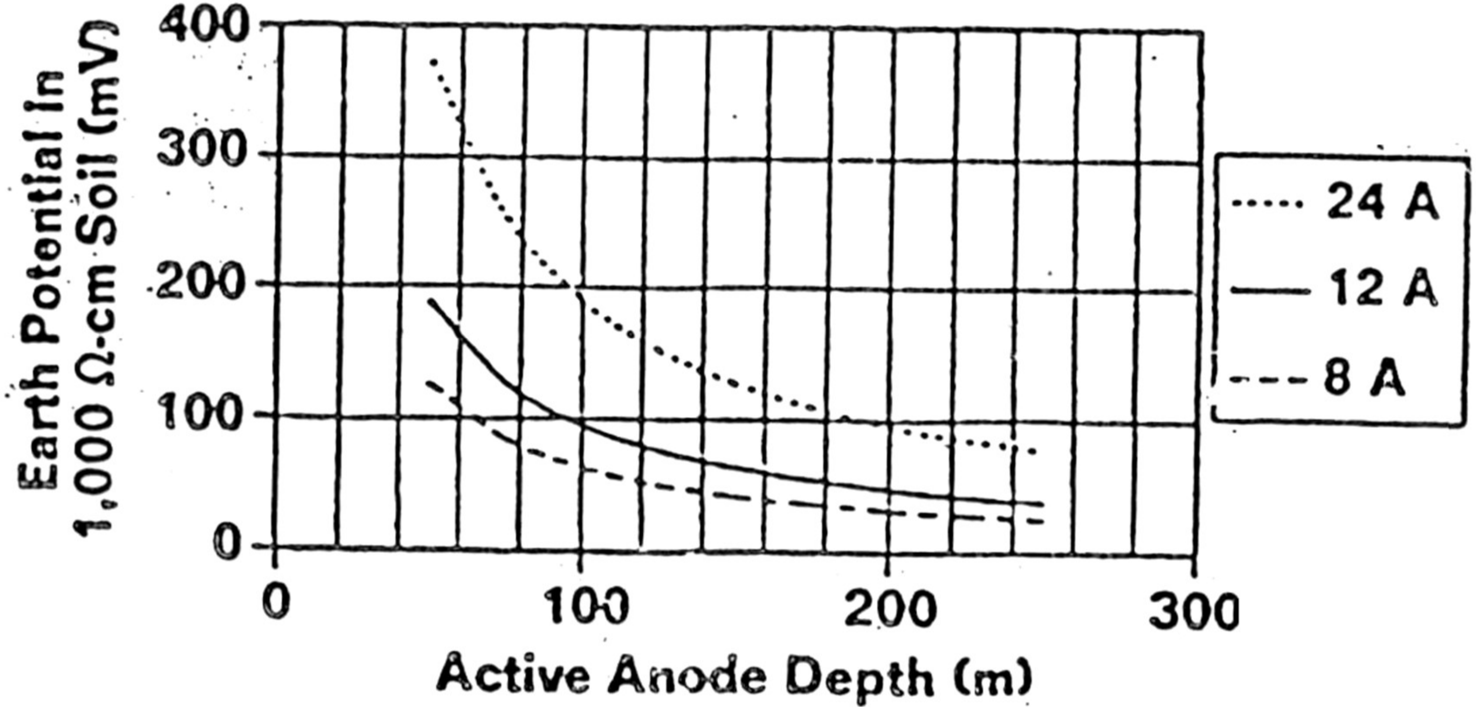


Fig. 2:Earth Potential Increase at the Pipeline from a Proximate Deep-Anode Bed

Compressor Stations Sites

- The pipeline is electrically continuous with the compressor station to minimize electrical isolation maintenance.
- Compressor station underground structure: gas, vent, air, and instrumentations lines, and a small amount of AC grounding using insulated conductors and galvanized groundbeds.
- There are steel foundations piles at 7 stations in Canada and 2 in the US.
- Current requirement for steel piling ~5.3 mA/m^2.
- Typical current requirement for compressor stations without steel piles = 18 A, with steel piles = 30 A.

Horizontal Directional Drilled Crossing

- The pipeline is installed under several rivers and major highways using Horizontal Directional Drilling (HDD).
- Two concerns:
  - ❖Effect of pulling the tubes on the coat;
  - ❖Few HDD crossing where the pipes would not be tied into adjacent sections until the second year of construction.
- For the first concern: measure coat conductance before typing pipe into mainline adjacent sectors.
- For the second concern: design a temporary CP system using anodes (Fig. 3).

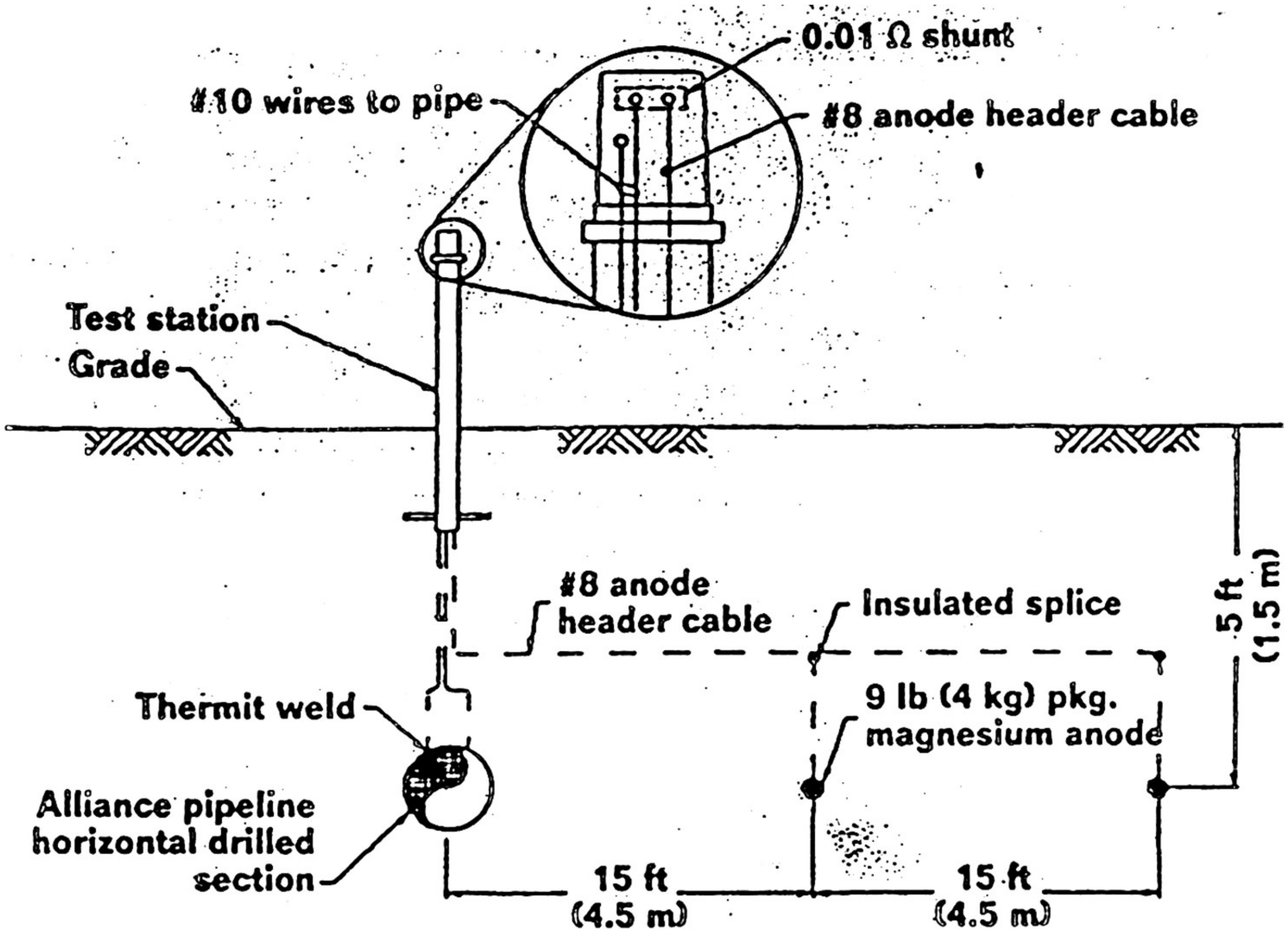


Fig. 3:Temporary Magnesium Anode CP for Horizontal Directional Drilled Sections not Tied in to the Main Pipeline during the First Year of Construction

Final Design

- Deep-anode groundbeds: using high-silicon chromium iron anodes in a coke breeze column with a vent tube.
- All anode cables: run into a junction box at top of groundbed & connected to a positive bus.
- At compressor stations: depth of groundbed 50 to 81m, each bed containing 10 to 22 anodes, anode column varied bet 35 to 72m (Fig. 4).
- Resistance to ground of anode beds: calculated to vary from 0.5 to 1.3 Ω.
- At mainline block valves: groundbed depth: 81m, A three – anode column (11m) located at the bottom of the hole (Fig.5).
- Resistance – to – ground of these anode beds: calculated to vary from 0.9 to 2.9 Ω.

