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Prolonging the lives of buried crude-oil and natural-gas pipelines by cathodic protection.

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Abstract

In Nigeria, a major problem is the corrosion of the external surfaces of such pipelines, which are not usually adequately safeguarded during construction. A cathodic-protection(CP) system should be applied to the pipeline before this period.

Keywords: Corrosion, buried pipes, cathodic protection, impressed current, sacrificial anode

Nomenclature and Abbreviations

A	-	Surface area (m^2)
AC	-	Alternating current (A)
ASME	-	American Society of Mechanical Engineers
BFD	-	Basis for the design
c	-	Corrosion allowance(mm)
C_a	-	Anode capacity [given as 0.125A-yr/kg at 50% efficiency]
CP	-	Cathodic protection
d	-	Anode diameter (m)
d_i	-	Internal diameter of pipe (= 0.254m)
D	-	Pipe diameter (m)
DC	-	Direct current (A)
DPR	-	Directorate of Petroleum Resources
E	-	Driving potential (V)
F	-	Area Factor
F_u	-	Utilisation factor [= 85%]
GNP	-	Gross National Product

I	-	Current per anode (A)
IC	-	Impressed current
ICCP	-	Impressed current cathodic-protection
L	-	Length of pipeline (metres)
N	-	Number of galvanic anodes
NACE	-	National Association of Corrosion Engineers
NWT	-	Net wall-thickness (metres)
p	-	Soil resistivity (ohm-cm)
P	-	Pipeline's design-pressure (bar)
PC	-	Protection current (A)
Q	-	Production flow-rate in barrels per day (bpd)
R	-	Resistance of vertical anode
Re	-	Reynolds number
SMYS	-	Specified minimum yield stress(N/m^2)
SUTS	-	Specified ultimate tensile-strength
t	-	Wall thickness (m)
t_c	-	Anti-corrosion coating thickness (mm)
t_m	-	Minimum required wall thickness (i.e. sum to ensure that the mechanical strength, corrosion and erosion requirements are satisfied)
T	-	Estimated anode life (years)
TP	-	Thickness-measurement point
V	-	Speed of crude oil (= 2.43 m/s)
W	-	Weight of an anode (kg)
ν	-	Kinematic viscosity (= 2.05 x 10^{-6} cSt)
ρ	-	Density of conveyed crude oil (= 0.8207kg/m^3)

GLOSSARY

Corrosion is the gradual deterioration of a metal surface when it is in contact with an electrolytic medium.

Ground-bed: One or two anodes are installed below the earth's surface for the purpose of supplying cathodic protection.

Impressed-current system uses an external current source (usually a rectified direct-current) to power a grounded anode from which current flows through the earth to the pipeline's surface over appreciable distances, thus eliminating all corrosion circuits otherwise active on the surface of the pipeline.

Lag period is the pipeline construction duration i.e. initial period during which the new pipeline is in the ground without cathodic protection.

Sacrificial or galvanic anode system: An active metal (like Zn or Mg) is connected to a buried

pipeline to reduce its corrosion. The anode metal corrodes and in doing so discharges an electrical current to the pipeline.
Water cut is the percentage by volume of water contained in the crude oil and water mixture.

Introduction

Leakages from pipelines occur frequently and are tolerated in Nigeria despite its economy depending predominantly on the revenue gained from the sale of crude oil and related products, which are usually transported using such pipeline networks. The leakages are caused primarily by corrosion [1] as a result of the exposure of the inner surface of the pipeline to water. However, corrosion of the external surfaces of pipelines also occurs because of the exposure to their external environment. Such external coatings form an insulating layer over the metallic surfaces. Each coating isolates the metal from direct contact with the surrounding corrosive electrolyte, e.g. soil or sea water. It interposes a high electrical resistance, such that the electrochemical reactions cannot readily occur. However, such coatings, when inappropriately applied, may contain holes (referred to as "holidays"), which act as corrosion initiation sites. Holidays in coatings may also develop, while the pipeline is in service, as a result of degradation of the coating by either a harsh environment, soil stresses, relative movement of the pipe with respect to the surrounding ground and or other defects not related to pipeline construction [2].

Modern coatings permit the use of a low current-density (CD) (of less than 0.01 mA/m^2) for the effective cathodic-protection (CP) of the external surface of a pipeline[3] to ensure that external corrosion is drastically reduced. The present investigation is focused on ensuring adequate protection of the external surface of the pipeline against external corrosion during the construction stage of a pipeline network. Modern underground pipelines tend now to be designed with protective coatings, supplemented by CP systems to protect the pipelines against external corrosion [4]. The two categories of CP are the impressed-current system and the sacrificial-anode system.

