Review Article

Review of solar cathodic corrosion prevention, control and monitoring of pipelines, tanks and other structures

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Abstract

Inspite of the measures of use of galvanized pipelines and thick anti-corrosion coating of oil pipelines and other metal structures, corrosion of their material still go on, leading to deterioration and systems failure including spills and consequent environmental degradation, huge expenditure on repairs, replacements, cleaning of spills, compensation to flowline communities and revenue loss due to lost man hours before repairs and replacements. If this situation is allowed to continue a chunk of the budgets of oil companies will always go to solving corrosion problems every year. There is therefore urgent need to arrest the situation through use of a combination of adequate coating, CP design and use, pigging and modern remote corrosion monitoring techniques, whose principles and applications are all presented in this work, and which can serve as a blueprint for protecting and remote monitoring of pipelines against corrosion, ensuring no loss of pipelines or oil and thus an increase in revenue generation.

INTRODUCTION

Corrosion is an electrochemical or chemical reaction, between a material usually a metal and its environment, which causes deterioration of the material and its properties. In other words, corrosion is the gradual wearing away and eventual destruction of a metal or alloy etc as a result of its oxidation by air, water or chemicals (Fantana, 1986). Rusting of iron is an example of metal corrosion. Cathodic Protection (CP) is the protection of a metal structure against electrolytic corrosion by making it the Cathode in an electrolytic cell by coupling it with a more electronegative metal or by means of an impressed electromotive force (EMF) (Reading, 2001; Chambers, 1979).

Deterioration of buried metal structures still occur in buried, submerged and even surface metal structures even after coating them elaborately. The most economical way of prolonging the lives of metal structures is combination of application of CP and suitable coating. (Roth, 2004). Corrosion can be remotely monitored using telemetry system which is a system that transmits data captured by instrumentation and measurement devices to remote recording and analysis station (Evans, 1981).

Historical Development of Cathodic Protection

Sir Humphrey Davy in 1824 successfully protected copper cathodically against corrosion by coupling it to iron or zinc. Edmund Davy protected iron bouys by attaching zinc blocks. A zinc alloy particularly suitable for sacrificial anode was produced by Robert Mallet in 1840. CP was incidental to the mechanism of galvanizing

$$Zn + OH^- + H_2O \rightarrow HZnO^{2-} + H_{2\,W}$$

which was first patented in 1837.

Application of impressed electric current for underground structure protection started around 1910 and since then CP

use has spread with thousands of kilometers of buried pipelines and cables, and metal structures and chemical equipment now protected effectively by CP (Uhlig, 1965).

Principle of Cathodic Protection

If the entire surface of a threatened structure is made to act as a cathode of an electric cell by connecting it to a source of enough negative electricity, then any positive ion which comes that way will be neutralized and there will be no positive charge for the formation of metal ions.

   Hence the metal cannot go into solution (Parker, 1962). Surfaces of metals such as brass, aluminum, steel, lead and copper in soils or aqueous media can be effectively protected against corrosion by connecting them to an external applied electric current, which reduces the corrosion virtually to zero for indefinite time. CP cannot be used to avoid corrosion above water line since the impressed current cannot reach metal areas out of electrolyte contact (Uhlig, and Evans, 1965, 1981).

   Factors like length of pipe or area of tank requiring protection, availability of power, soil resistivity, quality of pipe coating used, determine the design of the CP system to be used for protecting a particular system, which usually require an individual study.

Types of Cathodic Protection (CP)

Electrolytic CP

In this CP, the corroding object or object to be protected is made the cathode of an electrolytic cell and is supplied with direct current from an outer current source. A rectifier or a solar module can serve as the current source. The auxiliary anode of the cell is usually insoluble, and can be chosen from platinum, lead, carbon, nikel or graphite, iron (Wranglen, 1932). The positive terminal of the direct current source is connected to the auxiliary electrode and the negative terminal to the structure to be protected. The source of DC may be a rectifier connected to national grid, or solar module supplying low-voltage DC of several ampires. Motor generator can be used although the maintenance is troublesome. Extensive structure may require to have more than one anode, each connected to its own generator.

