CEOCOR

Comité d'Étude de la Corrosion et de la Protection des canalisations

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A.C. CORROSION ON CATHODICALLY PROTECTED PIPELINES

Guidelines for risk assessment and mitigation measures

2001

The guidelines indicated herein are informative; no responsibility will be assumed by CEOCOR as body or by its individual members for any action taken in consequence of the information given here.

PREFACE

This book about a.c. corrosion on cathodically protected pipelines is a guideline for risk assessment and mitigation measures. It continues the CEOCOR tradition of drawing up guidelines for the corrosion protection of pipelines.

Corrosion specialists were alarmed in 1988, the year of the first discovery of damage to cathodically protected pipelines by a.c. corrosion. Confidence in cathodic protection suffered accordingly.

After the initial surprise, the phenomenon of a.c. corrosion was investigated thoroughly in different countries and also discussed in sector A of CEOCOR. Preventive mitigation measures and criteria to judge the risk assessment were developed.

These goals were only partially achieved. Today we are beginning to understand the mechanisms and conditions for a.c. corrosion. This book, a summary of our knowledge as it stands today, is to inform corrosion specialists of the problem and direct their attention to a.c. corrosion.

The book was prepared by a group of corrosion specialists (listed below). Their experience and knowledge and their personal hard work was essential to bringing the work to a successful end. Our thanks go to them and their co-workers.

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FOREWORD

This booklet is particularly aimed at specialised people involved in the corrosion protection of buried metallic structures. It is also useful for engineers, managers and people dealing with the operation of underground metallic structures such as telecommunication cables, water, gas and oil transport pipeline systems who will benefit from understanding the origin, nature and possible operating consequence of a.c. influences.

The managers of electricity power lines, as well as transport systems fed with a.c. will also be interested in the phenomena described in the booklet as in the near future they could also be involved in terms of costs and operation of their systems.

The influence of a.c. has grown consistently in these last years due to the huge development of transport systems fed with a.c. (see high speed trains) and the extreme attention devoted to the coating quality and the overall integrity of pipelines.

Whilst containing theoretical considerations and laboratory research studies and related experiences, this booklet also covers the practical approaches to the solution of common problems associated with a.c. influence. It may be of interest to notice that the booklet has been conceived and prepared well before European Standard works on this subject have been started.

CEOCOR has already set up an ad hoc group to follow further researches and advances in the field of a.c. influence that will periodically up-date the information gathered after the publication of this first booklet.

We are confident that this booklet is of great benefit to the wide world of corrosion and cathodic protection engineers and specialists. It represents an important step to the scientific progress in this very special technical field.

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President of CEOCOR
Pierre Leroy

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SUMMARY

A new corrosion phenomenon has been added to the list of corrosion phenomena, and it is related to a.c. currents.

These usually result from a.c. voltages induced into the pipeline where the pipeline route is in parallel with, or crosses, high voltage power lines or electrified railways.

The implications of the influence of alternating currents on buried pipelines are of great concern to all pipeline owners in Europe. The relevance of the interference is always increasing; for operational personnel (touch and step voltages); adverse effects to cathodic protection equipment and for the protection of buried metallic structures from corrosion.

Among the factors that contribute to increased a.c. voltages on buried pipelines are:
- growing number of high voltage power lines
- a.c. operated high speed traction systems
- high isolation resistance of modern pipeline coatings.

On pipelines suffering from a.c. interference traditional pipe-to-soil potential measurements DO NOT GUARANTEE efficient cathodic protection against corrosion. A specific approach to assess the effectiveness of cathodic protection should be adopted.

Further laboratory research is still needed to explain the basic mechanisms of a.c. corrosion, mainly in order to determine methods for assessing the a.c. corrosion risk.

The main aims of this booklet are:
- to inform technical people of the problems
- show that there is a real risk of a.c. corrosion on buried pipelines
- provide examples of practical actions to reduce/minimise corrosion risks.

Safety aspects related to a.c. influence on pipelines are not covered in this booklet. (see references 1 and 2).

Some laboratory and field experiences are illustrated in this booklet, the conclusions drawn should not be considered as final since the experiments are still in progress.

The real nature of the a.c. corrosion phenomenon has not yet been fully investigated.

1 - Introduction

The primary factor in alternating current electrolysis is current density. This statement was made in The Engineering Journal, the journal of the Engineering Institute of Canada, and was made in 1927.

A long time has passed since then and a.c. effects have been experienced and investigated in depth.

More recently, since 1986, some instances of corrosion on gas pipelines due to alternating current ($16^{2/3}$ and 50 Hz) have been reported in Europe (see annexe 2, 3 and 4). In all these cases, the measured cathodic protection values, measured with conventional techniques and instruments, satisfied the conventional criteria. It is most probable that some previous corrosion failures have not been recognised as being caused by alternating current because cathodic protection personnel have not been made aware of a.c. corrosion risk.

The a.c. influence is referred to as «inductive», «resistive» or «capacitive» interference in technical literature.

In recent years, throughout Europe, a number of corrosion cases have been discovered that can clearly be attributed to a.c. corrosion.

From the information available (which is probably only a small percentage of all cases), the following summary can be made:

- number of a.c. corrosion cases known in Europe: 23
- number of leaks: 4
- number of observed corrosion attacks: 709

A.c. influence and the associated corrosion risks are certain to increase because of the following main factors:

- installation of new and more powerful electricity lines;
- continuously improved coating quality;
- improved methodology to achieve almost perfect coating on new pipelines;
- construction of new high-speed train systems all over Europe.

Typical case of a.c. corrosion on a PE coated pipeline
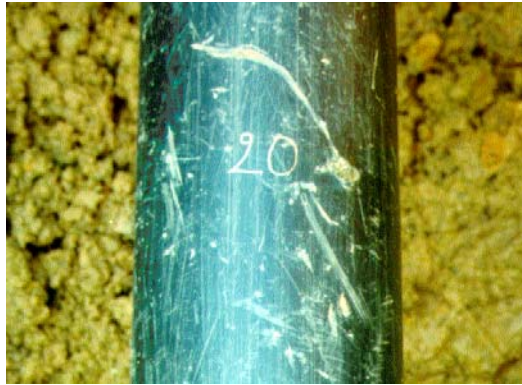
Photo 1: coating defect (15x20 mm) on top line of the pipeline
the size of the hole in the coating is a few mm²)

Photo 2: oxide (40x40 mm) and corrosion product

Photo 3: corrosion (diameter 5 mm, depth 0,5 mm)

1.1. Interfering sources

Main interfering sources for a.c. are:
- high voltage aerial or buried power lines;
- long, parallel, power lines;
- high speed traction systems (usually fed by a parallel feeding line 132 kV and a 25kV line).

1.2. Parameters that affect a.c. corrosion

Corrosion is caused by current exchange between soil and metal. This exchange of current depends on the voltage induced on pipelines.
The amplitude of induced voltage is due to various parameters such as:
- distance between phase cables;
- distance between the high voltage electricity lines and the pipeline;
- overhead line operating current;
- pipeline coating resistance.
Corrosion is mainly influenced, or associated with:
- a.c. current density;
- on and off potential values;
- size of coating defect;
- local soil resistivity;
- local soil chemical composition;
- formation of salts at the metal/soil phase boundary due to cathodic protection reaction.

2 - Fundamental aspects

When a steel pipe is interfered by alternating current, an a.c. voltage can be measured between the pipe and remote earth. With reference to figure 2.1 the following quantities can be identified:

- **$U_{AC,on}$** is equal to the a.c. voltage that can be measured between pipe and remote earth. This a.c. voltage includes the IR-drop existing in the soil as well as the "true a.c. voltage" existing directly at the pipe surface.
- **$U_{AC,off}$** is the a.c. voltage existing directly at the steel surface ("true a.c. voltage"), i.e. with no contribution from IR-drops due to spread resistance (see section 2.3). Note that there may be a time delay as well as a non-linear relation between $U_{AC,on}$ and $U_{AC,off}$
- **$E_{d.c.,off}$** is the IR-free potential on the steel surface ("true potential"), e.g. with CP but without a.c.
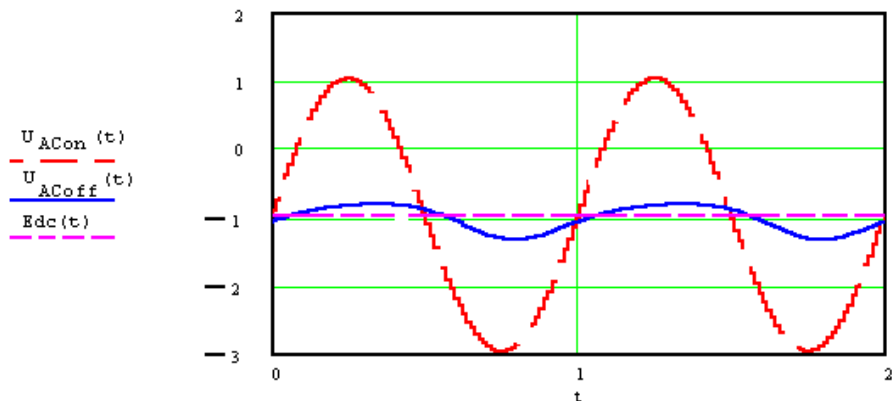
Fig. 2.1 Illustration of $U_{A.C.}$ and $E_{d.c.}$

The a.c. voltage produces an a.c. current flowing from the pipe through any coating defect to remote earth. The magnitude of this a.c. current depends on the magnitude of the impedance existing from the pipe via a coating defect to remote earth.

