



The Development of an Enhanced Intelligent System for Corrosion Protection of Underground Pipelines: Leveraging Capacitive Heuristics - Controlled Sensors

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Abstract This paper will illustrate some of the principles of building expert systems. Corrosion of metallic structures in petroleum products pipelines brings about various problems such as reduce life of the structure, loss of money, materials etc. It is important to adopt methods to eliminate, lessen the effects and electronically (real-time) monitor corrosion of pipeline. The intelligent system concept for corrosion protection of pipelines is actually a merging of ideas about fault tolerant equipment (Cathodic protection system /anodic protection system) and integrated expert system, that is expert system embedded in microprocessor chips to form an integrated hardware/software package. This expert system (ES) consists of three components: a knowledge base, inference engine and a working memory. In a pipeline system protected by a cathodic /anodic protection device, the presence of corrosion can be represented by strange deposits called tri-iron tetra oxide (Fe_3O_4) or millscale on the lines. These can be detected using sensors as inputs to a process (ES) which takes the data from the sensors, checks the extent of corrosion, control, then turns on/off various actuators for early warning and life prediction at monitoring base stations on real-time basis. The sensors software are also embedded together with the ES in the same microprocessor chips.

The full mitigation potentials imbedded in all the corrosion control measures- (Design, inhibitors, material selections, cathodic/anodic protection, protective coatings, alteration of the environment)-, can only be completely harnessed by the introduction of a real-time monitoring mechanism in the techniques.

Keywords intelligent system; knowledge base; corrosion; pipeline structures; sensors

Introduction

“At US\$ 1.8 trillion, the annual cost of corrosion worldwide is over 3% of the world’s GDP. Yet, government and industries pay little attention to corrosion except in high – risk areas like aircraft and pipelines” – George F Hays: Director world corrosion organisations [1]. Though pipelines in exception and risks prone, it is still monitored manually by using the pipe-to-earth potential measurement device [4], in Nigeria and most developing countries of the world despite its unacceptability by human systems. No wonder the common site of oil spillages in our environment. The proper material selection, protection, corrosion control and a functional electronic (realtime) monitoring mechanism can help to reduce this wastage due to corrosion. Wastage on corrosion includes wastage of materials, energy and money. It is so important to study the cause of corrosion, introduce methods to control it or reduce its effects and electronically monitor the methods on real-time basis. The effective use of cathodic/anodic protection system and its real-time monitoring can reduce or sometimes entirely eliminate corrosion problems. There are different sources of attack on pipeline and bridge structures which will result in corrosion of it in seawater and underground platforms. For the success of the corrosion prevention effort, the proper real-time monitoring of corrosion rate and wastage of structures should be done.



Regular scheduled visual inspections and measurements, which characterize manual monitoring are subject to human error, bias and incapacitation. Hence it should be de-emphasized.

Enormous amount of crude petroleum, gas and petroleum products are transported through main pipelines [2]. At petroleum processing plants, process pipelines are used for the transportation of many products, from crude petroleum to diverse end products. Interplant pipelines connect various processing plants with one another and also with storage tanks. The operating conditions of pipelines of petroleum processing plants depend on a number of factors, depending on the type of products to be pumped, the pressure and the temperature of transported media [2]. Depending on their operating conditions, pipelines may be made of metallic or non-metallic tubes. In most cases they are made of carbon steel, but in special cases e.g catalytic cracking reforming, hydrogen refining, isomerisation, manufacture of synthetic alcohols, acids etc, alloy steels (containing Cr, Ni and Mo). Copper and copper alloys, nickel and nickel alloys, aluminum and plastics have also been used for the construction of pipelines [2]. High alloy steels are high in Cr (Up to 18%), Ni (upto 20%), and also contain minor amount of niobium, titanium and boron. Tubes made of such austenitic alloys can withstand temperatures upto 1100°C and possess high resistance to corrosion at working temperatures. They also have good weld ability [2].

The diameter of the tubes and their applications depending on pressure, temperature and quality of the metal are specified by state standards. [2]. Seamless tubes made of carbon steel grades Cr2, Cr3, Cr4, Cr5 are widely used for making process pipeline in weakly corrosive media upto 450°C. In some cases, welded tubes are used, e.g for pumping of petroleum products and vapours at wall temperatures less than 300°C [2]. Stainless steel tubes of diameter 25-64mm and 3-8m long are sometimes replaced by tubes made of steel grades Cr2 or Cr3 lined inside with polyethylene (1.5 – 2mm layer), glass (1-2m layer) or rigid PVC (2mm or thicker layer). Such tubes can be used for the transportation of aggressive media at gauge pressures upto 1.5 Mpa and 60- 100 °C [2]. Bimetallic tubes made of carbon steel/stainless steel or carbon steel/copper etc are also used in recent plants [2]. As a matter of fact, from the aforementioned steel is the most used metal in pipeline and bridge construction and it is so much corrodible. Having been sunk deep down (beneath the soil) in corrosion-causing service conditions, coupled with long interval maintenance culture, Petroleum Product pipelines and bridges are very much affected by corrosion. Intelligent system for corrosion protection of underground is actually a merging of ideas about fault-tolerant equipment (cathodic protection system) and integrated expert system. This expert system for corrosion protection of underground Petroleum product pipeline is a user-friendly interface for implementing/processing corrosion protection heuristics in the absence of human expert using computer software. An expert system is a high performance problem solving (software) computer program, capable of simulating human expertise in a narrow domain [3]. The enhanced intelligent system for corrosion protection of underground PPP and bridge structures will help the user to get the proper advice as if from the expert to solve the issues related to corrosion of steel structures in a pipeline on real- time basis.

Enhanced Intelligent System

This enhanced intelligent system uses the following knowledge:

- (a) About mechanisms of capacitors.
- (b) About mechanisms of the growth and breakdown of passive films to determine the appropriate strategy (heuristics) in steel and protective coating respectively.

Integrated Expert System

Computer hardware size and price reductions have made it feasible for complex equipment to contain its own dedicated computer running an expert system that takes care of the equipment in some way [7]. The integrated expert system could handle tasks like monitoring and controlling equipment operation, detecting and diagnosing equipment faults, assisting in correcting the fault, and planning ways to work around the faults until they are corrected.

A typical expert system embedded in microprocessor chips consists of three components

An inference engine, a knowledge base and a working memory. The key element to expert system performance is the embodied domain expert's knowledge and not any kind of formalisms or inference method [5].



Knowledge in a specific domain consists of declarative descriptions, relationships, and procedures. Declarative descriptions refer to a collection of facts, constraints, dependencies and laws about the domain. Procedural descriptions include a series of steps or actions to be performed, to achieve a specific goal. Expert system contains knowledge about their own structure and operations; thus they may also reason about their function example, provide information on how and why they perform in a certain way [5]. Expert systems instead of following a deterministic sequence of actions, use a few general procedures to find the solution of a problem. Expert systems use specific information about the domain which can guide through the state space and reduce the search time.

Corrosion

The fundamentals/principles of corrosion

Cells and Batteries: Anodes and Cathodes of a corrosion cell may be close together or far apart but must maintain electrical contact to complete the circuit for current flow [8].

