DESIGN OF ANODE GROUND BED FOR AN IMMPRESSED CURRENT CATHODIC PROTECTION SYSTEM

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A thesis submitted in partial fulfillment of the requirements for the Degree of
Master of Technology
(Pipeline Engineering)

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Declaration

This is to certify that the project report titled **"Design of Anode ground bed for an impressed current cathodic protection system"** is being submitted by **Mr. V V Raghavendra sastry**, in partial fulfillment of the requirements for the award of the degree of MASTER OF TECHNOLOGY (Pipeline Engineering) of U.P.E.S. Dehradun. This is a bona fide record of the work carried out by him under our guidance and supervision. Further, certified that this work has not been submitted for the award of any other degree or diploma.

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"GUIDANCE IS PERVASIVE AND IT ENLIGHTENS"
I HERE EXPRESS MY SINCERE THANKS WHERE IT IS DUE

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V Raghavendra Sastry Vedula

ABSTRACT

The ideal design for a cathodic protection system is one which will provide the desired degree of protection at the total minimum total annual cost over the projected life of the protected structure. Total annual cost means the sum of costs of power, maintenance, and charges against the amount of capital invested. Both the operating cost and the installation cost depend on the resistance of the anode bed. This quantity occupies central role in the design of any anode bed of the ICCP system. This project aim is to design such a ground bed and anode combination which will drain the current from the line at a certain point for the least annual cost. The process that is followed for this design of anode bed in accordance with NACE RP-01-69 and RP – 072-85 is viz, review of soil resistivity, review of current requirement test, select anode, and determine the number of anodes needed to satisfy the current density limitations. Determine the number of anodes for the system's life expectancy, determine the number of anodes needed to meet the maximum anode ground bed resistance requirements, select anodes to be used, select the area for placement of the anodes. Determine the total circuit resistance.

Key words: ***cathodic protection system, Anode, ICCP System, Ground bed, resistance, soil Resistivity, current density, NACE RP 01-69, RP-072-85***

Definitions

Amphoteric metal: A metal that is susceptible to corrosion in both acidic and alkaline environments.

Anode: The electrode of an electrochemical cell at which oxidation occurs. (Electrons flow away from the anode in the external circuit, which is normally metallic. The anode is the electrode where corrosion occurs and metal ions enter solution.)

Anodic polarization: The change of the electrode potential in the noble direction resulting from the flow of current between the electrode and electrolyte.

Cable: One conductor or multiple conductors insulated from each other.

Cathode: The electrode of an electrochemical cell at which oxidation occurs

Cathodic Protection: A technique to control the corrosion of a metal surface by making that surface the cathode of electrochemical cell.

Conductor: A material suitable for carrying an electric current. It may be insulated or bare.

Continuity Bond: An intentional metallic connection that provides electrical continuity

Corrosion: The deterioration of a material, usually a metal, that results from a reaction with its environment.

Corrosion potential: the mixed potential of a freely corroded pipe surface with reference to an electrode in contact with the electrolyte

Corrosion rate: The rate at which corrosion proceeds (It is either expressed as weight loss or penetration per time.)

Criterion: Standard for assessment of effectiveness of a cathodic protection system.

Current density: The current to or from a unit area of an electrode.

Electrical Survey: Any technique that involves coordinated electrical measurements taken to provide a basis for deduction concerning a particular electrochemical condition relating to corrosion or corrosion control.

Electrode: A conductor used to establish electrical contact with an electrolyte and through which current is transferred from an electrolyte.

Electrolyte: A chemical substance containing ions that migrate in an electric field. For the purpose of cathodic protection, electrolyte refers to soil or liquid adjacent to and an contact with a buried or submerged metallic piping system, including the moisture and other chemicals contained therein.

Foreign Structure: Any structure that is not intended as a part of the system of interest.

Galvanic Anode: A metal which, because of its relative position in the galvanic series, provides protection to metal or metals that are nobler in the series, when coupled in an electrolyte.

Galvanic series: A list of metals and alloys arranged according to their corrosion potentials in a given environment.

Impressed current: Direct current supplied by a cathodic protection system by utilizing an external power source.

Interference: Any electrical disturbance on a metallic structure as a result of stray current.

IR Drop: The voltage across a resistance in accordance with ohms law.

Line Current: The direct current flowing through pipe.

Pipe-to-Electrolyte potential: The potential difference between the pipe metallic surface and electrolyte that is measured with reference to an electrode in contact with the electrolyte.

Reference electrode: A reversible electrode with a potential that may be considered constant under similar conditions of measurement. (Example: Saturated copper /copper sulfate, saturated calomel, and silver/silver chloride.)

Stray current: current through paths other than the intended circuit.

Voltage: An electromotive force or difference in potential between two electrodes expressed in Volts.

Wire: A slender rod or filament of drawn metal. In practice, the term is also used for gauge conductors (6mm^2 [No. 10AWG] or smaller).

Codes and standards

NACE SP 0169-2007 Standard practice for control of external corrosion on underground metallic pipeline and piping systems.

NACE 10A190 Measurement technique related to criterion for cathodic protection of underground system.

NACE RP 0177 mitigation of AC and lightening effects on metallic structures and corrosion control system.

NACE RP 0286 Isolation of cathodically protected system pipelines.

NACE 554276 cathodic protection monitoring for buried pipelines.

NACE RP 0572 Standard recommended practice for design installation and operation of a cathodic protection system.

ISO 8062 Recommended practice for impressed current cathodic protection system for underground pipeline.

ASTM B338 Grade 1 or 2 Standards and ASTM A 518 M-86 Grade III standard for the selection of MMO anode and its constituent materials.

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Abbreviations

1. ASTM: American standards for testing of materials.
2. AJB: Anode Junction box.
3. AC: Alternating current
4. AGB: Anode Ground Bed
5. CP: Cathodic Protection
6. Dia: Diameter
7. DC: Direct Current
8. GB: Ground Bed'
9. ICCP : Impressed current cathodic protection
10. MMO: Mixed metal oxide
11. NACE: National Association of corrosion engineers
12. PSP: Pipe to Soil Potential
13. ROW: Right of Way
14. TR : transformer Rectifier unit

1. INTRODUCTION

1.1 Philosophy of Cathodic protection:

The first practical use of cathodic protection is generally credited to Sir Humphrey Davy in the 1820s. Davy's advice was sought by the Royal Navy in investigating the corrosion of Copper sheeting used for cladding the hulls of naval vessels. Davy found that he could preserve copper in sea water by the attachment of small quantities of iron or zinc; the copper became, as Davy put it, "cathodically protected".

Cathodic protection can, in principle, be applied to any metallic structure in contact with a bulk electrolyte. In practice its main use is to protect steel structures buried in soil or immersed in water. It cannot be used to prevent atmospheric corrosion.

Structures commonly protected are the exterior surfaces of pipelines, ships' hulls, jetties, foundation piling, and steel sheet-piling and offshore platforms. Cathodic protection is also used on the interior surfaces of water-storage tanks and water-circulating systems. However, since an external anode will seldom spread the protection for a distance of more than two or three pipe-diameters, the method is not suitable for the protection of small-bore pipe work.

Cathodic protection has also been applied to steel embedded in concrete, to copper- based alloys in water systems, and, exceptionally, to lead-sheathed cables and to aluminum alloys, where cathodic potentials have to be very carefully controlled.

1.2 Principles of cathodic protection

Corrosion in aqueous solutions proceeds by an electrochemical process, and anodic and cathodic electrochemical reactions must occur simultaneously. No net overall charge builds up on the metal as a result of corrosion since the rate of the anodic and cathodic reactions are equal. Anodic reactions involve oxidation of metal to its ions, e.g. for steel the following reaction occurs.

$$Fe \text{ -----> } Fe_{2+} + 2e \qquad (1)$$

The cathodic process involves reduction and several reactions are possible. In acidic water, where hydrogen ions (H^+) are plentiful, the following reaction occurs.

$$2H^+ + 2e \longrightarrow H_2 \qquad (2)$$

In alkaline solutions, where hydrogen ions are rare, the reduction of water will occur to yield Alkali and hydrogen.

$$2H_2O + 2e \longrightarrow H_2 + 2OH^- \qquad (3)$$

However, unless the water is de aerated reduction of oxygen is the most likely process, again Producing alkali at the surface of the metal.

$$O_2 + 2H_2O + 4e \longrightarrow 4OH^- \qquad (4)$$

Reactions (1) and (2) are shown schematically in Fig 1 where anodic and cathodic sites are Nearby on the surface of a piece of metal.

We can change the rate of these two reactions by withdrawing electrons or supplying additional electrons to the piece of metal. It is an established principle that if a change occurs in one of the factors under which a system is in equilibrium, the system will tend to adjust itself so as to annul, as far as possible, the effect of that change. Thus, if we withdraw electrons from the piece of metal the rate of reaction (1) will increase to attempt to offset our action and the dissolution of iron will increase, whereas reaction (2) will decrease. Conversely, if we supply additional electrons from an external source to the piece of metal, reaction (1) will decrease to give reduced corrosion and reaction (2) will increase. The latter case will apply to cathodic protection. Thus, to prevent corrosion we have to continue to supply electrons to the steel from an external source to satisfy the requirements of the cathodic reaction. Note that the anodic and cathodic processes are inseparable. Reducing the rate of the anodic process will allow the rate of the cathodic process to increase. These principles may be expressed in a more quantitative manner by plotting the potential of the metal against the logarithm of the anodic and cathodic reaction rates expressed as current densities. Typical anodic and cathodic curves are illustrated in Fig 2. The corrosion current, I_{corr}, and the corrosion potential, E_{corr}, occur at the point of intersection of the anodic and cathodic curves, i.e. where anodic and cathodic reactions rates are equal. If electrons are "pumped" into the metal to make it more negative the anodic dissolution of iron is decreased to a negligible rate at a potential E_1, whereas the rate of the cathodic current is increased to I_1.

Hence, a current I_1 must be supplied from an external source to maintain the potential at E_1 where the rate of dissolution of the iron is at a low value.

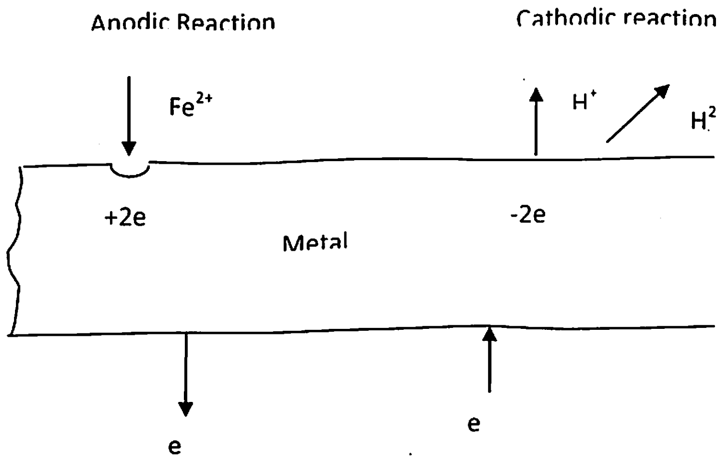


Fig 1: anodic and cathodic reactions on a metal

If the potential is reduced to E_2 (Fig 2) the current required from the external source will increase to I_2. Further protection of the metal is insignificant, however, and the larger current supplied from the external source is wasted. The metal is then said to be over-protected.

