

A Proposed Systematic Concept To Evaluate The Performance Of Cathodic Protection Of Buried Pipe Line In The Soil

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Abstract-Both corrosion process and cathodic protection process could be explained totally by an electric quantities. The proposed electric concept of corrosion process comes from the +ve charge available in the solution which by attachment to the atoms of the metal convert them into +ve ions. These +ve charge Q_p discharge to the remote earth through a stray capacitance between metal outer surface area (o.s.a) and earth. Consequently, a building up potential between pipe and earth takes place as $Q = C \times V$. The soil around the pipe consist the dielectric material of the stray capacitor between cylindrical metal o.s.a and the co axial imaginary earthing cylinder.

For coated pipe line, the cylindrical capacitor condition (pipe metal o.s.a + coating + soil layer + imaginary earth coaxial cylinder) is a reflection of the pipe condition either it is subjected to corrosion or it is cathodically protected. For any pipeline segment, the parameters around such segment which affect directly on the cathodic protection level could be compared with the insulation condition and the protection current I_p obtained from the intelligent pig. Such parameters are combined in one factor called the soil factor S_f which equal to $S_f = (1/K) pH H \text{ Log } \rho$ where pH is the power of Hydrogen, H is the humidity, ρ is the soil resistivity at H= 10% and K is the dielectric constant of the compound dielectric around the cylindrical segment (coating + soil layer). For the worst case of coating deterioration, the dielectric constant will equal to the dielectric constant ϵ_r of the soil at H= 10%. The status of cathodic protection level or the corrosion level could be obtained for any segment from the onion curves which correlate the soil factor S_f and the protection current I_p at different half cell voltage V_{hc} levels.

I. INTRODUCTION

The only way in which atoms of the metal may detach themselves from the surface and enter the solution is in the form of positively charged ions. These ions can not be formed unless there are +ve charges available in the solution which by attachment to the atoms of the metal convert them into ions. Wherever there is water (polarization & electric dipole [1]), there are some hydrogen ions formed by its dissociation and these ions are always available to give their charges to the metal atoms. Regardless of the number of hydrogen ions present and regardless of the ability of the solution to keep supplying them as they are used up in the corrosion process, there will be no positive ions formed if an adequate supply of electrons (negative charges) is maintained at the surface of the metal to combine with and thus neutralize all the positive charges that drift or attached that way on hydrogen ions [2]. Then the cathodic protection is a process taking place at the boundary of the metal, where the maintain of a continuous negative charge prevents the formation of any metal ions. This continuous charge is maintained by connecting the structure to some source of energy which is capable of supplying direct current. The amount of current which must be supplied to maintain the continuous negative charge is determined by the rapidity with which the charge is used up in neutralizing hydrogen ions and in leaking uselessly away because of the lack of protection of isolation. The terminal through which current enters the electrolyte (soil) is the anode, and is usually subject to corrosion by the current; the terminal through which the current leaves the electrolyte is the cathode and is protected from corrosion by the current.

Protection of a buried pipeline is accomplished by using a combination of coating and cathodic protection [3]. Primary protection is achieved by using coatings to provide an insulating barrier between the pipeline and its corrosive environment. Cathodic protection is applied to a pipeline to provide corrosion protection at coating defects and therefore is considered to be a supplementary system while with a badly deteriorated coating, the cathodic protection is considered the primary corrosion protection system. Where cathodic protection is used as the primary corrosion protection system, as with badly deteriorated coating, problems with monitoring, adequate distribution of protection current and maintenance of the cathodic protection arise. Assuring pipeline integrity is a complex procedure that begins during design and construction of the pipeline where the pipe

materials, construction procedures, internal and external coatings, commissioning and testing establish the pipeline's integrity capabilities. Many systems are used in assuring the integrity of pipeline that include: [4][5]

- * Surveillance
- * Excavations
- * Hydrostatic testing
- * Leak Detection surveys
- * Intelligent pigging
- * Close interval surveys

The major sources of pipe line incidents related to Natural Gas pipelines are: [6]

Source	% of Incidents
Chemical, Bacterial , Sour Gas	4.0
General Corrosion	9.0
Pitting Corrosion	13.5
<i>Stress corrosion Cracking</i>	1.5
Mechanical Damage	44.0
Earth movement	8.0
Construction	7.5
Material Defect	12.5

Most of the above mentioned defects could be detected nowadays by using a number of pipeline inspection pigs [7] , [8] that provide information about metal loss, dents, cracks and strains that assist in estimating current and future safe operating conditions, remaining life or the potential for life extension of the pipeline. A proposed new method in assuring pipeline integrity could be obtained if we can get the cathodic protection level along the buried pipeline length by deduce a relation ship between the current passed through the pipeline segment I_p , surrounding parameters which affect directly on corrosion process (a new parameter called the soil factor) and the cathodic protection level V_{h-c} .

II. THE ELECTRIC THEORY OF CORROSION PROCESS

The proposed electric theory of corrosion depending on the concept of the +ve charge Q_p created on the outer surface area of the buried pipe line due to the building up potential $V_{p,PE}$ between the pipe and the remote earth. The created charge Q_p is dissipated to the surrounding medium (corrosion process) through a stray capacitance $C_{p,PE}$ between the pipe and an imaginary coaxial cylindrical earth. The dielectric constant of the soil ϵ_{r2} act with the dielectric constant of the pipe coating material ϵ_{r1} as a coaxial cylindrical capacitor with compound dielectric. As ϵ_{r1} of the coating material is decreased, the total capacitor is decreased (two capacitors are in series) then charge $Q = C \times V$ is decreased i.e. corrosion process is decreased. If deterioration of coating material occurred, then ϵ_{r1} is increased i.e. total capacitance of the compound dielectric is increased i.e. corrosion process is increased as the created charge on metal outer surface area Q will be increased.