Galvanic (Sacrificial) CP

In galvanic CP the structure to be protected is made the cathode of the galvanic cell, the anode of which is a base metal: magnesium or zinc, and which by being sacrificial, protects a valuable steel structure. The anode is called sacrificial because it is consumed during the protection of the steel structure (Burns and Bradley, 1976).

   The magnesium alloy or other material used as anode in galvanized CP is sacrificed in generating the current, so that the anodes need periodic replacement. This may constitute inconvenience and expenditure. Electrolytic CP is more convenient than galvanic CP.

 DC Source for Electrolytic CP

The structures to be protected are often located in remote areas where there is no grid electricity supply. Even in areas where grid electricity is available it is not stable and not constantly supplied. Gas turbine and petrol engine generations can be used solely or as backup to the grid power supply. This is however very costly to run. A cheaper, steady and more reliable source of power for generating the direct current required for electrolytic CP is solar energy which are easily available in both urban and remote areas at relatively low cost and does not need regular attention except for vandalization by locals. This system can produce DC power steadily throughout the year if it is backed up with well regulated battery for storing power in the day and supplying power at night.

Statement of Problem

Inspite of the measures of use of galvanized pipelines and use of thick anti corrosion coating of oil pipelines, tanks and other structures, corrosion of their materials still go on. In Nigeria a huge amount of money is spent annually in the maintenance and replacement of corroded oil pipes due to reaction of the pipes with their environment. Petrol stations also have this problem with their buried tanks for fuel dumps. If this situation is allowed to continue without check a chunk of the oil company's and petrol dealer's budgets will always go into the corrosion control every year.
There is therefore, an urgent need to arrest this situation through proper and adequate design CP, and use of modern remote Corrosion Monitoring Techniques.

Corrosion Monitoring

Corrosion monitoring is important for measuring the rate of corrosion and ensuring that the rate of corrosion remains within acceptable limits through suitable corrosion measurement methods. One of the most widely used forms of corrosion monitoring is corrosion coupons. The gravimetric technique is a physical method used to determine quantitative effectiveness of cathode protection according to the formula:

$$Scp = \frac{M_0 - M_1}{M_0} \times 100\%$$

Where Scp is effectiveness of CP, M_0 is corrosion loss of unprotected steel, M_1 is corrosion loss of cathodically protected steel. (Duncan, B. 2000 and Jankowski, J. 2002). The corrosion rate is calculated using the formula:

$$\text{Corrosion rate (mpy)} = \frac{534W}{DAT}$$

Where mpy is mils penetration per year (μmyr^{-1}). W is weight loss (g), D is density (g/cm^3). A is area (cm^2) and T is time (hours).

Good corrosion monitoring technique enhances the ability to identify external pipeline corrosion, thus allowing corrective action to be taken before severe damage develops. A computerized database can be established for proper day to day structures corrosion control (Thompson, N.G.).

Objectives of the Study

At the end of this study, it is expected that a blueprint for CP of pipelines and tanks against corrosion and remote monitoring of pipelines and tanks would be established. The objectives of this work are as follows:
To study the design and installation of;
1.   Ground bed for the CP of given pipelines and tanks
2.   Corrosion monitoring test posts for given pipelines and tanks
3.   Central remote monitoring system and
4.   Evaluate coating and inhibition systems.

Scope of the Study

This research work is confined to CP by impressed current method, corrosion control and remote monitoring technique of pipelines and tanks, using pigging and telemetry systems.

Literature Review

Corrosion is a reaction between a material and its properties. The reaction converts metal into an oxide, salt or some other compound (Fantana, 1986).

Economic Importance of Corrosion

It has been observed that about 10% of total world metal output is lost to corrosion annually; the cost of corrosion to the United States in 1978 was estimated at 4.2% of GNP (Syrett, 2001). The total cost of corrosion to the United States in 2003 was determined to be 6% of the GDP. This implies that the US. spent thirteen times the gross productivity of Nigeria just to fight corrosion. About 1000 tones of steel get rusted away every single day (Higgins, 1991). Replacement cost of iron and steel products, loss of time and production and consequent damages are usually many times the cost of the new metal required for replacement. Large savings can be made by controlling corrosion (Twort, 2004).

