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Reliability Analysis For Subsea Pipeline Cathodic Protection Systems

SCHOOL OF INDUSTRIAL AND MANUFACTURING SCIENCES

PhD Thesis

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Abstract

Subsea pipelines, as the main transportation means for oil and gas produced offshore, are a key element of the production system. Cathodic protection systems (CPS) are used in combination with surface coatings to protect the pipeline from external corrosion. Although cases of pipeline failure due to external corrosion remain rare, such failures can have catastrophic effects in terms of human lives, environment degradation and financial losses.

The offshore industry was led to the use of risk analysis techniques subsequent to major disasters, such as Piper Alpha and Alexander Kjelland. These accidents made the development and use of risk analysis techniques of highly significant interest, and reliability analysis is presently becoming a more important management tool in that field for determining reliability of components such as pipelines, subsea valves and offshore structures.

This research is based on an analysis of subsea pipeline cathodic protection systems and on a model of the electrochemical potentials at the pipeline surface. This potential model uses finite element modelling techniques, and integrates probabilistic modules for taking into account uncertainties on input parameters. Uncertainties are used to calculate standard deviations on the potential values. Based on the potentials and potential variances obtained, several parameters characteristic of the cathodic protection system reliability, such as probability of failure and time to failure, are calculated. The model developed proved suitable for simulating any pipeline, under any environmental and operational conditions. It was used as a reliability prediction tool, and to assess the effects of some parameters on the cathodic protection system reliability.

Acknowledgements

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Merci à **mes parents**, à **toute ma famille** et aux **amis** qui m'ont soutenu et encouragé tout au long de mes recherches. Gracias tambien a una flor con espinas quien me recordaba que la vida debe ser vivida.

Content Overview

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Notations

General

α	transmission coefficient.
η	overpotential (Volts).
∇	Nabla operator.
Ω	Ohm symbol (resistance unit).
ρ	radial term in a polar reference system.
ρ_0	radius of the pipeline.
σ	conductivity (Ohm.m).
σ_x	standard deviation of the X values.
a	Tafel coefficient.
b	Tafel coefficient.
E/E_0	see E/V_0.
$\boldsymbol{F}$	Faraday's constant.
i_0	equilibrium electrode exchange current density (Amperes per squared meter).
I_0	equilibrium electrode exchange current (Amperes).
n	number of electrons exchanged in a corrosion equation.
R	perfect gases constant.
V	electrochemical potential.
V_0	standard electrode potential (Volts).
z	number of electrons exchanged in a corrosion equation.

Mathematical Expressions

[X]	design the matrix X, which can be a n by n, a 1 by n or a n by 1 matrix.
$\aleph$	Group of the natural integers (0, 1, 2,... ∞).
[1, N]	segment a to b: value comprised between a and b.
$\in$	included into: $x \in [1, N]$: x being included into the group comprised between 1 and N.
$\forall$	"for all": $\forall i \in [1, N]$: for all value of i comprised between 1 and N.

Glossary

cathodic protection system:	system used to protect a structure against corrosion. These consist generally of a set of sacrificial anodes or impressed current units. Protective coatings are used to increase protection. These coatings are considered in this thesis as part of the cathodic protection system.
holidays (coating ~):	holes in the pipeline coating leaving bare areas of steel.
reliability index:	see "*safety margin*"
safety margin:	equivalent to the "*reliability index*" used in structural reliability analysis. See definition in [Carter, 86].
singular (matrix):	matrix is said to be singular when the sum of all the equations which constitute it is always equal to zero.
system:	system should be understood as short for "cathodic protection system", in particular in the expressions "system reliability" and "system probability of failure".
tridiagonal (matrix):	matrix which only has non null member on one of its diagonal and the two adjacent line of values.

Quotations

Edmund X. DeJesus, Byte, October 1995, pp.81

Health and Safety Executive (HSE), "*A guide to the pipelines safety regulations 1996*", pp.22

Sir Arthur Conan Doyle, "*The Memoirs of Sherlock Holmes*"

T.H. Rogers, "*Marine Corrosion*".

Alain Villemeur, "*Reliability, availability, maintainability and safety assessment*", Vol 2, John Wiley and sons, updated 1991, ISBN 0-471.93049-0, pp.504.

1. Introduction

1.1. Subsea Pipelines Cathodic Protection Systems Reliability

1.1.1. Subsea Pipelines And External Corrosion Protection

The first oil and gas offshore production platforms in the North Sea appeared in the mid 1960's. Since that time, platforms have been designed, constructed and installed in increasingly deeper waters and at greater distances offshore. In addition, a growing network of subsea pipelines and flowlines has been established so that hydrocarbons produced may be transported safely and efficiently to both offshore and onshore locations for further processing. In the North Sea alone, nearly two hundred platforms have been installed to date, along with over six and a half thousand kilometres of pipeline network ([DTI, 95]). An example of field organisation is given in Figure 1-1.

Subsea pipelines are exposed to harsh environmental and operational conditions which would cause internal erosion-corrosion and external corrosion if no protective measures were taken. Externally, the environment corrosivity depends on a number of factors, such as water temperature, oxygen concentration, current speeds and seabed nature. External corrosion protection is ensured by the application of a protective coating at the surface of the pipeline ([DNV, 93], pp29) in combination with the use of a cathodic protection system, which generally consists of sacrificial anodes attached at regular intervals along the surface of the pipeline.

Cathodic protection systems are designed to maintain the pipeline electrochemical potential below a maximum limit. While the pipeline potential remains below this limit, the external corrosion rate is neglected. The potential limit depends mainly on environmental characteristics such as water temperature, oxygen concentration and burial state. Standards provide values for different marine locations ([DNV, 93]).

1.1.2. Cathodic Protection Systems Design And Inspection Practice

A method commonly used for designing a pipeline cathodic protection system consists of copying a design which proved satisfactory for an existing pipeline. Providing the existing and new cathodic protection systems have to be used for similar pipelines, the design should also prove to be satisfactory. This technique, described as "statistical", is occasionally used by operators and supported by the National Association of Corrosion Engineers ([NACE, 75]).

When this technique is not applicable, the corrosion engineer has to use others design methods. Standards such as [DNV, 93] and [DE, 84] provide guidances for underwater pipeline cathodic protection systems design. These present step by step procedures as well as sets of checks which have to be carried out to ensure the validity of the cathodic protection system over the lifetime of the pipeline.

Computerised tools have also been developed to help the corrosion engineer in the design process. These range from simple spreadsheets to more complex design software. Summerland ([Summerland, 95]) developed a spreadsheet which calculates the weight of anode required according to pipeline and environmental parameters. This spreadsheet simply follows the calculations described in standards. More complex systems such as PROCAT ([Wrobel, 83]) or CAPDES ([Corrocean, 93], [Strommen, 87]) actually model the potential at the surface of the pipeline. Such software can be used for analysing the influence of parameters such as anode material or coating type on the design. They can also help optimising design parameters, in particular the anode sizes and spacing.

Whichever design technique is used, the corrosion engineer usually ensures that the design obtained complies with cathodic protection system design standards. Due to the conservative assumptions used in these standards, cathodic protection systems tend to be over-designed and failures remain a rare event. When failure does occur, it is usually due to high levels of coating breakdown or to exceptional environmental conditions. Hedborg ([Hedborg, 91]) described the special conditions of a sector of the Gulf of Alaska, where higher oxygen solubility and high tidal velocities increase the current demand on cathodic protection systems, reducing its life expectation.

Even when such conditions arise, inspections usually prevent actual failures. It is a legal requirement to carry out an inspection on a regular basis ([NACE, 75]). Initial inspection is required after the cathodic protection system has been actually installed, to determine if it satisfies requirements and operates effectively. Afterward, surveys should also be carried out annually. When inspection results show that the cathodic protection system presents signs of weakness, sacrificial anodes are usually retrofitted as judged necessary to ensure that standard rules are respected as long as the pipeline remains in operation. Cathodic protection system failure cases are therefore uncommon.

1.1.3. Cathodic Protection System Reliability

Although uncommon, cathodic protection system failures do occur occasionally. Once failed, the electrochemical potentials on the external surface of the pipeline go over the maximum limit required to ensure corrosion protection, and areas of the pipeline may be subjected to corrosion. Corrosion occurs in particular at the location of coating damage or at pipeline section joints. Metal losses reduce the pipeline wall thickness and increases the risk of leakage or burst. Effects may be exacerbated if corrosion takes place at the same location on the internal side of the pipeline. In most cases, inspection reveals problems with the cathodic protection systems before any corrosion occurs. Nevertheless, analysis of pipeline failure cases reveals that external corrosion is one of the causes of failure ([PARLOC, 96]). This fact supported the interest in developing a reliability prediction analysis tool for subsea pipeline cathodic protection system.

The usefulness of such a tool was also emphasised when considering that, as the pipeline network ages, an increasing number of pipelines are reaching their initial design lifetime ([Coates, 93]). When field resources or new extraction technologies increased the field exploitation duration, platforms and pipeline may have to be used beyond this design lifetime. Torgard presented the case of the Norpipe, which was used to transport gas coming from a more recent field ([Torgard, 89]). In that case, the cathodic protection system for the whole pipeline had to be reviewed and analysed. Anodes were tested individually, metal samples were checked for inter-crystalline corrosion, current outputs measured at different positions around the anodes, in order to better estimate their life expectation.

In such cases, the ability to estimate more easily the cathodic protection system safe life would allow the operator to improve his asset management through optimised inspection and maintenance scheduling. Comprehensive analysis such as the one presented by Torgard are complex to carry out, and pose problems in particular for buried pipelines. They can not be used for a large number of pipelines, and no other specific tool appeared to be available to provide an estimation of the cathodic protection system lifetime.

1.1.4. New Probabilistic Analysis Requirements

The MAPD (Major Accident Prevention Document) should contain sufficient information to demonstrate that all hazards relating to the pipeline with the potential to cause a major accident have been identified and the risks arising from those hazards have been evaluated" - HSE, [HSE, 96]

Following the Piper Alpha incident, the awareness of the offshore industry toward risk analysis has been greatly increased. While reliability analysis techniques have been developed and applied intensively in the aerospace, nuclear and electronic industry, these techniques are still being studied and developed for offshore applications.

The earliest analysis carried out for subsea pipelines are pure statistical analysis. They are based on data collected from operators related to pipeline failure, sorted and analysed according to design parameters, operational and environmental conditions. The latest compilation to date is presented in the PARLOC report ([PARLOC, 96]). This report provides average pipeline failure rates, usually expressed in "per 1000km per year".

Experience proved that such information has limited interest for reliability analysis. Operators and agencies such as HSE, while supporting these type of analysis, are considering new, more appropriated techniques. Most recent directives encourage the development of new inspection strategies based on probability based inspection, and target orientated safety level requirements ([Madsen, 92], [HSE, 96]). For such approach, it is necessary to develop reliability analysis tools which can be used to estimate the probability of failure of offshore structures. Operators are therefore incited to develop such tools to estimate offshore structures reliability.

The following sections describe existing reliability analysis tools. Requirements for the development of reliability analysis tools fulfilling latest standards demands are also discussed.

1.2. Reliability Prediction

1.2.1. Conventional Reliability Analysis

Several conventional techniques are available for assessing component and system reliability, failure causes and consequences. These are well documented in many academic publications ([Villemeur, 92], [Billinton, 92]). The Failure Modes and Effects Analysis (FMEA), for example, consists of analysing a component or system, identifying the potential modes of failure, and looking at the consequences of failures on the component or system.

Such techniques offer limited interest for cathodic protection system reliability analysis due to its intrinsic nature. The protective coating and the sacrificial anodes, main components of the cathodic protection system, follow a continuous wear out degradation process. The cathodic protection system reliability decreases progressively in time, and failure is reached when the overall condition is not good enough to ensure corrosion protection in any point along the pipeline.

The degradation process being in most cases non uniform, the level of protection and the reliability vary along the pipeline according to a number of parameters. In order to apply conventional techniques to cathodic protection system reliability analysis, the pipeline would have to be divided into a number of sections. Each section could then be analysed individually according to local environmental and operational parameter values. Such an approach would provide an approximation of the section's reliability, but the interactions between section's condition could not be easily taken into account.

1.2.2. Failure Data Collection And Statistical Analysis

The pipeline database developed for carrying out the reliability analysis presented in the PARLOC report appeared to have limited uses for pipeline reliability analysis. Modifications are currently being considered to accommodate more information related to the pipeline and cathodic protection system design, as well as environmental and operational parameters. This information would be used for more sophisticated mathematical analysis, possibly based on discriminent analysis and Bayesian updating methods. Several similar analyses have been developed and are described in the following paragraphs.

Chuang ([Chuang, 87]) analysed onshore pipeline failure data, based on a set of 671 pipeline segments over a period of 30 years. The data was analysed as a function of several parameters such as pipeline length, diameter, age and cumulative number of leaks per hundred feet. A Bayesian updating model was implemented to integrate new inspection results and analyse the effects of some parameters in time.

De La Mare ([De La Mare, 93]) used a set of data compiled from North Sea pipelines and failure reports (similar to the PARLOC) and carried out discriminent analysis based on seven pipeline parameters, i.e. length, diameters, thickness, lifetime, steel quality, operating pressure, concrete weight coating. He showed how these parameters can be analysed by discriminent methods in order to estimate their effects on the system failure rates. A discriminent function is used to define a score which reflects the pipeline tendency to fail.

Straightforward statistical analysis proved to have limited interest for cathodic protection systems reliability analysis. This is mainly due to the insufficient number of existing, reported and documented failure cases, but also to the limited possibility to model precisely complex system.

1.2.3. Inspection And Maintenance Prioritisation

Another approach to pipeline reliability analysis has been developed on the form of prioritisation inspection and maintenance decision analysis tools. These tools provide guidance to the operator for reducing inspection and maintenance costs, by pointing out most likely failure, therefore increasing the pipeline reliability.

Hill presented the Relative Index of Pipeline Safety (RIPS) method, which considers several design, operational and environmental parameters to analyse the combination of the consequences of an accident with an assessment of its likelihood ([Hill, 92]). A similar analysis tool, the Risk Assessment Prioritisation (RAP) has been developed by the U.S. Department of Transportation for onshore pipelines ([Wolf, 94]). Nessim also developed such an analysis method based on an estimation of the consequences of failure and of the cost of inspection and maintenance operations ([Nessim, 95]). Consequences are analysed in terms of economic loss, casualties and residual spill. The analysis indicates which pipeline sections are to be inspected or maintained in priority. Similar studies have also been carried out specifically for non destructive inspection planning optimisation ([Pedersen, 92]).

These approaches allow operators to analyse the condition and reliability of pipelines, but have only a limited interest for the present analysis. Targets set in new standards require a quantitative determination of the system reliability, which can not be provided by these models without further developments.

1.2.4. Stress-Strength Analysis

The stress-strength analysis method is widely used for different types of mechanical systems, ranging from ball bearings to nuclear plants, and the technique is presented in several academic publications and articles. Carter presented a well documented description of this method ([Carter, 86]). The stress-strength method is based on an analysis of the system strength and stress, both parameters being described in a probabilistic way. From this analysis, various parameters indicators of the cathodic protection system reliability such as safety margins and probability of failure can be calculated.

The stress-strength method presents several advantages for the modelling of cathodic protection systems reliability. It is, in particular, well adapted for systems subject to wear-out degradation process, which is the case for pipeline protective coating and sacrificial anodes. The pipeline electrochemical potential is an indicator of the condition of the cathodic protection system, and can be related to the system stress, while the system strength can be assimilated to the maximum potential limit required by standard to ensure adequate cathodic protection.

Software such as PROBAN is a general reliability analysis program, which integrates stress-strength analysis tools ([VSS, 91]). The system or component analysed has to be modelled, and results of modelling are input to the PROBAN software, which carry out probabilistic analysis ([Maymon, 93]). Such a tool offers a wide range of analysis possibilities, and could be used for the present analysis. The main limitation to its use is due to the fact that the system (or component) modelling and the probability analysis are carried out separately. Only part of the system (or component) model results could be integrated into the probabilistic analysis, and uncertainties on the input parameters could not be easily taken into account in the system modelling itself.

For modelling the system and using PROBAN for data analysis, the operator would have to use both software and learn how they interact. The resulting analysis tool would be fairly complex, and require a lot more experience for use and later modification. The development of a separate model and integrated probabilistic analysis tools offers better flexibility.

1.2.5. Pipeline Potential Modelling

The stress-strength analysis can be carried out directly by using pipeline potential values obtained during inspection. This analysis would enable the operator to estimate quantitatively the cathodic protection system reliability at the time of inspection, as required by new standards. But when considering cases where the pipeline reach their design lifetime or where this lifetime is to be extended, it is necessary to forecast the cathodic protection system changes in time, under various environmental and operational conditions. Through the modelling of the potential changes, it would then be possible to forecast the cathodic protection system reliability.

Various models have been developed for calculating pipeline potentials. Strommen ([Strommen, 79]) presented a model based on the finite element method. He described the basic equations used to model the pipeline potentials and current densities, along with results obtained, demonstrating in particular the effects of coating defect sizes.

The boundary elements method was later used in several models. This technique was applied for PETROBAS by the Civil Engineering Department the Federal University of Rio de Janeiro, to develop the PROCAT computer system ([Wrobel, 83]). This model proved to give potential values similar to the ones measured on actual jacket structure. Strommen also developed models based on this technique ([Strommen, 87], [Strommen, 88]). Actual potential readings are, in that model, used as boundary condition. A variation was developed by Cicognami ([Cicognami, 90]) who integrated time dependant boundary conditions.

These models proved to provide good results for modelling electrochemical potential on pipelines and other offshore structures. Their deterministic nature nevertheless limits possible uses for the present analysis. Probabilistic results could be obtained by using such models in Monte Carlo simulations, but it is likely that the resulting model would become too demanding in terms of computer calculations.

Reliability analysis based on asymptotic methods have also been developed. The general concept has been presented by Breitung ([Breitung, 92]). For this method, the system parameters are gathered in the form of a one-dimensional matrix. This technique makes possible the integration of probabilistic parameters, through integrating uncertainty elements into the description vector. The vector is analysed to determine under which conditions the system fails. This method can be used as base for Monte Carlo analysis. Baker ([Baker, 92]) used it for offshore structures reliability analysis. This method can become too complex when the number of parameters considered is too high. This is the case in the present analysis, mostly if environmental conditions change along the pipeline and the pipeline has to be divided into a large number of sections.

After considering the different methods available, it was decided to develop a separate pipeline potential model, applicable to any pipeline design, environmental and operational conditions. This model should also take into account uncertainties on input parameters, and generate probabilistic results. A previous pipeline potential model developed at Cranfield University by Reiffers was used as the base of the model ([Reiffers, 85]). This model is based on the finite elements method. Probabilistic calculations had to be added to the general finite elements method to integrate input parameters uncertainties and generate the probabilistic outputs.

1.2.6. Development of Integrated Reliability Analysis Tools

Software development is an important aspect of this project. Ames ([Ames, 94]) underlined the need for computer tools in the offshore industry at a time when engineers and technicians have to handle a workload increased both by the reduction of personnel and by new requirements set by standards such as the ones presented earlier on.

Software tools can guide the user and ease her/his work by limiting the amount of knowledge required, for example, to run routine data checking. Graphical presentations and reports can be generated automatically, and point out important details of the analysis. An increasing number of software tools have been and are being developed for various applications. The tools presently developed are concerned with improving the presentation of inspection results. The systems presented by Beller and Kuhlman ([Beller, 93], [Kuhlman, 95]) analyse internal inspection results and present them clearly to the user, pointing out clearly major flaws and defects.

Software is essential to handle the large amount of data required to describe precisely the information related to a pipeline, its cathodic protection system, environmental and operational conditions, mostly as these parameters change as a function of distance along the pipeline as well as time. Tools have been developed in industry for this purpose. Darwich presented IPDOS (Integrated Pipeline Design and Operation System), a database system used to store information related specifically to pipelines ([Darwich, 94]). This system stores for each pipeline information related to its design, construction, maintenance, operational and environmental parameters.

1.3. Project Objectives

The aim of the research reported in this thesis was to develop a reliability model for subsea pipeline cathodic protection systems. The project was supported by EPSRC and several representatives of the offshore industry which expressed their interest in that field of research.

The project direction was set in agreement with the advice and guidance provided by oil industry representatives, according to the information gathered from existing pipelines and models. In order to ensure a successful development, three main objectives were defined.

- Develop a methodology for subsea pipeline cathodic protection system reliability prediction.
- Develop the tools necessary for managing the data required to describe the pipeline, cathodic protection system as well as their environment and changes in time. This tool should help analysing the cathodic protection system's behaviour and generating relevant information regarding its reliability.
- Test the model developed, and prove its usefulness for straightforward reliability analysis, as well as for investigating the effects of design environmental and operational parameters on the system reliability.

These points have been developed in the following thesis.

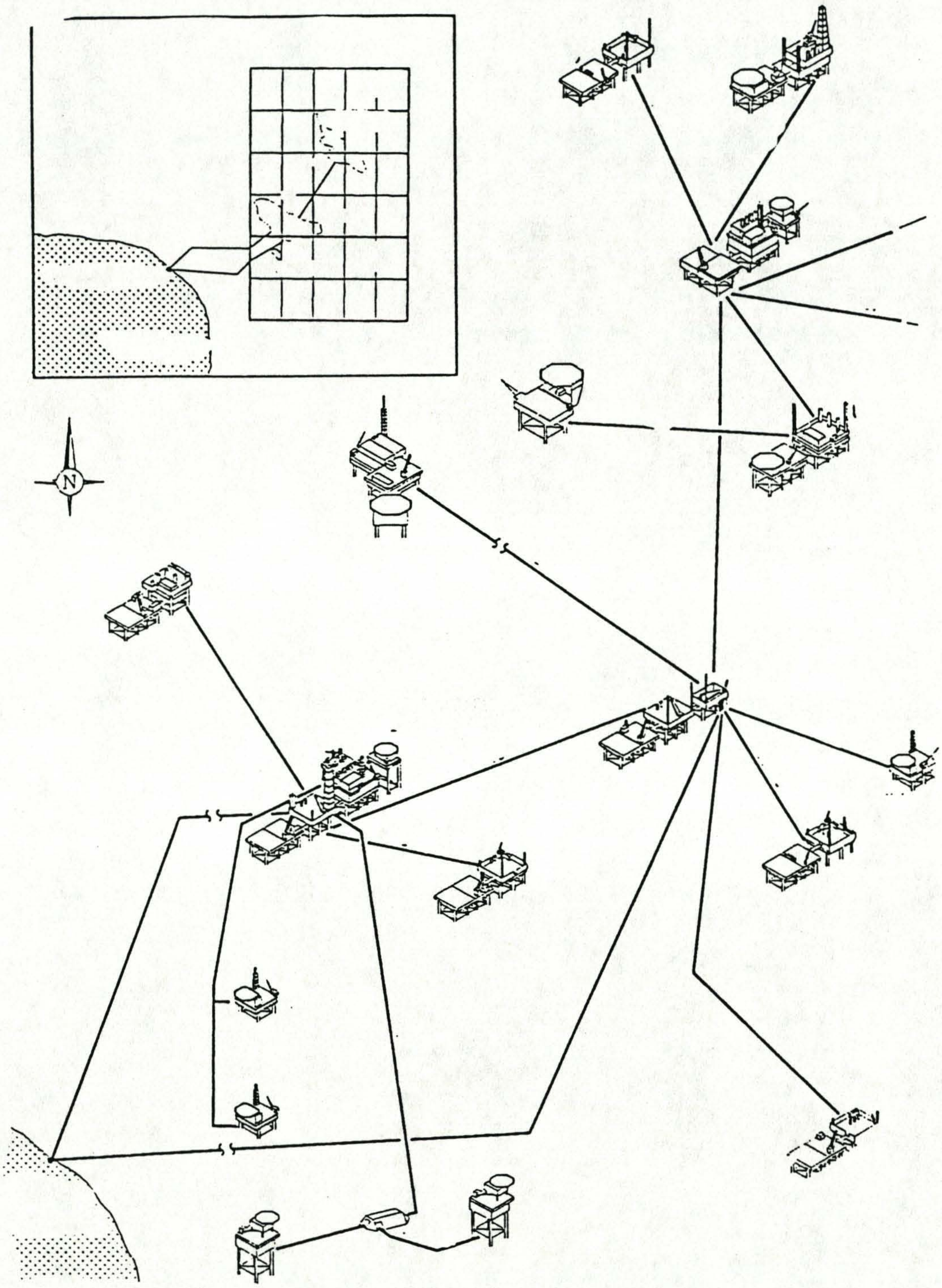

Figure 1-1: Example of field organisation.

2. Principles Of Corrosion And Cathodic Protection

"It is a natural habit of metal to corrode unless prevented by human endeavour",
T.H.Rogers

2.1. Aqueous Corrosion

2.1.1. Corrosion In Aqueous Environment

Corrosion of steel in aerated sea water occurs by a mechanism that involves at least two reactions. The anodic reaction, which is dissolution of iron, and a cathodic reaction which is normally oxygen reduction. These two reactions can be written as follows:

anodic reaction: $2\,Fe \rightarrow 2\,Fe^{++} + \boldsymbol{4\,e^-}$ (Equ. 2-1)

cathodic reaction: $O_2 + 2\,H_2O + \boldsymbol{4\,e^-} \rightarrow 4\,OH^-$ (Equ. 2-2)

The resultant reaction is described as follows:

$2\,Fe + O_2 + 2\,H_2O \rightarrow 2\,Fe^{++} + 4\,OH^-$ (Equ. 2-3)

or: iron + dissolved oxygen + water → ferrous ions + hydroxyl ions

When a piece of unprotected steel in placed in an aqueous environment, anodic and cathodic sites appear at its surface, as illustrated as shown in Figure 2-1. If these sites migrate during the corrosion process, uniform corrosion occurs. Generally, inhomogeneities due to discontinuities in the metal structure or surface generate localised corrosion resulting in the generation of pits, which reduces the integrity of metallic structures.

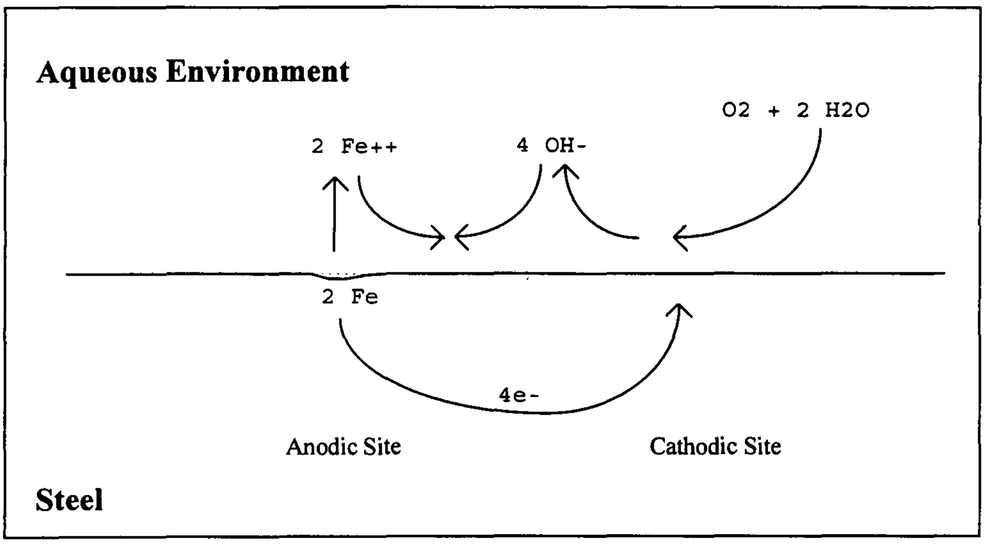

Figure 2-1: Graphic representation of the corrosion process.

2.1.2. Polarisation Curves and Corrosion Rates

2.1.2.1. Polarisation Curves

The prediction of corrosion rate is a key issue in corrosion engineering. Polarisation curves provide information concerning the corrosion rates of different metals and alloys, in different environments. These are obtained by measuring the output current of a piece of metal submitted to a variable potential, under various temperatures, pH and ionic species concentrations. The anodic current densities generated during polarisation are proportional to the corrosion rates. Polarisation curves are traditionally obtained by plotting the electrode potentials against the logarithm of the absolute values of the current densities. An example is presented in Figure 2-2.

E°_a and E°_c are the open circuit potentials for the anodic and cathodic reactions. The difference between these two potentials provides the driving force for the corrosion reaction. At the cathode, electrons are provided at the surface of the metal, and, due to the slow reaction rate of Equation 2-2, a build up in the metal charge causes the surface potential to decrease. At the anodes, electrons move toward the cathodic sites under the field gradient (see Equation 2-1 and Figure 2-1), and the deficiency of electron causes the potential to increase. The change in potentials are called cathodic and anodic over potentials (η_c and η_a).

As the cathodic and anodic potentials respectively decrease and increase, the rates of the cathodic and anodic corrosion reactions increase (Equations 2-1 and 2-2). At equilibrium, cathodic and anodic potentials are equal to E_{corr}, the corrosion potential.

The two types of polarisation, activation and concentration are described in the following sections.

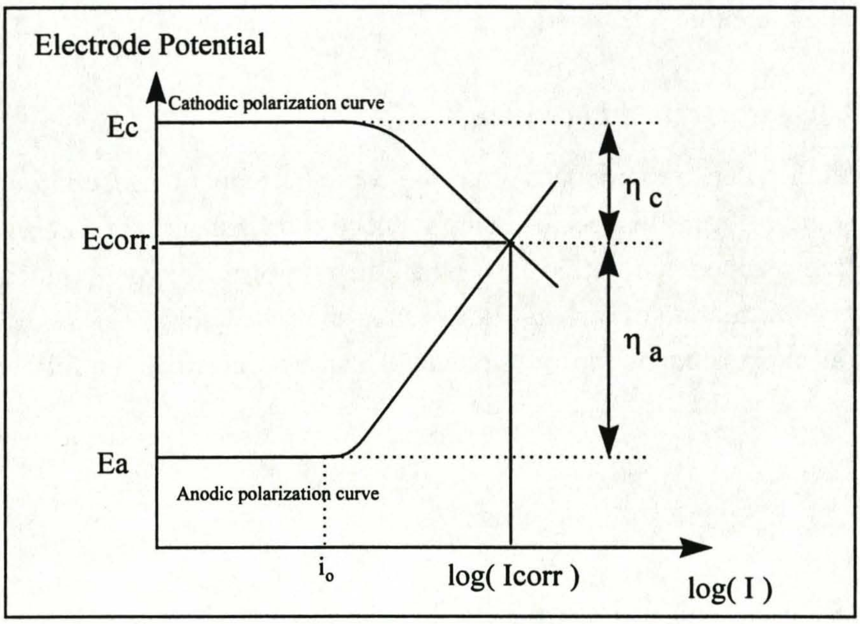

Figure 2-2: Example of polarisation diagram.

2.1.2.2. Activation Polarisation

When the rate of the electrons flow is controlled by a step of the half-cell reaction, the reaction is said to be under activation or charge transfer control. Thermodynamic shows that the value of the current applied can be expressed as follows ([Jones, 92]):

$$i = i_0 \cdot e^{\frac{\alpha \cdot n \cdot F \cdot \eta_c}{R \cdot T}} - i_0 \cdot e^{\frac{-(1-\alpha) \cdot n \cdot F \cdot \eta_c}{R \cdot T}} \qquad \text{(Equ. 2-4)}$$

where: η_c is the cathodic over potential (V),

i is the current density (A/m^2),

i_o is the exchange current density (A/m^2),

α is the transfer coefficient,

F is Faraday's constant (Coulombs.equivalent^{-1}),

n is the number of equivalents exchanged,

T is the temperature (K)

R is the perfect gases constant.

A simplified equation, valid when the value of the over potential is high enough, is given by Tafel, and described as follows:

$$\eta = a + b \, \mathrm{Ln}(\frac{i}{i_0}) \qquad \text{(Equ. 2-5)}$$

where: a and b are the Tafel coefficients.

2.1.2.3. Concentration Polarisation

Concentration polarisation occurs when the cathodic reduction reaction depletes the adjacent solution from the species being reduced. For instance for steel in seawater, the corrosion reaction can not go faster than the rate of the oxygen reduction, which is dependant on the rate of arrival of oxygen at the metal surface. The concentration polarisation expression of the over-potential can be described as follows ([Jones, 92]):

$$\eta_c = \frac{R \cdot T}{n \cdot F} \cdot \ln(1 - \frac{i}{i_{limit}}) \qquad \text{(Equ. 2-6)}$$

where: i is the current exchanged between the surface of a pipeline and the field (Amp/m^2),

i_{limit} is the limiting current for the cathodic area (Amp/m^2),

η_c is the cathodic over potential, negative (in Volts),

n is the number of electrons exchanged in the corrosion process,

T is the temperature (K),

F is the Faraday's constant,

R the perfect gases constant.

The limiting current density can be calculated from the following equation:

$$i_{limit} = \frac{D_z \cdot n \cdot F \cdot C_B}{\delta} \qquad \text{(Equ. 2-7)}$$

where: i_{limit} is the value of the limiting current density ($A.m^{-2}$),

D_z is the value of the diffusivity of the reacting species (m),

C_B is the solution concentration in reacting species ($mol.m^{-3}$),

δ is the thickness of the diffusion layer (m),

F is Faraday's constant ($Coulombs.equivalent^{-1}$),

n is the number of equivalents exchanged.

The value of the limiting current is affected by the oxygen concentration and its diffusion coefficient. When the oxygen concentration is low, its supply at the surface of the pipeline is limited, and the corrosion process is limited. Figure 2-3 presents the effects of the limiting current on the polarisation diagram.

Concentration polarisation is usually absent for anodic polarisation of iron dissolution reaction.

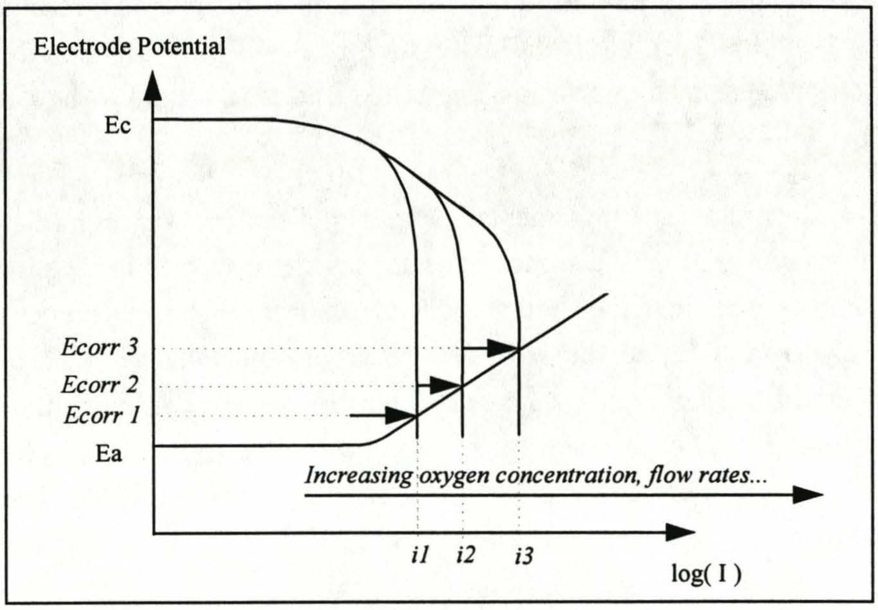

Figure 2-3: Effects of limiting current on Evans diagrams.

2.2. Cathodic Protection

2.2.1. Principles of Cathodic Protection

If electrons are supplied at the surface of the metal (cathodic sites in Figure 2-1), the cathodic potential is expected to fall. While the rate of the cathodic reaction will be increased (Equation 2-2), the metal dissolution rate will fall (Equation 2-1). Under such conditions, the metal corrosion rate is reduced, and is said to be cathodically protected.

Figure 2-4 illustrates and comments, on a simplified polarisation diagram, the modifications which occur when sacrificial anodes are connected to the pipeline. The pipeline and anode material potentials change from their reference potentials (respectively E_c and E_a) to the same "short circuit" potential (E_{sc}). The resulting galvanic current (I_{g_sc}) provides protection to the pipeline. Its corrosion rate decreases from I_{corr} to $I_{corr\text{-}sc}$. The presence of solution resistance (R) between the pipeline surface and the anodes reduces the effect of the galvanic current. The pipeline corrosion current is then reduced from I_{corr} to $I_{corr\text{-}R}$. This is usually named the IR-drop effect.

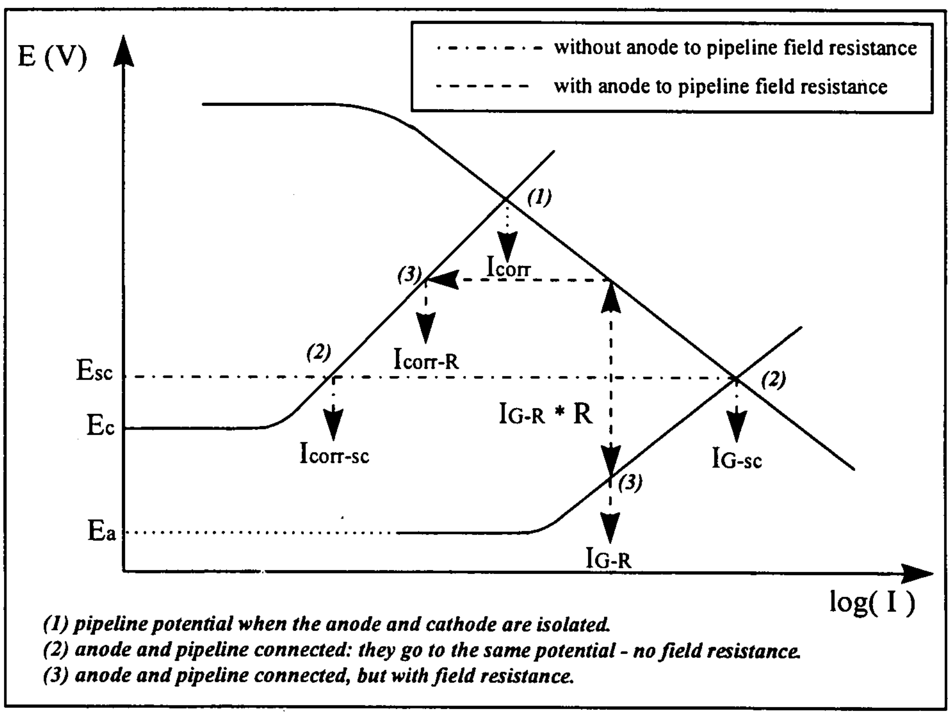

Figure 2-4: Effects of the sacrificial anode on the polarisation diagram.

2.2.2. Types of Cathodic Protection

One method of supplying electrons at the surface of the pipeline is to connect it to a DC power source. This method is called the Impressed Current method. The power source links the surface of the pipeline to an anode, at the surface of which electrolytic reaction occurs. The anode material selected is more electro-positive (noble) than the pipeline metal. This type of anode will remain unconsummed and sustains alternative anodic reactions, based on environment elements, typically water and chloride ions, as described below:

$$2\,H_2O \rightarrow O_2 + 4H^+ + 4e^- \qquad \text{(Equ. 2.8)}$$

and $$2Cl^- \rightarrow Cl_2 + 2e^- \qquad \text{(Equ. 2.9)}$$

The principle of the impressed current method is illustrated in Figure 2-5a.

Electrons can also be provided by sacrificial anodes. These are made of a metal less noble than the pipeline metal, and therefore corrode faster than the pipeline metal. When the sacrificial anodes are electrically connected to the pipeline surface, the potential difference drives the electrical currents which protects the pipeline surface. A sacrificial anode cathodic protection system is illustrated in Figure 2-5b.

The impressed current method is not a generally practical system for subsea pipelines. Significant lengths of cabling would be required for connecting the pipeline surface to power supply units, which are preferably installed in dry places. This implies high electrical losses as well as important risk of damage, for the cabling as well as power supply. The electrical equipment requires frequent inspection and checking. The use of sacrificial anodes for subsea pipelines is advised by standards ([DNV, 93]).

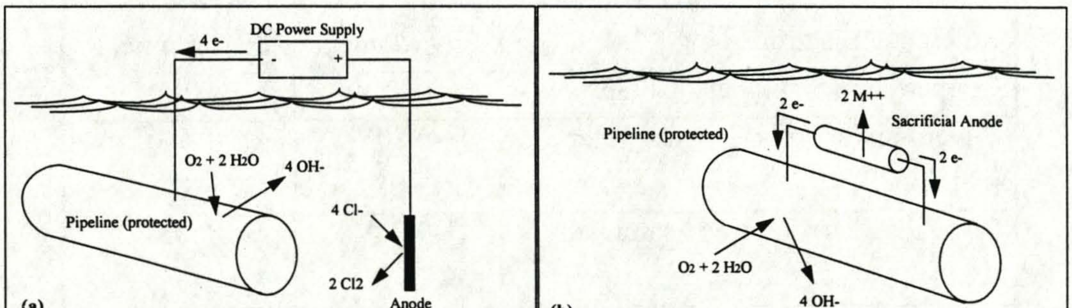

Figure 2-5: Impressed current and sacrificial anode cathodic protection.

2.2.3. Criteria For Corrosion Protection

Corrosion rates are considered negligible or tolerable if they remain below levels of the order of 10^{-3}mm/year ([Gummow, 93]). Using Faraday's laws, this corrosion rate limit can be converted into a current density limit. Such a limit remains a poor indicator of the corrosion protection. Cathodic current densities depend greatly on other factors such as oxygen concentration and flow rates, and clearly the current density is not a matter of choice, but a function of the environmental conditions.

Potential level provides a better indicator of the corrosion protection. The accepted criterion for full protection in aerated sea water is a polarised potential inferior to -0.80 $V_{vs.Ag/AgCl}$. Over this maximum limit, the metal corrosion rate becomes significant, and increases with the potential. Table 2-1 presents the potential limits retained by BSI for various reference electrodes in aerobic and anaerobic environments ([BSI, 73]).

A minimum potential value of $-1.0V_{vs\ Ag/AgCl}$ is also considered in order to avoid over-protection. At values lower than this limit, water may start to be electrolysed:

$$2H_2O \ + \ 2e^- \rightarrow \ 2OH^- \ + \ H_2 \qquad \text{(Equ. 2.10)}$$

Hydrogen gases may be produced at the surface of the metal which may result in damage to the metal itself through hydrogen induced cracking mechanisms ([Gummow, 93]). Coating and calcareous deposits which protect the pipeline surface from corrosion may also be damaged. Anode consumption rates would also be increased, which would reduce their life expectation. Figure 2-6 illustrates the correlation between potential and protection levels. Adequate protection is ensured while the pipeline potential remains in a certain range.

Environment / Reference Electrode	Aerobic Environment	Anaerobic Environment
Copper/copper sulphate (SCSE)	-0.85V	-0.95V
Silver / silver chloride / sea water (Ag/AgCl)	-0.80V	-0.90V
Silver / Silver Chloride / saturated KCl	-0.75V	-0.85V
Zinc / sea water	+0.25V	+0.15V

Table 2.1: Metal potential for full protection of iron and steel, measured against various standard electrodes. In sea water, silver/silver chloride reference electrodes are the most frequently used.

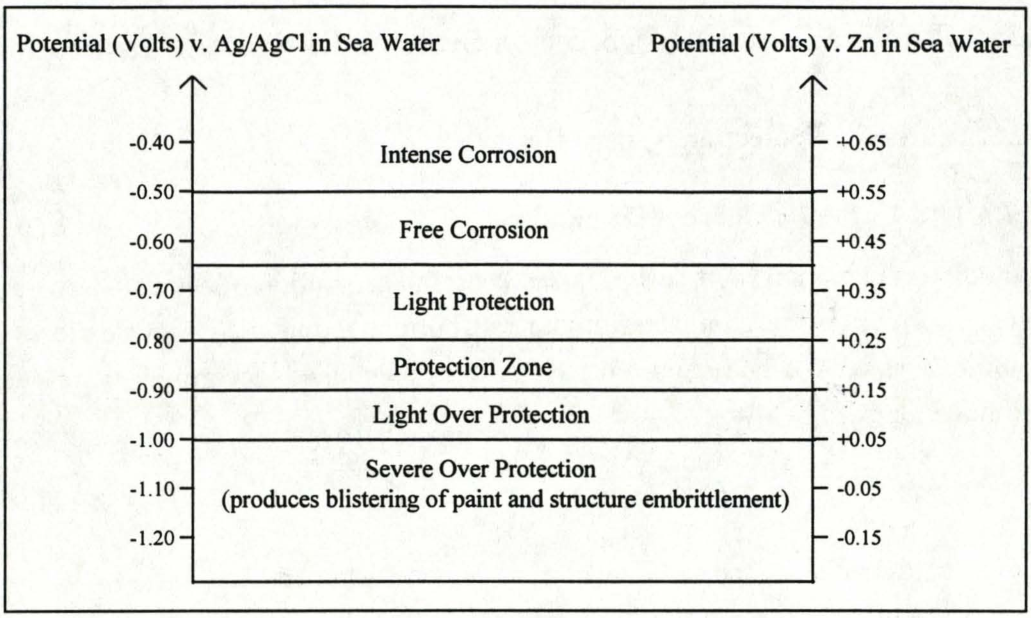

Figure 2-6: Potential level related to protection level.

2.3. Pipeline Cathodic Protection Systems Design and Inspection

2.3.1. Cathodic Protection System Design

2.3.1.1. Cathodic Current Demand

Cathodic protection system design is based on the estimation of the cathodic current demand, which is the equivalent amount of current required to protect the overall pipeline surface. Cathodic current demand is calculated according to a general formula expressed below:

$$I = A \times (i' \times p + i'' \times (1 - p)) \qquad \text{(Equ. 2-11)}$$

where: I is the value of the cathodic current demand (Amperes),

A is the total area of the structure (m^2),

i' is the minimum design current density for bare steel (A/m^2),

i" is the minimum design current density for coated steel (A/m^2),

p is the coating breakdown, that is the fraction of pipeline which lost its coating.

Values for the design current densities (i' and i") and coating breakdown are provided by standards ([DNV, 93] and Appendix 4).

2.3.1.2. Calculation of the Sacrificial Anode Mass

During consumption, the anode material generates a certain amount of current. This current has to meet the total cathodic design current demand. The total mass of anode material is usually calculated using the following equation ([Eliassen, 79], [Wyatt, 82], [Chendge, 91]):

$$W = \frac{c \cdot I \cdot T}{u} \qquad \text{(Equ. 2-12)}$$

where: W is the total mass of anode required (kg)

I is the value of the overall cathodic current demand (Amperes),

c is the anode material consumption rate ($kg.A^{-1}.yr^{-1}$),

T is the expected lifetime of the system (Years),

u is the anode utilisation factor (non dimensional).

Appendices 1 and 2 gather information regarding the anode material and anode type characteristics.

Knowing the amount of anode material required, the corrosion engineer defines the sacrificial anodes size and distribution which will provide the best protection for the entire length of the pipeline ([DNV, 93]).

2.3.1.3. Achieved Current

The total anode output current depends on the area of anodes exposed and on the anode material characteristics. The corrosion engineer has to check that the anodes can provide a sufficient level of current ([Eliassen, 79]). The anode current output can be calculated using Ohm's law:

$$I = \frac{\Delta V}{R} \qquad \text{(Equ. 2-13)}$$

where: ΔV is the driving potential (in Volts), equal to the difference between the anode closed circuit potential (V) and the level of protection required (see Figure 2-6).

R is the estimated anode resistance (in Ohms). This resistance depends on the anode shape and size, and can be calculated using different models ([Cochran, 82]). For bracelet anodes for example, the McCoy formula can be used. It is expressed as follows:

$$R = \frac{0.315 \cdot \rho}{\sqrt{A}} \qquad \text{(Equ. 2-14)}$$

where: ρ is the environment (sea water, mud, sand...) resistivity (Ohm.m).
A is the anode total area (m^2).

According to the results obtained, the corrosion engineer may increase the total weight of sacrificial anode material if the current achieved appears to be insufficient. He can do so by either reducing the anode spacing and/or increasing the anode size. This process is repeated until the design proves to be adequate for the lifetime considered.

2.3.2. Inspection of Subsea Pipelines

Inspections provide the operator with information concerning essentially the pipeline potentials, current densities, anode conditions and coating holidays.

Potential values are obtained by measuring the potential difference between a reference electrode and a measuring electrode positioned close to the pipeline surface. This operation is usually carried out by remotely operated vehicles (ROV) ([Lebouteiller, 80], [Weldon, 92]), as illustrated in Figure 2-7. As the reference electrode environment changes with the ship position, frequent calibrations are required. Measurement precision may therefore vary during the inspection process ([Britton, 91-2]).

The pipeline potential survey data is given to the operator in a standard report. The essential part of the document consists of potential measurements. Graphical representations indicate the potential level all along the inspected pipeline or section of pipeline, as illustrated in Figure 2-8. Crosses on these graphs indicate the position where the measuring unit have been in contact with the pipeline ("stabbing"). These measurements are particularly interesting when carried out directly on the anodes, as they then give an indication of the anodes current outputs which can be used to estimate their life expectation. They also indicate if the anodes are still properly connected to the pipeline and are not passivated.

Early inspections provide valuable information on the condition of the pipeline cathodic protection system and can be used as a baseline for its performance at a later time. They can also indicate problems which may occur early in the life of the pipeline, such as severe coating breakdown or anode disconnection.

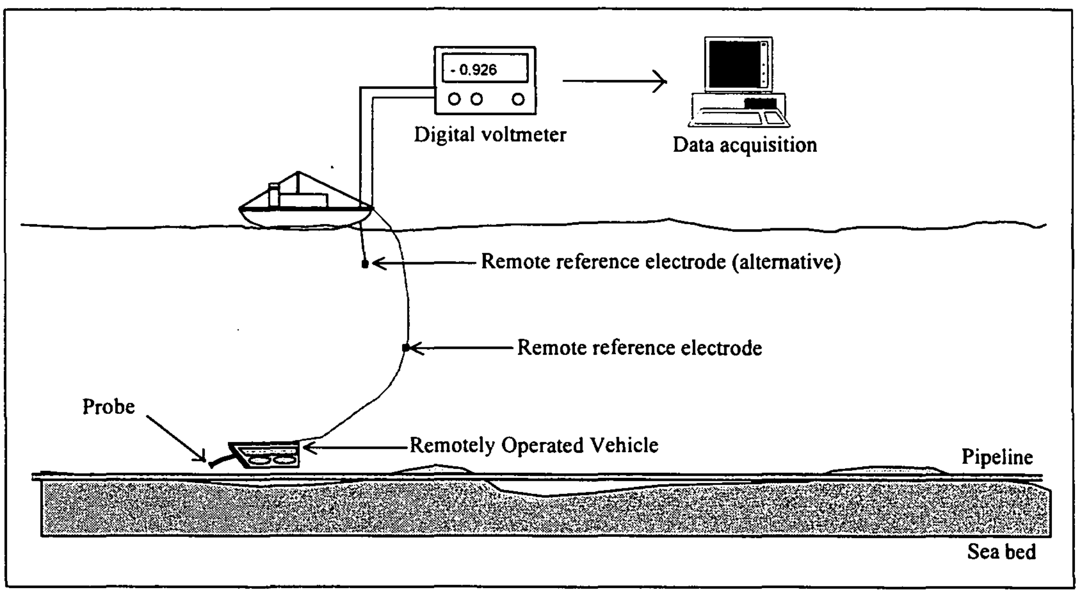

Figure 2-7: Pipeline potentials monitoring.

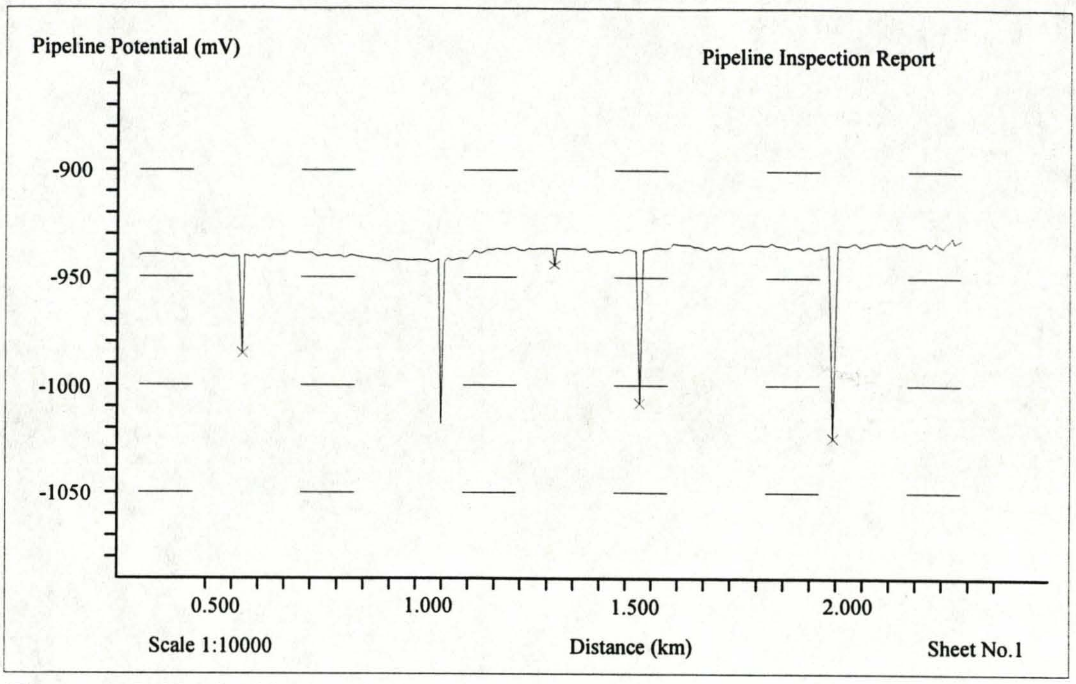

Figure 2-8: Typical inspection result: presentation of the level of potential along a pipeline.