Anodes and cathodes can form on the same piece of metal. When two dissimilar metals are in contact, for example copper and steel, one usually behaves as the anode all over its surface, while the other is all cathode [8]. The metal with less corrosion resistance becomes the anode (or anodic) and the more corrosion resistant metal becomes the cathode (or cathodic). For the example given, iron becomes the anode and copper becomes the cathode [8]. When an anode and cathode form a cell and current flows, a potential difference, or voltage, exists between the anode and cathode. These principles are the basis for the automobile battery, which contains a sulphuric acid solution. The same principles apply to the so called dry cell or dry battery. It is really not dry, because moisture or water must be present to form ions and to conduct current. The case is made of zinc and the centre post is carbon. Carbon is a conductor of electricity and behaves like a metal in this respect [8]. When the switch is closed (completing the circuit), the zinc corrodes and acts as an anode [8]. The carbon is inert and corrosion resistant and acts as a cathode. A voltage (about 1.5v) is set up and current flows. The reason electrical energy is obtained from such a cell is that the zinc corrodes or goes into solution.

Magnesium is also used in dry batteries because it is corroded quite readily by many environments.

Electromotive- force series

Accurate determinations of potentials for various elements resulted in the electromotive-force (emf) series in this case a hydrogen electrode is the reference electrode. When two metals are in contact, corrosion of the anodic member of the couple is accelerated. This is called galvanic corrosion, or two-metal corrosion. The greater the potential of the cell, the greater is the effect of galvanic corrosion [8].

Passivity: Another exception to the information supplied by the emf series concerns passivity. Passivity in a metal refers to a relatively inactive state in which it (the metal) displays a more noble behaviour than thermodynamic considerations predict. Passivity can be more simply defined as the reason a metal does not corrode when it should [8]. The following examples will clarify this point.

Chromium and the stainless steels become passive, or exhibit passivity, because of the formation of a protective film on the surface of the metal. This could be an oxide or an absorbed oxygen film that acts as a barrier, thus protecting the metal from the environment [8].

Aluminum is a reactive metal and is high in the emf series. But it possesses good corrosion resistance. This metal quickly forms a surface coating of aluminum oxide which stops further corrosion by many environments [8]. As a matter of fact, passivity is a consequential measure of corrosion resistance of passivating metals.

Quantitatively, the upper and lower limits of corrosion resistance measure is synonymous to the growth and breakdown of passive films heuristics

Films growth according to the logarithmic rate law

$$L = a + B \ln t \quad (1)$$

or an inverse logarithmic law.

$$1/L = C - D \ln t \quad (2)$$

Where L is the film thickness and A, B, C, and D are constants. Furthermore many passive films exhibit photo effects that can be explained only by assigning semiconductor properties to the film. [5] indeed, a picture is



emerging or passive films being highly doped semiconductors existing under the influence of a strong electric field [5].

One of the earliest models for the growth of passive films is that due to Cabrera and Mott [5]. This model assumed that [1] the film grows by the transport of cations across the film to the film-solution interface, where they react with electrolytes; [2] the penetration of cations through the film is assisted by the high electric field. [3] The electric field strength is constant throughout the film and is equal to ϕ_f/L , where ϕ_f is the total potential drop across the film. For potentiostatic condition ϕ_f is constant; Eq (4) and (5) the rate limiting step for film growth is the emission of metal cations from the metal into film. The assumptions noted above yield the following expression for the differential film growth rate law:

$$\frac{dL}{dt} = N \Omega \nu \exp \left[\frac{-W + q a \phi_f}{KT} \right] \quad [1] \quad (3)$$

Where N is the number of mobile cations per unit surface area, Ω is the molecular volume per cations, ν is the vibrational frequency, W is the activation energy for the entry of cations into the film, q is the charge on the cations, a is the jump distance, and KT is the thermal energy. This equation can be integrated approximately to yield an inverse logarithmic rate law:

$$\frac{1}{L} = C - D \ln t \quad (4)$$

$$C = \frac{2}{q a \phi_f} \left\{ W - K t \ln \left[\frac{2(W - 39KT)^2 N \mu \nu}{\dots} \right] \right\} \quad (5)$$

$$D = \frac{2KT}{q a \phi_f} \quad (6) [5]$$

Also mathematical development of the point defect model yields the following integral rate law:

$$\exp \left[\frac{2KL - 2K^2L^2}{2KA(B-1)t} \right] = 2KA(B-1)t \quad (7) [1]$$

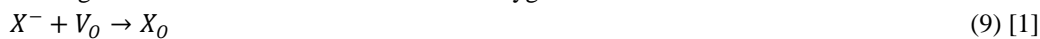
where $K = \frac{F \phi_f}{RT}$, ε is the electric field strength and A and B are constants that depend upon the fundamental electrochemical and thermodynamic parameters for the system. For sufficiently thick films ($L > A$) this equation converts to the logarithmic equation

$$L = \frac{\ln 2KA(B-1) + \ln t}{2K} \quad (8) [1]$$

This model has been subjected to extensive evaluation for passive films formed on iron and nickel in borate and phosphate solutions, and it has been found to provide a quantitative description of the film growth phenomena [1].

A considerable amount of work has been reported on the breakdown of passive

Films, particularly in halide solutions [1]. The numerous models that have been proposed to explain passivity breakdown, and hence the initiation of pitting corrosion, include the competitive ion adsorption theory, complexation theory, ion penetration theory, Chemical mechanical theory and the point defect model. In this later case (Lin et al, 1981), the initiation of pitting is due to the accumulation of cation vacancies to form a cation vacancy condensate at the metal film interface [1]. Once the condensate reaches a critical size, mechanical instability occurs and pitting attack ensues. The enhanced flux of cation-vacancies across the film is envisaged to result from the halide ions into oxygen ion vacancies at the film solution interface:



Followed by the Schottky pair reaction



To generate cation vacancies. Mathematical development of this model leads to the following expressions for the critical breakdown potential (V_c) and the induction time (t_{ind}):

$$V_t = \frac{4.606RT}{xF\alpha} \log \left(\frac{J_m}{J_o u^{-x/2}} \right) - \frac{2.303RT \log a_x}{\alpha F} \quad (11) [1]$$

$$t_{ind} + \Sigma^1 = \left[\exp \left(\frac{xF\alpha \Delta V}{2RT} \right) - 1 \right]^{-1} \quad (12) [1]$$

$$V = V - V_o \quad (13) [5]$$

$$\Sigma^1 = \frac{\Sigma}{J_o u^{-x/2} [Cl]^{-x/2} \exp \left(\frac{xF\alpha V_c}{2RT} \right)} \quad (14) [1]$$



Where \sum, J_m, J^0 and u are constants, and a_x is the activity of the halide ion X^- in the solution. These equation have been found to provide a quantitative amount for the breakdown of passive films on iron and nickel in chloride containing solutions[1]. The quantitative nature of equations (11) and (12) in describing the breakdown of passive films therefore leads credence to the validity of the model.

The determination of corrosion resistance of protective coating following the aforementioned evaluation for passivity, the corrosion resistance of protective coating applied can be computed on real time basis using this enhanced intelligent system. ie in a dual control system using cathode protection on coated pipelines and bridge substrates(structures). This can be used for determining the effectiveness of protective coating in corrosion environments. Hence corrosion resistance = Passivity.

Galvanic Series: The potential available to promote the electrochemical corrosion reaction between dissimilar metals is suggested by the galvanic series, which list a number of common metals and alloys arranged according to their tendency to corrode when in galvanic contact (Table 1). Metals close to one another on the table generally do not have a strong effect on each other, but the further apart any two metals are separated, the stronger the corroding effect on the one higher in the list. It is possible for certain metals to reverse their position in some environments, but the order given in table 2 is maintained in natural waters and the atmosphere. The galvanic series should not be confused with the similar electromotive force series, which shows exact potentials based on higher standardized condition that rarely exist in nature.