The Water Board Corporations and the oil and gas sectors of Nigerian economy stand to make a lot of savings by protecting and monitoring their pipelines and systems. A major problem facing the NNPC and its subsidiary, the pipeline and Products Marketing Companies is the uncertainty about the conditions of the underground bulk transmission pipelines (Burns and Bradley, 1967).

Cost of Pipeline Repairs

The factors which determine the cost of pipeline repairs include:

Location of the pipeline, flowline community issues, size of pipelines and type of product.
The table below shows a repair work cost data carried out on corrosion leaks from 1998 to 2000 in Nigeria (Aneme, SC. 2004).

Table 1. Corrosion repair work cost data

Year	Description	Cost (millions)
1998	8" Delivery line	N40.5
1999	8" Delivery line	N46.5
2000	8" Delivery line	N28.6
	Total	**N115.6**

Cost of Cleaning Spilled Crude

Corrosion eventually causes leakage of pipes and tanks and consequent spillage of crude oil or fuel. Cleaning of the leakage is expensive and the cost of the cleaning is related to the volume of crude spilled. Clearing cost in Nigeria by SPDC from 1998 to 200 is summarized in the table below.

Table 2. Pipeline Spill Clean-up Data

Year	Vol. of Spill (Barrels)	Cost (millions N)
1998	20001	1280.4
1999	1100	795.4
2000	151	194.0
Total	**21252**	**2269.8**

Environmental Degradation Cost

Spillage of crude causes a lot of degradations which include destruction of: human lives, homes, crops, fishes, animals, vegetation, micro-organisms, potable water, farm land, leading to payment of compensation to affected communities by SPDC as shown in the table below.

Table 3. Cost of Corrosion Related Community Compensation (Aneme, S.C, 2004)

Year	Compensation (Millions N)
1998	1067
1999	291
2000	485
Total	1843

Environmental Impact of Corrosion

Economic and environmental effects of metal structures failures and oil pipe spill can be avoided by preventing them. Metal structures failures can cause huge loss of man hours between failure time and replacement time. Oil spills caused by corrosion are harmful to marine birds, mammals, fish and shellfish and responsible for extensive environmental deterioration, damage to agriculture and wildlife, erosion and soiling of environment of buildings, visibility and air pollution when flared (American Petroleum Institute, 1999; Gordon, 1991). Oil spills due to corrosion of pipelines continue to occur in the Niger Delta regions of Nigeria because of inadequate protection of oil pipelines. The SPDC in Nigeria according to its data admitted that there were 170 serious oil spills caused by corrosive pipelines between 1997 and 1999.

Pipelines Protection

Transmission and gathering underground pipelines kilometer lengths in US number up to 119,000, and for gas transmission and gathering up to 528,000. Recent survey records of major US. Pipeline companies indicate that the primary loss of pipeline protection was due to coating deterioration (30%) and inadequate CP current 26%. The rest is associated with general maintenance monitoring and repairing problems.

Methods of Corrosion Prevention

The reasons for prevention of steel include corrosion resistance, lubrication aesthetic appearance and wear resistance

beside CP, metallic and organic coatings are used to provide protection against corrosion of metallic materials. There are five primary methods of corrosion prevention and control (http://www.corrosioncoot.com/method/index.htm): Design, inhibitors, coatings, materials selection, cathodic protection.
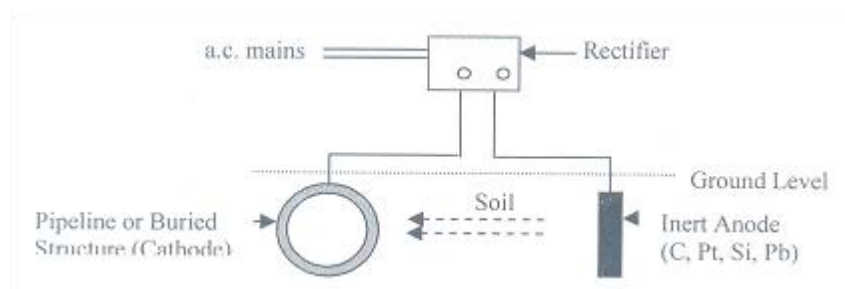
Cathodic Protection