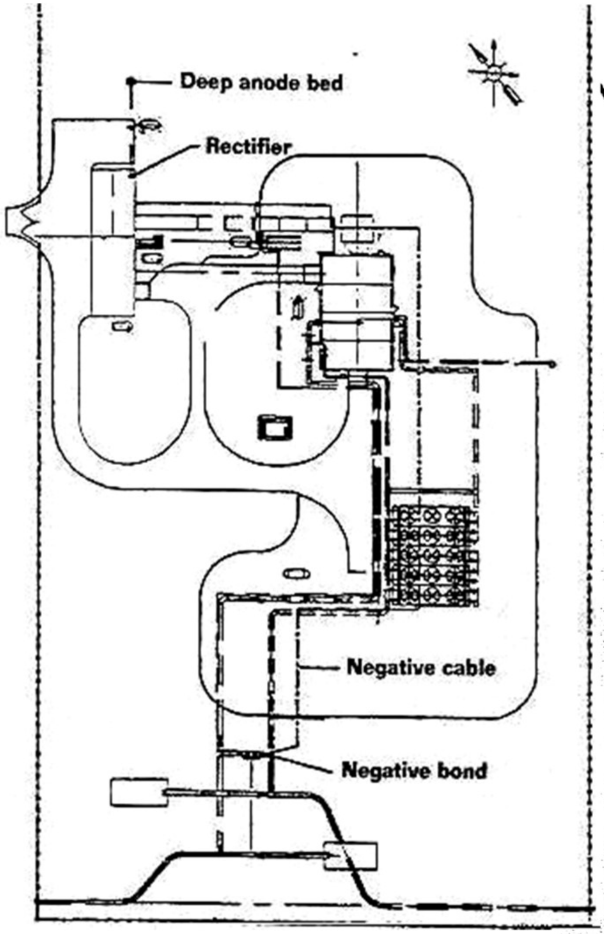


Fig. 4: Typical CP Layout at Compressor Station

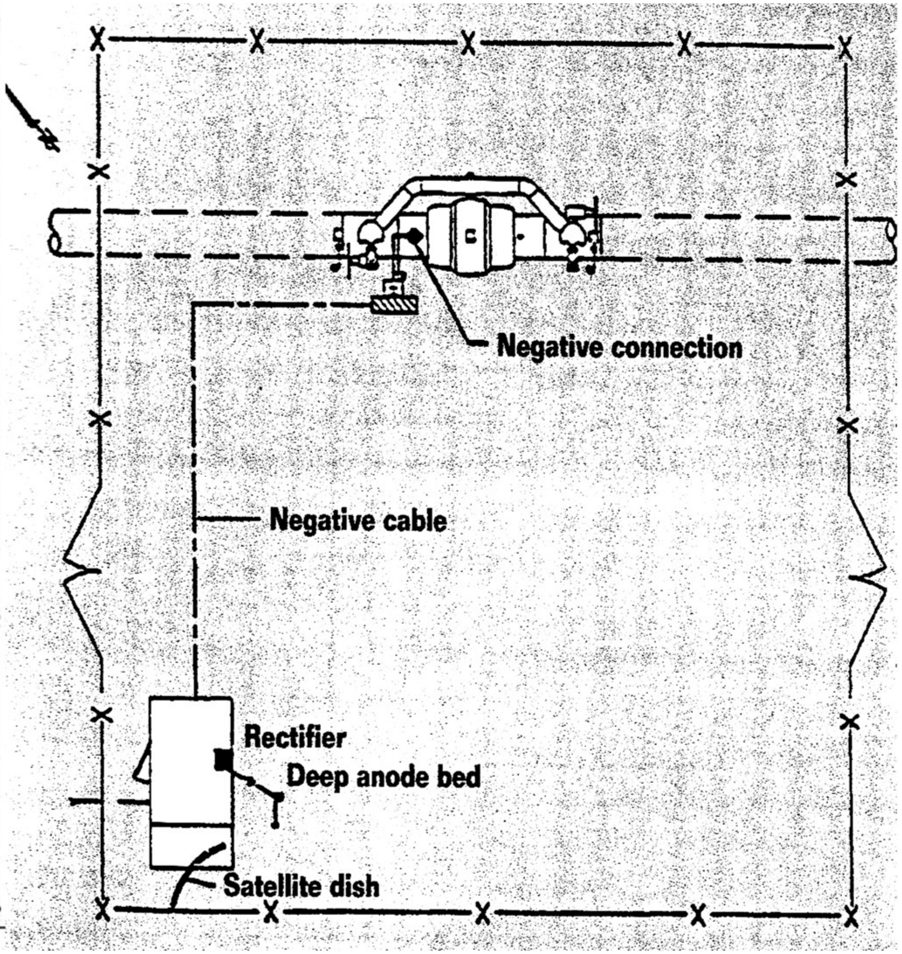


Fig. 5: Typical CP Layout Main Line Block Valve Sites

Rectifiers

- Constant - current air – cooled: 60 V, 50, 60 or 80 A at compressor stations, 40 V, 8 or 12 A at mainline block values.
- Rectifiers were connected to the supervisory control and data acquisition system (SCADA) to permit remote monitoring.

Test Stations

- At 3.2 km intervals.
- Foreign line test stations were installed wherever practicable.
- These were limited to crossings within 61 m. should there be interference at remote crossings, mitigation will be effected as required.

Electrical Isolation

- Main pipeline is electrically continuous, block valves are welded into the line.
- Isolation at delivery / meter stations.

CASE STUDY(2)

CASE STUDY (2)
HYDROGEN INDUCED CRACKING
(MATERIAL PERFORMANCE, JUNE, 1992)

The Incident

- Failure date: 1988.
- Oil transportation pipeline failed by HISCC.
- Leak caused by hydrogen-induced SCC.
- Location: Rotterdam-Antwerp pipeline (RAPL), the Netherlands.
- Pipe diameter 34 inches, wall thickness 7.8 mm.
- The pipe material: grade x-60 (API 5L Specifications).
- Product temperature range from 12 - 30^{o}C.
- Operating pressure: 35 bar.
- Before leakage, pressure was increased to 42 bar, (still below the maximum allowable service pressure, 52 bar).
- The pipeline is cathodically protected by impressed current technique.
- An additional sacrificial anode of magnesium is used.
- The Mg anode came close to the pipe, due to soil subsidence.
- Soil subsidence was also thought to cause plastic deformation of the pipe.

Failure Investigation:

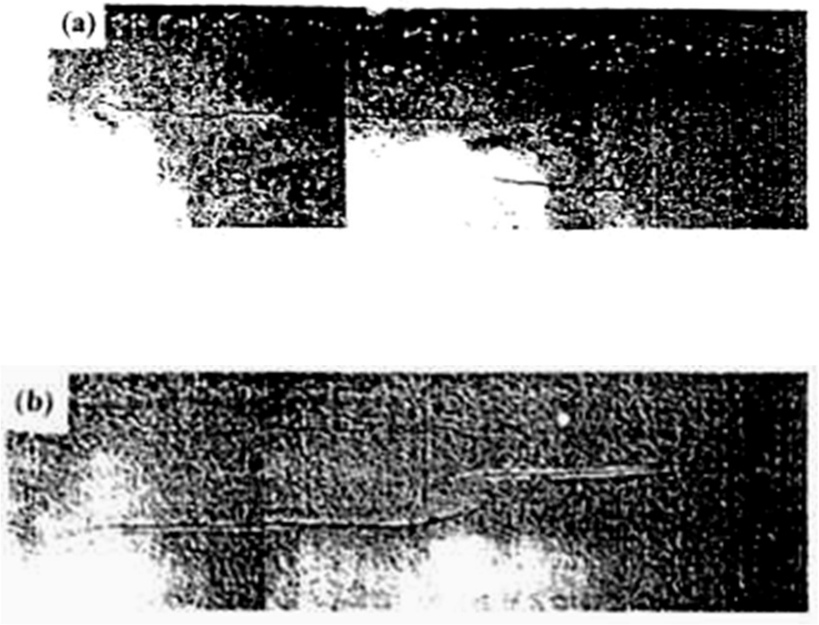
- Visual inspection.
- Inspection for mechanical damage and reduction in thickness by both optical and SEM investigation.

Failure Analysis:

- SEM examination showed a quasi-cleavage-like brittle fracture with several secondary creaks.
- Binocular and SEM investigation indicated that crack initiation took place at the outer surface of the pipe. The jagged crack appearance with a tending toward stepwise cracking suggested hydrogen in the cracking process.
- No plastic deformation.
- Type of crack: trans-granular.
- Hydrogen was evolved during cathodic protection.

SSRT under Cathodic Polarization Condition:

- Potential more negative than -850 mV (vs. Cu/$CuSO_4$) reference electrode was measured.
- The cathodic protection (on potential) of this pipe section was-1400 mV vs. Cu/$CuSO_4$.
- Potential drop over the coat was 300 mV (vs. Cu/$CuSO_4$).
- This potential value was negative enough for hydrogen evolution.
- Consequently, hydrogen-induced cracking occurred.
- Confirmation of the measured findings by SSRT tests at different applied potential values.