Table 1: galvanic series of metals and alloys in seawater [10]

Metal or Alloy	Potential in Volts (Ag / AgCl Ref)
Magnesium	-1.64
Aluminium anode	-1.15
Zinc	-1.03
Aluminium alloy	-0.90 to -0.93
Cast iron	-0.61
Carbon steel	-0.71
High strength steel	-0.60
High strength steel	-0.60
430 stainless steel (active)	-0.57
304 stainless steel (active)	-0.53
410 stainless steel (active)	-0.52
Yellow brass	-0.36
Copper	-0.36
Admiralty brass	-0.30
430 stainless steel (passive)	-0.22
316 stainless steel (active)	-0.18
410 stainless steel (passive)	-0.15
304 stainless steel (passive)	-0.08
316 stainless steel (passive)	-0.06
Platinum	+0.26

The three-layer iron oxide scale formed on steel during rolling varies with the operation performed and the rolling temperature. The dissimilarity of the metal and the scale can cause corrosion to occur, with the steel acting as the anode (-ve) in this instance[10]. Unfortunately, mill scale is cathodic (+ve) to steel, and an electric current can easily be produced between the steel and the mill scale. This electrochemical action will corrode the steel without affecting the mill scale (6).

Corrosion Control

(a) Protective Coatings

Surface treatments, and in particular protective coatings, are widely used to control corrosion in this varying forms[10]. The problems of corrosion should be approached in the design stage, and the selection of a protective coating is important. Paint systems and lining materials exist that slow the corrosion rate of carbon steel surfaces. High-performance organic coatings such as epoxy, polyesters, polyurethanes, vinyl, or chlorinated rubber help to satisfy the need for corrosion prevention. Special primers are used to provide passivation, galvanic protection, corrosion inhibition, or mechanical or electrical barriers to corrosive action.



Corrosion Inhibitors or Inhibitive Coating: A water soluble corrosion inhibitor reduces galvanic action by making the metal passive or by providing an insulating film on the anode, the cathode or both. A very small amount of chromate, polyphosphate or silicate added to water crates a water soluble inhibitor. A slightly soluble inhibitor incorporated into the prime coat of paint may also have a considerable protective influence (6). Inhibitive pigments in paint primers are successful inhibitors except when they dissolve sufficiently so leave holes in the paint film. Most paint primers contain a partially soluble inhibitive pigment such as zinc chromate, which reacts with the steel substrate to form the iron salt. The presence of these salts slows corrosion of steel. Chromates, phosphates, molybdates, borates, silicates, and plumbates are commonly used for this purpose. Some pigments add alkalinity, slowing chemical attack on steel. Alkaline pigments, such as metaborates, cement, lime, or red lead, are effective, provided that the environment is not too aggressive. In addition, many new pigments have been introduced to the paint industry such as zinc phosphosilicate and zinc flake.

Barrier Coatings: Are used to prevent the electrolyte from reaching the component surface. Examples of barrier coatings include painted steel, structures, steels lined with thick acid-proof brick, steels lined with rubber like materials, or steels electroplated with a noble metal (e.g. chromium, copper, or nickel). Protection is effective until the coating is penetrated, either by a pit, pore, crack, or by damage or wear. The substrate will then corrode preferentially to the coating (since it is anodic to the coating material), and corrosion products will lift off the coating and allow further attack.

Generally, electroplated coatings that are completely free of pores and other discontinuities are not commercially feasible. Pits eventually form at coating flaws, and the coating is penetrated.[10] The substrate exposed at the bottom of the resulting pit corrodes rapidly.

A crater forms in the substrate, and because of the large area ratio between the more noble coating and the anodic crater, the crater becomes anodic, and high corrosion current density results. Electrons flow from the substrate to the coating as the steel dissolves. Hydrogen ions (H^+) in the moisture accept the electron and, with dissolved oxygen, form water at the noble metal surface near the void. Use of an intermediate coating that is less noble than a surface coating but more noble than the base metal can result in the mode of corrosion shown in Fig 1.

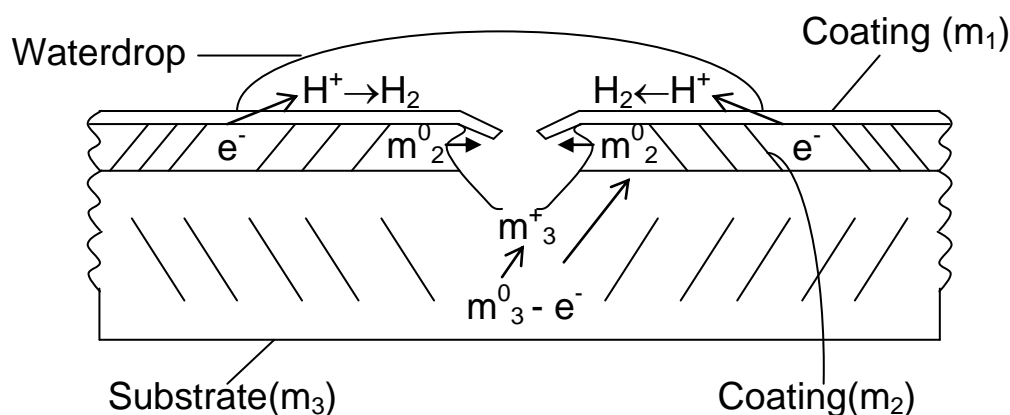


Figure 1: Result in Corrosion Mode [8]

This would be typical of a costume jewelry item with a brass substrate, an intermediate nickel coating, and a tarnish-resistant gold top coat. It is also exemplified by nickel-chromium coating systems (6).

Sacrificial Coatings: Which corrode preferentially to the substrate, include zinc, aluminium, cadmium, and zinc – rich paints. Initially these sacrificial coatings will corrode, but their corrosion products are protective and the coating acts as a barrier layer. If the coating is damaged or defective, it remains protective as it is the coating that suffers a attack and not the substrate. Figure 2 shows the sacrificial (galvanic) protection offered by a zinc coating to a steel substrate.



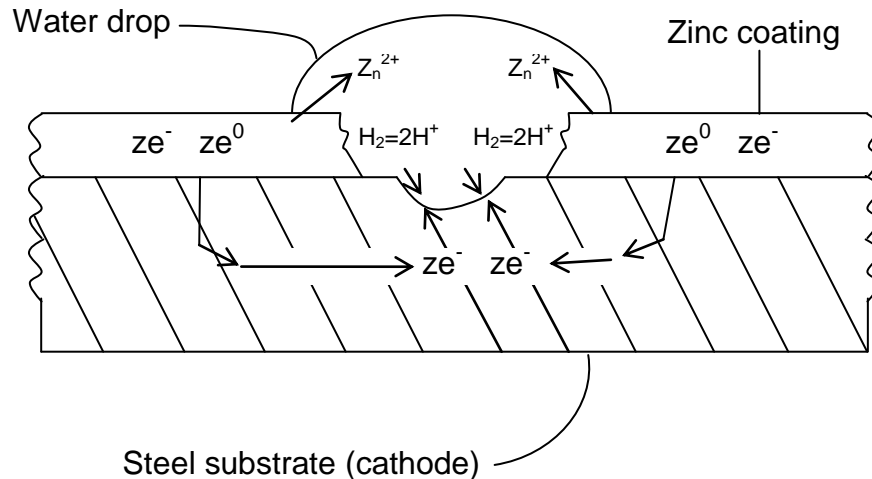


Figure 2: Sacrificial Galvanic Protection [8]

(b) Cathodic Protection: Involves the reversal of electric current flow within the corrosion cell. Cathodic protection can reduce or eliminate corrosion by connecting a more active metal to a metal that must be protected [8]. The use of cathodic protection to reduce or eliminate corrosion is a successful technique of long-standing use in marine structures, pipelines, bridge decks, sheet piling, and equipment and tankage of all types, particularly below water or underground. Typically, zinc or magnesium anodes are used to protect steel in marine environments, and the anodes are replaced after they are consumed [8]. As a matter of fact, the electric current of the protective all will deteriorate the expendable material used for anodes while the more valuable structure is protected [1]. In effect, cathodic protection consists of making the potential of the electrolyte or soil positive so the potential of the structure being protected [1]. This is accomplished when current is impressed into the soil from a ground bed or a galvanic anode. Because electric current will flow from a positive potential medium to a negative or less positive potential medium, current will enter the structure from the soil instead of leaving it, thus eliminating the corrosion action [1].