This section seeks to give an overview of the fundamental aspects of how a.c. voltage, impedance and a.c. current are interconnected through physical and chemical parameters related to a coating defect, and how a.c. corrosion may develop in this case.

2.1. Electrical modelling

The total pipe to soil impedance may be regarded as a sum of the spread impedance (Z_s), and the polarisation impedance Z_p related to the electrochemistry of the pipe-soil interface (figure 2.2 - A).
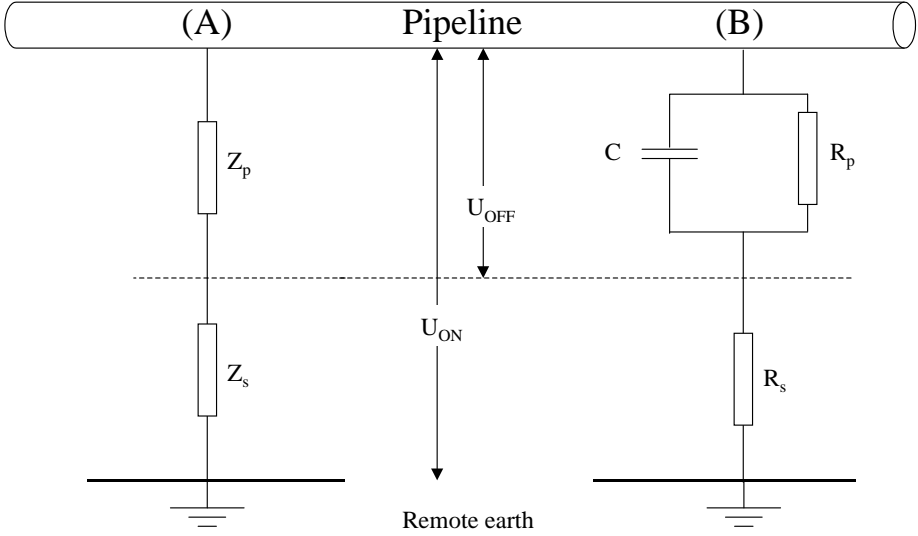
Fig. 2.2 Illustration of simplified electrical equivalent circuits used to describe the pipe to soil impedances.

The spread impedance is generally considered to be resistive impedance, i.e. the term *spread resistance* (R_s in figure 2.2 - B) is more accurate. The IR-drop occurs across the spread resistance.

In the phase boundary between the pipe metal and the soil, the electrochemical double layer exists. This double layer may be considered electrically as a plate capacitor (C in figure 2.2 - B). The capacitance of the electrochemical double layer depends on the chemical composition of the soil solution, which defines the dielectric constant ε. It's unit is farad [F = As/V]. The capacitance may play a key role in the a.c. corrosion behaviour in the sense that if the charge of the double layer reaches a critical value, irreversible electrochemical processes through the double layer initiate. This can be for example the anodic dissolution of the steel:

$$Fe \rightarrow \quad Fe^{2+} + 2\,e^- \qquad\qquad (2.1)$$

or reduction of oxygen or hydrogen evolution as cathode processes both causing production of alkalinity (OH⁻):

$$O_2 + 2\,H_2O + 4\,e^- \;\rightarrow\; 4\,OH^- \qquad\qquad (2.2)$$
$$2\,H_2O + 2\,e^- \;\rightarrow\; 2\,OH^- + H_2 \qquad\qquad (2.3)$$
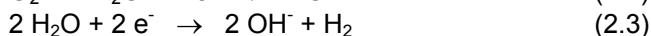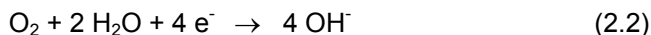
The metal dissolution may initiate, when the metal to soil-potential increases over the protection potential. The reduction of oxygen takes place at potentials lower than the equilibrium potential of the O_2 electrode, and the evolution of hydrogen takes place at potentials lower than the equilibrium potential of the H_2 electrode.

The resistance defined by such electrochemical processes is known as the polarisation resistance (R_p in figure 2.2 - B). This should be taken only as a generic term, since the polarisation resistance is far from linear. It depends on the chemistry in the vicinity of the pipe surface, and on the pipe potential. Processes that are not limited by diffusion generally exhibit an exponential behaviour between current and potential:

$$i = i_0 \cdot \left[\exp\!\left(\frac{E - E_0}{\beta_a} \right) - \exp\!\left(\frac{-(E - E_0)}{\beta_c} \right) \right] \qquad\qquad (2.4)$$

where E is the electrode potential, E_0 is the equilibrium electrode potential i_0 is the exchange current density existing when $E = E_0$, and β_a and β_c are the anodic and cathodic Tafel slopes related to the particular process.

The polarisation impedance (Z_p) of figure 2.2 (A) may then be regarded as a parallel couple of the polarisation resistance Rp and the double layer capacitance C. As such, it includes real- as well as imaginary impedance, hence may cause a time delay (phase angle) between voltage and current as indicated in figure 2.1.

These ideas of the mechanism of a.c. corrosion lead to the following statements for criteria for the judgement of the risk of a.c. corrosion:

- the amount of charge fed to the electrochemical double layer before the irreversible processes are initiated depends on the current density, on the frequency and on the chemical composition of the soil.
- By the first approximation the use of the current density as a criterion seems a good approach. Laboratory investigations show that a current density of around 30 A/m^2 gives satisfactory results as a criterion to detect a.c. corrosion. This value depends on factors like frequency, composition of soil solution at the phase boundary, etc.
- If there are anodic irreversible processes, the metal to soil potential may rise above the protection potential. Consequently the off potential

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measurement shortly after switch off of the current could be used as a criterion. Until now, the time constants of the discharge of the electrochemical double layer and of the depolarisation at the metal to soil boundary are not known. Laboratory investigations show that off-potential measurement measured less that 1 ms after switch off can lead to satisfactory results as a criterion for the potential to detect a.c. corrosion.

The spread resistance is known to be the primary parameter determining the level of a.c. current for a certain a.c. voltage. The possible criteria for the judgement of the a.c. corrosion risk can only be tested with coupons connected to the pipeline. The spread resistance of coupons is controlled by physical parameters related to the coupon geometry and size as well as chemical parameters related to the soil chemistry and the modification of the chemistry in the vicinity of a coating holiday caused by the cathodic protection current and the a.c. current.

It is very important to acknowledge the chemical and physical influences, which determine the current flow trough a coating holiday, i.e. the physical and chemical influences on the spread resistance. In the following chapters, some experiences regarding physical and chemical influences on spread resistance of coupons and coating holidays are collected.

2.2. Physical/geometrical influence on spread resistance

The area dependent spread resistance R'_s of a circular probe may be calculated from the specific soil resistivity ρ_S and the diameter d of the exposed area:

$$R'_S = \frac{\rho_S}{2 \cdot d} \qquad\qquad [\Omega] \qquad\qquad (2.5)$$

The current density resulting at a coupon with area A under a driving voltage U is found according to Ohm's law as:

$$i = \frac{U}{R \cdot A} = \frac{8 \cdot U}{\pi \cdot \rho_S \cdot d} \qquad\qquad [\text{A/m}^2] \qquad\qquad (2.6)$$

Therefore, with a given driving voltage U and constant soil resistance, an increasing current density with decreasing diameter d of the holiday is to be expected.

Considering also the effect of the thickness h of the coating of a pipe, the spread resistance R_S of a circular holiday with diameter d in the coating is

composed of the pore resistance R_F and the area dependent spread resistance R'_S:

$$R_S = R_F + R'_S = \frac{4 \cdot \rho_F \cdot h}{d^2 \cdot \pi} + \frac{\rho_S}{2 \cdot d} \qquad\qquad [\Omega] \qquad\qquad (2.7)$$

Apart from the specific resistance of the electrolyte inside of the pore (ρ_F) and in the soil (ρ_S), the spread resistance Rs also depends on the thickness h of the coating.