3. Pipeline External Corrosion Parameters And Reliability Modelling

"The notion of safety is often used in a subjective way. It is essential to develop quantitative approaches before it can be used as a functional tool in decision making", Alain Villemeur

3.1. Reliability And Cathodic Protection System Parameters

3.1.1. Reliability And Stress-Strength Analysis

3.1.1.1. Cathodic Protection System Failure Definition

Along the pipeline length, the potential values vary with environmental and operational parameters such as the coating breakdown, temperature or burial state. The functionality of the cathodic protection system also decreases in time. The protective coating permeability increases, coating holidays and disbondments appear and increase in size. As anodes are consumed, their surface area decreases, and so does their ability to deliver current (see Equation 2-14). In some cases, anodes may be completely consumed, or become disconnected from the pipeline surface. The anode becomes ineffective. The level of protection therefore decreases, and the pipeline potential increases, along with the steel corrosion rate on the pipeline surface. A cathodic protection system is considered failed when the electrochemical potential exceeds the maximum limit defined by standards on any part of the pipeline (see Figure 2-6).

As the cathodic protection system efficiency decreases, the potential increases. The reliability of the system is therefore a function of its ability to maintain the value of the potential all along the pipeline below the maximum allowable potential limit.

3.1.1.2. Stress and Strength Analysis

The reliability modelling approach used in this study is based on a stress-strength analysis method. The "stress" is associated with the level of the electrochemical potential at the surface of the pipeline, and the "strength" is related to the maximum allowable electrochemical potential which ensures corrosion protection.

Stress-strength analysis is based on a comparison between the system inherent strength and stress. These depend on the design as well as operational and environmental conditions. In the stress-strength analysis, stress and strength are represented by distributions, characterised by a mean value and a standard deviation, as illustrated in Figure 3-1. Through this approach, it is possible to take account of the general cathodic protection system condition, reflected by the mean potential values, as well as particular location conditions on which extreme values appear.

The strength, for the purpose of the present analysis is represented as a distribution of null variance, with a mean value equal to the maximum potential value set equal to the single value defined earlier in Chapter 2 (see Figure 2-6 and Table 2-1) and illustrated in Figure 3-2. The stress distribution is defined by the values of the electrochemical potential calculated for a set of points at the pipeline surface. The number and position of these points are defined by the user (see Chapter 4).

As the potential variance increases with time, while the difference between the stress distributions mean values and strength decreases (Figure 3-2). The probability of failure increases with the degree of intersection of the two distribution curves. These distribution expressions can be used to obtain a mathematical expression of the system's probability of failure.

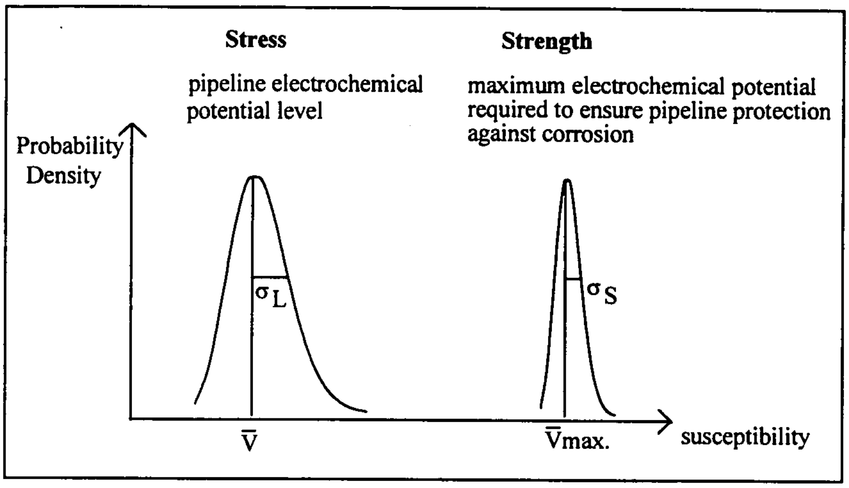

Figure 3-1: Distributed stress and strength.

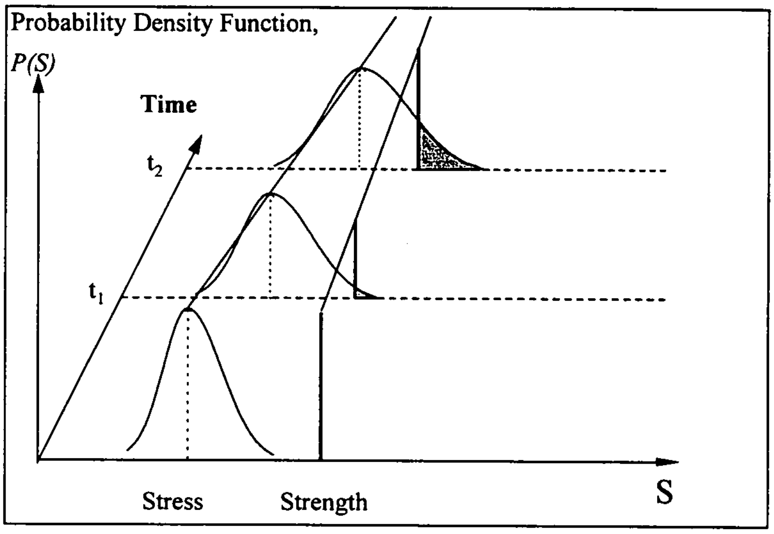

Figure 3-2: Evolution of the stress-strength interference with time.

3.1.2. Practical Reliability Analysis Parameters

3.1.2.1. Reliability And Probability of Failure

Regarding the stress-strength interference model, several parameters can be calculated to estimate the system reliability ([Dhillon, 88]). The probability of failure of the system can be described as the probability that the pipeline potential exceeds the maximum allowable potential, and is calculated as follows:

$$F = P(V_{pipeline} > V_{max}) \quad \text{(Equ. 3-1)}$$

and the reliability, R, is equal to:

$$R = 1 - F \quad \text{(Equ. 3-2)}$$

If we consider that $p_{Vmax}(x)$ and $p_{Vpipeline}(x)$ are the probability density functions of the maximum defined potential and pipeline potential, we can write:

$$F = \int_{-\infty}^{+\infty} p_{Epipeline}(x) \int_{-\infty}^{x} p_{Emax}(y)\, dy\, dx \qquad \text{(Equ. 3-3)}$$

This expression can only be used literally when a mathematical expression of the parameter values are available. In practice, the expressions of these distributions have to be calculated from a discrete set of values, obtained from inspection or modelling. Various types of distributions have to be tested in order to obtain the best fit to the inspection or modelled data. Ways to estimate the probability of failure through the system safety margins were therefore considered.

In these equations, the overall pipeline potential are considered, as calculated in various points along the pipeline. This option was preferred to analysing the potential distribution on the worse pipeline section potential for several reasons. First of all, considering the whole pipeline potential gives a better idea of the pipeline condition, which is what the operator requires. This makes particularly sense as most pipeline cathodic protection systems are in good condition. Furthermore, when particular conditions arise on any particular section, it is possible to run a similar reliability analysis on the section, as described latter on in the analysis.

3.1.2.2. Safety Margin

The safety margin parameter takes into account the mean values of the pipeline potential and maximum allowed potential, and the standard deviation around these mean values. It therefore gives an indication of the system probability of failure. It can be expressed as follows ([Carter, 86]*):

$$SM = \frac{\overline{E}_{max} - \overline{E}}{\sqrt{\sigma^2_{E_{max}} + \sigma^2_E}}\,{}^{\dagger} \qquad \text{(Equ. 3-4)}$$

The mean value and standard deviation of the pipeline potential values are calculated using either inspection results or potential values obtained by theoretical modelling. If it is assumed that the potential values follow a normal distribution, the probability of failure can be derived directly from the safety margin and expressed as follows:

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* the term "Safety Margin" is more typical of the mechanical reliability field and has been preferred in the present analysis. In other reliability analysis field, this parameter is also named "Reliability Index".

† the maximum allowed potential being considered as single value, we actually used in the present analysis: $\sigma^2_{Vmax} = 0$

$$F = 1 - Norm(- SM) \qquad \text{(Equ. 3.5)}$$

where: Norm is the standard normal distribution function

The value of the probability of failure can be therefore calculated by using the following expression:

$$F = 1 - (0.5 \times erfc(\frac{SM}{\sqrt{2}})) \qquad \text{(Equ. 3.6)}$$

where: *erfc*() is the complementary error function.

Due to the lack of data, it was not possible to verify if the potential values along the pipeline could be modelled using a normal distribution. This assumption was nevertheless used to simplify the analysis. If later analysis would show that this assumption is not acceptable, it would be possible to implement a more appropriated approximation.

3.1.2.3. Risk Levels

Risk acceptability varies with the type of activity and the industry considered, and even from one company to another. Risk is, in particular, significantly less acceptable when human lives are involved. The increasing public awareness of environmental issues also reduces greatly the acceptability of environmental risks. In order to take into account the consequence parameter, the risk can be expressed as follows:

$$Risk = f(\text{Probability of Failure, Consequences}) \qquad \text{(Equ. 3.7)}$$

where f is a function defined according to the system analysed.

In the context of this analysis, failure of the cathodic protection system only implies that the pipeline starts to become unprotected, and has not therefore actually failed. Providing that actions are taken to repair the cathodic protection system, failure has only repercussions on the maintenance policy. In this particular study, the consequence term of Equation 3-7 was not considered. The risk was therefore analysed as a direct function of the probability of failure. Figure 3-3 presents a general risk scale ([Hill, 92]), which can be used in order to define a risk acceptability limit, in terms of occurrence per year. The definition of a precise risk limit can not be specified precisely here. The value of 10^{-6} has been used for the purpose of testing the present model, but a definite value would have to be defined by standards, in agreement with offshore companies. This limit may depend on the type of pipeline, as well as factors linked to its environment, operating conditions and maintainability.

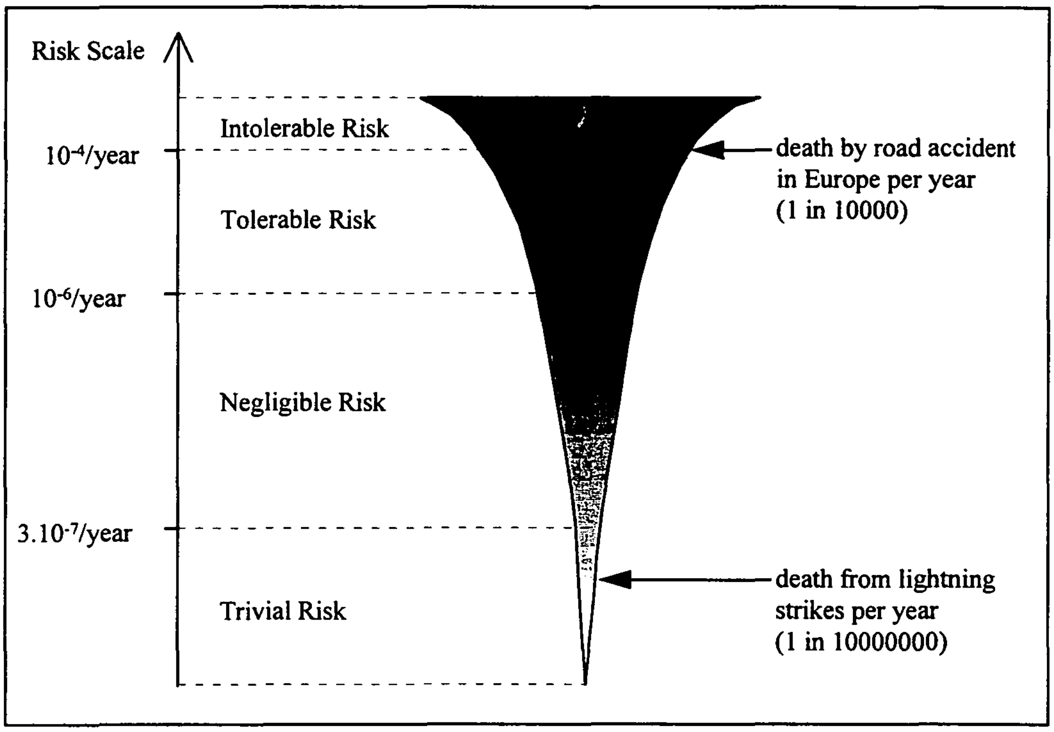

Figure 3-3: General values for risk acceptability criteria.

3.1.3. Maximum Potential Limit And Probabilistic Modelling

The maximum potential required to ensure corrosion protection has been defined in Chapter 2. The definition is based on a single value. It would be possible to distribute this value for using it into the stress-strength interference model. The maximum potential value defined by standard could be used as a mean value, and a standard deviation could be calculated according to estimated uncertainty on this parameter.

The assumption made to have a single maximum potential value simplifies the equations and calculation requirements. It would be possible to further develop the model later on in order to take into account a distribution of the maximum potential value.

3.1.4. Pipeline Potential Probabilistic Modelling

3.1.4.1. Reliability Analysis And Potential Modelling

The standard method for evaluating a cathodic protection system is to analyse the pipeline potential values obtained during inspections to check that the pipeline potential lies between the defined limits at various points along the pipeline. Most of the pipeline potential inspection reports provide only this type of information, along with anode lifetime expectations and any anomalies found such as coating defects, spans, presence of debris, etc. Other methodologies can be developed to analyse the pipeline potential. Analysis of the potential values distribution gives a better insight into the potential trend and cathodic protection system reliability. Another improvement can be brought in by analysing in the same way inspection results obtained for the same pipeline in previous inspections. Comparing the results obtained at different times would help analysing the system changes and increase the understanding of underlying causes.

The purpose of this project was to go one step further, and to develop a tool which would enable the operator to analyse past and present pipeline potentials, as well as forecast potential changes. Such a tool can be used to estimate quantitatively the system reliability, and to forecast the safe life of a pipeline cathodic protection system. In order to develop such a tool, it was necessary, in the first place, to develop a pipeline potential model, which was integrated to the reliability analysis model.

3.1.4.2. Pipeline Potential Modelling and System Parameters

The pipeline potential model developed is based on a model previously developed at Cranfield University ([Reiffers, 85]). The basic modelling method, based on electrical circuit analogy and finite elements analysis, proved to give good results, and was reused. This model is described in detail in Chapter 5. Part of the modifications brought to Reiffers' model consisted of increasing its flexibility, that is its ability to model any pipeline and cathodic protection system design, under any operational and environmental conditions. The model had therefore to be modified in order to take into account as many of the system parameters as possible.

Due to the lack of availability of some of the system parameters, or the lack of knowledge about their changes with time, inputting such parameter values directly into a deterministic model would lead to questionable results. This is particularly the case where these parameters have a large influence on the model output. Such parameters had to be entered in a probabilistic form, that is as a most probable value with an estimate of its uncertainty. The initial model had therefore to be redesigned on order to integrate these probabilistic values.

The following section presents the analysis of the cathodic protection system parameters, carried out to define which data should be used in a deterministic form, and which ones had to be modelled probabilistically.

3.2. Cathodic Protection System Parameters

3.2.1. Definitions

3.2.1.1. Pipeline Cathodic Protection System And Environment

The physical system considered in the analysis needs first to be defined. The main parts are the pipeline and anodes of the cathodic protection system, along with its immediate environment, that is the sea water, soil and adjacent structures are also included. Surrounding human activities are also included, as they have in some instances important effects on the pipeline and cathodic protection system, i.e. coating damage due to external impact.

This physical system is considered as a single element in the in the reliability analysis.

3.2.1.2. Pipeline Sections

Some parameters do not have constant values along the pipeline. The pipeline temperature, percentage of burial or level of coating breakdown for example will change with the location considered on the pipeline.

In order to model the pipeline potentials, the pipeline is divided in a set of sections. These sections sizes and positions are defined when modelling the pipeline, prior to running the calculation modules. Each anode is also considered as one section.

A value can be defined for each variable parameter of each section. These values are considered as constant over the length of the section, as described in Figure 3-4 for the coating breakdown values. These values can be defined according to inspection results, engineers estimations, or can be random generated. In the model developed, the coating breakdown values were generated accorded to the values of other parameters, such as burial state, temperature and activity level around the pipeline section considered, independently of the other section values.

When a greater level of precision is required, the section size can be reduced. This increases the number of sections, and make possible to take into account parameters changes over shorter pipeline lengths.

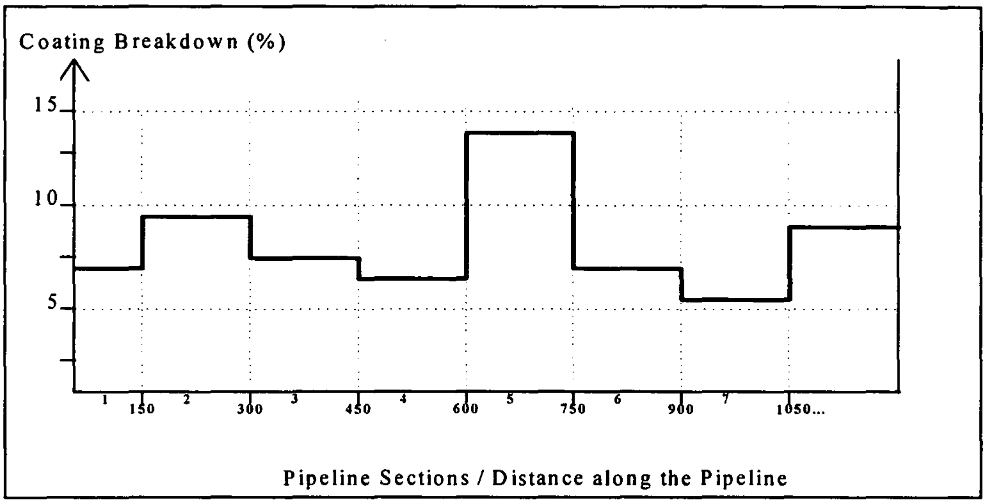

Figure 3-4: Definition of pipeline sections.

3.2.1.3. Parameters Definitions

The following section describe all the parameters which influence the cathodic protection system reliability. In the first place, these parameters are described in a deterministic way, in order to understand and analyse their influence on the cathodic protection system. Later on, the relative importance of each parameter will be discussed and conclusion drew about which of these parameters have a greater influence on the cathodic protection system reliability, and which present the highest level of uncertainty for the modelling.

3.2.2. Parameters Description

3.2.2.1. Pipeline Parameters

This section gathers all the information related to the pipeline dimensions and materials characteristics. Most of these parameters are essential to the potential and reliability modelling. The main parameters defined are:

- Pipeline **length**.
- Pipeline **diameter**.
- Pipeline **age** or installation data.
- Pipeline **expected lifetime**. This is the length of the period of time during which the pipeline is supposed to be operational.

- Pipeline **steel grade**: grade of the steel used to build the pipeline. This parameter is important if a special grade of steel is used. These types of steel are not frequently used for subsea pipelines.

- Pipeline **steel reference potential** (V_0).

- Pipeline **wall temperature**. Pipeline wall temperature depends both on the temperature of the sea water and on the temperature of the fluid carried. Sea water temperatures range from -2°C at the poles to 35°C on the equator. They are also subject to seasonal variations and changes in winds and currents. The pipeline internal temperature is usually higher at one end of the pipeline, and decreases due to cooling effects of the environment.

  Temperature affects environment parameters such as water viscosity and diffusion coefficients. Oxygen concentration, limiting current and therefore corrosion rates increase with temperature. Higher temperature also tends to help the development of marine organisms and bacteria, which may in certain condition increase the corrosion rates (see sulphate reducing bacteria section). Another effect of temperature is to decrease the coating resistivity, which increases the through-coating current densities. Standards describe how maximum protection potentials are to be modified as a function of temperature (-1mV/°C for temperature between 25 and 100°C , [DNV, 93] pp30).

- **Installation criteria**. The quality of the installation procedure can affect greatly the initial weight-coating and coating damages, and affect later changes of the level of coating breakdown. When installed under adverse weather conditions, a pipeline may lose as much as 10% of its weight coating. It is nevertheless difficult to quantify the effects of this parameter, due to the lack of information available from operators.

3.2.2.2. Environmental Parameters

The environment imposes conditions which influences the corrosion processes as well as the anodes and protective coating degradation. We are concerned here essentially with the pipeline external environment. Internal parameters other than temperature do not affect the cathodic protection system. The parameters considered are:

- **Burial state**. The degree of burial usually varies along the pipeline as well as in time, particularly under the effect of sand waves and currents. When burial state changes frequently, inspections only provide part of the information required, that is the level of burial at given times. Buried areas tend to be better protected against damages caused by anchors, fishing nets or dropped objects. On the other hand, when pipelines carry hot products, burial tends to retain heat, which may have damaging effects (see temperature section).

- **Spans sizes and locations**. Such sections can be subject to vibrations which may lead to pipeline and coating damages, especially if the span location remains the same over a long period of time.

- **Mud/sand/sea water resistivity**. These affect mainly the anode consumption rates. Their values are generally well known, and depend on the area and soil considered.

- **Oxygen concentration**. Oxygen is an essential element of the corrosion process, and corrosion rates are directly dependant on the availability of oxygen at the surface of the pipeline (see Equations 2-2, 2-7, Figure 2-3 and Appendix 4). Knowing the level of the oxygen concentration is therefore important for the system analysis.

- **Sea water velocity**. Sea water velocity around the pipeline is linked to waves and tidal effects. Water flows decrease the thickness of the oxygen diffusion layer, and therefore increase the cathodic current demand ([Hedborg, 91], [Rose, 87]). They can also affect the level and stability of the calcareous deposits, and, on pipeline spans, generate vibrations which may contribute to coating degradation.

- **Calcareous deposits**. When cathodic protection is applied, an excess of hydroxyl ions (OH^-) develops at the surface of the pipeline (see Equation 2-2). Sea water contains bicarbonates ions which form a pH-dependant equilibrium with carbonates ions. An increase in the hydroxyl ions induces a rise in the pH, which displace the equilibrium in favour of the carbonate ion (CO_3^{2-}), which reacts with calcium ions to form calcium carbonate, an insoluble product. These reactions can be described as follows:

$$HCO_3^- \leftrightarrow H^+ + CO_3^{2-} \qquad \text{(Equ. 3.8)}$$

$$Ca^{2+} + CO_3^{2-} \rightarrow CaCO_3 \qquad \text{(Equ. 3.9)}$$

Similarly, magnesium ions may form an insoluble hydroxide through the following reaction:

$$Mg^{2+} + 2OH^{-} \rightarrow Mg(OH)_2 \qquad \text{(Equ. 3.10)}$$

Both reactions occurs at the surface of a cathodically protected subsea pipeline, and form a produce called calcareous deposit. This deposit interfere with oxygen mass transfer, and protect the pipeline from corrosion in the same way a protective coating does. Rose has shown how calcareous deposit can reduce cathodic current densities for bare steel from over 1300mA/m^2 when clean, down to around 170mA/m^2 after calcareous deposit has been building up for about ten days (see [Rose, 87], pp.46). Calcareous deposit are insoluble, but their mechanical stability is affected by water flows and vibrations. When damaged, they nevertheless reform rapidly.

- **Sea water pH**. This influences the corrosion processes by modifying the system equilibrium parameters. Equilibrium electrochemical potential values are calculated from standard potential values by using the Nernst equation ([Jones, 92], pp45-46). pH also affects not only the speed but also the type of the type of the calcareous deposit. Only small increase in pH are required for the formation of calcium carbonate. Magnesium hydroxide deposits appear when pH is superior to 9.3. This parameter is important when considering that magnesium hydroxide tends to be less mechanically resistant and produces more easily damaged deposits. Coating deterioration may also be influenced by pH (see sulphate reducing bacteria section).

- **Sulphate reducing bacteria (SRB)**. Sulphate reducing bacteria produce sulphide and therefore increase the pipeline corrosion rates. These bacteria can be found in some soils, typically waterlogged soil containing a large fraction of clay. They are particularly active within a certain range of temperature and pH, typically pH 4 to 9, and between 10 and 45°C ([MC, 83]).

- **Activity level**. The presence of human activities at the vicinity of the pipeline increases the risk of coating and pipeline deterioration. These are mainly caused by dropped objects and fishing nets causing weight and protective coatings deterioration ([Moshagen, 80], [Tominez, 92]). It is generally possible to determine areas where human activities increase such risks. Pipeline sections located close to platforms, reservoirs and well heads present higher risk to be hit by objects dropped from boats or platforms. Pipeline sections located on fishing areas are more likely to be hit by fishing nets or anchors.

- **Stray currents**. Stray currents generally result from interacting cathodic protection systems. Electric currents are drained away from a cathodic protection system by another structure, such as pipeline, platform or well. The element with the lowest level of protection tends to drain some current from the other elements, which may become unprotected and corrode.

Stray currents also appear while welding operations are carried out ([Britton, 91]), or where electrical installations are located close enough to the pipeline ([Nyman, 88]). Their effects depend on the current intensity and on the length of the period over which they are drained.

Systems are used to record stray currents on onshore pipelines and structures ([Solomon, 92]), but similar system cannot be easily used for off-shore applications, and information is seldom available about stray current for subsea pipelines.

3.2.2.3. Corrosion Parameters

These characterise the corrosion processes and are used in the corrosion equations. The parameters considered are:

- The **design current densities**. Design current densities give an idea of the level of current density a bare steel area would require in order to be protected against corrosion. Current densities depends on a number of parameters such as temperature, oxygen concentrations, calcareous deposits, etc... Typical values are provided by standards for various sea locations (see Appendix 4).

- **Electrochemical parameters**. The Faraday's constant (F), perfect gases constant (R) and Tafel constants are part of the corrosion equations and their values.

- **z**. This is the number of electrons exchanged during the corrosion processes. This number depends on the type of reaction considered, and will change according to the anode material considered.

3.2.2.4. Inspection And Operating Data

Inspections provide the operator with information about the pipeline condition at various dates. Information collected during external pipeline inspection concerns, in particular, pipeline potentials, current densities, anode conditions and life expectations, burial state, spans, observable coating holidays and the presence of unexpected objects. Some form of internal inspection may also provide information related to pipeline wall thinning due to external corrosion.

Inspectors usually provide the operators with reports, listings and disks of inspection data, and in some cases videos of the inspection. Assessment of the pipeline and cathodic protection system is also provided.

Although conventional, the inspection process may be affected by several factors. Inspection quality varies with environmental conditions, equipment and technique used ([Steele, 93]). Inspection companies tend not to define clearly the level of precision achieved. All together, inspection quality is a rather difficult parameter to assess. This section described more the type of parameters which would have to be considered to evaluated the quality of the inspection process.

- **Inspection frequency**. Though inspection frequency is usually guided by inspection results, there is aspect of inspection frequency which are of use for the system description. Generally speaking, system knowledge increases with the inspection frequency. Failure prevention is also improved due to both an increase in the amount of data available for analysis and the possibility to analyse more frequently failure indicators.

- **Type of inspection**. This parameter describes the technique and equipment used to run the inspection. In some cases, inspection may only be run on a part of the pipeline, which has also an effect on the data analysis.

- **Environmental conditions during inspection**. This concerns mainly the weather conditions, the time required to carry out the inspection. Bad weather conditions increase the risk of measurement errors due to remotely operated vehicle positioning as well as drifting in the calibration of the measurement system. Under adverse weather conditions, the time required for carrying out the inspection also tend to increase, which also induce similar calibration problems.

- **Inspection quality**. Inspection techniques and equipment used for inspection will influence the inspection quality. Various equipments and techniques would provide various results quality. Human factors also have to be considered. If the person making the measurement or controlling the remotely operated vehicle during inspection is highly skilled and work under good conditions, he will be able to make better readings and therefore increase the quality of the inspection results. Inspectors should provide a guaranteed and reasonable level of precision. Little information is presently available for this point.

Burial state also influences the quality of the measurement, as direct measurements at the surface of the pipeline and anodes can not be made on buried pipelines.

- **Inspection reports quality**. Report quality influences later analysis of the information provided. The precision, amount, relevance as well as format of the information provided by the operator should also be considered to estimate the report quality.

- **Operating Data**. This regroup all the information related to the changes in operating conditions and repairs operated on the line, coating and sacrificial anodes. These may affect the behaviour of the cathodic protection system.

3.2.2.5. Protective Coating Parameters

While protective coatings are not entirely impermeable to water and oxygen, they reduce corrosion to a great extent when applied to the surface of a metal. They act as a resistive barrier to current flows, and provide most of the corrosion protection. On most offshore structures and in particular on pipelines, it is not economic to install cathodic protection system without applying a good quality coating. The cathodic protection then mainly ensures that corrosion remains under control when the coating quality decreases, whether it is due to an increase in its permeability to water and oxygen or to the appearance of coating holidays.

The coating degradation rate and level of coating breakdown are conditioned by several parameters, described in this section.

- **Pipeline storage** quality and **surface preparation**. The attention given to the pipeline surface prior to coating as well as the protection of the coated pipeline sections during storage and transport affects the quality of the coating, and therefore the coating breakdown ([Mullen, 92], [Wolf, 93]). Adequate surface preparation prior to coating also increases the adherence of the coating. The purpose of surface preparation is to remove all oils, greases, soluble salts and all forms of contamination ([Newman 92], [Mullen, 92], [Beavers, 93]). Certified coating inspection can improve the coating quality ([Steele, 93]).

- **Coating type**. When selecting an external coating for pipeline, several parameters have to be considered. These include in particular its adhesion (resistance to disbondment), durability (resistance to chemical, physical and biological deterioration), service temperature range, flexibility (tensile elongation) and impact resistance. The techniques used to apply the various coating also influences their respective quality. These parameters influence the coating resistance to environmental aggressions ([ffrench-Mullen, 86], [Banach, 87], [Wolf, 93], [Senkowski, 94]). Standards provide estimation of coating breakdown for different types of coating ([DNV, 93]). In practice, effects of other parameters such as temperature should be considered (see Appendix 3). New coatings are developed and should prove with time to offer better protection against corrosion ([Mullen, 92], [Cox, 93], [Duncan, 93]).

- **Coating thickness**. Both mechanical and electrical resistance tends to increase with the coating thickness.

- **Presence of concrete/weight coating**. A concrete coating is often added for reducing buoyancy and to increase the stability of the pipeline on the seabed. This concrete coating tends to provide extra protection to the pipeline coating itself. ([Barlo, 93]).

- **Percentage of coating breakdown**. This parameter is related to all the previous parameters. It increases with time, but the rate of increase and the initial values are difficult to estimate. In addition, unexpected accidents can modify the level of coating breakdown. Coating disbondment also accounts for a rather high percentage of the coating breakdown. In cases of coating disbondment, the coating is still present, but a layer of water can circulate between the pipeline surface and the coating. When disbondment appears on risers, the heat may stimulate the water circulation, and therefore the corrosion rate. Furthermore, even though the coating may be physically in place, its permeability to water may be high enough to let water and oxygen go through ([Banach, 87]). In this case the coating efficiency is reduced.

3.2.2.6. Anode Parameters

Sacrificial anodes are manufactured on demand according to design requirements. These define essentially the anode types, sizes, material and number. Manufacturers are expected to provide anodes with test certificates. The characteristics considered in the model are:

- **Type of anode**. Most anodes used on pipeline are half-shell or segmented bracelet anodes. The anode type affect mainly its utilisation factors, that is the fraction of the anode which can be expected to deliver adequate current at the end of the anode lifetime (see typical values in Appendix 2).

- **Anode material**. Sacrificial anodes are usually made of aluminium or zinc alloys, which are duly tested in order to determine material characteristics. Several parameters are used in the corrosion equations. The main parameters linked to the anode material are: the number of electrons exchanged in corrosion process, the driving potential, the exchange current density and electrochemical efficiency. Examples of values are presented in Appendix 1.

- **Anode sizes and weight**. Usual sizes range from 0.1 to and 1.2 metres in diameter, and 10 to 1000 kilograms. Anode weight is an important parameter, and is one of the calculation outputs.

- **Anode spacing**. Anode spacing usually varies mainly with the pipeline diameter and the level of coating breakdown expected. Anodes have only a protective effect over a limited length of pipeline, due to the effect of the environment resistivity (Figure 2-4).

3.3. Cathodic Protection System Parameters Analysis

3.3.1. Parameters Availability And Influence

3.3.1.1. Data Availability

The information related to subsea pipeline cathodic protection systems is contained in various reports related to their designs, installation and inspection. These provide information related to the pipeline and cathodic protection systems characteristics, environmental and operational conditions, along with parameters related to the pipeline condition at different periods of its lifetime.

During this project development, it appeared that such information was not always readily available. Operators appear to have difficulties providing the data required. Likewise, it was found that inspection reports were difficult to gather. This difficulty appeared to increase with the pipeline age.

The availability of the various system parameters had to be considered for the development of the model. The level of availability for one parameter is estimated according to two factors, that is the difficulty encountered to obtain the parameter value, and the precision of the value obtained. Due to the subjectivity of these two criteria, no precise function can be defined to estimate parameter availability. Estimation is based on operator' and corrosion engineer' experience, as well as on the experience gained while developing the project.

3.3.1.2. Parameter Influence On The Model

The influence of model parameters on the system output varies from one parameter to another. The parameter influence criteria reflects the importance each parameter has on the pipeline potential and cathodic protection system reliability.

Assumptions regarding parameter influences are based on physical or mathematical analysis, as well as on common sense. Tests carried out on purpose built models and on initial versions of the potential model helped quantify the parameters influence. Such approach may not give good results in all cases when the system studied is complex and parameters influence each others. Here again, the quality of the estimation is increased by the knowledge of the system, which can help reduce errors due to misjudgement.

3.3.1.3. Parameter Importance For Risk Modelling

The relative importance of each parameter is obtained by combining the parameter availability and influence on the model. This gives an indication of the parameters importance for the pipeline potential and reliability modelling. This importance increases with the parameters influence, and decreases with the data availability. A graphical presentation is given in Figure 3-5.

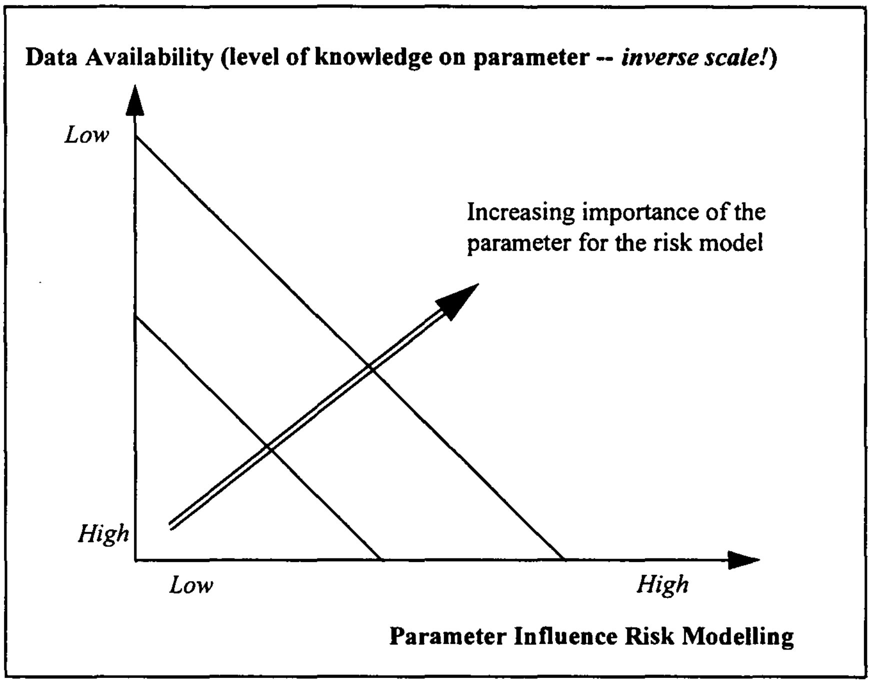

Figure 3-5: Definition of the parameter influence on the model output accuracy

3.3.2. Parameters Analysis

3.3.2.1. Parameters Grading

The parameters have been sorted according to the criteria defined previously (see Figure 3-5). The parameters considered are ranked according to their availability and their influence on the calculation results.

Index values have been estimated according to the information provided by operators (during meetings or in design and inspection results documentation provided), standards, articles and academic publications. The results of the estimations are presented in Table 3-1 and a graphical representation is given in Figure 3-6. It appears from this analysis that the coating breakdown parameter most affects the model uncertainty.

3.3.2.2. Inter-Dependency Analysis

The cathodic protection system analysis was also used to define inter-dependencies between the various parameters. The results are used to define the organisation and classify the model input. Figure 3-7 presents the result of the data inter-dependence analysis.

It appears here that most parameters can be related to the level of coating breakdown, which partly explains the high level of uncertainty on the coating breakdown.

Parameters	Availability[‡]	Influence on Modelling[§]
Coating breakdown percentage	1	5
Pipeline sections storage, coating preparation	1	3
Stray currents	1	3
Sulfate reducing bacteria	1	3
Pipeline installation criteria	1	2
Design/limiting current densities	3	5
Water velocity	3	3
Activity level (localised mechanical damages)	3	3
Mud/sand/sea water resistivity	3	3
Percentage burial and spans location	3	3
Calcareous deposits	3	3
Oxygen concentration	3	3
Sea water / soil pH	3	3
Operational data	3	1
Anode type and sizes (length, external radius)	4	3
Anode number/spacing	4	3
Coating thickness	4	3
Pipeline temperature (°C)	4	3
Anode material (z, V_0 and I_0)	5	3
Pipeline material reference potential (V_0)	5	3
F (Faraday's constant)	5	3
R (perfect gases constant)	5	3
Tafel constants	5	3
z (number of electrons exchanged in corrosion process)	5	3
Nature of coating	5	3
Steel grade	5	3
Age and expected lifetime (years)	5	3
Pipeline length/diameter (meters)	5	2
Concrete weight coating	5	2
Inspection parameters (type, frequency, environmental conditions, quality...)	5	2

Table 3-1: Estimation of the parameters' precision availability and influence on the calculation results.

‡ data availability. A grade is estimated, going from 1 (low level of availability) to 5 (high level of availability).

§ influence of parameter value on the modelling results. A grade is estimated, going from 1 (low level of influence on the modelling results) to 5 (high level of influence on the modelling results)

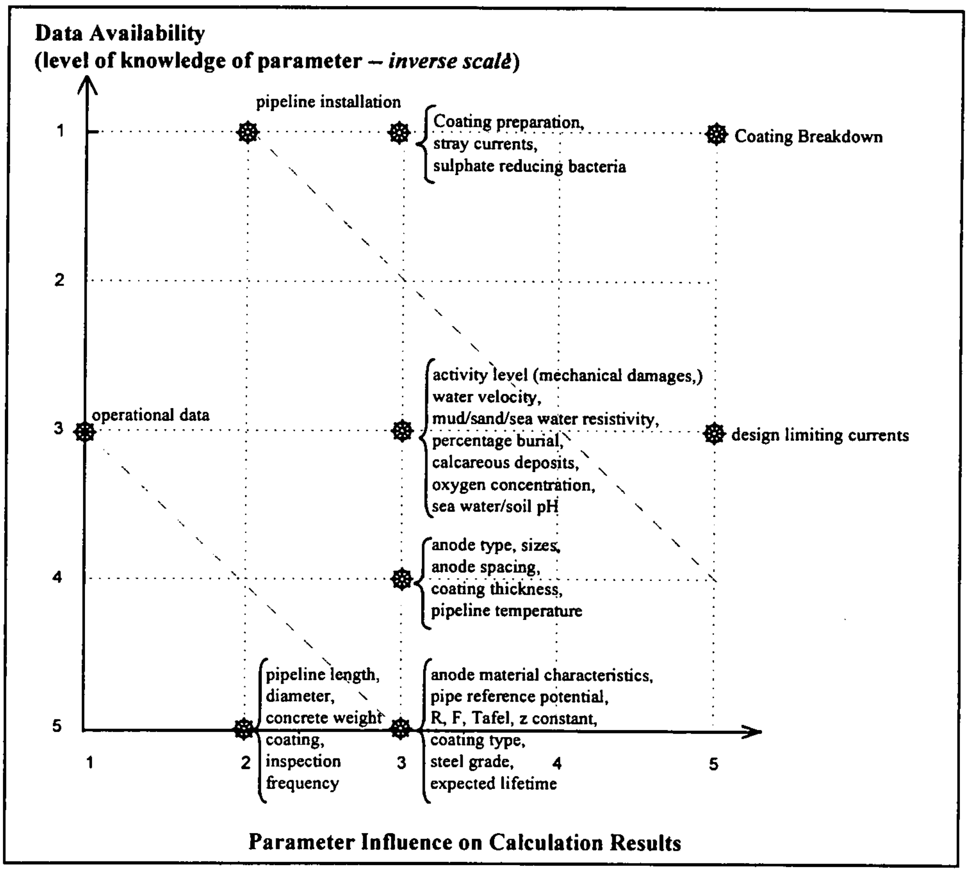

Figure 3-6: Data availability and parameter's influences analysis.

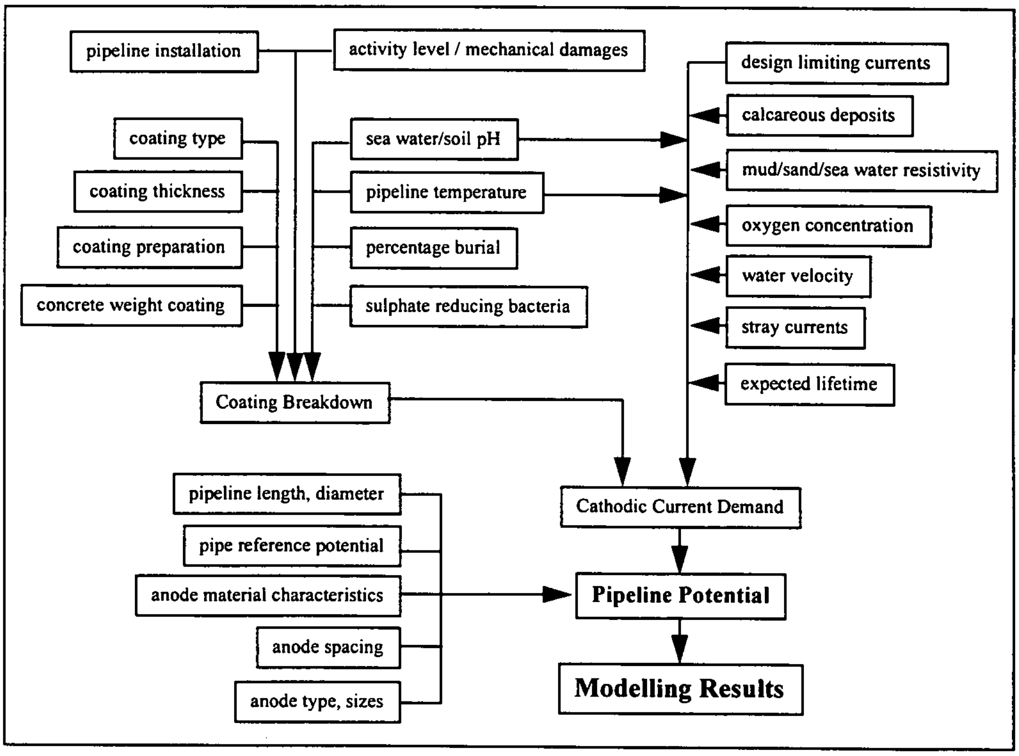

Figure 3-7: Parameter dependency description.

3.3.3. Parameter Values And Uncertainties Definition

3.3.3.1. Parameter Uncertainties And Model Complexity

Integrating uncertainties on the potential model input parameters increases the model and calculation module complexities (see Appendix 9). It appears from the previous analysis that the coating breakdown is the central element of the model, both by its influence on the cathodic protection reliability and by its dependence on the other parameters.

In order to limit the model complexity, it was decided that only uncertainties on the coating breakdown would be considered in the pipeline potential model. The other parameters are also considered in the reliability model, but only taken into account in the pipeline potential model through their effect on the coating breakdown. Some of these parameters values are used to calculate an estimation of the coating breakdown uncertainty on each of the pipeline section.

3.3.3.2. Coating Breakdown Uncertainties

The overall pipeline coating breakdown mean value is defined by the model operator. The other model parameters are used to distribute the coating breakdown value. The uncertainties on the coating breakdown parameters is used in the pipeline potential model to calculate an uncertainty on the pipeline potential, as illustrated in Figure 3-8.

Several distributions can be used to describe the coating breakdown for each pipeline section ([Crowder, 91]). It was assumed that, for each pipeline section, the coating breakdown was defined by a mean value and a standard deviation. A Normal distribution was used to describe ***each pipeline section*** coating breakdown, as illustrated in Figure 3-9. The section coating breakdowns are considered as statistically independent, and depends only on the pipeline overall mean coating breakdown value, and on the other parameter values, which may be different from one section to the other.

It was not possible, in the context of this thesis, to model precisely the influences of the defined parameters on the coating breakdown. No reference to any such analysis could be found either in the literature or from operators. For the purpose of testing the pipeline potential and reliability model, a basic analysis was therefore carried out. It provided a way to generate a coating breakdown variances according to the other parameters defined. The formulae used are presented in Appendix 8. These equations have no mathematical, physical or chemical relevance, and are simply used for testing the other aspect of the reliability analysis. This way was preferred to a random generation of the coating breakdown uncertainties as it provide a way to take into account the known changes of some of the parameters along the pipeline, such as for example the temperature and activity.

Operators and coating industry appeared to be interested in sponsoring research project on that field. The results obtained from such projects could be integrated to this model later on.

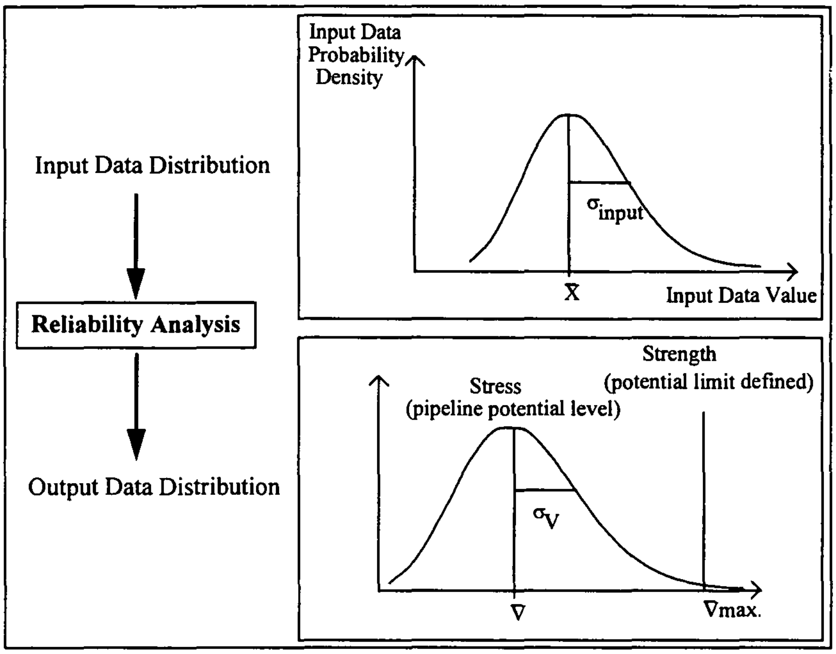

Figure 3-8: Effects of the input parameter distribution on the calculation results.

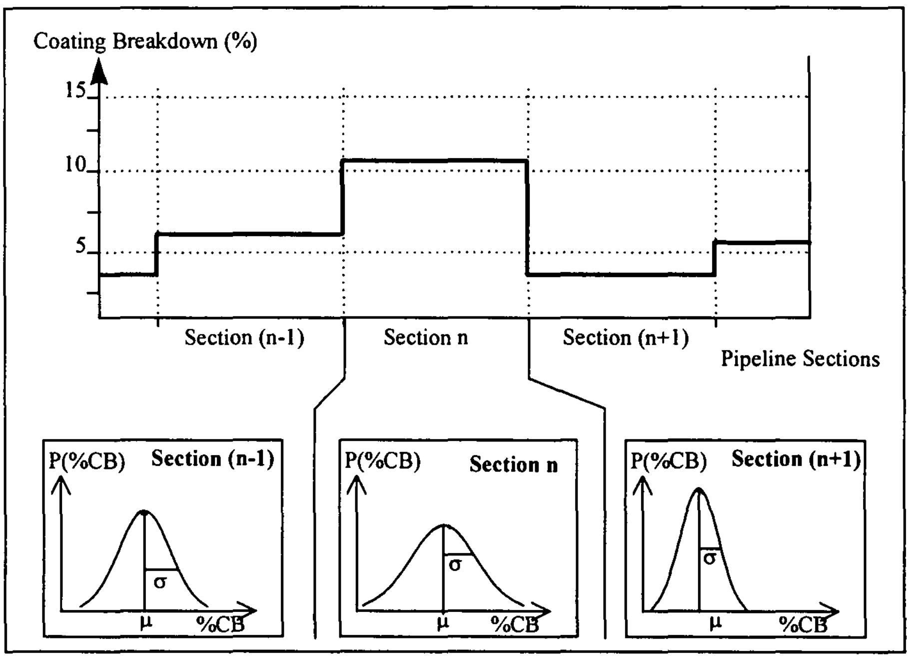

Figure 3-9: Coating breakdown distribution for each pipeline section.

3.3.3.3. Other Parameters

Most of the other parameters used in the model are defined by the user as single deterministic values. These values are gathered from inspection reports or derived from operator's experience. Tables 3-2a and 3-2b presents the list of all these parameters, whether they are used in the model, and the way they are generated in the modelling process.

When modelling a pipeline cathodic protection system reliability, the user define the parameter values according to the available information related to the modelled pipeline. Unknown parameter values are estimated according to experience.

Parameter Name	Generated
pipeline length	design parameter - deterministic
pipeline diameter	design parameter - deterministic
pipeline age or installation date	design parameter - deterministic
pipeline expected lifetime	design parameter - deterministic
pipeline steel grade	design parameter - deterministic
pipeline reference potential	design parameter - deterministic
pipeline wall temperature	operational data - deterministic
pipeline installation criteria	operational data - deterministic
burial state	operational data - deterministic
spans sizes and locations	operational data - deterministic
mud/sand/sea water resistivity	design parameter - deterministic
oxygen concentration	design parameter - deterministic
sea water velocity	design parameter - deterministic
calcareous deposits	*included in the design current densities*
sea water pH	***not used***
sulphate reducing bacteria (SRB)	***user defined***
activity level	***user defined***
stray currents	***not used***
design current densities	design parameter - deterministic
electrochemical parameters	design parameter - deterministic
z	design parameter - deterministic

Table 3.2a: List of parameters used in the model.

Parameter Name	Generated
inspection frequency	***not used***
type of inspection	***not used***
environmental conditions	***not used***
inspection quality	***not used***
inspection reports quality	***not used***
operational data	***not used***
pipeline prior-coating storage and surface preparation	***not used***
coating type	design parameter - deterministic
coating thickness	design parameter - deterministic
concrete/weight coating	design parameter - deterministic
coating breakdown	***user defined*** **OR** ***estimated by model***
anode type	design parameter - deterministic
anode material	design parameter - deterministic
anode sizes and weight	design parameter - deterministic
anode spacing	design parameter - deterministic

Table 3.2b: List of parameters used in the model.

4. Pipeline Potential Modelling

4.1. Model's Definition

4.1.1. Basic System of Equations

4.1.1.1. Electrical Analogy

Corrosion processes can be regarded as the sum of electrons and ion fluxes inside a defined system. For a given system, these fluxes balance the thermodynamic parameters of the different elements, in order to reach a steady state. The system, as defined earlier, consists of the pipeline and its environment, sea water and soil.

In order to analyse the system, the pipeline is divided into a series of adjacent sections. Each anode is regarded as a section, and in between anodes pipeline segments are divided into shorter sections, as presented in Figure 4-1. Each section is in contact with adjacent sections and with its environment, that is the surrounding sea water and sea bed. We also consider the environment to be divided into sections or volumes. Each one of these sections and volume is represented as a node in our model. We therefore consider anodic, cathodic and field nodes (see Figure 4-1).