Consider a cylinder pipeline segment, it's length = L mt buried barely in a soil have a dielectric constant = ϵ_r and a soil resistivity = $\rho \Omega$. mt, the humidity of the soil is $H \%$ and the power of hydrogen = pH . Under the assumption that the pipeline segment does not subjected to any of an external effects as pipe crossing, road crossing, which cause a stray effect, a charge Q will be created on o.s.a and a building up $V_{p,PE}$ across a stray capacitance $C_{p,PE}$ takes place. The capacitor plates considered to be the cylindrical o.s.a of the pipeline segment with radius $a = r_1$ as the first plate while the area of an imaginary co-axial cylinder with radius $b = r_2$ is the second plate. The system is illustrated in Fig. 1

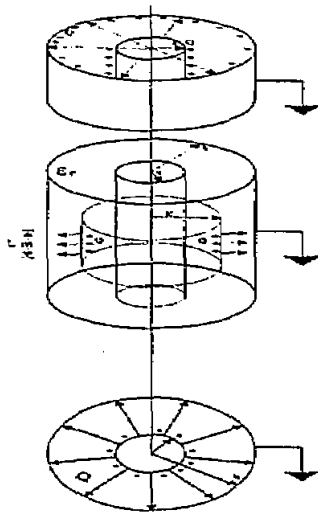


Fig. 1 Bare pipe line segment with the imaginary coaxial remote earth

If C_{p-PE} discharges its stored energy, a stray current I_{p-PE} will flow to the earth. In other words, such system could be represented more clearly as shown in Fig. 2.

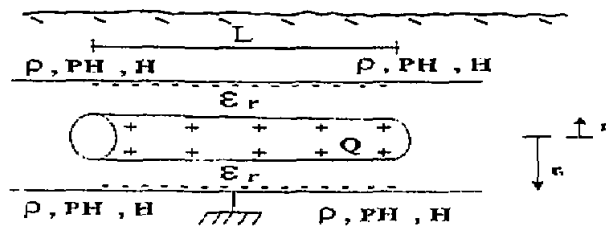


Fig. 2 Schematic diagram of bare pipe line segment with the surrounding medium parameters

III. MEASURING THE CURRENT I_p THROUGH THE PIPE LINE SEGMENT

This is a new idea of the voltage drop technique to measure the protection current I_p passed through the buried pipeline. By considering a pipe line with total length L mt, if such length is divided into segments with length L mt./segment

$$\text{then : Total length} = \text{segment length} \times n$$

$$L = n L_{seg.}$$

Electrically, the pipe line could be considered as: total resistance = segment resistance $\times n$ as shown in fig. 3

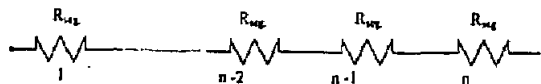


Fig. 3 Electrical analogue of the total pipe line length

Now if the voltage drop between two points is measured then the protection current I_p could be obtained by the equation :

$$I_p = \frac{\Delta V}{R_{seg}} \quad (1)$$

i.e. an additional voltage drop canister could be added with the available intelligent pig to measure the protection current I_p as shown in fig. 4 and by using GPS technology to determine the segment position [9]

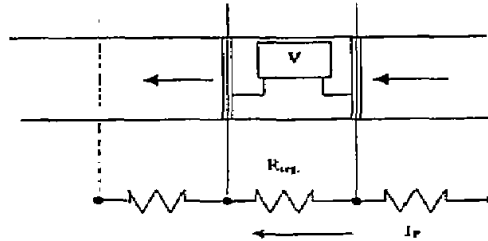


Fig. 4 voltage drop canister pigged with the fluid through the pipe line

For an example, suppose the following:

Pig run speed $v = 1 \frac{ml}{sec.}$
 Recorded sample rate = 32 HZ
 Time = $1/f = 1/32 \text{ sec}$
 Segment length $L_{seg} = v \times T = 3.125 \text{ cm}$

Now, the measured protection current could be considered as a reflection of the cathodic protection level. Many questions arise :

- What is the relation between the protection current I_p and the half cell voltage $V_{h.c}$ for the pipe line segment.
- What is the affect of the surrounding medium on the protection current I_p .
- What is the factor by which the cathodic level of the pipe line segment could be obtained.
- What is the proof of the Electric theory of corrosion.

IV. THE DIELECTRIC CONSTANT ϵ_r OF THE SOIL

Almost from the start of the application of the electrolytic corrosion protection techniques, calculations have been required to quantify the amounts of current that are to be passed between the anodes and cathodes in the system. Not only are the magnitudes of the currents important but their distribution is a matter of considerable significance [10] . Formula that were derived for the behaviour of capacitors, magnetic and electric fields, and for electric transmission lines were adapted to calculate the values of conductance and distribution of current from cathodic protection anodes. Calculations are only possible by these classical formula for simple geometries, and a typical situation is shown in Fig. 5 which shows a cylindrical electrode spaced from a large flate plate cathode.

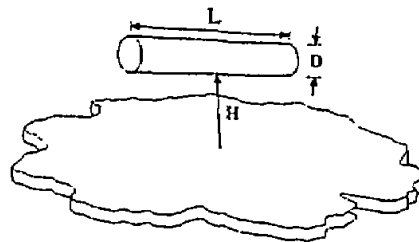


Fig. 5 Stray capacitance of an anode w.r.t large flat plate

A formula that expresses the capacitance C in picofarads between the two surfaces is given in equation (2) [10] :

$$\frac{1}{c} = \frac{4.139}{LK} \left[\log \frac{2h}{r} + \log \left[\frac{\frac{L}{2} + \sqrt{\frac{L^2}{4} + r^2}}{\frac{L}{2} + \sqrt{\frac{L^2}{4} + 4h^2}} \right] \right] \quad (2)$$

Where D,L,h are in cm, K is the dielectric constant ϵ_r and $D=2r$

In a corrosion Process of the pipeline, the pipe line segment which is subjected to corrosion could be considered as an anode while the remote coaxial earthing cylinder is to be considered the large flat plate cathode.

According to that assumption, which it will be verified it's correction later, then if a rectangular plate of iron spaced by h from a pipeline segment L with outer radius r and the space between them is filled with soil and by substituting in equation (2), the dielectric constant ϵ_r could be obtained for many different soil resistivities. Fig.6 Shows the trend line of the capacitance C_{P-PL} and the factor $pHH \log \rho = K_s S_f$, where K_s is the dielectric constant of the soil and S_f is the soil factor .