Sacrificial (or Galvanic) Anode CP System

This is accomplished by connecting a metal (Zn or Mg) anode to each section of the underground pipeline. The anode will corrode and, in so doing, will discharge an electric current to the pipeline. (The current output of such a galvanic anode installation is typically much less than that which is obtained from an impressed-current CP system). In low-resistivity environments (e.g. marine or swamp locations), typical current outputs for a 40kg

Mg anode, at an efficiency of 70%, range from 50 to100 milliamps. (An impressed current system can generate as much as 60amps depending on the design and operating requirements).

Galvanic-anode installations are used mostly on underground structures, where CP current requirements are relatively small and where the soil resistivity is low, say less than 10,000 ohm-cm [5]. The galvanic anode system is self powered and does not require an external power-source. When the current requirement is small (i.e. below 500 milliamps), a galvanic system is more economic than an impressed-current system.

Impressed-current CP system

This is commonly used in the oil and natural-gas industry: it is more effective than the sacrificial anode system and the preferred means for protecting buried cross-country pipelines. An external current source (usually a DC source) powers a grounded anode, from which current flows through the earth to the pipeline's external-surface, sometimes over appreciable distances, thus eliminating all corrosion otherwise occuring on the pipeline's external metallic surface. This practice is usually carried out as a statutory supplement, after applying a protective coating on the pipe's surface.

A variety of factors affect the effectiveness of an ICCP system: soil resistivity, coating material, choice of power source and current requirements are influencial. Generally, ICCP systems are used to protect large bare and coated structures in the presence of high-resistivity electrolytes. The design of an IC system must take into account the likelihood of coating damage occurring and the possibility of creating stray currents, which may adversely affect other structures. A typical IC system is made up of a power source, transformer rectifier, ground-bed, cables and junction boxes.

Literature Review

Krause[6] identified corrosion as the deterioration of a material (usually a metal) as a result of its reaction with its environment. Corrosion is inevitable in our ambient environment and constitutes a major problem for the crude-oil and natural-gas industry and pipeline operators. The rate of corrosion can be controlled by the use of protective coatings, CP as well as the choice of appropriate materials for the pipeline and/or corrosion inhibitors.

Installing an effective protection system is deemed to be highly economic and constitutes only about 1% of total project cost for the pipeline.
Bird [7], using the Saudi Arabian Oil-Company experience, reviewed the external corrosion of two 22-year old commissioned pipelines crossing the Arabian desert. External corrosion protection was an applied tape-wrap, supplemented by an ICCP system, which was implemented after both pipelines were commissioned. No mention was made of maintaining the technical integrity of the new pipeline against external corrosion during the construction period. Anene [8] concluded that increasing the wall thickness is not a recommended solution for an integrity problem as the pipeline will continue to corrode until a CP system is installed. Operating a commissioned pipeline, with effective external CP, will result in considerable cost savings in life-time maintenance and an overall reduction in environmental and health hazards associated with leaks that would have occurred resulting from external corrosion of the pipeline.

The use of an expensive alloy as the material of a pipeline(in order to inhibit its corrosion) is uneconomic [9]. Eliassen and Hesjerik [10] concluded that, for most pipelines buried in high-resisitivity soil, the CP current demand is high. However the pipeline's integrity can be threatened by severe interference problems, e.g. arising from the presence locally of a direct current for a local electric railway. (For operational pipelines, the external corrosion risks are generally dependent on the anodic-current densities). Also, alternating current interference from near-by high-power transmission lines can be a major source of a pipeline's external corrosion. Hence, careful pipeline-route selection is important.

On-line monitoring of the CP system, for all operational pipelines, will identify zones of likely problems for implemenation or remedial actions and so probably reduce the rate of a pipeline's leaks due to external corrosion[10]. Secondly, corrosion-integrity management, for each operating pipeline, should ensure a safer and more reliable operation as well as improved safety for the public and the company's operational staff. All faults and abnormalities should be reported immediately. Prompt repairs to all identified damaged coatings are recommended in order to ensure the on-going effectiveness of the protection system.