Application of Cathodic Protection

There are two proved methods of applying cathodic protection to underground metallic structures (1) galvanic or sacrificial anodes, and (2) rectifier ground beds. With each method a d-c current supply is made available for the protection of a buried structure. The choice of the method to be used depends upon a number of economic and technical considerations. Each method has advantages and disadvantages.

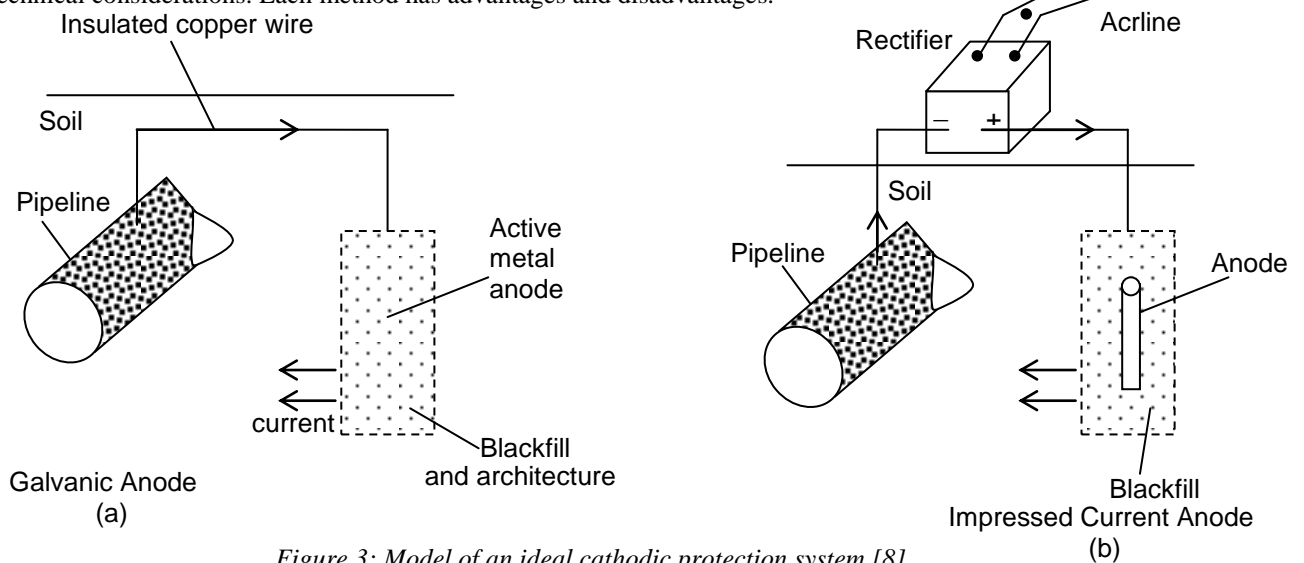


Figure 3: Model of an ideal cathodic protection system [8]

Galvanic Anodes: Galvanic anodes are applicable and effective where current requirements are low, where structures to be protected are well coated, and where low soil resistivity exists. The main advantages of galvanic anodes are as follows:

1. No external power supply necessary
2. Minimum maintenance costs after installation
3. Seldom causes interference problems to foreign structures
4. Installation costs are low
5. Little or no right-of-way or easement costs – the main disadvantages are:
 1. Limited driving potentials and current output
 2. Soil resistivity limitations
 3. Not too applicable for large-diameter pipes (4) mutual interference in multiple or parallel installations

When a galvanic anode is connected to an underground metallic structure and buried in the soil, as seen in Figure 3 (a), a galvanic cell is developed. The anode consists of a metal which is electronegative to the structure; thus it becomes anodic and corrodes while the structure is protected. Zinc and magnesium are the two main metals used as galvanic anodes. Both metals are normally electronegative to steel, lead, and copper, which are the usual metals protected against corrosion [8]. The galvanic anodes are generally packed or buried with a chemical backfill consisting of gypsum, bentonite clay and sodium sulphate. These chemicals permit a higher and more stable working potential, reduce undesirable polarization effect, allow lower anode-to-earth resistance, and distribute the corrosion attack over the entire anode.

The solution potential of zinc (in a chemical backfill) is approximately -1.1V measured to a copper sulphate electrode. The solution potential of magnesium measured in the same manner is approximately -1.155V. Considering a pipe-to-soil potential of 0.85V as the protective criterion of a steel pipeline, the driving potential of zinc is 0.25V, while magnesium is 0.75V. The actual ampere-hours per pound of zinc is 335 as compared to 500 for magnesium.

The following formulas may be used to determine the life expectancy of a given weight of an anode with its current output known or to determine the necessary anode weight for a desired life of an anode at a known current output:

$$L_m = \frac{57.08 \times W}{i}, \quad L_z = 38.24 \times W \quad [10]$$

where L_m = life of magnesium anode, yr

L_z = life of zinc anode, yr

W = weight of anode, Lb

i = milliamperes output of anode [10]

N/B: (aiv) corrosion may be encouraged on a steel surface by the presence of mill scale. Mill scale can be seen on the surface of new iron and steel in the form of blue-black layers of iron oxide, some of which is harder than the parent metal. The mill scale is electrically positive relative to the iron or steel, so it is cathodic to the parent metal i.e. the steel or iron (anodic) decaying or corroding if unprotected.

In the above formulas the current efficiency of zinc is assumed to be 90 percent and for magnesium 50 percent of their theoretical output (Faraday's law) per pound [10].

The principal controlling factor for the current output of galvanic anodes is the resistivity of the soil they are buried in. It is seldom practical or economical to install galvanic anodes for cathodic protection on soils having resistivities above 5000 ohm-cm [10]. The current output of a galvanic anode has an inverse relationship with the resistivity of the soil surrounding it. For example, the current output of a 17-Lb magnesium anode (Galvopak) buried in a soil of 1000 ohm-cm and connected to a steel structure would be approximately 150ma. Buried in a soil of 2000 ohm-cm the output would be approximately 75ma, while in a 500 ohm-cm soil it would be approximately 300ma. The following formulas and Table X may be used to determine the approximate current output of a magnesium anode with the soil resistivity known: $i = 150,000$

Where i = current output, ma

P = soil resistivity, ohm-cm

F = factor from table X



Biase: Some group of coaters sent to the field to fill up the consumed anode, can decide to divert the chemicals for their personal use. How will (40) this be known immediately through manual monitoring? But if it were real-timed, update signals will be Table 2 transmitted electronically to personnels individually at their comfort zones for decision making.