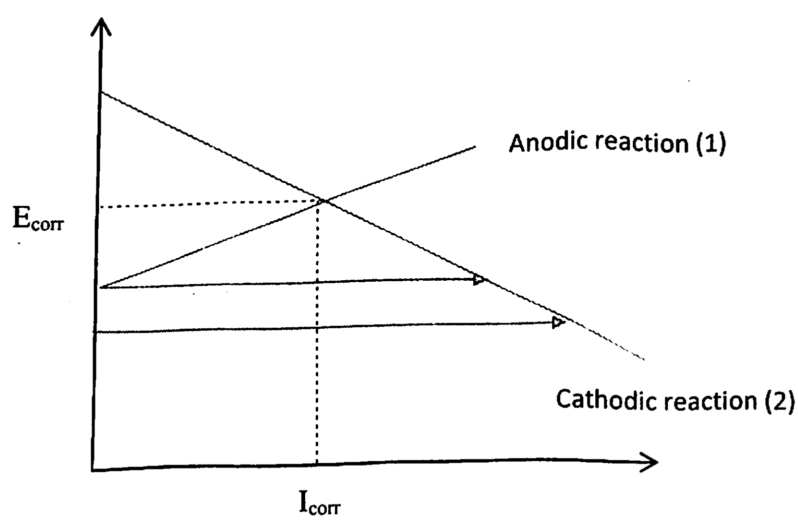


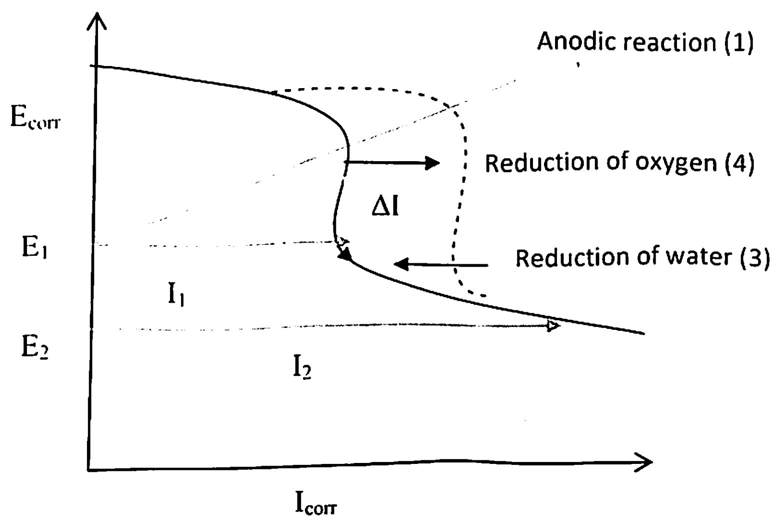
Figure 2: Anodic and cathodic reaction kinematics

In aerated neutral or alkaline solutions the cathodic corrosion process is usually the reduction of oxygen. The kinetics of this cathodic process is controlled by the rate at which oxygen can diffuse to the surface of the metal, which is slower than the rate of consumption of oxygen by the cathodic reaction. Thus, the rate of this reaction does not increase as the potential of the metal is made more negative but remains constant unless the rate of supply of oxygen to the surface of the metal is increased by, for example, increase fluid flow rate. The influence of flow velocity on cathodic protection parameters is illustrated in Fig 3. A current of I_1 is initially required to maintain the metal at the protection potential E_1. However, if the flow rate is increased the limiting current for the reduction of oxygen is increased (dotted line) and the current required to maintain the metal at the protection potential is increased by ΔI. Thus, the current density required to maintain the correct protection potential will vary with service conditions. Clearly, cathodic current density is not a good guide as to whether a structure is cathodically protected. The correct protection potential must be maintained if corrosion is to be prevented.

If the structure is over-protected and the potential is reduced to a potential region where reduction of water (reaction 3) can take place, further current will be required from the External source and current will be wasted. In Fig 3 reducing the potential from E_1 to E_2 will increase the current required from the external source from I_1 to I_2 as a result of an increased rate of reduction of water.

Excessive negative potentials can cause accelerated corrosion of lead and aluminum because of the alkaline environments created at the cathode. These alkaline conditions may also be detrimental to certain paint systems, and may cause loss of the paint film. Hydrogen evolution at the cathode surface may, on high-strength steels, result in hydrogen Embrittlement of the steel, with subsequent loss of strength. It may also cause disbanding of any insulating coating: the coating would then act as an insulating shield to the cathodic protection currents.

Figure 3. Diffusion controlled reduction of oxygen



1.3 Methods of applying cathodic protection

Cathodic protection may be achieved in either of two ways. By the use of an impressed current from an electrical source, or by the use of sacrificial anodes (galvanic action).

1.3.1 Impressed current type:

The arrangement for protecting a buried pipeline is illustrated in Fig 4. The buried pipe receives current from a DC power source via an auxiliary inert electrode buried in the ground. The pipe becomes the cathode and the auxiliary electrode the anode. The auxiliary electrode sometimes consists of scrap iron. In this case the iron will dissolve from the anode by reaction (1) and the electrode is described as a consumable anode. If the anode is a noble metal or an electrochemically inert material, the surrounding environment will be oxidized and in water reaction will occur.

$$2H_2O \text{--------}> O_2 + 4H^+ + 4e \qquad (5)$$

In saline solutions, however, chlorine may be produced at the anode. This may Present problems in confined spaces. A range of materials have been used as non-consumable anodes for impressed-current systems.

The sort of properties required by these anodes is

A. good electrical conduction,

B. low rate of corrosion,

C. good mechanical properties, able to stand the stresses which they may be subjected To during installation and in service,

D. readily fabricated into a variety of shapes,

E. low cost,

F. able to withstand high current densities at their surfaces without forming resistive Barrier oxide layers, etc.

The following materials have been used as anodes:

- Magnetite, carbonaceous materials (graphite)
- High silicon iron (14-18% Si),
- Lead/lead oxide, lead alloys,
- Platonized materials (such as tantalum, niobium, titanium).

Platinum with its high resistance to corrosion would be an ideal anode material but has the major disadvantage of very high cost.

In practice, voltages up to 100 V and high current densities are possible on impressed-current anodes (see Table 1). Thus, large areas of a structure can be protected from a single anode and, because of the high driving voltage; the anode can be placed remote from the structure.

Table 1 property of impressed current anodes

Anode Material	Max Volts	Typical current density $A\text{-}m^2$
Platinum/niobium	100	250 – 1500
Lead/ silver/ Antimony	100	250 – 1000
High silicon iron	100	200
Graphite	-	200

1.3.2 Sacrificial Anode type:

To understand the action of sacrificial anodes for cathodic protection it is necessary to have in mind the galvanic series of metals. The galvanic series for a few selected metals in sea water is shown in Table 2. When the tendency for metal to go into solution as metal ions increases (leaving an excess of electrons on the metal surface), i.e. the metal becomes more electronegative.

$$M \text{ -------> } M^{+} + e \qquad (6)$$

Thus, since zinc, aluminum and magnesium are more electronegative than steel they are increasingly able to supply electrons to the more electropositive steel when in electrical contact in water, and will effect cathodic protection of the steel surface. Clearly, if steel was coupled to copper in sea water, steel would supply electrons to copper which would become cathodically protected, and the corrosion of the steel would be enhanced.

Table 2: Galvanic series of some metals in sea water

Electropositive
Platinum
Titanium
Stainless steel
Monel
Copper
Lead
Iron, cast iron, steel
Cadmium
Zinc
Aluminum
magnesium
Electronegative

The cathodic protection of a steel pipe with sacrificial anodes is illustrated in Fig 5. Electrons are supplied to the steel pipe, via the electrical connection, and a corresponding amount of anode material goes into solution as metal ions, according to the laws of electrolysis.

Some anode material is lost by self-corrosion, and the anodes are not converted to electrical energy with 100% efficiency. Zinc, aluminum and magnesium area the metals commonly used for sacrificial cathodic protection. Some anode properties are shown in Table

The driving voltage of sacrificial anodes is now compared with impressed-current anodes, and sacrificial anodes must be located close to the structure being protected. Although almost any piece of zinc etc could provide cathodic protection over a short period of time, cathodic protection schemes are usually required to operate over periods of several years.

Anodes can lose their activity and become passivated, developing a non-conducting film on their surfaces so that they no longer are able to supply current.

Table 3. Properties of sacrificial anodes

Anode Material	Density	Potential Volts Cu/CuSo4	Amp-hrs per kg	Typical anode current density.
Zn	7.1	-1.10	780	0.5 – 2
Al	2.7	-1.15	2700	0.6 – 2.5
Mg	1.7	-1055	1230	1.5 – 5.6

. This can be avoided by careful control of the Concentrations of trace impurities in the anode materials, and by alloying. For zinc anodes the level of iron, for example, must be kept below 0.005% for satisfactory long-term operation of the anodes. To prevent passivation of aluminum anodes, alloying with, for example, indium has been found to be successful. The previously successful alloy with mercury is now disliked on environmental grounds.