In the electrical analogy, the corrosion processes are regarded as exchanges of ions and electrons between the different nodes. Electrical resistance values characterise the exchanges between adjacent nodes. These resistances depend on the nature of the nodes, their geometry and thermodynamic characteristics. Considering the various parameters of the system, it is possible to calculate the values of the current between the different nodes as well as the potential values on the nodes.

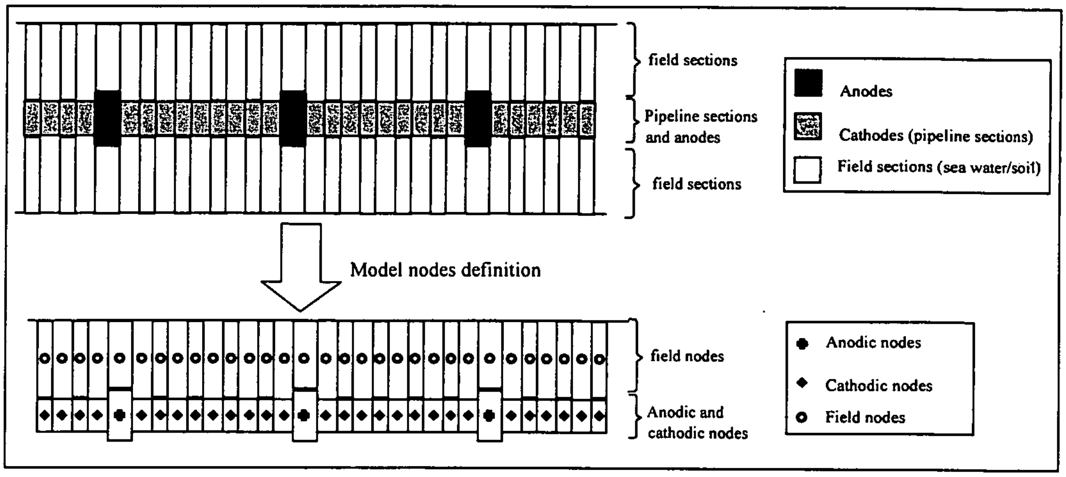

Figure 4-1: Definition of the model's sections and nodes.

4.1.1.2. Basic Electric Equations

Ohm's law is used to describe the connection between the system nodes. The basic Ohm's law is expressed as follows:

$$V = I \cdot R \qquad \text{(Equ. 4-1)}$$

or:

$$I = V \cdot G \qquad \text{(Equ. 4-2)}$$

where: V is the value of the potential differences between two nodes (Volts),
I is the value of the current flowing between two nodes (Amperes),
R is the value of the equivalent resistance of the field between the two nodes (Ω),
G is the equivalent conductance ($G = R^{-1}$), in Ω^{-1}.

If we consider a simple system, based on one anode, one cathode and two field elements as presented in Figure 4-2, we can write:

$$V_c - V_a = I \cdot (R_a + R_f + R_c) \qquad \text{(Equ. 4-3)}$$

where: V_c is the value of the potential at the cathodic node (pipeline surface),
V_a is the value of the potential at the anodic node (anode surface),
I is the value of the current (Amp.) flowing between the anodic and cathodic nodes,
R_a is the value of the anode resistance,
R_f is the equivalent value for the field resistance,
R_c is the value of the cathodic resistance (pipeline surface).

The value of the resistances along the pipeline are neglected, as they are very low compared to other resistances present in the system.

The potentials are evaluated at each node. The value of the currents circulating in between the nodes can then be calculated, providing the values of the resistances and conductances are defined.

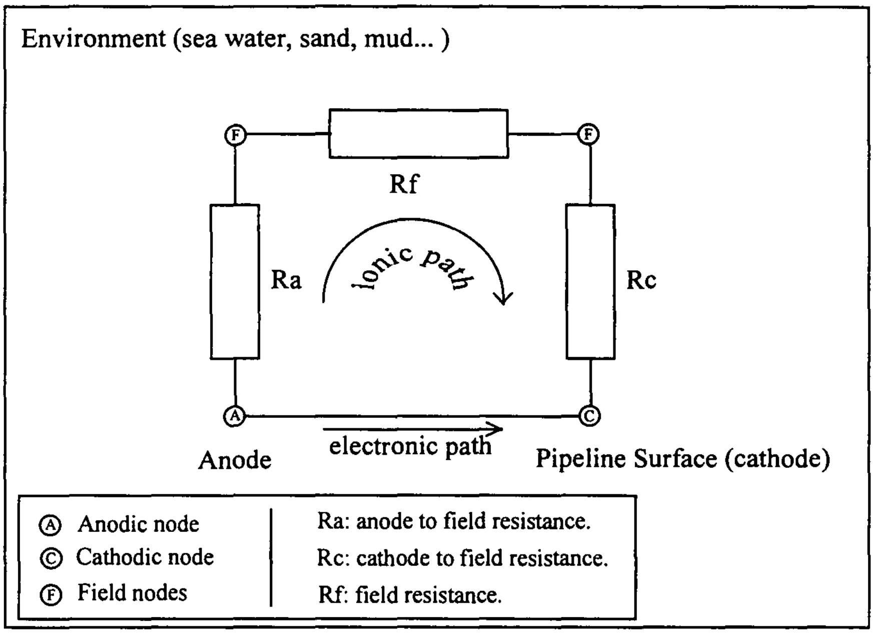

Figure 4-2: Basic circuit model.

4.1.1.3. General Notations

In order to keep a clear view of the calculations carried out, a system of notation had to be defined. The system is regarded as composed of two main groups of nodes, the nodes situated in the field, and the nodes situated at the pipeline surface. The pipeline surface nodes can be either anodic or cathodic.

V_f and I_f represent the values of the potentials and currents for the nodes situated in the field, and V and I represent the same parameters for the nodes situated at the surface of the pipeline, as shown in Figure 4-3. R_f (or G_f) represent then the values of the resistances (or conductances) between two nodes situated in the field, and R (or G) represent the resistances (or conductances) of the field situated in between a node at the surface of the pipeline and a node situated at the surface of the pipeline.

The two sets of nodes are then numbered from 1 to N, N being the total number of different sections considered. We therefore have N field nodes, and N anodic or cathodic nodes. Figure 4-4 gives a global presentation of these notations.

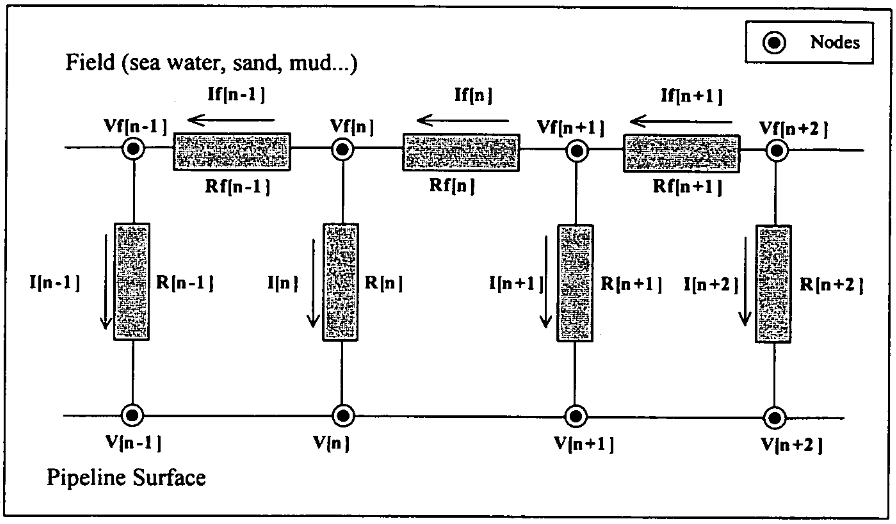

Figure 4-3: General notations.

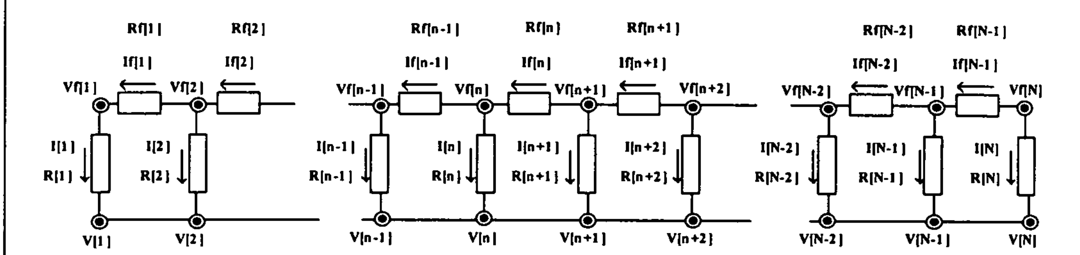

Figure 4-4: Representation of the notation convention for the system nodes.

4.1.1.4. Basic Electrical Equations

According to the general notations we have:

$$(V_n - V_{fn}) \cdot G_n = I_n \qquad \text{(Equ. 4-4)}$$

$$(V_{fn-1} - V_{fn}) \cdot G_{fn-1} = I_{fn-1} \qquad \text{(Equ. 4-5)}$$

$$(V_{fn} - V_{fn+1}) \cdot G_{fn} = I_{fn} \qquad \text{(Equ. 4-6)}$$

for any value of n comprised between 2 and (N-1).

The sum of the currents at one node being null, we also have:

$$I_{fn} = I_{fn-1} + I_n \qquad \text{(Equ. 4-7)}$$

The combination of the previous sets of equations gives:

$$G_{fn-1}.V_{fn-1} - (G_{fn-1} + G_{fn}).V_{fn} + G_{fn}.V_{fn+1} = -I_n \qquad \forall n \subset [2, (N-1)] \text{(Equ. 4-8)}$$

This equation is used in order to build up the system of equations used in this model. Only the field potentials are used in this expression. The size of the system of equations to be solved will therefore be N. The values of the pipeline potential can later be derived from the values of the field potentials, and the size of the system of equation to be solved is therefore reduced.

4.1.1.5. Primary System

The primary system of equations is obtained by using Equation 4-8. This equation is correct for each node, except the first and last. In these cases, the equation is expressed as follows:

$$G_{f0}.V_{f0} - (G_{f0} + G_{f1}).V_{f1} + G_{f1}.V_{f2} = I_1 \qquad \text{(Equ. 4-9)}$$

and: $$G_{fN-1}.V_{fN-1} - (G_{fN-1} + G_{fN}).V_{fN} + G_{fN}.V_{fN+1} = I_N \qquad \text{(Equ. 4-10)}$$

By considering that:

$$V_{f0} = V_{f1} \qquad \text{(Equ. 4-11)}$$

and $$V_{fN+1} = V_{fN}, \qquad \text{(Equ. 4-12)}$$

we obtain:

$$-G_{f1}.V_{f1} + G_{f1}.V_{f2} = I_1 \qquad \text{(Equ. 4-13)}$$

and: $$G_{fN-1}.V_{fN-1} - G_{fN-1}.V_{fN} = I_N \qquad \text{(Equ. 4-14)}$$

Using this, we can then build the primary system, and its matrix expression. The matrix expression is then of the shape:

$$\begin{pmatrix} -Gf_1 & Gf_1 & 0 & \dots & 0 \\ Gf_1 & -(Gf_1 + Gf_2) & Gf_2 & 0 & \dots \\ 0 & \dots & \dots & \dots & 0 \\ \dots & 0 & Gf_{N-1} & -(Gf_{N-1} + Gf_N) & Gf_N \\ 0 & \dots & 0 & Gf_{N-1} & -Gf_{N-1} \end{pmatrix} \cdot \begin{pmatrix} V_1 \\ V_2 \\ \dots \\ V_{N-1} \\ V_N \end{pmatrix} = \begin{pmatrix} I_1 \\ I_2 \\ \dots \\ I_{N-1} \\ I_N \end{pmatrix}$$

which can be expressed in a more condensed way as follow:

$$[G_f].[V] = [I] \qquad \text{(Equ. 4-15)}$$

$[G_f]$ is a tridiagonal matrix. It is also singular, and will accept an infinity of solutions. It is therefore necessary to de-singularise this system prior any attempt to solving it. This is done by integrating the boundary conditions.

4.1.2. Boundary Conditions

4.1.2.1. Basic Electrochemical Equations

The boundary conditions are introduced as a second set of equations, derived from the corrosion equations presented in Chapter 2. For the cathodic areas (pipeline surface), the electrochemical charge transfer reaction occurs at a high rate, and the corrosion process is ruled by a concentration polarisation law. For anodic areas, the process is ruled by an activation polarisation law.

4.1.2.2. Cathodic Areas

On the cathodic areas (pipeline surface), the corrosion process is limited by a limiting current (i_{limit}), which is the maximum value of the corrosion current (see expression in Equation 2-7). The expression of the overpotential is provided by Equation 2-6. This equation can be expressed as follows:

$$I_n = I_{limit} . (1 - e^{k.\eta}) \qquad \text{(Equ. 4-16)}$$

Using this equation, it is possible to replace the overpotential value (η) by its expression in function of the current (I) and of the field potential (Vf) at the node n. We have by definition, at a cathodic node n:

$$\eta_{cn} = V_n - V_{0n} \qquad \text{(Equ. 4-17)}$$

The electrical circuit equation linking the field and the pipeline potentials can be used then to express the overpotential in function of the current intensity and of the field potentials. This gives:

$$V_n - Vf_n = R_n . I_n \qquad \text{(Equ. 4-18)}$$

By combining Equations 4-17 and 4-18, we obtain:

$$\eta_{cn} = V_{0n} - Vf_n - R_n.I_n \qquad \text{(Equ. 4-19)}$$

We then obtain by combining Equations 4-16 and 4-19:

$$I_n = I_{limit} \cdot (1 - e^{k.(Von - Vfn - RnIn)}) \qquad \text{(Equ. 4-20)}$$

This formula can be used for all the cathodic sites.

4.1.2.3. Anodic Areas

At an anodic nodes, activation polarisation is prevalent. Equation 2-4 defined earlier is used on these sites to introduce the boundary conditions. The pipeline potential can then be linked to the field potential using the Equation 4-19. By replacing this expression of η_{an} in Equation 2-4, we obtain:

$$\frac{I_n}{I_{On}} = e^{\alpha.k.(Von - Vfn - RnIn)} - e^{-(1-\alpha).k.(Von - Vfn - RnIn)} \qquad \text{(Equ. 4-21)}$$

4.1.2.4. Second System of Equations

These equations (Equations 4-20 and 4-21) can be used for linking the current intensities (I) and the field potentials (V_f) at each anodic or cathodic node. The resulting set of equations is described as follows:

$$\begin{cases} node\ 1: & I_1 = I_{\text{limit},1} \cdot (1 - e^{k\cdot(V_{0,1} - V_{f,1} - R_1 I_1)}) \Leftarrow \text{(cathode)} \\ node\ 2: & I_2 = I_{\text{limit},2} \cdot (1 - e^{k\cdot(V_{0,2} - V_{f,2} - R_2 I_2)}) \Leftarrow \text{(cathode)} \\ \ldots\ldots & \\ node\ \text{n}: & I_n = I_{\text{limit,n}} \cdot (1 - e^{k\cdot(V_{0n} - V_{fn} - R_n I_n)}) \Leftarrow \text{(cathode)} \\ node\ (\text{n}+1): & I_{n+1} = I_{0,(\text{n}+1)} \cdot (e^{\alpha\cdot k\cdot(V_{0,(n+1)} - V_{f,(n+1)} - R_{n+1} I_{+1n})} - e^{-(1-\alpha)\cdot k\cdot(V_{0,(n+1)} - V_{f,(n+1)} - R_{n+1} I_{n+1})}) \Leftarrow \text{(anode)} \\ node\ (\text{n}+2): & I_{n+2} = I_{\text{limit,(n+2)}} \cdot (1 - e^{k\cdot(V_{0,(n+2)} - V_{(f+2)n} - R_{n+2} I_{n+2})}) \Leftarrow \text{(cathode)} \\ \ldots\ldots & \end{cases}$$

which can be expressed in a more general way as:

$$\begin{cases} node\ 1: & I_1 = f_1(I_1, V_1) \Leftarrow \text{(cathode)} \\ node\ 2: & I_2 = f_2(I_2, V_2) \Leftarrow \text{(cathode)} \\ \ldots\ldots & \\ node\ \text{n}: & I_n = f_n(I_n, V_n) \Leftarrow \text{(cathode)} \\ node\ (\text{n}+1): & I_{n+1} = f_{n+1}(I_{n+1}, V_{n+1}) \Leftarrow \text{(anode)} \\ node\ (\text{n}+2): & I_{n+2} = f_{n+2}(I_{n+2}, V_{n+2}) \Leftarrow \text{(cathode)} \\ \ldots\ldots & \\ node\ \text{N}: & I_N = f_N(I_N, V_N) \Leftarrow \text{(cathode)} \end{cases}$$ (Equ. 4-22)

The resulting system can be described as a matrix system, as presented below:

$$[I] = [F] . ([V_f] , [I])$$ (Equ. 4-23)

This system of equations is combined to the one obtained previously (Equation 4-15) in order to define the final system which needs to be solved.

4.1.3. System of Equations

4.1.3.1. Anodic Equations

We can write by combining the expressions presented in Equations 4-8 and 4-21:

$$G_{fn-1}.Vf_{n-1} - (G_{fn-1}+G_{fn}).V_{fn} + G_{fn}.V_{fn+1}$$

$$= I_0 .(e^{\alpha . k . (Vo[n] + R[n].Gf[n-1].Vf[n-1] - (1 - R[n].(Gf[n-1]+Gf[n]).Vf[n] - R[n]. Gf[n] . Vf[n+1])} - e^{-(1-\alpha).k . (Vo[n] + R[n].Gf[n-1].Vf[n-1] - (1 - R[n].(Gf[n-1]+Gf[n]).Vf[n] - R[n]. Gf[n] . Vf[n+1]))})$$

(Equ. 4-24)

This gives us an expression of the potential ($V_{f,n}$) at an anodic node, considering both the connections to the adjacent nodes ($V_{f,\ (n-1)}$ and $V_{f,\ (n+1)}$), and the boundary conditions.

4.1.3.2. Cathodic Equations

We can write by combining the expression presented in Equations 4-8 and 4-20:

$$G_{f(n-1)}.V_{f(n-1)} - (G_{f(n-1)}+G_{fn}).V_{fn} + G_{fn}.V_{f(n+1)}$$

$$= I_{limit} .(1 - e^{k . (Vo[n] + R[n].Gf[n-1].Vf[n-1] - (1 - R[n].(Gf[n-1]+Gf[n]).Vf[n] - R[n]. Gf[n] . Vf[n+1])})$$

(Equ. 4-25)

This gives us the expression of the potential ($V_{f,n}$) at a cathodic node, considering both the connections to the adjacent nodes ($V_{f,(n-1)}$ and $V_{f,(n+1)}$), and the boundary conditions.

4.1.3.3. General Expression

The system studied in this case is built up using these two types of equation. We can express this system of equations in a more general way as follows:

$$[G_f][V_f] = [F]([V_f]) \qquad \text{(Equ. 4-26)}$$

[F] being the set of non-linear equations defined.

This is the system we have to solve in order to get the field potential values. The solution will satisfy the boundary conditions, and be such that the current intensities balance the global electrical circuit.

In order to implement a solving method, this system has been rearranged. The system of equations solved is actually defined as follows:

$$[G_f][V_f] - [F]([V_f]) = 0 \qquad \text{(Equ. 4-27)}$$

4.1.4. Computation Of The Conductances and Resistances

4.1.4.1. Conductances Modelling

Preliminary tests showed that the conductances and resistances values used in the model have a critical effect on the results obtained. If the field resistances are for example under-estimated, the system reacts as if the various elements of the model were virtually disconnected. In this case, the calculation modules tend to find that the anodic and cathodic elements tend to have potentials close to their respective reference potential. These conductances and resistances had therefore to be precisely defined in order to obtain realistic values, and a model was developed to provide estimations. The calculation process is explained in Appendix 7.

4.1.4.2. Example Of Conductances Values Obtained

Figure 4-5 presents the results of the field conductances calculations for a 30" pipeline (0.762 meter of out-wall diameter) of 216 meters in length with three bracelet anodes (0.2 meter length, 0.962 meter out-wall diameter).

The conductances curve shape is linked to the potential field around the pipeline, as illustrated in Figure 4-6. Close to the anodes, the potential drop is very important, and it decreases further away form the anode. The current exchanged between two adjacent anodes being constant at any point between the two anodes, the shape of the conductances curve is explained by Ohm's law.

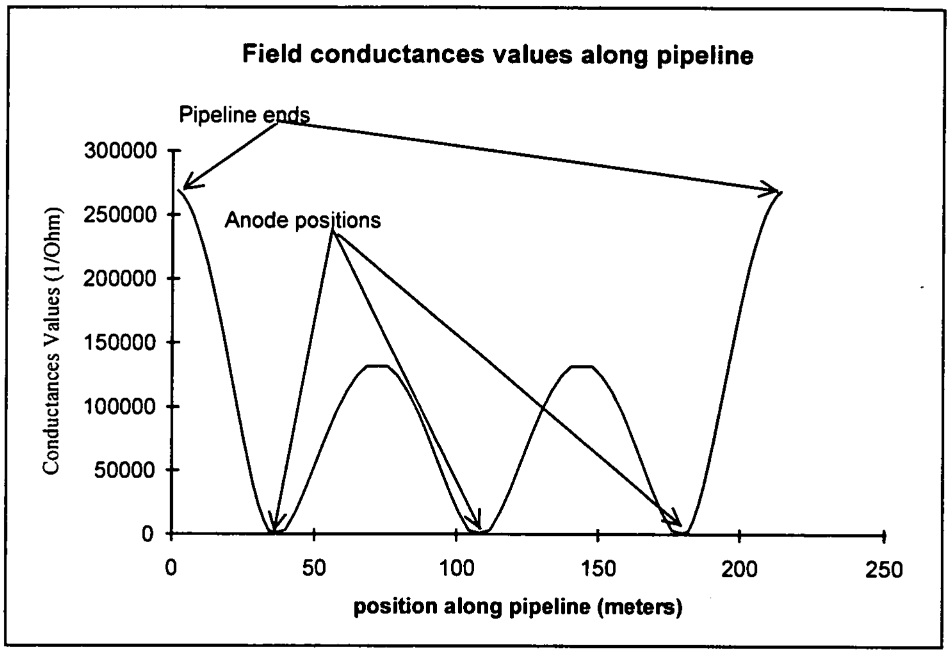

Figure 4-5: Example of conductance's values.

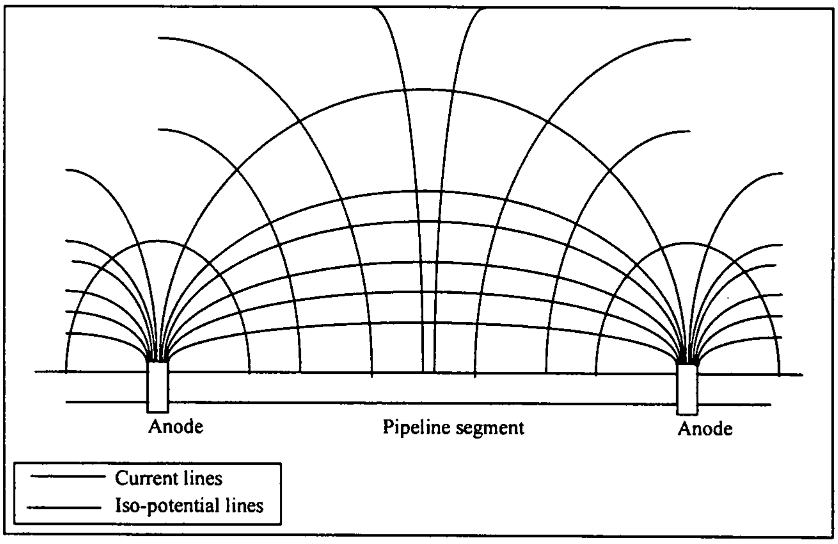

Figure 4-6: Description of the field potential shape.

4.1.4.3. Example Of Resistances Values Obtained

Considering the pipeline described in the previous section, the anode resistance obtained was equal to 0.077 Ohm. This values is close to the value obtained with the McCoy's formula (Equation 2-14):

$$R_A = \frac{0.315 \cdot 0.2}{\sqrt{\pi \cdot 0.942 \cdot 0.2}} \approx 0.082\ \Omega$$

(with, $\rho = 0.2$ Ohm.m; anode radius = 0.942 m; anode length = 0.2 m)

4.2. Model Outputs

4.2.1. Field Potentials

Solving the system of equations presented earlier (Equation 4-26) required a significant amount of tests and analysis. Several algorithms had to be tested on various expressions of the system. The Newton and Newton-Raphson methods were first used, but only the more elaborated Newton-Raphson method, which integrates a step minimisation technique ([Press, 92]), gave positive results for all type of designs and conditions. In order to implement this algorithm, Equation 4-26 had to be transformed into an equivalent one, presented below:

$$[G_f][V_f] - [F]([V_f]) = 0 \qquad \text{(see Equ. 4-27)}$$

The basic equations (Equations 4-21 and 4-20) were therefore modified as follows:

- for an anodic node:

$$I_0 .\left(e^{\alpha . k . (Vo[n] + R[n].Gf[n-1].Vf[n-1] - (1 - R[n].(Gf[n-1]+Gf[n])).Vf[n] - R[n]. Gf[n] . Vf[n+1])} - e^{-(1-\alpha).k . (Vo[n] + R[n].Gf[n-1].Vf[n-1] - (1 - R[n].(Gf[n-1]+Gf[n])).Vf[n] - R[n]. Gf[n] . Vf[n+1]))}\right)$$

$$- (G_{f(n-1)}.V_{f(n-1)} - (G_{f(n-1)}+G_{fn}).V_{fn} + G_{fn} .V_{f(n+1)}) = 0 \qquad \text{(Equ. 4-28)}$$

- for a cathodic node:

$$I_{limit} .(1 - e^{k . (Vo[n] + R[n].Gf[n-1].Vf[n-1] - (1 - R[n].(Gf[n-1]+Gf[n])).Vf[n] - R[n]. Gf[n] . Vf[n+1])})$$

$$- (G_{f(n-1)}.V_{f(n-1)} - (G_{f(n-1)}+G_{fn}).V_{fn} + G_{fn} .V_{f(n+1)}) = 0 \qquad \text{(Equ. 4-29)}$$

The system of equation studied can be expressed as follow:

$$\begin{cases} \text{- node 1:} & L_1(V_{f1}, V_{f2}) = 0 \\ \text{- node 2:} & L_2(V_{f1}, V_{f2}, V_{f3}) = 0 \\ \ldots\ldots & \\ \text{- node (n-1):} & L_{(n-1)}(V_{f(n-2)}, V_{f(n-1)}, V_{f(n)}) = 0 \\ \text{- node n:} & L_n(V_{f(n-1)}, V_{f(n)}, V_{f(n+1)}) = 0 \\ \text{- node (n+1):} & L_{n+1}(V_{f(n)}, V_{f(n+1)}, V_{f(n+2)}) = 0 \\ \ldots\ldots & \\ \text{- node N:} & L_1(V_{f(N-1)}, V_{fN}) = 0 \end{cases} \qquad \text{(Equ. 4-30)}$$

which can be expressed as:

$$[L]([V_f]) = 0 \qquad \text{(Equ. 4-31)}$$

The Newton-Raphson algorithm was implemented using an existing module ([Press, 92]). This module reaches convergence faster and with a better chance of success if the system solution is close to zero. The previous system of equation was modified in order to cater for this constraint, and an hyperbolic arc-sinus function was applied to the system of equations. The system actually solved by the algorithm is expressed as follows:

$$\text{ArcSh}(\,[L]\,([V_f])\,) = 0 \qquad \text{(Equ. 4-32)}$$

The solution of this system is then defined as the set of potential values $[V_f]$ for which the system of non-linear equations [L] is equal to 0.

The general equation is then differentiated using Taylor equations. We have:

$$[L]\,(\,[V_f] + [\delta V_f]\,) = [L]([V_f]) + [Jac]\times[\delta V_f] + O(\,[\delta V_f^2]) \qquad \text{(Equ. 4-33)}$$

where: $[\delta V_f]$ is the matrix of the differences between the values of $[V_f]$ between two iterations,

[L] is the system of functions studied,

[Jac] is the Jacobian matrix obtained with [L],

O(x) is a function converging faster than x^2 toward 0 when x tends to 0.

If we consider that the set of field potentials $[V_f]$ is close enough to the system's solution, we have:

$$[\delta V_f^2] \approx [0] \qquad \text{(Equ. 4-34)}$$

and: $$[L]\,(\,[V_f] + [\delta V_f]\,) \approx [0] \qquad \text{(Equ. 4-35)}$$

we can then estimate the value of the set of δV as follows:

$$[\delta V_f] = -\,[Jac]^{-1}\,.\,[L]([V_f]) \qquad \text{(Equ. 4-36)}$$

Considering an initial set of guessed values for the potentials $[V_{f,\,ini}]$, we can calculate a set of $[\delta V]$ and update the initial guess as follows:

$$[V_f] = [V_{f,\,ini}] + [\delta V] \qquad \text{(Equ. 4-37)}$$

The $[V_f]$ values are updated until a convergence criterion is met. This criterion is expressed as follow:

$$\text{modulus}([L] ([Vf])) \leq \varepsilon \qquad \text{(Equ. 4-38)}$$

where: modulus([L] ([Vf])) is the value of the modulus of the function [L] at point $[V_f]$,

ε is the precision required.

The algorithm used converges towards the system solution within a reasonable number of iterations, providing the initial estimation of the field potentials is close enough to the solution. A special module was developed to calculate a potential estimate for each node of the system.

4.2.2. Current Intensities

Using the previous results and the initial system of equations (Equation 4-15), it is possible to calculate the values of the current intensities flowing between the field and the pipeline sections. The values of these intensities are obtained by solving the following system of equations:

$$[I] = [Gf][Vf] \qquad \text{(see Equ. 4-15)}$$

These values can then be used to calculate the values of the pipeline potentials, and the values of the anode consumption's.

4.2.3. Pipeline Potential

The values of the pipeline section potentials can at this point be calculated using the following formula:

$$V_n - V_{fn} = -R_n \cdot I_n$$

$$\Leftrightarrow \quad V_n = V_{fn} - R_n \cdot I_n$$

where: V_{fn} is the value of the field potential (Volts),

V_n is the value of the potential at the surface of the pipeline (Volts),

I_n is the value if the current exchanged between the pipeline and the field for each node considered (Amperes).

4.2.4. Anode Consumption

As the characteristics of the sacrificial anodes used for the system and values of their current output are known, it is possible to calculate the consumption of each anode for each period of time. We use the formula presented in Equation 2-12.

The anode consumption being calculated, the anode remaining weight is calculated as follows:

$$W_{remaining}(t = t_i) = W_{initial} - \sum_{t=t_0}^{t=t_i} W_{consumed}(t) \qquad \text{(Equ. 4.39)}$$

4.2.5. Potential Variances

Potential variances are calculated at the same time as the actual potential values, according to the values defined for the coating breakdown uncertainties. Details about these calculations are presented in Appendix 9. These are used mainly for the system reliability analysis, to define a confidence interval for the potential value obtained for each pipeline section.

4.2.6. Other Model Outputs

Overall, the pipeline potential calculation module produces twenty different result files. These files contain in particular the values of the potentials and currents for each period of time, and the anode consumptions. The list of the output files is provided in Appendix 11. Some of these results can be plotted and checked using a module developed for the Unix environment, based on Uniras functions.

Additional result files contain information regarding the pipeline potential extremums and variances, the system safety margin and reliability. This file is used in the general user interface. Details are given in Chapter 6.

4.3. Calculation Organisation And Initialisation

4.3.1. Time Periods Definition

Part of the interest of the model reside in the possibility to analyse cathodic protection system reliability over any time length. This time length is divided into periods, in order to observe and analyse the system reliability in time. The definition of the periods is illustrated in Figure 4-7. The period lengths are defined by the user. For each period, a set of parameter values are defined for each node of the system. Considering this fact, only the computer memory capacity limits the number of periods modelled. Potential calculations are carried out for each period.

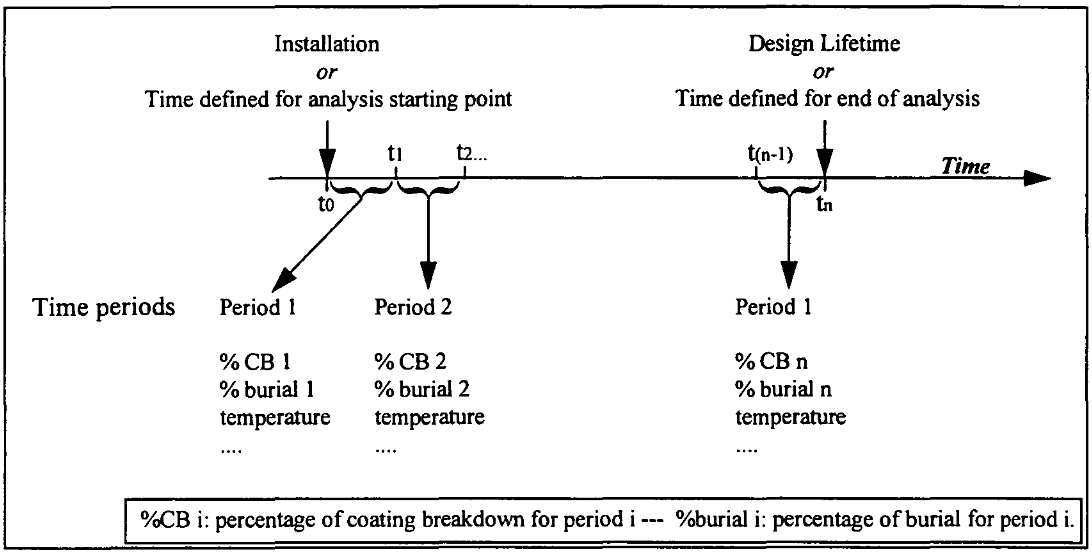

Figure 4-7: Definition of the analysis total duration and periods of time.

4.3.2. Calculations Sequence

For each time period, it is necessary to carry out a series of calculations. These calculations are described as a computation "loop". The sequence of the calculations is described in Figure 4-8. The main steps are:

1) Calculate the values of the conductances and resistances for the pipeline studied.

2) Define the values of cathodic current demand for each defined section of the pipeline.

3) Calculate the values of the field potential (main part of the calculation).

4) Calculate the values of the current densities (deduced from the field potentials).

5) Calculate the values of the pipeline potentials and potential variances (deduced from the field potentials, the current densities and the resistances).

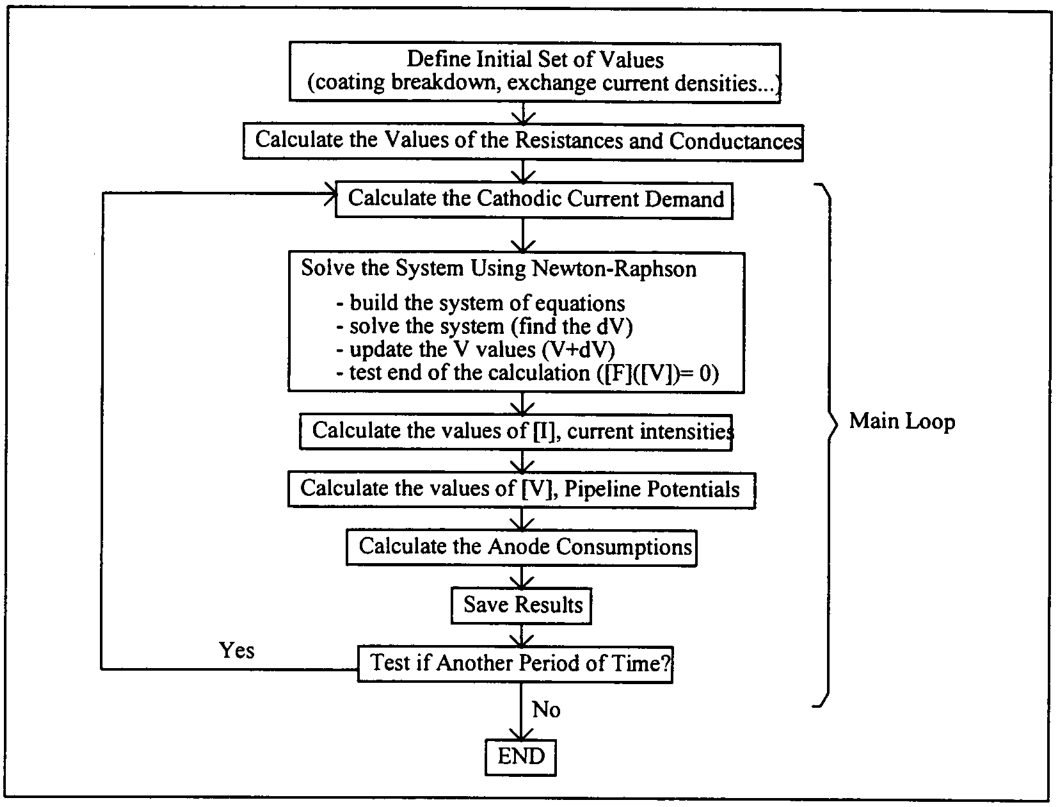

Figure 4-8: Chart of the pipeline potential computation steps.

5. Reliability Analysis Process

5.1. Reliability Analysis Data

5.1.1. Reliability Data And Uncertainties

The reliability analysis process carried out is based on the analysis of the pipeline potentials, current densities and anode consumption. These data are provided by inspection or calculated using the pipeline potential model presented (see model outputs in Appendix 11). The potential model made possible carrying out reliability prediction analysis.

Uncertainties are defined for inspection and modelled data. Uncertainties on inspection data are due to measurement errors, interferences and measurement unit calibration errors. Uncertainties on the modelled potential are derived from the uncertainties defined on the coating breakdown values. Both types of uncertainties can be taken into account in the reliability analysis. Figure 5-1 illustrates the general reliability analysis process and data origins.

The potential values can be analysed directly, but are also used to calculate indicators of the cathodic protection system condition, essentially the safety margins and reliability factor.

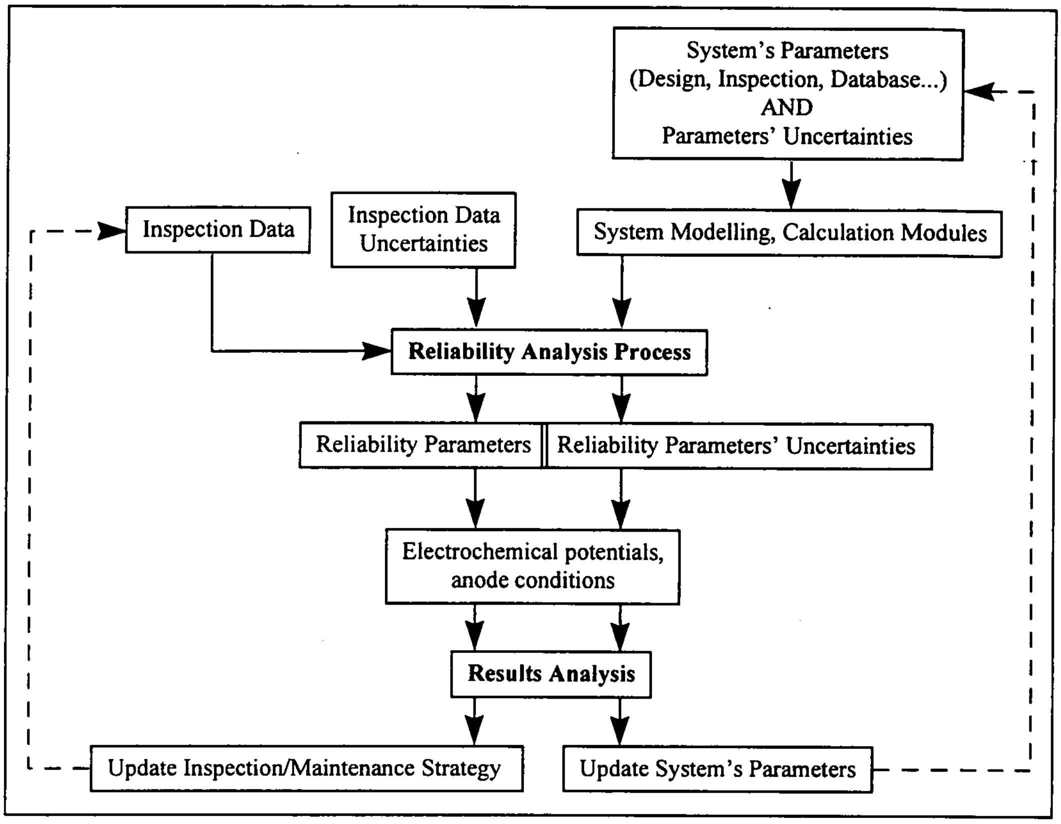

Figure 5.1: Reliability data and uncertainties.

5.1.2. Global And Localised Analysis

The inspection and modelling results can be analysed in two ways:

- **Globally**. The parameters are analysed over the whole pipeline. This provides the operator with general information about the system condition,

- **Locally**. Only a defined section of the pipeline is analysed. This provides localised information, and can help detect and analyse localised failure.

The data is used to estimate the system reliability and to provide the operator with guidance regarding the inspection and maintenance policies. The system reliability can be considered for statistical analysis and make possible clear representations of the cathodic protection system reliability changes in time.

The global analysis may in some cases not be sufficient. Local analysis needs to be carried out when anomalies in the potential values are detected along the pipeline. The results can help the operator decide on the need for further localised or global inspection, as well as on maintenance operations.

5.2. Reliability Indicators

5.2.1. Potential Checking

The value of the pipeline potential is the most significant indicator of the cathodic protection system condition. Potential values indicate whether the cathodic protection standards criteria are achieved. Figure 5-2 presents an example of the results obtained with the pipeline potential calculation module. A set of coating breakdown and coating breakdown uncertainties are defined for each period of time of the analysis, 50 periods of time for a 50 years analysis period in that case. For each set of coating breakdown, a set of potential values and potential standard deviations are calculated. Each one is the result of a single deterministic run of the pipeline potential calculation module. In order to preserve comprehensibility, Figure 5-2 presents only the pipeline potential obtained for 7 out of the 50 periods of time.

In this example, it appears that the pipeline potentials exceed the defined limit of $-0.80V_{vs.Ag/AgCl}$ (see Table 2-1) between the eleventh and thirteenth year. The important changes in the potential profile which appear between these two periods of time are due to the fact that a large number of anodes have been consumed. The analysis of this type of graph provides information about localised problems, which can be due to anode disconnection or heavy coating breakdown/disbondment on some parts of the pipeline.

The analysis of the potential distributions gives a better way to analyse the changes in time of the cathodic protection system reliability, as illustrated in Figure 5-3. This graph is obtained by analysing statistically the set of pipeline potential values obtained from the pipeline potential calculation module. A mean value and standard deviation are calculated, and the distribution curve is drew assuming a Normal distribution of the potential.

The potential distributions are used to define a general mean potential and the standard deviation of the potential distribution around the mean value. This representation gives a better insight of the general cathodic protection system condition. Similar analysis can be run locally on a set of pipeline sections.

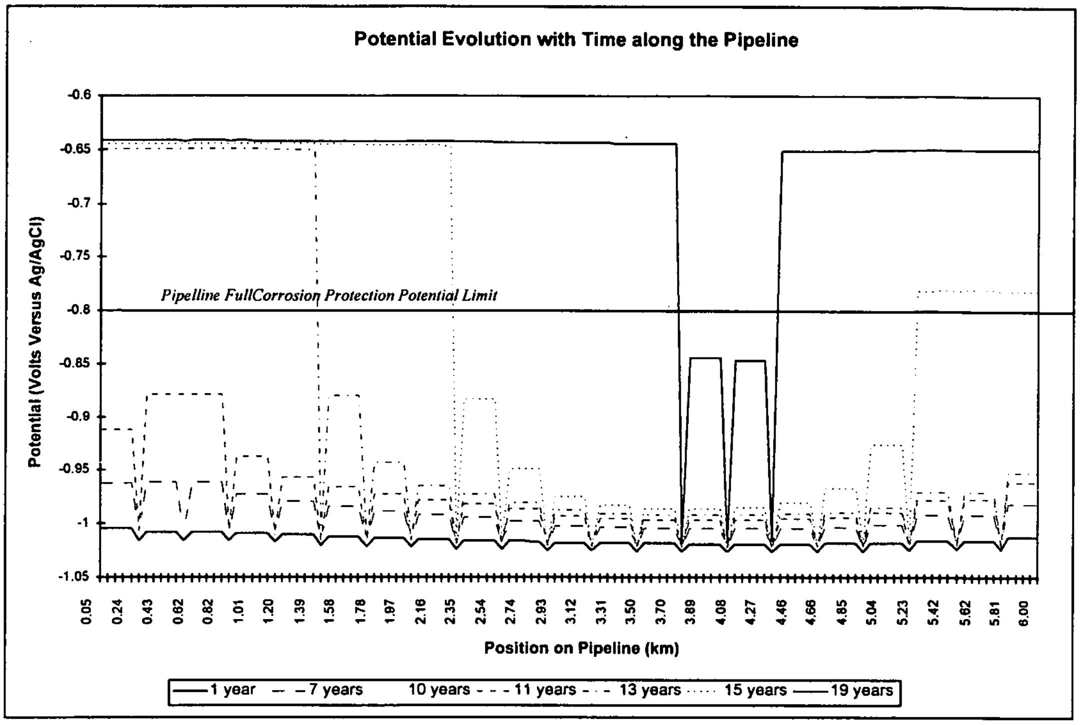

Figure 5.2: Example of pipeline potential modelling results.

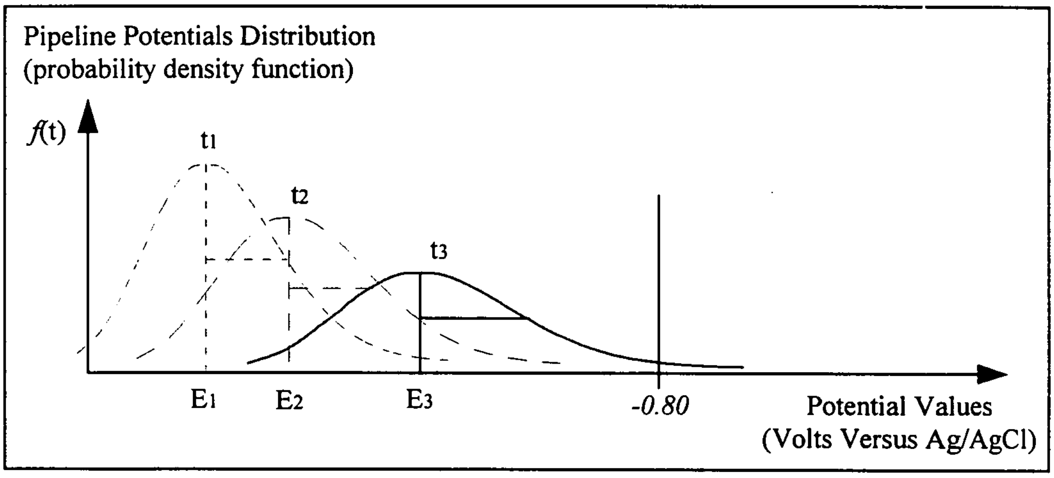

Figure 5.3: Analysis of the potential distribution changes in time.

5.2.2. Potential Uncertainties

The potential uncertainties provided by the pipeline potential model (see Appendix 9) are used to define a confidence interval for the potential value obtained for each pipeline section. Figure 5-4 presents an example of the uncertainty band obtained for one pipeline at a defined time (see more details about the case study in Chapter 8).

It is important to consider and represent this confidence interval, as uncertainty may in some cases be very high. It then reduces the confidence the operator may want to give to the model results. Such approach can also be considered for inspection results.

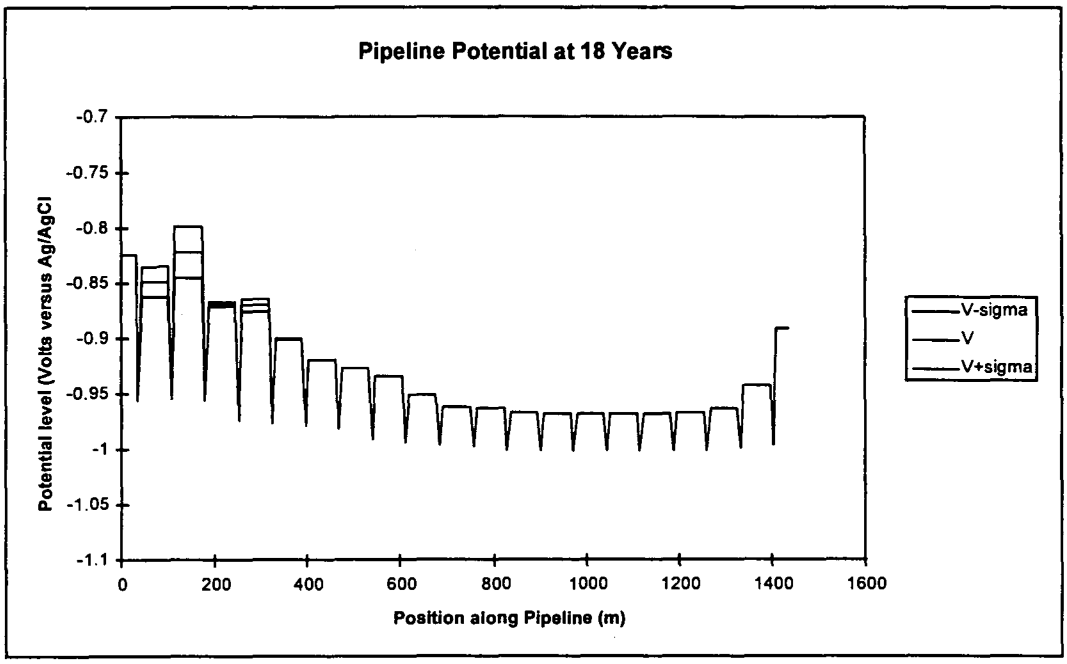

Figure 5.4: Example of confidence interval for the pipeline potentials for one period of time (18th year).

5.2.3. Anode Consumption Checking

Cathodic protection system failures tend to occur over a fairly short period of time, as illustrated by the results presented in Figure 5-2. Once one or more anodes have been consumed, the pipeline protection decreases dramatically over certain pipeline sections. In the example presented in Figure 5-2, change occurs after 10 years, when one anode (the second anode from the left end of the pipeline) appears to have been consumed.

At this point, the pipeline is still protected. However, due to interactions, adjacent anodes start to protect the segments of pipeline initially protected by the consumed anode, and their consumption rates increase greatly. These anodes in turn are consumed rapidly. Large sections of pipeline become unprotected over a relatively short period of time. Figure 5-5 shows how the maximum pipeline potential curve changes from a very slow increase up to year 19 to a very rapid increase afterward, as anodes start to become completely consumed.

Monitoring the anode conditions, and in particular measuring the anode current output, gives useful information of the system evolution before complete consumption. Unfortunately, inspection does not always provide such data, in particular when anodes are buried, or when the potential measurement is carried out at a distance from the pipeline. The potential calculation module provides an estimation of the anode consumption, which can be used for analysis. This allows the operator to detect localised problems on the line at an early stage. It also gives a good indication of the level of system degradation.

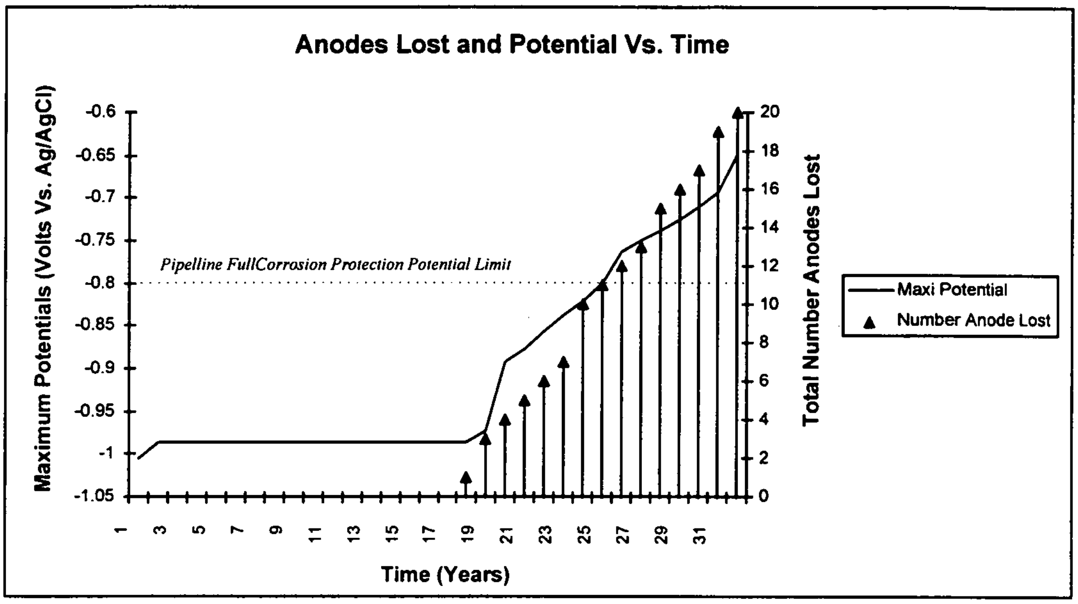

Figure 5.5: Example of anode loss and mean pipeline potentials changes in time.