Table 2: Output Factor

Anode Size, Lb	Factor
3	0.59
5	0.66
9	0.81
17 (Galvopak)	1.00
32 (Galvopak)	1.16
50 (Galvopak)	1.22

To estimate the approximate current output of a zinc anode the above formula can be used by multiplying it by a factor of 0.27. In other words, the current output of a zinc anode for a given resistivity soil is 27 percent of the current output that would be anticipated in a similar magnesium anode installation. For example, the approximate output of a 33-cb zinc anode in a 750 ohm-cm soil would be as follows:

$$i = \frac{150,000 \times 1.16 \times 0.27}{750} = 62.4 \text{ (Ma)} [10]$$

N/B: Though the life expectancy of an anode may be determined to enable us monitor/know when to maintain or refill the system, it is this subject to error due to human biase. Hence real-time mentoring still remains the best strategy.

The choice of the type of galvanic anode to use in the application of cathodic protection is an economic problem. The cost per pound of magnesium is approximately twice that of zinc. Although magnesium, with its higher driving potential, delivers grater currents, it also is consumed more rapidly. In a given soil-resistivity environment the magnesium will be consumed 2.5 times faster than zinc. Without restrictions in the circuit the cost of magnesium would be 5 times that of zinc, when the anode provides sufficient protection. The magnesium anode would be overprotecting the structure, resulting in a wast of power. However, sufficient current output is a limiting factor of zinc anodes. Considering all the variable factors involved, the use of zinc anodes is generally more economical where soil resistivities are below 1500 ohm-cm.

Rectifier-Ground Beds: The second method of applying cathodic protection to underground metallic structures is with the use of impressed currents from an external source. Figure 3 shows a typical rectifier-ground bed installation utilizing an existing a.c power supply. The external source of power can also be provided from a motor-generator unit and from a wind-driven generator. These methods are used only in areas where an a.c power supply is not available. Discussion will be limited to rectifiers because they constitute, by far, the major percentage of impressed current method of application of cathodic protection.

The advantages of the rectifier-ground bed method of applying cathodic protection are:

1. Larger current outputs
2. Applicable in high-resistivity-soil environments
3. Flexibility of current output control
4. Applicable for bare and poorly coated structures
5. Protects larger and more expensive structures

The disadvantages of the rectifier-ground beds are

1. Higher installation costs
2. Higher maintenance costs
3. Monthly power costs
4. Interference problems with foreign lines

The theory involved in the rectifier-ground bed method is to develop an electrolytic cell making the structure to be protected the cathode and the ground bed of the rectifier the anode. The ground be consists of a number of parallel graphite, carbon, duriron, or junk iron anodes. As current is impressed into the earth at the ground bed, the anodes are consumed. The structure, being connected to the negative of the rectifier, receives the current



from the soil and is protected. The protective current from the rectifier is usually sufficient to overcome the galvanic currents, leaving the anodic areas of the structure.

Referring to Figure 3 the rectifier is being supplied with an a.c power supply at 110V, which is measured by the power meter in kilo watt hours. A switch box is installed in the a.c circuit that contains either a thermal or a magnetic circuit breaker for protection against overloads and surges. The alternating current is directed to the rectifier unit, containing a step-down transformer to reduce the voltage to a desirable value and a rectification element which converts the alternating current to direct current using copper oxide stacks, selenium stacks, or silicon diodes. The uni direction current is then directed from the positive side of the rectifier to the ground bed, where it is impressed into the earth. The current migrates through the ground and enters the pipeline at all points within the range of the rectifier. The pipeline is the negative return or external circuit of the electrolysis cell [10].

Three main systems of installing ground beds are used by corrosion engineers. In each system the anodes can be installed vertically or horizontally:

1. **Remote ground bed:** The ground beds are installed at a remote point from the structure to be protected. This type of ground bed is generally used on bare and coated pipelines where a large spread of the protective current is desired. Although greater distribution of protective current is attained with this method, interference problems with foreign lines is greater and property easement costs are higher.
2. **Distributed anode ground bed:** This method is used when protecting a networks of piping and structures such as found at compressor or pump stations, tank farms, and pipeline terminals. The anodes of the ground bed are distributed at various points and often in a non-geometric pattern. This is done to overcome the shielding effect of one structure by another.
3. **Horizontal continuous or parallel-type ground bed:** This type of ground bed can be installed with a continuous or semi-continuous coke breeze bed in a horizontal ditch with graphite anodes installed in parallel at certain intervals. This is a very effective method of protection for bare pipelines in highly corrosive environments, where foreign structures are in close proximity of the structure to be protected. The cost of installation is approximately twice that of an equivalent remote type of ground bed, but, owing to extremely low ground bed resistances, the power cost for a given current output is approximately one third to one half that of a remote-type rectifier ground bed having a circuit resistance of 1 ohm.

The following factors must be considered when designing a rectifier ground-bed system:

1. Type and condition of the structure
2. Availability of a power supply
3. Property easements
4. Soil resistivity
5. Current requirement
6. Equipment and material necessary
7. Interference problems with foreign lines
8. Accessibility

The type and condition of the structure to be protected is the first and most important consideration in designing a rectifier ground bed system. Whether a structure is coated or not, the condition of the coating, the size and length of the structure to be protected, and the electrical continuity of the structure are all factors that must be primarily considered. With a power supply available and with tentative property right secured, tests can be made for the design of a rectifier-ground bed.

The soil-resistivity tests also serve to determine the depth of anodes in the ground and whether the anodes are to be installed vertically or horizontally. After a ground bed site has been established, a current requirement test is performed using a temporary ground bed which a portable generator or storage batteries. Structure-to-soil potential tests are made at various points with the test current from the ground bed turned intermittently on and off. Establishing an apparent current requirement for cathodic protection, interference tests should then be performed on foreign structures in the area which may be effected by protective current. The interference tests should be made while the temporary ground bed is still set up. If serious exposures of foreign structures are



revealed, it may be necessary to relocate the site of the ground bed. If exposures to foreign structures are moderate and can be relieved with resistance bonds, the approximate amount of current drainage from those structures should be determined. The total current drainage from the foreign structures is added to the apparent current requirement to obtain the total current requirement for the protection of the original structure [10].

With the current requirement established, the ground bed is designed to give a relatively low circuit resistance. This can be done in several ways. A number of empirical formulas are available which will enable the determination of the number of parallel anodes required in the ground bed for a desired circuit resistance at a given soil resistivity environment [10]. A system often used by corrosion engineers is to install the rectifier complete with the power supply before installing the ground bed. As each anode of the ground bed is installed, the circuit resistance is obtained by reading the d.c amperes and voltage and applying ohm's law as the power is turned on. When the desired resistance value is attained the installation of anodes is ceased [10].

With a given circuit resistance and current requirement values known, the rated voltage of the rectifier can be determined. It is good practice, particularly on newly constructed coated lines, to select a rectifier capacity (amperes and volts) approximately twice the design values. The extra power may be needed in the future as the coating deteriorates.

Accessibility to a rectifier site would be considered when planning on installation because the power meter must be read at regular intervals. In addition, periodic inspections and maintenance work will be necessary [10].

Note: What if the site is unmotorable, unaccessible, for periodic inspection and reaching of power meter practically by human standards (off / on shore, deserts, war zones, etc), due to potential dangers these platforms poses to human existence? Consequently negating manual monitoring efforts. Here comes the need for a real – timed monitoring system sequel to maintenance works; here time for periodic maintenance will be made longer and unbiased, hence saving cost.