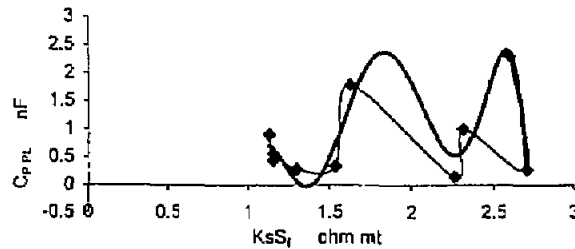


Fig.6 The capacitance C_{P-PL} and the factor $pHH \log \rho$ at $H = 10\%$

V. CORROSION & THE BATTERY ACTION (SOURCE OF ENERGY)

If the pipeline segment is short circuited with the rectangular plate through an ammeter connected in series, a circulating current I_{P-PL} directed from pipe to the plate takes place. The current is directed from the lower surface area to the higher surface area i.e. the pipe act as an anode while the rectangular plate act as an cathode. The I_{P-PL} is considered the maximum stray current from pipe to plate i.e. maximum corrosion. Fig. 7 Shows the system and the electrical analogue of such system while table 1 show the comparison between the battery cell and the corrosion cell .

Battery Cell	Corrosion Cell
Anode	L.S.A Lower surface area
Cathode	H.S.A Higher surface area
Electrolyte	ϵ_r of soil + pH + H
Discharge Current	Stray Current
Charge current	Cathodic Protection charging current

Table 1 The Comparison between the corrosion & battery cells

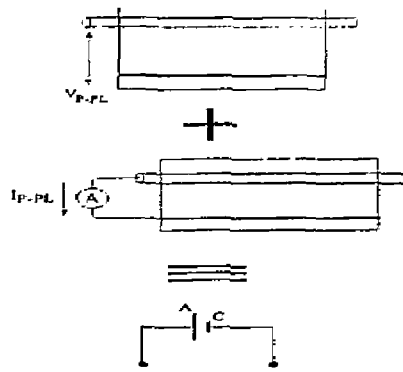


Fig. 7 Corrosion cell and the equivalent battery action

In practical case, any metal structure buried in the ground is considered the L.S.A i.e. as an anode w.r.t the huge ball of iron at the earth center which is considered the H.S.A i.e. the cathode.

If the L.S.A is isolated from H.S.A through a proper insulation then the corrosion cell is not completed i.e. protection of metal structure from corrosion. In other words, the stray current (discharging) could be compensated by external source (charging) to avoid corrosion i.e. cathodic protection process. Fig.8 a, b shows the relationship between the building up voltage V_{P-PL} between L.S.A & H.S.A (pipe and plate), the short circuit circulating current I_{P-PL} w.r.t the factor $pH H \text{Log } \rho$ ($K_s S_f$).

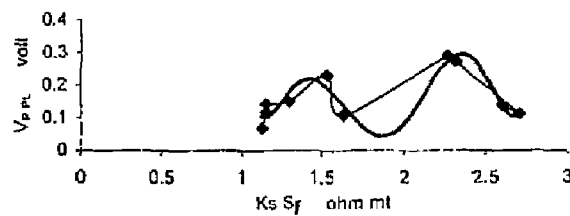


Fig.8 (a) The building up voltage V_{P-PL} between L.S.A & H.S.A (pipe and plate) and the factor $pH H \text{Log } \rho$ at $H = 10\%$

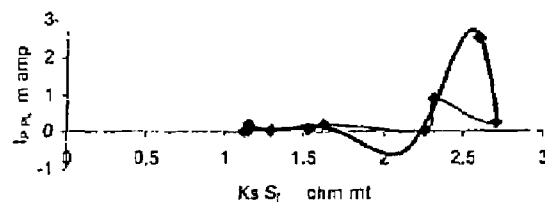


Fig.8 (b) The short circuit circulating current I_{P-PL} and the factor $pH H \text{Log } \rho$ at $H = 10\%$.

The volt ampere of the corrosion cell of pipe-plate at maximum stray current could be obtained i.e. $I_{(stray)_{max}} = I_{P-PL}$. Then the volt ampere of such cell is equal to $V_{P-PL} * I_{P-PL}$. Fig.9 shows the relationship between the power of such source and the factor $pH H \text{Log } \rho$ at $H = 10\%$.

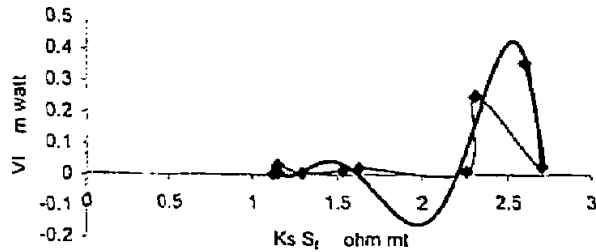


Fig.9 Power of the battery source and the factor $pH H \text{ Log } \rho$ at $H = 10\%$

VI. ELECTRICAL ANALOGUE CIRCUIT OF THE CORROSION AND CATHODIC PROTECTION PROCESS

In corrosion process, the metal pipe could be considered as a current source (stray current) to the surrounding medium (stray capacitor to the remote earth) i.e the electrical analogue circuit of the pipe line segment with the surrounding medium effect could be represented as a current source connected in series with the stray capacitance between metal o.s.a and the remote earth. Consequently, the corrosion process could be electrically simulated for both bare pipe and at bad condition of coating material as in fig.10

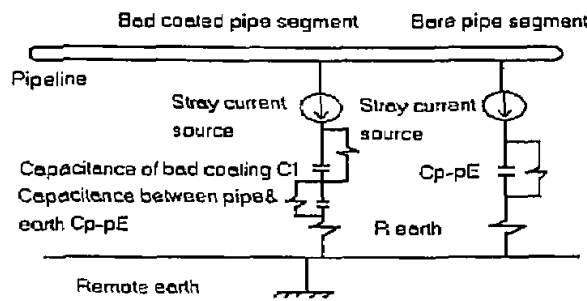


Fig. 10 Electrical analogue circuit of the corrosion process

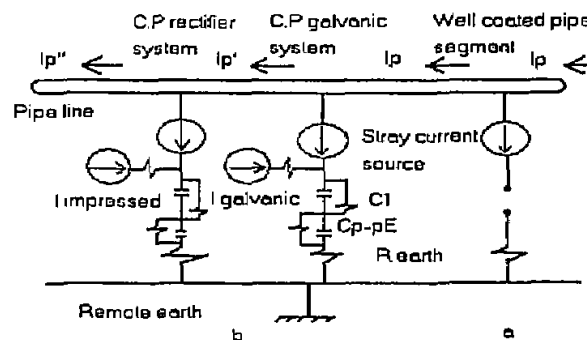


Fig.11 The electrical analogue circuit of the cathodic protection process (a) by using well coating material (b) by using galvanic and impressed current system