5.2.4. Safety Margin and Reliability Parameters

Safety margin and reliability can be used as concise indicators of the cathodic protection system condition. These parameters provide a simple way to estimate the system reliability. The safety margin is calculated using the expression presented in Equations 3-4. This formula makes use of the pipeline potential and maximum allowable potential mean values and standard deviations. In the present analysis, it is considered that the maximum allowable potential is a single value, with a null standard deviation, as presented in Figure 5-3. From the safety margin value, the systems probability of failure can be estimated using the expression presented in Equation 3-6. Safety margin and probability of failure value ranges and equivalence are presented in Figure 5-6. The operator can check that the system remains within the defined boundaries. It is also easy to study the evolution of such parameters in time, and carry out a dynamic analysis.

The reliability tends to remain extremely close to 1[†], and thereafter decreases slowly. It then decreases very quickly when the cathodic protection system is close to failure. These changes are illustrated in Figure 5-7. Even representing the reliability changes in a logarithmic scale did not help much, as it was necessary to change the scale limits (maximum and minimum) as the reliability decreases. Safety margin was more easily represented in time, as illustrated in Figure 5-8.

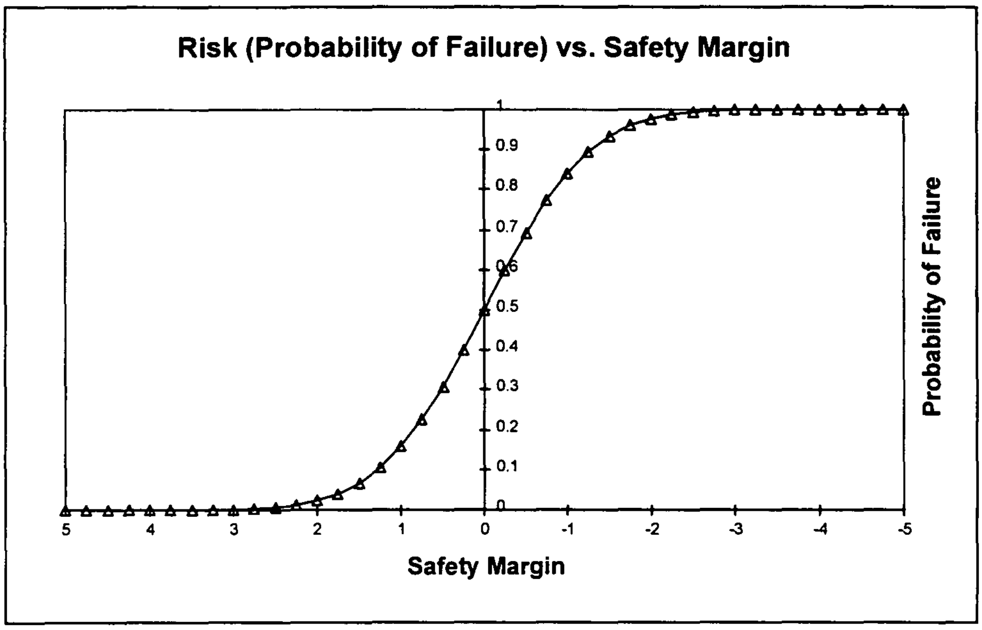

Figure 5.6: Comparison reliability level and safety margin.

[†] actually "equal" to 1 when using double precision numbers in the calculation modules, that is a precision level of 10^{-20}.

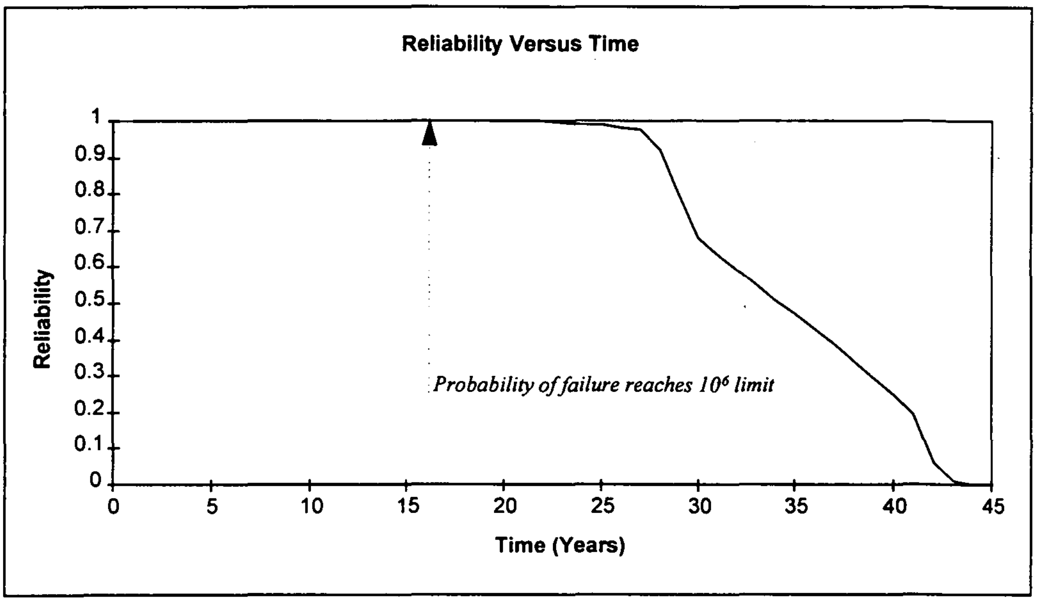

Figure 5.7: Reliability versus time.

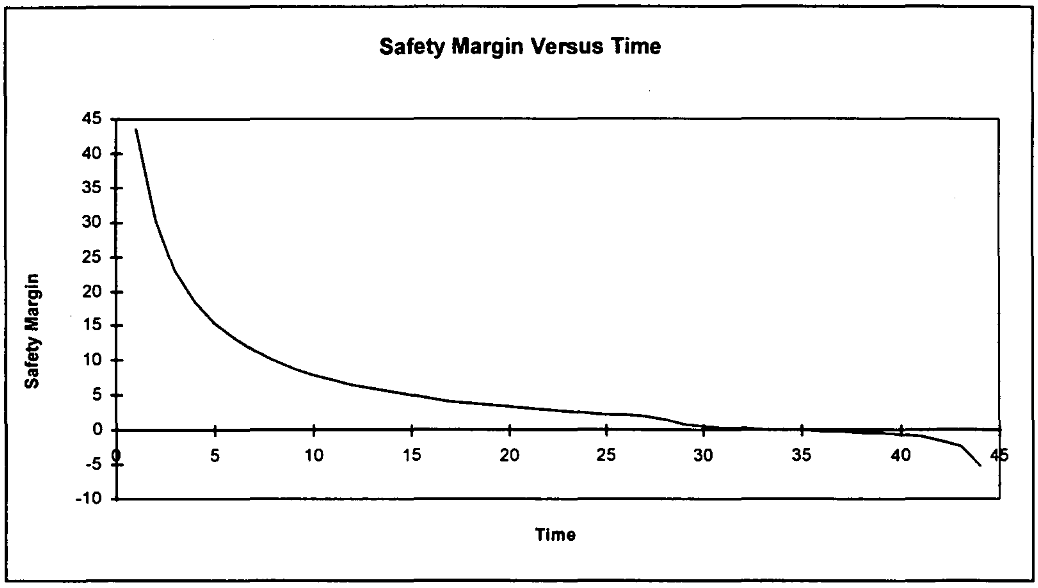

Figure 5.8: Safety margins versus time.

5.2.5. Safety Margin Derivatives

The representation of the safety margin in time can be used for presenting the safety margin and the equivalent reliability. They give a good representation of this parameter, and therefore in the system condition, changes in time. It is possible to gain insight in the system changes by analysing the safety margin versus time curve.

The first and second derivatives were calculated and presented in the general analysis result form (see Figure 5-10). These curves emphasise anomalies and proved to give interesting indications about the system changes.

5.2.6. Localised Analysis

The safety margin and probability of failure can also be calculated locally for segments of the pipeline. The analysis of these two parameters in time over pipeline segments can provide interesting results, mostly when localised problems are pointed out early enough in the system's life. Figure 5-9 presents the comparison of the analysis carried out for a whole pipeline and a section of the same pipeline. Such an analysis can help track localised anomalies in the cathodic protection system. It is necessary to keep in mind that problems linked to coating degradation and subsequently anode consumption, require an early detection or forecast (see Figure 5-5, [Congram, 94], [Coates, 95]).

In the case illustrated in Figure 5-9, the coating breakdown was considered initially to be close to zero, and thereafter constant in time. It appeared that under such conditions, the safety margin decreases first sharply from the initial period (at low level of coating breakdown) to a fairly steady state where the safety margin decreases only very slowly. This steady state is broken when anodes start to be completely consumed. In such a case, it is clear that although the overall pipeline safety margin value remains over the alert criteria, only a localised analysis would reveal localised safety margin decreases, due for example to coating mechanical damage. This local damage would be in that case hidden by the general pipeline and coating "good" condition.

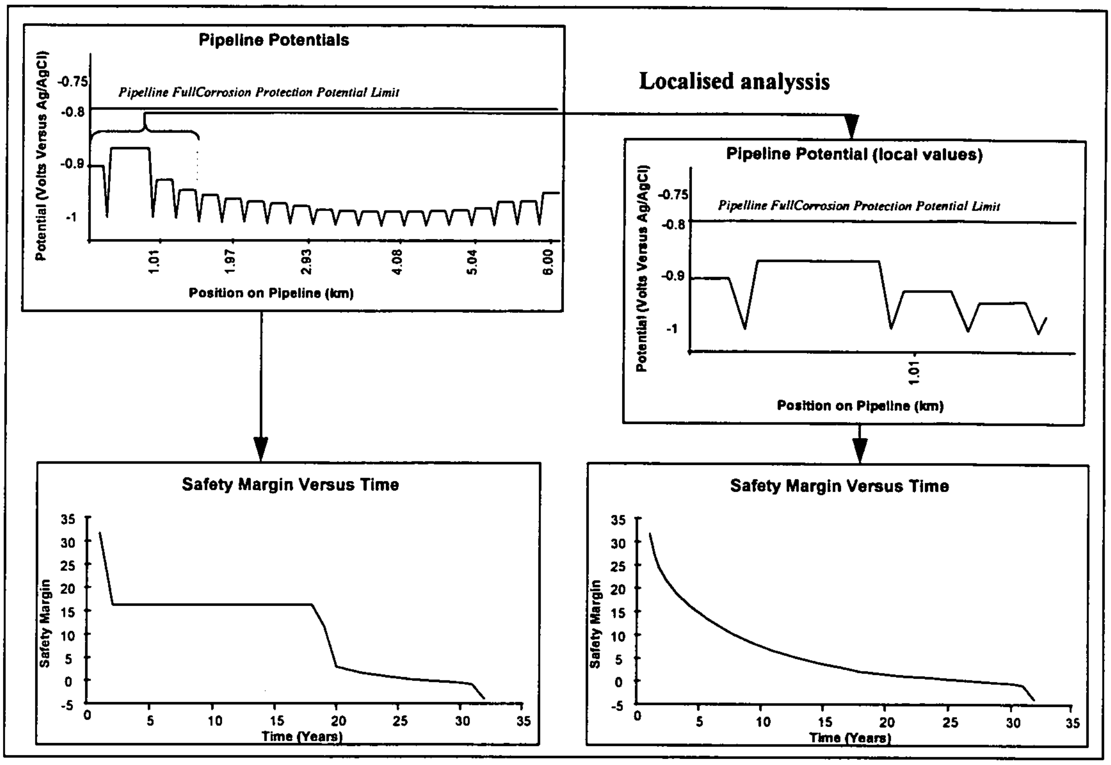

Figure 5.9: Example of localised analysis results.

5.3. Automated Reliability Analysis

5.3.1. Data Analysis Process

The reliability analysis process can be complex. It is necessary to check a large number of parameters, such as potential, current densities, anode consumption, plus uncertainties on each one of them. These data have to be analysed, graphical presentation created, and, when required, new localised analysis rerun. All this analysis requires a fair amount of data treatment.

As for the data input and management operations, computerised analysis system can help the user to carry out certain analysis. This limits the amount of work to be carried out, and reduces the risk of errors during data manipulations. In addition, the reliability analysis data can be stored in a computerised format, which allows later use and manipulation for new types of analysis.

5.3.2. Integrated Interface

The user interface developed integrate results presentation and analysis tools. The user interface developed is used to input the data, run reliability analysis and present graphically results to the user (see details in Chapter 6). An example of the output is presented in Figure 5-10[‡].

Only the main parameters are presented in this graphical output. It provides just a view of the system condition in time, and give a good insight about the cathodic protection system reliability changes in time. Most of the graphical presentation presented in this report have been built aside, using spreadsheet tools.

[‡] In the pipeline reliability analysis example presented in Figure 5-10, the system is failed after 22 years, and results after that time limit should not be considered, as in particular the potential variances which appear to decrease after that date.

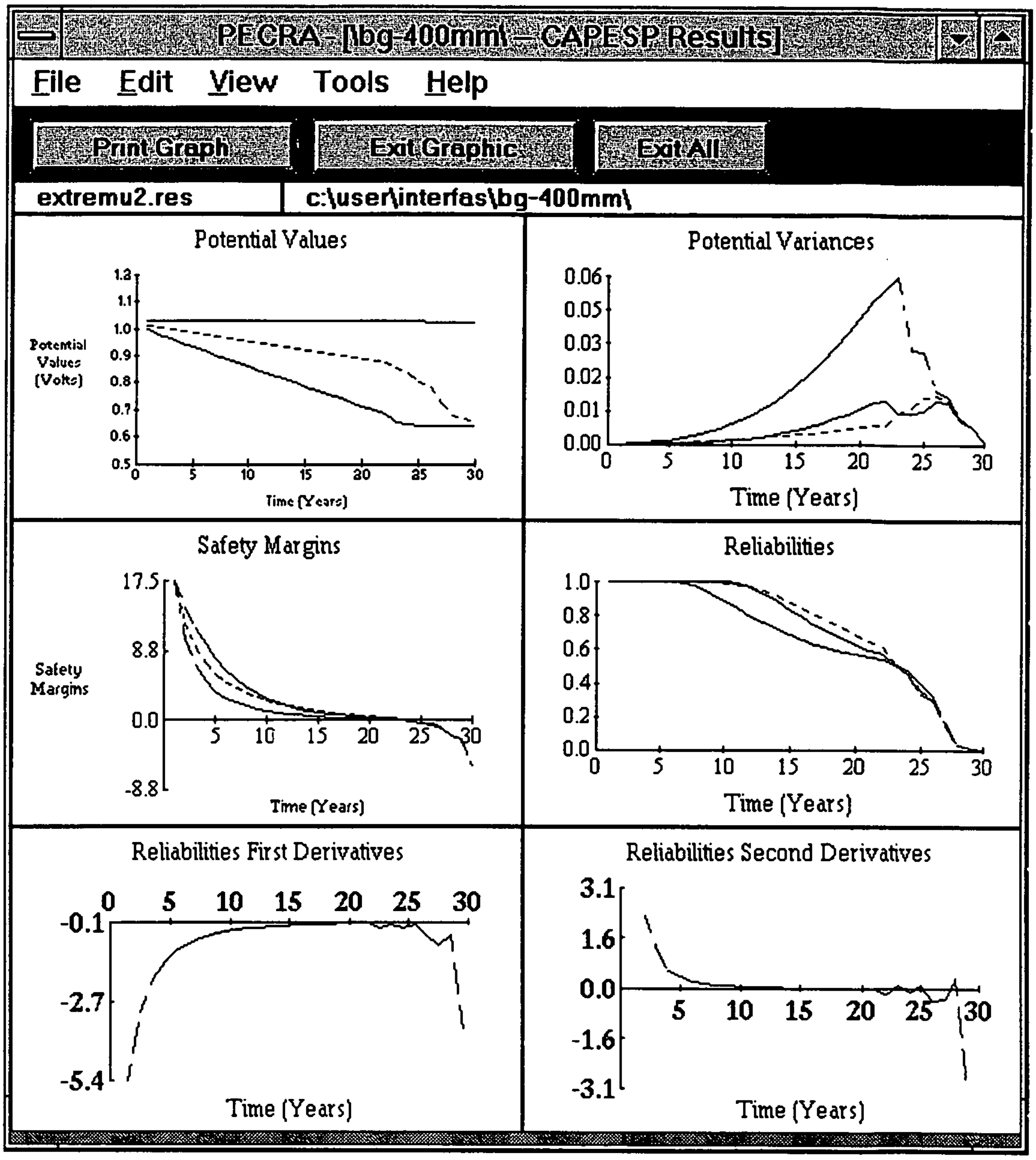

Figure 5.10: Example of analysis results as presented in the user interface.

6. Data Input and Storage

"There is gold in your data, but you can't see it", Edmund X. DeJesus

6.1. Pipeline External Corrosion Data Storage

6.1.1. Data Representation And Storage

The parameters retained for describing the system have been listed in Chapter 3. Only parameters such as pipeline length or steel grade can be described by a single value. Most of them change along the pipeline length as well as in time, and have to be stored and manipulated in the form of data arrays.

The sizes of these arrays depend on the number of sections used to model the pipeline (see Figure 3-4) and on the number of time periods defined (see Figure 4-7). Arrays used to store *location **or** time* dependant parameter values are one dimensional, when arrays defined for both *location **and** time* dependant parameters are two dimensional.

Temperature for example might vary along the pipeline. For each section, an average value is defined. The parameter values are averaged for each section.

Similarly, the level of coating breakdown is bound to change from one section to another, as well as in time. A coating breakdown value is therefore defined for each section and each period. The coating breakdown values are therefore stored into a two-dimensional array.

6.1.2. Necessity of Data Management Tool

6.1.2.1. Data Accessibility

Data accessibility is a key element for the reliability analysis. The ability to access and manipulate easily the system parameters increases the possibilities to carry out more comprehensive and complex analysis. Data accessibility proved to be a source of problem for this project. Two aspects are considered.

First of all, accessibility of the data from the *raw* information, that is gathering operators and inspections information. One of the first problems encountered during the project development, was linked to the accessibility of relevant data and to their extraction from operator files. Experience has shown that data are not always readily and easily available. Inspection results proved to be rich in information, but not presented in an accessible way. Data extraction from these reports requires important manual work, and transforms reliability analysis into a tedious process.

Second aspect is linked to the accessibility of the data once collected from the *raw* information. The parameters values have to be stored in a form which ease the input to the pipeline potential model. Again, experience showed that this process was also a source of problems. Considering the large amount of data required to describe the sections dependant and time dependant system parameters, mistakes in the generation of the file input occurred frequently. While significant mistakes resulted in obviously abnormal results, minor ones could go through, giving plausible results.

6.1.2.2. Usefulness Of A User Interface

The development of a general data management environment appeared as the best solution for solving the data accessibility problem. The reliability analysis model was therefore integrated into a general user interface which includes data input and data storage facilities.

Similar approaches have been developed by companies for inspection data ([Cowling, 90], [Darwich, 94]). The Inspect database developed by ATL Dynamic System in conjunction with BP Engineering Ltd. offers a way to store inspection data and to run analysis on them. A similar approach was used here to develop the user interface. This development proved to be an essential part of the project, and a fundamental element of the reliability analysis philosophy.

6.1.2.3. Integration Of The Analysis Tools

The advantages of an interface go beyond just data input and storage. The development of tools such as connection to database and access to calculation and analysis modules eases the analysis process. Database can be accessed to obtain information related to other pipelines as well as data regarding some of the parameters, in order to obtain for example ranges of usual values. Modules can also check automatically that various parameters have consistent values. This can prevent errors being made when parameter values are dependent. Access to graphical representation of parameters also eases input data checking processes.

Integrated analysis tools can also help saving time for the reliability analysis. When an operator wants to check the reliability of the system, he may just want to call a function that gives him the minimum and maximum electrochemical potential along the pipeline. He may also want to analyse more precisely the distribution and evolution in time of these potentials, or to carry out this analysis on a certain section of the pipeline. Such analysis would take time and efforts if carried out manually. Tools integrated into the interface can carry out such analysis in seconds. The general data organisation and analysis integration in depicted in Figure 6-1.

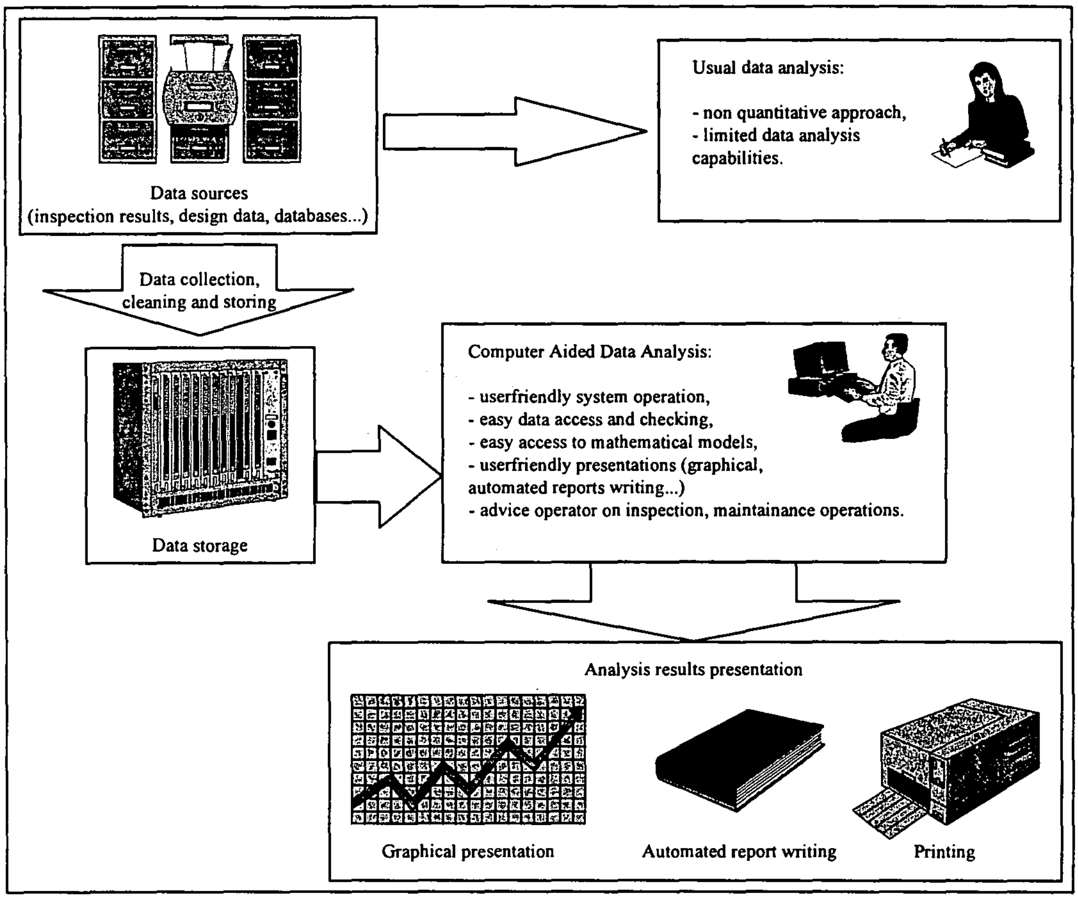

Figure 6.1: An approach to integrated data management and analysis.

6.1.3. Design Requirements

6.1.3.1. Data Entry And Storage

The general user interface has to be developed around the data management system. All the other modules have to be developed around this element. Figure 6-2 presents the bases of the general system organisation.

The data management system has to offer functionalities similar to the one of a database, allowing the user to input, check, modify and save the defined information in a user-friendly way. The data input follows a defined procedure, which depends on the data organisation described later in this chapter.

System flexibility is an important parameter. Data input may come from various sources, and inspection reports for example are never exactly presented in the same way. The way data are entered should be easily modified in order to accommodate all forms of input.

Analysis modules should also be easily integrated. They can help the user estimate parameter values when these are missing, or run automatic data checking to verify data validity. The system could check for example that the level of coating breakdown actually increases with time. It could also check data consistency when several parameters are dependent. While using the interface, the operator may also find necessary to introduce new data, generate new outputs, develop new analysis tools or modify existing ones. It is therefore necessary make sure that such modifications can be easily implemented.

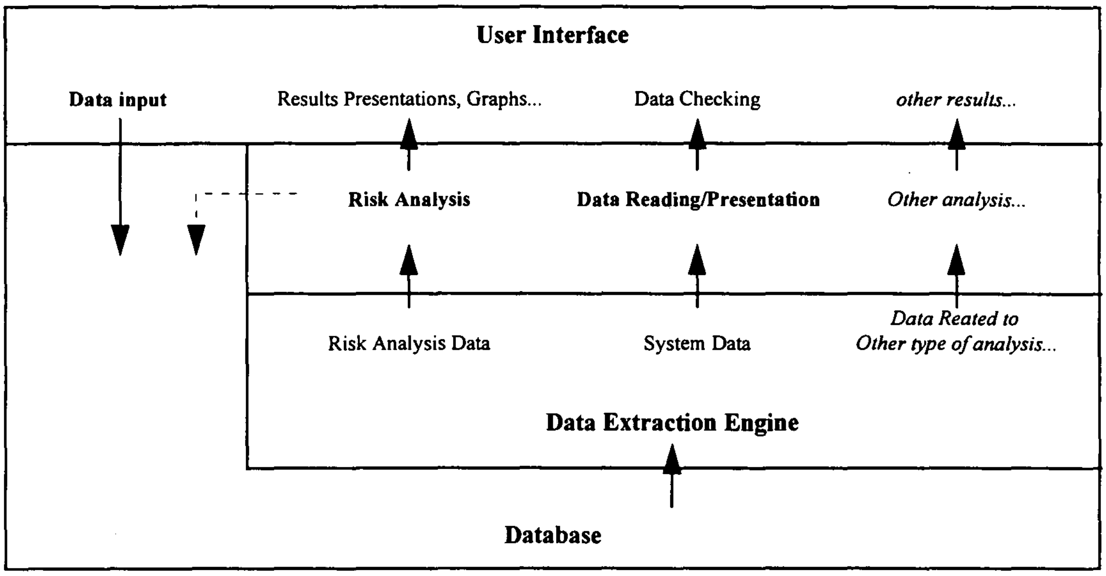

Figure 6.2: General data management organisation.

6.1.3.2. Data Storage Limitations

The size of the database is an important parameter in the development of the system. Numerous parameters are used to describe the system, and storing all the information requires a large amount of memory. While defining a different value for each pipeline section and period of time for each parameter defined (see Chapter 3) would give the maximum modelling flexibility, such an approach would increase greatly the amount of work required for entering the data. This would also increase the amount of memory required to store and manipulate the data. It is therefore essential to assess the amount of disk space required at design stage.

The approach used here consists of storing the data in one or two-dimensional arrays. These require much space, and are mainly necessary for running analysis, when parameter values need to be discretised. Optimised data storage could be achieved by using functions to describe parameter changes in time as well as along the pipeline. A set of tools can be used to extract the data required to fill the arrays used by the calculation modules, as illustrated in Figure 6-3. A lot of analysis would be required for defining these functions, and such an approach can not be considered for the present analysis.

The database developed simply integrates the data related to a pipeline in arrays. Such a system would become heavy and slow in some conditions, in particular when analysing a long pipeline over a long period of time, but proved good enough for the purpose of the project. The design would have to be reconsidered though if more parameters were to be considered as variable along the pipeline and/or in time.

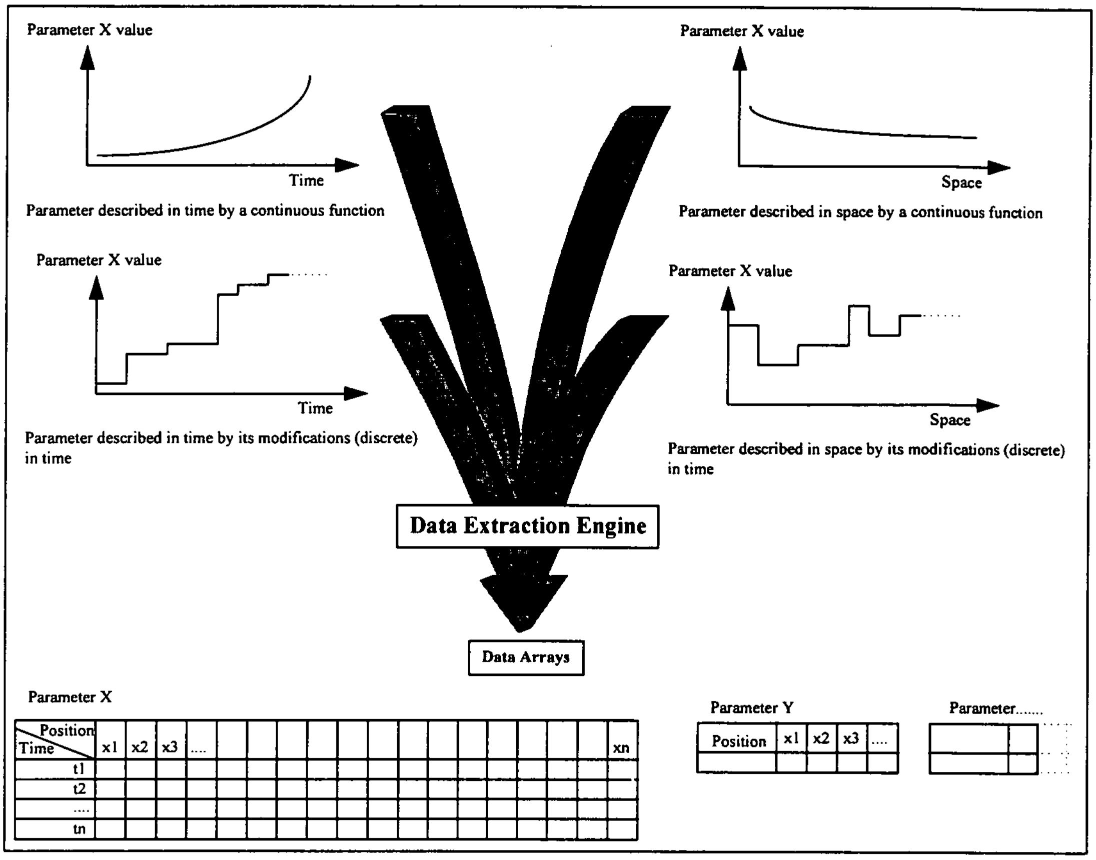

Figure 6.3: Optimisation of the data storage.

6.2. Interface Developed

6.2.1. Data Entry

6.2.1.1. Windows Interfacing

The interface development has been carried out using Microsoft Visual Basic 3.0, on a personal computer[1]. This programming language provides Windows interfaces. The data appears on windows such as the one presented in Figure 6-4. Other data entry windows and data graphical presentation windows developed are presented in Appendix 5.

Windows interfaces are user-friendly and offer great flexibility for inputting, checking and modifying the data. Interface flexibility and user-friendliness are usually function of the amount of programming put into the software development. Users actions should be anticipated as much as possible.

The main constraint set on the interface is linked to the definition of the data array sizes. The number of anodes, for example, is set early in the system definition and is used to dimension the anode data array. Once data have been entered into the array, modifications of the number of anodes reset the array dimension, and anode data have to be reinitialised or re-entered.

The data organisation had therefore to be considered attentively while developing the interface. It is necessary to define precisely in which sequence the data is to be entered. Data input forms appear in a specified sequence. The user can browse through them, backward and forward, but only in the defined order. Default values are set when the pipeline model is created. The user has to go through the various forms and to set the parameters values.

[1] Pentium 100mhz, 16 MB RAM.

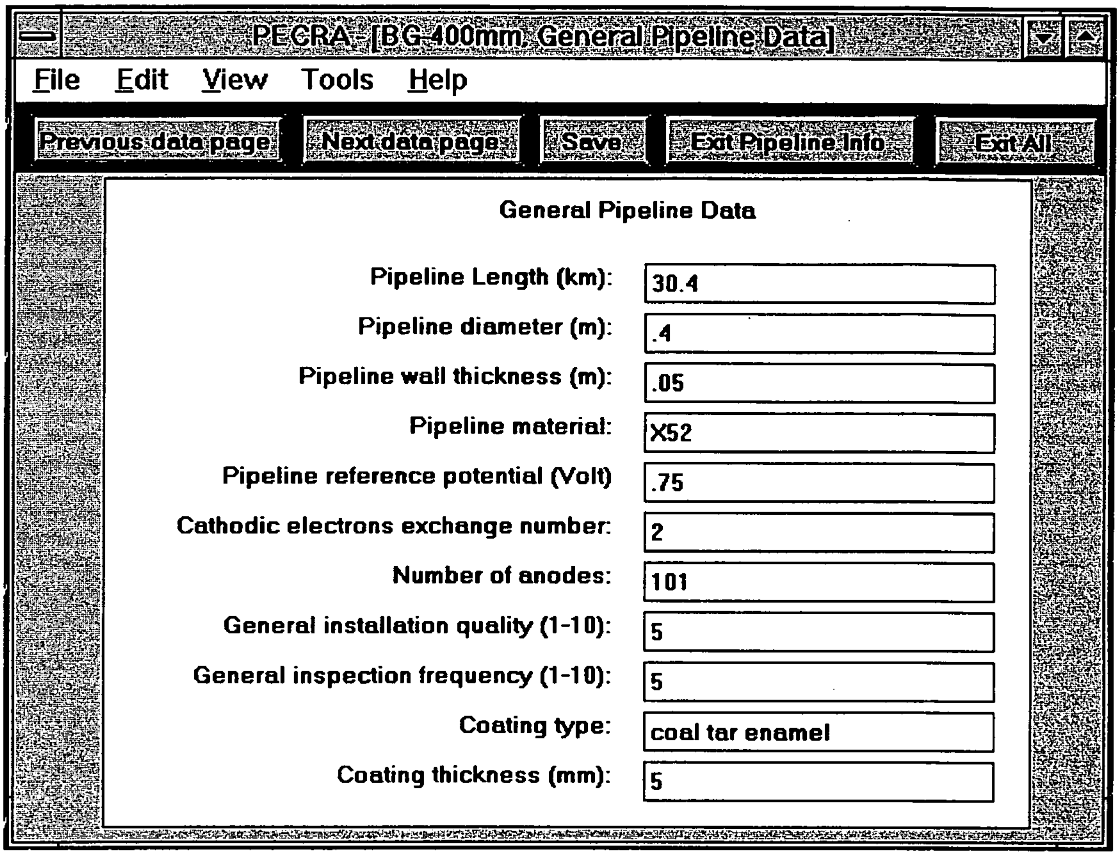

Figure 6.4: Example of user interface window.

6.2.1.2. Pipeline, Corrosion, Environment and Anodes Data

The data entered have been described earlier, and the windows developed for this data entry are presented in Appendix 5. Some parameters such as the "*general installation quality*" have no technical validity and the value entered is not actually used in the reliability analysis. These data have been defined for later use. Their interest would show when such data is available, and when a large number of pipelines are analysed the results could then be interpreted in order to qualify and quantify the effect of the parameter.

6.2.1.3. Time Dependent Parameters

The analysis time length is divided in shorter periods, defined by the user who decides on their number and lengths. A data entry window has been defined to allow the user to enter these parameters (see Appendix 5, Figure A5.5). The mean values of the coating breakdowns for each period of time are also entered at this level. This mean value is used to define the values of the coating breakdowns all along the pipeline, according to the values of other parameters such as the burial state and the activity level. The user can choose between different options for the mean coating breakdown growth function.

In order to limit the effort put in the software development, it was decided to consider that only the coating breakdown values were changing in space and in time. All the other parameters are considered as time independent. This assumption is again made in order to reduce the amount of software development and to limit the size of the storage space. For further development, more parameters might be considered as time and space dependent.

6.2.2. Graphical Presentation

Most of the data has to be entered by hand in the tables. When these tables become large, it becomes difficult to check the data. A graphical representation offers then an easy way to check the data entered. The interface developed offer the user with the possibility to plot some of the parameter values. An example of output plots was given in Figure 5-10. The other data plots available are presented in Appendix 5.

6.2.3. Data Storage

When the data have been entered, they are then saved to a file, in an ASCII format. All the data is stored in one file. The data is stored sequentially, and its organisation is defined inside the software. Here again, no optimisation has been used. When the system considered is large, the data file can easily take up to a few mega-bytes of disk space.

6.3. Interface Outputs And Analysis Tools

6.3.1. Potential Modelling Module's Interface

The modelling of the electrochemical potentials along the pipeline has been defined as an important part of the pipeline reliability analysis. A calculation module carrying out this modelling has been implemented. It will be described to a greater extent in the following chapters. This module makes use of the data stored in the interface database to carry out the calculation. Only part of this data is used in the calculation.

Due to the significant amount of calculation required for this calculation, this module has been implemented on another platform, Decstation 5000/200 under a Unix environment. The user interface extracts the required data from the database, and produces a file which is transferred to the potential modelling module. This module produces result files which are then sent to the user interface for analysis.

6.3.2. Reliability Analysis Results Presentation

The results from the pipeline potential modelling are then integrated to the interface. It carries out some analysis and generates result graphs. These graphs are presented in later chapters: they allow the operator to check the analysis results. Only part of the information is displayed: details can be obtained by checking the result data files.

6.3.3. Tools Development And Integration

The tools developed and integrated to the user interface are the base of the reliability analysis. A minimum development approach has been taken for the present analysis, again in order to investigate and demonstrate the feasibility of a totally integrated reliability analysis system. This interface is not static, and caters for a large range of changes related to the parameter definitions, the data storage as well as the calculation tools available.

Altogether, this still fairly basic system required over 25000 lines of code of Microsoft Visual Basic programming language. This is the main reason why a more sophisticated and satisfactory interface could not be developed in the context of this research.

7. Potential Modelling Tests And Results

7.1. Testing Procedure

7.1.1. Test Objectives

The main objective of these tests was to check the accuracy of the pipeline potential model. Inaccuracies may have three categories of origins: errors in the model, inadequacy of the algorithms used for solving the model and additional errors in the computer implementation. Several series of tests were carried out.

Initial tests were carried out to check the values of the potentials, current densities and anode consumption obtained. Once these results proved adequate, it was necessary to check the stability of the solving method, that is the ability of the calculation module to solve the system for any pipeline and cathodic protection system designs. The result presented in this chapter have been obtained with the final version on the model.

7.1.2. Case Study Definition

The results presented here are based on the design of a 900 millimetres trunkline run by British Gas. The general parameters of this trunkline are given in Table 7-1.

For presentation purposes, only the first 1.44 km of pipeline were modelled. The model is run for a period of fifty years, divided into fifty periods of one year.

Pipeline length	38.25 km
Pipeline diameter	900 mm
Anode diameter	1020 mm
Anode number	≈532
Anode length	0.35 m
Anode spacing	72 m
Coating	Fusion Bonded Epoxy

Table 7.1: 900 mm BG trunkline main parameters.

In the user interface, it is possible to set the mean coating breakdown increase rate to linear, exponential, S-shaped (sigmoide) or user-defined (the user defines the coating breakdown value for each period of time). For the tests presented here, the mean coating breakdown is defined as increasing linearly from 0% for the first period to 20% for the last one. These values are high enough to cause the cathodic protection system to fail completely within the fifty years.

For each individual pipeline section and period of time, the coating breakdown values are defined as a function of the pipeline mean coating breakdown and of local environmental conditions particular to the section considered. These are used as described in Appendix 8 to calculate these values. As a consequence, the coating breakdown for each individual pipeline section also increases linearly. This would change if the values of environmental parameters, such as the burial state or the activity level would also change in time. In that case, the coating breakdown increasing rate would vary in any way and independently from coating breakdown in other defined sections.

The mean coating breakdown values are distributed for each period according to the values of other parameters such as the temperature and the burial state. While the pipeline design characteristics have been copied from an existing pipeline, the environmental and operational parameters have been set arbitrarily. They reflect various conditions which may be encountered along a normal pipeline. The resulting coating breakdown values and distributions are presented for some of the fifty periods in Figures 7-1 and 7-2. As shown on these graphs, the coating breakdown levels increase much faster on the section of pipeline comprised between 100 and 400 meters. This can be explained by the combined effects of the following parameters:

- The level of activity. It is set to its maximum at this level, due to the proximity of the platform. The risk of coating damages due to dropped or dragged objects is therefore very high.

- The burial state. The pipeline is considered unburied over these sections, which increase the risk of coating damage.

- The temperature, which is considered still fairly high at this level.

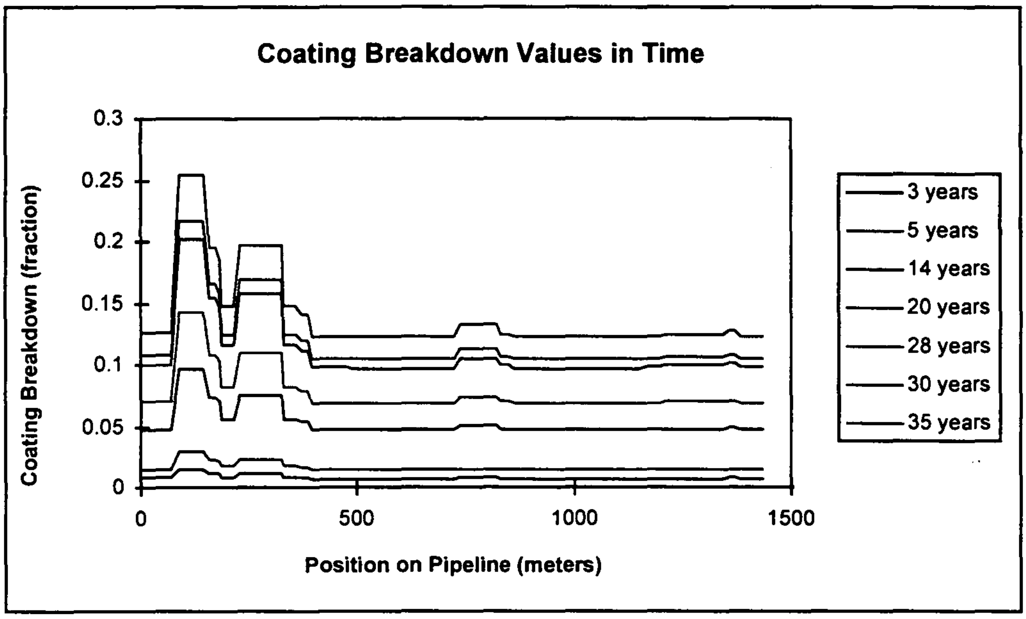

Figure 7-1: Evolution of the coating breakdown most likely values.

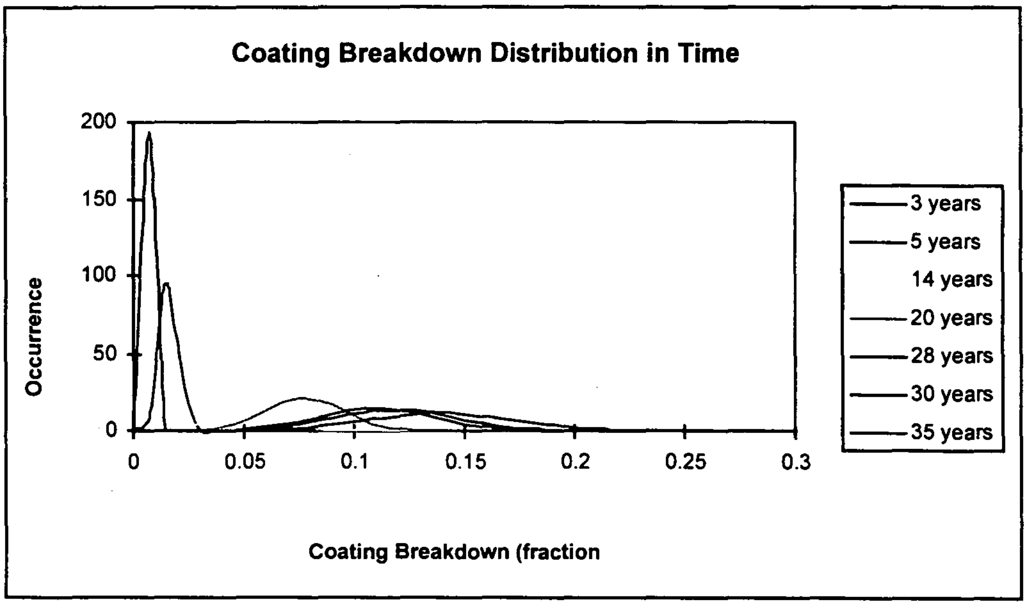

Figure 7-2: Level of distributed coating breakdown along the pipeline.

7.2. Case Study Results

7.2.1. Potential Level

The results of the pipeline potential calculations are presented in Figure 7-3. The maximum potential values come from the pipeline sections with the lower protection, and the minimum values from the anodes. In normal conditions, the anodes do not polarise, and remains at a low potential, close to their reference potential. The difference between the maximum and minimum potential therefore increases. The details on the 400 first meters of the pipeline show how the pipeline potential increases when an anode becomes consumed (see Figure 7-4). A similar effect would appear if the anode became disconnected or polarised.

If we consider the mean, minimum and maximum potentials (Figure 7-5), it appears clearly that the $-0.8V_{vsAg/AgCl}$ potential limit is passed after about 27 years. The pipeline is therefore not protected after that time. This graph also shows how the potentials drop dramatically after the cathodic protection system started to present signs of weakness.

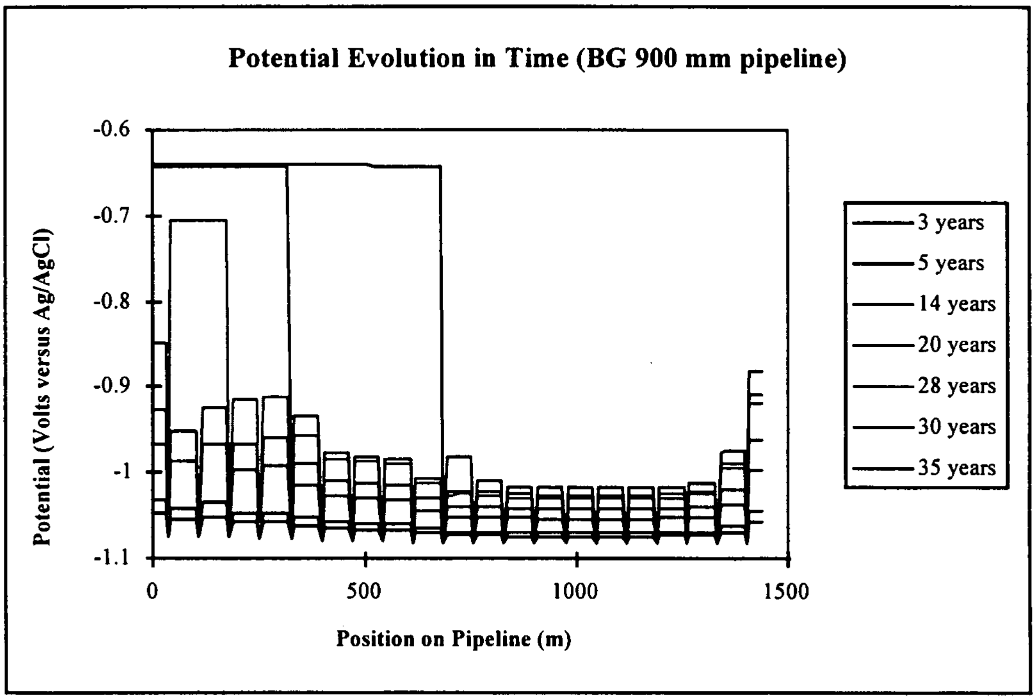

Figure 7-3: Result of the pipeline potentials modelling over the length of the pipeline.

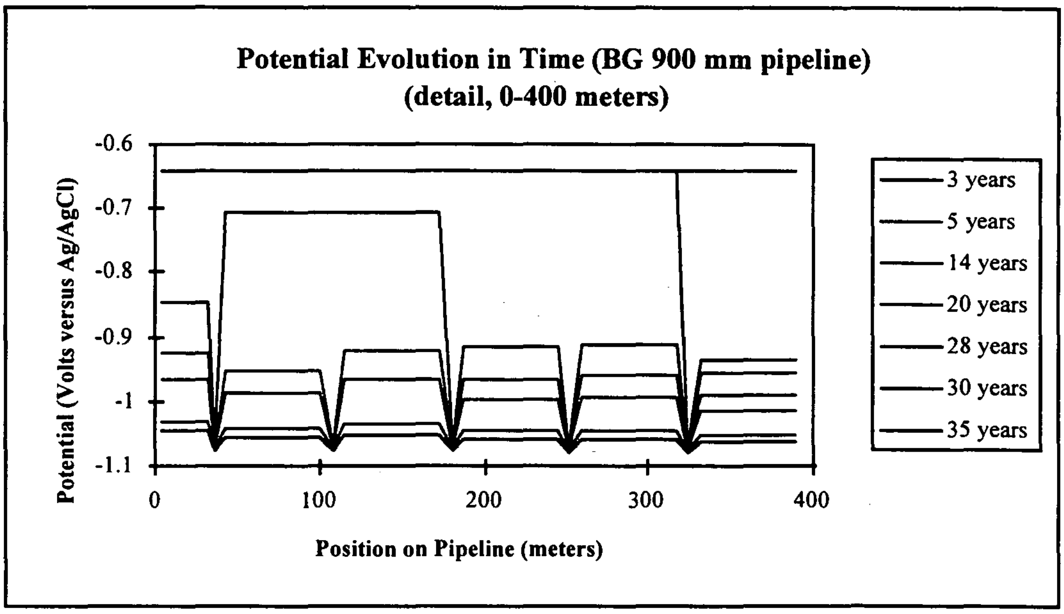

Figure 7-4: Details of the potentials around the zone with high level of coating breakdown.

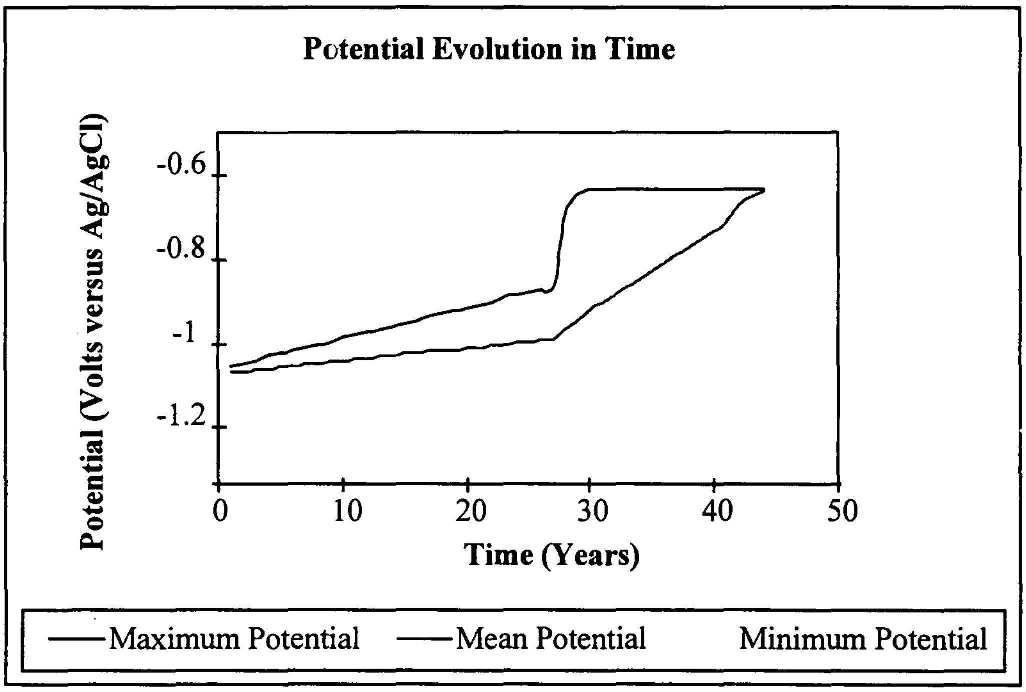

Figure 7-5: Evolution of the potential level in the case of distributed coating breakdown (minimum, mean and maximum values for each period).

7.2.2. Potential Values And Level Of Coating Breakdown

7.2.2.1. Design And Actual Coating Breakdown

While running initial pipeline potential tests, it appeared that the coating breakdown values provided by standard such as [DNV, 93] for designing cathodic protection systems are extremely high. They are recognised as conservative by the offshore industry. When using these values to test the model on existing pipeline cathodic protection systems, the expected lifetime obtained was in an order of 2 or 3 lower than the actual design lifetime.