With the assumption that $\rho_F = \rho_S$, the current density resulting from physical effects as a function of the size of the holiday, the soil resistivity and the influencing a.c. voltage may be calculated by means of equation (2.7) and Ohm's law.

From figure 2.3 it can be seen that for small diameters of the holiday the current density is essentially constant and is determined by the resistance R_F in the coating pore. For larger diameters the current density decreases inversely proportional to the diameter of the holiday. It is proven that the current density increases when the area of the coating defect decreases.
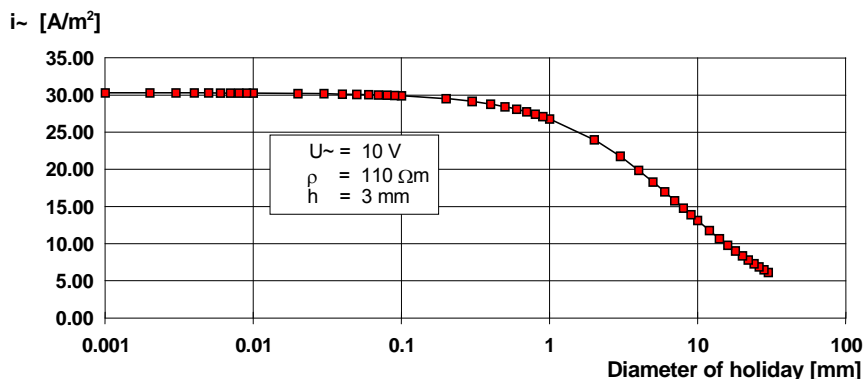
i~ [A/m²]

Fig. 2.3 A.c. current density as a function of the holiday size

Despite these physical effects, experience from practice shows that modifications of the spread resistance is obviously caused by the cathodic protection current and cannot be explained with the basic physical effects alone:

- for coupons without CP and a.c. load (reference coupons) significant deviations due to weather influences are to be expected. Minimum and maximum values vary approximately by a factor of 2, whereby the highest values were observed in summer times;
- the spread resistance of the coupons without CP increases with increasing exposure time since the developing rust layer will hinder the current transition. It has been observed that the increase during a three-year testing period was 20 %;
- for coupons without CP, but with a.c. current load, the spread resistance is virtually equal as for coupons without a.c. current load and without CP;
- for coupons with CP and with a.c. current load the spread resistance may increase by as much as 100 times or decrease by as much as 60 times;
- for coupons with CP and with a.c. current load the spread resistance behaves virtually equal as for measurement probes with CP, but without a.c. current load.

2.3. Chemical influence on spread resistance

Besides the physical influence on the spread resistance as described above, the chemistry formed locally in a coating defect largely contributes to the variation of the spread resistance as described in the following.

2.3.1. Chemical reactions caused by the cathodic protection current

At coating holidays where the cathodic protection current reaches the steel surface cathodic reactions occur. They cause oxygen reduction (2.2) and hydrogen evolution (2.3). In both reactions hydroxyl ions (OH^-) are generated which leads to a pH increase at the phase boundary.
In the region of the cathode (holidays in the coating) the cathodic protection current transports the anions present in the soil (hydrogen-carbonates, sulphates, nitrates, OH^-, chlorides, etc.) away from the cathode towards the anode, and the cations (among others calcium, sodium, potassium and magnesium ions) towards the cathode.
The OH^- production and the intensity of the ion migration described is directly proportional to the current density at the holiday. In the soil adjacent to the holiday it causes the formation of salts (alkaline and earth alkaline hydroxides) in the region of the holidays, the quantity, the composition and the properties thereof depend on the composition of the soil. Up to now relatively little is known about the influence of the composition of the soil and of the water (soil water) on the resulting metal hydroxides. For instance it is not known whether the type of

emerging hydroxides depends only on the cations dissolved in the soil water, or whether also cations bound in macro complex anions such as layer silicates (e.g. clay) are included in the hydroxide formation process. However, the cations present in the soil can be divided into two groups according to their effects, namely alkaline and earth alkaline metal cations.

2.3.2. Salts formed from earth alkaline cations

The earth alkaline cations Ca^{2+} and Mg^{2+} form hydroxides with relatively weak dissolvability, which decreases strongly with increasing pH level. The pH level is highest at the metal/electrolyte phase boundary because the production of the OH^- occurs directly here (being the cathode site). Since the OH^- ions as anions migrate away from the cathode, an OH^- profile is established where the $OH^-$ concentration decreases with increasing distance from the phase boundary. In those areas where the dissolvability product of $Ca(OH)_2$ is found, $Ca(OH)_2$ is precipitated.

$$Ca^{2+} + 2\ OH^- \rightarrow \{Ca(OH)_2\} + H_2O \qquad\qquad (2.8)$$
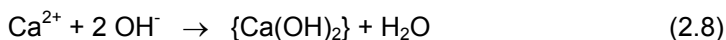
Through the uptake of CO_2 which may be present in the soil at a concentration level 25 times higher as in the atmosphere this $\{Ca(OH)_2\}$ may be transformed into an even less dissolvable carbonate (limestone).

$$\{Ca(OH)_2\} + CO_2 \qquad\qquad \rightarrow \{CaCO_3\} + H_2O \qquad\qquad (2.9)$$
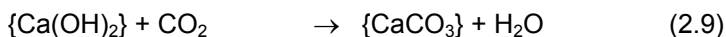
The reaction scheme for magnesium ions takes an analogous course to the one explained for calcium ions. In the case where only earth alkaline cations are present, this precipitation may occur directly at the metal/electrolyte phase boundary (fig. 2.4).
These precipitations may result in the formation of high resistivity cover layers which increase the spread resistance of the bare steel and, after some time, will reduce the access of the protecting current. This effect may be heavy to the extent that the protecting potential will no longer be obtained at such coupons.

Fig. 2.4   Soil water with only salts of earth alkaline metals.
Precipitation of low-dissolvability hydroxides of earth alkaline cations at the metal / electrolyte phase boundary

2.3.3. Salts formed from alkaline cations

In the case where alkaline cations only (no earth alkaline cations) are present in the soil, the same electrochemical reactions occur as with the earth alkaline cations.

However, the NaOH, KOH or LiOH salts formed in the region of the holidays are highly dissolvable and, in addition to that, strongly hygroscopic, i.e. they do not form weakly dissolvable precipitations. They rather absorb water from the environment and form an aqueous alkaline solution, e.g. sodium lye.

$$Na^+ + OH^- \quad \rightarrow \quad NaOH \qquad\qquad (2.10)$$

Through the reception of CO_2 from the soil the NaOH is transformed into soda which is equally strongly dissolvable:

$$2\,NaOH + CO_2 \quad \rightarrow \quad Na_2CO_3 + H_2O \qquad (2.11)$$

Information about dissolvability and hygroscopicity of those salts are presented in table 2.1.

The formation of the hygroscopic lyes in the region of the holidays results in a decrease of the spread resistance and to an increase of the protection current and also a.c. current to such holidays.

Salt	Dissolvability [g/L]	rF_{kr} [%]
NaOH	420	8.9
KOH	1070	9.3
$Ca(OH)_2$	1.85	~99.5
$Mg(OH)_2$	0.009	~100
Na_2CO_3	71	87
K_2CO_3	1120	43.2
$CaCO_3$	0.015	~100
$MgCO_3$	0.11	~100

Table 2.1 Dissolvability and hygroscopicity of reaction products.

A hygroscopicity of 87 % for Na_2CO_3 means that in an environment with a relative humidity of more than 87 %, Na_2CO_3 will be present as aqueous solution, below 87 % as crystalline salt. The aqueous solution gives rise to a decrease of resistivity of the adjacent soil, whilst the crystalline salt gives rise to an increase of it.

2.3.4. Mixtures of alkaline and earth alkaline cations

Depending on the concentration ratio between alkaline and earth alkaline cations in a mixture of alkaline and earth alkaline cations either high resistivity covering layers or low resistivity lye solutions are formed. The occurring processes are sketched in fig 2.4.
During the initial phase the cathodic protection current causes the cations to migrate towards and the anions away from the holidays. This ion migration depends on the concentration and the mobility of the ions in the aqueous phase of the soil.
As a measure for the ion mobility the equivalent conductivity Λ [$\Omega^{-1}cm^2mol^{-1}$] may be used (see table 2.2).
In the case where during the starting phase a surplus of Ca^{2+} is present in the region of the holiday, precipitations of $Ca(OH)_2$ will occur (fig. 2.5).