Pipelines are generally designed with an expected minimum service life of 25 years [11]. So in order to survive the harsh underground surroundings in which these pipelines are laid, they should be protected from external corrosion by appropriate coatings and supplemented with CP systems. The coatings must be tough and adhere well to the pipes' external surfaces, while CP is generally achieved via an IC system applied after pipeline commissioning in order to maintain the pipeline's technical integrity. The IC system is recommended for operational pipelines and should be designed in accordance with NACE RP0169-2002 [12]. However, little or no consideration is at present given to the deterioating integrity of pipelines during assembly in Nigeria, despite the often long unexpected delays during this construction period. The provision of a protective system for a pipeline throughout this construction stage is desirable.

The problem

A pipeline with an external protective coating and supplemented by a CP system is regarded as fully guarded against external corrosion provided the installed CP system delivers a protective potential of at least 850mV for a saturated copper/copper sulphate electrode contacting the electrolyte. Measurement of the defence achieved is undertaken after specified time intervals in accordance with regulations issued by the Directorate of Petroleum Resources (DPR) [13].

The CP system's voltage-drops must be measured across the pipeline-to-soil interface to ensure a valid indication. The procedure pertinent to overall maintenancel involves:-

- Measuring or calculating the voltage drop(s).
- Reviewing the previous performance of the CP system.
- Evaluating the physical and electrical characteristics of the pipeline and its environment.
- Determining, through regular checks, whether or not there is evidence of corrosion.

Before the present investigation, no one in Nigeria had focused on protecting pipelines which subsequently are to be buried, during the construction period prior to commissioning.

The project life cycle

The model in Figure 1 shows the complete project-cycle which consists of five main phases [14], and should help direct attention to achieving pipeline integrity before commissioning.

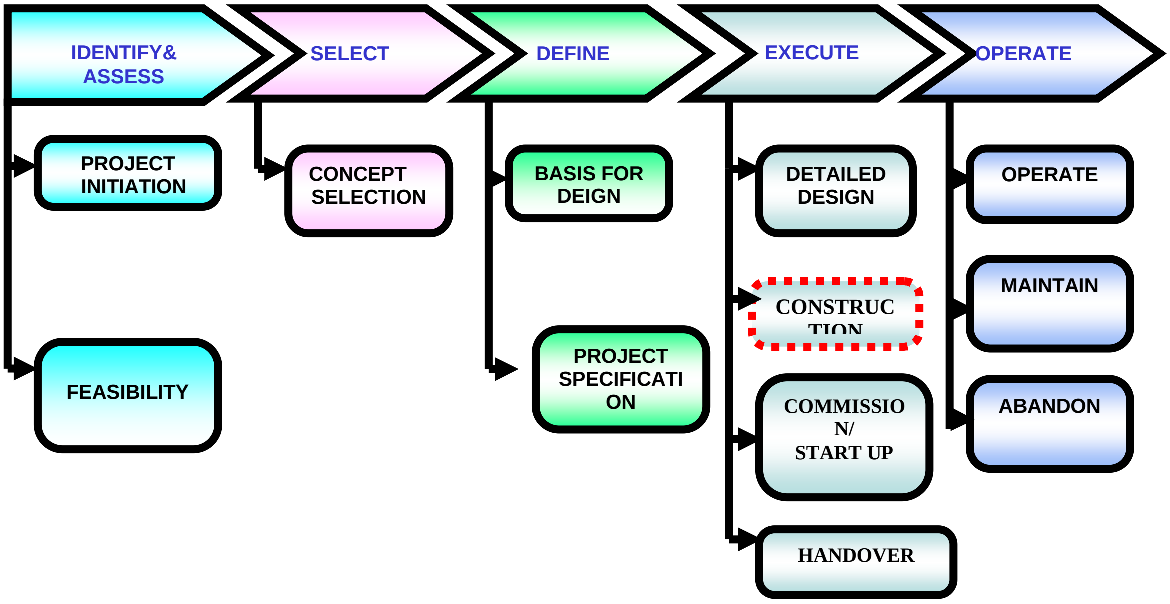


Figure1 The project's life-cycle.

We shall focus on the problems of the technical integrity of new pipelines due to external corrosion during the construction period. In previous studies, it has been assumed that external corrosion of the pipeline will only commence after pipeline commissioning, but, in reality, relatively rapid external corrosion is initiated immediately the steel pipeline is placed in contact with the soil during the pipeline's assembly [15].

Solution to the identified problem

Each CP system is usually designed and installed after commissioning the pipeline. Then, the system is balanced to deliver the required minimum protection potential of -850mV for the effective defence of the new pipeline. Thereafter schemed monitoring, inspection and maintenance of the installed system is desirable to ensure the effective protection of the pipeline against external corrosion[16].