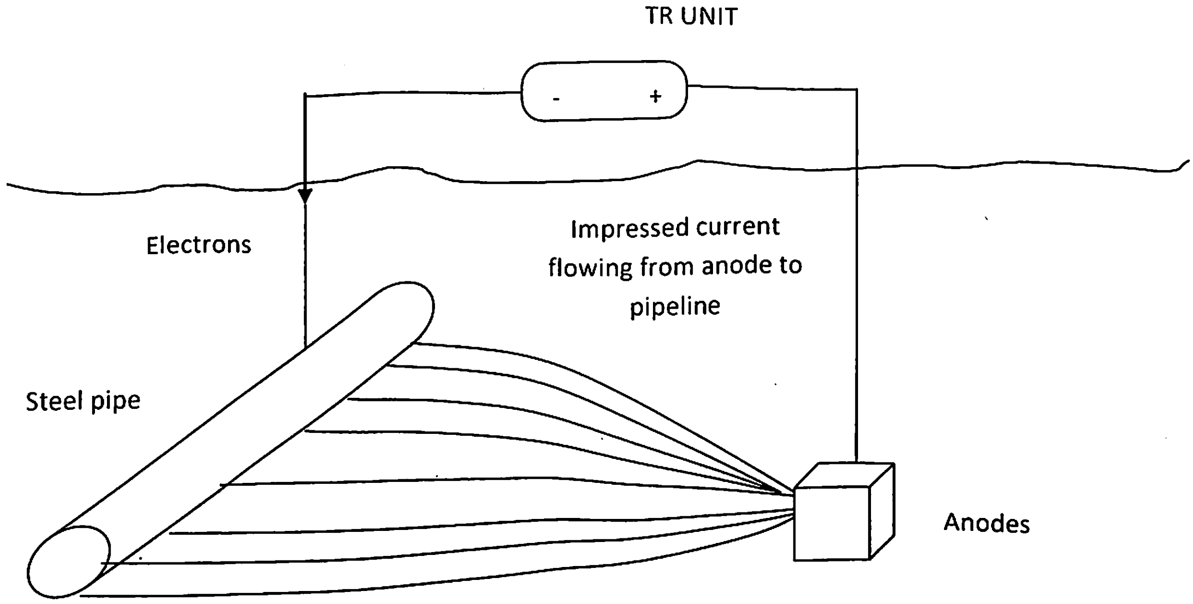


Figure 4. Application of cathodic protection by impressed current method

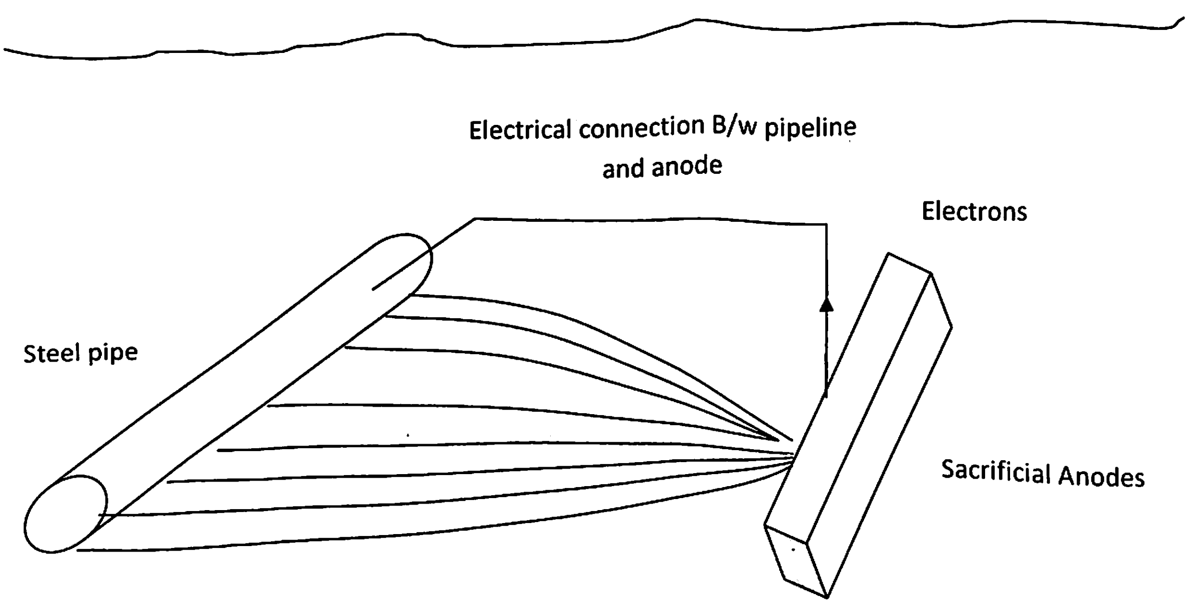


Figure 5. Application of sacrificial type cathodic protection system

2. ANODES AND ANODE BED

2.1 Anode:

NACE RP0169-96 definition of an anode is "the electrode of an electro chemical cell at which oxidation occurs". Either galvanic protection system or an impressed current cathodic protection system this anode is the vital and most important component. So lot of care is taken in the design stage of the cathodic protection system on which type of anode is to be used. There are different anodes of each kind separately for both impressed current type and galvanic type.

This project is dealt with the design of an impressed current cathodic protection system anode ground bed design and so in this document all the emphasis is on the anodes that are used in the ICCP system ground bed. Following discussion is on the types of anodes for the ICCP system that are available in the market and their specification tables. The data in these tables was used in the further parts of document for the design purposes.

2.1.1 Impressed current anodes:

A.) Solid Anodes

Scrap iron is seldom used as anode material today. When applied, it includes old steel girders, pipes, tram lines or railway lines (30 to 50 kg nr1) which are welded together. A suitable cable is brazed onto them. The anode in the vicinity of the cable connection must be well insulated with bitumen (in soils) or cast resin (in water) so that the exposed copper cable cannot be anodically attacked at defects in the insulation.

Since the anodic dissolution of iron takes place with almost 100% current efficiency through the formation of Fe (II) compounds, 1 kg of iron gives about 960 A h. This high weight loss requires the use of a large amount of scrap iron. For a protection system that requires 10 A, at least 2 tons of scrap iron are necessary for 20 years of service life. Iron anodes in the ground are always embedded in coke. Low cost and good stability during transport make up for the high material Consumption.

Magnetite, Fe3O4, conducts electrons because of its defect structure. The resistivity of pure magnetite lies between 5.2 x 10~3 Q cm and as high as 10 X 10~3 Q cm. Magnetite occurs as the mineral (kirunavara and gellivare) in northern Sweden and is mined in large amounts as iron ore. The melting point can be lowered by adding small amounts of other minerals. Cast magnetite is glass hard and free of pores. Formerly only cylindrical compact anodes were produced because of the difficulty of casting this material. According to production data the anode consumption is 1.5 g A4 a"1 calculated from an anode current density of 90 to 100 A m^{-2} Consumption increases with increasing anode current density but it is still very low even at 160 A nr2 giving 2.5 g A"1 a~l Magnetite anodes can be used in soils and aqueous environments, including seawater. They endure high voltages and are insensitive to residual ripple. Their disadvantage is their brittleness, the difficulty in casting, and the relatively high electrical resistance of the material.

Graphite has an electron conductivity of about 200 to 700 Q.~l cm"1, is relatively cheap, and forms gaseous anodic reaction products. The material is, however, mechanically weak and can only be loaded by low current densities for economical material consumption. Material consumption for graphite anodes initially decreases with increased loading and in soil amounts to about 1 to 1.5 kg A"1 a"1 at current densities of 20A m^{-2}.The consumption of graphite is less in seawater than in fresh water or brackish water because in this case the graphite carbon does not react with oxygen.

B.) Noble Metals and Valve Metals Coated with Noble Metals

Impressed current anodes of the previously described substrate materials always have a much higher consumption rate, even at moderately low anode current densities. If long life at high anode current densities is to be achieved, one must resort to anodes whose surfaces consist of anodically stable noble metals, mostly platinum, more seldom iridium or metal oxide films (see Table 4). Cotton proposed solid platinum as a material for impressed current anodes. Such anodes are capable of delivering current densities of 104A m^{-2} under suitable conditions. The driving voltage is practically unlimited, and the consumption rate, assuming optimum conditions, is very low—in the region of less than a few milligrams A"1 a"1. This applies chiefly at relatively low current densities in seawater where there is good dispersion of the hypochlorous acid that is formed. When noble materials have to be used to achieve high anode current densities in poorly conducting electrolytes, the anodic consumption of platinum increases due to the formation of chloral complexes and are then directly dependent on the current density. In addition, in solutions containing little chlorine, the more soluble PtO2 instead of PtO is preferentially formed due to the dominance of oxygen evolution at the anode surface, so that the consumption of platinum also rises. However, the loss is small so that solid platinum is actually an ideal anode material. Such anodes are very heavy because of the high density of platinum (21.45 g cnr3) and are uneconomical because of the very high purchase price of platinum. For this reason anodes of another metal are used whose effective surfaces are coated with platinum.

Platinum on titanium is the best-known anode of this type. The use of platinum on the so-called valve metals was first mentioned in 1913 Titanium is a light metal (density 4.5 g cm"3) that is capable of anodic passivation. The passive film is practically insulating at driving voltages of less than 12V. The current in a NaCl solution is very small up to a potential of UH = +6 V, but rises steeply above this value. The oxide film on titanium, which initially consists of the orthorhombic brookite, is replaced by tetragonal anatase as the thickness of the film increases .If the oxide film, however, is damaged with increasing potential, then it is only regenerated at potentials of UH < 1.7 V. This critical self healing potential is thus less positive than the above-mentioned critical breakdown potential of +6 V.

C.) Metal Oxide-Coated Valve Metals

Good results are obtained with oxide-coated valve metals as anode materials. These electrically conducting ceramic coatings of p-conducting spinel-ferrite (e.g., cobalt, nickel and lithium ferrites) have very low consumption rates. Lithium ferrite has proved particularly effective because it possesses excellent adhesion on titanium and niobium. In addition, doping the perovskite structure with monovalent lithium ions provides good electrical conductivity for anodic reactions. Anodes produced in this way are distributed under the trade name Lida. The consumption rate in seawater is given as 10~3 g A"1 a"1 and in fresh water is about 6 x 10~3 g A"1 a"1. With bedding in calcium petroleum coke, the consumption rate is less than 10~3 g A"1 a"1. The anodes are very abrasion resistant and have a hardness of 6 on the Mohs scale; they are thus much more abrasion resistant than platinized titanium anodes. There are no limitations in forming these anodes as is also the case with platinized titanium anodes. The polarization resistance of these anodes is very low. Therefore, voltage variations at the anode surface resulting from alternating voltage components in the supplying rectifier are very small. The current loading in soil with coke backfill is 100 A m^{-2} of active surface, in seawater 600 A m^{-2} and in fresh water 100 A m^{-2}. They offer great advantages over high-silicon iron anodes as deep well anodes because of their low weight.

TABLE 4.Composition and properties of solid impressed current anodes (Without back fill)

Type	Composition (Wt %)	Density (g cm^{-3})	Anode current density (Am^{-2})		Anode Consumption (g A^{-1} a^{-1})
			Max	Avg	
Graphite	100	1.6 to 2.1	50 to 150	10 to 50	300 to 1000
Magnetite	Fe^3O^4 + additions	5.2	--	90 to 100	1.5 to 2.5
High Silicon Iron	14Si, 1C remainder Fe	7.0 to 7.2	300	10 to 50	90 to 250
Lead Silver alloy 1	1 Ag, 6Sb, Remainder Pb	11.0 to 11.2	300	50 to 200	45 to 90
Alloy 2	1Ag, 5Sb, 1Sn remainder Pb	11.0 to 11.2	300	100 to 250	30 to 80
Lead platinum	Lead + Pt pins	11.0 to 11.2	300	100 to 250	2 to 60

TABLE 5. Data of impressed current anodes for the use in soil

Anode Material	Iron		High Silicon Iron			Graphite			Magnetite	Lithium Ferrite on titanium
Length			0.5	1.2	1.5	1	1.2	1.5	0.9	0.5
Diameter			0.04	0.06	0.075	0.06	0.06	0.08	0.04	0.016
Weight (kg)	56	43	16	26	43	5	6	8	6	0.2
Density (g cm^{-3})	7.8	7.8	7	7	7	2.1	2.1	2.1	5.18	6 to 12
Practical loss without backfill (kg A^{-1} a^{-1})	10	10	0.2 to 0.3			1	1	1	0.002	0.001
Practical loss with coke backfill	5	5	0.1			0.2 to 0.5			-	< 0.001
Life per 1A per anode without coke backfill	5	4	50	80	140	5	6	8	200	120
Life per 1A per anode with coke backfill	10	8	160	260	430	10	12	16	-	> 120
Danger of fracture	None		Moderate			High			Moderate	None
Recommended installation site	Extended anode installation in coke back fill, in poorly conducting soil.		Mostly used for impressed current anodes with long life, without coke backfill			Aggressive soils and aqueous solutions, also without coke backfill			Soil Sea water	Deep anodes Sea water

TABLE 6.Composition and properties of noble metals with metal oxide coatings

Substrate metal	Density (g cm^{-3})	Coating	Density (g cm^{-3})	Coating Thickness (μm)	Anode Current Density (Am^{-2})		Allowable Max Driving Voltage (Volts)	Loss (mg A^{-1} a^{-1})
					Max	Avg		
Platinum	21.45	Platinum	21.45	Solid	> 10^4			< 2
Titanium	4.5	-		-			12 to 14	
Niobium	8.4	-		-			About 50 (< 100)	
Tantalum	16.6	-		-			> 100	
Ti, Nb, Ta		Platinum	21.45	2.5 to 10	> 103	600 to 800		4 to 10
Ti, Nb, Ta		Lithium-ferrite	6 to 12	< 25	> 100 to 600	100 to 600		< 1 to 6

Table 7 .The operating characteristics for MMO coating loadings are shown below

Electrolyte	Maximum Design Current Density	Anode life
Carbonaceous backfill	50 A/m2	20 years
Calcined petroleum coke	100 A/m2	20 years
Fresh water	100 A/m2	20 years
Brackish water	100 A/m2 - 300 A/m2 *	20 years
Sea Water	600A/m2	20 years

Table8. MMO anode dimensions and current output for different environments

Environment	Anode Size (mm)	Current Output (amps)	Life (Years)
Petroleum Coke Soil Freshwater	19 x 1200	7	20
	25 x 500	4	20
	25 x 1000	8	20
	25 x 1200	9.6	20
	25 x 1500	12	20
	32 x 1200	12	20
Seawater	19 x 1200 45	45	20
	25 x 500 25	25	20
	25 x 1000 50	50	20
	25 x 1200 60	60	20
	25 x 1500 75	75	20
	32 x 1200 75	75	20

All the data and the tables presented in the above part of this document is with reference to the **ASTM B338 Grade 1 or 2 Standards and ASTM A 518 M-86 Grade III standard** for the Anode materials and MMO anode substrate properties.