In case of cathodic protection process if the protection current either it is greater than the stray current (net current will flow through the pipe) or less than the stray current (net current will flow through the stray capacitor to the remote earth), the c.p level of the pipe line segment could be determined if the protection

current before and after the pipe line segment is measured by using voltage drop canister pigged with an intelligent pig tool .

For well coated pipe line segment , the electrical analogue circuit is as in fig.11a . Also , fig.11b shows the electric analogue circuit of the pipe line segment which is cathodically protected by galvanic system or impressed current system .

VII. CLARIFICATION OF CORROSION PROCESS OF SOME APPLICATIONS BASED ON PROPOSED ELECTRIC THEORY OF CORROSION

A. Effect of earthing network on C.P. level

In a terminal contains a lattice of buried pipes and earthing network as shown in fig 12, a building up voltage between pipes and earth $V_{p,PE}$ takes place through the stray capacitance $C_{p,PE}$ between the pipe and earth. It means that corrosion takes place at points have stray capacitance with earth in case of insulation deterioration of the buried pipe.

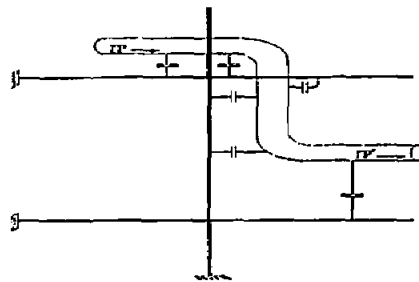


Fig. 12 Stray capacitance between pipe line and earthing network

B. Effect of pipe crossing and /or parallel pipes on C.P. Level:

The same idea as mentioned before, a stray capacitance between the two pipes $C_{p,p}$ either at exposing surface area at crossing point or along the two parallel pipes exposing spacing area as shown in Fig. 13

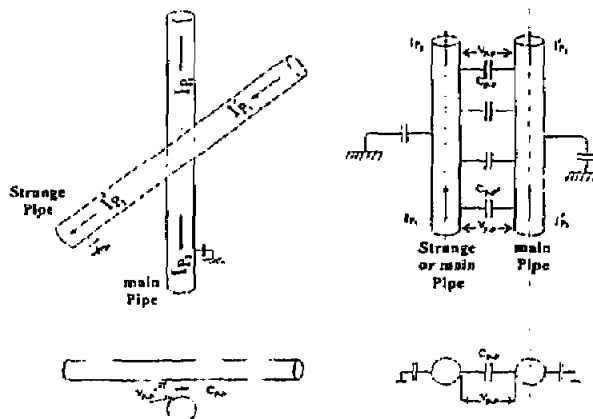


Fig. 13 Stray capacitance and building up potential between crossed pipes and parallel pipes

Each pipe has it's own cathodic protection level and/or L.S.A & H.S.A concept (Battery action). If there is a difference in potential i.e. $V_{p,p}$ exist, one plate act as +ve plate with respect to the other plate i.e. charge transfer from pipe to pipe through the stray capacitance between them. In other words , one of the pipe will be cathodically protected (- ve side of $C_{p,p}$) while the other one will be subjected to corrosion (+ ve side of $C_{p,p}$). In

this case it is too difficult to solve such problem of corrosion especially for long parallel pipes until the technology of intelligent pig appears which detect the insulation deterioration along the route of the pipeline.

Such technology [11] till the moment doesn't prospect either the start of corrosion phenomena or c.p level along the total pipeline segments . This means that if it is able to measure the protection current I_p passed through the pipeline segments, it could prospect the case of each segment, either it is cathodically protected or it is subjected to corrosion.

VIII. DEDUCTION OF THE SOIL FACTOR S_t PARAMETER

A. Effect of soil permittivity:

Consider a pipeline segment Fig.14 coated with an insulation with dielectric constant ϵ_{r1} and the pipe is buried in soil. As mentioned before , a layer of the soil around the pipe create a stray capacitance C_{P-PE} between the pipe wall and the earth. The dielectric constant of C_{P-PE} capacitor is equal to ϵ_{r2} . The pipeline segment in this case, could be considered as cylindrical capacitor with compound dielectric.

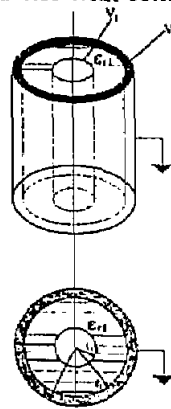


Fig. 14 Cylindrical capacitor of the pipe line segment and the compound dielectric of coating material and soil layer

Let :

- r_1 = outer radius of the pipeline segment
- r_2 = outer radius of the pipeline segment with coating ϵ_{r1}
- r_3 = outer radius of the coaxial earthing cylinder , layer ϵ_{r2}

obviously, there are two capacitors joined in series, the total capacitance of the pipe line segment is:-

$$C_{tot} = \frac{C_1 C_2}{C_1 + C_2}$$

i.e. the total capacitance decreased. In other words the coated pipeline segment is isolated from the H.S.A (Battery action theory) i.e. Battery action is decreasing as C_{tot} is decreasing by-decreasing of ϵ_{r1} value. The ideal case of preventing corrosion at $C_{tot} \approx$ zero i.e. Battery cell is dead and equal to zero volt. The above mentioned clarification is simply considered the electric point of view of corrosion preventing by using coating method.

At points where deterioration of insulation occurred, the total capacitance increased i.e battery action is increased. In other words, Battery action is increasing as C_{tot} is increasing by increasing of ϵ_{r1} value. The worst case of corrosion at $C_{tot} = C_{P-PE}$ (Stray capacitance from pipe to earth through ϵ_{r2}).