In order to obtain reliability analysis results comparable with actual cathodic protection systems behaviour, it was necessary in the first place to estimate which were the most probable coating breakdowns ranges.

7.2.2.2. Inspection Results Analysis

In order to do so, the model was used to analyse some pipeline inspection results provided by operators. These pipeline and cathodic protection system characteristics were entered into the model, and tests carried out using several sets of coating breakdown values. The coating breakdown values were considered as realistic and probable when the potential values obtained in the model were comparable to the potential values read during inspection.

Figure 7-6 presents the potential reading on a 8 years old pipeline, and is extracted from an inspection report. This pipeline and cathodic protection system has the same characteristics as the pipeline used in the tests presented in this chapter (see Table 7-1). It appears from this plot that the pipeline potential value lays between -1.08 $V_{vsAg/AgCl}$ and -1.06 $V_{vsAg/AgCl}$.

If we consider a mean potential level of -1.07 $V_{vsAg/AgCl}$, and compare this value to the values obtained by modelling the same pipeline (see Figure 7-4), it appears that this level of potential is close to the values obtained for the 3rd year. At that time, the level of mean coating breakdown is comprise between 1 and 2%, that is well under the values specified in standards.

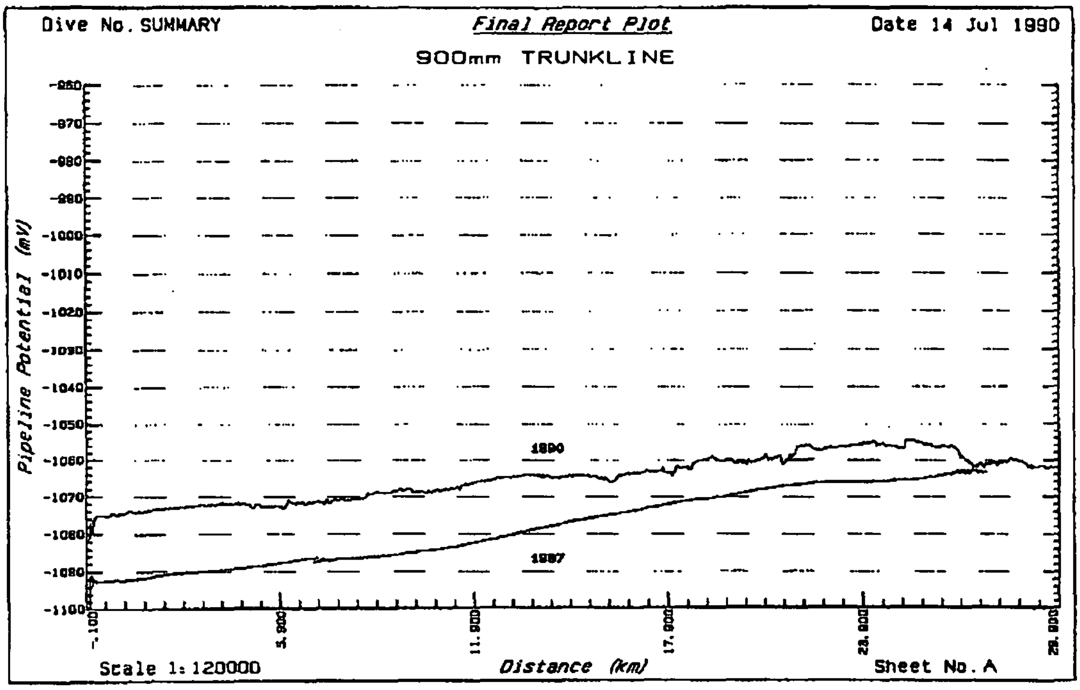

Figure 7.6: Example of potential values obtained during inspection.

7.2.2.3. Results Analysis

Due to the lack of precise and comprehensive pipeline and coating information, it was not possible to validate these results. Nevertheless, they appear to be corroborated by some inspection analysis such as the one presented by Torgard ([Torgard, 89]).

In that case, the pipeline cathodic protection system was designed for an initial 20 years lifetime. At the end of this design lifetime, a comprehensive inspection carried out shown that the cathodic protection system lifetime could be extended by at least another 35 years, giving the pipeline a safe life of about 3 times its initial design lifetime. Considering the fact that this pipeline cathodic protection system design was based on an estimated coating breakdown of 10%, it is obvious that this value is conservative.

Actual coating breakdown values are probably much lower, and closer to the value obtained in this analysis. Torgard also writes that a 2% coating breakdown is commonly accepted as a rule of thumb for cathodic protection systems. These facts appear to sustain the validity of the pipeline potential model.

The coating breakdown values used in the pipeline reliability model were revised according to these results.

7.2.3. Current Values

The current values of the pipeline sections obtained from the calculation module for different times are presented in Figure 7-7 for the cathodic (pipeline) sections and in Figure 7-8 for the anodes. Again, the tendency follows the level of the coating breakdowns along the pipeline. These values are mainly used to check the current balance between the anodes and the pipeline cathodic sections and to calculate the values of anode consumption.

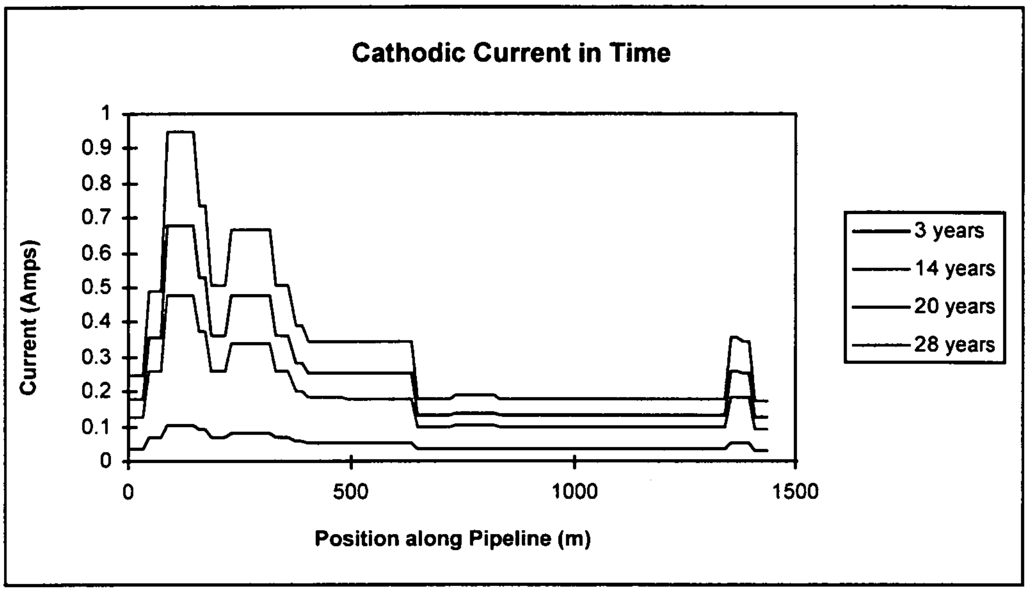

Figure 7.7: Cathodic current demand evolution in time.

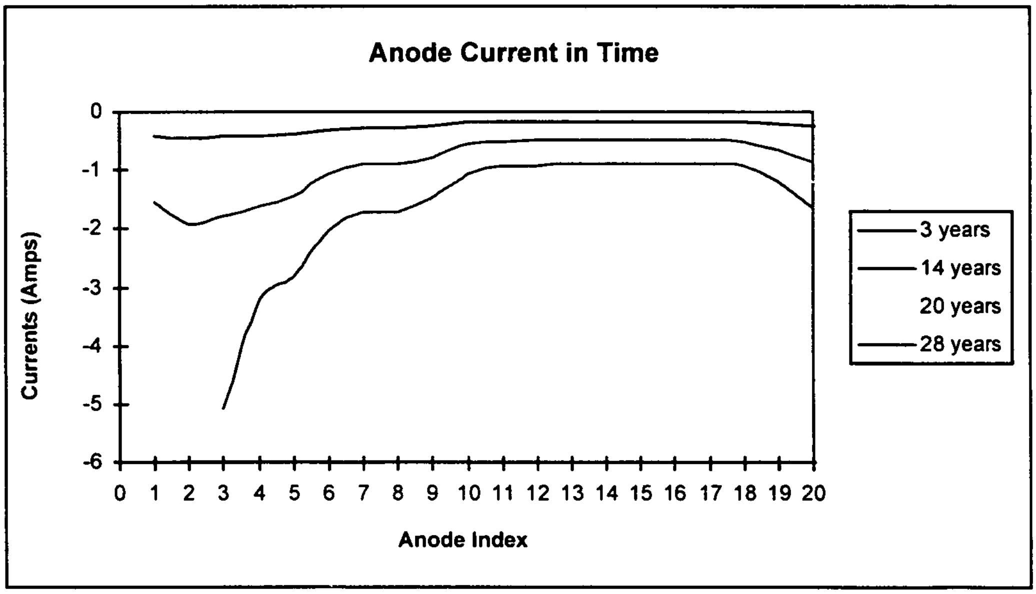

Figure 7.8: Anode current output.

7.2.4. Anode Consumption

The anode consumption is calculated for each period of time, and the anode weights are updated. When an anode is completely consumed, it is removed from the pipeline, that is the anodic section is transformed into a cathodic section in the model. A list of the anodes removed is produced as an output file which can be analysed. Figures 7-9 and 7-10 present respectively the evolution of the anode weights and number. It appears again that anodes are consumed quicker over the first 400 meters of the pipeline, where the coating breakdown is higher. This also explains why this part of the pipeline becomes unprotected earlier (see Figure 7-3).

Usually, the pipeline tends to become unprotected locally when a few adjacent anodes have been consumed. This depends on the cathodic protection system design. If the design is conservative, typically using 0.35 meter anodes every 50 meters on a 400mm diameter pipeline, the system may remain protected even after several adjacent anodes have been consumed.

In all cases, once one anode has been consumed, the consumption of adjacent anodes tends to increase. Eventually, the distance between two adjacent anodes will be too high, and sections of the pipeline become unprotected.

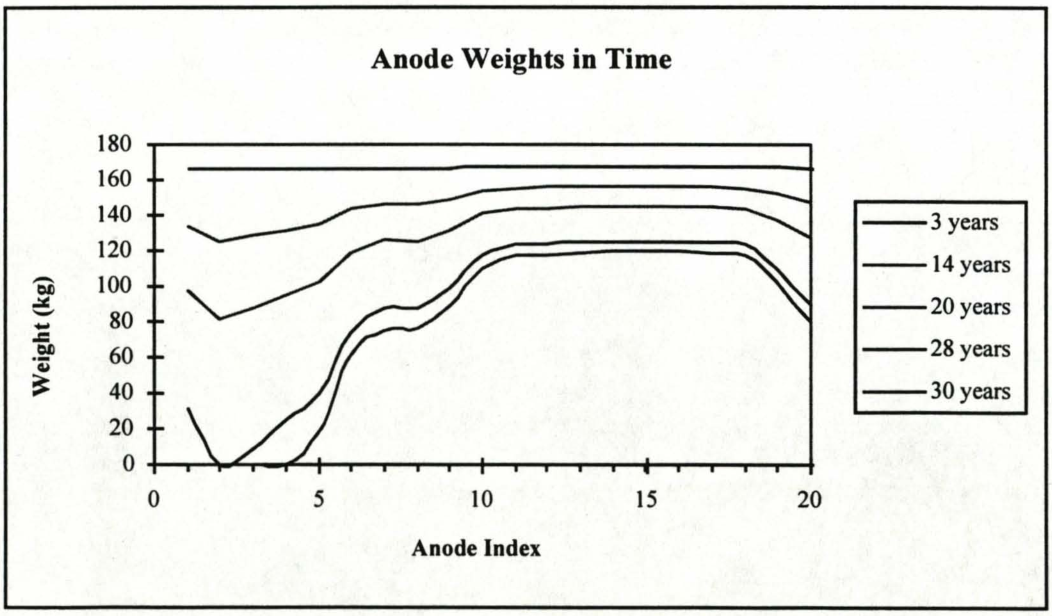

Figure 7.9: Anode weight evolution.

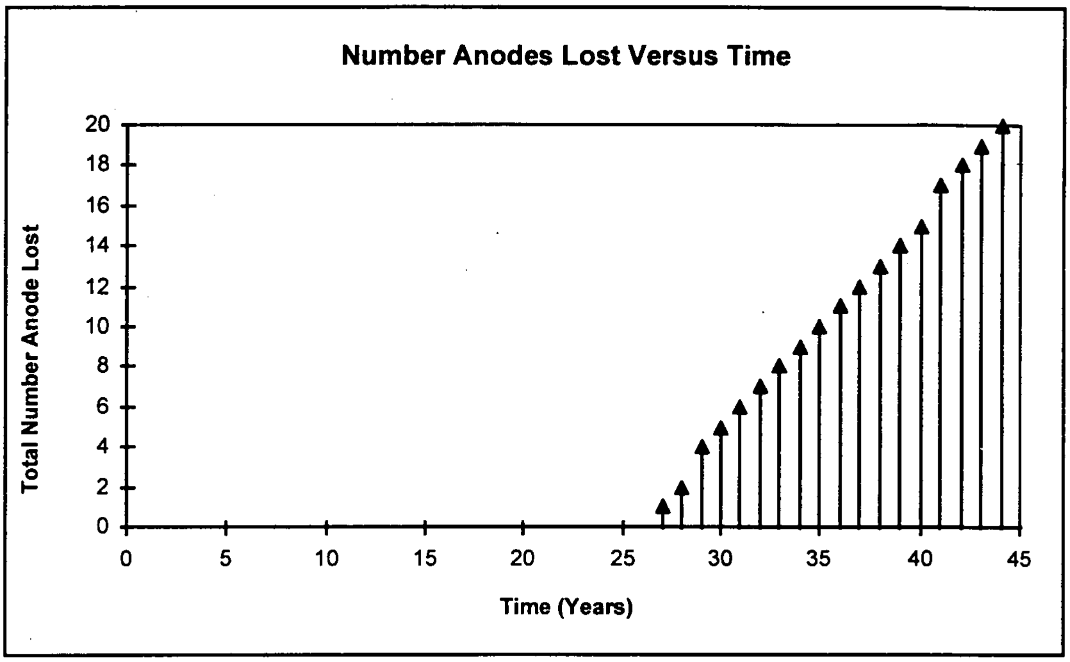

Figure 7-10: Evolution of the anode weight and number.

7.3. Analysis Of Results

7.3.1. Potential Distributions

The potential distribution obtained for some of the time periods are presented in Figure 7-11. The form of the distributions are those expected of the coating breakdown distributions (see Figure 7-2). Over the lifetime of the pipeline, the potentials become closer to the maximum limit, and the standard deviation of the distribution increases.

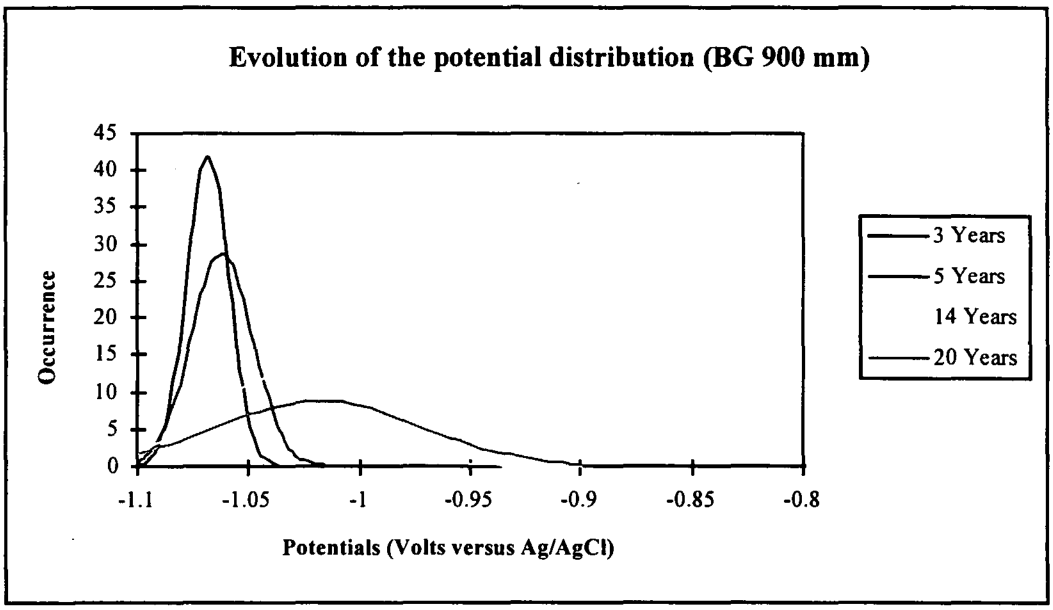

Figure 7-11: Evolution of the potential distributions.

7.3.2. Potential Variances

Figure 7-12 presents the values obtained for the potential variances. They increase while the general uncertainty on the cathodic protection system increases. They then start to decrease as the anodes are consumed, and the system potential reduces to the pipeline reference potential. The anomaly is due to the consumption of the some anodes, which induces a sharp change in the system balance. The values of these variances can be used in the risk analysis to define an interval of confidence for the pipeline potential obtained.

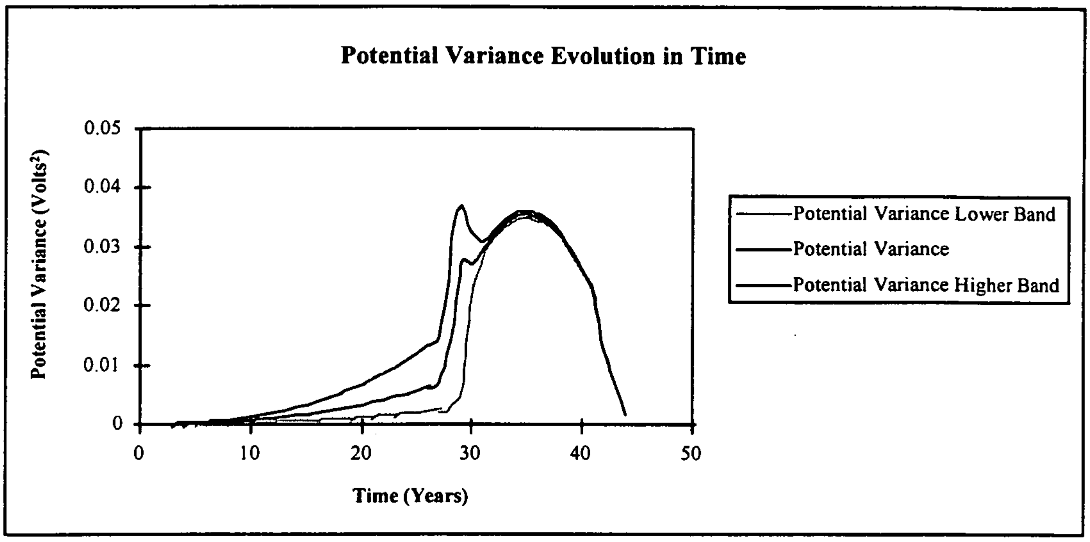

Figure 7.12: Potential variance evolution in time.

7.3.3. Anode Polarisation Curve

The anode polarisation curves were plotted and compared to the theoretical polarisation curve obtained with Equation 2-4. This equation is used in the potential calculation to model the anodic nodes behaviour. The results are presented in Figure 7-13. It appeared from the tests that empirical and theoretical curves have similar characteristics. The empirical curves tend to be shifted from the theoretical curve.

This difference appeared to be linked to the convergence criteria chosen for the system resolution. Reducing the convergence criteria increases the precision of the results obtained, but also increases the time required to reach convergence. In some cases, the calculation module may not converge at all if the level of precision required is too high. A compromise had therefore to be done, and results appeared to be adequate for the purpose with the precision level chosen.

Other tests were run in order to check the effect the temperature on the anodic polarisation curve. Figure 7-14 presents the results obtained on the same pipeline design, but when anodes are set to different temperatures. The polarisation curves evolve again as expected. The anode efficiency decreases as the temperature increases.

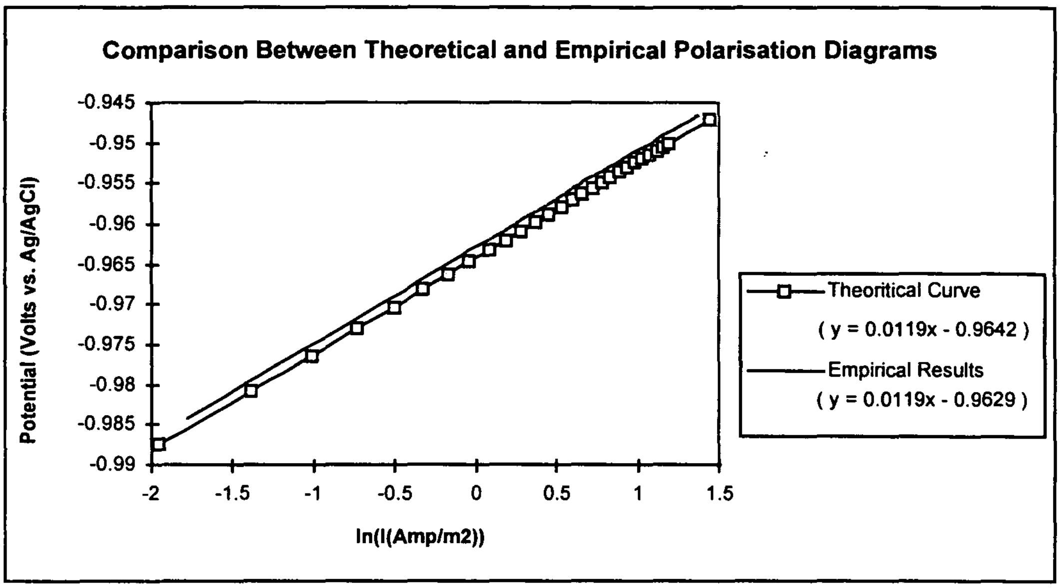

Figure 7-13: Comparison between the calculation output and the theoretical polarisation curve.

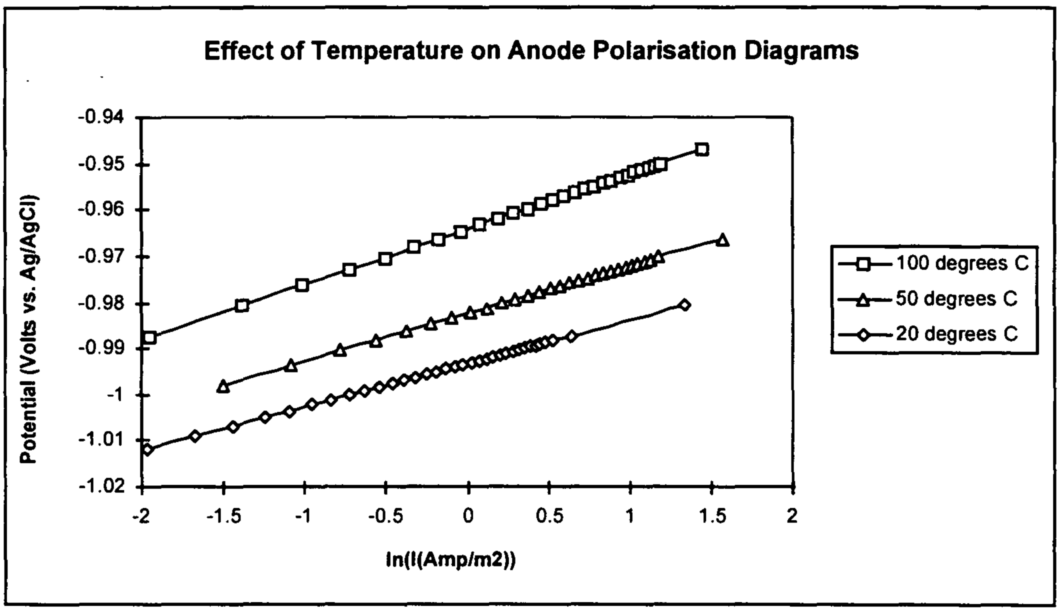

Figure 7-14: Effect of temperature on the anodic polarisation curve.

7.3.4. Conclusion About The Pipeline Potential Model

The calculation modules proved to cope with any pipeline and cathodic protection designs, for any number of periods of time, and for any number of pipeline sections. The modules solve the system of equations in all conditions. Limitations appeared though when long pipeline were modelled and a large number of sections defined. The time required for solving the system of equations then increase, and several hours of calculations may be needed to obtain results. This should not be regarded as a major problem though as the software, initially developed for DecStations, can be recompiled for more modern workstations (such as Alpha-Stations) presently available.

The values obtained for the potentials, current densities and anode consumption during the tests appeared to be similar to values presented in the inspection reports. The model also appeared to behave in accordance with expectations when environmental and operational conditions are modified.

Further tests would be required to fully validate the potential model itself and make sure the level of precision obtained on the results is good enough under any conditions. This could be the object of a separate project (see further development section). For the purpose of this project, that is reliability analysis, the model developed proved to give adequate results.

8. Reliability Analysis Results

8.1. Test Procedure

8.1.1. Tests Objectives

The reliability prediction is based on the results obtained in the pipeline potential model, such as the one presented in Chapter 7. Several indicators have been defined to analyse the cathodic protection system reliability and its changes in time (see Chapter 5).

To analyse the behaviour of these reliability criteria, tests were carried out using different pipeline and cathodic protection system designs, under various environmental and operational conditions. For each case study, the pipeline potential was modelled for a defined period of time, reliability analysis parameters were calculated and related graphs plotted.

These tests also illustrate the complexity of the analysis process. The calculations require a fair amount of data processing and analysis. Although the most important part of the analysis has been automated and integrated to the user interface, further details and graphs had to be build independently.

8.1.2. Definition Of The Case Studies

The tests presented in this chapter are based on two pipeline cathodic protection system designs. These are typical designs, and are representative of the results obtained on various types of pipelines. The two cathodic protection systems main characteristics are described in Table 8-1. They were modelled under various conditions over a period of fifty years.

8. Reliability Analysis Results

8.1. Test Procedure

8.1.1. Tests Objectives

The reliability prediction is based on the results obtained in the pipeline potential model, such as the one presented in Chapter 7. Several indicators have been defined to analyse the cathodic protection system reliability and its changes in time (see Chapter 5).

To analyse the behaviour of these reliability criteria, tests were carried out using different pipeline and cathodic protection system designs, under various environmental and operational conditions. For each case study, the pipeline potential was modelled for a defined period of time, reliability analysis parameters were calculated and related graphs plotted.

These tests also illustrate the complexity of the analysis process. The calculations require a fair amount of data processing and analysis. Although the most important part of the analysis has been automated and integrated to the user interface, further details and graphs had to be build independently.

8.1.2. Definition Of The Case Studies

The tests presented in this chapter are based on two pipeline cathodic protection system designs. These are typical designs, and are representative of the results obtained on various types of pipelines. The two cathodic protection systems main characteristics are described in Table 8-1. They were modelled under various conditions over a period of fifty years.

	A400	A900
Commissioning	1974	1982
Pipeline length	30.4 km	38.25 km
Pipeline diameter	400 mm	900 mm
Anode diameter	520 mm	1020 mm
Anode length	0.3 m	0.35 m
Anode number	≈102	≈532
Anode spacing	300 m	72 m
Anode type	bracelets	bracelets
Coating type	fusion bonded epoxy	coal tar enamel
Remarks	- designed for short term use. - pipeline is decommissioned. - a few anodes were added in order to compensate loss of corrosion protection coating.	- designed for long term use. - still in use at current date.

Table 8.1: A900 and A400 pipelines main parameters.

8.2. Reliability Analysis Indicators

8.2.1. Potentials And Potential Variances

These results are based on the pipeline A900 design presented earlier. The results obtained for this pipeline with the potential model have been presented in Chapter 7. An analysis of the potential changes shows that the $-0.8V_{vs.Ag/AgCl}$ potential limit is passed after twenty seven years (see Figure 7-5). This value is obtained if we consider the mean potential values. If taking into account the potential variance calculated (see Figure 7-12), it appears then that the potential confidence interval goes over the maximum potential limit. Figure 5-4 presented the pipeline potential confidence interval obtained at eighteen years for the pipeline A. The detail of that graph presented in Figure 8-1, shows clearly that the maximum of the level of confidence reaches the $-0.8V_{vsAg/AgCl}$ potential limit at that time.

It is difficult to appreciate the incidence of the confidence interval in terms of probability of failure. The width of the confidence interval depends on the values defined for the coating breakdown uncertainties, and therefore can not presently be clearly defined. In the present case, the coating breakdown uncertainties were set to up to 100% for some of the pipeline sections, that is a standard deviation of 6% of coating breakdown at eighteen years. Such a value is not unrealistic, and gives a high probability of failure after 18 years. This value differs greatly from the 27 years obtained by direct observation of the potential level. The difference depends mainly on the knowledge of the level of coating breakdown.

It also depends on the level of confidence used for defining the potential values band. A plus-minus one and two standard deviation band ($\pm\sigma$ and $\pm 2\sigma$) give respectively a 68% and 95% confidence on the potential value.

This type of analysis could also be used for inspection data, where uncertainties on the potential values can be modelled similarly. Inspection reports usually miss out such analysis, usually because of the lack of knowledge of the inspection data precision.

The result obtained mainly provide a way to represent and identify areas subject to higher risk of failure.

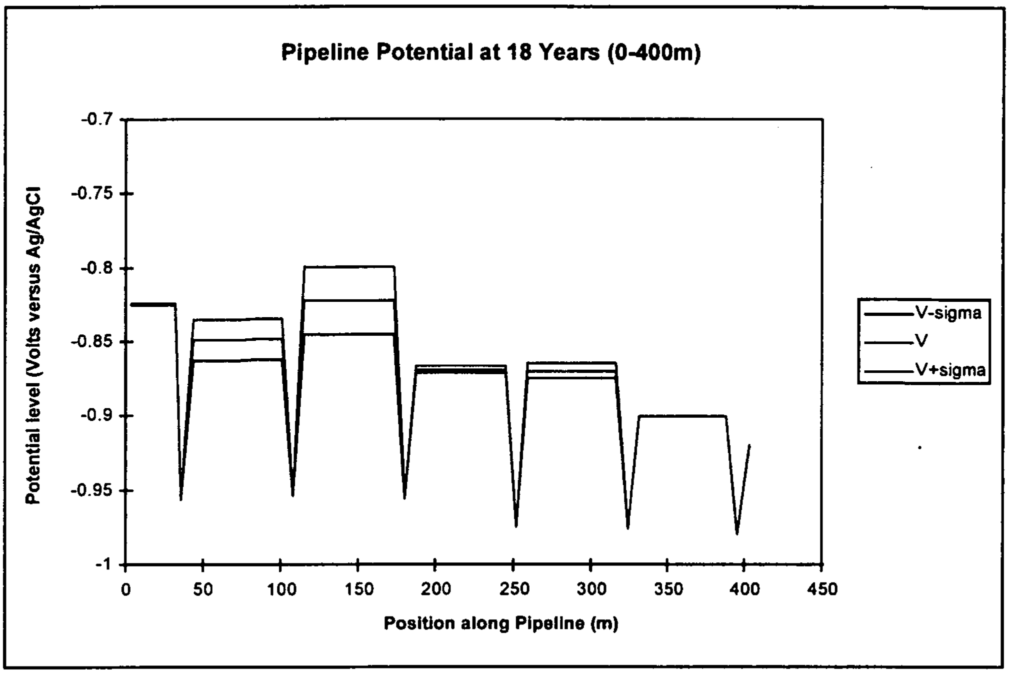

Figure 8.1: Example of confidence interval for the pipeline potentials, between 0 and 400 meters.

8.2.2. Safety Margin and Reliability Results

Safety margin, reliability and probability of failure are calculated for each period of time, using the formula presented in Equations 3-4 and 3-6. The results obtained are presented in Figures 5-8 and 5-7. As seen on these two graphs, the cathodic protection system reliability drops drastically just after 22 years. By plotting the probability of failure on a logarithm scale, it appears that for a maximum risk value of 10^{-6} (the levels of risk have been presented Figure 3-3), the safe life is reached between 16 and 17 years (Figure 8-2).

This safe life depends essentially on the level of risk acceptance, that is the limit defined for the maximum risk level. Such value would be defined either by standard or operators. In the perspective of the present analysis, it is used as a relative reference.

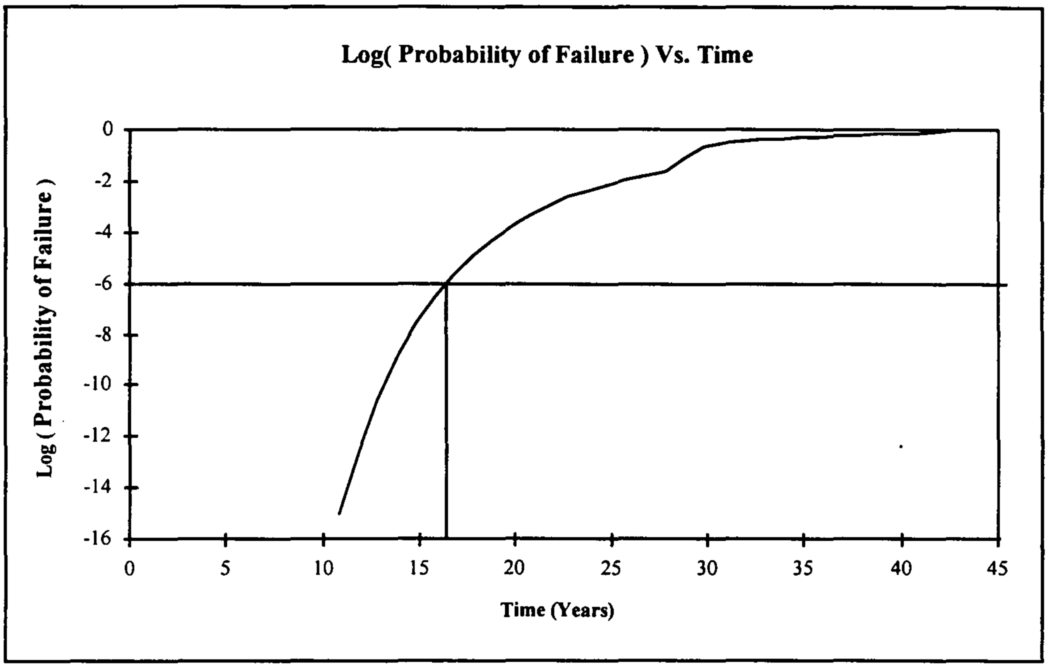

Figure 8.2: Probability of failure (logarithm scale) versus time.

8.2.3. Safety Margin Derivatives

The safety margin first and second derivatives are used to emphasise anomalies in the cathodic protection system changes. Figures 8-3 and 8-4 present the values obtained for the present case study. Three anomalies appear on the graphs, around 14, 18 and 25 years. These anomalies characterise a change in the safety margin curves. The first derivative curve presents a negative peak, while the second derivative curve oscillates.

While the 25th year anomaly is linked to the drop of potential which occurs around that time, and is linked to the loss of the first anode (see Figure 7-5), the 14th and 18th year anomalies are not linked to any obvious change in the cathodic protection system. They are caused by changes in the safety margin decreasing rate changes at these times (see Figure 5-8). Passed certain levels of coating breakdown, the effect of the cathodic protection system on the pipeline potential changes. The anodes can not protect the pipeline as efficiently, which creates the changes in the safety margin curve.

In the context of the reliability analysis and prediction, anomalies in the safety margin derivatives do not indicate that the cathodic protection system is actually failing, but rather that the cathodic protection system condition is changing. When these anomalies appear, more attention is to be given to other reliability parameters and to the general cathodic protection system condition, to check that the minimum level of safety required is ensured.

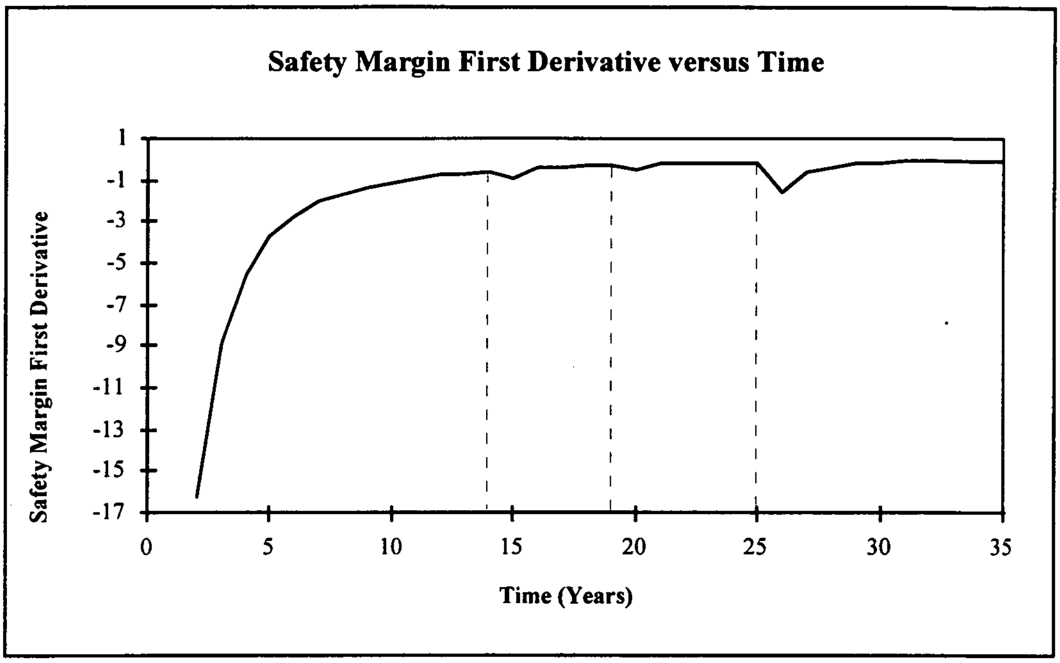

Figure 8.3: Safety margin first derivative.

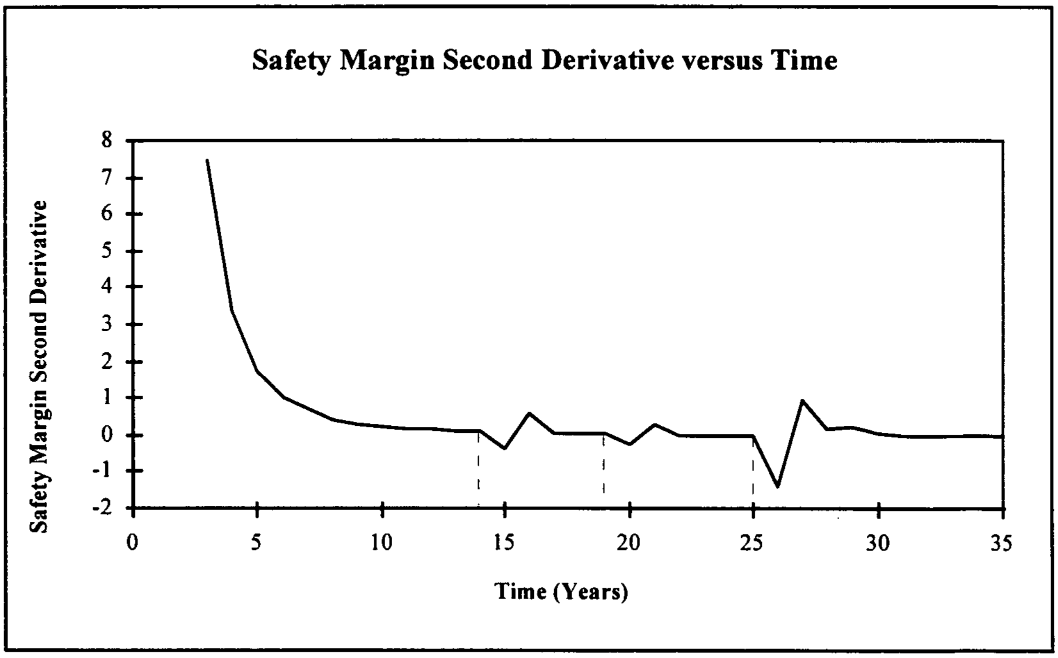

Figure 8.4: Safety margin second derivative.

8.2.4. Anode Consumption And Potential Shifts

Anode sizes and spacing are calculated in such a way that the cathodic protection system can maintain the pipeline potential under the maximum limit over its whole lifetime. The distance over which an anode provides cathodic protection depends mainly on the anode maximum output current, as well as on the coating breakdown on adjacent pipeline sections. The higher the coating breakdown, the higher the demand on the anode, and the more limited in space its protective effect. The anode ability to deliver current also decreases while they are consumed.

When considering the cathodic protection system failure, it appeared that two cases have to be considered. These are illustrated by the two case studies described here. Figures 8-5, 8-6, 8-7 and 8-8 present a comparison of the reliability and safety margin derivatives with the number of anodes lost for the A900 and A400 pipelines.

In the case of the A900 pipeline, anodes are longer, and their spacing reduced (see design parameters presented in Table 8-1). This is typically the case of cathodic protection systems designed for a long lifetime (typically 25-35 years) and/or for pipelines with a large diameter (say over 600 mm), and is linked to the cathodic protection system design calculations (see Chapter 2). Under these conditions, the reliability passes the minimum limit before any anode become consumed (see Figure 8-5). The level of coating breakdown becomes too high, and the cathodic protection system can not provide the current demand. Such failures are difficult to predict, and would occur more frequently when the coating type is subject to high level of damage and disbondment. In such cases, the pipeline potential needs to be checked in detail.

Things are different for the A400 pipeline (see design parameters presented in Table 8-1). The cathodic protection system is designed there for a shorter periods of time (10 to 20 years), anode spacing is much more important, and anodes tend to be consumed faster. It is there the total consumption of an anode which appears to trigger the cathodic protection system failure. In that case, it is necessary to observe individually anode consumption rates, to forecast early anode consumption and cathodic protection system failure (see Figure 7-9).

When analysing the cathodic protection system reliability, attention should therefore be given to the cathodic protection system design parameters. Pipeline size, anode sizes and spacing indicate which parameter should receive increased attention when analysing the reliability data.

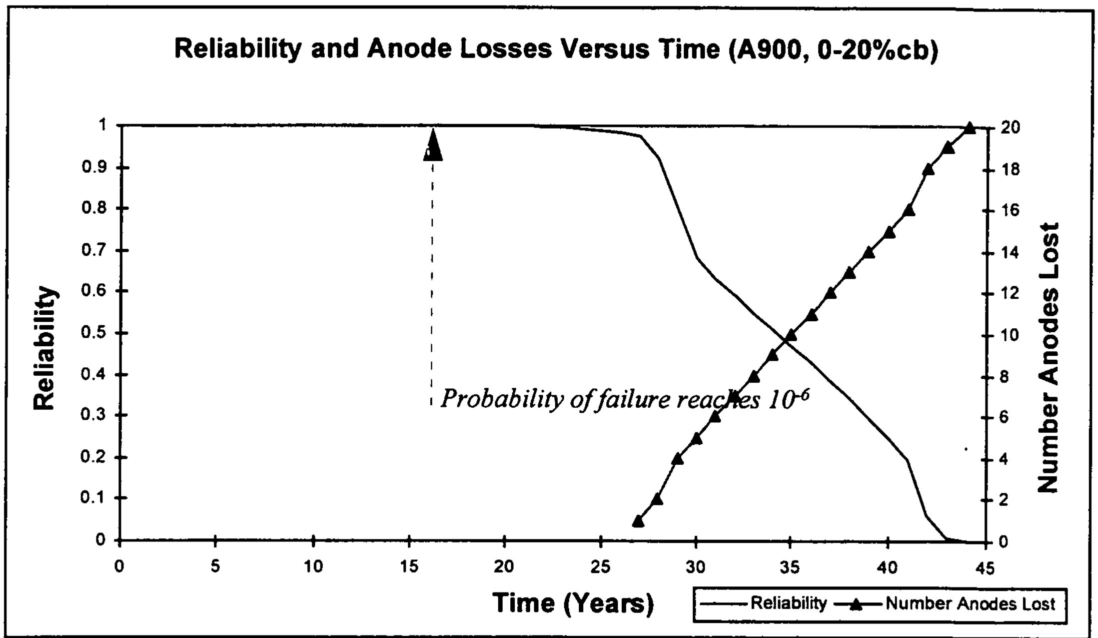

Figure 8.5: Reliability and anode losses versus time for the A900mm pipeline.

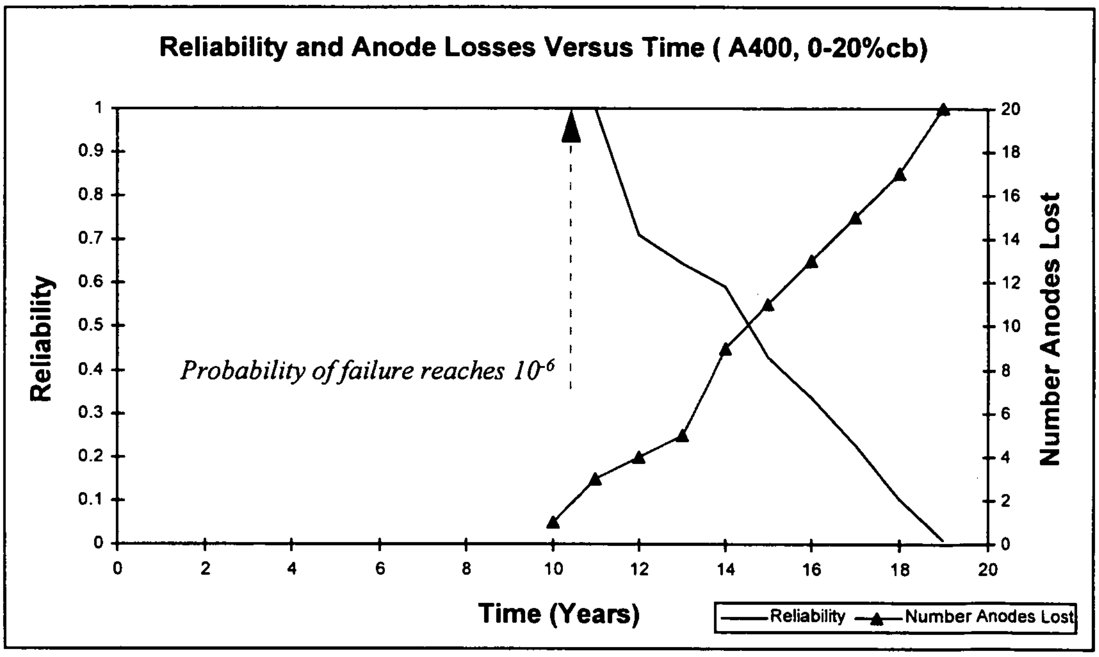

Figure 8.6: Reliability and anode losses versus time for the A400mm pipeline.

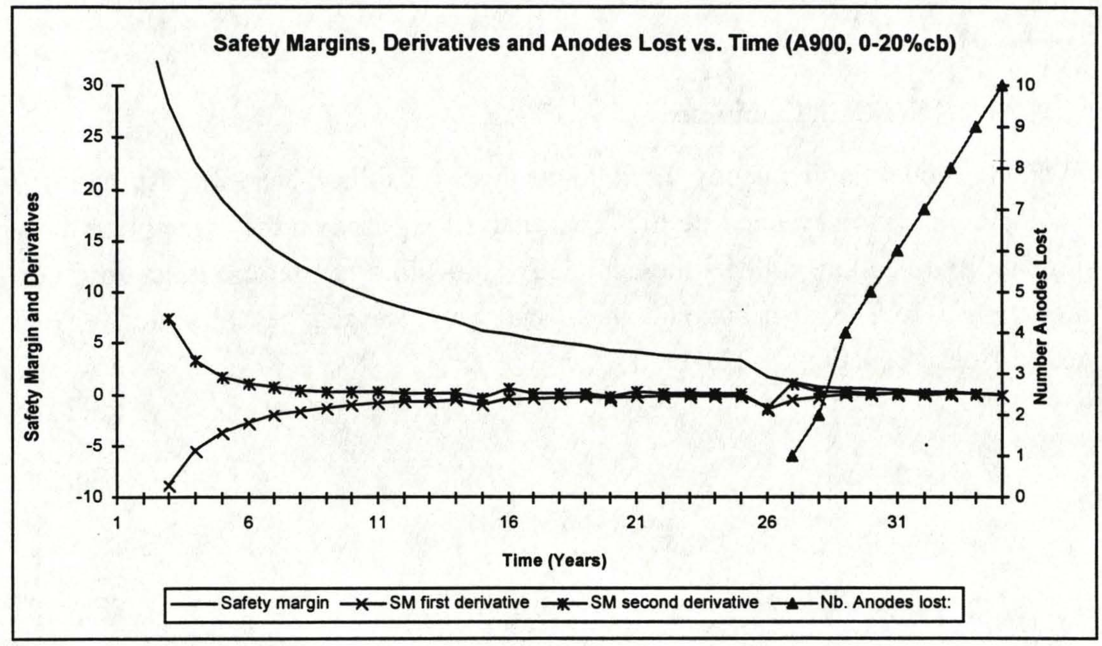

Figure 8.7: Safety margin, derivatives and anode losses vs. time for the A900 pipeline.

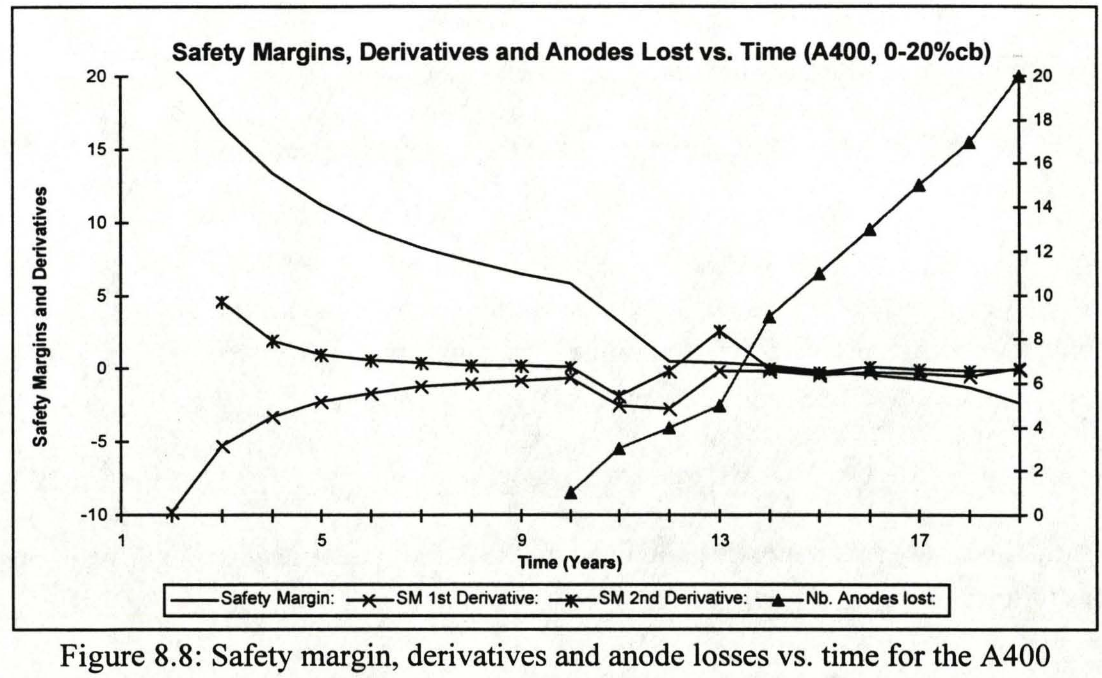

Figure 8.8: Safety margin, derivatives and anode losses vs. time for the A400 pipeline.

8.2.5. Weibull Analysis

8.2.5.1. Weibull Technique

Weibull model is frequently used to analyse reliability data for estimating the cathodic protection system safe life. This analysis is based on the assumption that the probability of failure follows the cumulative probability of failure function given in Equation 8-1. The distribution's mean and variance can be calculated by using expressions (Equations 8-2 and 8-3).

$$F(t) = 1 - \exp\left(-\frac{t}{\eta}\right)^{\beta} \qquad \text{(Equ. 8.1)}$$

$$\text{mean} = \eta \times \Gamma\left(1 + \frac{1}{\beta}\right) \qquad \text{(Equ. 8.2)}$$

$$\text{Var} = \eta^2 \times \left\{ \Gamma\left(1 + \frac{2}{\beta}\right) - \Gamma^2\left(1 + \frac{1}{\beta}\right)\right\} \qquad \text{(Equ. 8.3)}$$

where $\Gamma(\,)$ is the Gamma function.