Cations	Λ [$\Omega^{-1}cm^2mol^{-1}$]	Anions	Λ [$\Omega^{-1}cm^2mol^{-1}$]
H^+	349.8	OH^-	197.6
Na^+	50.1	Cl^-	76.3
K^+	73.5	HCO_3^-	75
Mg^{2+}	53.1	SO_4^{2-}	80
Ca^{2+}	59.5	NO_3^-	71.4

Table 2.2 Equivalent conductivity Λ [$\Omega^{-1}cm^2mol^{-1}$] of various ions

The density of those precipitations may grow to such an extent that a compact or porous covering layer will emerge which will reduce the feed of the protecting current.

If, however, during the starting period alkaline cations will reach the phase boundary, the pH level may strongly increase. Due to the hygroscopicity of the resulting reaction products the electrolyte resistivity at the phase boundary will decrease and the cathodic protection current increases, even accelerating the processes involved. After some time an equilibrium state will be reached (fig. 2.5). In the region of the phase boundary a high lye concentration (pH value 12 to 14) has developed. OH^- migrates away from the phase boundary. With increasing distance from the phase boundary the pH level decreases. In the pH range from 9 to 12 $Mg(OH)_2$ and $Ca(OH)_2$ are precipitated and, if CO_2 is present in the soil, transformed into the carbonates. By this process the soil in this region will be solidified and baked together.

2.3.5. Effects of these processes on the spread resistance

These chemical processes in the region of the holidays in the coating have a significant influence on spread resistance of the latter. Results with coupons having an area of 1 cm^2 have shown that the spread resistance may increase by as much as 100 times or may decrease by as much as 60 times, depending on the composition of the soil.
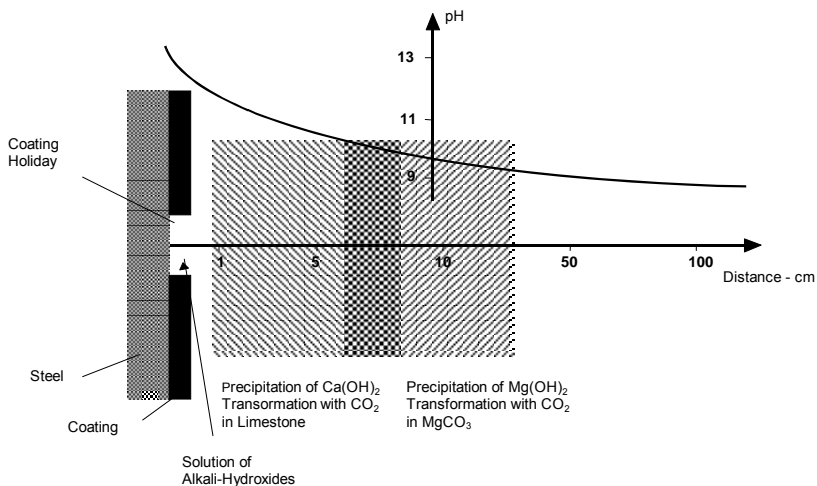
Fig. 2.5 Soil water with a mixture of earth alkaline and alkaline metal salts. Precipitation of low dissolvability hydroxides of earth alkaline cations in a certain distance at the metal / electrolyte phase boundary.

3 - Laboratory measurements

In the following, examples of techniques, used in the laboratory in order to characterise factors related to the a.c. corrosion phenomenon, are given. However, the techniques are applicable in the field (on coupons) as well. The techniques have been divided into measurements related to electrochemical characterisation and measurements related to corrosion rate estimation under a.c. influence.

3.1 Electrochemical measurements

3.1.1 D.c. polarization curve

A d.c. polarization curve describes in general the current flowing to or from a metal exposed in a certain solution as a function of the potential of the metal under steady state conditions. From the curve, the electrochemical behaviour of the metal in that solution as a function of the potential can be assessed. The condition of the metal is normally

described as either immune (achieved under well functioning cathodic protection), actively corroding, or passive (corrosion products cover the metal thus creating effective corrosion protection).

In relation to a.c. corrosion, the following limitations are underlined:

- the condition of the metal (immune, active, passive) under d.c. cannot be expected to be similar under a.c. conditions (otherwise a.c. induced corrosion could not occur);
- the time constants of the involved electrochemical processes cannot be assessed;
- the corrosion rate under a.c. cannot be extracted from the curve;
- the possibility of a.c. induced corrosion in a certain environment cannot directly (at least at present) be assessed from the curve.

Figure 3.1 is a schematic example of a d.c. polarization curve, showing regions of immunity, active corrosion and passivity of the metal. In addition, the open circuit potential, region of proper cathodic protection, as well as regions of hydrogen evolution and oxygen evolution are shown.
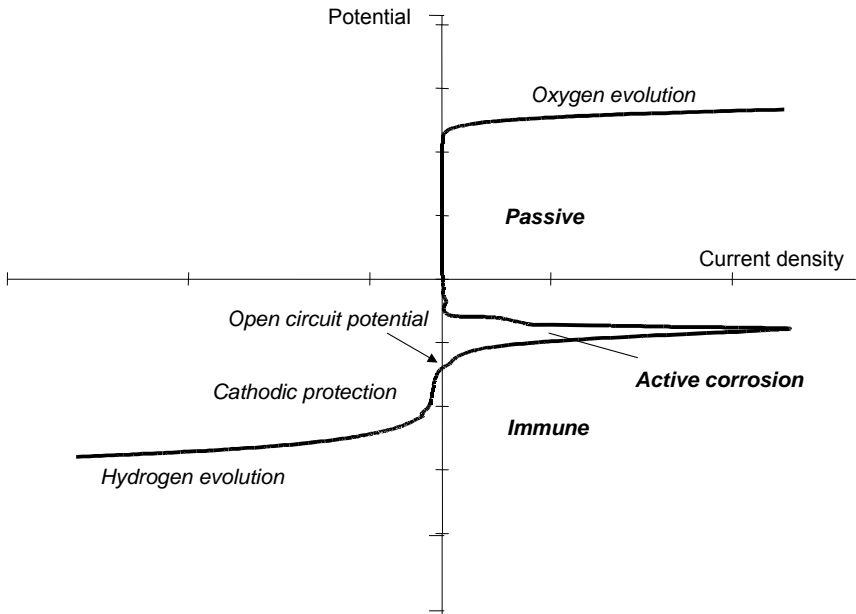

Fig. 3.1   Schematic of a d.c. polarisation curve illustrating regions of immunity, active corrosion, and passivity.

3.1.2. Square wave signal switching

By square wave signal switching is meant the switching of either current or potential from one steady state to another steady state to be reached. The instant off technique is one such signal switching technique, since the current is interrupted and the potential measured just after the IR-drop disappears, however, prior to depolarization of the metal. If the potential is followed throughout an extended period of time, the potential decay can be recorded and the mathematics of the decay described.

- The electrode time constants may be assessed from this technique.
- IR-drops may be identified.
- Superimposed a.c. may influence on the behaviour.
- Time constants related to reference electrode used may be difficult to identify.

3.1.3. Electrochemical impedance spectroscopy (EIS)

The electrochemical impedance spectroscopy measurement (EIS) is a scan of the impedance of the metal over a wide range of frequencies, say from the micro or millihertz region to the kilo or megahertz region. The measurement requires an offset potential or offset current, and a choice of the amplitude of the sinusoidal perturbation around the offset. An idealized output of such impedance measurements is shown in figure 3.2. The Nyquist plot gives the real and imaginary part impedance in a vector diagram, whereas the Bode plot gives the magnitude of the impedance and the phase between voltage and current as a function of the applied frequency.
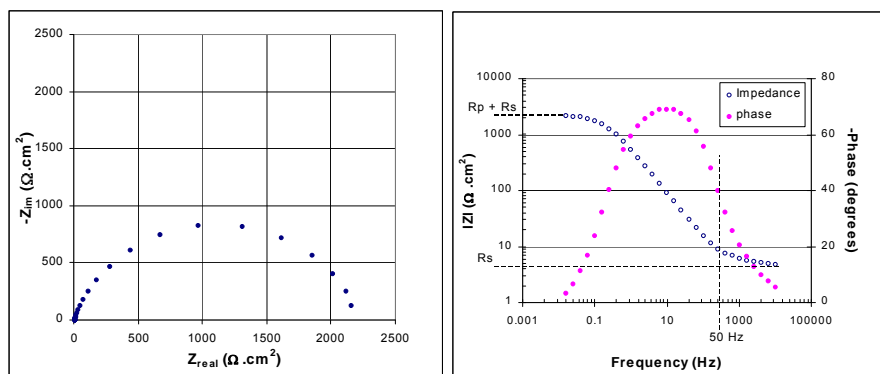
Fig. 3.2   Idealised Nyquist plot (left) and Bode plot (right) resulting from an EIS measurement.