Current Requirements for Cathodic Protection

The current requirements for cathodic protection of underground metallic structures depends upon several factors:

1. The bare surface area of the structure
2. The resistivity of the soil
3. Polarization effect on the structure

Studies performed by a number of investigators have shown that it requires anywhere from 1 to 20 ma of current to protect one square foot of bare surface. The resistivity of the soil the structure is buried in has a great bearing on the current requirement. The higher the soil resistivity is surrounding the structure, the lower will be the current requirement for complete cathodic protection. For average soil-resistivity conditions, it will require 1 to 3 ma of current per square foot of bare metal surface. In seawater or in extremely low resistivity soils such as marshes or swamps, the current requirements are much higher than the average. This may be due to the ease in which depolarization takes place on the protected surface. Another contributing factor may be that in lower soil resistivity environments, galvanic or corrosive currents are of higher intensity and will require larger countercurrents to overcome them.

In the application of cathodic protection of coated structures, the current requirements per square foot are considerably lower than bare structures. For example, the current requirement for the complete protection (-0.85V criterion) of 68.1 miles 30-in, coated pipeline, in the Texas Eastern System, having an average coating resistance of 99.200 ohms per sq ft (coating conductivity of 10.08 μ ohms per sq ft) is 4.83 amp or 1.17 μ amp per sq ft of pipe surface [10].

Figure 4 shows the use of this instrument for determining the potential between a pipeline and the surrounding soil [10]. A survey of an area using this instrument enables one to determine the corrosivity of different areas or soils [10].

Note: This monitoring mechanism is prone to error, bias and unsecure in this digital age. It will be replaced with the capacitive corrosion transducer.



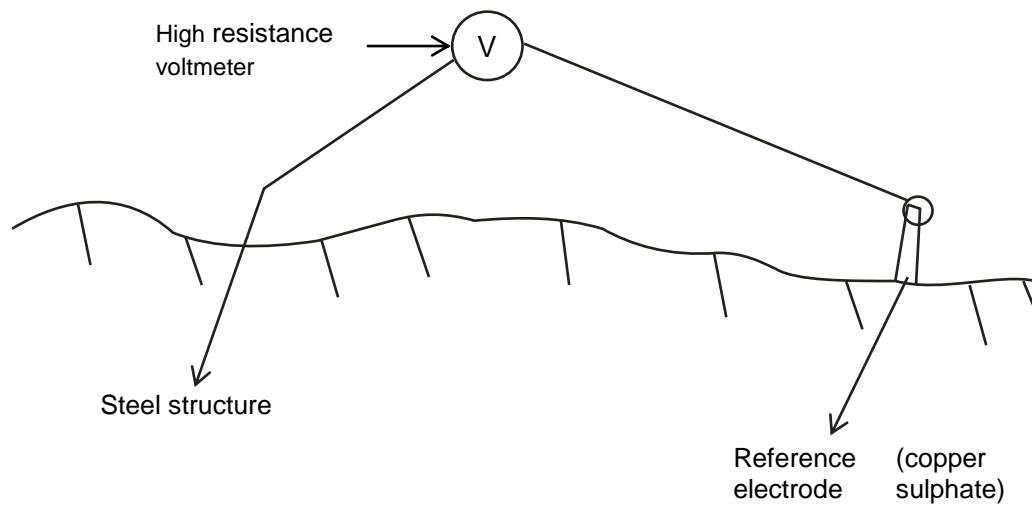
Criterion for Protection:

Figure 4: Manual Monitoring Model/Device [10]

The pipe-to-soil test has been established by corrosion engineers as a standard measurement technique in studying corrosion and cathodic protection of underground metallic structures. The copper sulphate half cell electrode is commonly used by corrosion men to contact soil, particularly where steel structures are being tested. Normally pipe-to-soil potentials of unprotected steel pipelines will vary between -0.30 and -0.70V . Variations of pipe-to-soil potentials along pipelines indicate voltage drops in the soil between various points.

This means that galvanic currents will flow through the soil between the anodic and cathodic points, with the intensity of the current flow depending upon the circuit resistances of the galvanic cells. If the pipe-to-soil potentials along a pipeline were of equal value, no galvanic currents would flow and the structures would not corrode.

When enough counter currents are supplied to a corroding section of pipeline to exactly zero or nullify the galvanic current, the pipe-to-soil potentials at the anodic points on the structure will be equal to pipe-to-soil potentials of the cathodic points: thus the voltage drop between the various points are zero (application of Ohm's law). The point of potential equalization is usually at or near the pipe-to-soil potential of the anodic point [10]. For example, if the pipe-to-soil potential of the anodic point is -0.65V , corrosion would be retarded if the pipe-to-soil potential of the cathodic point is brought to this value (made more negative). This is the basis of one of the criteria employed by corrosion engineers.

A second criterion, and one very commonly used, is to achieve and maintain a pipe-to-soil potential of -0.85V , or more negative on the entire structure to be protected. This value represents overprotection in most instances. For well coated structures, however, this criterion is the most practical and economical one to use. Extensive survey for peak anodic potentials can result in higher expenditures than by simply using the -0.85V criterion. For bare structures this criterion will often represent a waste of power and large sums of money because current requirements would be so unreasonably high and normally much more than necessary to retard corrosion [10].

A third criterion for cathodic protection is to produce a negative change in pipe-to-soil potentials of 0.25 to 0.30V from the initial or unprotected potentials [10]. This criterion is more applicable to bare or poorly coated structures than the -0.85V criterion, but it still represents a large measure of overprotection and the waste of power.

A technique of applying cathodic protection to bare structures which is often employed by corrosion engineers with good results is "hot-spot" protection. This requires a surface potential survey in conjunction with a soil-resistivity survey to locate apparent anodic points on a pipeline [10]. Cathodic protection is applied to these anodic points.

In selecting a criterion for cathodic protection, the most important thing to remember is to choose one that will retard corrosion and will permit reasonable installation and maintenance costs [10]. The key to effective



corrosion control is to reduce the leak frequency of a structure to a minimum value by using cathodic protection and other techniques with minimum expenditures.

Note: This criteria is still characterized by the errors surrounding manual monitoring. What if the site engineers submits a biased potential record/log? This criterion for protection can only work effectively in ideal systems, which is not attainable with humans in this part of the globe. Have the need for a real-timed monitoring strategy. As a matter of fact, it is meant to remove the human interface from the monitoring system or evaluate structures that cannot be visually inspected.

Anodic Protection

Anodic protection is based on the formation of a protective film on metals by externally applied anodic currents. To anodically protect a structure, a device called a potentiostat is required. A potentiostat is an electronic device that maintains a metal at a constant potential with respect to a reference electrode.