Interference may occur between pipelines or other metallic installations, for instance, pipelines or metallic structures, that are not protected, carry currents when they are within the electric field of a CP system and will discharge these currents back to the protected pipeline. This may result in an accelerated external-corrosion attack at the point of current discharge on the protected pipeline. This problem is solved by shielding the pipeline or by installing electric bonds between the pipelines. Generally, interference problems are most severe in high-resistivity soil [17].

Economic justification for Cathodic Protection

It is usually cost effective to justify the adoption of CP system, i.e. it is far cheaper in the long term, to install a properly designed CP system on a pipeline network than have to locate and repair pipeline leaks. Installation of CP systems has considerably extended the operational lives of pipeline networks, while operating the pipelines within their safe design envelopes. For cases where a comparison has been made between installing a CP system on a new pipeline rather than increasing the wall thickness through an additional corrosion allowance, it can be seen that the cost of the additional wall thickness far exceeds the cost of installing the appropriate CP system. Furthermore, the pipeline, even with the extra wall thickness, but without CP system will corrode and reach a state when provision of CP is the only option to avoid external corrosion induced leaks [5].

The costs of corrosion management after pipeline commissioning, in Australia, the United Kingdom, Japan and several other advanced countries, are about 3 → 4% of the gross national product (GNP). In the USA, the result of a similar study at the request of the American Congress showed that the cost of all corrosion management is about 4.2% of the GNP or $180 billion per year: this is a combination of both direct and indirect costs after pipeline commissioning. This figure is actually higher because external corrosion commences from the start of construction. The situation is probably worse in Nigeria because of the particularly aggressive environments and working practice that are ineffectve.

Pipeline design

CP should not be regarded as an alternative to external coating, but rather as supplementary to ensure protection against external corrosion.

The following data are used as the basis for the design (BFD) in the present pipeline project:

Daily production-rate of crude-oil	: 60,000 bpd
Relative density of crude-oil	: 0.8207
Kinematic viscosity of crude-oil	: 2.04 cSt
Dynamic viscosity of crude-oil	: 1.67 cP

Pipeline surface roughness	; 0.025mm
Temperature of flowing crude-oil	: 40^0C max.
Design pressure	: 1100 psig (76 bar)
Depth of ground cover	: 0.90m
Design life	: 25 years
Annual corrosion rate of pipeline	: 0.1mm/yr
Water content of soil	: 30% average
Ambient temperature	: 18^0C minimum ; 35^0C maximum

Hydraulics and Mechanical Design.

Pipe diameter

For all cross-country buried pipelines, the conveyed liquid's recommended speed lies between 0.5m/s and 5m/s. The design speed for crude oil within the Obigbo-North pipeline in Nigeria was recommended to be in the range of 0.7 to 2.43 m/s. For this pipeline design, calculations, the upper value of 2.43 m/s was chosen.

The piping diameter can be is determined [18] using the equation

$$V = (0.0119 \times BPD) / D^2 \tag{1}$$

where V = Flow speed = 2.43 m/s

Q = Production flow rate = 60,000 bpd

D = Pipe diameter

Therefore, D = 0.254m

Reynolds number (Re)

The Reynolds number provides an indication of the flow regime expected in the pipeline network while in operation and is given by:

$$\mathrm{Re} = \frac{\rho V d_i}{\mu} = \frac{V d_i}{\upsilon} \tag{2}$$

where ρ = density of crude oil = 0.8207kg/m^3

d_i = internal diameter of pipe = 0.254m

ν = kinematic viscosity = 2.05×10^{-6} cSt

If **Re < 2300**, the flow is **laminar** and if **Re >4000**, the flow is fully **turbulent** [19].

The Reynolds number for this flow in this pipeline is given by:

$$\mathrm{Re} = \frac{2.43 \times 0.8207 \times 0.254}{1.67 \times 10^{-3}} = 303$$

Hence, the flow is laminar.