The measurement offers the following possibilities in relation to a.c. corrosion:

- spread resistance can be measured directly;
- the polarization resistance of the metal can be assessed;
- the time constants of the involved processes can be assessed;
- the above quantities are believed to be linear only for small values (~10 mV) of applied amplitude, but both small and large (more realistic) amplitudes can be applied;
- the a.c. corrosion rate cannot be assessed from the measurement.

3.2. Corrosion rate estimation

In conventional d.c. cases, the electrochemical techniques described above apply for corrosion rate assessment. However, they fail in the a.c. case, and other techniques have to be applied, among which the weight loss measurement or visual inspection and the ER measurement are preferred.

3.2.1 Weight loss and visual examination

The weight loss measurement is the most straightforward way of characterizing the degree of corrosion. It simply relates the average corrosion rate appeared within some time of exposure as the weight loss divided by the period of exposure. The technique may be refined by using microscopy to characterize the corroded surface, e.g. in terms of the degree of localized corrosion, measurement of its depth etc. However, the method requires some time of exposure, i.e. some time of corrosion in order to give a fair picture of the corrosion.

- The technique quantifies average corrosion rate over an extended period of time.
- The technique is quite slow since a certain amount of material loss is necessary before the weight loss can be measured accurately.

3.2.2 Electrical resistance (ER) technique

The electrical resistance (ER) technique is based on the phenomenon that the electrical resistance in a metal element increases when the cross section of the element decreases due to corrosion.

Figure 3.3 is an example of an ER measurement and associated calculation of corrosion rate throughout time for cathodically protected steel under a.c. interference.
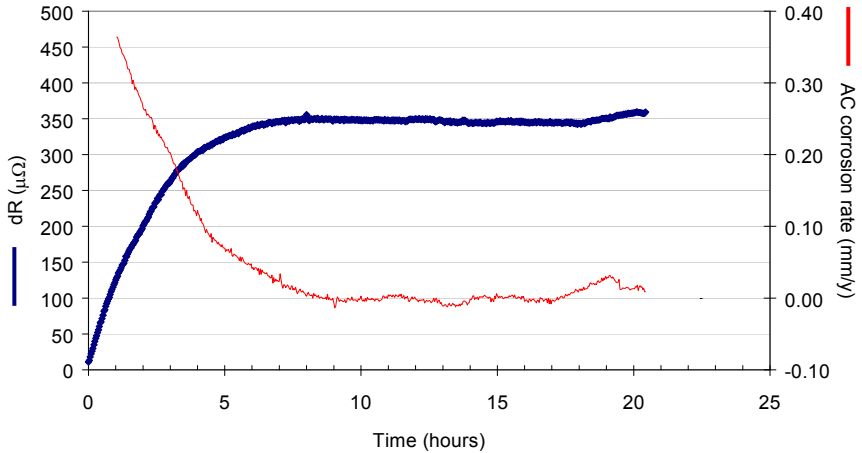
Fig. 3.3   Example of ER measurement and calculated corrosion rate as a function of time for cathodically protected steel superimposed with a.c.

- Very high resolution of resistance measurement and compensation for temperature effects makes the ER technique capable of measuring instant corrosion rates.
- The technique can be applied in any environment regardless of presence of water, and regardless of the type of electrical signal applied from external sources (i.e. the technique can be used under a.c. conditions).

4 - Evaluation of a.c. corrosion risk

The likelihood of a.c. corrosion can be evaluated according to different approaches:
- calculating induced a.c. on pipelines;
- measurements on site.

4.1. Calculating induced a.c. on pipelines

4.1.1. General

This approach is convenient during the design stage of the interfering or the interfered structure. It allows prediction of a.c. corrosion likelihood in future situations and to plan countermeasures accordingly.

In view of excessive voltages on pipelines, due to high voltage power lines and overhead traction wires, the configuration of the interfering and interfered structure and connected equipment have to be considered from an electrical point of view. All parameters, which determine the electrical behaviour of the interfered and the interfering structure with respect to each other, must be taken into account.

They apply to:
- the electrical behaviour of the high voltage power line or the traction line (height, current, voltage, lines, relative location of phase cables to each other, etc.);
- the electrical behaviour of the pipeline to the environment (coating, soil, earthing, etc.) and to the electrical behaviour between different parts of the pipeline (equipotential bondings, isolating joints, etc.).
- geometrical arrangement between pipeline and high voltage power lines or overhead traction wires (length of parallel routing, reciprocal distance, angle of crossing, etc.).

For calculations, worst conditions (voltages, currents) should be considered.

As these are not obvious it may be necessary to perform several calculations (several trains or short circuits at different locations, different load conditions on high voltage power lines, etc.) to find the most severe interference.

Characteristics and location of high voltage power lines, traction lines, pipeline sections and connected equipment should be considered in design conditions, including all the mounted safety devices as they are at the time of calculation.

4.1.2. Evaluating when calculations of induced a.c. should be made

Inadmissible voltages on pipelines due to overhead traction lines and high voltage power lines may be expected and need further examination if one of the following applies.
The distance between the overhead line and the pipeline is less than

$$d = 300 \cdot \rho^{1/2}$$

with   d (m) = distance between the overhead line and the pipeline
         ρ (ohm·m) = soil resistivity
(e.g. 7500 m in case of a 50 ohm·m resistivity soil)

In an urban environment, due to the presence of other metal structures in the soil (power and telecommunication cables, gas and water pipelines), this distance may be shortened.
- the length of parallelism is longer than 2000 m

4.1.3. Parameters to be considered

For the traction lines or high voltage power lines parameters such as mentioned hereafter are important as input to the mathematical model to describe the source of interference and should therefore be mentioned by the owner of the interfering source:
- currents (A) and voltages (V) in the conductors under high load or short circuit conditions;
- the height (m) above ground and the position of phase wires between each other (m) (measurements on towers);
- the location and characteristics of earthing systems of the towers (ohm), the voltage limiting devices.
For all pipelines and connected equipment, within the limits defined in point 4.1.2. parameters such as mentioned hereafter are important as input to the mathematical model to describe the sensitivity of the system to interference and should therefore be mentioned by the pipeline owner:
- the co-ordinates of pipelines and high voltage lines (to calculate distances between both systems);
- the pipeline length within the exposure area (km);
- the burial depth of the pipeline (m);
- the pipeline outer diameter (mm);
- the wall thickness of the pipeline (mm);
- the isolating coating thickness (mm);
- the isolation coating resistance (Ohm/m^2);
- the pipeline resistivity (Ohm·mm);

- the electrical characteristics of the transported medium (if other than gas);
- soil resistivity (Ohm·m);
- the location and the characteristics of the groundings, the voltage limiting devices, the polarisation cells, the electrical and/or electronic equipment, the cathodic protection devices, and the isolating joints.

Calculations are performed on pipelines and high voltage lines, using average values for parameters which may not be constant, i.e. soil resistivity, etc.

The parameters to be considered may vary according to the applied calculation algorithm.

Calculations considering normal conditions (voltages, currents) may be performed to allow for comparison with measurements in the field.

4.1.4. Calculation algorithms and results

Calculation algorithms are defined in Volume III of the ITU-T (CCITT) Directives (capacitive, inductive and conductive coupling) and in the CIGRE-report (see references).

The results are long term and short term voltages in the different sections of the interfered structures.

4.2. Measurements on site

As a first approach some preliminary measurements may be performed on interfered pipelines. Depending on the results, more specific actions may be taken, such as:
- measurements on coupons;
- specific measurements;
- dedicated surveys.

4.2.1. Preliminary measurements

On pipelines sections within the exposure area as defined in 4.1.2. the following measurements may be performed:
- pipe to soil a.c. voltage measurements between the pipeline and a reference electrode at test points (instantaneous measurements);
- the time of execution of each measurement shall be accurately recorded, to allow for calculation of the induced a.c. later under the same conditions as during the measurements;
- a.c. current measurement on existing pipeline earthing;
- ohmic resistance of pipeline earthing;

- soil resistivity at locations where pipe to soil a.c. voltage measurements have been taken;
- 24 h recording of measurements at locations showing the highest induced a.c. for high voltage power lines and sections interfered by a.c. traction systems.

All measurements on pipelines must be carried out in the following conditions:
- all CP stations, drainages and bonds shall be connected and in normal operation condition;
- all groundings shall be connected (polarisation cells, ac discharge devices, capacitors, etc.);
- the reference electrode should be located at the ground surface, as close as possible to the pipeline.

4.2.2. Specific measurements

In sections where a.c. voltages are higher than 10 V or where the voltages along the pipeline show variations to lower values, indicating possible ac discharge, specific measurements on site should be performed.

No single measuring technique or criterion for the evaluation of a.c. corrosion risk is yet accepted to assess a.c. corrosion.