We consider the studding of the worst case of corrosion at $C_{tot} = C_{P-PE}$ i.e. buried bare pipe line segment case (deterioration of the coating insulation) .Now, we can state that , cathodic protection level is increased by the decreasing of the capacitance of the cylindrical capacitor (compound dielectric "coating + soil")

- i.e Corrosion $\propto C_{tot}$
- i.e. Cathodic protection $\propto 1/\epsilon$

B. Effect Of The Coating Material ϵ_{r1} :

Now, for capacitors joined in series, charge is the same [12]

$$Q = C_1V_1 = C_2V_2 \quad (3)$$

Hence, the voltage gradient is given by the equation :

$$\frac{g_{max.1}}{g_{max.2}} = \frac{\epsilon_{r2} \cdot r_2}{\epsilon_{r1} \cdot r_1} \quad (4)$$

i.e. voltage gradient is inversely proportional to the permittivity and the inner radius of the insulating material.

$g_{max.2}$ is the voltage gradient of the soil layer around the pipe. The ideal case of preventing corrosion is when $g_{max.2} = \min.$ i.e. $\epsilon_{r1} = 1$ i.e. the coating material is air which is not practical.

C. Effect of soil resistivity:

At the same humidity (H) and the same power of hydrogen (pH) it is found that.

$$\text{Cathodic protection} \propto \log \rho$$

D. Effect Of pH Factor:

It is obviously clear that, increasing of Humidity H is associated by the decreasing of the power of hydrogen pH. That means that the presence of H^+ due to humidity trend the pH factor of the soil to the acidity region i.e. the soil in such case becomes more corrosive medium.

$$\text{Corrosion} \propto \text{pHH}$$

E. The Soil Factor S_f :

It is now clear that the soil medium parameters affect directly on the cathodic protection level C.P. and the following combination of parameters $(1/K_s)\text{pHH} \log \rho$ is equal to the soil factor S_f (at room temperature) :

$$S_f = (1/K_s) \text{pHH} \log \rho \quad (5)$$

Where:

K_s = Dielectric constant of the soil at $H = 10\%$

(worst case at $\epsilon_{r1} = \epsilon_{r2} = \epsilon_r$ of the soil)

pH = power of Hydrogen of the soil

H = Humidity of the soil %

ρ = Soil resistivity in Ω . mt. at $H = 10\%$

The importance of the soil factor is that it is combining all parameters which can affect directly on the cathodic protection level or in corrosion process. Such factors which can be obtained by a direct measurement. This means that if it is possible to study the relationship between S_f factor and the V_{P-PE} , I_p , C_{P-PE} , V_{h-c} , then the status of cathodic protection level of any segment buried in the ground could be obtained.

IX. THE SOIL FACTOR CHARACTERISTICS

A. The soil factor and the stray capacitance :

The stray capacitance C_{P-PE} is affected by the change of the soil factor S_f i.e. corrosion process is changed as C_{P-PE} is changed or in other words corrosion is changed by the change of the soil factor S_f . The C_{P-PE} value could be obtained in terms of soil factor S_f almost through a third order algebraic equation.

The boxes of the same soil resistivity and at the same value of the soil factor S_f , it is found that the $C_{p,PE}$ value is not constant. That's because of the change of the power of hydrogen pH is associated by the change of the dielectric constant ϵ_r of the soil around the bare pipe. In other words, as the pH value is decreased i.e. H^+ layer around the pipe is increased, the corrosion is increased. From Electric point of view, as pH is decreased ($H^+ \uparrow$) the stray capacitance $C_{p,PE}$ is also increased i.e. corrosion process is increased. A sample is shown in fig. 15.

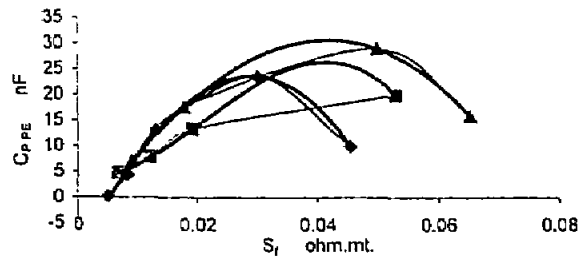


Fig. 15 $C_{p,PE}$ and S_f characteristic for boxes 1,2,3

B. The Soil Factor S_f And Pipe To Earth Potential $V_{p,PE}$ to keep $V_{h,c} = -0.85$ v :

The building up voltage between pipe to earth $V_{p,PE}$ to keep $V_{h,c} = -0.85$ v could be represented in terms of the soil factor S_f . The ($S_f, V_{p,PE}$) curves could be matched with a trend line which is mostly represented by a 3rd order algebraic equation. It is also clear that $V_{p,PE}$ is increased negatively to keep the C.P level at $V_{h,c} = -0.85$ v by the decrease of pH factor ($H^+ \uparrow$). A sample is shown is fig. 16, i.e.

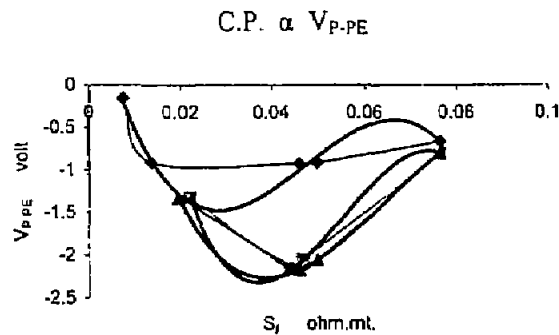


Fig. 16 $V_{p,PE}$ and S_f characteristic for boxes 28,29,30

C. The Soil Factor S_f And The Charge $Q_{c,p}$ Required To Be On The Metal O-S-A To Keep $V_{h,c} = -0.85$ v :

The -ve charge $Q_{c,p} = (C_{p,PE} V_{p,PE} - Q_p^+)$ required to keep metal $V_{h,c} = -0.85$ v could be obtained in terms of the soil factor S_f . All curves for all Boxes which correlate ($S_f, Q_{tot.}$) Could be represented mostly by a trend line and by a 3rd order algebraic equation. The curves show, for the boxes have the same soil resistivity, as pH is decreased ($H^+ \uparrow$), the charge $Q_{tot.}$ required is also increased i.e. corrosion is increased by the increase of the discharge rate of Q_p through $C_{p,PE}$ and cathodic protection is increased by the increase of -ve charge $Q_{c,p}$ on metal o.s.a. i.e

$$\text{Corrosion} \propto +ve Q_p \quad \& \quad \text{C.P.} \propto -ve Q_{c,p}$$

A sample is shown bellow in fig. 17.