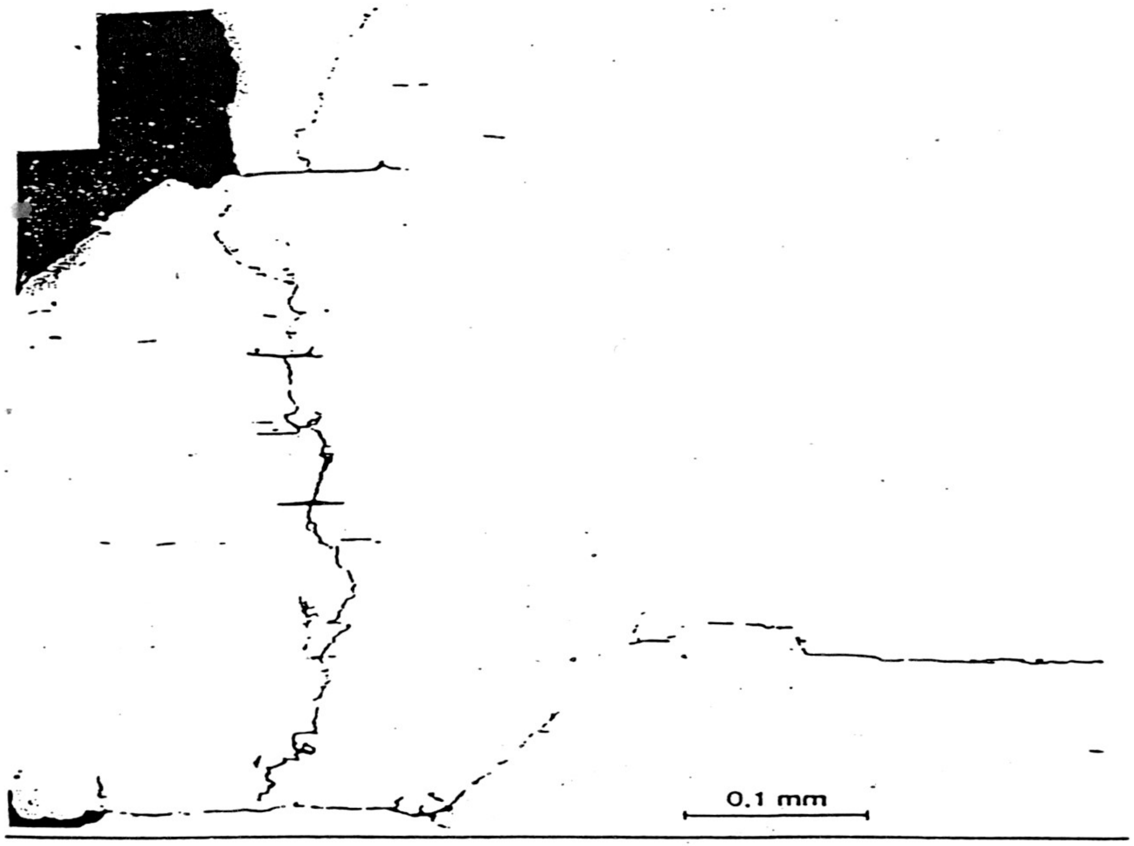


Outer (a) and inner (b) surface of the pipe at the location of the crack

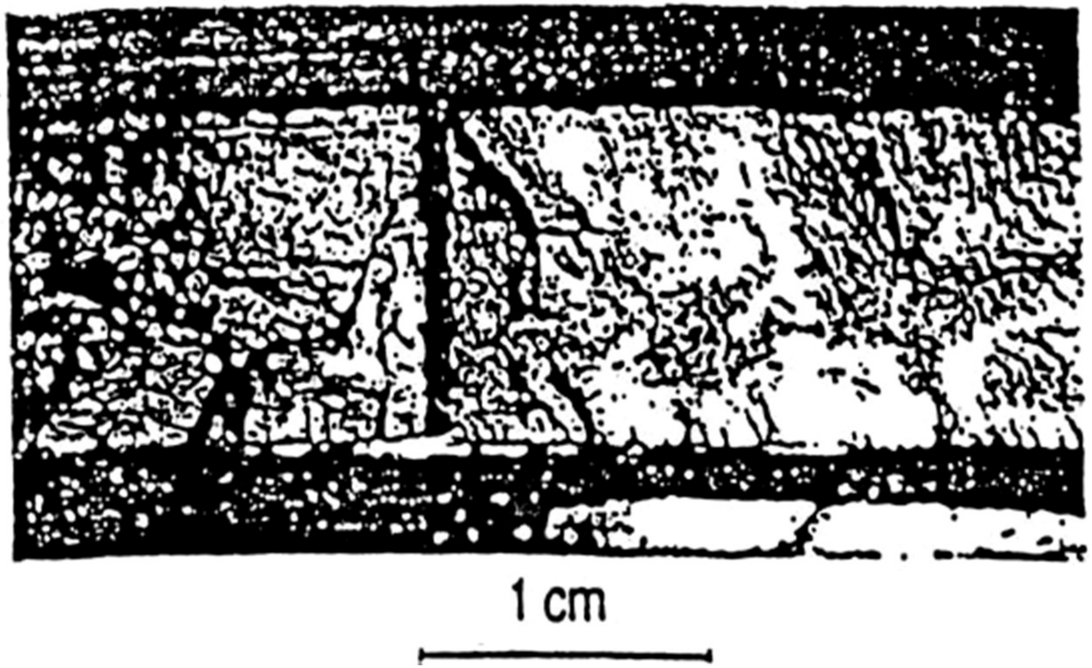
Table 1: Chemical composition of X-60 line pipe material and specification for API5L

	%C	%Mn	%P	%S	%Nb	%V	%Ti
X60	0.18	1.30	0.017	0.014	0.005	0.055	0.005
API5L	<0.26	<1.35	<0.04	<0.05	>0.005	>0.02	>0.03

The surface crack showing preference for propagation via inclusions



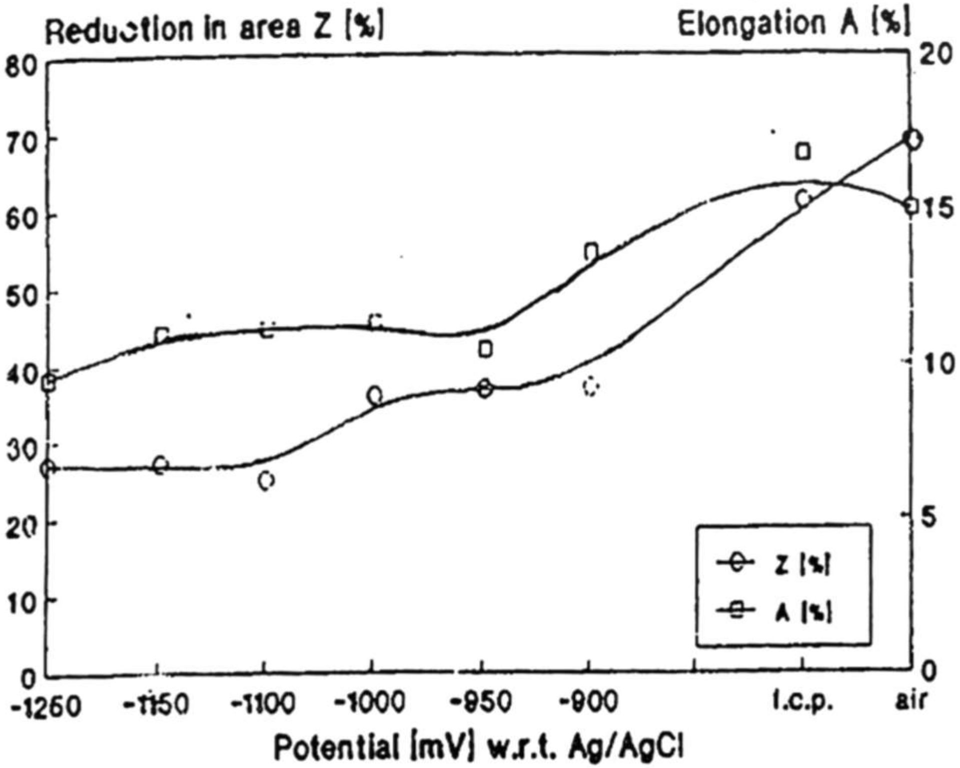
Cross-section through crack showing branching and tendency to step-wise cracking



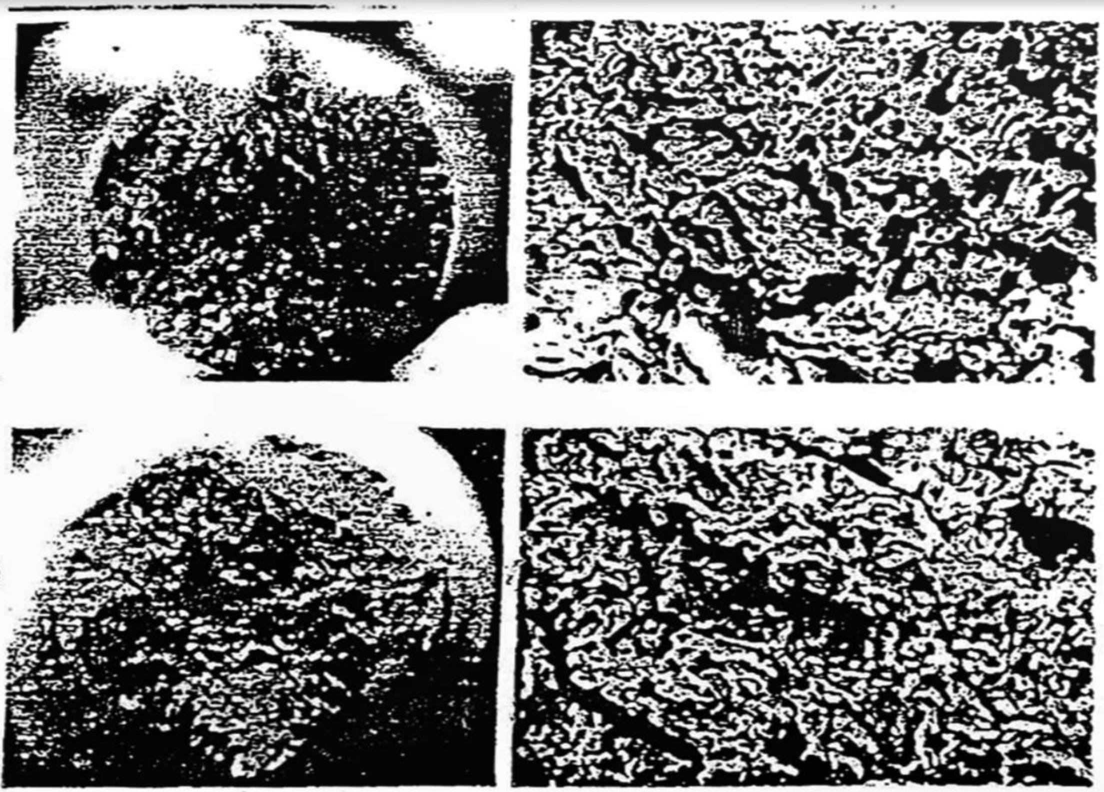
Binocular photograph of fracture surface showing several crack initiation steps in the outer pipe surface