Some specific measurement techniques with associated criterion are used:
- pipe-to-soil potential;
- current density;
- $J_{a.c.}/J_{d.c.}$ (current density ratio).

4.2.2.1. Pipe-to-soil potential

Measuring method

A steel coupon with known coating holiday surface is installed into the soil close to the pipeline, and electrically connected to the pipeline, to experience the same cathodic protection current and ac interference as the pipeline under investigation. The coupon will be allowed to polarise.

A reference electrode, permanent or portable, will be placed into the soil as close as possible to the coupon, preferably integrated with the coupon, For measuring purposes the instant E_{off} coupon to soil potential may be measured by disconnecting the coupon from the pipeline (measuring the potential without IR drop).

To perform the measurements automatically a measuring system may be used.

This measuring system consists of an electronic recording device that reads and stores data periodically and desynchronised from the a.c.

interference. The device measures the potential when the coupon is connected to the pipeline (Eon), disconnects the coupon from the pipeline, via a reed relay, measures the Eoff potential 1 msec after disconnecting, and connects the coupon to the pipeline again. Together with the Eon potential the current to the coupon is measured and recorded. Approximately 20 msec afterwards, this cycle is repeated.

Due to the desynchronisation of the measuring cycle from the a.c. interference, measurements will be taken at any time within the a.c. interference-period, including peak values.

Evaluation of a.c. corrosion risk
Using this measuring technique, the pipeline is considered protected from ac corrosion if the coupon-to-soil Eoff potential is at any moment more negative than the protective potential range, which is -0,850 mV for iron or steel in aerobic or -0,950 mV in anaerobic soil containing sulphate-reducing bacteria.

4.2.2.2. A.c. current density

Measuring method
A steel coupon with known coating holiday surface is installed into the soil close to the pipeline, and electrically connected to the pipeline, to undergo the same cathodic protection current and a.c. interference as the pipeline under investigation.

An ammeter is introduced in the connecting wire to measure the RMS value of the ac current. Small currents should be measured as a voltage drop on a resistor (1 ohm or less) or by using a zero-resistance ammeter. The RMS current density is than calculated.

Evaluation of ac corrosion risk
Using this measuring technique, the pipeline is considered protected from a.c. corrosion if the RMS ac current density is lower than 30 A/m^2.

4.2.2.3. Current density ratio ($J_{a.c.}/J_{d.c.}$)

Measuring method
A steel coupon with known coating holiday surface area is installed on or into the soil close to the pipeline, and electrically connected to the pipeline, to experience the cathodic protection current and ac interference as the pipeline under investigation.

An ammeter is introduced in the connecting wire to measure the dc and the RMS a.c. value of the current. Small currents should be measured as a voltage drop on a resistor (1 ohm or less) or by using a zero-resistance ammeter.

From these values the ratio $J_{a.c.}/J_{d.c.}$ is calculated.

Evaluation of ac corrosion risk
Using this measuring technique, if the RMS a.c. current density to d.c. current density ratio:
- is lower than 3, the a.c. corrosion risk is considered to be low
- is between 3 and 10, the a.c. corrosion risk is considered to be medium, and further investigation is advised
- is higher than 10, a.c. corrosion risk is considered to be high and immediate mitigation measures should be taken.

4.3. Coupon, design and installation

When applying coupons it must be considered that their spread resistance will be modified by physical parameters (area, soil resistivity) as well as by chemical ones (formation of cover layers or formation of hygroscopic salts caused by cathodic protection current) (see also chapter 2.)
The findings of the first investigations of corrosion damages on pipelines showed corrosion at coating fault locations of approximately 1 cm^2. For this reason and for practical reasons, a coupon area of 1 cm^2 is recommended for monitoring and for evaluation of ac corrosion risk.
A.c. corrosion mainly happens on small/very small coating faults, since on smaller coating faults higher current densities are concentrated. If larger coupon areas are used, the corrosion risk at smaller coating faults cannot be evaluated either by the current density criterion, or by the potential criterion.
Different types of coupons for a.c. corrosion risk evaluation can be used:
- non-permanent portable coupons (e.g. rod coupons) for a.c. current density and potential measurements;
- permanent buried coupons (e.g. corrosion coupons) for a.c. corrosion evaluation, a.c. current density, potential measurements, measurements of development of spread resistance.

4.3.1. Non-permanent portable coupon characteristics and installation (short term measurements)

Coated steel rod coupons with known coating holiday surface (e.g. 1 cm^2) are often used for short-term measurements.
The rod coupon is driven into the soil close to the pipeline and electrically connected to the pipeline via a connecting wire, to experience the same cathodic protection current and a.c. interference as the pipeline under investigation.

Rod coupons are used to perform measurements as described in 4.2.2.1. Specific measurement techniques on site.

Their shape allows easy insertion into the soil and good electrical contact with the soil.

A typical rod coupon is represented in Figure 4-A.

The measurements with the non-permanent portable coupons do not take into account the long term changing chemistry due to CP currents (see chapter 2.).

4.3.2. Permanent buried coupon characteristics and installation (long- term measurements)

Coupons are often used for long term evaluation of a.c. corrosion likelihood. They are also known as corrosion coupons.

The corrosion coupon is installed into the soil close to the pipeline and electrically connected to the pipeline via a connecting wire, to experience the same cathodic protection current and ac interference as the pipeline under investigation.

Often a set of three corrosion coupons is installed at the same location. Care must be taken to:

- assure for good long term electrical contact between the coupon and the soil;
- install the corrosion coupon in the same soil conditions as the pipeline;
- the position of the corrosion coupon and the permanent reference electrode to each other;
- the influence on the coupon, due to neighbouring structures, potential gradients or other coupons;
- not to install too many coupons at the same location.

On these coupons, specific measurements may be performed (see 4.2.2.):

- potential measurements;
- current measurements;
- spreading resistance measurements.

After a certain time (e.g. 12 months), the corrosion coupon is excavated and examined for corrosion. If corrosion marks are present, corrosion of the pipeline at coating holidays can be expected.

Reference electrodes, that are installed for a long period of time may leak

the electrolyte solution into the soil, changing the soil characteristics and increasing current demand of the coupon.

Typical corrosion coupons with their construction characteristics are represented in Figure 4-B, Figure 4-C and Figure 4-D.

A typical corrosion coupon installation is represented in Figure 4-E.

4.4. Coating fault location and soil characteristics

In the interfered sections (see 4.1.2.), the following actions could be taken:
- coating fault location survey over the entire section by methods, able to detect small coating defects (down to 1 cm^2);
- measurement of soil resistivity and burial depth of the pipeline at the location of small coating faults, detected by the survey;
- excavation of the pipeline at some coating faults, where induced a.c. calculations indicate maximum values, chosen according to voltage gradient, a.c. voltage or soil resistivity measurements;
- further investigations on typical small coating defects by a.c. voltage recording during 24 h, and soil resistivity and pipeline depth measurements at coating faults;
- intelligent pig runs optimised to detect small metal losses.

If corrosion is found at small coating defects, all the coating faults showing similar characteristics should be excavated and repaired.

Soil resistivity

Low or very low soil resistivity in the neighbourhood of the pipeline may increase a.c. corrosion by allowing high ac current drainage from the pipeline to the soil.

Soil resistivity may be determined by the 4 point Wenner method, either in the field or using a soil box.

The spread resistance R_S (ohm) of a coupon can be calculated from the equation

$R_S = \rho / 2d$

With   d (m) = diameter of the coupon
        ρ (ohm.m) = specific soil resistivity

By means of the spread resistance of the coupon, the change in the soil resistivity over time can be monitored.

Care should be taken to
- measure the soil resistivity at sufficient depth (in the field)
- use soil from the neighbourhood of the pipeline (soil box).