The Weibull analysis is based on the plot of the following expressions:

$$\mathrm{Ln}(-\mathrm{Ln}(1-F(t))) = f(\mathrm{Ln}(t)) \qquad \text{(Equ. 8.4)}$$

If the data analysed follows a Weibull law, the plot obtained should be linear. The η and β coefficients can be determined by analysing that curve. If it can be approximated to a line of the expression:

$$y = a.x + b \qquad \text{(Equ. 8.5)}$$

If the linear approximation is good enough, the β and η coefficients can be estimated as follows:

$$\beta = a \qquad \text{(Equ. 8.6)}$$

$$\eta = e^{-\frac{b}{a}} \qquad \text{(Equ. 8.7)}$$

8.2.5.2. Uncertainty On The Time To Failure

The β value, indicator of the cumulative distribution curve shape, is at all time very high (see Figure 8-10). This indicates that the cathodic protection system failure occurs over a very short period of time (see Equation 8-1). This fact also appeared in the analyse of other parameters presented earlier, and only highlight the fact that attention should be given to all reliability parameters defined for assessing the cathodic protection system condition.

8.2.5.3. Estimation Of The Time To failure

Figure 8-9 presents Weibull analysis curve obtained with the probability of failure values obtained when analysing the A900 pipeline over 38 years. At that time, the correlation between the curve obtained and the linear fitting is poor. Weibull analysis appear to give better results earlier in the pipeline lifetime (see Figures 8-10 and 8-11).

After 14 years, the correlation between the Weibull curve and the linear approximation is close to 0.999. At that time, the estimation of the A900 cathodic protection system lifetime is of 18 years, close to other approximations obtained earlier. As time passes, this safe lifetime estimation increases, but the linear correlation decreases, and so does the quality of the results of the Weibull analysis.

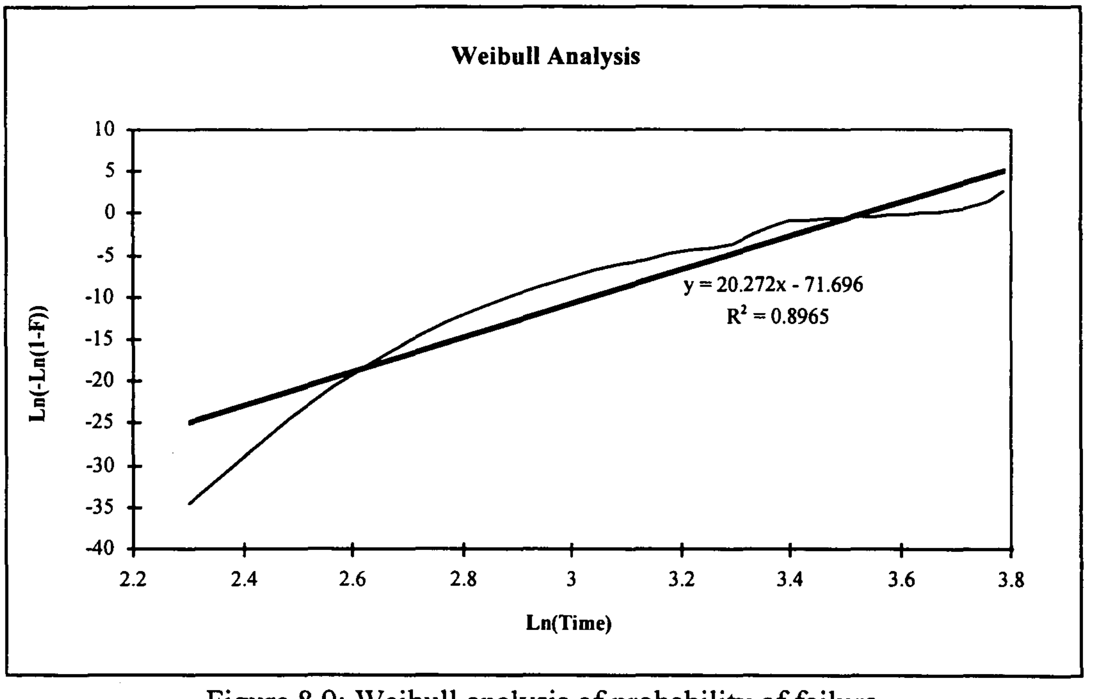

Figure 8.9: Weibull analysis of probability of failure.

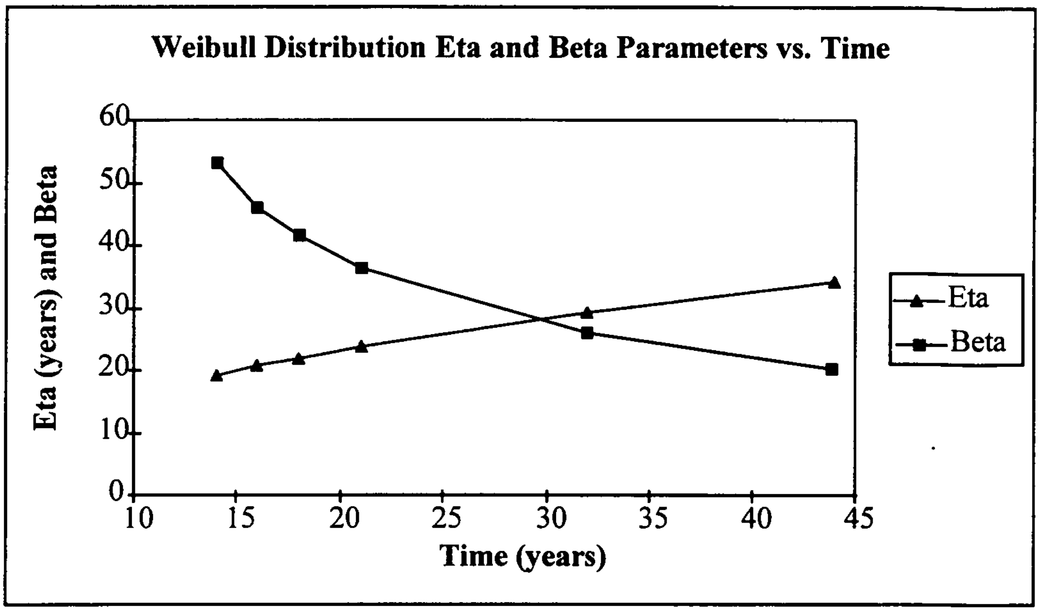

Figure 8.10: Weibull analysis: eta and beta parameter in time.

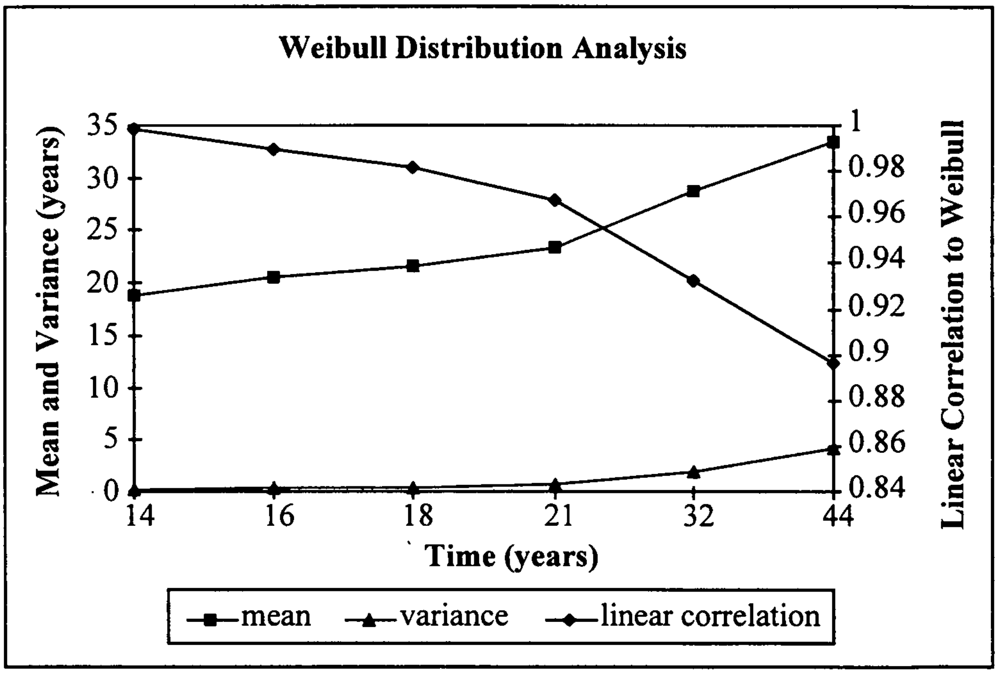

Figure 8.11: Weibull probability distribution mean-variance and correlation with actual data in time.

8.3. Coating Breakdown And Reliability Changes

8.3.1. Effects of Coating Breakdown On The Cathodic Protection System Reliability

The importance of the coating breakdown has been pointed out all along this report. The following sections present an analysis of the coating breakdown effects on the cathodic protection system reliability. The results presented have been obtained by considering various values and ranges of coating breakdown. For each case, the model was run in order to obtain the values of the pipeline potential at different times. A time to failure was also calculated considering the maximum potential limit criteria.

8.3.2. Constant Coating Breakdown

For this series of tests, the coating breakdown values were considered as constant over the whole analysis period. The time to failure values obtained for different coating breakdown's levels are presented in Figure 8-12.

As expected, as the level of coating breakdown decreases, the cathodic protection system predicted lifetime goes toward infinity. The curve obtained has an exponentially decreasing shape. This reflects the fact that the cathodic protection system deterioration rate increases much faster than the level of coating breakdown.

These results are interesting for estimating average coating breakdown values. It shows how a cathodic protection system lifetime of 10 to 15 years can only be reached if the coating breakdown values remain fairly low, that is of the order of a few percents (under 5%). Such value is much lower that the typical values presented in standards.

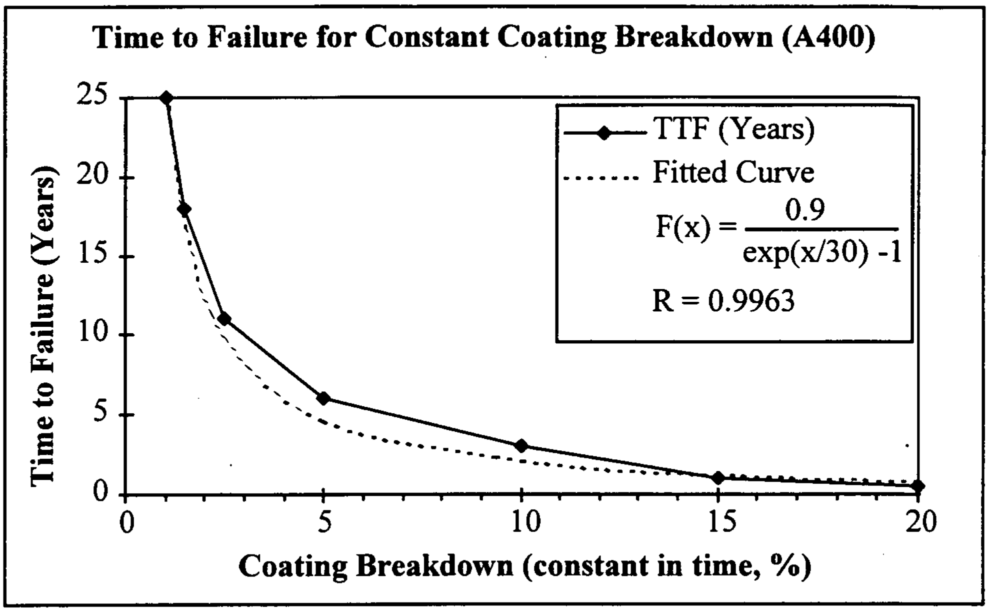

Figure 8.12: Time to failure versus coating breakdown (constant coating breakdown).

8.3.3. Coating Breakdown Range

Figure 8-13 presents the result of the test carried out on the A400 pipeline for various ranges of coating breakdown. Coating breakdown is considered to increase linearly over the period of the analysis (i.e. 50 years).

It appears again that the time to failure decreases much faster than the coating breakdown. Again, it appears that safe lifetime of about 10-15 years are reached only if the coating breakdown values remain within a certain range, lower than 20%.

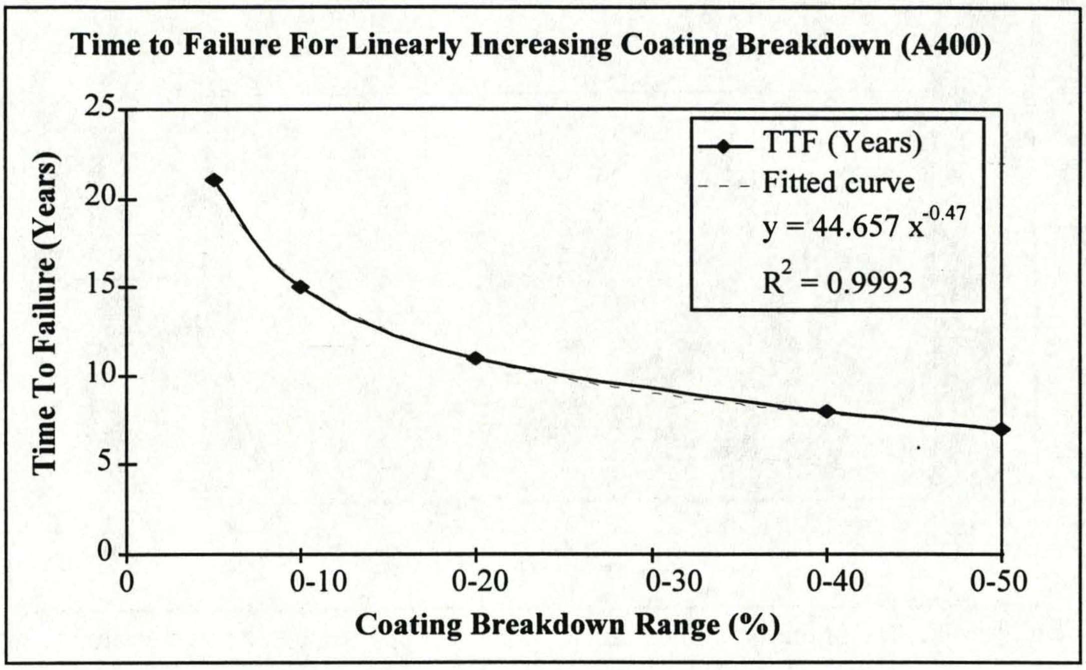

Figure 8.13: Time to failure versus coating breakdown (coating breakdown increasing linearly with time).

8.3.4. Effect Of Coating Breakdown Growth Function

The coating breakdown degradation process influences significantly the safe life of the pipeline cathodic protection system. For the purpose of this analysis, several coating breakdown evolution functions were defined (see user interface details in Appendix 5). The coating breakdown was mainly modelled as linearly or exponentially increasing in the analysis, as illustrated in Figure 8-14.

The effect on the time to failure is illustrated in Figure 8-15 for the A400 and A900 pipeline designs. The results show how the coating breakdown growth function affects the time to failure. An analysis of inspection results would enable the operator to define which function better describes the coating breakdown growth. Descriptive function would depends on the type of coating, as well as lifetime considered and environmental parameters.

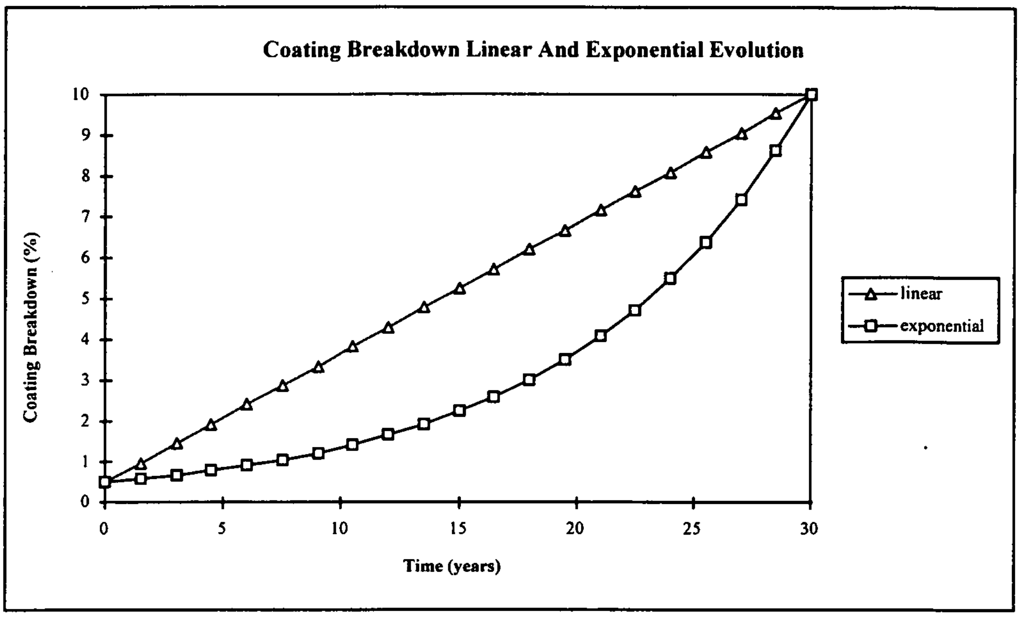

Figure 8.14: Comparison linear and exponential coating breakdown evolution.

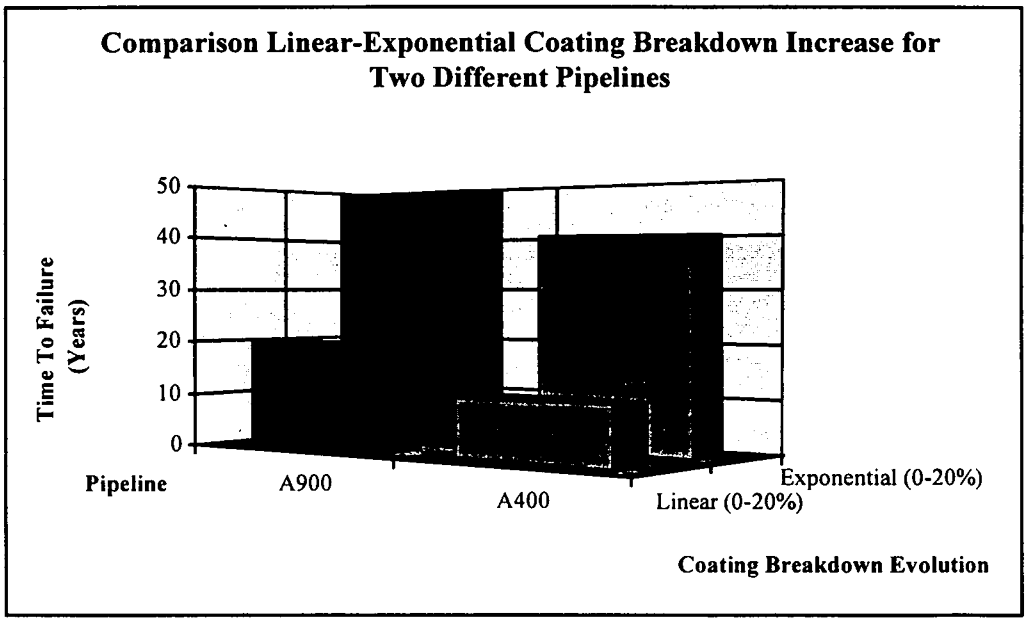

Figure 8.15: Time to failure for different pipelines and various coating breakdown ranges.

9. Discussion

9.1. Potential Modelling And Data Availability Issue

9.1.1. How Much Coating Breakdown?

Data availability has been a major concern for the development of the present model. Some of the parameters required as input appeared to be difficult to obtain, or with only a low level of precision.

This is the case of the coating breakdown, one of the key parameter in the pipeline potential model. It influences greatly the cathodic current demand and anode consumption. Unfortunately, coating breakdown is influenced in turn by a number of other parameters, going from pipeline pre-coating preparation, installation conditions to on site environmental and operational conditions. All these parameters modify the coating physical and chemical stability, its resistance to sea-bed stresses and impact, and its adhesivity. Most subsea pipelines being weight coated, and often buried, there is little information related to the level of coating breakdown can be obtained through direct inspections. Coating holidays can only be detected by visual inspection, on unburied sections of pipelines, where weight coating is non existent or has been removed.

There is presently no method available for evaluating precisely the level of coating breakdown for a certain type of coating, after a certain number of years, under specific environmental and operational conditions. The coating breakdown is only estimated, with a rather high level of uncertainty. Values presented in standards for cathodic protection system design are in particular regarded by industry as over-estimated (see Appendix 3). Case studies presented in this thesis showed that sacrificial anodes are consumed very quickly if the coating breakdown reaches such values. This is mainly explained by the fact that the values presented in standards include safety factors, resulting in an over-design of the cathodic protection systems. No alternative values are officially defined and accepted.

9.1.2. Pipeline Potential Modelling Validation

Uncertainty on the coating breakdown has been a limiting factor for the development of the pipeline potential model, in particular when testing the model, and checking the accuracy of the potential calculated. Inspections providing little information regarding the coating breakdown, tests had to be carried out for determining which level of coating breakdown gave potentials similar to the ones obtained by inspection. Considering the level of knowledge regarding the coating breakdown, it is not possible, at the present time, to fully validate the pipeline potential model developed.

This situation should change as operators' attitude toward this issue evolves. Data acquisition techniques are improved all the time, and new measuring units are being developed to enable the operator to obtain continuous potential and current density measurements. Such units are already installed on some more recent pipelines. They will help monitor changes at the surface of the pipeline, and hopefully help analyse coating degradation rate.

Knowledge related to coating degradation is also increased as new testing methods are developed for evaluating coating resistance, degradation factors. These are used for testing newly developed coating, but help improve the general knowledge.

The understanding of the coating degradation process should benefit from these new techniques and experiments in the next few years. Full validation of the pipeline potential model should then be reconsidered. If any modification is required in the pipeline potential model, it should only consist of tuning the software to set the calculated potential values as exactly as possible to the level of the potential values obtained through inspection. The level of precision on the measured potential would also have to be clearly defined, and preferably as low as possible. There again, inspection company do not provide clear information, and hopefully the definition of measurement uncertainties will become a requirement by standard in a close future.

9.1.3. Potential Modelling Results

Considering the previous sections, it may seem dangerous to make any statement regarding the value of the results obtained through the pipeline potential model. At the present stage of the development, potential obtained appear to be satisfactory. Potential rises when coating breakdown increases, anode potential increases when the current demand is high on adjacent pipeline sections, etc... The difference in the potential values between sections with different coating breakdown appears also satisfactory, and so does the general pipeline potential level.

Uncertainties in the results obtained remain, but the potential model developed offers sufficient precision for testing the reliability analysis model and demonstrating the methodology defined. Any pipeline design and environmental conditions can be modelled, over any period of time. This gives the level of flexibility required for analysing real cases and the effects of various parameters on the pipeline potential and anode consumption levels. The model calculates, in particular, changes in the potential, current density, anode consumption. These values are calculated at different points along the pipeline surface, at different time, and are used as the base of the calculation of the reliability parameters.

9.2. Potential Modelling And Probabilistic Analysis

9.2.1. Integration Of The Probabilistic Calculations

The analysis developed is based on the integration of the probabilistic calculations into the deterministic potential model. The probabilistic model has been developed separately, but is based on the same electrical analogy used for the deterministic model (see details about the deterministic model in Chapter 4). Some of the calculations carried out in both models being similar, calculation results have been reused whenever possible (see details in Appendix 9).

This approach helped reducing the amount of calculation needed for the two models. All possible ways for optimising the system solving methods, reducing the amount of memory and time required for running the calculations have been used. At some point of the development, running a simple case study, that is a short pipeline with only a few anodes, took up to a few hours. Considering the number of matrices and complex equations used in the pipeline potential model, combining the deterministic and probabilistic calculation modules helped reduce the amount of calculation required. Gains are particularly significant when modelling long pipelines with a large number of sections.

9.2.2. Definition Of The Coating Breakdown Uncertainties

Uncertainties on the coating breakdown are calculated according to several other input parameters, such as the coating thickness, the pipeline temperature, the percentage of burial or the level of activity around the pipeline section. Uncertainty may therefore vary from one pipeline section to the next one.

The coating breakdown uncertainties are calculated according to the equations presented in Appendix 8. These expressions have been developed considering the general interactions between the coating and its environment, and have a qualitative rather than quantitative value. If the level of coating breakdown tends to increase with the values of one of the parameter value, then the value of the coating breakdown uncertainty also increases accordingly.

Again, due to the lack of knowledge related to the coating breakdown and coating degradation processes, it is not presently possible to develop more specific and qualitative equations. The equations developed and integrated into the model are adequate for demonstrating the features of the probabilistic model and run case studies, but not for estimating specifically and quantitatively the effects of the parameters conditioning the coating breakdown uncertainties. Future improvement of coating knowledge should help provide better methods for estimating and modelling these uncertainties.

9.2.3. Standard Deviation On The Potential Values

Uncertainties on the coating breakdown are grafted on the pipeline potential model and used to calculate uncertainties on the potential. These uncertainties are actually expressed in terms of standard deviations (σ). The standard deviation on the potential depends on the coating breakdown uncertainty. Considering the qualitative rather than quantitative value of the coating breakdown uncertainties, standard deviations on the potential are also to be considered on as qualitative. They give an indication of the standard deviation on the pipeline potential rather than a precise value.

Again, this approach has been considered as acceptable at the present time for demonstrating the utilisation and usefulness of this parameter. It is used mainly for defining a domain of confidence around the potential value obtained. The analysis of this domain of confidence influences the reliability analysis, as described in the following sections.

9.2.4. Potential Confidence Interval

The domain of confidence around the pipeline potential is defined as equal to the mean (or deterministic) potential value plus or minus a number of standard deviation ($\overline{V} \pm n\sigma$), as illustrated in Figure 9-1a. The domain of confidence is an indicator of the pipeline potential precision, and its analysis is part of the reliability analysis. A graphical representation of this domain of confidence gives the operator a better insight on how close the potential may actually be from the maximum limit. This representation may affect the operator's decisions when planning inspections and maintenance operations.

In critical cases, in particular when the pipeline potential becomes closer to the maximum allowable potential limit, considering the domain of confidence gives a better insight on how safe the cathodic protection system is. Providing no indication of this domain of confidence may lead the operator to think that the potential is still beyond the maximum limit when in fact the probability that the potential is already over that limit is not negligible.

These remarks also apply to inspection results presentation and analysis. Considering the fact that potential measured are only known with a certain degree of precision, the information related to measurement uncertainties can be integrated in a similar way. Graphical representation provided by inspection companies prevent the operators from apprehending the true value of inspection results. The software developed could be used there for integrating and representing these uncertainties.

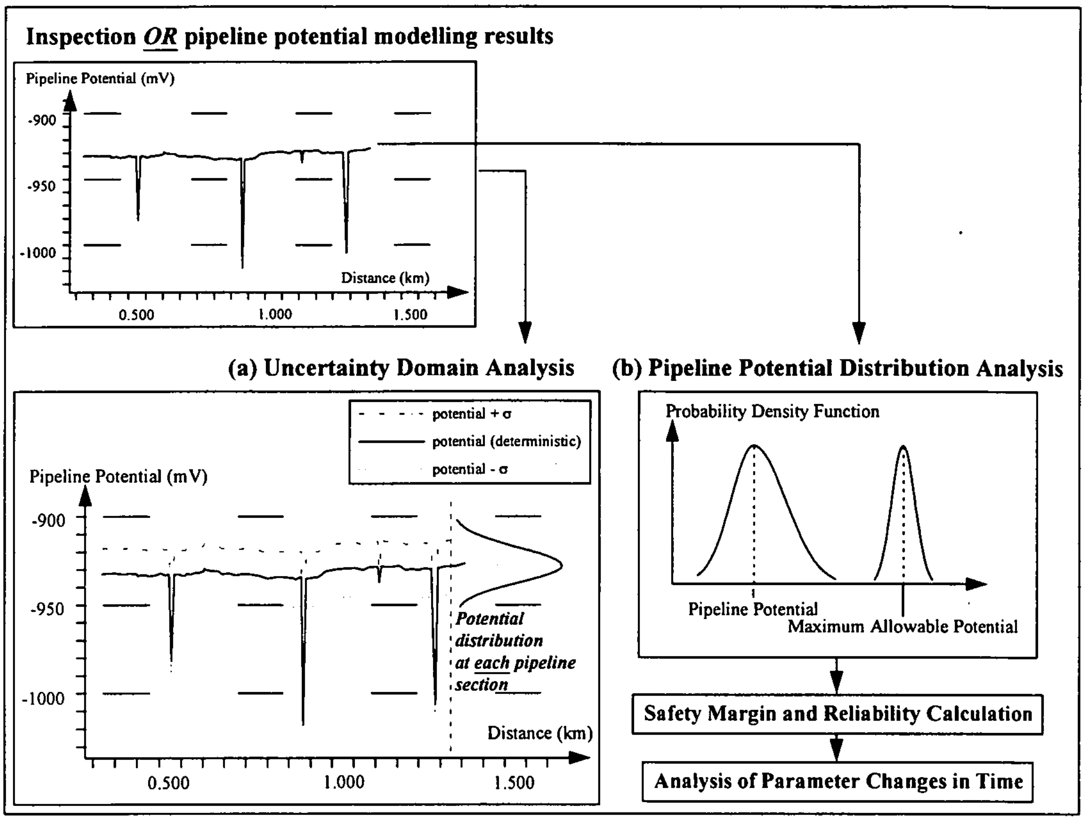

Figure 9.1: Potential uncertainty analysis (a) and potential distribution analysis (b).

9.3. Pipeline Potential And Reliability Parameters

9.3.1. Analysis Of The Potential Values Along The Pipeline

Pipeline potential values are calculated at different positions along the pipeline. The set of values obtained are used to analyse the distribution of the pipeline potentials, as illustrated in Figure 9-1b. The analysis is used for calculating the mean pipeline potential and the distribution standard deviation.

Providing a graphical representation of this distribution gives a visual and easily interpreted indications on the state of the cathodic protection systems conditions. The shape of the distribution curve indicates how far the potential mean value is from the maximum potential limit, and how much the potential values are spread around that mean value. The comparison of the potential distribution changes over time indicates even more clearly how the pipeline potential, and therefore the cathodic protection system reliability, changes. Such representation can be useful, in particular in cases when the potential level appears to increase in an unexpected way from one period of time to the next one. It would also be interesting to find such representations in inspection reports.

9.3.2. Anode Consumption And Losses

At the early stage of the pipeline lifetime, some anodes may be electrically disconnected from the pipeline surface, becoming then inefficient, without inducing cathodic protection system failure. This may be the case as long as the cathodic current demand remains low enough for the sacrificial anodes to provide without difficulty. But tests showed that, in most cases, the cathodic protection system fails when some anodes are completely consumed (or disconnected).

Anode consumption rate is therefore an important parameter of the cathodic protection system reliability analysis. Monitoring the anode consumption gives indications about weaker sections of the pipeline. It can also help predict failure, in particular when the pipeline potential appears to increase, that is the level of cathodic protection decreases. If at the same time, anodes appear to have fairly high consumption rate and to be close to total consumption, then the operator should consider maintenance operation prior to failure.

9.3.3. Safety Margin And Reliability

The operator is also interested in a simple way to represent the cathodic protection system reliability. Used in conjunction with the distribution analysis, the stress-strength interference methodology provides ways to calculate more general and synthetic indictors of the cathodic protection system condition. The safety margin and reliability calculated are two simple expressions which provide the user with a simple indication of how the cathodic protection system is behaving. This information can be exploited to analyse the cathodic protection system condition.

The safety margin and reliability parameters are more easily manipulated and analysed than a set of potential values measured or calculated at different points along the pipeline. This is in particular true when analysing the changes in the cathodic protection system condition in time.

In the user interface developed, the results presentation window presents graphs of the changes in time of the safety margin and reliability. By consulting these graphs, the operator can quickly assess the cathodic protection system condition. Figure 9-2 illustrates how the reliability prediction results can be used as a warning and base of discussions for planning maintenance and repair operations, when potential analysis may reveal failure too late.

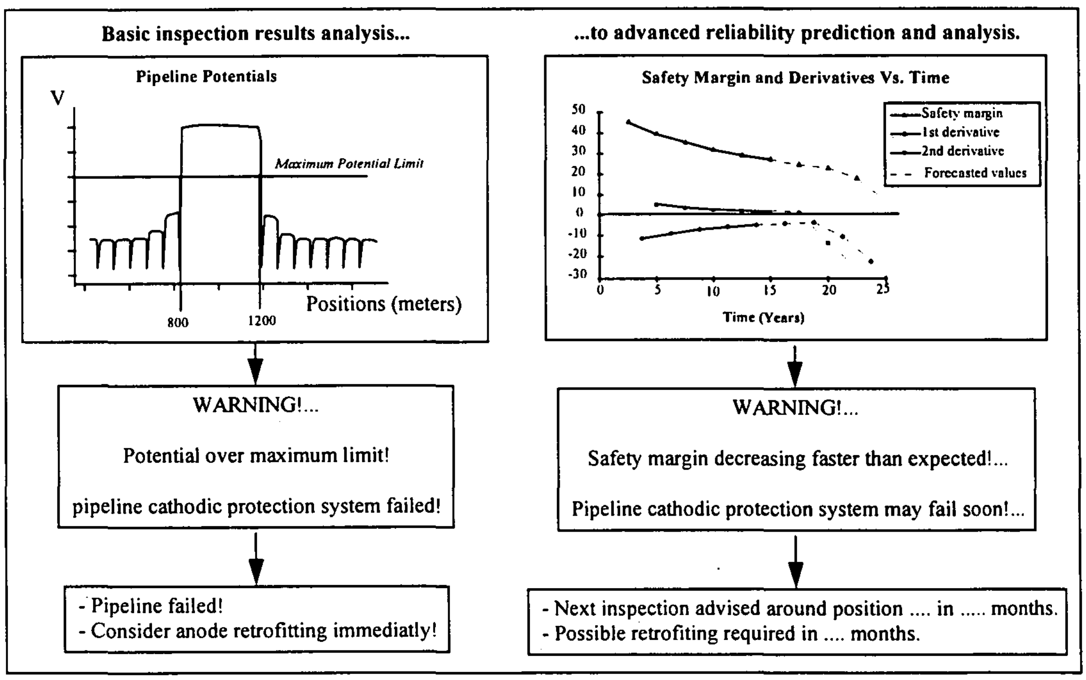

Figure 9-2: Inspection result analysis: two levels of warning.

9.3.4. Safety Margin Derivatives

All anomalies in the safety margin versus time curves are significant for the reliability analysis and prediction. The safety margin first and second derivatives emphasise such anomalies, and help detect them. They can be used as indicators in the reliability analysis process. Graphs of the safety margins first and second derivatives are also included in the interface results presentation window.

Once anomalies appear, more caution has to be given to the inspection or modelling results. It is then necessary to analyse more into details other parameters, investigate possible causes, and to ensure that no major problem occurs at any point along the pipeline.

Major anomalies are linked to important potential drops. These usually appear when anodes are accidentally disconnected or totally consumed, or when large areas of the coating are damaged. Minor anomalies tend to indicate a decrease in the ability for the anodes to protect the pipeline.

9.3.5. Definition Of Safety Levels

Latest standards consider the use of target defined reliability analysis. In practice, and essentially due to the lack of available reliability analysis tools, no precise technique has been defined and described for the estimation of the reliability. Consequently, no reliability or probability of failure limit has been defined either. The probability of failure acceptance limit of 10^{-6}, used for the case studies presented, has been defined in a subjective way, only for demonstrating the use of the model.

For defining a standardised limit, it would be necessary for the different parties involved to agree, in the first place, on an analysis technique for estimating the cathodic protection system reliability. The analysis technique and tool developed in the context of this research could be used for this purpose. Through its use for various pipeline cathodic protection systems, a reliability limit could be defined and adopted by standards. Such definition would have to be developed in parallel with improvements of the inspection data quality, an essential element of the analysis.

9.3.6. Localised And Global Analysis

Although the safety margin and reliability provide concise information about the general cathodic protection system conditions, caution should be taken when using these parameters. The values obtained, being global, may hide localised problems which may occur at particular points along the pipeline. Localised coating breakdown due to impact or coating disbondment may increase current demand, anode consumption, and may cause a rise in the potential level. Such effect may not appear in the safety margin and reliability parameters if the overall rest of the pipeline is properly protected. The operator therefore needs to consider both these parameters along with the detailed pipeline potential analysis.

To limit this type of problems, it is possible to calculate the safety margins and reliability for parts of the pipeline. Initial analysis could be used to divide parts of the pipeline which would have to be analysed separately. Criteria for defining these sections could be linked to environmental conditions such as the level of human activity, the percentage of burial or the temperature.

9.3.7. Weibull Analysis

The Weibull analysis appeared to provide useful information for the reliability analysis. Estimation of the cathodic protection system safe life was similar to the values obtained with the stress-strength method, at least when analysing the probability of failure in the early stage of the cathodic protection system lifetime. Afterward, the quality of the analysis results appeared to decrease. Such analysis can be integrated into the reliability analysis process, but results have to be manipulated with caution.

9.4. Reliability Analysis And Software Development

9.4.1. Importance Of The User Interface

Major considerations had to be given to requirements linked to quantitative reliability analysis processes. Modelling occupies a large part in such analysis, and the data requirements are important. The more information available on the various parameters and their changes in time, and the more precise the analysis can be.

When the number of parameters makes their manipulation difficult, only computer interface can ease the user's work by offering efficient data management tools. The user interface helped increase efficiency in the analysis process and reduce the amount of work required for data gathering and manipulation operations. It proved to be an essential element in the reliability analysis process.

9.4.2. User Interface And Analysis Efficiency

The Microsoft Windows interface developed integrates step by step analysis procedures for guiding and helping the user in its work. The pipeline, cathodic protection system, environmental and operational parameters can be input and modified at will. When input data are defined, the user can generate files required for running potential modelling case studies and generate reliability analysis parameters. Essential outputs can then be presented graphically to the user on the form of graphs. Knowledge required for manipulating the reliability analysis model has been reduced as much as possible, in order to ease user's work.

The interface also makes possible the development of more complex analysis, through automated or semi-automated data analysis routines. For example, the interface developed calculates automatically the safety margin derivatives, presented in the graphical displays, used to decide whether further data analysis is required or not. This allows unexperimented users to carry out complex analysis, requiring from their part only limited knowledge of the data and underlying reliability analysis calculations.

9.4.3. User Interface And Data Management

The database system integrated to the user interface plays an important role in the data management. The Windows forms defined for entering the data ensure that the data format remains consistent. Parameters unit defined can be clearly presented to the user. Some typing mistakes can be also detected automatically by checking that the value entered for a parameter remains in a certain range, and is of a certain data type (i.e. text, boolean, integer...). When required, the user can also access databases of environmental or material parameters for checking possible or most probable values.

Once entered, the information is stored into files, using again a standard format. Data can be accessed and checked easily. This is particularly interesting when analysing the influence of some parameters on the cathodic protection system reliability. It also limits the risk of mistakes while manipulating data, increases the data availability, and reduces the time required to search and gather the information required for the analysis. The information is gathered and entered once for all. It is also ready for other types of analysis which may be later developed.

9.4.4. Limitation In The Present Development

In the present form, the interface incorporates the main functionalities and tools required to help the user in managing his reliability analysis cases. The level of analysis carried out and guidance provided to the user by the interface depends on the amount of knowledge built into it. This knowledge should grow as the operator uses the model and software for analysing various pipeline cathodic protection systems. The interface and reliability analysis processes will change with time. More than a finished product, the interface and data management tools developed can be regarded as an initial approach to a fully integrated system. It was an essential part of a reliability analysis tool.

As presently developed, the interface offers the flexibility required for integrating progressively the knowledge acquired by experience. Such modifications would nevertheless require an experienced programmer and a good knowledge of the model to easily integrate new modules and results display accordingly to new requirements defined by experience acquired. A professional software package should allow the user to modify and customise the application in order to easily integrate new parameters input, calculation modules and result displays. But the amount of software development required to reach this level of flexibility and adaptability is largely higher than the amount of work allocable to software development in the context of this project. The implementation of the pipeline potential model required over 40000 lines of code in C language, while the interface required around 25000 lines of Microsoft Visual Basic. That represents already a large amount of programming, and does not take into account code rewriting required as the model was modified. Further development would be required to make it into a marketable product which could be distributed to operators. A professional software based on the same model and analysis would require several man years of software development.

9.5. Further Developments

9.5.1. Pipeline Potential Modelling

Several important developments can be carried out to improve the pipeline potential model. The main points requiring attention are listed below.

- *Pipeline potential model full validation.* This would require a large amount of work, mainly for gathering both the design and inspection information from the operators. Such an approach was impaired during the development of this project, due to the difficulty to access the required information. As standards support the use of quantitative reliability analysis techniques, operators become more aware of the importance of reliability analysis. They are incited to develop reliability analysis tools as well as improved inspection techniques and easily accessible computerised data storage. This will facilitate the potential model testing.

- *Coating breakdown study and analysis.* Part of the work required for validating the pipeline potential model will consist of increasing the knowledge on the coating degradation processes and coating breakdown. Part of the improvements would come from new coating testing methods. It is presently considered to use the potential model developed in a reverse way, in a Monte Carlo way, to define which level of coating breakdown would actually give the level of potential measured.

- *Application of the potential model to on-shore pipeline.* In its present form, the model and software can be used for analysing pipelines in various aqueous environments. Aqueous environment can be sea water as well as seabed mud or sand. The environment being defined by its resistivity, any type of soil can be in fact considered for the modelling. This covers to a certain extent on-shore soils. Limitations to using directly the model in its present form for on-shore pipelines are linked to the fact that on-shore pipelines are usually protected by impressed current systems. The model only considers sacrificial anodes, and can not handle impressed current cathodic protection systems without modifications. Benefits from these modifications could be important considering the much larger number of on-shore pipelines and the higher frequency of failure due to external corrosion.

- *Application of the potential model to other structures such as platforms and wellheads.* The problem is there more complex, but the same basic modelling techniques can be applied. Difficulties may be encountered for modelling the potential field shape around the structure in that case. It might then be advised to consider reusing other models developed for offshore structures. The probabilistic dimension of the analysis could then be integrated to these models in a way similar to the one used for the present analysis.

9.5.2. Cathodic Protection Systems Reliability Analysis

Several companies expressed their interest and provided financial support throughout the project development. This interest and support were motivated by the increase in demand for reliability analysis techniques and tools. Further developments of the present model have already been considered. The main analysis tools which could be developed and added to the present model are listed below.

- *Improvements of the reliability analysis.* These should be carried out through the analysis of a number of pipeline cathodic protection systems. The higher the number of case studies, the more comprehensive the resulting reliability analysis procedure and the better the guidance and advice given by the interface to the user.

- *Integrate Bayesian updating methods.* This would make possible an easier integration of the inspection results into the reliability analysis modelling, and help reducing uncertainties on the model parameters and calculation outputs.

- *Develop a tool for calibrating pipeline cathodic protection systems efficiency.* Such a tool would be used for analysing initial inspection data, and determine the level of protection ensured by the cathodic protection system *soon after the pipeline installation.* The results would be used to analyse later inspection results.

- *Check the validity and consistency of inspection data.* It would compare inspection results obtained at various times. Comparison would help diagnose abnormal changes in potential, whether they are caused by important and unexpected coating degradation, or by measurement errors. Advanced analysis may enable the user to correct measurement errors, sometimes caused by changes or errors in the measurement unit calibration.

- *Provide a standard checking for the pipeline cathodic protection systems.* Experience would convert the model into a tool to estimate quantitatively pipeline cathodic protection systems reliability, giving a grade which could be compared to a standard scale.

9.5.3. Toward Integrated Reliability Analysis Tool

In several parts of this project, the need for data management tools and advanced user interfaces for carrying out reliability analysis has been pointed out. While considering further developments for the potential and reliability analysis model, it is also important to discuss improvement of the user interface. Main improvement points are described below.

- *Improvement of the interface data management system.* Improved access to data bank related to environmental, coating parameters should be considered. Some work may have to be carried out for developing adequate databases required specifically for this work.

- *Integration of tools for comparing cathodic protection systems.* This would make possible easy comparative analysis of several pipelines. Sophisticated tools for analysing the effects of some parameters on the cathodic protection system reliability could be developed, along with more conventional statistical analysis similar to the one presented in the PARLOC report ([PARLOC, 96]).

- *Combination of an external and internal reliability analysis model.* An internal corrosion reliability analysis model is being developed at Cranfield University ([Strutt, 96]). This model uses part of the information already stored into the database developed for the cathodic protection system analysis model. The other parameters required could be integrated to the database, and the same interface could be used for both models. The interfacing development of the model would be based on existing interface and therefore be easier. This would represent a major step toward an integrated pipeline corrosion reliability analysis.

- *Development of a general offshore installations reliability analysis tools.* The possibility to integrate analysis tools developed for other pieces of equipment into the general interface is already considered. A more general reliability analysis tool could be developed for integrating, along with the pipeline reliability analysis model, other models such as Warburton's, related to subsea valves and currently under development at Cranfield University ([Warburton, 95]). Both models could be used separately if required, and further analysis of systems composed of pipelines and valves could be carried out. Further integration of reliability analysis tools developed for other pieces of equipment such as platforms or wellheads could also be considered. The data management tools required for such a general tool would integrate a much larger number of data, and required much more complex data organisation system. A generalisation of this tool could lead to the development of a more general model, applicable to on-shore piping systems or even complex on-shore structures such as chemical plants.

- *Integration of more sophisticated analysis tools.* Again, once the database used to store the system general parameters is set up, development of more sophisticated computer tools is made much easier. Bayesian updating methods have been described earlier on, but beyond these, one can think about the development of expert systems. Such system would automatically build up knowledge by learning from experiences. It could be used automatically analyse inspection and potential prediction data, draw conclusions on the system condition, and generate suggestions about possible measures to take for repair and maintenance operations.

The software development was carried out on work-station[1] for the potential modelling, and personnel computers for the user interfaces[2]. These systems proved adequate for the development present software, but hardware limitations appeared when analysing long pipelines. Processing speed could become an issue there, and limitations appeared for presenting calculation outputs. Potentials and other parameters may be calculated for hundreds of thousands of points at the surface of a pipeline, and most graphical presentation package struggle for drawing graphs using such a large number of values. The analysis and modelling approach would remain similar for further developments, but hardware and software development tools requirements may have to be rethought, considering using larger computer configurations and optimised graphical packages.

1 Dec-Stations 5000.

2 Pentium 90Mhz, 16mbites of RAM, SCSI controller.

10. Conclusion

"It is a capital mistake to theorize before one has data", Sir Arthur Conan Doyle

10.1. Limitations Due To Lack Of Data

Early in the development of this project, data availability appeared as a major issue. Some of the system parameters, such as in particular the coating breakdown, were only known with a limited degree of precision. It appeared at that stage that the pipeline potential model could not be fully validated, and that consequently, the results of the reliability prediction analysis, based on the output of the pipeline potential model, would also have to be used with caution.

It is despite and in full awareness of these limitations that the reliability analysis model was developed and the software implemented. Further analysis of the problem showed that uncertainties due to the lack of data could be actually used in the modelling process. Furthermore, the strong demand from the offshore industry for reliability analysis tools was an incentive for carrying out this development.

10.2. Integration Of The Input Parameter Uncertainties In The Reliability Modelling

No system can ever be perfectly known and modelled. Uncertainties are an inherent part of system analysis and therefore of the reliability modelling. For the pipeline potential modelling, uncertainties came from some of the model input parameters. The problem was not the uncertainties themselves, but rather how to deal with them. The method used consisted of taking into account these uncertainties in the model to calculate standard deviations on the pipeline potential and other output parameters. The formulae used to calculate the standard deviation on the output parameters have been developed separately, and have been grafted into the pipeline potential model, in order to reuse, where possible, the results of the calculations carried out in this model.

It was, in that way, possible to model uncertainties on the input parameters, even though it was not possible to define a clear method for estimating these uncertainties. In the case studies presented, the coating breakdown uncertainties defined are estimations, with no real physical and/or experimental background. They have been used as academic material to help prove that modelling the system reliability was possible, and that it could give conclusive results.

10.3. Reliability Analysis Model Developed And Direct Uses

The reliability analysis model developed and software implementation can be used to analyse any subsea pipeline cathodic protection system, under any environmental and operational conditions. It provides operators with a tool for analysing the pipeline potential and estimating quantitatively the system reliability. It also allows the operator to forecast the changes in the system and predict reliability over any period of time. Figure 10-1 (p.147) illustrates the main features of the reliability analysis model developed.

The model has, in its present form, several applications. It can be used in particular for recently installed and ageing pipelines. On recently installed systems, the stress-strength analysis model developed could be used for calibrating the pipeline cathodic protection system reliability. On ageing pipelines, and particularly pipelines which are about to reach their initial design lifetime or pipelines which are planned for use beyond this time, the model can be used to predict the cathodic protection system reliability, and forecast how it may change in the future. There, the operator could use the results for estimating the remaining safe life of the cathodic protection system, and for deciding if maintenance operation is required.

10.4. Interest For Demonstrating The Reliability Analysis Methodology

The model developed is based on the integration of several tools and analysis techniques. The central part of the model is a quantitative modelling of the pipeline potential, on which probabilistic calculation methods have been grafted to accommodate input parameter uncertainties. The model output are analysed using a stress-strength interference method. These calculation modules are built into an interface which helps the user for managing data (input / graphical presentations / storage), running reliability analysis, and presenting results.

The software developed only integrates part of the facilities a marketable software would. Most of the results obtained from the probabilistic potential model are not presented in the interface, and a number graphs have to be drawn aside, using a spreadsheet. Nevertheless, its development was essential for demonstrating and testing the methodology defined for the reliability analysis process. It helped prove that the stress-strength interference method was applicable and gave interesting results.

It also helped discover problems related to quantitative reliability analysis, which are linked, in particular, to the definition of risk acceptability levels and to the lack of data. Acceptability levels would have to be defined by standard after a reliability analysis method as also been defined. The lack of data will hopefully reduce, as operators adopt new approach toward data management and reliability analysis.

10.5. Improvements Brought To The Reliability Analysis Process

The model and software tool developed proved to have brought improvements at different levels of the cathodic protection system reliability analysis. The parameters calculated and their graphical presentations help give a better insight of the systems reliability.

- **System changes in time**. The reliability and safety margin parameters can be used as indicators of system changes in time. The values used may be calculated from previous inspection results or predicted using the pipeline potential model. Such presentations proved to give a good view of how the cathodic protection system is behaving.

- **Potentials distribution**. Graphical presentations of the potentials distribution also proved to be a good indicator of the cathodic protection system behaviour. It can be used for direct pipeline potential checking, and for analysing the changes of potential (mean value, standard deviation) in time.

- **Potential uncertainty**. Uncertainty is calculated for each section of pipeline, and appeared essential to any potential analysis, whether these potentials are modelled or measured during inspection. Not considering these uncertainties may in some cases lead to major error in the estimation of the cathodic protection system reliability.

Hopefully, the model developed and presented in this thesis will demonstrate these points to operators, and show them that reliability analysis can improve greatly their approach to reliability analysis and consequently help them improve their asset management.

10.6. Data Management And Integrated Reliability Analysis Tool

Only a very simplified user interface was considered in the initial project development plan. As tests were carried out on longer pipelines, the number of elements defined to describe the pipeline and cathodic protection system in the finite element model increased to a point that manipulating the parameters required for describing the system also became an issue. The development of a more complex user interface appeared then as essential for entering, manipulating and storing the data.

From the experience built up during the development of this project, it appeared that a proper user interface was the only way to go when considering developing proper reliability analysis tools. The interface developed allows the user to manipulate easily data, to run reliability analysis without having to set up complex analysis processes, and to generate easily graphical outputs. Using such an interface requires limited training, and without requirement for understanding the underlying calculation process.

The interface produced offers only part of the facilities which should be incorporated into a professional reliability analysis software tool. More facilities should be included, in particular for the presentation and analysis of more of the model output. Only essential parameters are automatically displayed by the present interface. More graphs, most of which had to built through the use of spreadsheet, could be generated automatically, and presented on user request. Automatic analysis tools and decision making help modules could also be included. Figure 10-1 illustrates the features which could be included into such an interface. Its development would require a deeper analysis of the system parameters, and most of all a more comprehensive involvement of operators and inspection companies, for developing new inspection and data analysis methods. Bayesian updating techniques can, for example, be developed and integrated to help reduce uncertainties.