SSRT program and results (strain rate 10^{-6}/sec)

Test No.	Potential	Reduction in area(%)	Elongation (%)	Test Duration	
	w.r.t Ag/AgCl			(h)	(min)
17	Air	67	14	44	30
18	air	70	16	48	55
1	i.c.p.c	59	17	48	10
2	i.c.p.	62	16	47	55
3	-900	36	14	42	25
4	-900	38	13	39	12
9	-950	39	10	31	55
10	-950	36	11	34	40
11	-1000	40	11	39	55
12	-1000	32	12	39	15
7	-1100	22	11	34	25
8	-1100	28	12	36	5
13	-1150	28	12	38	55
14	-1150	25	10	36	24
5	-1250	28	10	33	35
15	-1250	23	11	36	35
16	-1250	30	8	30	25



Reduction in area Z and elongation A in SSRT tests in artificial ground water as a fuction of cathodic protection



SEM fractographs of SSRT specimen tested at the free corrosion potential (top) and at -950 mV vs, Cu/CuSO$_4$ (bottom)

CASE STUDY(3)

Deep Water Platform Protection Using Coating Combined With Cathodic Protection

The subsea protection design, comprising a combination of cathodic protection and coating, for two platforms installed in the Gulf of Mexico at a water depth of 620 ft (189 m) is described. The results of surveys undertaken after installation reveal potentials considerably more protective than the minimum protective potential. In addition to eliminating the retrofit, significant cost and weight savings were achieved.

IMPINGEMENT ATTACK
ALUMINUM-BRASS TUBED
HEATING BUNDLES

Equipment : Heating bundle

Material of construction: AI-brass tube of the bundle

Phenomenon: Impingement corrosion

Perforation in the upper two rows of tubes due to Impingement .

Introduction

Combined coating and cathodic protection for a sub-sea pipeline.

This pipeline transports oil from oil fields to central production platform, CPP.

Concept of coating combined with cathodic protection; 20 – 30Y.

History:

BP; Abudhabi and North Sea: Coal tar epoxy and al sacrificial anodes: Osberg B Jacket (109 m deep) North Sea.

Conco: in the Gulf of Mexico (1989): consideration for using the system based on a study in 1972.

Conco installed the first coated and cathodic protection protected platform (GI 47L) in Nov. 1983.

The coating was epoxy poly-amide typically used for tank lining system.

A standard design was used: with a bare area allowance of 25%.

Instrumentation anodes with auxiliary coupons and inspections revealed that it was conservation. Even 10% was still conservative.

The anode current for the 189Kg anode stabilized at approx. 0.3A. The current for this anode, for a polarized uncoated structure, would be ~ 3.5A.

Utilization of high initial current density is additionally incorporated into the C.P. design of the two green canyons deep water fixed platforms. An initial C.D. of 301 mA/m2 resulted in platform potentials of 0.95V (Ag/AgCl) on platforms in the Arab Gulf and North Sea.

Elongated trapezoidal anodes used resulted in:

1. *Higher current than conventional anodes.*
2. *Anodes polarized platform (lower maintenance C.D. requirements.).*

In the Arabian Gulf: this has been reflected in a 40% wt reduction in the anode requirements.

Use of a high initial C.D.: an additional advantage: rapid formation of a protective calcareous deposit.

Subsea Corrosion Protection System

Two Parts :

* Platform Structure
* Mud Mats

All Parts of Sub-Sea Platform Structure were coated.

Mud Mats were left Bare

Platform

The sub-sea platform structure was coated with a tank-lining-type epoxy system. Surface preparation was done to Steel Structures Painting Council white metal blast (SSPC-SP 5). Two coats were used, each 4 mils (102 μm) thick. Surface preparation, anchor profiles, weather conditions, coating times, etc., were monitored throughout the entire job.

The CP design was based on achieving an initial current density of 28 mA/ft (301 mA/m^2), based on a bare area allowance of 15 percent. This was accomplished for both platforms in accordance with the following approach. The 52A drilling platform is used as an example.

1. *Determine the bare area exposed to seawater (15 percent of the coated area).*

$$\mathbf{405.578 \times 0.15 = 60.837\ ft^2}$$

2. *Determine the anode resistance (R_A) using the initial anode dimension.*

$$R_A = \frac{0.0627\rho}{L} \frac{(\ln 4L - 1)}{r}$$

Where:

R_A = initial anode resistance (ohms),
□ = seawater resistivity (20 ohm-cm),
L = length of anode (120 in. [305 cm]),
r = cylindrical radius (in.).

The cylindrical radius for the trapezoidal anodes used was determined by:

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

Where:

C = a + 2b + c

With

A = 10.7 in.
b = 9.25 in.
c = 9 in.
C = 38.2 in.
r = 6.08 in.
R_A = 0.0352 ohm

3. The initial anode current output is determinate by:

$$I = \frac{\Delta E_{init}}{R_A} = \frac{0.5}{0.0352} = 14.2\,A$$

Where ΔE_{init} is the potential difference between the un-polarized platform and the aluminum-zinc-indium alloy anode

The initial platform current required is:

$$60{,}837\,ft^2\ x\,0.028\,\frac{A}{ft^2} = 1703\quad A$$

The total number of anodes required is:

$$\frac{1703A}{14.2\,A/\,anode} = 120\,anode.$$

Table (1): Comparison of Protection Systems

Central Production Platform	As Installed Coating and CP		Uncoated Standard CP Design	
	CPP	52A	CPP	52A
Net anode weight, lb/anode	900	900	725	725
Gross anode weight, lb/anode	1150	1150	875	875
Number of anodes	125	138	605	690
Total anode weight	143.750	158.700	529.375	603.750
Coating weight	28.573	32.446	--	--
Coating cost. $	678.600	770.600	--	--
Total anode cost. $	168.750	186.300	665.000	759.000
Total anode installation cost. $	100.000	110.400	484.000	552.000
Protection system weight, lb	172.323	191.146	520.375	603.750
Protection system cost. $	947,350	1,067,300	1,149,000	1,311,000

Table (2): Drilling Platform 52A Potentials Determined One Month after Installation

Location	Potential vs Ag/AgCl(V)		
	295 ft(A)	455 ft	610 ft
Leg A1	-0.998	-0.957	-0.945
Leg B1	-.0993	-0.947	-0.908
Leg A4	-1.00	-0.944	-0.900
Leg B4	-0.993	-0.936	-0.905
Leg C2	-1.00	-0.880	-0.882
Leg C3	-0.990	-0.860	-0.883
(B)	-0.990	-0.860	-0.788

A: Feet below sea level.

B: Four of 16 conductors partially driven

Mud Mats

- Magnesium Rods, (1" Diameter) with Core Diam. 0.135". Comprized the initial polarization system.
- Each Had 140 ft 43m of Mg. Rod Divided to Protect the Bare Areas.
- These Anodes would provide an initial C.D. of 30 mA/ft^2
- 14 Additional 900 lb (409 Kg.) of Al-Zn-In Anodes put on the Platform Structure to provide the Additional Maintenance current to protect the mud mats after initial polarization.
- So the total number of anodes recommended was

120 + 14 = 134 Anodes

Cost Effectiveness

- 1^{ry} Cost Effective Objective of coating: Eliminate risk of premature retrofit.
- Minor retrofitting in Deep waters Result in Costs Exceeding the costs of original protection system.
- Secondary cost effectiveness achieved is reflected) in comparison of as installed cost compared to the uncoated standard design.
- Table (1)
- Coating Cost $\simeq$ \$ 1.9/ft^2(20.45\$/m^2)
- Installation cost of anode = \$ 800/anode
- Coating load based on a coat thickness of 8 mils.

Protection System Evaluation

The protection on each leg of the 52A drilling platform was monitored one month after installation.

Legs with no anodes: Worst Condition (least polarization).

Points on Table 2 represent those furthest from anodes and where the shielding from the C.P. was greatest.

Areas most affected (least polarization): conductor bay (Table2).

Anode Life

The Anode Life is calculated by

$$L_t = \frac{WQF_U}{8760\ I}$$

Where:

L_t = effective lifetime in years,
W = net weight of anode (900 lb),
Q = anode capacity = 1250 A h/Ib (2756 A h/Kg),
F = anode utilization factor (0.9),
I = mean current output during lifetime, and,
8760 = number = of hours in one year.