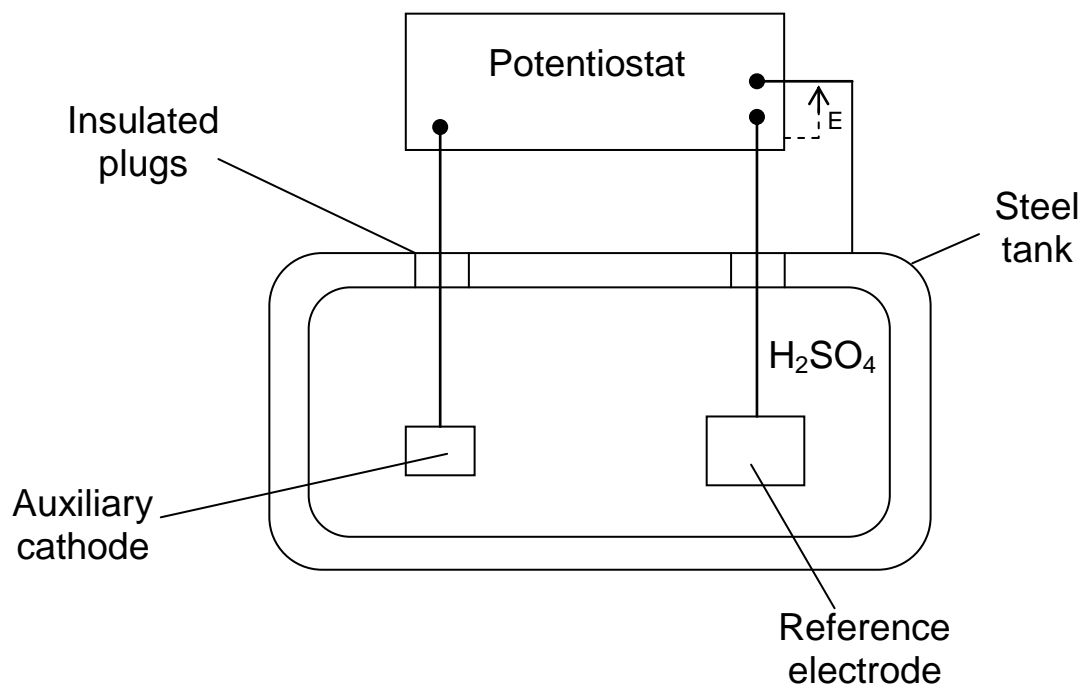


Figure 5: Anodic protection of a steel storage tank containing sulphuric acid [1]

For example, the anodic protection of a steel tank containing sulphuric acid is illustrated in figure 5. The potentiostat has three terminals, one connected to the tank, another to an auxiliary cathode, and the third to a reference electrode. In operation, the potentiostat maintains a constant potential between the tank and the reference electrode. The optimum potential for protection is determined by electrochemical measurements. Anodic protection can decrease corrosion rate substantially. Although anodic protection is limited to passive metals and alloys, most structural materials of modern technology contain these elements. The primary advantages of anodic protection are its applicability in extremely corrosive environments and its low current requirements.

Comparison of Anodic and Cathodic Protection:

Some of the important differences between anodic and cathodic protection: Each method has advantages and disadvantages, and anodic and cathodic protection tend to complement one another. Anodic protection can be utilized in corrosives ranging from weak to very aggressive, while cathodic protection is restricted to moderately corrosive conditions because of its high current requirement, which increases as the corrosivity of the environment increases. Hence, it is not practical to cathodically protect metals in very aggressive mediums.



Anodic protection, on the other hand, uses very small applied currents, and it can be utilized in strong corrosive mediums.

The installation of a cathodic protection system is relatively inexpensive since the components are simple and easily installed. Anodic protection required complex instrumentation including a potentiostat and reference electrode, and its installation cost is high. The operating costs of the two systems differ because of the difference in current requirements noted above. Throwing power, or the uniformity of current-density distribution, varies between the two types of protection. The throwing power of cathodic protection is generally low, which requires numerous closely spaced electrodes to achieve uniform protection. Anodic-protection systems have throwing power, and consequently, a single auxiliary cathode can be utilized to protect long lengths of pipe.

Anodic protection possesses two unique advantages. First, the applied current is usually equal to the corrosion rate of the protected system. Thus anodic protection not only protects but offers a means for monitoring instantaneous corrosion rate. Secondly, operating conditions for anodic protection can be precisely established by laboratory polarization measurements. In contrast, the operating limits for cathodic protection are usually established by empirical trial-and-error tests. Although various rapid evaluation methods for estimating the current requirements for cathodic protection have been suggested, all of these have proved to be unreliable to a greater or lesser degree, and the final choice is usually based on past experience [1].

The concept of anodic protection is based on sound scientific principles, and has been successfully applied to industrial corrosion problems. However, the incorporation of anodic protection into corrosion engineering practice has occurred very slowly since its introduction (1954) [9]. The reluctance of corrosion engineers to utilize this new method of preventing corrosion is probably due in large measure to their personal corrosion experiences and to classic corrosion literature [1].

Corrosion Rate Measurements

Mixed-potential theory forms the basis for two electrochemical methods used to determine corrosion rate. These are the Tafel extrapolation and linear-polarization techniques. The slope of this linear-polarization curve is related so the kinetic parameters of the system as follows:

$$\frac{\Delta E}{\Delta i_{app}} = \frac{B_a B_c}{2.3(i_{corr})(B_a B_c)} \quad (15) [1]$$

Where B_a and B_c are the Tafel slopes of the anodic and cathodic reactions respectively. The term $\Delta E / \Delta i_{app}$ is given in ohms (volts/amperes or millivolts/milliamperes). If the beta values for the reactions are known, corrosion rate may be calculated by substitution into equation (15).

The slope of a linear-polarization curve $\Delta E / \Delta i_{app}$ is controlled mainly by i_{corr} and is relatively insensitive to changes in beta values as shown in equation (15). Hence, it is possible to formulate a reasonably accurate approximation of equation (15). Assuming that anodic and cathodic beta values of 0.12 volts represent the average of all corrosion system, equation \otimes reduces to

$$\frac{\Delta E}{\Delta i_{app}} = \frac{0.026}{(i_{corr})} \quad (16) [1]$$

$$\frac{\Delta E}{\Delta i_{app}} = \frac{0.026}{i_{corr}} \quad \dots\dots\dots [1]$$

Equation (15), may be used to calculate the corrosion rate of a system without knowledge of its electrode-kinetic parameters. It can be applied to systems with activation or diffusion controlled ($B_c = \infty$) reduction reactions and yields corrosion rates differing by no more than a factor of 3 from the actual rate. Although the accuracy of this approximation may not always be sufficient, equation (15), provides a unique basis for rapidly measuring relative corrosion rates or changes in corrosion rate [1].

The advantages of electrochemical corrosion-rate measurements, particularly linear-polarization techniques are as follows:

1. These techniques may be used for accurately measuring very low corrosion rates (less than 0.1 MPY), which are both difficult and tedious to perform with conventional weight loss or chemical analytical

techniques. The measurement of low corrosion rates is especially important in nuclear, pharmaceutical and food processing industries, where trace impurities and contamination are problems.

2. Electrochemical corrosion rate measurements may be used to measure the corrosion rate of structures that cannot be visually inspected or subjected to weight loss tests. Underground pipes and tanks and large chemical plant components are examples [9].

Note: Though this exists, the importance of real-timed monitoring system cannot be over-emphasized.

A thorough assessment of the structure is necessary before selecting the maintenance coating system. HSE i.e. on VOC'S.

Health, Safety & Environment

Environmental regulations affect all types of coatings. Epoxy coatings, which traditionally were 50 to 60 percent solids by volume, are now 80 to 100 percent solids by volume to meet VOC (Volatile Organic Compounds) limitations. The usage of epoxy coatings varies from metal primers to specially products that currently have different VOC requirements [3]. The technology is available to achieve these high solids and low solvent demands while maintaining coating performance [3].

Fabrication shops especially are being restricted in total emissions by quantity and type of pollutant. Thus, many coatings are selected for their higher solids or less hazardous ingredients.

Emission permits, required of some coatings users, often specify the amount and types of solvents permitted to be used [3]. These restrictions pressure coatings formulation changes and favour emergence of further higher solids, solvent-free, or water-borne epoxy technologies.