<u>Friction Factor(f)</u>

This can be determined [20] from

$f = 0.0072 + 0.636/Re^{0.355}$ (3)

Thus, the friction factor for this flow in this pipeline is given by:

$f = 0.0072 + 0.636/(303)^{0.355} = 0.804$

<u>Wall thickness</u>

This is a critical factor with respect to the useful life of the pipeline. Its wall thickness, t should be dictated mainly by the internal pressure to which it is subjected and is given by the modified Barlow's equation [21] for circumferential stress as:

$$t = (P \times D) / (2 \times F \times SMYS \times E) \quad (4)$$

Thus, $t = (1100 \times 10.75) / (2 \times 0.6 \times 52000 \times 1) = 4.83$mm

Based on ASME 31.4 [21], $t_m = t + c$

Assuming a design life of 25 years and corrosion rate of 0.1mm/year,

$c = 0.1$mm/yr x 25 yrs = 2.5mm

Therefore $t_m = 7.37$mm

The closest commercially available size is 7.62mm.

Thus the 0.254m schedule 30 piping class was selected for the pipeline.

Reduced project life-cycle

The design life of most pipelines is 25 years under the specified design-conditions. The challenge is to develop a maintenance programme, which will ensure that this criterion is satisfied. The present analysis of pipeline defects indicates that most external corrosion failures were initiated during the pipeline's construction period due to a lack then of effective protection.

Implementation of solution

It is clear that present design and construction practice do not guarantee effective protection of pipelines during assembly. There is therefore a challenge to find a solution that will overcome this critical problem for the vast pipeline networks in the Niger Delta Area of Nigeria. The degradation implications of current practice of laying steel pipelines (in a corrosive medium) without effective protection against external corrosion is now acknowledged. There is an economic justification for protecting the new pipe during pipeline laying and assembly i.e. before, the pipeline is commissioned and a permanent ICCP is installed. By considering the relevant economics and ease of implementation, various options were considered; the sacrificial (galvanic) anode CP system was the preferred option. This system is most suitable for short-term periods of protection to prevent external corrosion. It is effective and will guarantee the required full protection against a pipeline's external corrosion during construction. The sacrificial-anode system is very cheap and most favoured compared with the more capital-intensive IC system. Generally, materials for the sacrificial-anode are readily available and easily installed, even in difficult terrain. This system has an economic advantage over the IC system for short duration usage. A typical layout of a sacrificial-anode system is shown in Figure 2.

Design details for the sacrificial (galvanic)-anode CP System

The 0.254m (diameter) x 12km (length) Obigbo pipeline [20] is detailed below. Magnesium and zinc are the two main types of galvanic anode materials used, but the former is more popular.

Generally, sacrificial (galvanic) anodes are used where the installation is for (i) a short period, (ii) a small current requirement and (iii) the pipeline is to be in contact with a soil of low resistivity. For effectiveness, the anode material should not be located more than 5m from the pipeline and must be surrounded by a bentonite/gypsum mixture.

The basic design data for the presently considered system are:

$L = 12$ km

$D = 0.254$m

$t = 0.036$m

$R = 500$ ohm-cm

$t_c = 5$ mm

$I = 0.1$ mA/m^2

$V = -0.670$ V

The pipeline's external surface area (A) is given by [18]:

$$A = 3.142(D + 2t_c)L = 0.9953 \times 10^4 \text{ m}^2 \quad \text{---------------} \quad (5)$$

Using a design current density of 0.1 mA/m^2, then the

Protection Current (PC) = A x I = 0.9953 A (i.e. approximately 1A)

From the magnesium-anode manufacturer's data, a 14.5kg high-potential anode should be 0.5m long and 13 cm in diameter with a potential of -1.75V. The average potential of the pipeline system is -0.67V.

Hence the net initial driving potential (E) is given by

$$E = -1.75V - (-0.67V) = -1.08V \qquad \text{-----------------} \qquad (6)$$

Using Dwight's [21] formula for the resistance of a vertical galvanic anode in soil gives

$$R = 0.005p/3.142L[\ln(8L/d) - 1] \text{ ohm/anode} \qquad \text{--------------} \qquad (7)$$

where p = 500 ohm-cm

L = 0.5 m

d = 0.13 m

Hence, R = 0.005 x 500/3.142 x 0.5 [ln (8 x 0.5 / 0.13) – 1] ohm/anode

= 3.867 ohm / anode.

But the maximum output current from each anode is given by;

$$I_{max} = E / R \qquad \text{---------------------------} \qquad (8)$$

$$= 1.08 / 3.867 \text{ A}$$

$$= 0.28 \text{ A}$$

The number of galvanic anodes required to protect the pipeline is given by;

$$N = I_t / I_a \qquad \text{-------------------------} \qquad (9)$$

where I_t = Total current required [0.9953 A]

I_a = Single anode current [0.28A]

N = 0.9953 / 0.28 anode = 3.55 anodes [i.e. in practice 4 anodes]

This implies that the anodes should be spaced at 3 km intervals.