PH measurement

When measuring pH values the pH level at the coupon surface is of great importance. This value should be determined immediately after excavation of the coupon, since the alkaline coupon surface is neutralised very rapidly by the carbon dioxide from the air. Best practice is to use pH indicator strips that indicate the pH with an accuracy of 0.5 units.
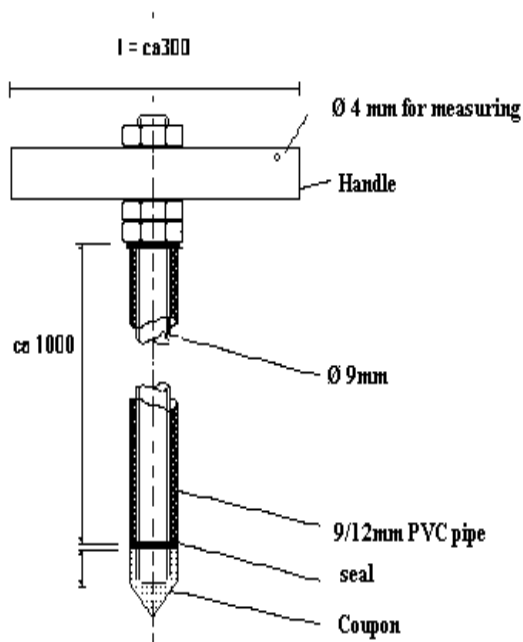
Figure 4-A Rod coupon
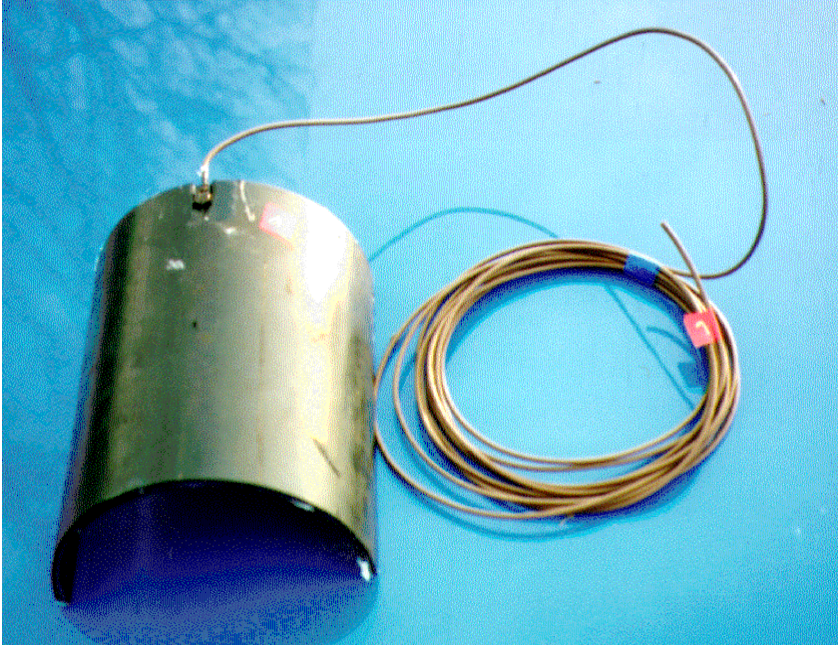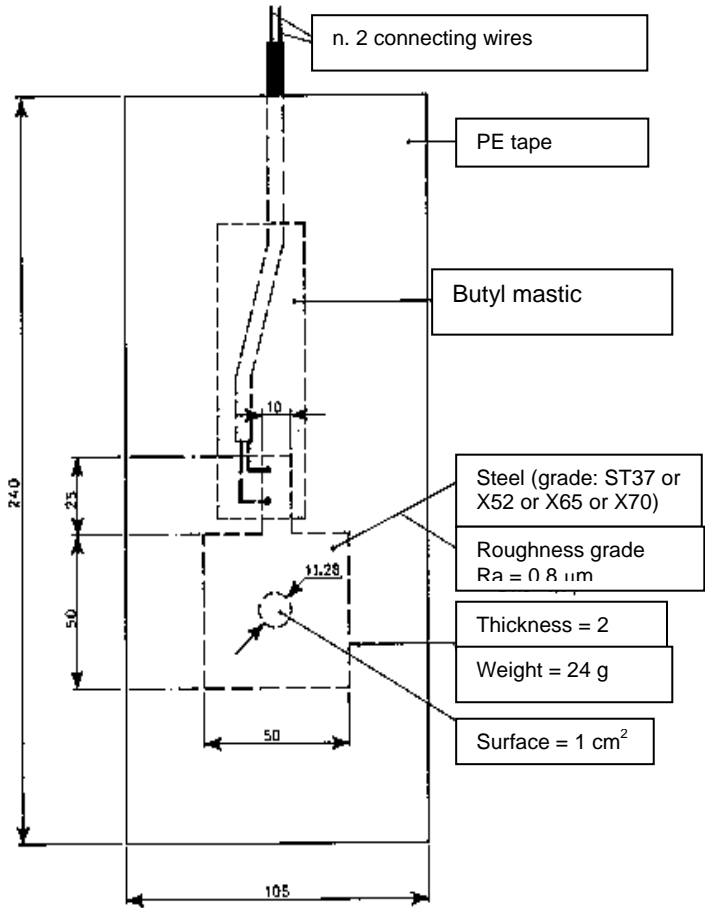
Figure 4-B Corrosion coupon

Fig. 4-C Corrosion Coupon

Coupon for simulating a small coating fault

n. 2 connecting wires

PE tape

Butyl mastic

10

240

25

Steel (grade: ST37 or X52 or X65 or X70)

Roughness grade Ra = 0.8 μm

11.28

Thickness = 2

Weight = 24 g

50

Surface = 1 cm^2

50

105

The steel plate is covered on both sides with butyl rubber PE tape. Before applying the tape the steel plate has to be painted with primer. Within the fault the primer has to be removed after having applied the tape.

Figure 4-D Corrosion coupon
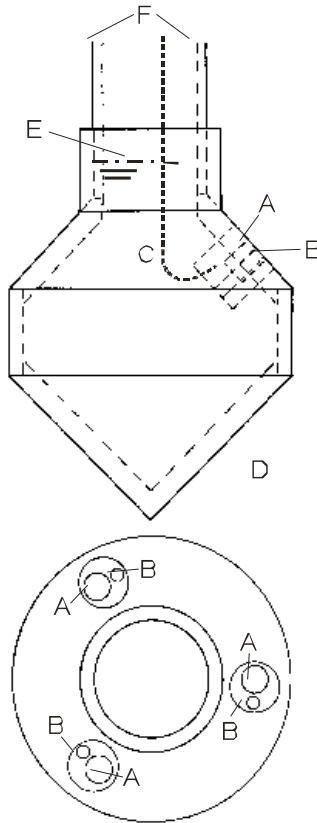
This coupon consists of 3 round steel cylinders whose cross section areas (A) of 1 cm^2 are tilted by an angle of 45° in respect to the earth surface. These steel cylinders are moulded in PVC together with a sintered glass filter (B) and the cable connected at the back (C). The steel cylinders are weighed. The moulded measuring probes are glued into a round cavity of a PVC body (D). The cables are led to the surface through the PVC tube (E). After assembly, the hollow PVC body (D) is filled up to the level (E) with a high viscosity pulp of bentonite and distilled water. For the potential measurement a mobile CSE reference electrode is put into the bentonite through the PVC tube (F). The measuring current loop leads from the CSE over the bentonite to the sintered glass filter and further through the soil interface to the measuring probe.

Figure 4-E Typical of corrosion - coupons
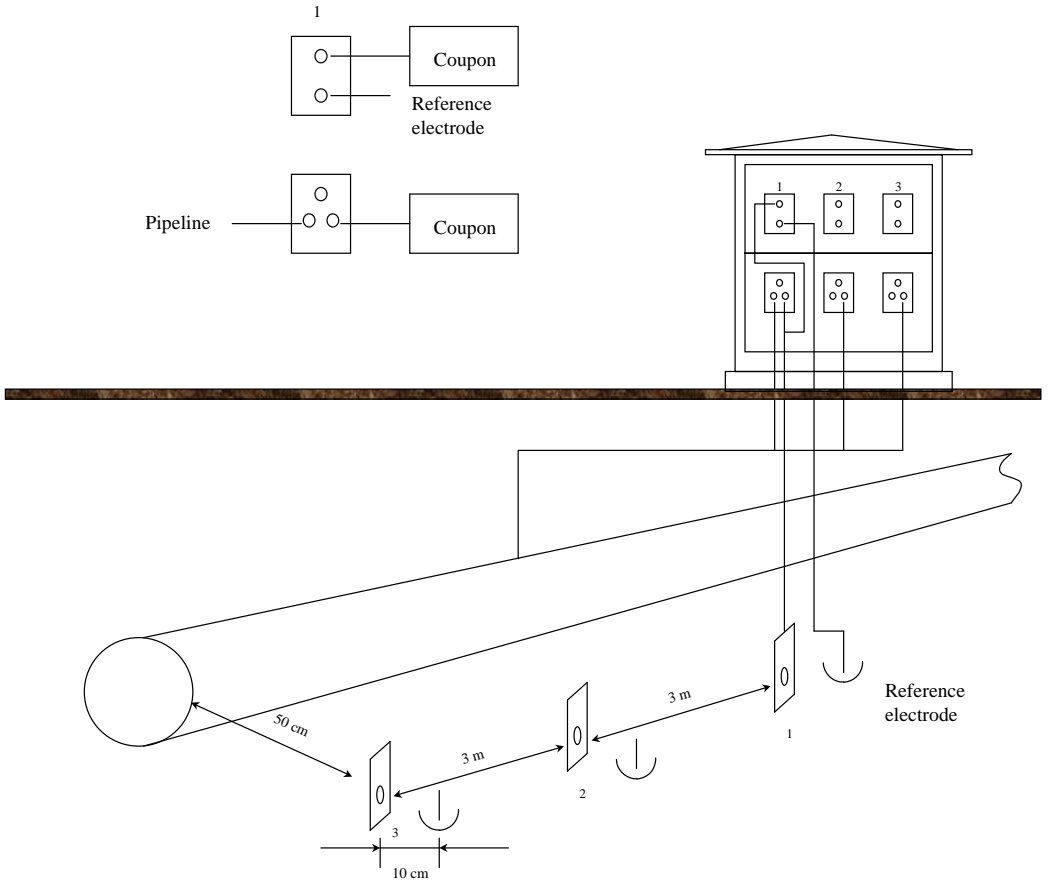
5 - Identification of an a.c. corrosion case

An a.c. corrosion case can generally be discovered either from product leakage or ad hoc measurements and consequent evaluation/excavations.