2.2 Anode bed

2.2.1 Introduction:

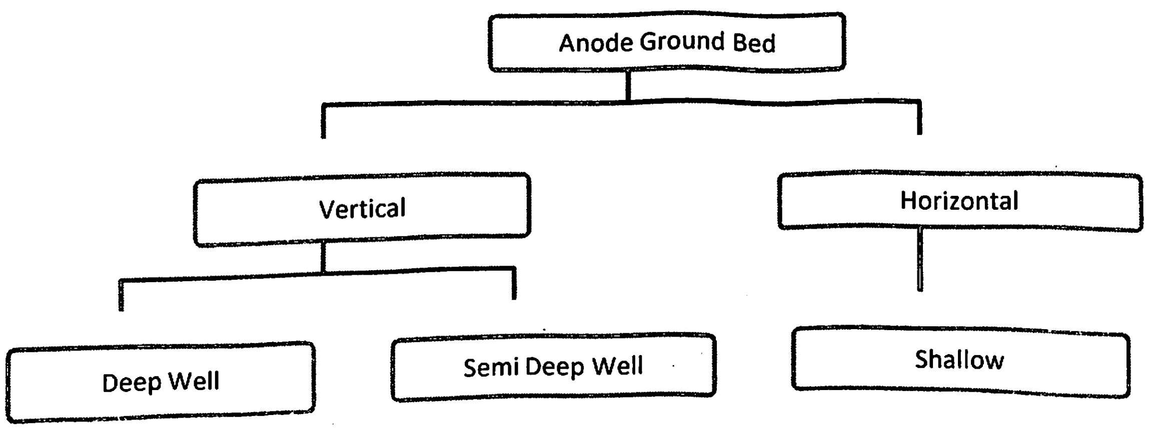
The most important part of all the components of a cathodic protection system either galvanic system or permanent system is the anode ground bed. An anode ground bed can be defined or better to say described (because there is no standard definition in existence) as a rectangular or square plot along the right of way or around the right of way of a pipeline system that contains anodes which can be arranged in different configurations depending on the soil resistivity and other parameters. Depending on the arrangement of anodes in the ground bed plot, different names have been given. But before this classification of anode beds they are also given names depending on their distance of the location from the carrier pipeline. If the location of anode bed is in the vicinity of the ROW or around the carrier pipeline then it is called as close ground bed, which is generally implemented in the sacrificial anode type cathodic protection system for less drive in voltage for the protection current to flow. And the second type is the one which is at 100 to 80 meter away from the ground bed and is called as remote ground bed. This type is implemented in the permanent impressed current cathodic protection system.

2.2.2 Types of anode beds:

There are mainly two types of anode ground beds. They are

- Vertical ground bed type.
- Horizontal ground bed type

The overall classification of the anode ground beds is as below:



2.2.3 Remote vs. close Ground bed

Flow of current from an external source to a pipeline (as is true when the pipeline is cathodically protected) will be accompanied by a potential difference between the earth and the pipeline. The potential difference is used in certain criteria for determining the degree of cathodic protection. Developing the desired potential difference can be accomplished in either of two ways:

- By making the pipeline negative with respect to remote earth, or
- By making the earth positive with respect to the pipe in local areas.

The first method uses remote ground beds, from which substantial lengths of pipeline can be protected. The second method uses close ground beds or anodes, which afford protection only in their immediate vicinity.

2.2.4 Remote Ground Beds

Current discharge, from an anode or group of anodes forming the ground bed, will cause voltage drops in the earth between points along lines radiating from the ground bed. Close to the ground bed, the voltage drop per unit of distance is relatively high. As one move away from the ground bed, this voltage drop per unit of distance becomes less and less until a point is reached beyond which no further significant voltage drop can be observed. This point may be considered as remote earth and establishes the radius of what is termed the area of influence surrounding the ground bed. Exactly as described above, current flowing to the protected pipeline also will cause a voltage drop in the soil adjacent to the line, and there will be an area of influence surrounding the pipeline. The ground bed may be said to be remote from the pipeline if it is far enough away such that there is no significant overlap between the area of influence surrounding the ground bed and the area of influence surrounding the pipeline i.e. it is at remote earth. Under such conditions, current flows from the ground bed into the general mass of the earth, which may be considered a resistance-less, or infinite, conductor. Current will then flow from this infinite conductor to the pipeline to be protected and cause a voltage drop across the resistance between the pipeline and this infinite conductor.

2.2.5 Close Ground Beds

The use of close anodes, or a series of anodes, is quite different from the remote type of installation just described. Their successful use depends on the area of influence surrounding each ground bed anode as has been discussed in general terms. For a better understanding of how close anodes are used, the conductive path between a ground bed anode and remote earth is examined in greater detail.

The current per unit of cross-sectional area of earth (current density) flowing away from a ground bed anode is highest close to the anode and decreases with distance. Where the current density is highest, the greatest point-to-point potential drops can be observed in the earth. The net result of this effect is that most of the potential drop to remote earth of a single anode normally is encountered within the first few feet.

2.2.6 Impressed Current Ground Beds

Design for impressed current ground beds should be based on the types of anode construction adopted by the corrosion engineer for his pipeline system. Typical construction sketches will be shown to illustrate principles involved, but others may be used if found more suitable for specific pipeline conditions. Generally the choices available are horizontal continuous, vertical shallow, vertical shallow parallel and deep well or borehole.

2.2.7 Horizontal Ground beds

The general construction of a horizontal ground bed is shown below. The figure below includes the essential features only. The carbonaceous backfill surrounding the anode, when well tamped, serves two functions:

- Being of a very low resistivity, it has the effect of increasing the anode size with resulting reduction in resistance to earth, and

- Most of the current is transmitted to the backfill from the anode by direct contact so that the greater part of material consumption should take place at the outer edges of the Backfill column.

Since a positive potential (voltage) is impressed on the entire ground bed assembly, it is absolutely essential that all header cable insulation, anode cable insulation, the connection between anode and cable tail (a manufacturer's function) and insulation of connections between cable tails and a header cable or cable runs to a test or junction be completely intact and moisture proof. If this is not maintained, current will be discharged through insulation imperfections, causing wires to corrode and sever in a relatively short period of time, thus losing connections to all or part of the ground bed. Connections between header cable and anode tail must be of permanent low resistance. The maximum permissible resistance of the anodes must be determined.

This is necessary because, in addition to resistance to earth of the anodes, other considerations must be analyzed to determine the total circuit resistance. These include the following:

- Back voltage between ground bed and pipeline,
- Resistance to earth of the pipeline at the ground bed location.
- Resistance of cable from the pipeline to power source and from the power source to and along the anodes comprising the ground bed

The **back emf (back voltage)** is that which exists between the anodes and pipeline in opposition to the applied voltage. For ground bed anodes with carbonaceous backfill, this will be, usually, in the order of 2 V. Some areas of unusual soil composition may result in higher back voltages but the 2-V figure is used commonly for design purposes unless experience in a specific area dictates otherwise. In practice, the back voltage at a working ground bed is determined by measuring the voltage between ground bed and pipeline (across the positive and negative rectifier terminals) immediately after switching the rectifier power OFF. The ground bed will always be positive to the pipeline. If the back voltage is 2V, it means it will require 2 V of the rectifier source voltage to overcome the back voltage before current can flow through.

Resistance to earth of the pipeline depends on the quality of the pipeline coating. The better the coating, the higher the effective resistances at the ground bed location. If current requirement tests made at (or in the vicinity of) the selected ground bed location had indicated that 20 A of applied current would cause a change in pipeline voltage (AV) of -1.5 V to a remote copper sulphate electrode (CSE), the effective pipeline resistance would be 1.5/20 or 0.075 ohm. For most calculations, the resistance of pipe to earth is normally considered to be negligible.

Cable resistance is the additive resistance of the cable from the pipeline via the power source to the first anode of the ground bed (assuming that the line of ground bed anodes is perpendicular to the pipeline), plus effective resistance of the header cable along the line of anodes or individual anode cables. This effective header cable resistance is less than that of the full length of the ground bed because all current does not flow the full length of the ground bed but is diminished as each anode connected drains off its share of current. Although subject to variations with differences in individual anode resistance and possibly other factors, it is practical to use the resistance of one half of the ground bed header cable resistance as the effective header cable resistance. Another important consideration in selecting the number of anodes is desired anode life and the dimensions of the column of coke breeze. If the minimum number of anodes or length/volume of the coke column that will give a satisfactory low ground bed resistance will not result in adequate life, the number of anodes or column size would have to be increased accordingly.

2.2.8 Vertical Anode Ground bed

The number of vertical anodes required to attain a required ground bed resistance can be determined by using the following formula based on all anodes being along a straight line, the most favorable ground bed configuration in most instances.

3. ANODE BED DESIGN FLOW CHART FORMULATION

The basic idea behind the formulation of the flow chart for this design procedure is to make the content clear and a good understanding of the anode selection criterion can be achieved with this flow chart.

Before forming the flow chart the formulae that are used in the design of this anode ground bed are described with nomenclature and table for constants if any are also presented below. All these formulae are in strict accordance with the NACE RP0169-96 NACE 10A190 standards.