The main current output is determined by ohm's low:

$$L = \frac{\Delta V}{R_d}$$

Where:
ΔV is the potential difference between the polarized platform and the aluminum anode and R_d is the anode resistance based on a derated radius. The derated radius is 50 percent of the initial radius (6.08 x 0.5). Substitution of this value into equation (1) results in an anode resistance (R_d) of 0.042 ohm.
For a platform polarized to -0.85V vs. Ag/AgCl, an anode life of 22 years is obtained. These Green Canyon platforms are more polarized than -0.85V vs. Ag/AgCl. . Platform potentials -0.900 and -0.950V vs. Ag/AgCl result in lifetimes of 29 and 40 years, respectively. The system life will exceed the 20-year design life.

Conclusions

A unique combination of coatings and CP has been used to protect the sub-sea portion of two deep water platforms. Potential surveys undertaken after installation demonstrates protection well beyond the minimum protective potential. The primary objective, namely the elimination of the retrofit risk, has been achieved. Additionally, cost and weight savings, when compared to conventional design, were of the order of $200.000 and 400.000 pounds, respectively. The system life will exceed the design life of 20 year.

CASE STUDY(4)

CASE STUDY(4)

A Corrosion Protection System For A North Sea Jacket

The Oseberg Field: North Sea

The Field Contains Two Platforms

- A: Process equipment etc ....

- B: Drilling & well head equipment .

Design Parameters

- Several nearby fields as well as the northern parts of the reservoir will be tied into the field centre through the B-platform .
- Design life of the steel jacket :40 Y.
- B-platform:

  8-legged steel jacket Tow-out wt. : 18,800 ton It has :-

  8 J-tubes collected in two J- tube caissons 4 fire and sea water caissons ,32 piles,

  38 conductors.

  All items to be protected for life time Total area to be protected: 70,000 m^2

Moreover, each well is included in the design: 5 A for
38.5 Y Water depth 109 m .

Corrosion Protection Design Consideration

Both I CCP and sacrificial anode systems were evaluated at the conceptual design stage .

Though ICCP is good from the weight point of view, it was rejected:

1- As the field center is **complex**

- -Two connected platforms
- -One export pipeline
- -Two nearby subsea wells
- -Several pipelines coming in from satellite fields

All these items has to be electrically insulated from each other. This would not be necessary if these items has to be protected by sacrificial anodes, completely interconnected and designed according to the same set of rules.

2. No ICCP system would be proven for a life time of 40 Y in the North Sea environment.

Protecting the bare jacket for 40 Y with sacrificial anodes required a substantial anode weight .

Two approaches to reduce weight : sacrificial anode

with different degrees of coating reducing the design C.D.

Table Comparison of different options.

Current Density Criteria:

- All experience at North Sea or elsewhere shows that the C.D. criteria was conservative
- For weight calculations : mean C.D. is important
- For the performance of the system: initial C.D. , and
- final C.D. are the important parameters

Figure-2 for C.D. (mean value) and C.D.(final value).

- ☐ Based on these consideration ,the current density values shown in the first line of table 2 where used.
- ☐ The new mean C.D.(line 3 of table 2), led to a reduction in weight. from 1500 ton to 1330 ton .
- ☐ Weight could be further reduced by coating.

Coating System Selection and Performance

☐ Two questions, once coating decision made:

- Which coating system to use

- How to include it in the CP decision

So: Revise Dn V criteria, (Fig. 3)

In Fig. 3 :

- Curve :" Mean" is used when calculating the necessary anode weight.
- Gives a factor to scale down C.D.
- In effect: gives the bare area of the jacket averaged over its lifetime.

Curve "Final": Important for distribution and sizing of anodes., and gives % of the jacket bare at any time.

For Actual design, (Fig.3) is used as follows:

Multiply mean C.D. (Line 1, Table 2) X Mean coating breakdown values (Fig. 3):

105 x 0.35 = 36.75 mA/m^2

Current Consumption at end of lifetime

= 80% (Fig.3)X jacket area x Final C.D. (Table 2)

= 0.8 x jacket area x 110 A

=6,160,000 A

- ❑ The coating breakdown factor is the most uncertain factor in the corrosion protection design.
- ❑ Since the current consumption will increase with time, the final current

density is rather high, consequently, the total current output from the anodes at the end of the lifetime must be rather high, thus the number of the anodes will be almost the same as if the jacket was uncoated.

- ❑ i.e. the coat only gives a weight saving, but the same installation cost, since there must be many relatively small anodes.

Selection of Anodes

❑AI-anodes were not popular:

  - possibility of passivation when the coating system is new and the current consumption is low.

❑Now AI-Zn-Hg, but AI-Zn-In has a better performance

❑Test on anodes , free corrosion:

- All anodes tested at -0.980 1.115 V (galvanostatic Polarization) indicated that AI-Zn-In gives best performance (Least and most negative potentials in a 3 month duration test) while AIZn-Hg anodes showed intermediate behaviour.

Selection of Anodes

- ❑ Galvanic currents between steel cathodes and different anodes: corroding freely for 3 months. Fig.5:
  - Anodes with smooth generally corroded surface performed best.
  - Heavily pitted, with large passive areas did not give sufficient current or low enough potential.

- ❑ The jacket will be almost completely covered with anodes (more than 2000). Drag will-be high. Cylindrical cross section anodes (instead of the more common trapezoidal.) will reduce the drag coef. from 1.7 to 1.4.

ACTUAL DESIGN SUMMARY

COA TING SYSTEMS

Jacket: Submerged Zone : coal tar epoxy: ***300J.l plus a white high-solid solvent less epoxy of --200J.l.***

- From splash zone down to -45m:

  as above plus additional *300 self polishing anti-fouling coating*

- Atmospheric zone:

  Zinc ethyl silicate primer, 280/-1 vinyl coat plus 50/-1 vinyl acrylic topcoat.

ACTUAL DESIGN SUMMARY

Coating Systems

- Conductors, submerged zone: solvent - free two component epoxy: **12mm.**
- Splash, atmospheric zones: abrasion resistant, solvent less epoxy 2 from 3.5 mm
- **Risers: All zones 20mm chloroprene rubber.**
- **J tubes: All zones same as jacket.**
- **Caissons jackets.**
- **Piles : No coating except internally from the mud-line to the pipe** opening, about elevation become mud line (-90m)

Cathodic Protection System

- Sacrificial Al-Zn-In
- All mounted on the structure none on risers, J-tubes, conductors or piles.
- Net anode weight: 211 Kg each.
- Number of anodes 2032 plus some small anodes for protection of special regions.
- Anodes are cylindrically shaped.
- Designed for 40Y, lifetime on, a completely coated structure with assumed 5% bare area initially.
- Design potential 800-1050 m V (vs. Ag/ AgCl sea water reference electrode)

Performance

- The jacket is equipped with a permanent potential and current monitoring system, -20 Zn deference electrodes and20 shunted monitoring anodes which are mounted in pairs over the jacket.
- **Fig. 8 :**

  Data on five of these pairs (on the Zn- sea water scale).

  Three electrodes show slower polarization than the other two.

  The first : in an environmentally affected area (-21m).

  The second: coating was deliberately removed (-7 4m) *The third* :mounted on a "bottle neck" leg just above the top of the piles.

Potential Monitoring

- During the 1st year after installation: the potential is less - negative than the protection potential.
- As long as the coating system is almost' intact, any environmental effects can hardly be expected.

Current Monitoring

- High initial current, decreasing, gradually, average current consumption: 105 mA/m^2 on jacket surface (5% bare initially).
- Each anode current: 180mA/m^2 , and the average current output from the 20 n10nitored anodes in less than this.

Conclusion

- The Oseberg B Jacket is protected by aluminum sacrificial anodes and a coal tar epoxy system. This ensures a fast polarization
- Represents a weight saving and a simple corrosion protection system that, based on one year of operation, seems to be reliable.

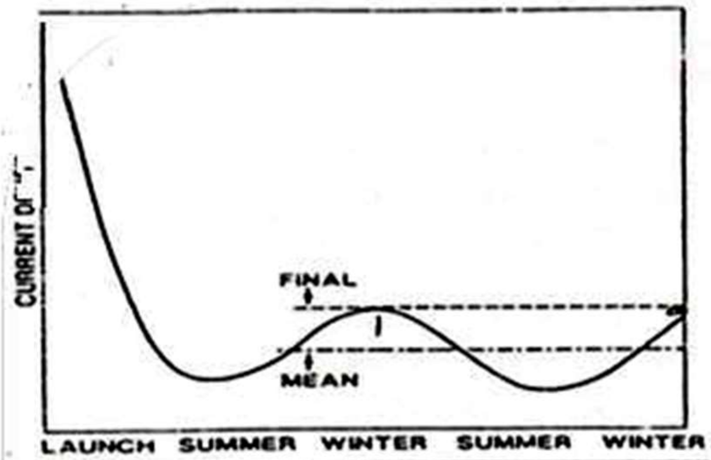


FIGURE 2

Schematic seasonal variation of cathodic current demand.

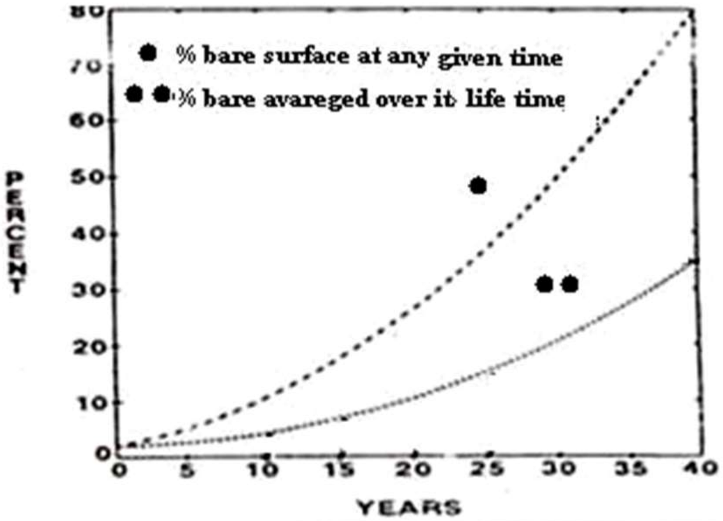


FIGURE 3

Coating breakdown curve used in cathodic protection design for the Oseberg B platform.