Because the pipeline will be polarised to at least a potential of -0.850V, the net driving force of the anodes is given by;

$E = -1.75\ V - (-0.85V) = -0.90V$

Current (I) per anode = 0.9 / 3.867 A = 0.23 A

Because the magnesium anodes operate at 50% efficiency, the estimated anode life [21] is given by;

$$T = 2/3F_u \times C_a \times W/I \qquad (10)$$

where F_u = 85%

C_a = 0.125 at 50% efficiency

W = 14.5 kg

I = 0.23 Amps

Hence, $T = 0.85 \times 0.125 \times 14.5 / 0.23 = 6.7$ years

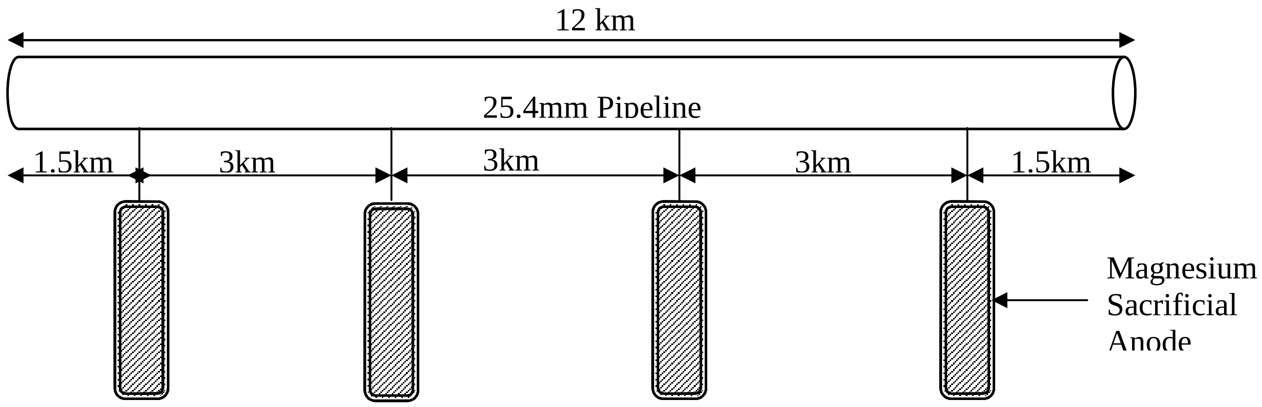
Thus the estimated anode life is taken as 7 years which includes the lag period.
The layout of the sacrificial anode is shown in Figure 2.

Field testing of the design

Both the sacrificial and the IC systems have proven to be reliable and effective means of secondary protection of underground pipelines against external corrosion. They have been used on both old pipelines, storage tanks and steel bridges with desirable results.

Following the findings and recommendations arising from this study, concerning the technical integrity of new underground pipelines with respect to external corrosion, the installation of temporary sacrificial anodes was implemented during the construction of the new 20.32mm internal diameter x 10.2km long Agbada pipeline with a 4.26mm wall thickness. This new pipeline project started in February 2004 (Q1-2004), construction work was completed in November 2005 and the pipeline fully commissioned by the end of December 2005.

The magnesium galvanic anodes were installed at four positions in accordance with the design layout shown on Figure 3.