3.1 Formulae for anode bed design:

E1. Calculation of attenuation constant α:

$$\alpha = \sqrt{\frac{Rs}{Rl}}$$

$$R_s = (\rho_s * L_s) / A$$

$$R_L = R_P / A_S$$

Here

Ps = Resistivity of steel (ohm-meter)

Ls = Length of pipeline unit (section)

A = Cross section area of the pipeline

Rs = Linear resistance of pipe line section

R_P = Coating resistance of 3LPE

A_s = surface area of the pipeline of unit length (1000m)

R_L = Coating leakage resistance (ohms)

E2. Calculation of protection span:

$$L_n = \frac{1}{\alpha} * \cosh^{-1}\frac{Vd}{Vx}$$

Maximum change in potential at drain point is Vd

Minimum change in potential will be steel natural potential i.e., Vx

E3. Pipeline current requirement:

$$I_t = A * I_p * S_f$$

Where A = total surface area of the pipeline

$$A = \pi * D * L$$

Here D = Diameter of the pipeline in meter

L = Length of the pipeline in meter

I_p = Pipeline current density

S_f = safety factor

E4. Calculation for the weight of selected anode for required Ampere output:

$$W = \frac{It * Cr * Y}{Ur}$$

Where: W = Total Anode Weight (kg)

It = CP current requirement

Cr = Anode consumption rate (0.1 kg/amp-year)

Y = Design life in years

Ur = Anode utilization factor

E5. Calculation of number of anodes based on current output of each anode:

$$I_a = 2\pi r l * I_{cd}$$

Where: 2r = Diameter of the anode

L = length of the anode

I_{cd} = Anode Surface current density

E.6 Calculation of total circuit resistance of the shallow horizontal ground bed:

$$R_T = \frac{Rb}{N} + R_{gb} + R_C + R_p$$

In the above formula:

E7. Individual anode to backfill resistance (R_b):

$$R_b = \frac{0.159 * \rho}{l} \left(\ln \frac{8l}{D} - 1\right)$$

ρ = Backfill resistivity (Ohm- meter)

l = length of the bare anode

D = Diameter of the bare anode

E8. DWRIGHT proposed an equation for the anode to backfill resistance (R_{gb}):

$$R_{gb} = \frac{0.159 * \rho}{L} \left(\ln \frac{4L^2 + 4L\sqrt{S^2 + L^2}}{D\,S} + \frac{S}{L} - \frac{\sqrt{S^2 + L^2}}{L} - 1\right)$$

In the above equation S = twice the depth of ground bed.

R_{gb} = total ground bed anode to back fill resistance

L = length of the ground bed

ρ = soil resistivity

E9. Anode tail cable resistance:

$$\frac{1}{Rca} = \frac{1}{Rca1} + \frac{1}{Rca2} + \frac{1}{Rca3} + \frac{1}{Rca4} + \ldots$$

E10. Header cable resistance:

$$R_{hc} = (R_{cable} * L_{+ve}) + (Rcable * L_{-ve})$$

R_{hc} = Total header cable resistance

R_{cable} = Cable resistance per meter

L_{+ve} = length of anode header cable

L_{-ve} = length of cathode header cable

E11. Total cable resistance:

Total cable resistance is given by sum of header cables resistance and the backfill to anode resistance

$$R_C = R_{ca} + R_{hc}$$

E12. Rating for the transformer rectifier unit:

$$V_{req} = (I_{req} * R_T) + B_{emf}$$

Here, B_{emf} = back emf of the TR unit (assumption)

All the above mentioned formulae from E1 to E12 are used in the design of the anode bed and the preceding design phase uses all the above formulae and the values of the constants used in the formulae are in accordance with NACE standards and for anode data ASTM standards.

The tables for the properties of different types of anodes with their properties and compositions are given in the previous part of the document from TABLE 1 to TABLE 5. All the data provided in that tables are with reference to the ASTM B3388 and B348 standards and also from the literature of HAND BOOK OF CATHODIC PROTECTION 3e chapters 1, 6, 7.

Also tables on the resistance of standard copper cables per foot were given which are helpful in finding the resistance of the anode and cathode header cables. TABLE 6 and TABLE 7 provide the required data and is with reference to the NACE publication "Control of pipeline corrosion" by AW Peabody Chapter 8, Page no 97.

Table 9 Resistance of copper conductors used as cables in the connections

	Resistance of stranded copper conductors in Ohms per foot times 10^{-3} at 25 C	
General use	Conductor Size (Awg)	resistance
Impressed current ground beds	4/0	0.0509
	3/0	0.0642
	2/0	0.0811
	1/0	0.102
	1	0.129
	2	0.162
	4	0.259
	6	0.410
Galvanic anode installations	8	0.654
	10	1.04

Pipeline test points	12 14	1.65 2.62
Instrument test leads	16 18 20 22	4.18 6.66 10.6 17.0

Table10. Correction factors for other operating temperatures of the standard copper conductors

Temperature C	= F	Multiply resistance at 25 C by
-10	14	0.862
-5	23	0.882
0	32	0.901
5	41	0.921
10	50	0.941
15	59	0.961
20	68	0.980
30	86	1.020
35	95	1.040
40	104	1.059

Depending on the soil resistivity survey along the pipeline and the anode ground bed plots total pipeline section can be categorized on the basis of the corrosive nature of the soil (NACE specified) as below

Table11. Corrosion severity on the basis of soil survey

Resistivity Range Ohm – cm	Corrosion activity
0 – 1000	Probably sever
1000 – 10000	Moderate to sever
10000 – 100000	Mild if aerated
>100000	Not corrosive

The minimum protection current density for different categories of soil resistivity according to NACE RP 0169 is given in the table below:

Table12. Minimum protection current densities

Pipeline surrounding resistivity	Minimum protection current density ($\mu A/m^2$)
> 100 ohm – cm	35
10 ohm – cm to 100 ohm – cm	50
< 10 Ohm - cm	100

3.2 Formulation of flow chart for the design of anode bed:

To formulate the flow chart for the design of the anode ground bed, a site for this ground bed is to be selected. General considerations for the selection of this ground bed are based on the issues mentioned below:

1. Are other underground metallic structures within the area of influence surrounding the ground bed?
2. Is the proposed site is on or off the pipeline ROW. If Off how to procure the rights?
3. If a rectifier powered ICCP is to be installed then is there a power line present?
4. Is the site reasonably accessible for construction and maintenance purposes?
5. Are there plans for construction like building or highways that make the site untenable in the near future?

Now once the ground bed is selected following is the algorithm for the design of all the parameters of the anode ground bed:

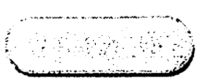
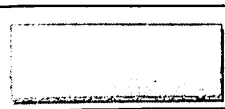
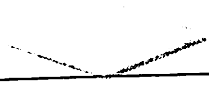
To start the design of anode bed for an ICCP system the procedure to follow is as below:

- Calculate the total length of line to be protected in meter.
- Calculate the surface area of the piepline of that particular length.
- Now from the soil resistivity survey readings available for that spread classify the total surface area obtained above into corrosive, moderately corrosive, less corrosive etc.
- This classification enables to decide the protective current density for the pipeline section.
- Now obtain the total current requirement for protection for each section of piepline.
- Using this value of current weight of the anode needed for delivering the obtained protective current can be calculated.
- Total weight of anodes divided by the current output of each anode gives total number of anodes.

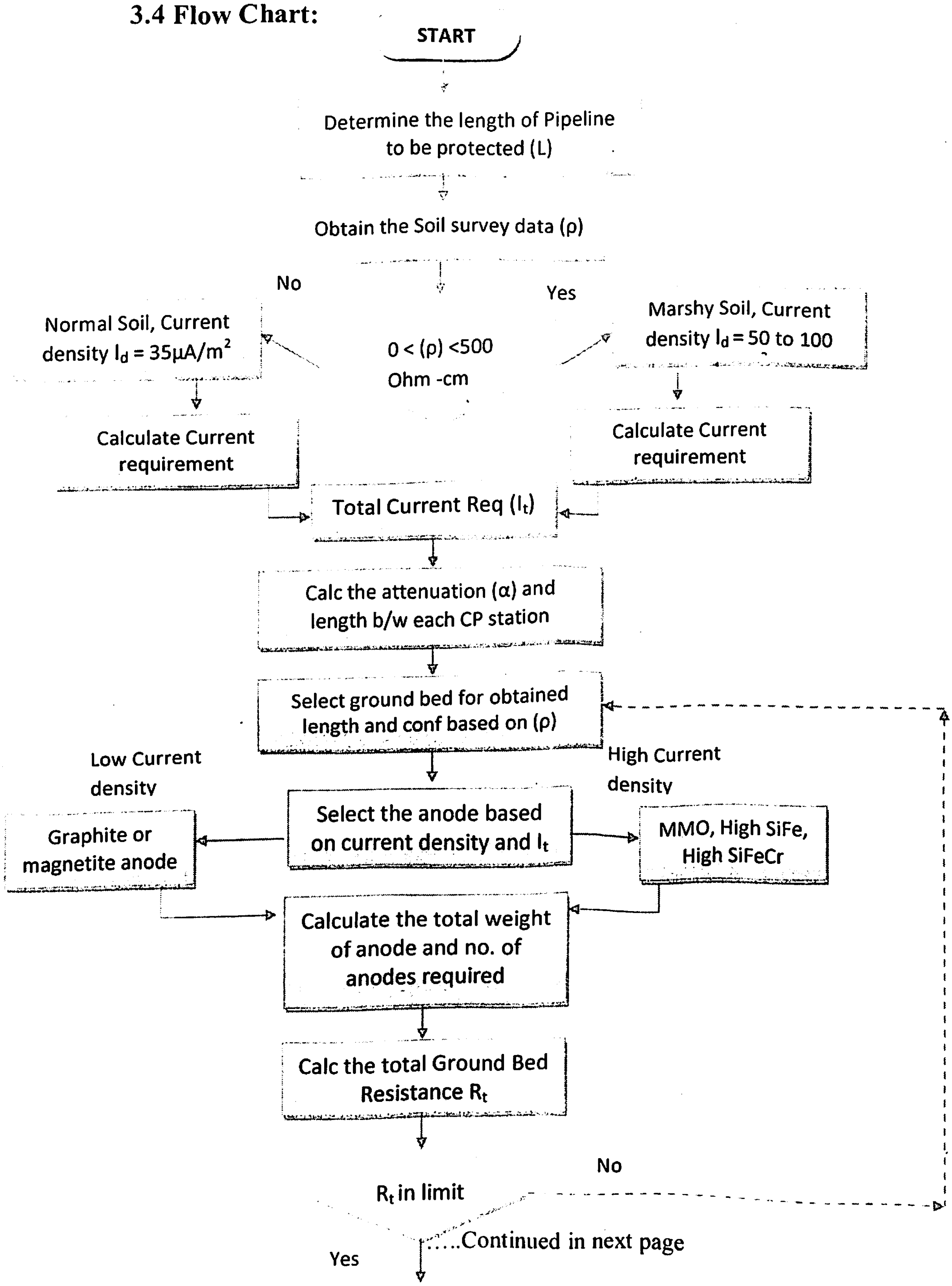
- Calculate the total circuit resistance of the Anode bed including the anode and cathode header cables resistances, backfill to earth resistance and anode to backfill resistance.
- This resistance multiplied by the current requirment of the particular section under the anode bed influence gives the voltage required for the protection of the piepline section.
- This completes the design of the anode bed for given length of pipeline.

Keeping in mind all the above considerations for the design of the anode bed a flow chart was formed as below. In the flow chart there are two decision boxes in which soil resistivity was considered in accordance with the table no. 12 and in the middle of the flow chart current densities were considered in accordance with tha data in the table no. 8. The legend for the flow chart is provided below.

3.3 Legend for the flow chart:

	Start or End of a Process
	Design Data and Calculation
	Decision Box
———▷	Feed Forward
- - - - - - - ▷	Feed back

3.4 Flow Chart:



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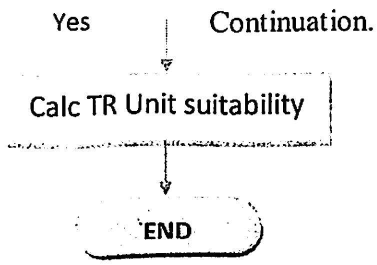
Yes
Continuation.
Calc TR Unit suitability
END

4. ANODE BED DESIGN FOR A 161.00 KM LONG APIX65 STEEL PIPELINE:

4.1 Introduction to the pipeline and the ROW:

M/s HPCL Mittal pipeline limited is implementing laying of pipeline for length of 1020.425 km approx with different size of OD pipeline i.e, 48"/28"/30" from COT mundhra to Bathinda. The complete project is divided into 2 parts.