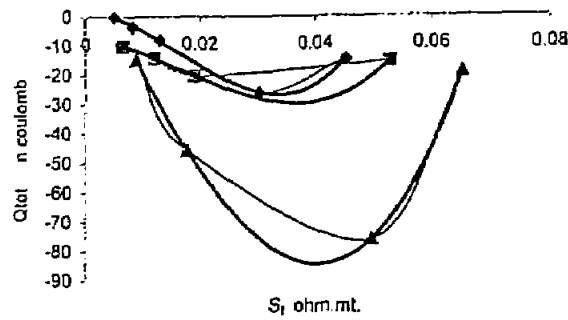


Fig. 17 Q_{TOT} and S_f characteristic for boxes 1,2,3.

D. The Protection Current I_p And The Half Cell Voltage $V_{h.c}$:

The linearity is obviously clear between the protection current I_p and the correspondent half cell voltage $V_{h.c}$. It is also clear and logic that by the increase of the Humidity and pH factors ($pH \uparrow$, $H^+ \uparrow$) i.e increase of soil factor S_f , the protection current is also increased for the same soil resistivity i.e.

$$I_p \propto -V_{h.c}$$

A sample is shown bellow in fig. 18

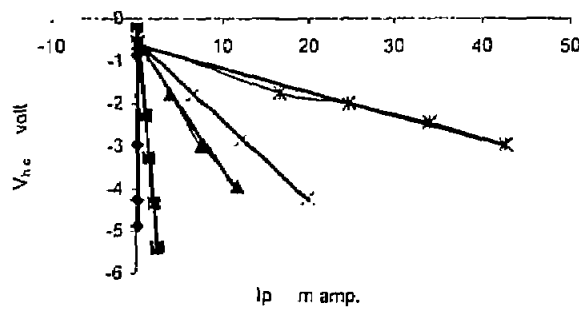


Fig. 18 I_p & $V_{h.c}$ characteristic for box 9.

E. The Soil Factor S_f And The Protection Current I_p at $V_{h.c} = -0.85$ v:

The protection current for the minimum threshold of the cathodic protection at $V_{h.c} = -0.85$ v could be obtained in terms of the soil factor S_f by mostly a 3rd order algebraic equation. The curves show for all boxes that by the increase of the soil factor value, the demand of the protection current is increased. This is because the soil factor is increased by the following two factors:

- 1- Increasing of pH H i.e. $H^+ \uparrow$
- 2- Deterioration of insulation i.e. $C_{p.PE} \uparrow$

i.e $I_p = f(S_f)$

a sample is shown bellow in fig. 19.

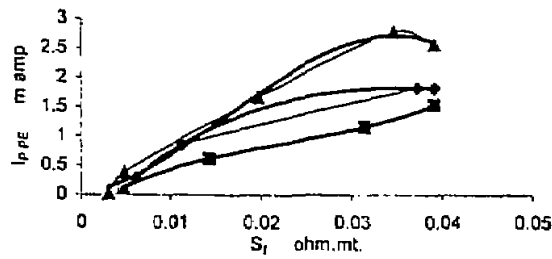


Fig.19 I_p & S_f c/c at $V_{h.c} = -0.85$ volt for boxes 16,17,18.

F. The Half Cell Voltage $V_{h.c}$ And The Pipe To Soil Potential $V_{P,PE}$:

The building up voltage $V_{P,PE}$ between pipe and earth is proportional to the voltage of the half cell $V_{h.c}$.

i.e $V_{h.c} \propto V_{P,PE}$

a sample is shown bellow in fig. 20

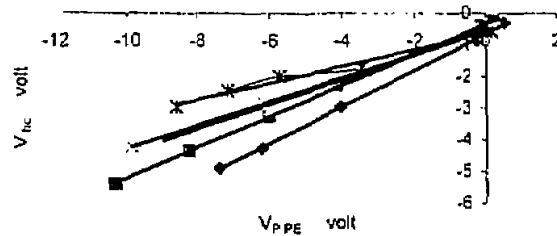


Fig.20 $V_{h.c}$ & $V_{P,PE}$ characteristic for box 9

G. The soil factor S_f and the min. Threshold of the Protection Current I_{P_T} at $V_{h.c} = -0.85$ v:

If a tangent line is drew between the points of the maximums of the protection current I_{P_T} at minimum and maximum soil factor, this tangent line is considered the minimum threshold line to ensure that the C.P. level will not below the value $-0.85V$.

i.e $I_{P_{tang}} \propto S_f$

The soil factor S_f and the minimum threshold of the protection current $I_{P_{tang}}$ at $V_{h.c} = -0.85$ volt for 10 different boxes are shown bellow in fig. 21.

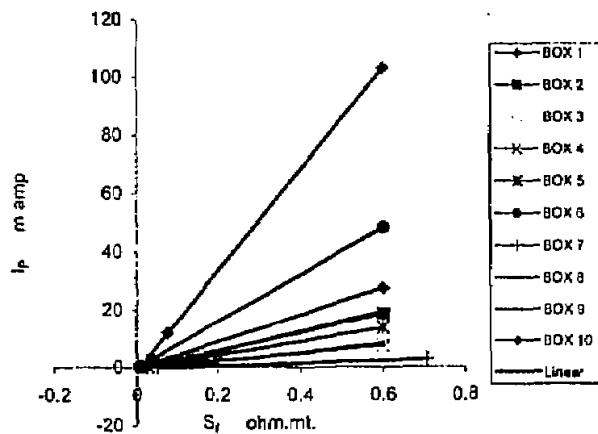


Fig. 21 Approximate min-Protection current I_p at half cell voltage = -0.85 v for all soil resistivity under test.