Cathode protection prevents or controls oxidation (rusting) of metal structures by imposing between the structure and the ground a small electric voltage that opposes the flow of the electrons, greater than the voltage present during oxidation. CP has galvanic and impressed current methods. In galvanic CP the structure to be protected is made the cathode of the galvanic cell, the anode which is a more reactive metal or alloy such as magnesium, aluminium or zinc and which being sacrificial provides the electric current that protects a valuable structure. In impressed current CP, the protected structure is the cathode and is supplied with direct current from an outer electrode being insoluble platinum or carbon or silicon or lead (Hunt, 1982; Ijomah, 1991).
Below are diagrammatic illustrations of galvanic CP and impressed current CP
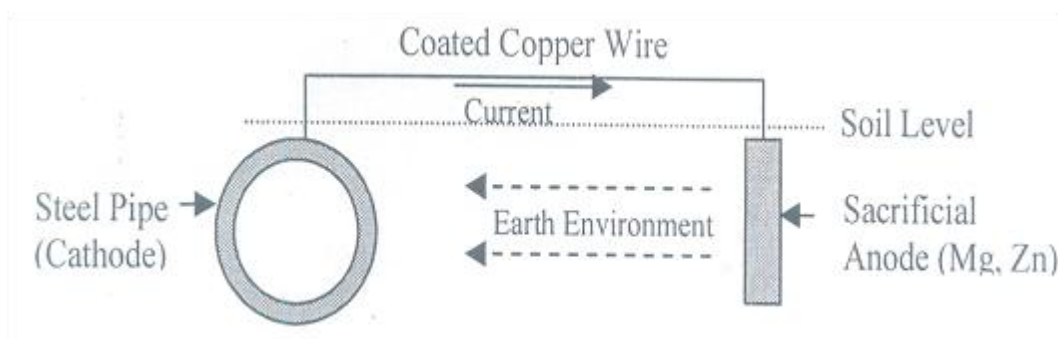
Figure 1. Galvanic Cathodic Protection of Underground Pipeline

No external source of emf is needed in galvanic CP. The magnesium alloy or other basic material is sacrificial in generating the required electric current and so the anodes wear out and need periodic replacement, a source of inconvenience and expense.

Figure 2. Impressed Cathodic Protection of Pipeline Using a Rectifier

In general electrolytic CP is more economical than galvanic method especially if long lines or large surface or poorly coated metal structures are involved. Current supply from the a.c mains is erratic and does not favour CP(Chambers, 1979).

Energy for CP

The required electrical energy sources are of two classes: Non-renewable and renewable
The non-renewable include thermal, coal and petroleum while the renewable include wind, ocean wave, solar and hydroelectric power sources. The electric current can be sourced from rectifiers powered by grid supply electric generators or sourced from PV systems. A stand alone photovoltaic system can be used to supply the power. It will be connected directly to the application device and power supplied during the sunshine hours conserved in storage batteries in the system can make power available during the night.
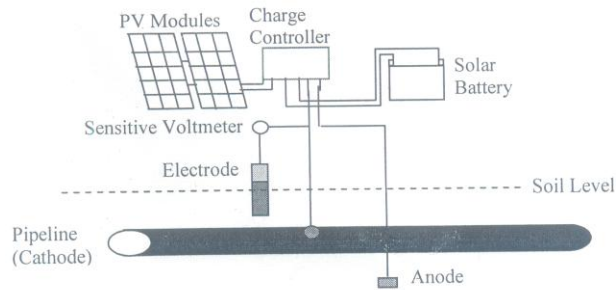The diagram below illustrates solar photovoltaic Electrolytic Cathode Protection of pipeline.

Figure 3. Cathodic Protection of Pipeline Using Photovoltaic Modules

Cathodic Protection Remote Monitoring Techniques

Cathodic protection systems are most effective with proper monitoring. Utilizing the latest electronic and communication technologies for remote monitoring, reduces the operational costs associated with traditional maintenance methods. Corrosion data collected via remote monitoring can be integrated into data management solutions to provide real-time information about corrosion control systems. The instrument is used to monitor structure-to-soil potentials at test posts or meter sets etc. it is programmed to record data at regular intervals, to generate reports, detect and report failures at the sites. CP remote monitoring technology allows engineers to monitor CP system at a central remote location. This CP system is more reliable and less manpower will be required for CP monitoring. Wireless monitoring and control of CP networks, can handle information from thousands of remote sites (Wausah, 2001).