TABLE 1

Weight Comparison Between Different CP Options (Gross Weight in Tons)

System	Zinc Anodes	Aluminum Anodes
Bare jacket	4103	1526
50%-coated jacket	3077	1145
100%-coated jacket	2052	763

TABLE 2

Current Density Criteria for CP Design, mA/m^2

Criteria According to	Mean	Initial	Final
Norsk Hydro Oseberg	105	160	10
DnV "old" (TN A703)	120	160	100
DnV "new" (RP B401)	90	180	120

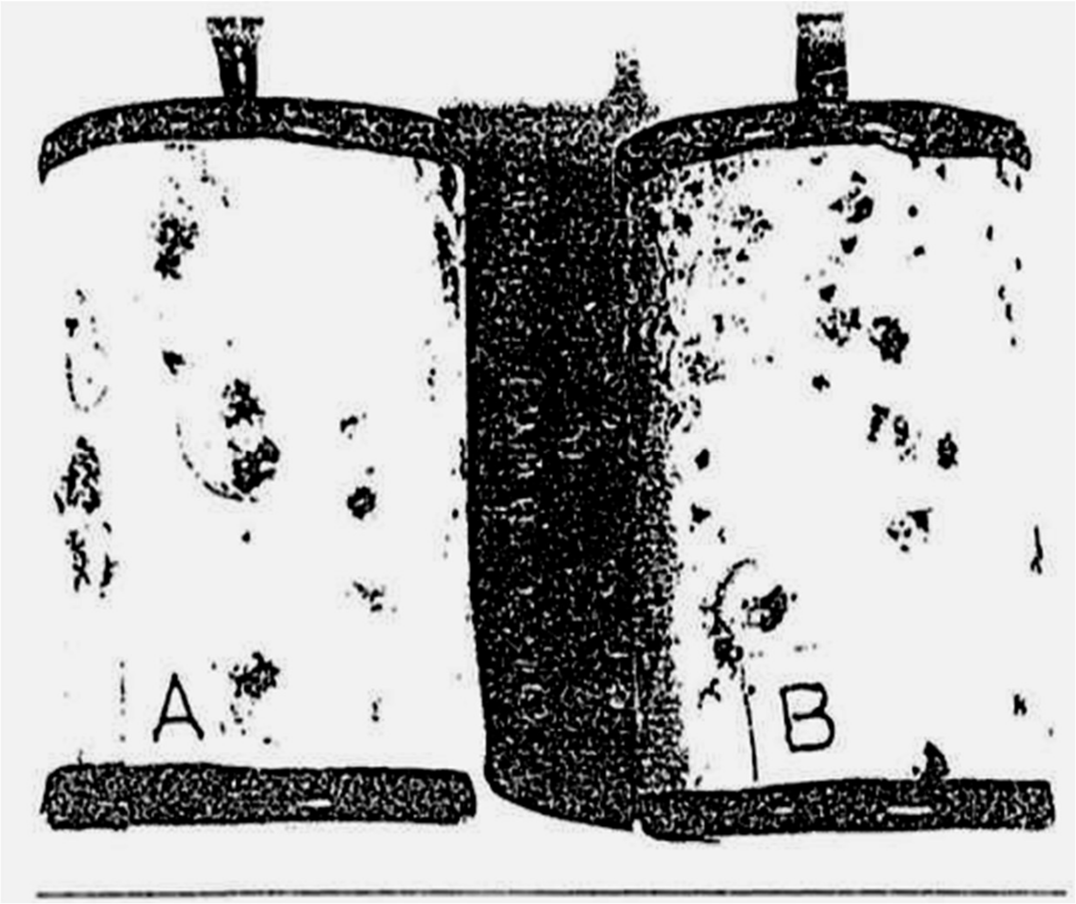


Fig. 5: Surface appearance after three months testing Al-Zn-In(3) A-Free corrosion B- 20 mA/m^2

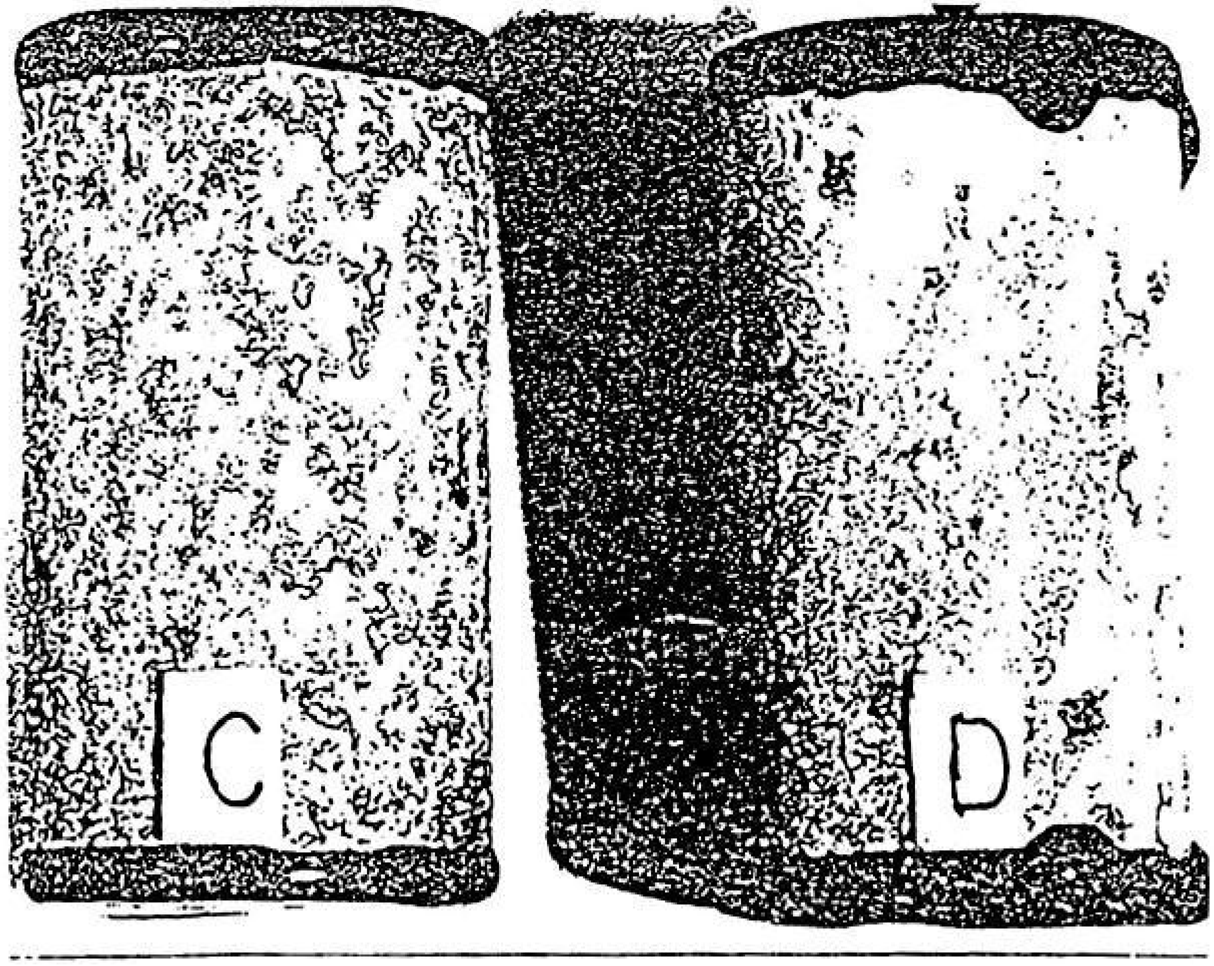


Fig. 6: Surface appearance after three months testing Al-Zn-In(1) C-Free corrosion BD 20 mA/m²