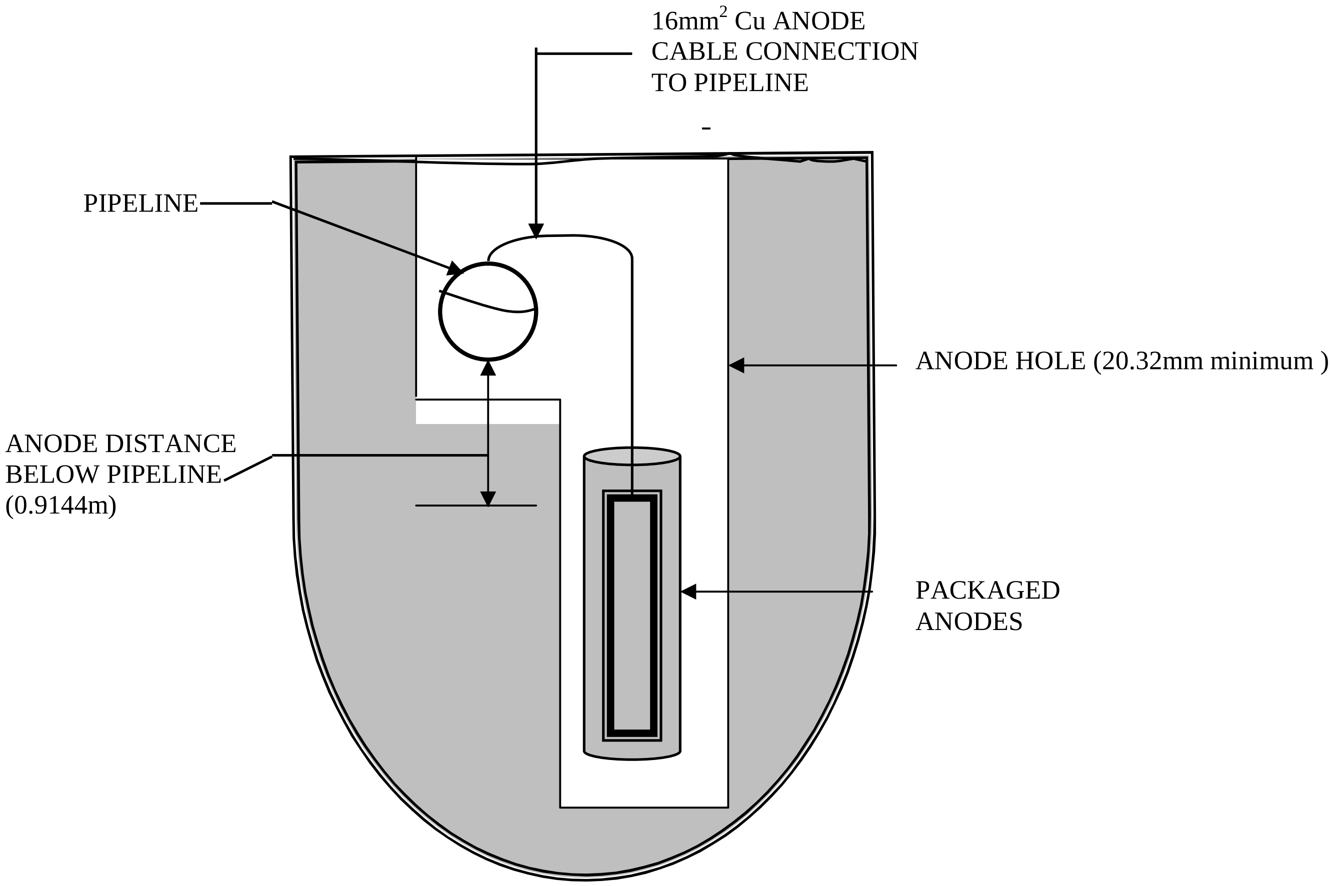


Figure 2 Schematic of the sacrificial-anode installation on pipeline

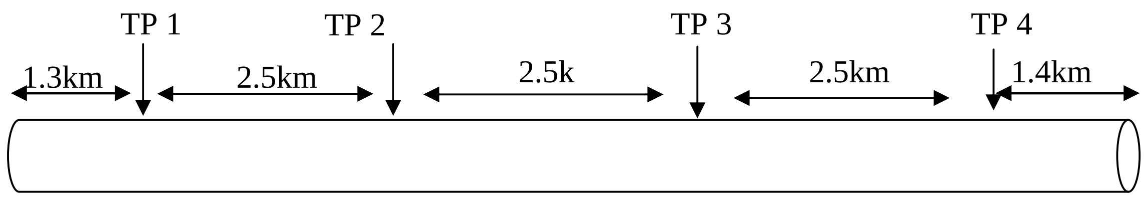


Figure 3 Schemaitc of the distribution of galvanic anodes along the Agbada pipeline (not to scale)

Ultrasonic measurements of the intergrity of the new pipeline's wall thickness were taken every six months during the construction period up to April 2005 using a calibrated DMS 2 Krautkramer ultrasonic thickness-gauge, which achieves an accuracy of 95%, i.e. far better than obtained with an intelligent pig dragged through the pipe. At each location where a measurement is to be made, the pipe is decoated to expose the bare metal and subsequently recoated using polythene tapes after each measurement The locations on a vertical section of the pipeline at which the measurement were taken are shown in Figure 4.