MATERIALS AND METHODS

Inhibitors

Some chemicals like salt promote corrosion while others inhibit corrosion. Organic amines, chromates and silicates are common inhibitors. Organic amines are absorbed on anodic and cathodic sites and stifle the corrosion current. Inhibitors promote the formation of protective films on the metal (cathode) surface (Wansah, 2007).

Resistivity Measurement

Soil resistivity is an important input into the design of CP.
The diagram below illustrates the Wenner four-pin method which is the best way of obtaining resistivity of soil.
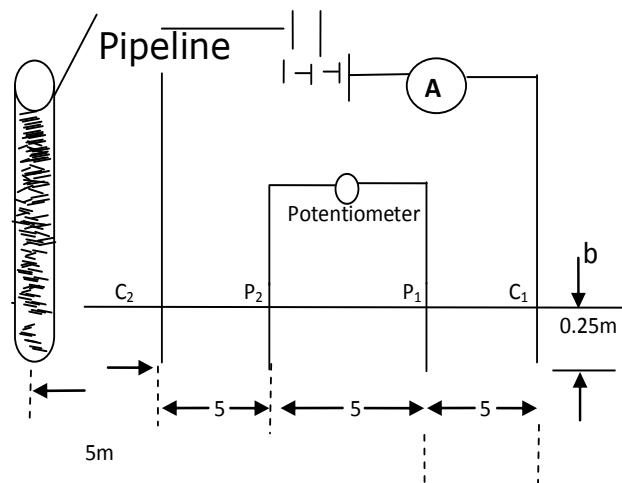

Figure 4. Werner Four- Pin Method of Soil Resistivity Measurement

The figure above shows four equally spaced metal pins driven into the soil in a straight line. The current source

terminals are connected to the outer pins C_1 and C_2 and the voltage measurement terminals are connected across the two inner pins as shown.

b is the electrode depth of the pins C_1, C_2, P_1, P_2,. The resistance (ohms) is read directly from the potentiometer and the resistivity is given by

$\rho = 2\Pi SR$
Where ρ = soil resistivity (ohm-m)
S = spacing between pin electrodes (m)
R = resistance measured (ohms)

Ground bed Design

Location that is specifically prepared to house single or combination of anodes is called a ground bed.

For impressed anode ground beds, the soil resistivity is determined at a selected location. The anode material and combination is chosen for a design of appropriate type of ground bed. Shallow horizontal, shallow vertical and deep well are three types of ground bed designs. For underground impressed current systems high silicon cast iron or graphite is used as anode material and in the ground the anode is surrounded by a carbonaceous backfill (coke breeze) which helps to reduce anode resistance to earth, extend anode life by allowing anodic reactions to occur on their surface and provide porous structure for escape of anodic gas products.

For single vertical anode resistance to earth, the deep anode ground bed resistance is given by Dwight's equation as

$$R_v = \frac{0.00521\rho}{L} \left(\ln \frac{8L}{d} - 1\right)$$

R_v = Resistance to earth of a vertical single anode (ohms) resistance for multiple anodes in parallel is calculated as

$$R_{MV} = \frac{0.00521\rho}{NL} \left(\ln \left(\frac{8L}{d}\right) - 1 + \frac{2L}{s} \ln 0.656N\right)$$

ρ = soil resistivity (ohms)
N = number of anodes in parallel
R_{MV} = Resistance of multiple vertical anodes in parallel to earth (ohm)
S = anode spacing (m)
L = anode length (m)
d = diameter of anode (m)
For a given impressed current the number of anodes required is given by:

$$NA = \frac{CR \times DL \times I}{UF \times Wt}$$

Wt = Anode weight (N)
NA = number of anodes
DL = desired life (years)
CR = Consumption rate (kg/amp-year)
UF = Utilization factor
I = required current (amps)
NA is given by NA = I/MD
Maximum discharge per anode (amps), MD is obtained from manufacturer's data.
Dwight's equation for multiple anodes installed horizontally is given by

$$R_H = \frac{0.00159\rho}{L} \left[\ln \frac{4L^2 + 4L\sqrt{S^2 + L^2}}{ds} + \frac{S}{L} - \frac{\sqrt{S^2+L^2}}{L} - 1\right]$$