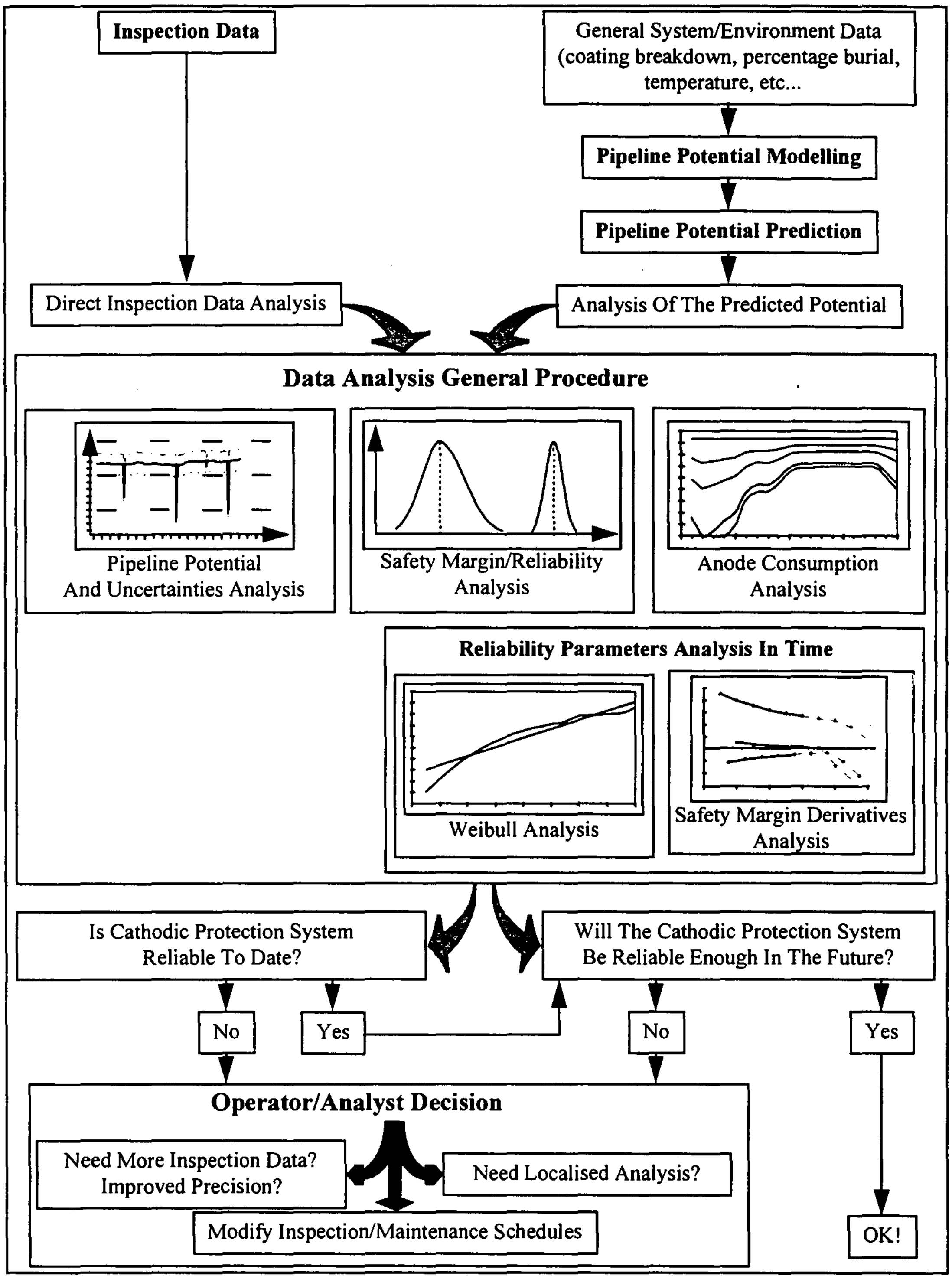

Figure 10.1: Summary of the inspection-reliability analysis methodology.

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Appendices

Appendix 1: Anode Material Characteristics

Anode material	Density (kg/m^3)	Environment	Temperature (^oC)	Driving Potential (mV)	Capacity (Ah/kg)	Open Circuit Potentia l (mV)	Consumption Rates (kg/A/Yr)
Al-Zn-Hg	-	seawater	5-30	200-500	2600-2800	-1050	3.1-3.4
Al-Zn-In	-	seawater	5-30	250-300	2500-2700	-1100	3.2-3.5
"	-	saline mud	30-90	100-200	400-1300	-1100	6.7-22
"	-	saline mud	5-30	150-250	1300-2300	-1100	3.85-6.7
Al-Zn-Sn	-	seawater	25	-	925-26000	-	3.4-9.5
Mg (High purity)	1799	seawater	-	-	1230	-	7.1
Zn	6920	seawater	-	200-250	760-780	-	11.2-11.5
"	6920	saline mud	25	-	750-780	-	11.2-11.7
"	6920	saline mud	0-60	150-200	760-780	-	11.2-11.5
Zn (US Mil. Spec.)	6920	seawater	25	-	760-780	-	11.2-11.5
Zn-Al-Cd	-	-	-	-	780	-1050	-

Appendix 2: Anode Type Characteristics

Anode Type	Model	Minimum u*	Maximum u*
Bracelet	basic bracelet	0.8	0.85
Long	long slender stand-off type	0.9	0.95
Plate		0.75	0.85
Sled	remote anode connected by cable.	-	-

*u: utilisation factor, dimensionless.

Appendix 3: Cathodic Protection Coatings Characteristics

Characteristics	l.e.	t°	% cb			i (mA/ m^2)		
Coatings			init	mean	final	init	mean	final
Thick film pipeline coatings	25	-	1	10	20	-	-	-
Vinyl systems	25	-	2	20	50	-	-	-
Epoxy high build	25	-	2	20	50	-	-	-
Rubber	25	-	1	5	10	-	-	-
Polyethylene (2-3 mm)	25	-	0.5	5	10	-	-	-
Reinforced bitumen on tar	25	-	1	10	20	-	-	-
Epoxy coal tar (0.3 mm)	25	60-80	2	20	50	13	20	26
Epoxy coal tar	-	<25	2	20	50	2	9	15
Epoxy coal tar	-	25-40	2	20	50	5	12	18
Epoxy coal tar	-	40-60	2	20	50	8	16	22
Epoxy coal tar	-	60-80	2	20	50	13	20	26

l.e.:life expectation (yrs), temperature (°C), %cb: percentage of coating breakdown in percent, according to DNV ([DNV, 93]), i: through coating current density (mA/m^2).

Appendix 4: Guidance On Design Current Densities For Cathodic Protection

Sea	i* initial	i* mean	i* final
Arabian Gulf	130	70	90
Australia	130	70	90
Brazil	130	70	90
Gulf of Mexico	110	60	80
India	130	70	90
Indonesia	110	60	80
North Sea (Northern)	180	90	120
North Sea (Southern)	150	90	100
West Africa	130	70	90

Table A4.1: Guidance on design current densities in mA/m^2 ([DNV, 93]).

Oxygen Concentration (ppm) Linear flowrate (m/s)	6	7	8	9	10
0	68	80	91	120	124
0.3	78	91	105	118	123
0.4	82	85	109	123	136
0.6	89	103	118	133	148
1	102	119	136	153	170
2	136	159	182	205	227
4	205	239	273	307	341

Table A4.2: Maximum current densities (mA/m^2) versus oxygen concentration and flowrate.

Appendix 5: Data Input Interface: Main Windows and Data Presentation Graphs

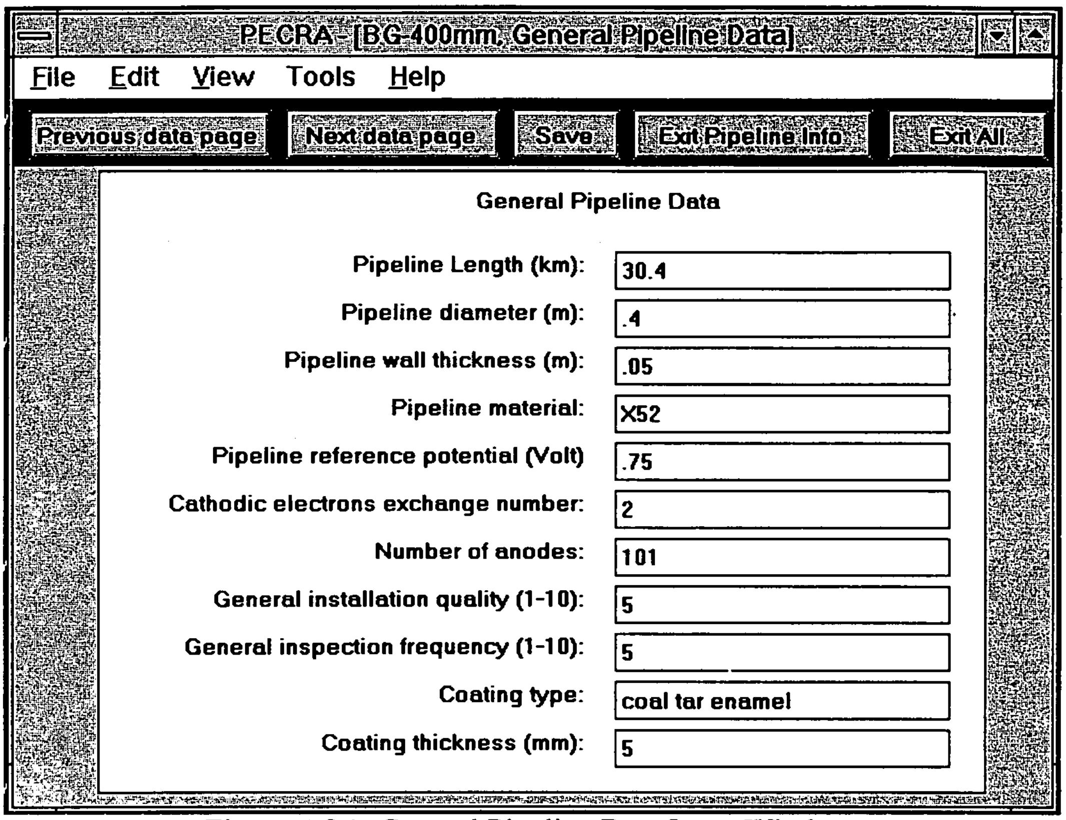

Figure A5.1: General Pipeline Data Input Window.

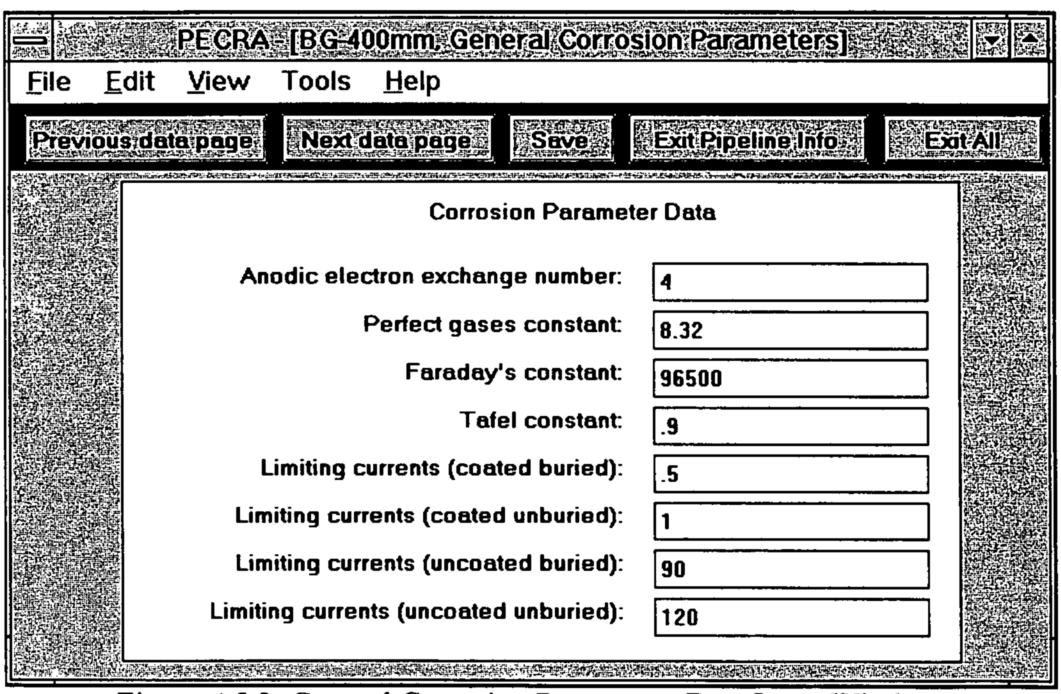

Figure A5.2: General Corrosion Parameters Data Input Window.

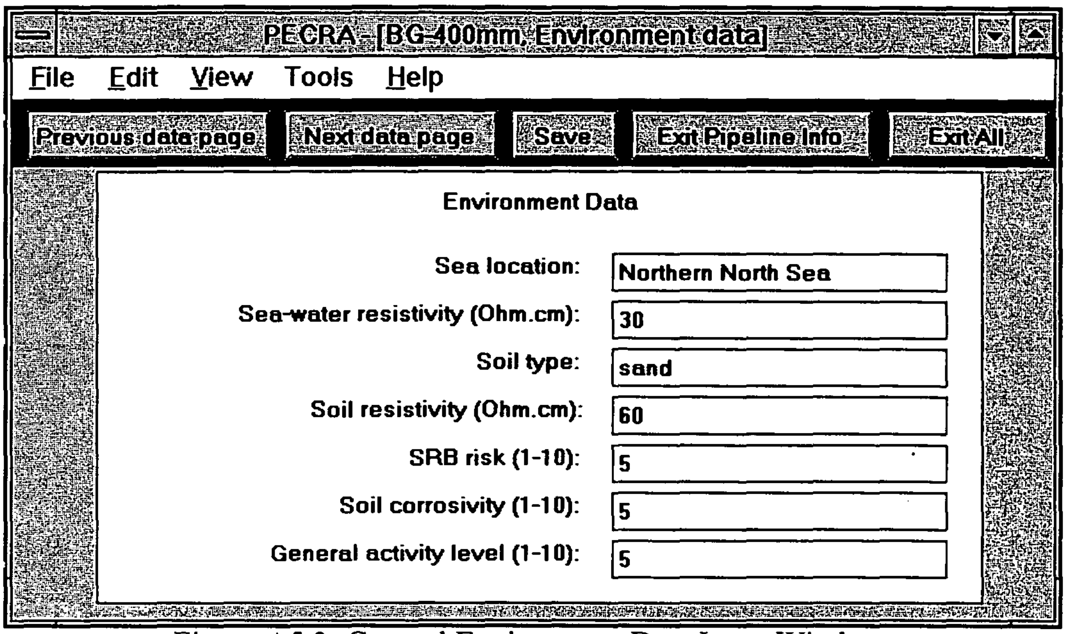

Figure A5.3: General Environment Data Input Window.

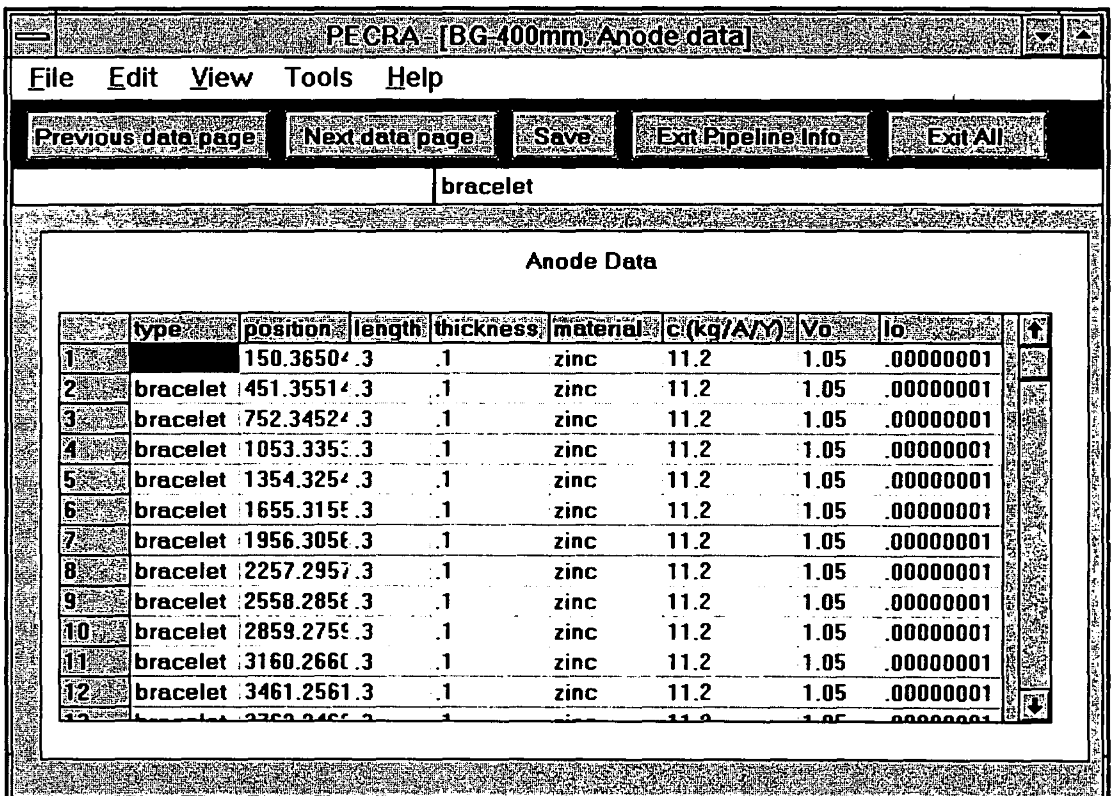

Figure A5.4: Anode Data Input Window.

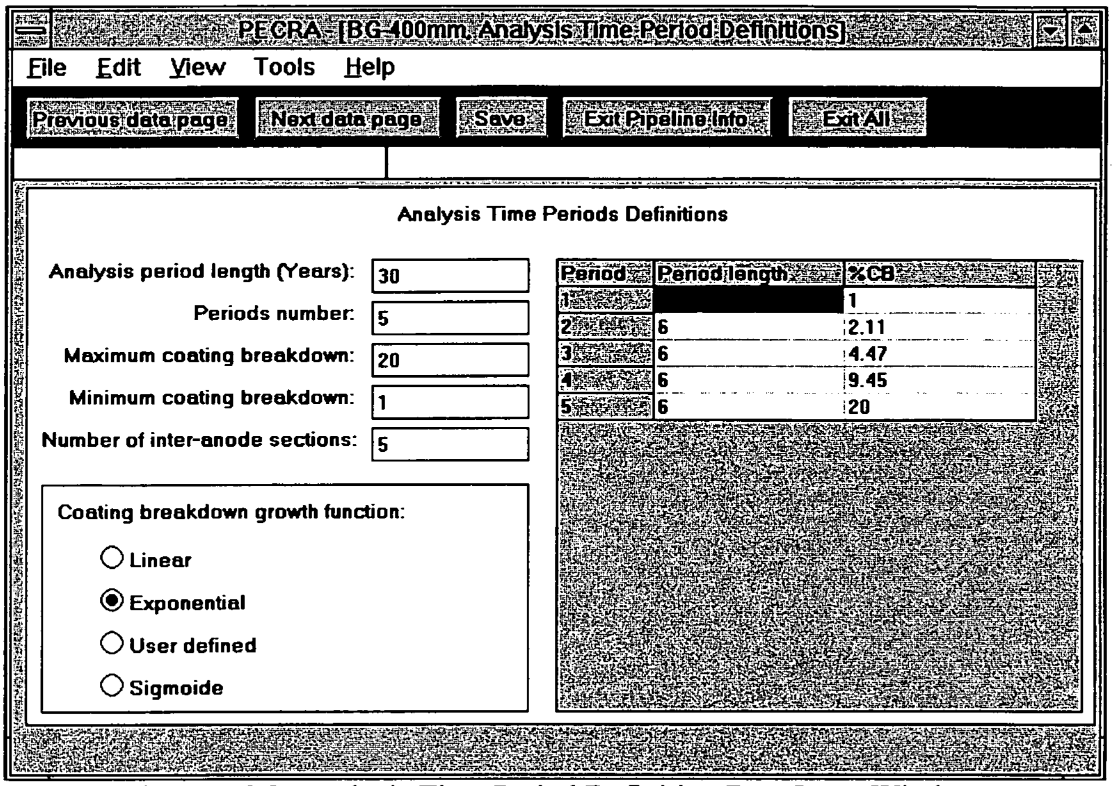

Figure A5.5: Analysis Time Period Definition Data Input Window.

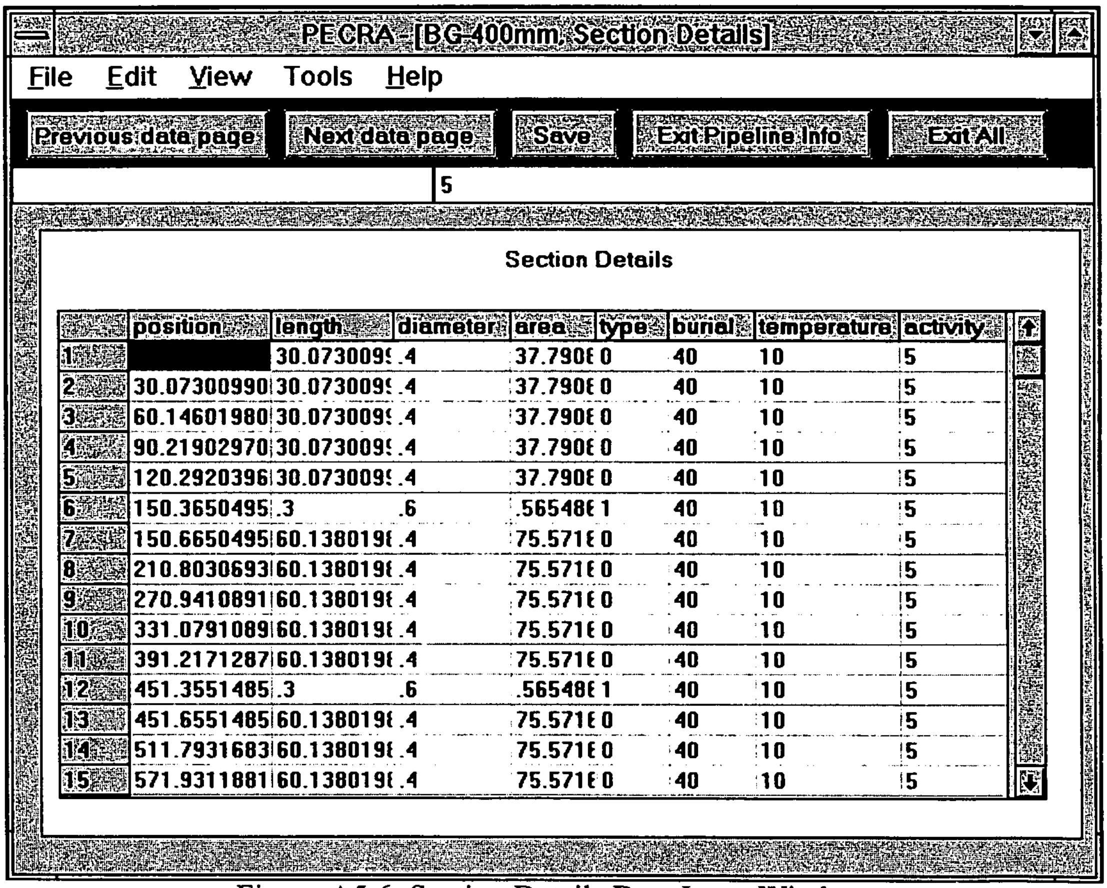

Figure A5.6: Section Details Data Input Window.

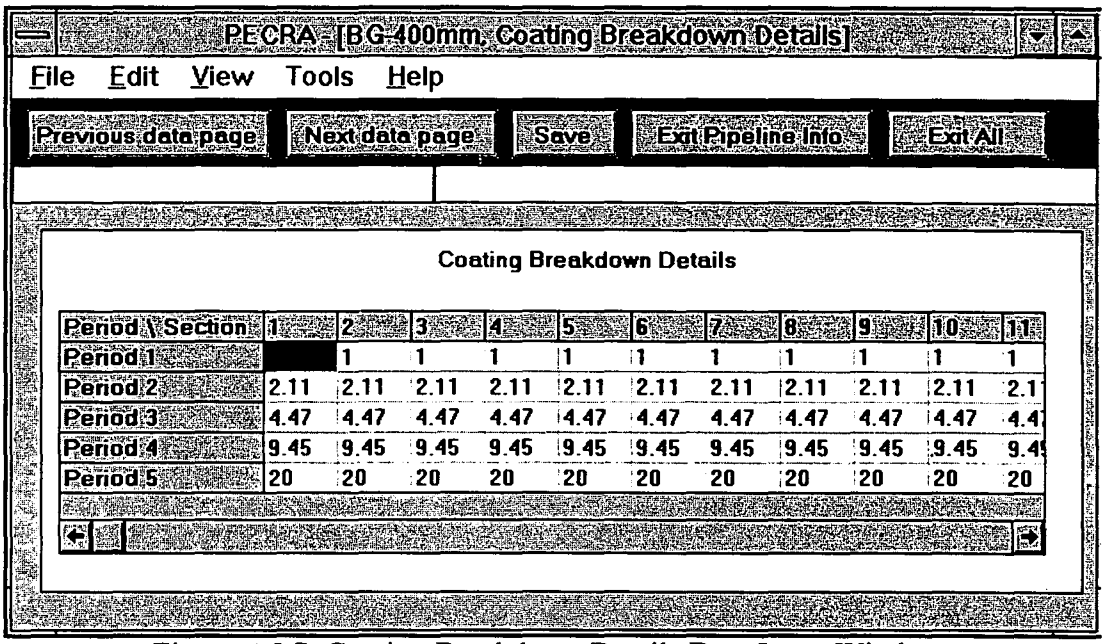

Figure A5.7: Coating Breakdown Details Data Input Window.

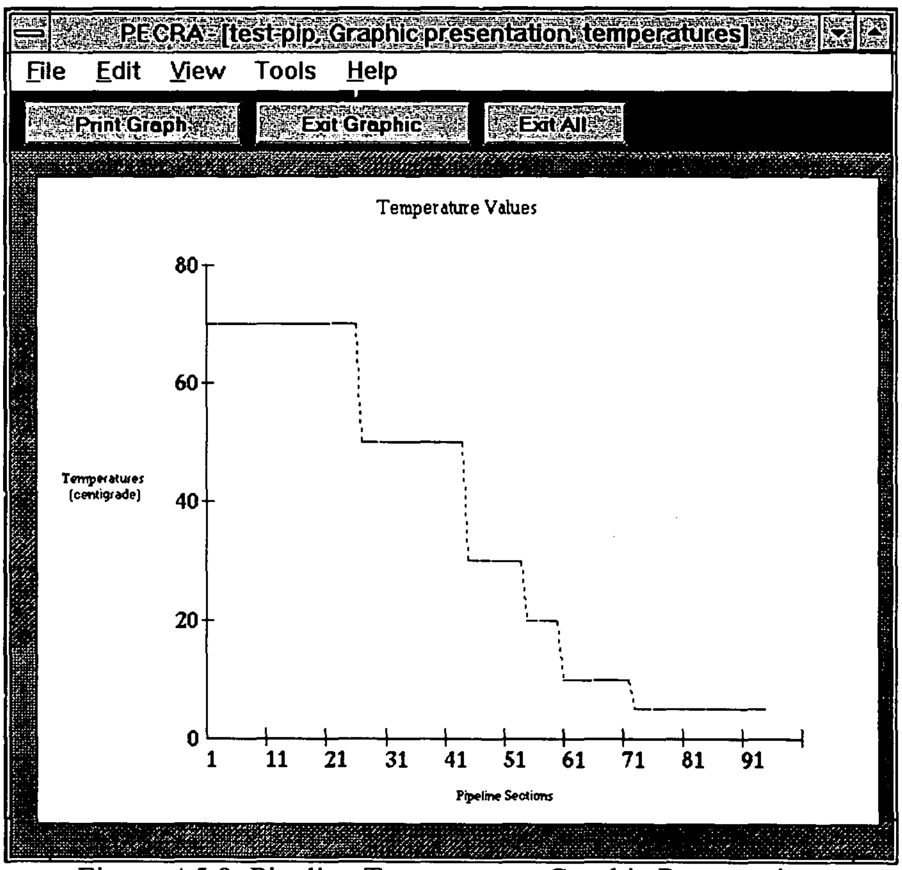

Figure A5.8: Pipeline Temperatures Graphic Presentation.

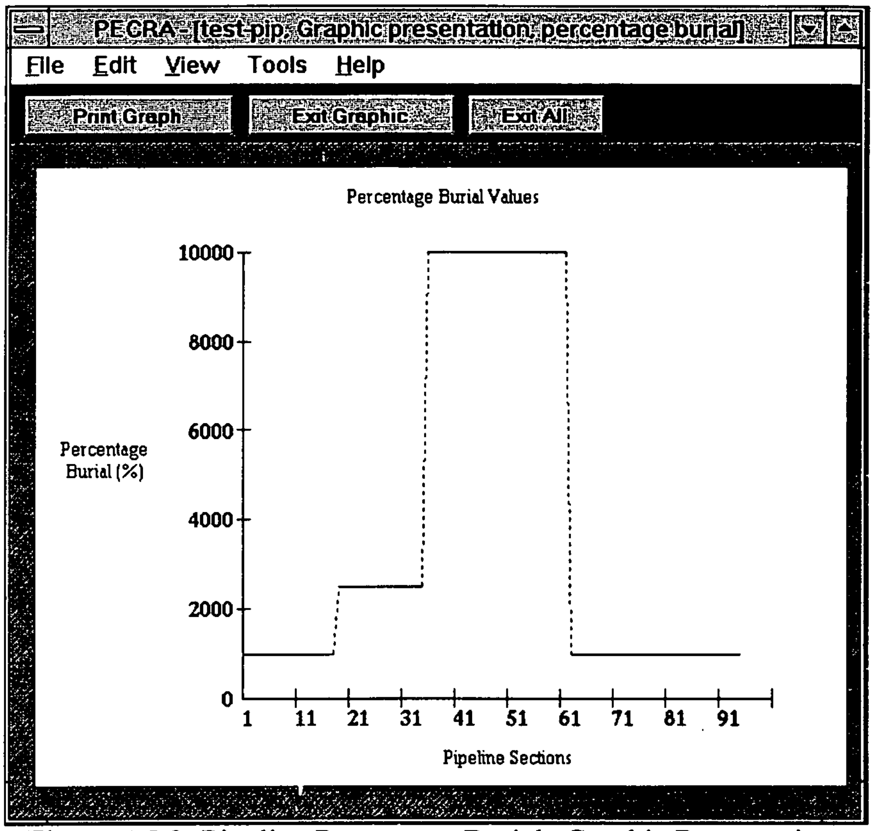

Figure A5.9: Pipeline Percentage Burials Graphic Presentation.

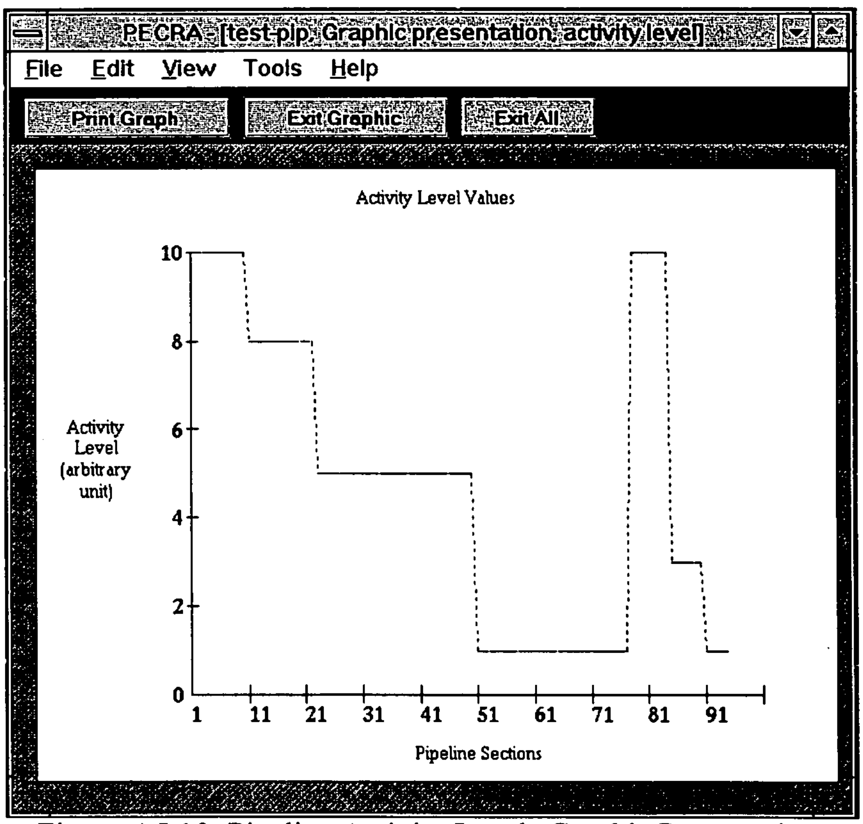

Figure A5.10: Pipeline Activity Levels Graphic Presentation.

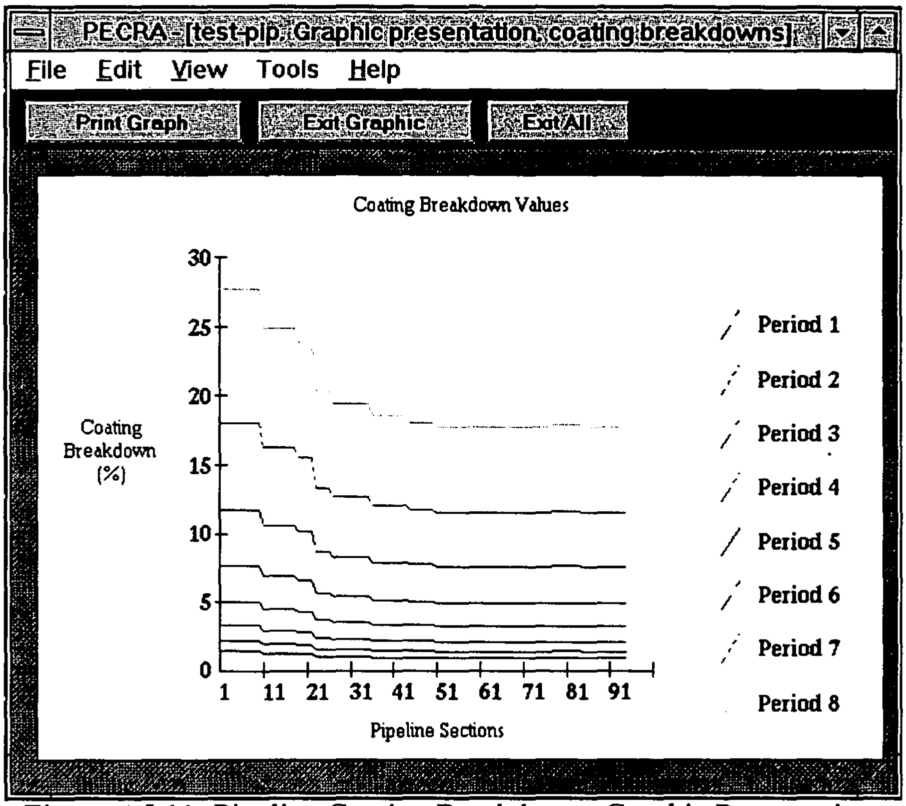

Figure A5.11: Pipeline Coating Breakdowns Graphic Presentation.

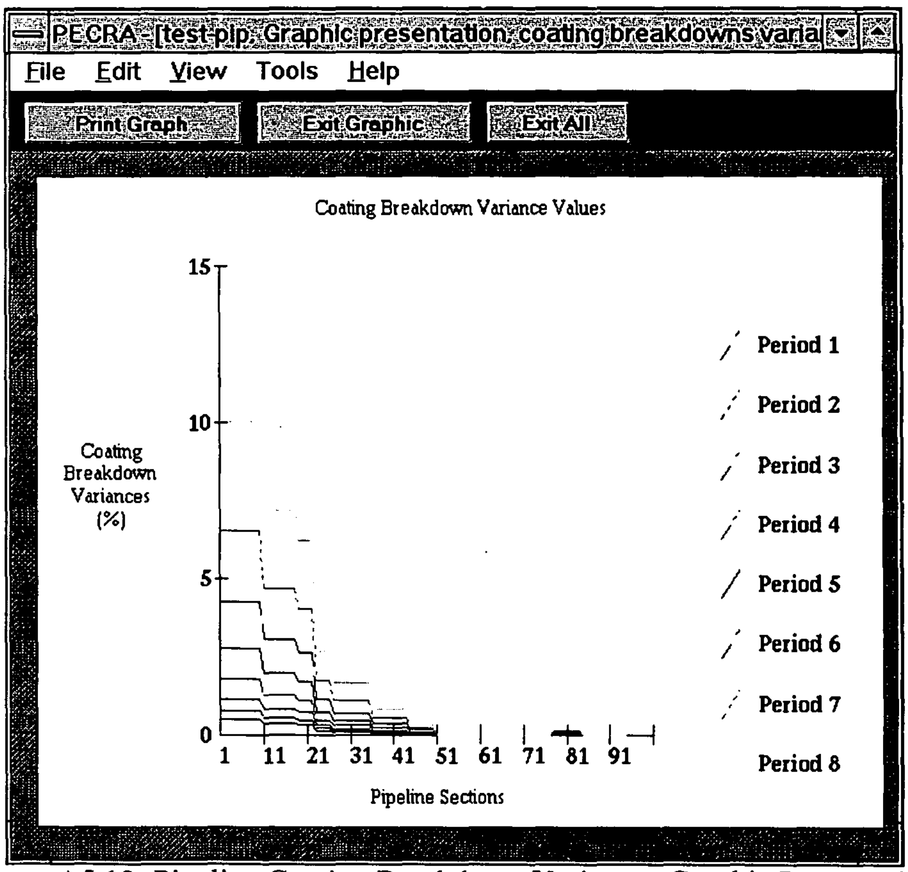

Figure A5.12: Pipeline Coating Breakdown Variances Graphic Presentation.

Appendix 6: List Of Parameters

The following parameters are used to describe and define the pipeline and its environment. These are listed in the way they are used in the software.

	Parameter name	Parameter description	Number of elements
1	pipe_length	length of the pipeline (m)	1
2	pipe_radius	radius of the pipeline (m)	1
3	anode_radius	radius of the anodes (m)	1
4	anode_length	initial length of the anodes (m)	1
5	nb_anodes	number of anodes	1
6	anode_position	position of the anodes along the pipeline (m)	nb_anodes
7	nb_sections	number of section in between two anodes (initial design value)	1
8	N	total number of sections (anodes and cathodes) considered	1
9	section_position	position of the end of each section	N + 1
10	nb_s	number of sections in between two anodes (table)	nb_anode +1
11	section_type	type of each section (0: cathode; 1: anode)	N + 1
12	section_area	area of each section	N + 1
13	life_time	required lifetime of the system	1
14	nb_periods	number of periods	1
15	L	length of each period	nb_period +1
16	i_c_b, i_c_u, i_u_b, i_u_u	values of the cathodic current demand	4
17	percent_burial	percentage of burial for each section	N
18	coating_breakdown	values of the coating breakdown for each section and each period of time	nb_periods * N
19	coating breakdown uncertainties	values of the coating breakdown uncertainties for each section and each period of time	nb_periods * N
20	T	temperature of each section	N+1
21	n	number of electron exchanged in the anodic process	1
22	GP_constant	values of the perfect gases constant	1
23	F	Faradays' constant	1
24	alpha		1
25	sea_resistivity	sea resistivity	1
26	soil_resistivity	soil resistivity	1
27	anode_type	type of the anode material (code for each material)	1

Appendix 7: Details About The Computation Of Conductances And Resistances

VII.A. General Solution of the Field Potential Equation

VII.A.1. Polar Expression of the Field Potential

The model developed is based on the basic field gradient expression ([Smythe, 89]):

$$\nabla^2 V = 0 \qquad \text{(Equ. A7-1)}$$

If we consider that the current density i can be expressed as:

$$i = \frac{\nabla \varepsilon}{\tau} = \sigma \,.\, \nabla \varepsilon \qquad \text{(Equ. A7-2)}$$

where: ε is the electromotance,
τ is the volume resistivity,
σ is the volume conductivity.

and that:

$$E = \nabla \varepsilon = - \nabla V \qquad \text{(Equ. A7-3)}$$

we obtain:

$$- \sigma \,.\, \nabla V = - i \qquad \text{(Equ. A7-4)}$$

where: - σ is the environment conductivity,
- ∇V is the Laplacian of the potential,
- i is the current density.

Considering that the initial current values are known and equal to the cathodic current demand for the cathodic area and to their balance at the anodes, it is possible to solve this equation by using a Fourier analysis. For this analysis, the basic element considered consists of half a pipeline section linked to two half anodes. The analysis is carried out for each segment of pipeline (that is sections of pipeline located between two anodes).

It is in the first place necessary to assess the values of potentials and current densities in the different parts of the system. This is done by solving the field gradient expression presented earlier on (Equation A7-1). We can express this equation in a polar reference system as:

$$\frac{\partial^2 V}{\partial \rho^2} + \frac{1}{r} \cdot \frac{\partial V}{\partial \rho} + \frac{1}{\rho^2} \cdot \frac{\partial^2 V}{\partial \Phi^2} + \frac{\partial^2 V}{\partial z^2} = 0 \qquad \text{(Equ. A7-5)}$$

(ρ, Φ and z being the co-ordinates in a polar reference frame)

Next step consist of solving this expression in order to achieve an expression of the potential and current at different distance of the pipeline, and at different positions along it.

VII.A.2. Decomposition of the Equation

If we consider that the value of the potential does not change with the polar angle Φ (viz. the value of the potential is uniform around the pipeline), then we can express the value of the potential as follows:

$$V = R(\rho) \, . \, Z(z) \qquad \text{(Equ. A7-6)}$$

where: ρ is the distance to the pipeline (relatively to the centre of the pipeline, in meters),
z is the position along the pipeline (in meters).

By combining this expression and Equation A7-5 we obtain:

$$Z(z) \, . \, \left(\frac{\partial^2 R(\rho)}{\partial \rho^2} + \frac{1}{\rho} \cdot \frac{\partial R(\rho)}{\partial \rho}\right) + R(\rho) \cdot \frac{\partial^2 Z(z)}{\partial z^2} = 0 \qquad \text{(Equ. A7-7)}$$

Which can be expressed as follows:

$$\frac{\left(\frac{\partial^2 R(\rho)}{\partial \rho^2} + \frac{1}{\rho} \cdot \frac{\partial R(\rho)}{\partial \rho}\right)}{R(\rho)} = - \frac{\frac{\partial^2 Z(z)}{\partial z^2}}{Z(z)} = k \qquad \text{(Equ. A7-8)}$$

where the parameter k is a constant. We can then split this equation into a z depending equation and a ρ depending one. We have:

Equation depending on z: $\frac{\partial^2 Z(z)}{\partial z^2} + k \cdot Z(z) = 0$ (Equ. A7-9)

Equation depending on ρ: $\frac{\partial^2 R(\rho)}{\partial \rho^2} + \frac{1}{r} \cdot \frac{\partial R(\rho)}{\partial \rho} - k \cdot R(\rho) = 0$ (Equ. A7-10)

VII.A.3. Solution of the z Dependant Equation

The solution of the first equation is of the type:

$$Z(z) = \cos(\alpha \cdot k) \qquad \text{(Equ. A7-11)}$$

or: $$d^2Z(z) = -\alpha^2 \cos(\alpha \cdot k) \cdot dz^2 \qquad \text{(Equ. A7-12)}$$

By replacing this expression of Z(z) in Equation A7-9, we get:

$$k = +\alpha^2 \qquad \text{(Equ. A7-13)}$$

What is more, the Z function is periodic of period 2*l* (2*l* being the length of the section analysed). We therefore have:

$$\alpha = \frac{2 \cdot \pi \cdot m}{2 \cdot l} \qquad (\forall m \subset \aleph)$$

$$\alpha = \frac{\pi \cdot m}{l} \qquad (\forall m \subset \aleph) \qquad \text{(Equ. A7-14)}$$

and $$k = \left(\frac{m \cdot \pi}{l}\right)^2 \qquad (\forall m \subset \aleph) \qquad \text{(Equ. A7-15)}$$

We can therefore write that an expression of Z is:

$$Z_n(z) = \cos\left(\frac{\pi \cdot m \cdot z}{l}\right) \qquad (\forall n \subset \aleph) \qquad \text{(Equ. A7-16)}$$

VII.A.4. Solution of the r Depending Equation

If we now consider the expression of k obtained earlier on (Equation A7-15), we can rewrite the equation A7-10 as:

$$\frac{\partial^2 R(\rho)}{\partial(\rho)^2} + \frac{1}{\rho}\cdot\frac{\partial R(\rho)}{\partial(\rho)} - (\frac{m\cdot\pi}{l})^2\cdot R(\rho) = 0 \qquad \text{(Equ. A7-17)}$$

If we consider k' as: $k' = \frac{\pi . m}{l} \qquad (\forall m \subset \aleph)$

We obtain:

$$\frac{\partial^2 R(\rho)}{\partial(\rho)^2} + \frac{1}{\rho}\cdot\frac{\partial R(\rho)}{\partial(\rho)} - (k')^2\cdot R(\rho) = 0 \qquad \text{(Equ. A7-18)}$$

A Bessel's function is solution of this type of equation ([Maclachlan, 46]). The variable of the solution is defined as ρ, the distance to the centre of the pipeline. We have:

$$R_n(\rho) = K_0(\frac{\pi\cdot m\cdot\rho}{l}) \qquad (\forall m \subset \aleph) \qquad \text{(Equ. A7-19)}$$

VII.A.5. Expression of the General Potential Solution

Combining the previous results, we can say that the general solution of our equation is obtained by summing the previous expressions for all the values of n. We have then (from Equation A7-6, A7-16, and A7-19):

$$V(\rho, z) = \sum_{m=1}^{\infty} A_m \cdot \cos(\frac{\pi\cdot m\cdot z}{l})\cdot K_0(\frac{\pi\cdot m\cdot\rho}{l}) \qquad \text{(Equ. A7-20)}$$

This is a general solution for our system, and it is necessary to determine the A_n coefficients by introducing the boundary conditions. We use then the values of the limiting currents defined earlier on, and the basic field equation (Equation A7-1).

VII.A.6. Expression of the General Current Density Solution

Using the initial equation linking i and V (Equation A7-1), and considering the radial term of the equation only (current flowing perpendicularly to the pipeline surface), we obtain:

$$i(\rho, z) = (-\sigma) . \frac{\partial V(\rho, z)}{\partial \rho} \qquad \text{(Equ. A7-21)}$$

where σ is the volume conductivity ($\Omega^{-1}.m^{-1}$).

This gives if we reuse Equation A7-20, we obtain ([Maclachlan, 46]):

$$i(\rho, z) = \sigma \cdot \sum_{m=1}^{\infty} A_m \cdot \cos(\frac{\pi \cdot m \cdot z}{l}) \cdot \frac{\pi \cdot m}{l} \cdot K_1(\frac{\pi \cdot m \cdot \rho}{l}) \qquad \text{(Equ. A7-22)}$$

We now have an expression of i and V in function of ρ and z, but we still have to determine the values of the A_n. In order to do so, we built another expression of the current densities along the pipeline by using the Fourier analysis.

VII.B. Integration of the Boundary Conditions

VII.B.1. Basic Model and Discretisation

In the model defined, the pipeline is divided into sections consisting of half a pipeline segment and two half anodes. The only parameters known are the global values of the environment conductivity, and the values of the current densities at the surface of the pipeline.

Each section is analysed separately. For each one, a theoretical infinite pipeline is created by duplicating infinitely the section considered, as shown in Figure 7-1. Proceeding this way, it is possible to use elaborate mathematical tools such as Fourier analysis in order to define values for the current densities, potential and thus conductances and resistances along the pipeline.

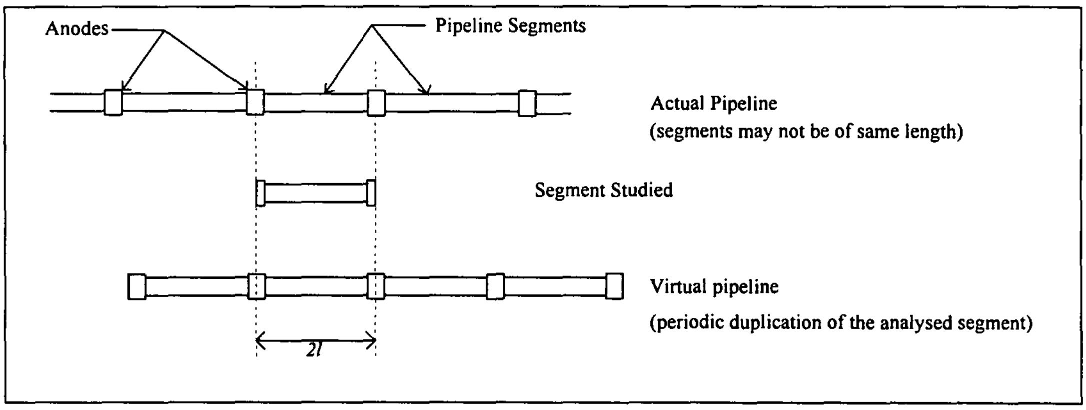

Figure A7-1: Definition of the model used for the conductance/resistance calculations.

The pipelines segments are then divided into sections, each of those being linked to a node of the mathematical model. It is therefore necessary to discretise the present model in order to be able to calculate average values of the conductances and resistances for the different sections.

If we consider that each segment of the pipeline analysed is divided into N sub-sections, we can associate each of these sections to a value of current density, as presented on Figure A7-2.

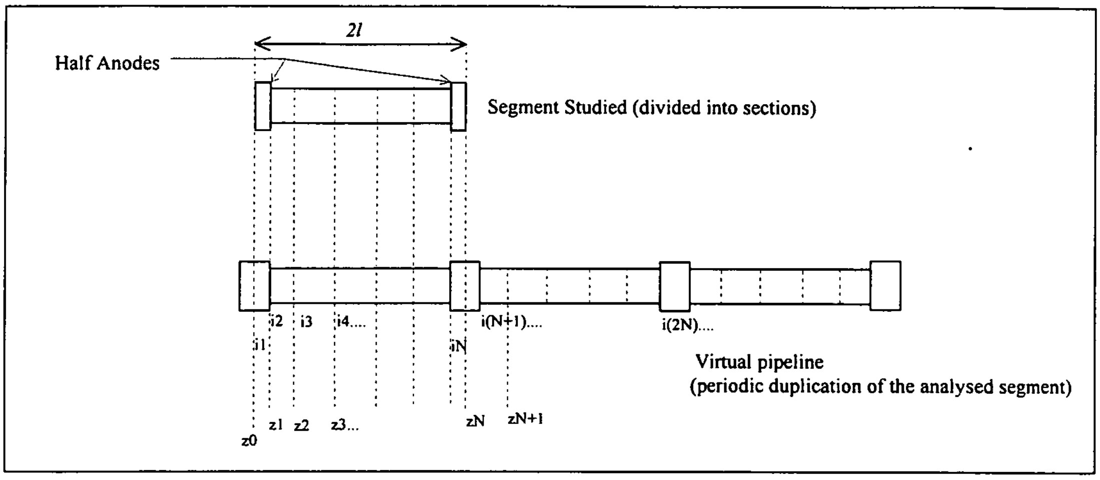

Figure A7-2: Pipeline discretisation: division of the segments into sections for the calculations of the conductances/resistances.

It is therefore necessary to reiterate this analysis on each section of the pipeline.

VII.B.2. Fourier Expression of the Current Densities

The values of the currents densities at the surface of this fictive pipeline are periodical, and can be modelled by the mean of a Fourier series. We consider that we have:

$$i(z) = \sum_{m=1}^{\infty} c_m \,.\, \cos\left(\frac{\pi.m.z}{l}\right) \qquad \text{(Equ. A7-23)}$$

where: z is the abscisse of the point considered,

l is half the length of the segment analysed,

c_n is the coefficients of the Fourier series ($n \subset \aleph$).

According to the Fourier formula, the values of the coefficients c_n are given by the following integral ([Maclachlan, 46]):

$$c_m = \frac{1}{l} \int_{-l}^{l} i(z) \,.\, \cos\left(\frac{\pi \cdot m \cdot z}{l}\right) dz \qquad \text{(Equ. A7-24)}$$

In the model, the current densities are averaged and considered as constant over the length of each section. Therefore, we note i_n the values of the current density over the length of the section running between z_{n-1} and z_n (see Figures A7-2 and A7-3). These values are also considered as periodical, and we have:

$i_n = i_{n+kN}$ $(\forall k \subset \aleph, \forall n \subset \{1,2,...N\}$, N being the number of sections defined)

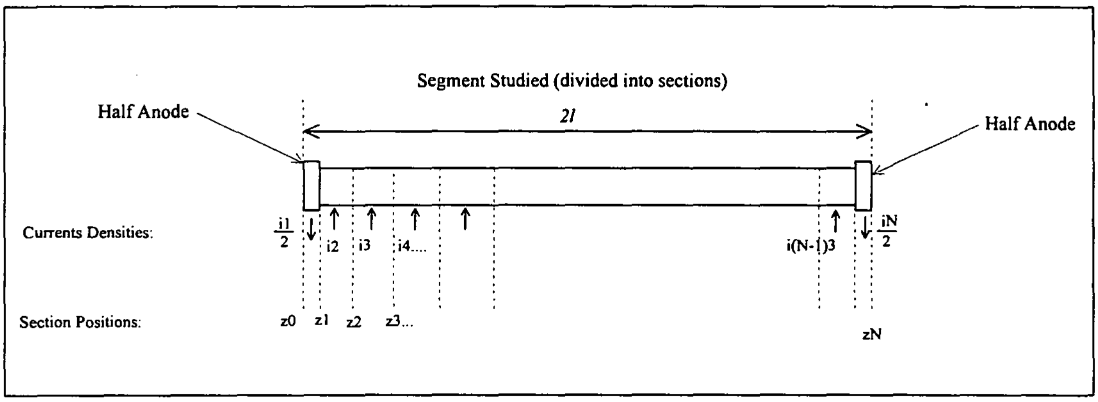

Figure A7-3: Details of the division of the pipeline segment analysed into sections.