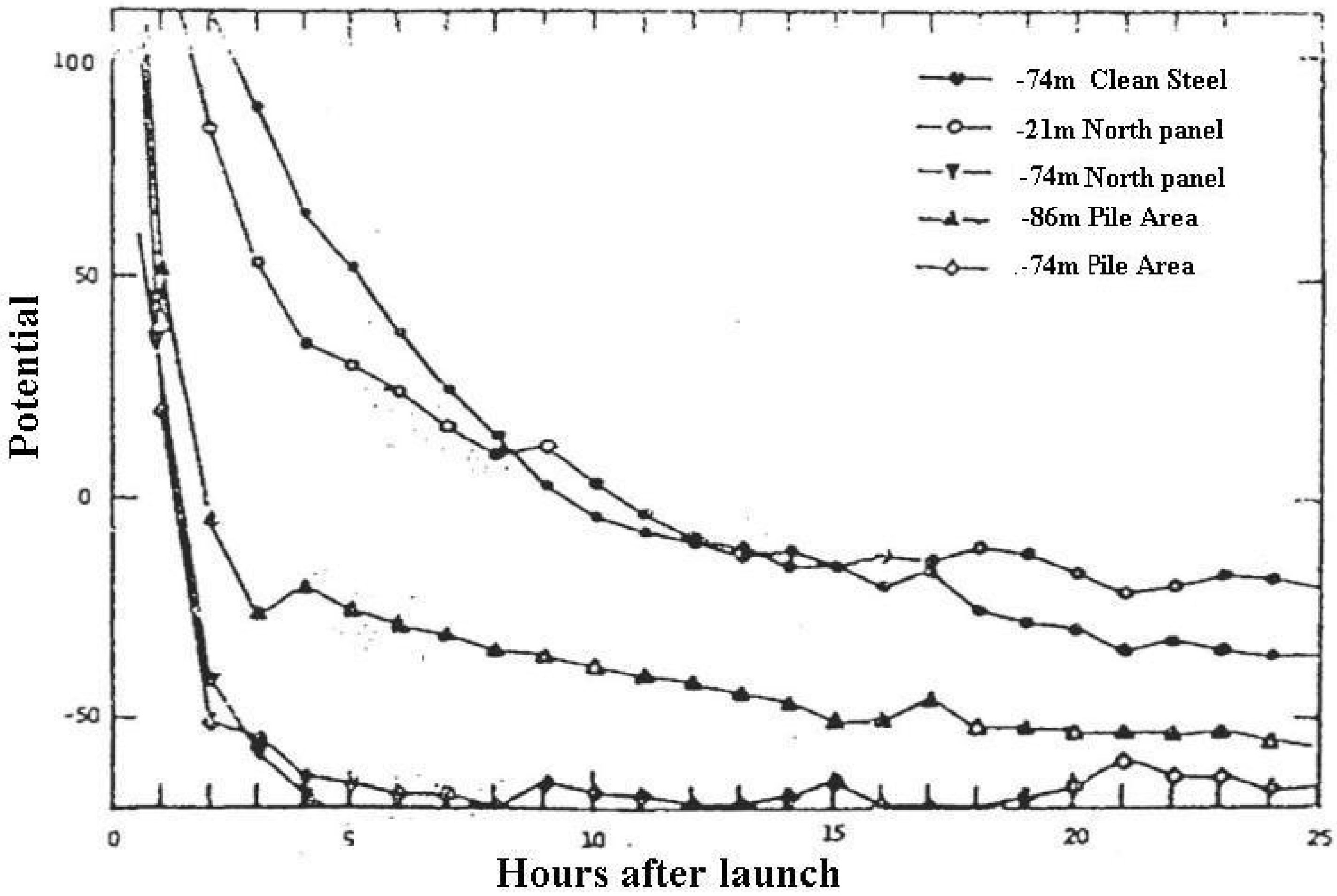


Fig. 8: Potential development during the first 24 hours after lunch of the jacket. Protection criterion is 0 mV on the Zn- seawater scale

CASE STUDY(5)

Cathodic Protection Of External Tank Bottoms

General

- The corrosion process as it relates to buried, partially buried, and submerged metallic structures is a naturally occurring phenomenon. The principles of this process and the benefits of cathodic protection (CP) in controlling this type of corrosion have been demonstrated in many different situations.
- Concern has increased, at an alarming rate, over failures of ground storage tank bottoms resulting from internal and external corrosion. This paper will discuss various options for CP of the external (groundside) surfaces of tank bottoms that are in contact with corrosive environments. The advantages and disadvantages of these options will be discussed, along with limitations that exist in determining the effectiveness of CP through traditional measurement techniques. Suggestions for an alternative design approach intended to improve protective current distribution will also be discussed.

C. P. Of Tank Bottoms

Sacrificial anode system:

For small diameter thank, effectively isolated from other underground structures.

Impressed current systems:

Where current requirement are substantial

Types of anode installations:

Horizontal or vertical, around periphery (Fig. 1).

Horizontal or vertical under tank bottom (Fig. 2).

Deep well configuration (Fig. 3)

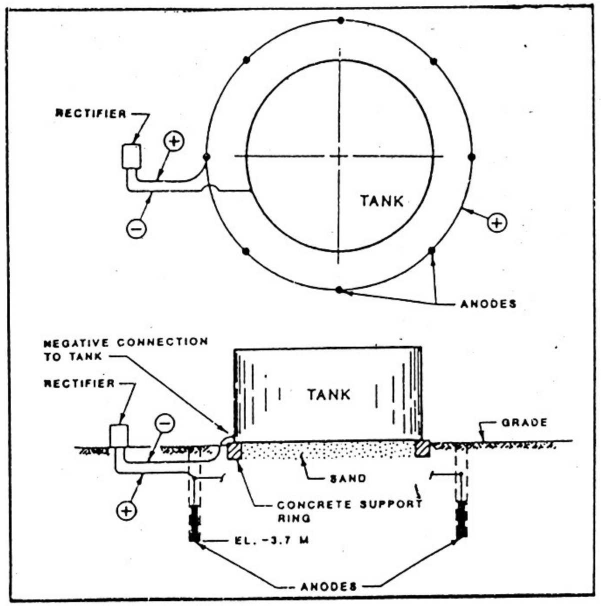


FIGURE 1 — Commonly installed vertical impressed

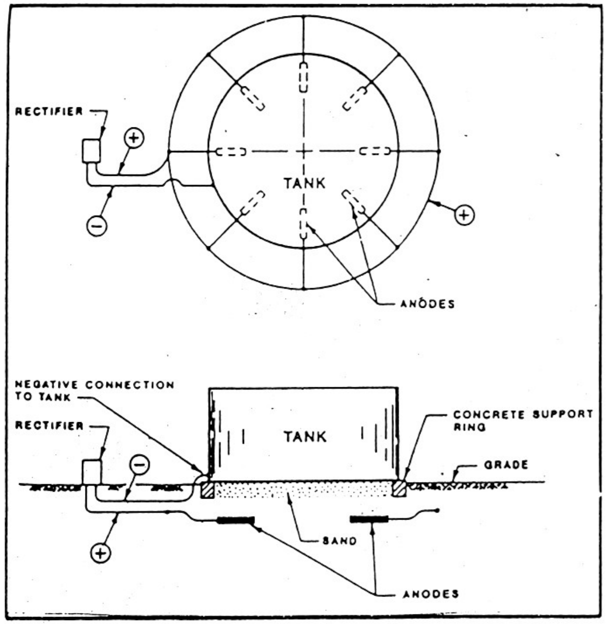


FIGURE 2 — Anodes installed under a tank bottom.

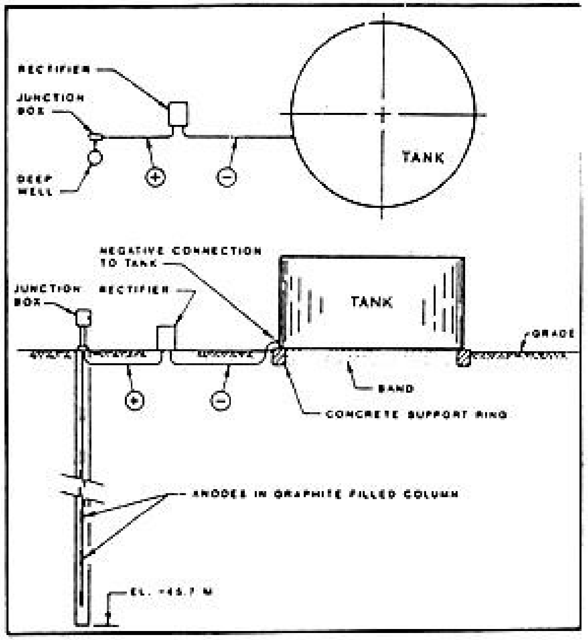


FIGURE 3 — Commonly installed deep well impressed current anodes.

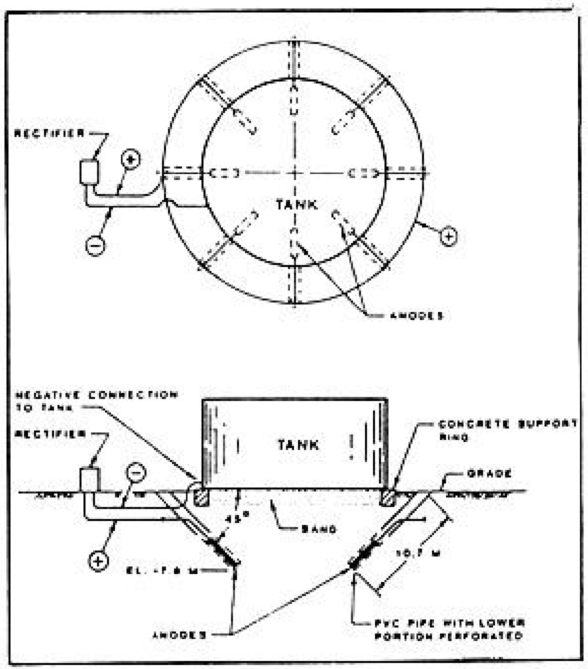


FIGURE 4 — New system approach: angled. Impressed current anodes.

Experience has shown

- Structure to earth potential at perimeter of tank does not indicate actual C.P. levels at center, particularly for large diameter tanks.
- Pot. Measurements at center & other parts are necessary.
- Liquid level in the tank as a significant factor.
- Certain C.P. designs may not be effective in providing adequate C.P. to tank bottom in certain areas.
- Using slant or angle drilling can improve current distribution (Fig. 4).
- Standard method to verify effectiveness of C.P.: Structure to soil potential. (High impedance voltmeter & reproducible ref. electrode).
- Natural potential of C-steel $\simeq$ 0.600 mV Vs $Cu/CuSO_4$. More positive values: means corrosion of structure, while more negative values: indicate protection (or well-coated).
- Effective protection at -0.85 V Vs $Cu/SuSO_4$ (One of the accepted criteria)

Problem of monitoring:

Inability to place portable reference electrode in close proximity to the underside.