R_H = resistance of horizontal anode to earth (ohms)
S = twice anode depth (m)

Deep Well Ground beds

A series of vertical anodes is required when the soil resistivity is very high. The vertical anodes are installed in deep well ground beds (up to 100m or more). The depth of the well is determined from the soil resistivity value with the Dwight's equation. A soil resistivity survey is carried out to determine the well depth. A basic design incorporates the use of a steel casing to prevent the collapse of the drilled hole. Several anodes are attached together with a rope and placed inside the casing. The remaining space is then filled with carbonaceous material. The deep well is then fitted with a vent to allow gas to escape. Gas entrapment increases ground bed resistance. Steel casing may not be necessary in certain rock formations. Deep well ground beds provide good current distribution. However they are very expensive to drill. The figure below illustrates the structure of a typical vertical anode installation.
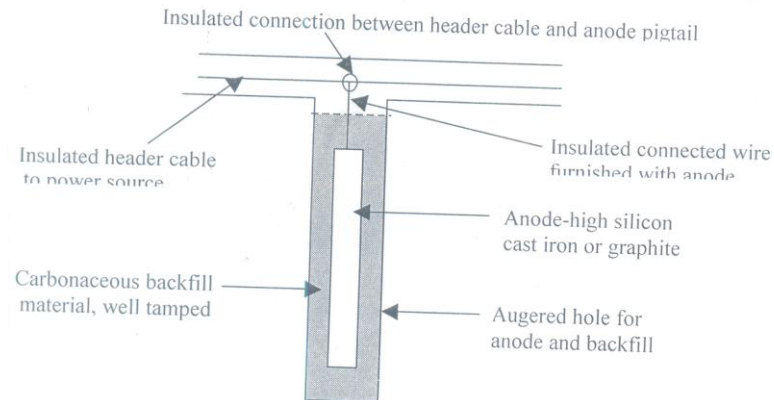
Figure 5. Typical Vertical Anode Installation
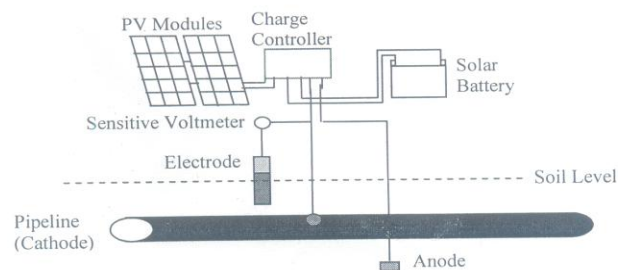
Figure 6. Cathodic Protection and Corrosion Remote Monitoring Unit

Corrosion Remote Monitoring System

Corrosion characteristics monitoring of a structure can lead to proper selection of longer life material, adequate corrosion control measures and durable and protective coatings. Modern corrosion monitoring technologies emphasize the highly time-dependent nature of corrosion damage. The integration of corrosion monitoring technology in existing systems can also provide early warning of costly corrosion damage and provide information on where the damage is taking place. CP remote monitoring unit (RMU) when installed, measures regulation output voltage and current, structure to structure potentials and solar modules output voltage.

A permanent copper-copper sulphate reference electrode is buried near the structure of the monitoring location and its lead wire is routed to the RMU.

A telephone line is connected to the RMU to enable communication with central computer. The use of a modem-equipped laptop computer will enable the CP system to be monitored remotely at any time (Wansah, 2007; Van Blaricum, 1997).

Pigging Technology

Pigs are devices inserted into pipelines, driven by product flow throughout the length of pipeline. Pigging activities perform the following functions: remove substances that might cause damage to process systems, prevent formation of

corrosion cells, provide data on system problems for immediate action, provides alternative to pipeline shut down for statutory inspection, removes debris of foreign matter in pipeline, removes deposits that might restrict flow and monitor operating and/or physical conditions of the pipeline. There are various types of pigs for various functions.

CONCLUSION

CP and corrosion remote monitoring technology reduce cost and amount of human effort required to maintain reliable CP systems. The remote monitoring equipment allows personnel to collect CP performance data from distant locations using a single modem-equipped compatible personal computer. This will eliminate the need for field site travels, increase rate and coverage of site evaluation; drastically reduce cost and free personnel for other duties.

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