H. The Soil Factor S_f And The Protection Current I_p at $V_{h,c} = -0.2^v \rightarrow -2^v$:

The protection current I_p could be represented in terms of the soil factor S_f and mostly by a 3rd order algebraic equations. The protection current is increased by the increase of pH H value at the same soil factor S_f value.

X. THE EXPERIMENTAL UNION CURVE

The union curves are the curves of the protection current I_p in terms of the soil factor S_f at different half cell voltage $V_{h,c}$ level, it is possible to obtain the following:-

- 1- The soil factor S_f if $V_{h,c}$ and I_p are known. (Soil characteristic)
- 2- The half cell voltage $V_{h,c}$ if S_f and I_p are known (cathodic protection level).
- 3- The protection current I_p if S_f and $V_{h,c}$ are known. (for C.P. design principles)

If case number 2 to be considered, then by using an intelligent pig equipped with voltage drop canister to measure the voltage drop of a pipe line segment to get I_p value and by measuring the parameters of ϵ_r , pH, H and $\text{Log } \rho$ of the soil to get the soil factor

Where: ϵ_r & ρ for the soil are measured at H=10%

Then by using union curves, the c.p. level of the pipe line segment could be obtained and the c.p. level of any buried pipeline could then be obtained.

Fig. 22 Show a sample of the union curve for the box 30.

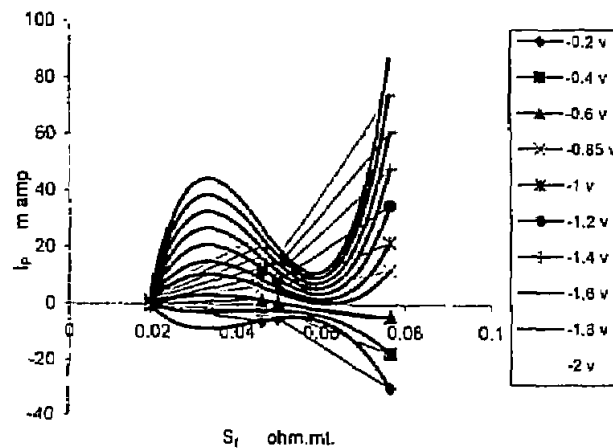


Fig. 22 The union curve of the box 30

X. DEDUCTION OF AN APPROXIMATE GENERAL EQUATION OF SEGMENT TOTAL CHARGE Q_{tot}

A. Deduction of the +ve charge Q_p

To calculate the +ve charge Q_p created on metal o.s.a of a pipe line segment buried barely in the ground, consider a pipe line segment L_{seg} buried in a soil has a dielectric constant ϵ_r , a soil resistivity ρ with power of hydrogen pH and humidity H % as shown in Fig. 23.

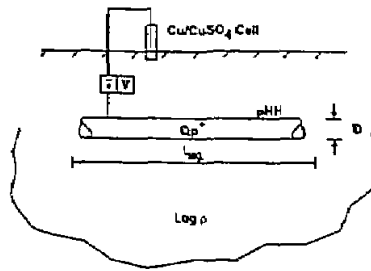


Fig. 23 Charge created on metal o.s.a due to surrounding medium effect

In case of no cathodic Protection systems are exist, the half cell voltage $V_{h.c}$ is proportional to the +ve charge Q_p created on the metal o.s.a due to the surrounding medium effect and consequently $V_{h.c}$ is proportional to the metal o.s.a while $V_{h.c}$ is inversely proportional to the soil resistivity ρ .

i.e.
$$V_{h.c} \propto \frac{Q_p^* \pi DL_{seg.}}{\log \rho}$$

as
$$\log \rho \propto \frac{1}{pHH} \propto \frac{1}{S_f}$$

it is found that

$$Q_p^* = \frac{C_7 V_{h.c}}{DL_{seg.} S_f} \quad (6)$$

Where :

- Q_p^* metal o.s.a charge due to surrounding effect in coulomb
- $V_{h.c}$ half cell voltage (pipe-soil) using cu/cuso4 half cell in volt
- D diameter of the pipe segment in meter
- L_{seg} the length of the pipeline segment in meter
- ρ soil resistivity in ohm-meter
- S_f the soil factor

B. Deduction of the natural charge factor C_7

The condition that:

at $I_p = 0$ $Q_{(0L)} = C_{p-PE} * V_{p-PE} |_{I_p=0} = Q_p^*$

from the correspondent tables, the factor C_7 could be deduced and the trend line of the factor C_7 is shown in figure 24.

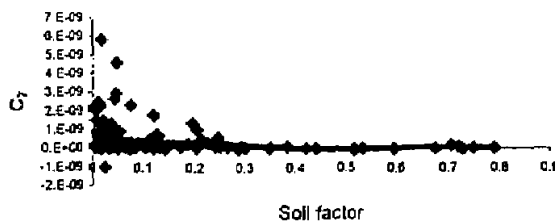


Fig. 24 Natural charge factor C_7 & S_f characteristics

C. Deduction Of The Cathodic Protection Charge $Q_{C.P}$

Consider a pipeline have a diameter = D and it's length is divided into n equally L_{seg} buried barely in a soil have a soil resistivity ρ . The system is cathodically protected by an impressed current technique. The ground bed of anodes dimension is $L_{G.B.} * D$ and is connected to the +ve terminal of the d-c power source. The -ve terminal of the d-c power source is connected to the end of the pipeline at nL_{seg} . The circulating current I_p takes place. The system as in fig.25 .

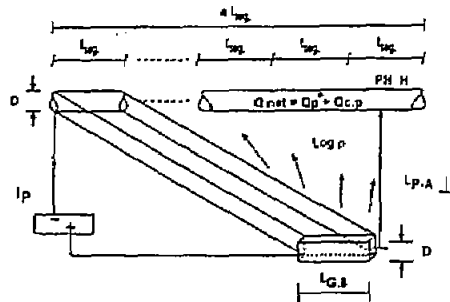


Fig. 25 Total charge on metal o.s.a due to surrounding Medium and cathodic protection effect.