PART A:

28" OD pipeline from mundhra terminal to chainage 544.20 km with a thickness of 0.0079 meter.

PART B:

30" OD pipeline from chainage 544.20 km to bathinda receiving terminal chainage 1014.140 km.

Part A of the project is again divided into 3 spreads.

This project deals with the design of anode bed for the section of pipeline that comes under SPREAD-1 i.e, from chainage 0.000km to chainage 161.350 km. which gets into an overall length of 161.350 km pipeline.

This design is done for two types of anode beds viz; **deep well type anode bed and shallow horizontal type anode bed.**

To start the design of anode bed for an ICCP system the procedure to follow is as below:

- Calculate the total length of line to be protected in meter.
- Calculate the surface area of the piepline of that particular length.
- Now from the soil resistivity survey readings available for that spread classify the total surface area obtained above into corrosive, moderately corrosive, less corrosive etc.

- This classification enables to decide the protective current density for the pipeline section.
- Now obtain the total current requirement for protection for each section of piepline.
- Using this value of current weight of the anode needed for delivering the obtained protective current can be calculated.
- Total weight of anodes divided by the current output of each anode gives total number of anodes.
- Calculate the total circuit resistance of the Anode bed including the anode and cathode header cables resistances, backfill to earth resistance and anode to backfill resistance.
- This resistance multiplied by the current requirment of the particular section under the anode bed influence gives the voltage required for the protection of the piepline section.
- This completes the design of the anode bed for given length of pipeline.

Before starting the above procedure for designing an anode bed, it is necessary to calculate the length of pipeline an anode bed can protect from its drain point. This is calculated with the help of a constant that is calculated from the pipe linear resistance and coating leakage resistance. This constant is termed as Attenuation constant **α.**

4.2 Design Calculations

4.2.1 Calculation of attenuation constant α:

The cross section area of the 161.350 spread pipeline section is:

$$A = \frac{\pi}{4}(D^2 - (D - 2t)^2)$$

Here D= Diameter of the pipe = 28" = 0.7112 mts.

t = Thickness of the pipe = 0.0079 mts.

So A = cross section area = 0.0175 sqmt.

Linear resistance of the pipeline of 28" OD and 7.9 mm thickness is given by

$$R_s = \frac{\rho s * Ls}{A}$$

Here ρs = Resistivity of steel (ohm-meter) = $1.8 * 10^{-7}$

Ls = Length of pipeline unit (section) = 1000 meter

A = Cross section area of the pipeline = 0.0175 sqmt

Rs = Linear resistance of pipe line section = 0.010 ohm

Coating leakage resistance of 28" pipeline having 3 LPE coating is given by:

$$R_L = \frac{Rp}{As}$$

Here R_P = Coating resistance of 3LPE = 20000 ohm meter.

A_s = surface area of the pipeline of unit length (1000m) = 2234.30 sqmt

R_L = Coating leakage resistance (ohms) = 8.95

Now the attenuation constant **α** is:

$$\alpha = \sqrt{\frac{Rs}{Rl}} \quad \text{-----→} \quad \textit{ref E 1}$$

So

$$\alpha = \sqrt{\frac{0.010}{8.95}}$$

$$\boxed{\alpha = 0.0334}$$

Now the protection span of each anode bed or indirectly each CP station is given by

$$L_n = \frac{1}{\alpha} * \cosh^{-1}\frac{Vd}{Vx} \quad \text{-----→} \quad \textit{ref E 2}$$

From the **NACE 10A190 & NACE's RP-0169-92** minimum criterion for pipeline protection

Max OFF potential = -1.180 V

Min OFF Potential = -0.900 V

Natural potential of bare steel = -0.450 V

Drift allowed = +100 or -100 V

So Maximum change in potential at drain point is Vd = -0.900 + or – 100 v approx say 0.73 V

Minimum change in potential will be steel natural potential i.e., Vx = 0.450 V

So

$$Ln = \frac{1}{0.0334} * \cosh^{-1}\frac{0.730}{0.450}$$

$$\boxed{L_n = 31.85}$$

So for every 31.85 km there should be an anode bed.

4.2.2 Selecting the ground bed site:

So for every 31.85 km along the pipeline length an anode bed is to be installed and the most important considerations that must be taken into account while selecting this location are given as below:-

1. Are other underground metallic structures within the area of influence surrounding the ground bed?
2. Is the proposed site is on or off the pipeline ROW. If Off how to procure the rights?
3. If a rectifier powered ICCP is to be installed then is there a power line present?
4. Is the site reasonably accessible for construction and maintenance purposes?
5. Are there plans for construction like building or highways that make the site untenable in the near future?

Once the ground bed site have been selected keeping all the above points in mind, the next step is to find the soil resistivity of the ground bed sites and there by the effective soil resistances for the design purposes.

4.2.3 Resistivity measurement at the ground bed locations:

The soil resistivity survey at the ground bed locations is carried out by wenners 4 pin method at the proposed PCP ground bed locations at a depth of 1.5m, 2.5m, 3.5m, 5m, 10m, 15m, 20m, . . .35m.

This survey is generally carried out all the proposed ground bed locations and the worst case of protection criterion is taken as the base for design purpose of rest of all ground beds. So in this project survey is carried out at all the proposed 6 anode bed sites and the chainage 35.300 km is considered as the base for the design of rest all ground bed locations.

The soil resistivity report of all the locations as below:

00.000 km chainage (ref: Annexure fig 1)

S.no	Chainage (KM)	Cp station location	Pin spacing(m)	Soil resistivity
1.	0.00	SV 1/ Plot A	1.5	7.53
			2.5	4.08
			3.5	5.05
			5	5.96
			10	8.79
			15	9.42
			20	0.00
			30	0.00
			40	00.00
			50	00.00
2.	0.00	SV1/ Plot B	1.5	8.47
			2.5	3.61
			3.5	4.61
			5	5.65
			10	10.04
			15	14.13
			20	12.56
			30	0.00
			40	0.00
			50	0.00

35.300 km chainage (ref: Annexure fig 2)

S.no	Chainage (KM)	Cp station location	Pin spacing(m)	Soil resistivity
1.	35.300	SV 2/ Plot A	1.5	39.56
			2.5	36.11
			3.5	39.56
			5	40.82
			10	55.98
			15	75.36
			20	62.80
			30	75.36
			40	00.00
			50	00.00
2.	35.300	SV2/ Plot B	1.5	49.92
			2.5	45.53
			3.5	43.96
			5	178.98
			10	200.96
			15	122.46
			20	113.04
			30	113.04
			40	50.24
			50	31.40

65.829 km chainage (ref: Annexure fig 3)

S.no	Chainage (KM)	Cp station location	Pin spacing(m)	Soil resistivity
1.	65.829	SV 3/ Plot A	1.5	55.98
			2.5	35.36
			3.5	39.56
			5	40.82
			10	39.56
			15	36.11
			20	62.80
			30	75.36
			40	00.00
			50	00.00
2.	65.829	SV3/ Plot B	1.5	50.24
			2.5	31.40
			3.5	43.96
			5	178.98
			10	0.00
			15	0.00
			20	0.00
			30	39.04
			40	49.92
			50	45.53

95.500 km chainage (ref: Annexure fig 4)

S.no	Chainage (KM)	Cp station location	Pin spacing(m)	Soil resistivity
1.	95.500	SV 4/ Plot A	1.5	65.21
			2.5	37.65
			3.5	45.23
			5	32.25
			10	120.23
			15	113.20
			20	125.63
			30	0.00
			40	0.00
			50	0.00
2.	95.500	SV4/ Plot B	1.5	23.21
			2.5	35.26
			3.5	52.32
			5	126.23
			10	152.32
			15	206.85
			20	132.52
			30	0.00
			40	0.00
			50	0.00

129.392 km chainage (ref: Annexure fig 5)

S.no	Chainage (KM)	Cp station location	Pin spacing(m)	Soil resistivity
1.	129.392	IPS 1/ Plot A	1.5	45.23
			2.5	37.85
			3.5	31.23
			5	46.21
			10	58.92
			15	115.32
			20	145.39
			30	210.36
			40	0.00
			50	0.00
2.	129.392	IPS 1/ Plot B	1.5	25.36
			2.5	31.85
			3.5	56.21
			5	45.26
			10	120.36
			15	159.32
			20	175.36
			30	220.96
			40	0.00
			50	0.00

161.30 km chainage (ref: Annexure fig 6)

S.no	Chainage (KM)	Cp station location	Pin spacing(m)	Soil resistivity
1.	161.30	SV 5/ Plot A	1.5	35.65
			2.5	31.25
			3.5	45.38
			5	56.98
			10	57.21
			15	126.23
			20	156.45
			30	50.13
			40	45.29
			50	0.00
2.	161.30	SV5/ Plot B	1.5	50.26
			2.5	38.26
			3.5	89.23
			5	97.36
			10	115.63
			15	127.88
			20	175.89
			30	215.36
			40	0.00
			50	0.00

Now by observing the soil resistivity data obtained from the graphs plotted for Pin spacing Vs soil resistivity (see ANNEXURE) and the conclusion from the plots is as below:

1. As the depth increases the soil resistivity increases.
2. At depth of 2.5 mts at all ground bed locations Plot A/Plot B the soil resistivity value is around 30 to 35 ohmmeter.

So from these two conclusions the decision taken is that:

1. The ground bed type for all the locations is a **shallow horizontal type ground bed**
2. The soil resistivity at 2.5 meter depth is considered for the design calculations.

Till now the in the design of the anode bed primary things to be known are concluded. Now the current requirement for protection of the pipeline length and in return weight of the anode required for the desired current output is to be determined.

4.2.4 Pipeline current requirement:

The amount of current required for the protection of the pipeline length of 161.35 km and diameter of 28" is given by multiplying the pipeline current density I_p with the total surface area of the pipeline length. Data in accordance with TABLE 12.