The values of these currents are defined as being the minimum current densities for the cathodic sites (surface of the pipeline). The values of the current densities for the anodic sites (anodes) is calculated in order to balance the cathodic current.

If we now consider the sections defined for each segment in order to discretise, we can write that :

$$c_m = \sum_{n=1}^{n=N} \int_{l_{n-1}}^{l_n} i_n \cdot \cos\frac{\pi.m.z}{l} \, . dz \qquad (\forall m \subset \aleph) \qquad \text{(Equ. A7-25)}$$

i_n being a constant, we can express the previous equation as follows:

$$c_m = \sum_{n=1}^{n=N} \frac{2}{l} \cdot i_n \cdot \left[\frac{1}{\pi \cdot m} \cdot \sin(\frac{\pi \cdot m \cdot z}{l}) \right]_{z_{n-1}}^{z_n} \qquad (\forall m \subset \aleph) \qquad \text{(Equ. A7-26)}$$

We also consider that the sum of current at the anode is the same as the sum of the cathodic current for the segment analysed,

$$z_1 \cdot \frac{i_i}{2} + z_N \cdot \frac{i_N}{2} = \sum_{n=2}^{n=(N-1)} i_n . z_n \qquad \text{(Equ. A7-27)}$$

By splitting the anodic and cathodic sections, we obtain:

$$c_m = \frac{2}{\pi \cdot m} \cdot i_{a1} \cdot \sin(\frac{\pi . m . z_1}{l}) + \sum_{n=2}^{n=N-1} \frac{2 \cdot i_n}{\pi \cdot m} \cdot (\sin \frac{\pi . m . z_n}{l} - \sin \frac{\pi . m . z_{n-1}}{l}) - \frac{2}{\pi \cdot m} \cdot i_{aN} \cdot \sin(\frac{\pi . m . z_{N-1}}{l}) \qquad \text{(Equ. A7-28)}$$

This expression can then be replaced into the initial Fourier expression of i(z) (Equation A7-23 p.174), which gives:

$$i(z) = \sum_{m=1}^{\infty} \frac{2}{\pi \cdot m} \cdot \left[\begin{array}{l} (i_{a1} \cdot \sin(\frac{\pi . m . z_1}{l}) \\ + \sum_{n=2}^{n=N-1} i_n \cdot (\sin \frac{\pi . m . z_n}{l} - \sin \frac{\pi . n . z_{n-1}}{l}) \\ - i_{aN} \cdot \sin(\frac{\pi . m . z_{N-1}}{l}) \end{array} \right] \cdot \cos(\frac{\pi \cdot m \cdot z}{l})$$

(Equ. A7-29)

VII.B.3. Determination of Series Terms

By equating the expression of the current density for $\rho = \rho_0$ (Equation A7-22 p.173) and equation A7-23, we obtain the following expression:

$$i(\rho_0, z) = \sum_{m=1}^{\infty} c_m \cdot \cos(\frac{\pi . m . z}{l}) = \sigma \cdot \sum_{m=1}^{\infty} A_m \cdot \cos(\frac{\pi \cdot m \cdot z}{l}) \cdot \frac{\pi \cdot m}{l} \cdot K_1(\frac{\pi \cdot m \cdot \rho_0}{l})$$

(Equ. A7-30)

Two infinite series being equal only when all their terms are equal, we can write that:

$$A_m = \frac{c_m}{\sigma \cdot \frac{\pi \cdot m}{l} \cdot K_1(\frac{\pi \cdot m \cdot \rho_0}{l})} \qquad \text{(Equ. A7-31)}$$

(c_m being given by Equation A7-28).

VII.C. Discretised Expression of the Potentials

VII.C.1. General Expression of the Potentials

The previous results give an expression of the potentials along the pipeline at different distance away from the pipeline surface (see Equation A7-20 (p.172) with an expression of A_m in Equation A7-31). This can be expressed as follows:

$$V(\rho, z) = \sum_{m=1}^{\infty} \frac{c_m \cdot l \cdot \cos(\frac{\pi \cdot m \cdot z}{l}) \cdot K_0(\frac{\pi \cdot m \cdot \rho}{l})}{\sigma \cdot \pi \cdot m \cdot K_1(\frac{\pi \cdot m \cdot \rho_0}{l})} \qquad \text{(Equ. A7-32)}$$

the c_m being expressed in Equation A7-28.

VII.C.2. Discrete Expression of the Potentials

We now need a discrete expressions of the potential values. These can be achieved by integrating the general value of the potential over the length of each section defined. We have:

$$V_n = \frac{1}{Z_n - Z_{n-1}} \cdot \int_{Z_{n-1}}^{Z_n} V(\rho, z) \, . \, dz \qquad (\forall n \subset \{1,2,... N\}) \qquad \text{(Equ. A7-33)}$$

By introducing the expression of V(ρ,z) (Equation A7-32), V_n can be expressed as follows:

$$V_n = \frac{1}{Z_n - Z_{n-1}} \cdot \sum_{m=1}^{\infty} \frac{c_m \cdot l \cdot K_0(\frac{\pi \cdot m \cdot \rho}{l})}{\sigma \cdot \pi \cdot m \cdot K_1(\frac{\pi \cdot m \cdot \rho_0}{l})} \int_{Z_{n-1}}^{Z_n} \cos(\frac{\pi \cdot m \cdot z}{l}) \cdot dz \qquad (\forall n \subset \{1,2,... N\})$$

(Equ. A7-34)

$$\Rightarrow V_n = \frac{1}{Z_n - Z_{n-1}} \cdot \sum_{m=1}^{\infty} \frac{c_m \cdot l \cdot K_0(\frac{\pi \cdot m \cdot \rho}{l})}{\sigma \cdot \pi \cdot m \cdot K_1(\frac{\pi \cdot m \cdot \rho_0}{l})} \cdot \left[\frac{\sin(\frac{\pi \cdot m \cdot z}{l})}{\frac{\pi \cdot m}{l}} \right]_{Z_{n-1}}^{Z_n} (\forall n \subset \{1,2,... N\})$$

Which gives eventually:

$$V_n = \sum_{m=1}^{\infty} \left(\frac{l}{\pi \cdot m} \right)^2 \cdot \frac{c_m \cdot \left(\sin(\frac{\pi \cdot m \cdot z_{n-1}}{l}) - \sin(\frac{\pi \cdot m \cdot z_n}{l}) \right)}{\sigma \cdot (z_n - z_{n-1})} \cdot \frac{K_0\left(\frac{\pi \cdot m \cdot \rho}{l}\right)}{K_1\left(\frac{\pi \cdot m \cdot \rho_0}{l}\right)}$$

$(\forall n \subset \{1,2,... N\})$ (Equ. A7-35)

The V_n can then be calculated. For the numerical implementation, it is necessary to determine a level of precision in order to stop the summation process once the terms start to be negligible.

VII.D. Calculation of the Conductances and Resistances

VII.D.1. Calculation of the Field Currents

As said earlier, the pipeline to field currents are estimated for the cathodic sites by using the minimum current densities values. The anodic currents are then calculated so that they balance the cathodic currents.

It is necessary to carry out the calculations by using currents (Amperes) and not current densities (Amperes per squared meters). We therefore have:

$$If_1 = I_1 = i_1 \, . \, A_1$$
$$If_2 = I_1 + If_1 = i_1 \, . \, A_1 + If_1$$
$$If_3 = I_2 + If_2 = i_2 \, . \, A_2 + If_2$$
....
$$If_{N-1} = I_{N-2} + If_{N-2} = i_{N-2} \, . \, A_{N-2} + If_{N-2}$$
$$If_N = I_N = i_N \, . \, A_N$$

where: If_i are the values of the field currents (in Amperes, $\forall i \subset \{1,2,...N\}$),
I_i are the values of the pipeline to field currents (Amperes, $\forall i \subset \{1,2,...N\}$),
i_i are the values of the current densities (in Amperes per square meters, $\forall i \subset \{1,2,...N\}$),
A_i are the values of the section areas (in square meters, $\forall i \subset \{1,2,...N\}$),

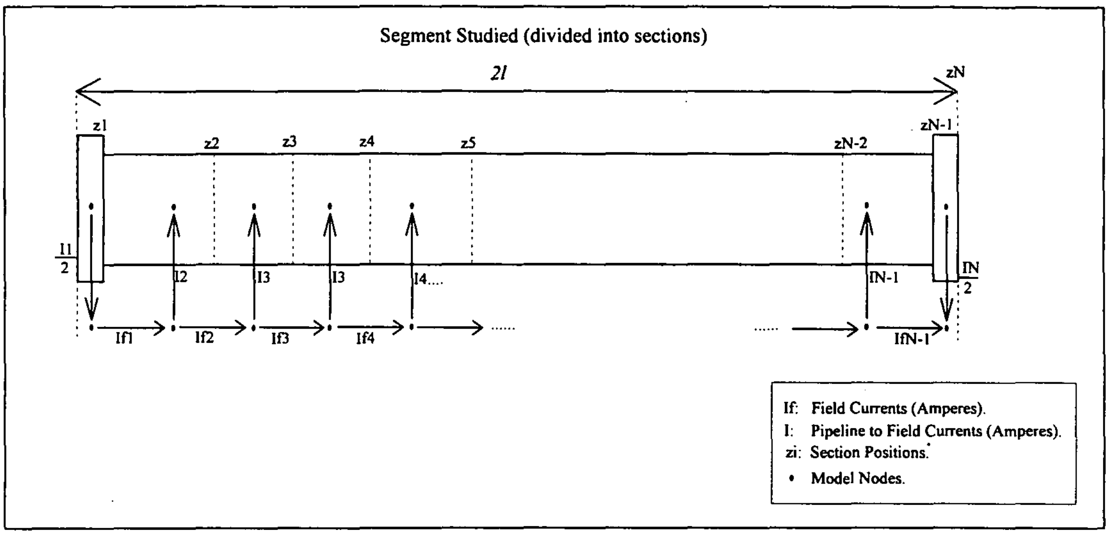

Figure A7-4: Details of the nodes and currents distributions.

These values can then be used with calculated values of the potentials for the calculations of the conductances and resistances.

VII.D.2. Calculation of the Conductances and Resistances

We can now make an estimation of the values of the conductances and resistances of the system. The basic Ohm law gives us:

$$R = \frac{V}{I} \qquad \text{(Equ. A7-36)}$$

or:

$$G = \frac{I}{V} \qquad \text{(Equ. A7-37)}$$

In the present model and considering the initial notation used for the system, we can write:

$$G_{fn} = \frac{If_n}{V_{n+1}(\rho) - V_n(\rho)} \qquad (\forall n \subset \aleph) \qquad \text{(Equ. A7-38)}$$

where ρ is the distance away from the pipeline at which the field potential is calculated.

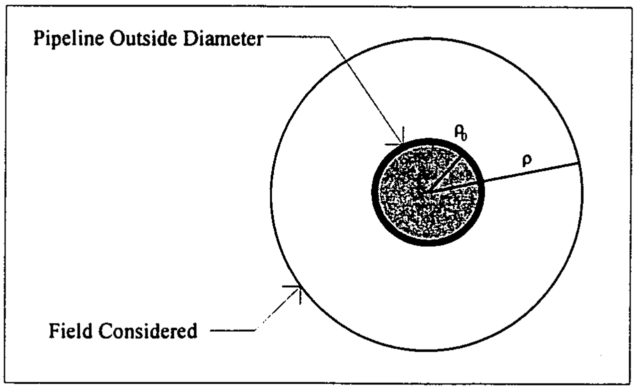

Figure A7-5: Representation of the field taken into account in calculations.

As for the values of the resistances in between the pipeline surface and the field, we have:

$$R_n = \frac{V_n(\rho_0) - V_n(\rho)}{I_n} \qquad (\forall m \subset \aleph) \qquad \text{(Equ. A7-39)}$$

These formula are suitable for any section of the pipeline. It is always necessary to check that the values of I_n and $(V_{n-1} - V_n)$ are not null or too low, as this may create a problem when implementing the software model.

VII.D.3. Particular Nodes

At the anode level, it is nevertheless necessary to modify the result as in this model, the anode is divided in two parts. Therefore, the final value of the resistance at this level is then obtained by considering that the two adjacent half-anodes are linked in parallel. We have:

$$\frac{1}{R_A} = \frac{1}{R_I} + \frac{1}{R_N^*} \qquad \text{(Equ. A7-40)}$$

R_N* being the values of the resistance for the adjacent half-anode: its value is calculated either with the previous or the next segment.

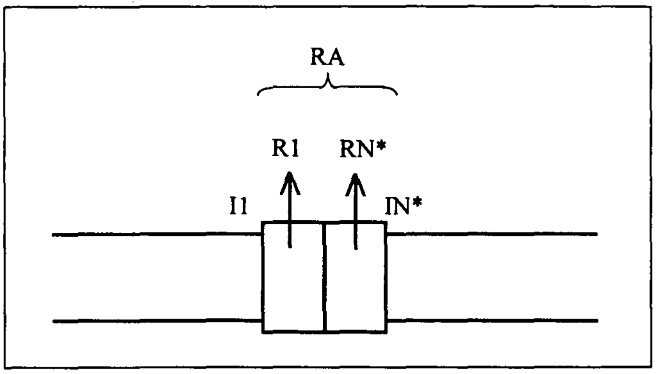

Figure A7-6: Calculation of the global anode resistance value.

As for the conductances calculations, it is necessary to check the values of the potentials in case of a perfectly symmetrical case. It may happen in this case that the values of the potential are so close that the difference is null (see Equation A7-38).

VII.E. Non-dimensional Equations

VII.E.1. Reason for the Non Dimensionalisation

In the model presented, several dimensional characteristics of the pipeline are to be taken into account. The main dimensional parameters are listed below:

- the lengths of the segments (equal to the anodes spacing),
- the length of the defined sections,
- the diameter of the pipeline,
- the level of the current densities considered,
- the environment conductivity.

When we come to consider actual pipelines, it appears that these parameters may vary by up to a factor ten. Although this remains a reasonable factor, it may have significant effect on the results when considering for example the Fourier series sums calculated in this case (see Equation A7-32 p.177), and the ratio used to calculate the conductances and resistances values (see Equation A7-39 p.180).

In both these calculations, precision parameters are used, for example in order to terminate the summation of the series. These precision parameters are integrated into the numerical model used to carry out these calculations. The dimensional aspect of the model may then affect the calculations, and the result may in certain cases be drastically modified.

In order to avoid this problem, it was chosen to reformulate the previously presented equations in order to achieve an non dimensional model.

VII.E.2. Definition of the Non-Dimensional Coefficients

The equations we have to reconsider are:

- the expression of the discretised potentials (Equation A7-35 p.178).
- the expression of the c_m used in the previous equation, actually linked to the expression of the current densities.

If we consider the discretised expression of the potentials (Equation A7-35, p.178) and the expression of the Fourier coefficients (equation A7-28, p.176) we have :

$$V_n = \sum_{m=1}^{\infty} \left(\frac{1}{\pi \cdot m}\right)^2 \cdot \frac{c_m \cdot \left(\sin(\frac{\pi \cdot m \cdot z_{n-1}}{l}) - \sin(\frac{\pi \cdot m \cdot z_n}{l})\right)}{\sigma \cdot (z_n - z_{n-1})} \cdot \frac{K_0\left(\frac{\pi \cdot m \cdot \rho}{l}\right)}{K_1\left(\frac{\pi \cdot m \cdot \rho_0}{l}\right)}$$

(Equ. A7-35)

and,

$$\begin{aligned} c_m = {} & \frac{2}{\pi \cdot m} \cdot i_{a1} \cdot \sin(\frac{\pi . m . z_1}{l}) \\ & + \sum_{n=2}^{n=N-1} \frac{2 \cdot i_n}{\pi \cdot m} \cdot (\sin \frac{\pi . m . z_n}{l} - \sin \frac{\pi . m . z_{n-1}}{l}) \\ & - \frac{2}{\pi \cdot m} \cdot i_{aN} \cdot \sin(\frac{\pi . m . z_{N-1}}{l}) \end{aligned}$$

(Equ. A7-28)

In these equations, the dimensions are given by the current densities, the length of the analysed segment ($2l$), the lengths of the sections (differences between z_n and z_{n-1}) and the environment conductivity (σ). In order to obtain non dimensional equations, we have to multiply both sides by a factor depending on the system dimensions. In order to eliminate these dimensions, it was decided to use the following coefficient:

$$k = \frac{\sigma}{l \cdot N . i_{moy}}$$

(Equ. A7-41)

where: ρ_0 is introduced in order to compensate for the (z_n and z_{n-1}) differences,

N is the number of sections defined in the segment.

i_{moy} has been added in order to scale the level of the current densities introduced. The expression for this average value is described below,

$$i_{moy} = \frac{\sum_{n=2}^{n=(N-1)} i_n \cdot (z_n - z_{(n-1)})}{(z_{(N-1)} - z_1)} \qquad \text{(Equ. A7-42)}$$

N was introduced in order to limit the effects of this parameter on the values of the non dimensional conductances (when the number of sections increases, their size decreases and the calculated values of the conductances increases). By multiplying by this factor, the non dimensional values are not affected by the number of section defined in the model.

We then obtain for the expression of the potentials:

$$\frac{V_n \cdot \sigma}{l \cdot N \cdot i_{moy}} = \sum_{m=1}^{\infty} \frac{\frac{c_m}{i_{moy}} \cdot \left(\sin(\frac{\pi \cdot m \cdot z_{n-1}}{l}) - \sin(\frac{\pi \cdot m \cdot z_n}{l}) \right)}{(\pi \cdot m)^2 \cdot \frac{(z_n - z_{n-1})}{\frac{l}{N}}} \cdot \frac{K_0\left(\frac{\pi \cdot m \cdot \rho}{l}\right)}{K_1\left(\frac{\pi \cdot m \cdot \rho_0}{l}\right)} \qquad \text{(Equ. A7-43)}$$

The expressions of the non dimensional potential and Fourier coefficients are then defined as:

$$V_{n,non\text{-}dim} = \frac{V_n \cdot \sigma}{l \cdot N \cdot i_{moy}} \qquad \text{(Equ. A7-44)}$$

$$c_{n,non\text{-}dim} = \frac{c_n}{i_{moy}} \qquad \text{(Equ. A7-45)}$$

The modifications on the Fourier coefficients values can then be reported directly into the expression of the current densities. The current densities used will therefore be obtained by simply using a similar expression:

$$i_{n,non\text{-}dim} = \frac{i_n}{i_{moy}} \qquad \text{(Equ. A7-46)}$$

This non dimensionalisation is to be carried out for the cathodic sections. The values of the anodic currents still have to be recalculated so that they always balance the cathodic currents.

VII.E.3. Reformulation of the Equations

As a first step, the initial current density values given for each section are to be scaled using the presented coefficient. Then using these values, the potentials values are to be determined by using the following formula:

$$V_{n,\text{non-dim}} = \sum_{m=1}^{\infty} \frac{c_{m,\text{ non-dim}} \cdot \left(\sin(\frac{\pi \cdot m \cdot z_{n-1}}{l}) - \sin(\frac{\pi \cdot m \cdot z_n}{l}) \right)}{(\pi \cdot m)^2 \cdot \frac{\frac{(z_n - z_{n-1})}{l}}{N}} \cdot \frac{K_0\left(\frac{\pi \cdot m \cdot \rho}{l}\right)}{K_1\left(\frac{\pi \cdot m \cdot \rho_0}{l}\right)}$$

(Equ. A7-47)

The terms of this series converge toward 0.

In this formula, the expressions of the Fourier coefficients remains the same as in equation A7-28 (p.176). Their non dimensionalisation is carried out when the current densities are non dimensionalised.

When calculating the values of the conductances and resistances, it will be necessary to redimensionalise the obtained values. When carrying out their calculations we use the values of the currents and not current densities. We have for the pipeline currents:

$$I_n = S_n \,.\, i_n = 2.\pi.(z_n - z_{(n-1)}).\rho_o.i_n \qquad (\forall m \subset \{1,2,\ldots N\})$$

and for the field currents:

$$I_{f,n} = i_{f,n} \,.\, S_{field}$$ (Equ. A7-48)

where S_{field} is an arbitrary field area defined as follows:

$$S_{field} = \pi \,.\, \{ (2.\rho)^2 - (\rho_o)^2 \}$$ (Equ. A7-49)

If we want to achieve an non-dimensional expression of the currents, we can then write for the pipeline currents:

$$\frac{I_n}{2 \cdot \pi \cdot \rho_0 \cdot l \cdot i_{moy}} = \frac{z_n - z_{n-1}}{l} \cdot \frac{i_n}{i_{moy}}$$ (Equ. A7-50)

and for the field currents:

$$\frac{i_{f,n}}{i_{moy}} = i_{f,\,n,\,nondim} = \frac{I_{f,n}}{S_{field} \cdot i_{moy}} \qquad (\forall m \subset \{1,2,...\,(N\text{-}1)\}) \qquad \text{(Equ. A7-51)}$$

When calculating the values of the non dimensional field conductances and resistances pipeline to field resistances, we have:

$$Gf_{n,non\text{-}dim} = \frac{i_{f,\,n,\,nondim}}{\Delta V_{f,\,nondim}} \qquad \text{(Equ. A7-52)}$$

and: $$R_{n,non\text{-}dim} = \frac{V_{f,\,n,\,nondim} - V_{n,\,nondim}}{i_{n,\,nondim}} \qquad \text{(Equ. A7-53)}$$

The values of the conductances and resistances can the be expressed as follows:

$$Gf_{n,non\text{-}dim} = \frac{i_{n,\,nondim}}{\Delta V_{f,\,nondim}} = \frac{\dfrac{I_n}{i_{moy} \cdot S_{field}}}{\dfrac{\Delta V_{f,\,n} \cdot \sigma}{l \cdot N \cdot i_{moy}}} = G_n \cdot \frac{l \cdot N}{\sigma \cdot S_{field}} \qquad \text{(Equ. A7-54)}$$

and:

$$R_{n,non\text{-}dim} = \frac{\Delta V_{n,\,nondim}}{I_{n,\,nondim}} = \frac{\dfrac{\Delta V_n \cdot \sigma}{l \cdot N \cdot i_{moy}}}{\dfrac{I_n}{2 \cdot \pi \cdot \rho_o \cdot i_{moy} \cdot (z_n - z_{n-1})}} = R_n \cdot \frac{2 \cdot \pi \cdot \rho_o \cdot (z_n - z_{n-1}) \cdot \sigma}{l \cdot N} \qquad \text{(Equ. A7-55)}$$

Which gives us an expression of the dimensional conductances and resistances.

Appendix 8: Estimations of the Coating Breakdown Variance.

Due to the lack of data related to the coating breakdown, it was not possible to define a clear function to express the coating breakdown variance. Rather than generating these values at random, using any type of statistical distribution, it was decided that a simple model could be used to calculate this variance, according to other environmental parameters defined in the model. Such a model makes the tests reproducible, and reflects the effects of local parameters such as for example burial state, temperature and activity level.

The adequacy of the expressions used is debatable. Defining more precise formula would require an extended analysis, based on coating testing and inspection data. This could be the subject of another research project, which has been suggested in the "*further developments*" section of the discussion. The results of such analysis could be later on integrated easily with the interface. It would be then just necessary to redefine the function called for calculating the coating breakdown variance. New parameters could also be taken into account.

The variance expression defined for this analysis is described below and several components are considered:

- the coating quality factor (σ), function of the general installation quality (*IQ*), the coating thickness (*CT*) and the maximum and minimum average coating breakdown (*mini_CB*, *maxi_CB*). We have:

$$\sigma = 5 + \frac{IQ \times CT}{1.001 + \frac{maxi\_CB - mini\_CB}{10}} \qquad \text{(Equ. A8.1)}$$

- the environment factors (β), function of the temperature in degrees centigrade (*t*), the risk of sulphate reducing bacteria (*SRB_R*) and the percentage of burial (*%B*). We have:

$$\beta = \frac{\frac{t}{10} \times SRB\_R}{100 + \%B} \qquad \text{(Equ. A8.2)}$$

- the coating degradation factor (γ), function of the activity level (*A*), the total analysis length (*L*), the period length (*l*) and the environment factors (β). We have:

$$\gamma = A \times \beta \times \sqrt{2} \times Log\left(\frac{l \times \beta}{L \times \sqrt{2}}\right) \qquad \text{(Equ. A8.3)}$$

Finally, the coating breakdown variance (*CB_var*) is expressed in function of the previous parameters and of the period's mean coating breakdown (*mean_CB*) as follows:

$$CB\_\text{var} = mean\_CB \times \left(1 - e^{-\frac{\gamma^2}{2 \times \sigma^2}}\right) \qquad \text{(Equ. A8.4)}$$

Appendix 9: Calculation Of The Calculation Output's Mean Values And Variances

Most of the uncertainties considered in the model come from the data used in the calculations. The input data is therefore described by a mean value, representing the best estimate of the input parameter value, combined with a standard deviation, introduced to take into account the uncertainty on this parameter. This appendix presents the various calculations carried out to estimate the uncertainty on the output parameters.

In the first place, it is necessary to define a mean value and standard deviation for the pipeline section's coating breakdowns, respectively $\overline{\%CB_n}$ and $\sigma_{\%CB}$. Considering the values of these parameters, it is possible to calculate the corresponding values for the limiting current density mean value ($\bar{I}_{Ln}$) and standard deviation (σ^2_{Iln}), which can be used in the calculation modules to evaluate the values of:

- the mean field potentials ($\overline{V_{Fn}}$),
- the field potential variances (σ^2_{Vfn}),
- the current density mean values ($\overline{I_n}$),
- the actual current density variances (σ^2_{In}),
- the mean pipeline surface electrochemical potentials ($\overline{V_{Sn}}$),
- the mean pipeline surface electrochemical potentials variances (σ^2_{Vsn}),

The following chapters describe the general calculation procedures.

IX.1. Calculation of the Current Demand Standard Deviations

The values of the equivalent current demands for each section of the pipeline are calculated using the coating breakdowns and design limiting current values, as described in Equation 2-11. If we express current demands only in terms of the coating breakdown parameter, we obtain:

$$I_{Ln} = f(\ \%CB_n\ ) \qquad \text{(n being the section's index)} \qquad \text{(Equ. A9-1)}$$

The value of $\bar{I}_{Ln}$ and σ_i, equivalent means and standard deviations for the limiting current densities, can then be calculated using the same function:

$$\bar{I}_{Ln} = f(\overline{\%CB_n}) \qquad \text{(Equ. A9-2)}$$

$\sigma_i = f(\sigma_{\%CB})$ (Equ. A9-3)

Having calculated the values of the limiting current densities mean and standard deviations, we can then use these in the general electrochemical potential calculation module to calculate the values of the potential mean and standard deviation values.

IX.2. Calculation of the Parameters Mean Values

The values of the electrochemical potentials are calculated by solving the following system of equations:

$[L]([V_f]) = 0$ (see Equ. 4-35)

The equations in the system are defined as follows:

- for a cathode $L_n = \sin^{-1}((\frac{I_n}{2 \cdot I_{Ln}}) - \sin^{-1}(0.5 \,.\, (e^{k(V_{\alpha c}-V_{Sc})} - 1))$

- for an anode

$$L_n = \frac{1}{k} \cdot \sin^{-1}(\frac{I_n}{2 \cdot I_{0n}}) - \frac{1}{k} \cdot \sin^{-1}\left[\frac{1}{2} \cdot \left(\exp^{\alpha k(V_{0Ac}-V_{Sn})} - \exp^{(\alpha-1)\cdot k \cdot (V_{0Ac}-V_{Sn})}\right)\right]$$

Values of the output parameters (system solutions) $\overline{V}_{Fn}$ are obtained by solving this general system of equations using the mean values of the input parameters. Given $\bar{I}_{Ln}$, we solve the following equation:

$[L](\overline{V}_{Fn}) = 0$ (Equ. A9-4)

We thus obtain values for the field and pipeline potentials ($\overline{V}_{Fn}$ and $\overline{V}_{Sn}$), and for the field current densities ($\bar{I}_n$), according to the values of the limiting current entered ($\bar{I}_{Ln}$).

IX.3. Calculation Of The Parameter's Standard Deviations

IX.3.1. General Equation

Knowing the uncertainties on the limiting currents, we want to estimate the values of the uncertainties on the field potentials. The initial equation (Equation A9-4) can be differentiated as follows:

$$\left(\frac{\partial L_n}{\partial V_{fp}}\right)_{V_{fn}} \cdot \partial V_{fp} + \left(\frac{\partial L_n}{\partial I_{Lp}}\right)_{I_{Ln}} \partial I_{Lp} = 0 \qquad \text{(Equ. A9-5)}$$

This equation can be expressed in a matrix form as follows:

$$[A_{ij}] \,.\, \partial V_f + [B_{ij}] \,.\, \partial I_l = 0 \qquad \text{(Equ. A9-6)}$$

The $[A_{ij}]$ matrix is tridiagonal with non-zero diagonal terms. The coefficient A_{ij} are calculated in the *newt* module used for calculating the field potential.

The $[B_{ij}]$ matrix is a diagonal matrix (only the diagonal terms are not equal to zero when derived in regard to I_{ln}). The $B_{ii} = 0$ when I refers to an anode element. These diagonal terms are expressed as follow (taking into account the fact that we take in the calculation modules the hyperbolic arcsin of the system equations, see Equation 4-36):

$$B_{ij} = \left(\frac{\partial L_i}{\partial I_{lj}}\right)_{\overline{I_{lj}}} = \frac{1}{I_{li}} \cdot \frac{\dfrac{\overline{I_i}}{2 \cdot \overline{I_{li}}}}{\sqrt{(1 + \dfrac{\overline{I_i}}{2 \cdot \overline{I_{li}}}^{\,2})}} \quad \text{for i=j,} \qquad \text{(Equ. A9.7)}$$

and: $B_{ij} = 0$ if $i \neq j$ and i refers to an anode.

All the parameters required to calculate the values of the A_{ij} and B_{ij} are already present in the calculation module.

IX.3.2. Link Between Pipeline Potential and Current Density Variances

In Equation A9-6, the differentials (∂V_f and ∂I_l) are approximated by δV_f and δI_l, respectively equal to ($V_f - \overline{V_{fn}}$) and ($I_l - \overline{I_{ln}}$), approximation valid for small deviations around $\overline{V_{fn}}$ and $\overline{I_{ln}}$. This gives a linearised equation of the δV_f in terms of the δI_l:

$$[A_{ij}] \,.\, \delta V_f + [B_{ij}] \,.\, \delta I_l = 0 \qquad \text{(Equ. A9-8)}$$

Rewritten more simply as:

$$\delta V_f = [c_{ij}] \,.\, \delta I_l \qquad \text{(Equ. A9-9)}$$

where the matrix $[c_{ij}]$ is equal to:

$$[c_{ij}] = [A_{ij}]^{-1} \cdot [B_{ij}] \quad \text{(Equ. A9-10)}$$

By solving these equations, we can calculate the values of the $[c_{ij}]$ matrix. The general expression of the matrix is therefore:

$$\left[c_{i,j}\right] = \begin{bmatrix} c_{1,1} & c_{1,2} & \cdots & \cdots & c_{1,N} \\ c_{2,1} & c_{2,2} & \cdots & & \vdots \\ \vdots & \cdots & c_{i,j} & \cdots & \vdots \\ \vdots & & \cdots & c_{(N-1),(N-1)} & c_{(N-1),N} \\ c_{N,1} & \cdots & \cdots & c_{N,(N-1)} & c_{N,N} \end{bmatrix} \quad \text{(Equ. A9.11)}$$

Equation A9-9 can be rewritten:

$$\begin{cases} \delta V_1 = c_{11} \cdot \delta I_1 + c_{12} \cdot \delta I_2 + \ldots \\ \delta V_2 = c_{21} \cdot \delta I_1 + c_{22} \cdot \delta I_2 + c_{23} \cdot \delta I_3 + \ldots \\ \vdots \\ \delta V_i = \ldots + c_{i,(i-1)} \cdot \delta I_{(i-1)} + c_{i,i} \cdot \delta I_i + c_{i,(i+1)} \cdot \delta I_{(i+1)} + \ldots \\ \vdots \\ \delta V_{(N-1)} = \ldots + c_{(N-1),(N-2)} \cdot \delta I_{(N-2)} + c_{(N-1),(N-1)} \cdot \delta I_{(N-1)} + c_{(N-1),N} \cdot \delta I_N \\ \delta V_N = \ldots + c_{N,(N-1)} \cdot \delta I_{(N-1)} + c_{N,N} \cdot \delta I_N \end{cases} \quad \text{(Equ. A9.12)}$$

Knowing the values of the δI_l, we can then calculate the values of the δV_f.

IX.3.3. Expression Of The Standard Deviations

From these values, it is then necessary to calculate the values of the standard deviations. The general formula used to calculate the standard deviation is detailed below:

$$\sigma_y^2 = E[(y - \bar{y})^2] \quad \text{(Equ. A9.13)}$$

or more explicitly by:

$$\sigma_y^2 = \int \ldots \int \left(y(x_1, x_2, \ldots, x_n) - \bar{y}\right)^2 \cdot f(x_1, x_2, \ldots, x_n) \cdot dx_1 \ldots dx_n \quad \text{(Equ. A9-14)}$$

where the function f() is the joint probability density function for the x_n's.

The covariance can be expressed as follows:

$$\sigma^2_{y_i y_j} = \int \dots \int \left(y_i - \overline{y_i}\right)^2 \left(y_j - \overline{y_j}\right)^2 \cdot f(x_1, \dots, x_n) \cdot dx_1 \dots dx_n \qquad \text{(Equ. A9-15)}$$

In our case, x_i and y correspond to the $\bar{I}_{ln}$ and $\overline{V}_{fn}$, and the previous equations can be rewritten:

$$\sigma_{\delta V_{fi} \delta V_{fj}} = E\left[(\delta V_{fi} - \overline{\delta V_{fi}}),(\delta V_{fj} - \overline{\delta V_{fj}})\right] \qquad \text{(Equ. A9.16)}$$

$$\sigma_{\delta V_{fi} \delta V_{fj}} = \iint (\delta V_{fi} - \overline{\delta V_{fi}}) \cdot (\delta V_{fj} - \overline{\delta V_{fj}}) \cdot \mathrm{f}(\delta I_{li}, \delta I_{lj}) \cdot dI_{li} \cdot dI_{lj} \qquad \text{(Equ. A9.17)}$$

We now consider that the uncertainty functions for the δV_f follows symmetric distributions (Normal for example), centered on 0. The mean values ($\overline{V}_{fn}$) are then equal to 0, and the Equation A9-17 can be rewritten:

$$\sigma_{\delta V_{fi} \delta V_{fj}} = \iint \delta V_{fi} \cdot \delta V_{fj} \cdot \mathrm{f}(\delta I_{li}, \delta I_{lj}) \cdot dI_{li} \cdot dI_{lj} \qquad \text{(Equ. A9.18)}$$

Considering now that the δV_f can be expressed in function of the δI_{li} (Equation A9-12), Equation A9-18 can be rewritten for the general case (except first and last equations):

$$\begin{aligned}\sigma_{\delta V_{fi} \delta V_{fj}} = \iint & (\dots + c_{i,(i-1)} \cdot \delta I_{(i-1)} + c_{i,j} \cdot \delta I_i + c_{i,(i+1)} \cdot \delta I_{(i+1)} + \dots) \\ & \cdot (\dots + c_{j,(j-1)} \cdot \delta I_{(j-1)} + c_{j,j} \cdot \delta I_j + c_{j,(j+1)} \cdot \delta I_{(j+1)} + \dots) \\ & \cdot \mathrm{f}(\delta V_{fi}, \delta V_{fj}) \cdot dI_{fi} \cdot dI_{fi}\end{aligned} \qquad \text{(Equ. A9.19)}$$

or:

$$\begin{aligned}\sigma_{\delta V_{fi} \delta V_{fj}} = \iint & (c_{i,1} \cdot \delta I_1 + \dots + c_{i,(i-1)} \cdot \delta I_{(i-1)} + c_{i,j} \cdot \delta I_i + c_{i,(i+1)} \cdot \delta I_{(i+1)} + \dots + c_{i,N} \cdot \delta I_N) \\ & \cdot (c_{j,1} \cdot \delta I_1 + \dots + c_{j,(j-1)} \cdot \delta I_{(j-1)} + c_{j,j} \cdot \delta I_j + c_{j,(j+1)} \cdot \delta I_{(j+1)} + \dots + c_{j,N} \cdot \delta I_N) \\ & \cdot \mathrm{f}(\delta V_{fi}, \delta V_{fj}) \cdot dI_{fi} \cdot dI_{fi}\end{aligned}$$

(Equ. A9.20)

As we consider that the distributions ruling each section's coating breakdown (and therefore current density) are independent, the terms cross-related to different sections in Equation A9-20 have a null integral (the covariance of two parameters is null). Equation A9-20 can be rewritten:

$$\sigma_{\delta V_{fi},\delta V_{fj}} = \sum_{p=1}^{N} (c_{i,p} \cdot c_{j,p}) \cdot \sigma^2_{\delta I_{lp}} \qquad \text{(Equ. A9.21)}$$

IX.3.4. Expression of the Current Intensity Variances

Knowing the variances on the field potentials, it is possible to calculate similar values for the current intensities, using the following expression:

$$I_n = G_{fn-1}.V_{fn-1} - (G_{fn-1} + G_{fn}) . V_{fn} + G_{fn} . V_{fn+1} \qquad \text{(see Equ. 4-8)}$$

This equation can be modified to express the δI in terms of the δV_f. We obtain:

$$\delta I = G_{fn-1} . \delta V_{fn-1} - (G_{fn-1} + G_{fn}) . \delta V_{fn} + G_{fn} . \delta V_{fn+1} \qquad \text{(Equ. A9.22)}$$

If we consider that the δV_{fi} are stochastic variable with a distribution f with a mean zero and a covariance matrix $\sigma_{\delta Vfi,\delta Vfj}$, we can write:

$$\sigma^2_{In} = \int \ldots \int (\delta I_n)^2 \cdot f(\delta V_{f1},\ldots\delta V_{fn}) \cdot d\delta V_{f1}\ldots d\delta V_{fn} \qquad \text{(Equ. A9.23)}$$

Which gives, by replacing δI by its expression in Equation A9-22:

$$\begin{aligned}\sigma^2_{In} = \int \cdots \int \; & (G_{f(n-1)} \cdot \delta V_{f(n-1)} \\ & - (G_{f(n-1)} + G_{f(n-1)}) \cdot \delta V_{f(n-1)} \\ & + G_{f(n-1)} \cdot \delta V_{f(n-1)})^2 \\ & \cdot f(\delta V_{f1},\ldots\delta V_{fn}) \cdot d\delta V_{f1}\ldots d\delta V_{fn}\end{aligned} \qquad \text{(Equ. A9.24)}$$

$$\begin{aligned}\sigma^2_{In} = \; & G_{f(n-1)}{}^2 \int \cdots \int \delta V_{f(n-1)}{}^2 \cdot f(\delta V_{f1},\ldots\delta V_{fn}) \cdot d\delta V_{f1}\ldots d\delta V_{fn} \\ & - (G_{f(n-1)} + G_{f(n-1)})^2 \int \cdots \int \delta V_{f(n-1)}{}^2 \cdot f(\delta V_{f1},\ldots\delta V_{fn}) \cdot d\delta V_{f1}\ldots d\delta V_{fn} \\ & + G_{f(n-1)}{}^2 \int \cdots \int \delta V_{f(n-1)}{}^2 \cdot f(\delta V_{f1},\ldots\delta V_{fn}) \cdot d\delta V_{f1}\ldots d\delta V_{fn} \\ & - 2G_{fn}(G_{f(n-1)} + G_{f(n-1)}) \int \cdots \int \delta V_{f(n-1)} \delta V_{fn} \cdot f(\delta V_{f1},\ldots\delta V_{fn}) \cdot d\delta V_{f1}\ldots d\delta V_{fn}\end{aligned}$$

(Equ. A9.25)

This eventually gives:

$$\sigma^2_{I_{lp}} = (G_{n-1})^2 \cdot \sigma^2_{V_{f,(n-1)}} + (G_{n-1} + G_n)^2 \cdot \sigma^2_{V_{fn}} + (G_n)^2 \cdot \sigma^2_{V_{f(n+1)}}$$
$$- 2 \cdot G_{n-1} \cdot (G_{n-1} + G_n) \cdot \sigma_{V_{f(n-1)},V_{fn}}$$
$$- 2 \cdot G_n \cdot (G_{n-1} + G_n) \cdot \sigma_{V_{fn},V_{f(n+1)}} \qquad \text{(Equ. A9-26)}$$
$$+ 2 \cdot G_{n-1} \cdot G_n \cdot \sigma_{V_{f(n-1)},V_{f(n+1)}}$$

IX.3.5. Expression of the Pipeline Potential Variances

Similarly, field potentials and pipeline potentials are related as follows:

$$V_{sn} = V_{fn} + R_n I_n \qquad \text{(see Equ. 4-18)}$$

We can then similarly estimate the values of the pipeline potential variances as follows:

$$\sigma^2_{V_{sn}} = (R_n G_{n-1}) \cdot \sigma^2_{V_{f,(n-1)}}$$
$$+ (1 + R_n(G_{n-1} + G_n))^2 \cdot \sigma^2_{V_{fn}}$$
$$+ (R_n G_n)^2 \cdot \sigma^2_{V_{f(n+1)}}$$
$$- 2 \cdot R_n \cdot G_{n-1} \cdot (1 + R_n(G_{n-1} + G_n)) \cdot \sigma_{V_{f(n-1)},V_{fn}} \qquad \text{(Equ. A9.27)}$$
$$- 2 \cdot (1 + R_n \cdot (G_{n-1} + G_n)) \cdot R_n \cdot G_n \cdot \sigma_{V_{fn},V_{f(n+1)}}$$
$$+ 2 \cdot G_{n-1} \cdot G_n \cdot \sigma_{V_{f(n-1)},V_{f(n+1)}}$$

IX.3.6. Generalities About the Calculations

In order to calculate the values of the standard deviations for the current intensities and the field potential (Equations A9-26 and A9-27), we have to calculate the four following terms for each pipeline section:

$$\sigma^2_{V_{f,(n-1)}}, \sigma_{V_{f(n-1)},V_{fn}}, \sigma_{V_{fn},V_{f(n+1)}}, \sigma_{V_{f(n-1)},V_{f(n+1)}} \equiv \sigma_{V_{fi},V_{fj}} \quad (i=n,n-1, j=n,n+1)$$

(Equ. A9.28)

Each one of these terms is calculated using Equation A9-21. In order to calculate these, using this equation straightforward, it would be necessary to store the whole $[c_{i,j}]$ matrix (a N by N matrix, N being the total number of sections defined for the pipeline modelling). This process would require a considerable amount of memory, mostly in the case where N is large.

A more optimised way to carry out these calculations without storing the $[c_{i,j}]$ matrix is by calculating the values of the $c_{i,j}$ coefficients column by column, according to Equation A9-10. At the end of each column calculation, one term can be added to the calculation of the standard deviation sum (Equation A9-21). Eventually, it is only necessary to store the field potential standard deviations in a 4×N matrix, with only one extra column matrix.

Appendix 10: Pipeline Potential Calculation Modules' Flowcharts

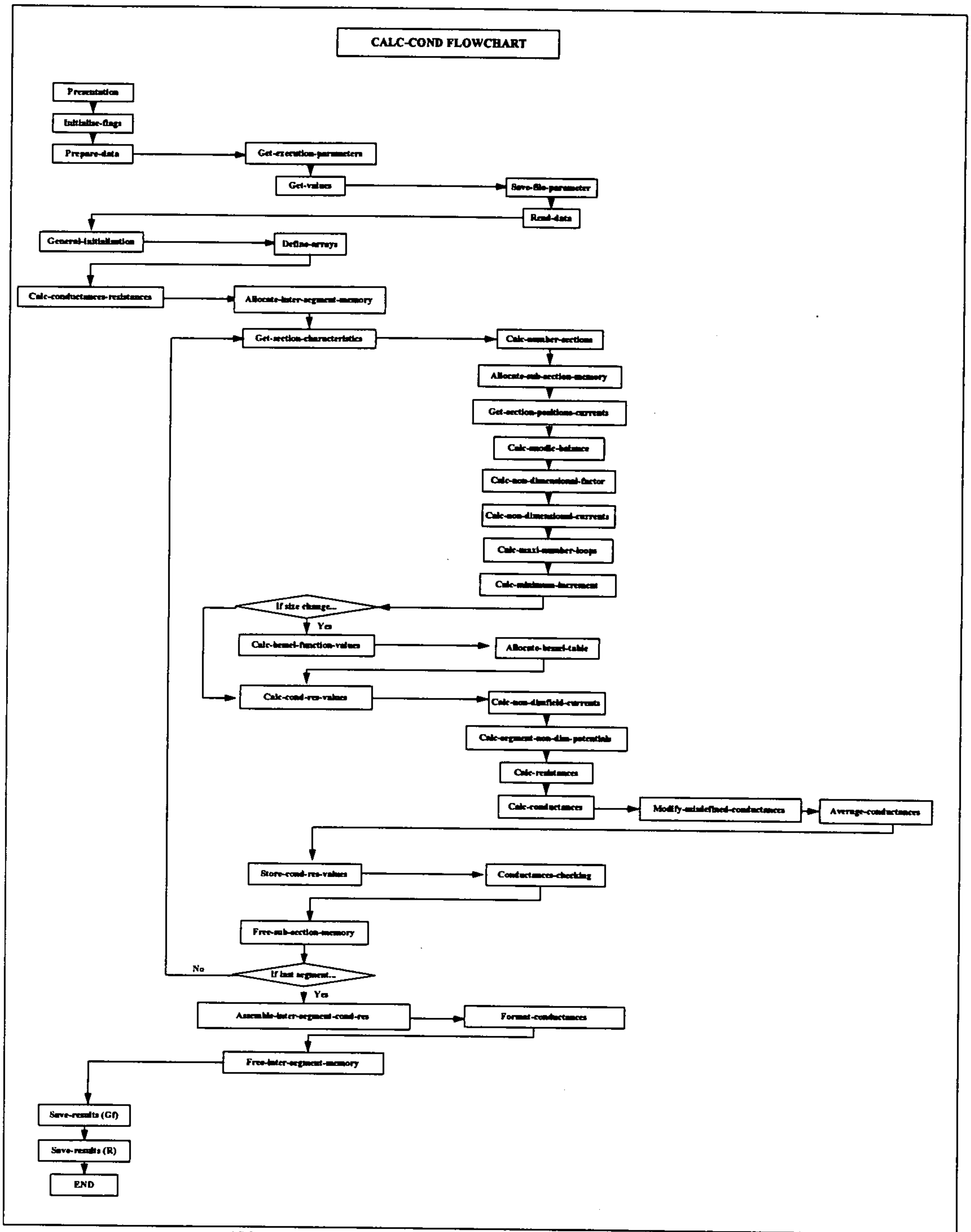

Figure A10-1: Calc-cond module flowchart.

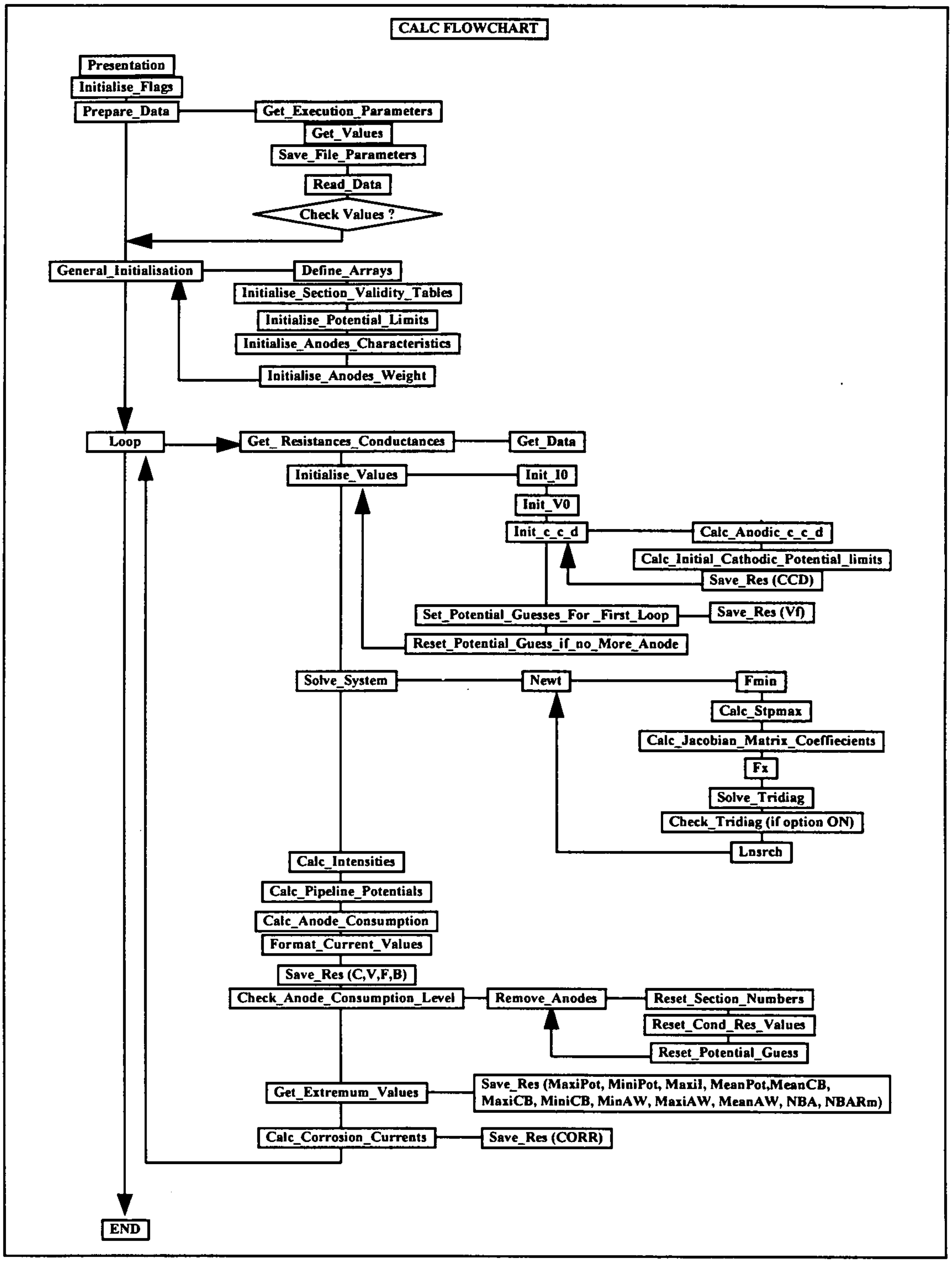

Figure A10-2: Calc module flowchart.

Appendix 11: List Of The Output Files Build By The Calculation Module.

Nb.	Code	Description
1	ANO-RM	list of the codes of the anodes removed when completely consumed.
2	AW	anode weight for each anode at each period of time.
3	B	values of the coating breakdowns for each section and period of time.
4	C	anode consumption for each anode and period of time.
5	CORR	values of the corrosion (mm) for each section and period of time.
6	D	current demand initial estimation.
7	EXTREM UM	this file is directly used by the user graphical interface. It gathers the values of the minimum, mean and maximum values of the pipeline potentials, pipeline potentialvariances, safety margins and reliability. These values are saved for each period of time.
8	F	field potential for each section and period of time.
9	G	values of the conductances for each section.
10	G_MODIF	values of the new conductances when they have been recalculated (when anode(s) get consumed).
11	I	current output for each section and period of time.
12	O	initial potential guesses for each section and period of time.
13	R	values of the resistances for each section.
14	R_MODIF	values of the new resistances when they have been recalculated (when anode(s) get consumed).
15	SP	position of the end of each section along the pipeline.
16	V	pipeline potential for each section and period of time.
17	VAR_I	variance on the current output for each section and period of time.
18	VAR_IL	variance on the limiting current for each section and period of time.
19	VAR_V	variance on the pipeline potential for each section and period of time.
20	VAR_VF	variance on the field potential for each section and period of time.

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