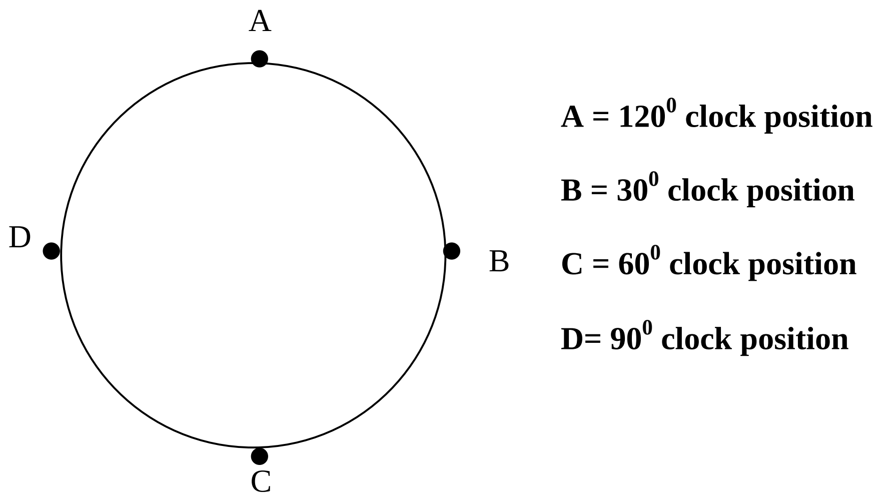


Figure 4 UT measuring positions

Tables 1 → 3 show the wall-thickness integrity measurements, obtained during the 18 months construction period, using the ultrasonic equipment. The worst defect within the monitoring period was a 0.23% wall loss which corresponds to less than a 1% wall loss for a five-year period. This clearly confirms that, as a result of the use of a galvanic anode system the technical integrity of the new pipeline was not affected significantly during the construction period.

Table 1 Wall-thickness measurement (in mm) March 2004

Location	A	B	C	D	Average	NWT	Mean % Wall Thickness loss
TP 1	4.26	4.26	4.26	4.26	4.26	4.26	0
TP 2	4.26	4.26	4.25	4.26	4.26	4.26	0
TP 3	4.26	4.26	4.26	4.26	4.26	4.26	0
TP 4	4.26	4.26	4.26	4.26	4.26	4.26	0

Table 2 Wall-thickness measurements(in mm) September 2004

	A	B	C	D	Average	NWT	Mean % Wall Thickness loss
TP 1	4.26	4.26	4.24	4.25	4.253	4.26	0.18
TP 2	4.26	4.26	4.25	4.25	4.255	4.26	0.12
TP 3	4.26	4.26	4.25	4.26	4.26	4.26	0.00
TP 4	4.26	4.25	4.24	4.26	4.253	4.26	0.18

Table 3 Wall-thickness measurement(in mm) April 2005

	A	B	C	D	Average	NWT	Mean % Wall Thickness loss
TP 1	4.25	4.24	4.24	4.24	4.243	4.26	0.23
TP 2	4.26	4.25	4.25	4.25	4.253	4.26	0.18
TP 3	4.26	4.26	4.24	4.26	4.255	4.26	0.18
TP 4	4.25	4.25	4.24	4.25	4.248	4.26	0.20

Internal Corrosion of Crude-oil Pipelines

Corrosion of the external surfaces of pipelines is only part of the problem: internal corrosion must also be prevented. After a recent (AD 2004) inspection it was found that up to 70% of the wall thickness (= 9.5mm) of pipeline leading from the USA's biggest oilfield, at Prudhoe Bay, Alska, had been removed by microbial bacteria, in the contained crude-oil within the pipelines. The consequent replacement of 32km of transit pipelines is likely to cost in excess of US $100million. The necessary shutdown of the plant, resulting in 400,000 barrels per day not being delivered, represents about USA $7million daily in forgone revenues.

Conclusion and Recommendations

Poor maintenance practices, leading to reduced operational capabilities, are associated with bad management. However, by good design of systems and services, overall lifetime maintenance costs can be reduced dramatically.

The sacrificial anode is a suitable method for the effective external protection of new pipelines during the construction period, while the IC system will provide such protection during the post-commissioning and the entire service/operation period of the pipeline. This will ensure that the technical integrity of the new pipeline will be maintained with no appreciable wall-corrosion loss both during the construction period and after pipeline commissioning. Implementation of the recommendations arising from this investigation should eliminate current new-pipeline leaks and so benefit all stakeholders and improve the safety of pipeline operations in Nigeria.

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