So current required, $I_t = A * I_p * S_f$ -----→ *ref E3*

Where A = total surface area of the pipeline

$A = \pi * D * L$

Here D = Diameter of the pipeline in meter = 0.711 meter

L = Length of the pipeline in meter = 161350 meter

I_p = Pipeline current density for soil resistivity of 10 ohm-m to 100 ohm-m = 50 mA/m^2

S_f = safety factor = 1.3

So $I_t = \pi * 0.711 * 161350 * 50 * 1.3$

I_t = 23426197.4687599977 mA

$$I_t = 23.426$$

So the protection current required for this length of pipeline is 23.426 A

4.2.5 Selection of the Anode for installation:

With reference to the Handbook of CATHODIC CORROSION PROTECTION by W. VON BAECKMANN W. SCHWENK and W. PRINZ chapter no: 7 **Metal Oxide-Coated Valve Metal type anode** is concluded to be used in the ground bed design. This is known as **MMO** anode with a trade name in the market LIDA. The main reason and the points considered in choosing this anode are as below:

1. Good results can be obtained with oxide -coated valve metals as anode materials.
2. With bedding in calcium petroleum coke, the consumption rate is less than 10~3 g A^{-1} a^{-1}.
3. The anodes are very abrasion resistant and have a hardness of 6 on the Mohs scale; they are thus much more abrasion resistant than Platonized titanium anodes.
4. There are no limitations in forming these anodes as is the case with Platonized titanium anodes.
5. The polarization resistance of these anodes is very low. Therefore, voltage variations at the anode surface resulting from alternating voltage components in the supplying rectifier are very small.
6. The current loading in soil with coke backfill is 100 A irr2 of active surface
7. They offer great advantages over high-silicon iron anodes as deep well anodes because of their low weight

Table 13.The Standard properties of MMO Anode are tabulated as below: **(ASTM B3388 and B348)**

S.no	Property	Description
1	Anode Type	Mixed Metal oxide Coated anode
2	Anode Application	Deep or shallow horizontal ground bed in neutral soil or fresh soil with carbonaceous backfill for protection of underground pipeline systems
3	Anode dimensions	Hollow tubular 500mm long by 25mm OD
4	Anode weight	3.0 kg
5	Anode material	Titanium substrate with MMO coating
6	Anode design life	30 years
7	Anode current output	4 Amperes
8	Anode current density with calcined coke	100 A/m^2
9	Coating resistivity	$6 * 10^{-5}$ Ohm-m
10	Anode consumption rate	0.1 kg/A/year with calcium petroleum coke backfill

4.2.6 Calculation for the weight of selected MMO anode for required 23.426 A Output:

The weight of the anode for ground bed on the basis of the current requirement amps obtained is calculated with the formula below: Data in TABLE 13 and TABLE 6 & 7.

$$W = \frac{It * Cr * Y}{Ur} \quad \text{-----}\rightarrow \quad \textit{Ref E4}$$

Where:

W = Total Anode Weight (kg)
It = CP current requirement
Cr = Anode consumption rate (0.1 kg/amp-year)
Y = Design life in years
Ur = Anode utilization factor

$$W = \frac{23.426*0.1*30}{0.85}$$

= 82.68 kg of anode is needed for the current output of 23.426 A

W = 82.68 kg

So approx 108* kg of anode can be installed in all the ground beds. Weight of each anode is 3 kg. So numbers of anodes required are

108 / 3 = 36 anodes over all

*This approx is done in view of weight of individual anode.

I_t (for each section):

I_t (for each section) = $A * I_p * S_f$

$A = \pi * 0.711 * 3200$

= 7147.75 sqmt

I_t = 7147.75 * 50 * 1.3

= 464603.85 mA

= 4.646 A or Approx 5 ampere

4.2.7 Weight of anode for each section of anode bed:

$$W = \frac{5.0 * 0.1 * 30}{0.85}$$

=16.34 kg

Approx = 18 kg

Numbers of anodes required are 18 /3 = 6 anodes (at each ground bed)

4.2.8 Calculation of number of anodes based on current output of each anode:

The current output per anode Ia can be calculated on the basis of the formula:

$I_a = 2\pi r l * I_{cd}$ -----→ *Ref E5*

Where:

$2r$ = Diameter of the anode (.025m)

L = length of the anode (0.5 m)

I_{cd} = Anode Surface current density (100 Amp/sqmt)*

$$So,\ Ia = 2 * 3.141 * (0.025/2) * 0.5 * 100$$

$$Ia = 3.92699 ampere$$

Approx 4 A.

No of anodes required for 24 amp current output is 24 /4 = 6 Anodes

Which is in contradiction with the result obtained above, but it's better to go by 36 anodes in regard of the safety and climatic changes in the soil of ground bed.

* With calcined petroleum coke

So finally,

A shallow horizontal ground bed at a depth of 2.5 meter from the ground with current rating of 24 amperes, i.e. 6 * 4 amperes anodes string is concluded as the design for the pipeline section.

4.2.9 Calculation of total circuit resistance of the shallow horizontal ground bed:

The shallow horizontal ground bed configuration is as shown in the figure below. In the below figure there are 3 possibilities for the current to get resisted:

1. Anode tail cables resistance
2. Header cables resistance
3. Anode to back fill resistance

   So the total resistance offered by the anode ground bed for the protection current to flow is given by the combination of all the above mentioned resistances.

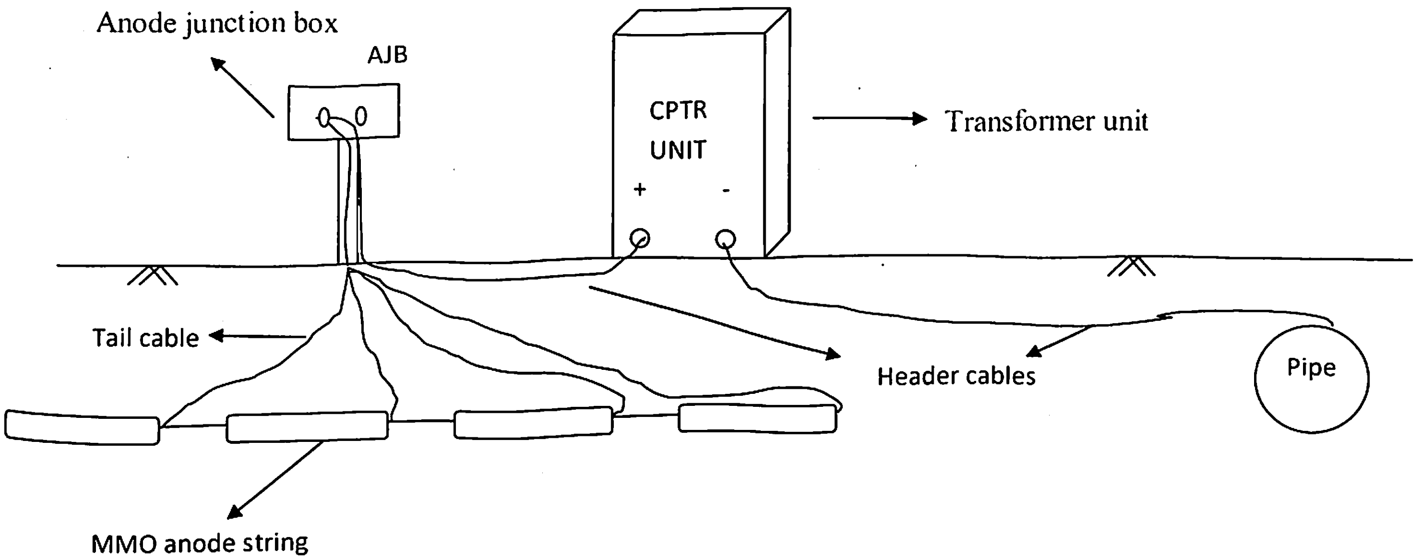

Figure 6: Typical Horizontal Ground bed anode arrangement with TR unit

a) **Individual anode to backfill resistance calculation:**

Backfill resistance is given by the formula as

$$R_b = \frac{0.159 * \rho}{l} (\ln \frac{8l}{D} - 1) \quad \dashrightarrow \quad \textit{ref E 7}$$

ρ = Backfill resistivity (Ohm- meter) = 0.5

l = length of the bare anode = 500 mm = 0.5 m

D = Diameter of the bare anode = 0.025 m

R_b = 0.6479 ohms

For multiple anodes in the ground bed DWRIGHT proposed an equation for the anode to backfill resistance as below:

$$R_{gb} = \frac{0.159 * \rho}{L} (\ln \frac{4L^2 + 4L\sqrt{S^2 + L^2}}{D\,S} + \frac{S}{L} - \frac{\sqrt{S^2 + L^2}}{L} - 1) \quad \dashrightarrow \quad \textit{ref E 8}$$

In the above equation S = twice the depth of ground bed.

R_{gb} = total ground bed anode to back fill resistance

L = length of the ground bed

ρ = soil resistivity at 2.5 meter depth (Avg of all ground beds)

At all ground beds Avg soil resistivity at 2.5 meter depth is = 35.644 ohm-m. So for safety consideration almost double the resistivity is considered. So

ρ = 70 ohm–m

L =60 m

S = (2.5 * 2) = 5 m

D = Diameter of ground bed anode.

= 0.1855 * (Ln (28849.913) + 0.07986)

= **R_{gb} = 1.191 ohms**

b) Anode tail cable resistance: (For Data Ref TABLE 9 and 10)

The equation for the anode tail cable is given by:

$$\frac{1}{Rca} = \frac{1}{Rca1} + \frac{1}{Rca2} + \frac{1}{Rca3} + \frac{1}{Rca4} + \ldots \quad \text{-----}\rightarrow \quad ref E\ 9$$

From the specifications of the cables used in the design

Cable size is 1C * 10 mm^2 650/1100 V

Resistance per meter of cable = 0.00172 ohm

Length of cable 1 is ca1 = 38 m Rca1 = 38.0*0.00172 = 0.06536

Length of gable 2 is ca2 = 31.4 m Rca2 = 31.4*0.00172 = 0.054008

Length of cable 3 is ca3 = 24.8 m Rca3 = 24.8*0.00172 = 0.042656

Length of cable 4 is ca4 = 18.2 m Rca4 = 18.2*0.00172 = 0.031304

$$\frac{1}{Rca} = \frac{1}{0.06536} + \frac{1}{0.05400} + \frac{1}{0.04265} + \frac{1}{0.031304}$$

$$\frac{1}{Rca} = 89.20973$$

$$\boxed{Rca = 0.0112 \text{ ohm}}$$

c) **Header cable resistance:** (For Data Ref TABLE 9 and 10)

The equation for the calculation of the resistance of the anode of cathode header cables each of lengths 150 m and 50 m respectively is

$$R_{hc} = (R_{cable} * L_{+ve}) + (Rcable * L_{-ve}) \quad \text{-----}\rightarrow \quad \textit{ref E10}$$

R_{hc} = Total header cable resistance

R_{cable} = Cable resistance per meter = 0.00049 ohm

L_{+ve} = length of anode header cable = 150 m

L_{-ve} = length of cathode header cable = 50 m

So, Rhc = (0.00049 * 150) + (0.00049 * 50)

$$\boxed{R_{hc} = 0.098 \text{ ohm}}$$

d) **Total cable resistance:** (For Data Ref TABLE 9 and 10)

Total cable resistance is given by sum of header cables resistance and the backfill to anode resistance

$$R_C = R_{ca} + R_{hc} \quad \text{-----}\rightarrow \quad \textit{ref E11}$$

$R_C = 0.0112 + 0.098$

$$\boxed{R_C = 0.1092 \text{ ohm}}$$

Total circuit resistance of the anode bed is given by the equation below:

$$R_T = \frac{Rb}{N} + R_{gb} + R_C + R_p \quad \text{-----}\rightarrow \quad \textit{ref E6}$$

R_p = pipeline to earth resistance (assumed) = 0.1 ohm

$$R_T = \frac{0.6479}{6} + 1.191 + 0.1092 + 0.1$$

$$\boxed{R_T = 1.508}$$

So the total ground bed resistance of the design is 1.508 ohm.

4.2.10 rating for the transformer rectifier unit:

The rating of the Tr/Rectifier unit can be estimated with the current requirement of the section and ground bed resistance obtained as below:

$$V_{req} = (I_{req} * R_T) + B_{emf}$$

B_{emf} = back emf of the Tr unit (assumption) = 2 volt

$$\text{So } V_{req} = (4 * 1.508) + 2$$

$$\boxed{V_{req} = 8.032 \text{ volt}}$$

So finally the rating of the transformers for the ground beds designed is to be 12V/12A TR units to meet the current and voltage requirements.