Placement of ref. electrodes at the perimeter: may yield erroneous results, especially when using distributed anodes installed along the periphery.

Table (1): Actual measurements showing a potential difference of $\simeq$ 300 mV between perimeters a center of tank.

So, recommended: At least one measurement taken at tank center.

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So, recommended: At least one measurement taken at tank center.

For new tank construction: permanent reference electrode and a lead wire underneath tank pad (Fig. 5) or a perforated PVC or FRP pipe (Fig. 6) for potential profiling.

For existing tanks: A hole can be bored (water jetting) in a configuration shown in Fig. 6.

Table (1): Potential Measurements Obtained Under a 36.6m Diameter Tank Bottom

Reference Electrode Location (m)	Tank-to-Cu/CuSO$_4$ (V)
Perimeter	-1.492
1.5	-1.379
3.0	-1.291
4.5	-1.242
6.0	-1.183
7.5	-1.151
9.0	-1.127
10.5	-1.109
12.0	-1.097
13.5	-1.109
15.0	1.109
16.5	-1.101
18.0 (center)	-1.112

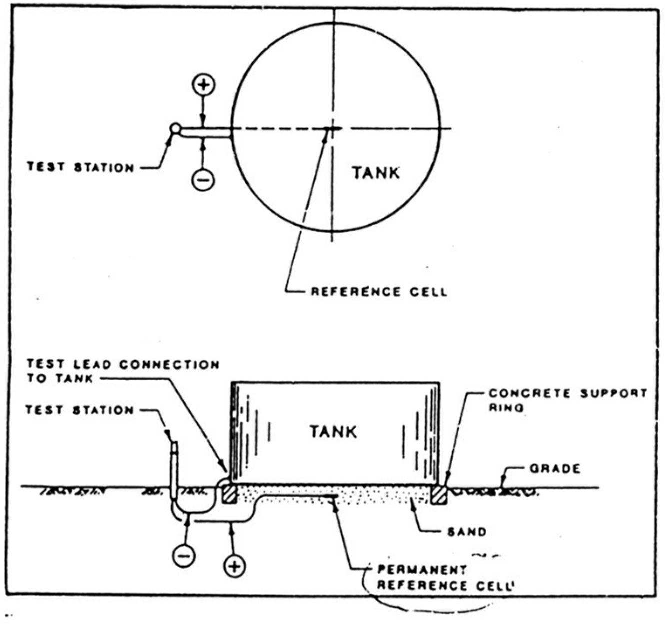


FIGURE 5 — Permanently installed reference cell and test station.

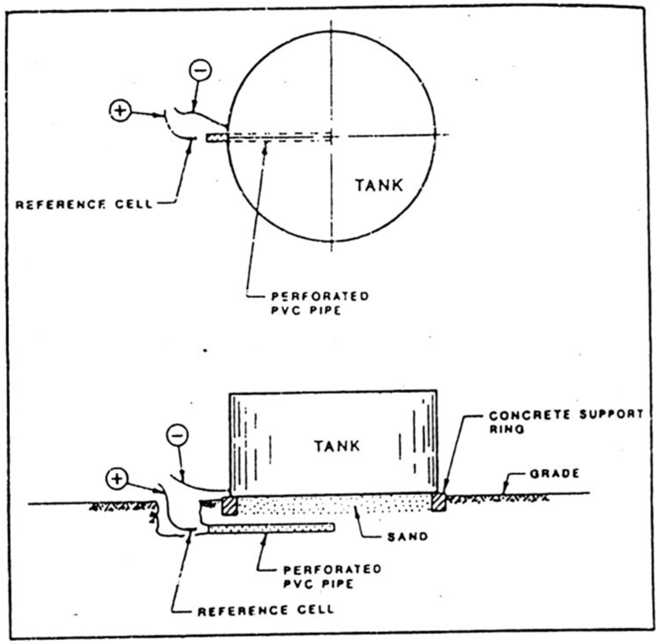
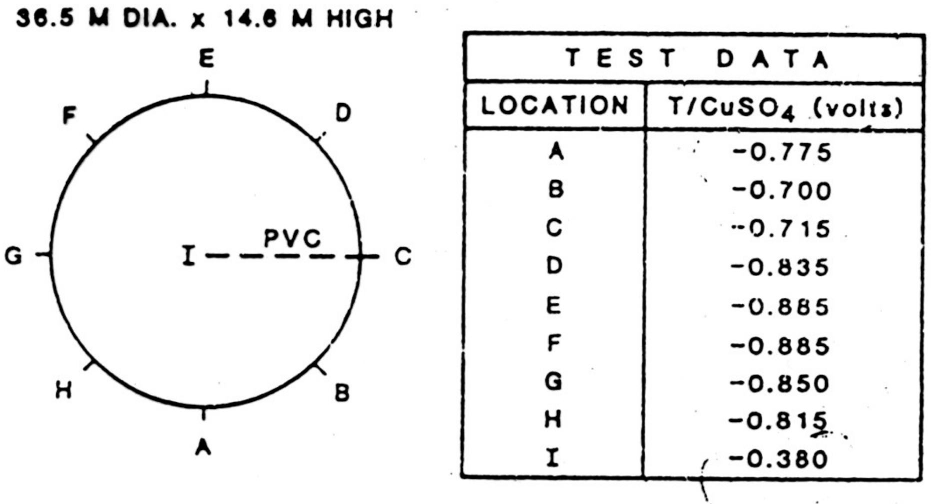


FIGURE 6 — Perforated pipe installed for reference cell access to tank bottom.

Typical Case Studies

Case No 1 (Fig. 7):

36.5m dia., 14.6m high C-steel ground storage tank.
Deep anode ground-bed installed in close proximity to tank (2.1 A).
Measurements at periphery & center of tank.

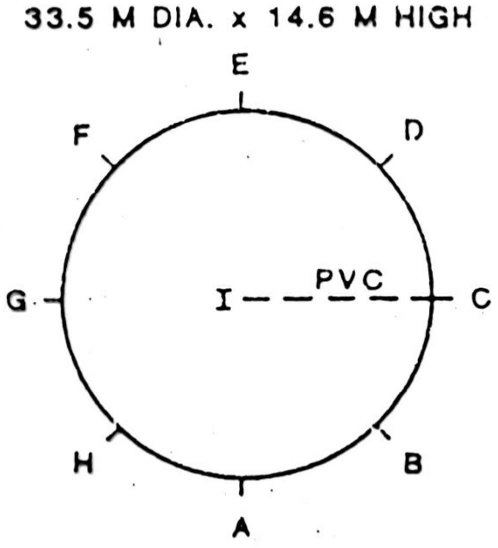


TEST DATA	
LOCATION	T/CuSO$_4$ (volts)
A	−0.775
B	−0.700
C	−0.715
D	−0.835
E	−0.885
F	−0.885
G	−0.850
H	−0.815
I	−0.380

FIGURE 7 — Typical Case Study No. 1: deep anode groundbed installed in close proximity to the tank (current = 2.10 A).

Case No 2 (Fig. 8):

- 33.5m dia., 14.6m high C-steel ground storage tank.
- Deep anode ground bed (2 A)
- Potential at center (0.640 V) does not satisfy the minimum accepted criterion.
- These examples indicate the critical nature of reference electrode replacement to assess degree of protection.
- Also: leakage current at lank perimeter (tank bottom at perimeter has the lowest resistance to earth).
- Under conditions of max product level, good contact at center, hence greater expected area & lowest resistance to earth, hence a higher required current.
- Testing on an empty tank may indicate adequate C.P. at center (limited amount of surface area being protected). Once the tank is filled, surface area in contact with earth increases & current density decrease.
- The success of the deep anode ground-bed system is usually predicted on relatively low, uniform soil sensitivities from the ground surface to the total depth of the ground-bed.
- Difficult to direct the ground-bed current to the tank bottom in areas of non-uniform soil resistively, particularly where high receptivity strata may lie between the tank bottom and the active anode area.
- Distributed anode ground-beds installed around the periphery of the tank, are intended to provide uniform distribution of the anode current to the tank.



TEST DATA	
LOCATION	$T/CuSO_4$ (volts)
A	-1.040
B	-1.150
C	-1.190
D	-1.110
E	-1.090
F	-1.070
G	-0.930
H	-0.950
I	-0.640

FIGURE 8 — Typical Case Study No. 2: deep anode groundbed installed in close proximity to the tank (current = 2.00 A).

New System Approach (Angle – Drilled Anodes)

Using distributed anodes at a 35 to 45 degree angle to the perimeter of the tank to a depth of 7.6 to 10.7m (Fig. 4): More uniform current distribution & higher protection levels at center.

In new installations of this type, potentials of – 1.00V at perimeter& -0.86V at center.

Easy to conduct these types of installations: by the use of pre-packaged or canistered anodes.

Summary

- The application of CP is an effective means of controlling corrosion on a tank bottom groundside. The success of the CP system is dependent on proper design and selection of the type of installation and effective monitoring of the level of protection being afforded the entire tank bottom (groundside). The use of angle-drilled anodes around the periphery of the storage tank should provide a better distribution of current to the center of the tank. Monitoring through the use of permanent reference cells installed under the base of the tank or reference cells passed through a slotted pipe installed under the center of the tank will provide an accurate indication of the true potential level. True potentials might not otherwise be realized by placing a reference cell around the perimeter of the tank.