Handling/Health Hazards: Handling epoxies requires the normal precautions associated with solvents, if they are present in the coating. Using solvent-borne coatings of any type necessitates that proper safety steps be followed regarding adequate ventilation, use of explosion-proof lights and equipment, especially in confined areas, and prevention of sparks, flames, or any other possible sources of ignition.

The newer, low VOC epoxy formulations require use of low molecular weight liquid epoxies, which can be skin sensitizers. Similarly, amine curing agents, especially aliphatic amines, are strong skin sensitizers, as are isocyanate curing agents. In addition, resin modifiers such as coal tar are excellent wetting agents, but they tend to remove protective oils from the skin. As a result, the epoxy and the curing agents can cause contact skin dermatitis in workers. To prevent dermatitis, good personal hygiene and protection are required. Protective clothing and creams can be used to prevent skin contact. A worker who has contracted dermatitis should be removed from the exposure area to avoid further exposure. After healing, workers often find that dermatitis can recur with reduced level of contact.

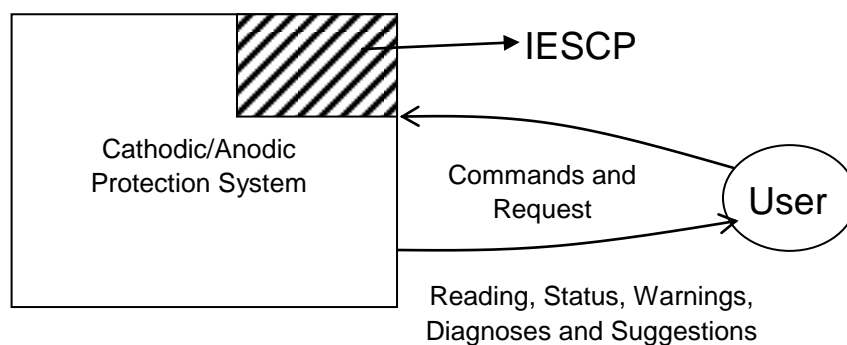


Figure 6: A Model of an Enhanced Integrated Expert-System for Corrosion Protection of Underground Pipelines (EIESCP)



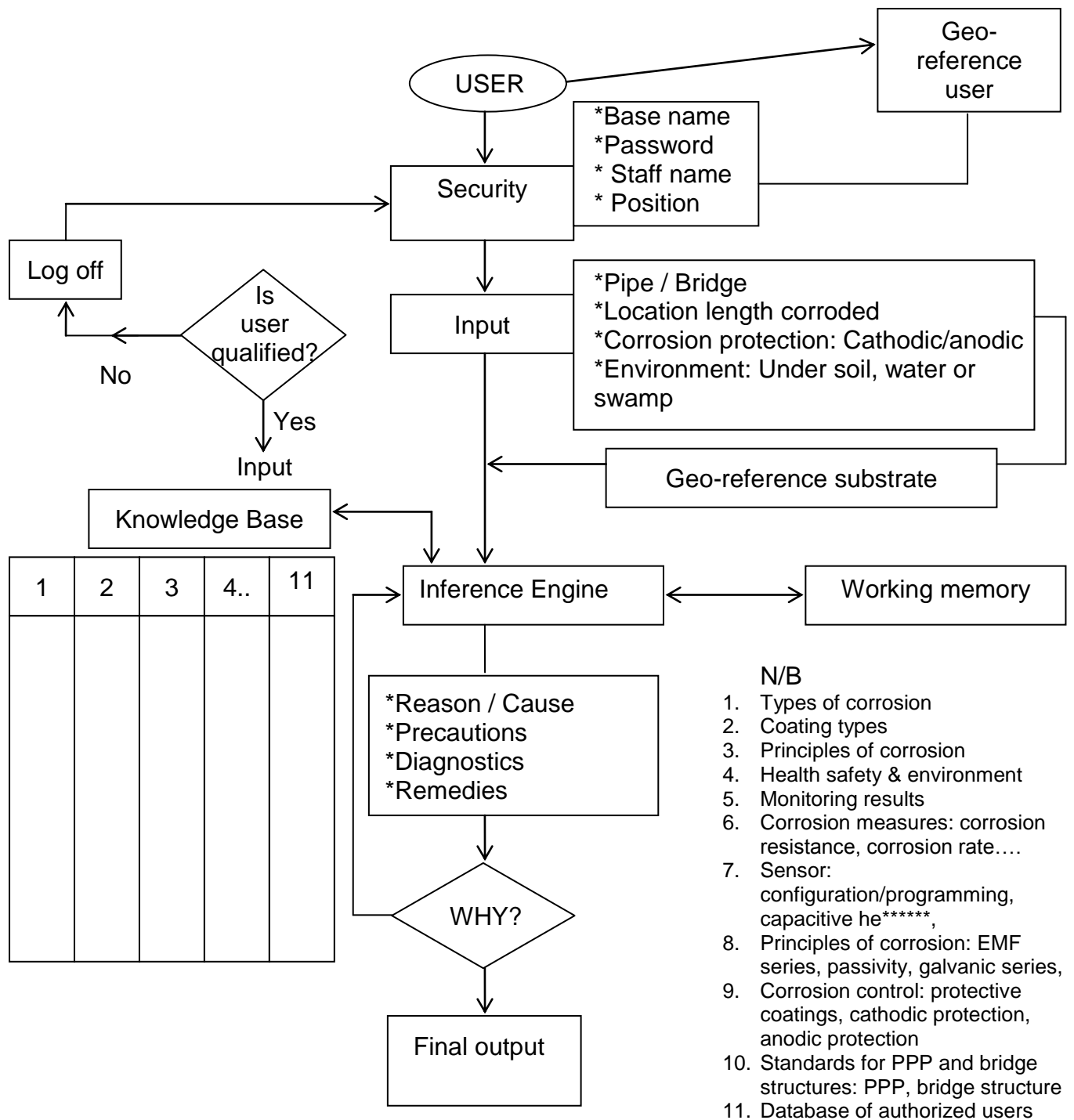


Figure 7: Enhanced Integrated Expert-System for Corrosion Protection of Underground Pipelines (IESCP)

Fumes and vapors can cause bronchial irritation, even with 100 percent solids coatings, especially if they are forced-cured. [3]. Adequate ventilation and use of appropriate respiratory protection are recommended [3]. Many high solids or solvent-free coatings can cause significant exotherm, or release of heat, if mixed in a large volume. If the materials get exceedingly hot or begin to smoke, the best precaution is to pour them out onto a flat surface to permit them to cool, or add materials such as sand to act as a heat sink. This material should then be disposed in accordance with solid/hazardous waste regulations.

The presence of leachable heavy metals in the formulation could cause residual material to be considered hazardous waste material even if no solvents are present [3]. However, it is likely the residual epoxy coating would not be considered hazardous.

Also, material safety data sheets must be reviewed to identify safe handling procedures and safety equipment.

EIESCP Components Model

1. Sensor - Input device [12] Sensor components /- Capacitor, wireless/cabled network of Accessories repeaters and routers
2. Process component/accessories: Microprocessor chips containing the expert system and sensor software [15]
3. Actuators (outputs) are real-time signals at the base stations powered by the integrated Expert System [14]

Conclusion

Conclusively corrosion always causes various damages to the pipeline structure. In this context, it is vital to monitor, find and implement electronically real timed methods which will help to eliminate corrosion or to minimize its effects. There are situations when the pipelines are inaccessible or unreachable to manual corrosion managers. There could also be bias among manual corrosion managers which are common factors among humans. These gaps or problems can be solved using this real time electronic device (EISCP). It consists of a sensor, microprocessor chips and actuators.

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