5 . CONCLUSION

The main objective of the project as stated in the abstract is to design a ground bed with optimum resistance value which can drain the desired current from the anode bed on to the surface of the object to be protected. For this resistance to be achieved in the design process careful approximations should be done in certain cases. For instance in the design calculation the current requirement for the section with a safety factor of 1.3 is 23.426 A. Now when current required for each individual section is approx 4 A. when weight of anode required for this current requirement is calculated it is 83.4 kg. Keeping in view weight of each anode and no. of ground bed locations an approximation on weight of anode is done at 108 kg. This is the closest approximation to achieve a uniform anode configuration at all the ground bed locations and that too with minimum ground bed resistance.

Another important outcome of the project is the flow chart that is developed from the standard procedures recommended in NACE 0169. This flow chart can aid the design of any ICCP ground bed for better decision making regarding anode selection. With the help of this flow chart in the present design MMO anode selection is made which reduced the ground bed resistance effectively.

The final design of the Anode Ground Bed (AGB) can be summarized as below:

1. For every 31.85 km of pipeline there should be an anode bed.
2. The ground bed type for all the locations is a **shallow horizontal type ground bed**.
3. The soil resistivity at 2.5 meter depth is considered for the design calculations.
4. The protection current required for this length of pipeline is 23.426 A approx 24 A.
5. 82.68 kg of anode is needed for the current output of 23.426 A.
6. Different Resistances of the ground bed are as follows:
   - I. Individual anode to back fill = 0.6479 Ω
   - II. Resistance of multiple anodes to ground bed = 1.191 Ω
   - III. Total Cable resistance = Anode tail cable + Header cable = 0.1092 Ω
   - IV. Total Ground bed resistance = 1.508 Ω
   - V. Rating of the transformer = 12V/12A

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ANNEXURE

A. Soil resistivity Vs pin spacing plots for the ground bed locations

In the graphs below the legend is as below:

Plot A graph:

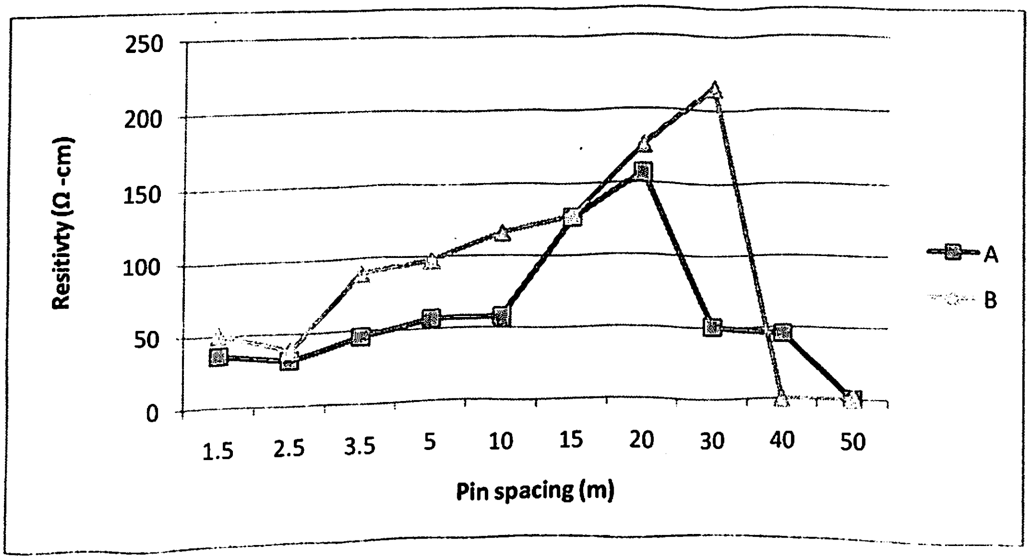
Plot B graph:

SCALE:

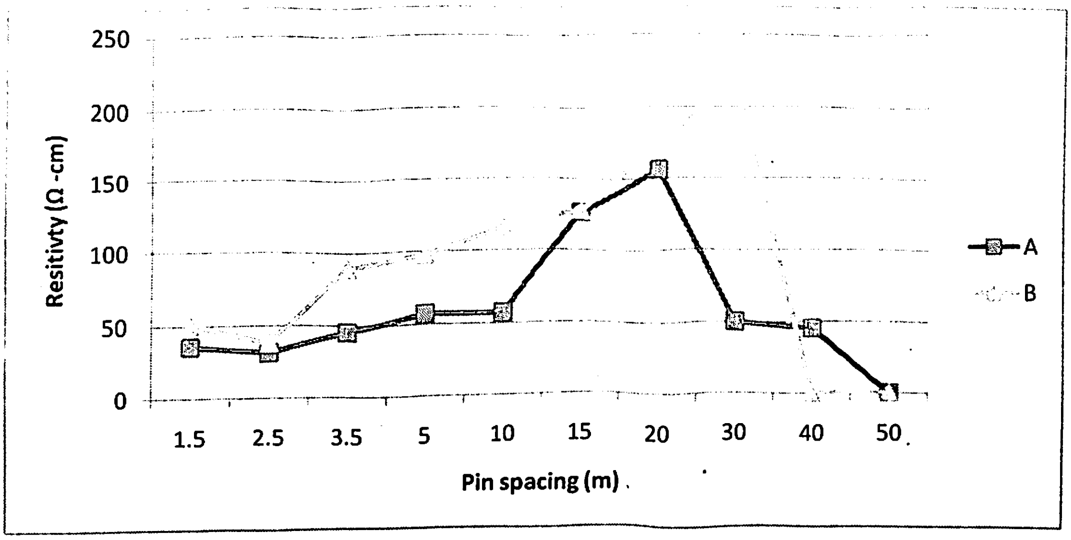
On X- axis 1.5 m

On Y- axis 50 Ω-cm

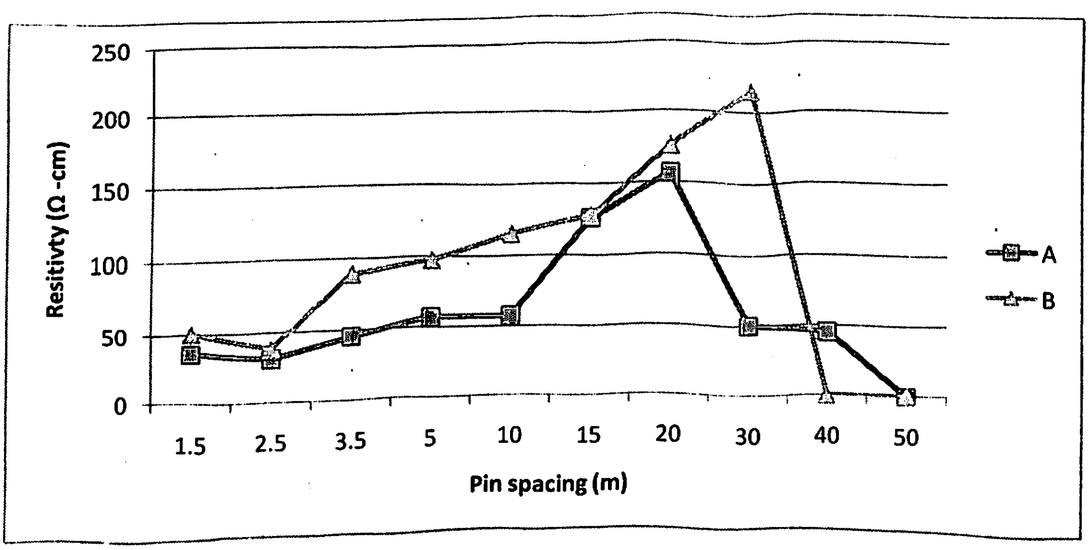
Plot1. Chainage 0.00 km



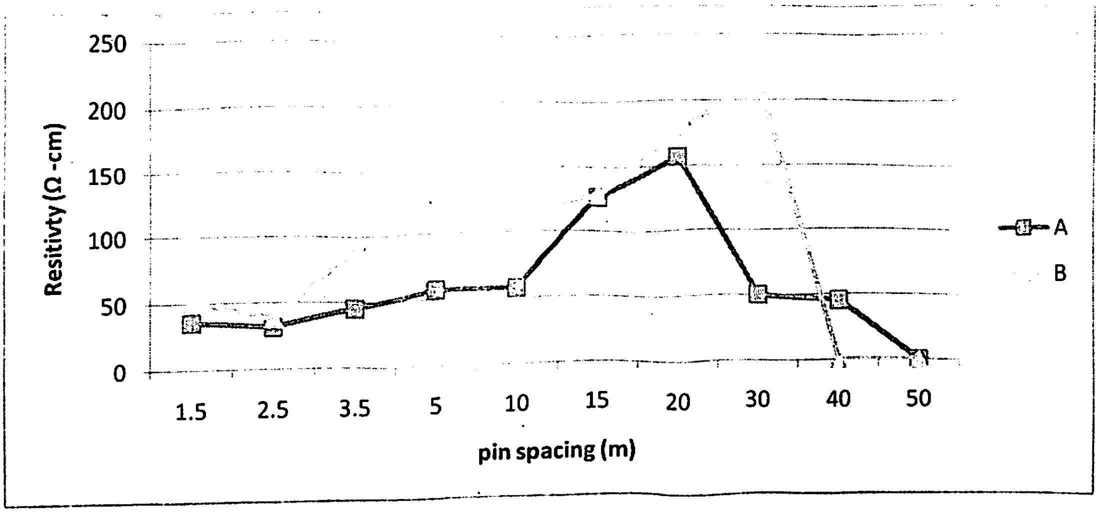
Plot2. Chainage 35.30 km



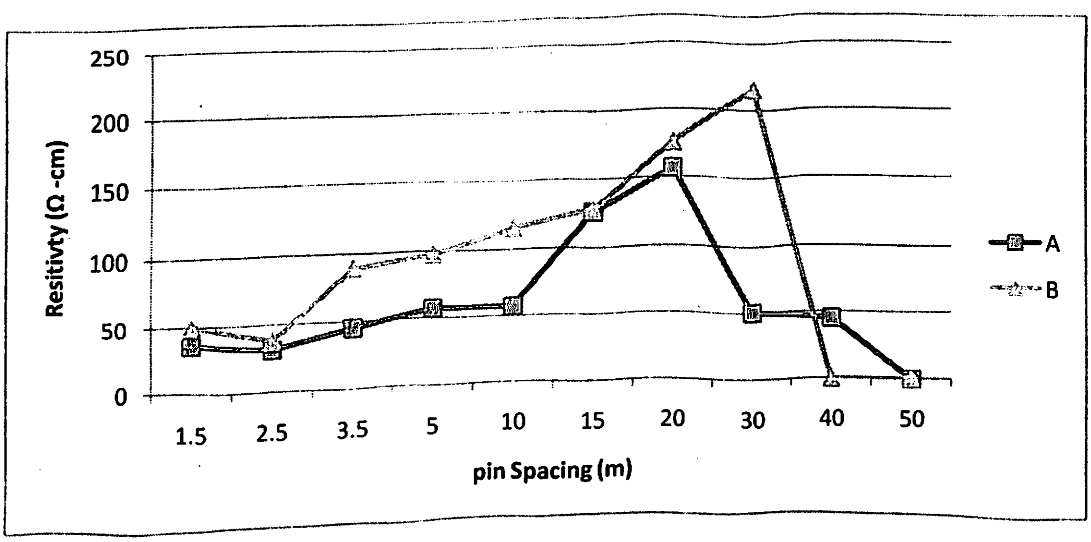
Plot3. Chainage 65.829 km



Plot4. Chainage 95.5 km



Plot5. Chainage 129.392 km



Plot6. Chainage 161.30 km