For each L_{seg} , the circulating current is inversely proportion to the total resistance between the ground bed and the line segment, while I_p is proportional to the charge $Q_{C.P}$. It is found that :

$$\therefore Q_{C.P} = C_{11} \left[\frac{D I_p - A L (L_{seg} + L_{G.B.}) + \frac{S_F}{C_6} (R_H + R_C^+ + R_C^- + R_A)}{S_F} \right] \cdot I_p \quad (7)$$

Where

- $L_{P.A}$: Perpendicular distance between line segment and ground bed pipe in mt
- $L_{G.B}$: Length of ground bed in mt
- R_H : Ground bed header resistance in Ω
- R_C^- : -ve feed back cable resistance in Ω
- R_C^+ : +ve cable resistance from d-c source to the ground bed header in Ω
- R_A : Total anodes resistance
- C_6 : $f(1/S_f)$

D. Deduction of the cathodic protection factor C_{11}

Say the condition that at $V_{h-c} = -0.85V$, V_{P-PE} could be obtained from $(V_{P-PE} \& V_{h-c})$ curves while I_p could be obtained from $(I_p \& V_{P-PE})$ curves

$$AS \quad Q_{tot} = Q_p^* + Q_{C.P} \quad (8)$$

$$\therefore Q_{C.P} = C_{P-PE} * V_{P-PE} - Q_p^* \quad (9)$$

then the factor C_{11} could be deduced and the trend line of C_{11} is shown in Fig. 26

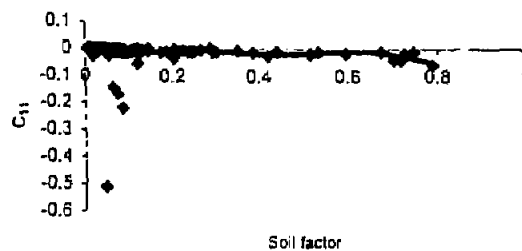


Fig. 26 The C.P factor C_{11} & S_f characteristics

E. Segment Total Charge Q_{tot}

From equation (6) , (7) & (8) , Q_{tot} is equal to:

$$C_{P-PE} * V_{P-PE} = C_7 \cdot \frac{V_{h,c}}{S_F D L_{scg}} + C_{11} \left[\frac{D L_{P-A1} (L_{scg} + L_{G,B}) + \frac{S_F}{C_6} (R_H + R_C^* + R_C^- + R_A)}{S_F} \right] \cdot I_P \quad (10)$$

As the onion experimental curves and onion theoretical curves approximately the same which proves that the total charge Q_{tot} is equal to the stray capacitance C_{P-PE} • the voltage V_{P-PE} to the remote earth. The comparison between practical and theoretical onion curves of box 1 as an example is shown in Fig. 27.

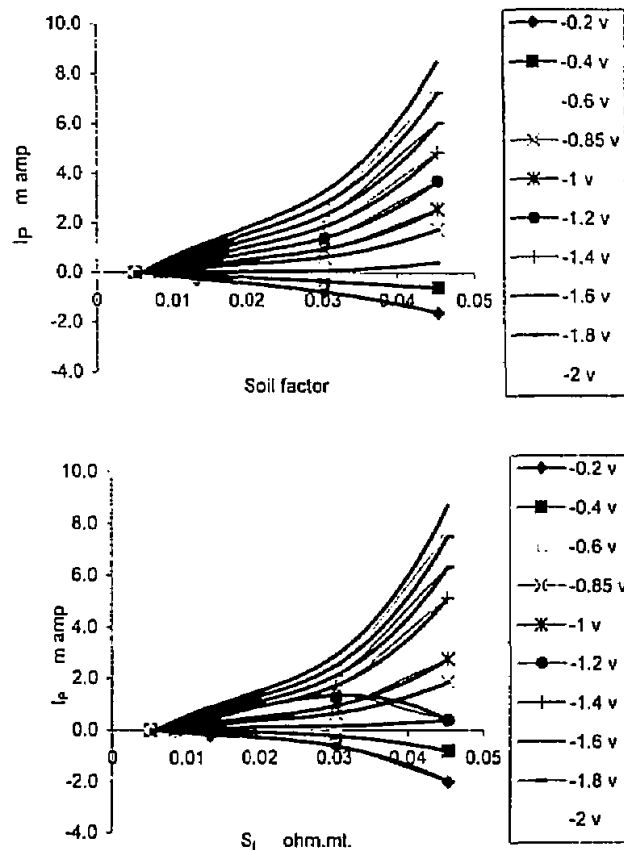


Fig. 27 The practical and theoretical onion curves of Box 1

XI.CONCLUSION

The proposed electric theory of corrosion is depending on the concept of the +ve charge Q_P created on the outer surface area of the buried pipe line due to the building up potential V_{P-PE} between the pipe and the remote earth. The created charge Q_P is dissipated to the surrounding medium (corrosion process) through a stray capacitance C_{P-PE} between the pipe and coaxial imaginary cylindrical earth. The dielectric constant of the soil ϵ_2 of the stray capacitance act with the dielectric constant of the pipe coating material ϵ_1 as a cylindrical capacitor with compound dielectric. As ϵ_1 of the coating material is decreased, the total capacitor is decreased (two capacitors are in series), then charge $Q = C \times V$ is decreased i.e. corrosion process is decreased. If deterioration

of coating material occurred, then ϵ_r is increased i.e. total capacitance of the compound dielectric is increased i.e. corrosion process is increased as the created charge on metal outer surface area Q will be increased.

For the pipeline cathodically integrity, many parameters affect directly on the cathodic protection level. The relation ship between all parameters are combined in a new factor called the soil factor $S_f = (1/K_s) \text{pHH} \text{Log } \rho$ which could be obtained by a direct measurement from the field. The importance of the S_f factor is to get the cathodic protection level $V_{h.c}$ along the pipe line at any pipeline segment if the protection current I_p passed through such segment is measured. I_p could be obtained by adding a voltage drop canister with the intelligent pig to measure ΔV segment. By using the onion curves which define the relationship between the soil factor S_f , current passed through pipelines segment I_p and the correspondent C.P. level, any unknown factor from ($V_{h.c}$, I_p , S_f) could be obtained from the other two known factors.

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