When corrosion arises on a pipe lying nearby to parallel power lines or a.c. fed traction systems, a careful verification of the origin of the corrosion should be made.

The actual presence of an a.c. pipe-to-soil voltage is generally a pre-requisite for attributing the corrosion to a.c., but cases may exist where the a.c. voltage (inductive of resistive influence) may have been present previously.

During excavation on sites where a.c. corrosion is suspected, soil resistivity and pH measurements should be performed near to the excavated site.

A collection of corrosion product should be made and examined in the laboratory.

In order to recognise an a.c. corrosion case, the following questionnaire may be used:

ASSESSMENT OF AN A.C. CORROSION CASE (*)

Is it an a.c. corrosion case?

DATA	YES	NO
Presence of an a.c. voltage on the pipeline		
Presence of a coating fault (usually very small size - up to some cm^2)		
Presence of a corrosion		
C.P. measurements showed values within acceptable criteria		
pH values very high (typically more than 10)		
The shape of the corrosion is a rounded pit (like a negative of a sphere)		
The corrosion pit is much larger than the coating defect		
The corrosion products can easily be removed in one piece		
After removal of corrosion products, a hard black layer is visible on the steel surface		
Low/very low soil resistivity		
Presence of a large disbonded area beneath the coating (a halo is visible on the steel around the corrosion pit)		
Presence of a layer far from the corroded area or within the corrosion products having high quantities of calcium carbonate		
Presence of magnetite within the corrosion products (it can be ascertained by a permanent magnet)		
Presence of a hard-stone soil formation		

(*) If most of the answers are YES, it can be concluded that most probably it is an a.c. corrosion case.

6 - A.c. corrosion mitigation

If the output parameters of a CP rectifier cannot be set in order to obtain the protective values measured according to paragraph 4.2.2.1.1, then mitigation measures must be provided. Mitigation measures against ac-corrosion either aim at avoiding coating defects or at reducing the ac-current density at coating defects. The different methods may be subdivided as follows:

- increasing the distance between pipeline and high voltage line;
- optimum arrangement of phases and earth wires;
- earthing of pipeline;
- compensation of induced voltage;
- installation of isolating joints;
- repair of coating defects;
- exchange of soil in the vicinity of pipeline;
- use of parallel earthing cables.

6.1. Increasing the distance between pipeline and high voltage line/electrified railway

This measure has to be considered during the design of the pipeline or of the high voltage line/electrified railway. Increasing the distance between the pipeline and the high voltage line/electrified railway reduces the level of induced voltage on the pipeline. Fig. 6.1 shows changes of induced voltage depending on the distance of parallel routing.
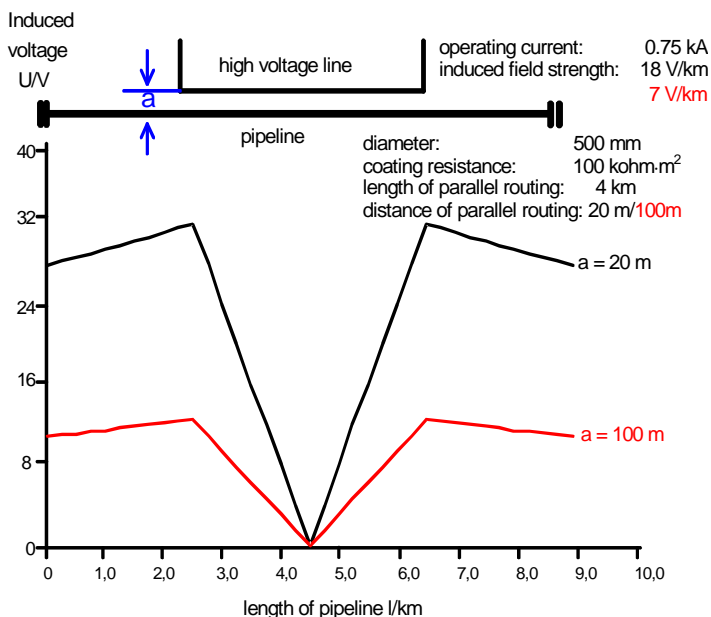
Fig. 6.1 Influence of increasing distance between a pipeline and the outermost phase wire of a parallel routed high voltage line on the induced voltage

6.2. Optimum arrangement of phase and earth wires of the high voltage line/electrified railway

The design of the high voltage pole and arrangement of earth wires are essential parameters, when calculating the induced a.c. voltage, because it is the geometrical difference of the distance from the pipe to each phase wire, which governs the calculation.

The "cheapest" way to reduce the induced voltage is to transpose the phase wires, which means physically changing the position of the phase wire on the high voltage pole, three times at least, within an interfered area. This measure includes:

- geometrical arrangement of phases R, S, T on the pole;
- geometrical arrangement of earth wire(s);
- location of transposition poles.

6.3. Earthing of pipeline with earth electrodes

Grounding is equal to a reduction of coating resistance of a pipeline and is an effective measure to reduce the induced voltage. Reduction of the induced voltage to less than i.e. 10 V demands groundings with a resistance less than a few ohms. Grounding is well known for protecting a pipeline against inadmissible touch voltages. Its principle is shown in fig. 6.2.
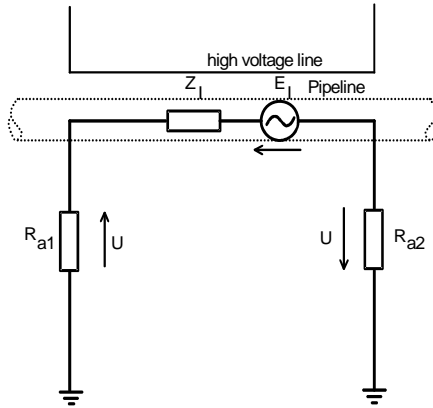

Fig. 6.2 Equivalent circuit of a grounded pipeline interfered by high voltage line

Z_L means the impedance per unit length of pipeline, E_L the induced electric field strength per unit length. In fig. 6.2 the coating resistance and those sections of pipeline exceeding the parallel routing with the high voltage line are neglected for the purpose of admissible simplicity. At the end of parallel routing the pipeline is grounded with earth electrodes $R_{a1}=R_{a2}=R_a$.

In practice concentrated earth electrodes at the ends of a parallel routing may be used or a continuous earthing, i.e. location of earth electrodes are (more or less) equally distributed along the pipeline. The choice of the appropriate measures shall take into account the ground resistance necessary to achieve the determined reduction of induced ac-voltage (e.g. by using computer simulation programmes).

The following considerations are based on concentrated earthing of a pipeline interfered by a high voltage line. According to fig. 6.2 it is:

$$\frac{U}{R_a} = \frac{E_L}{2R_a + Z_L}$$

U is the voltage between pipeline and remote earth:

$$U = \frac{E_L}{2 + Z_L / R_a}$$

For $R_a \gg Z_L$ (this generally corresponds to a non-grounded pipeline) therefore $U = E_L/2$. An effective earthing is achieved, if $R_a = Z_L/2$, which is generally sufficient to reduce induced voltages at admissible touch voltages.

The impedance of a steel pipeline is in the order of 0.5 Ω/km for technical frequencies of 50 Hz and $16^{2/3}$ Hz. Thus the reduction of interference voltage to some % of E_L - as it may be necessary to achieve sufficient reduction of ac-current densities may require low grounding resistances of earth electrodes. Under certain soil conditions (e.g. bed rocks near ground surface), it may be difficult to achieve enough low ohmic grounding resistance.

As an example of possible installation of grounding, the earthing strips (e.g. copper, zinc) of certain length are placed in the soil and connect to the pipeline. The length of the strip must be calculated to achieve the sufficient grounding with a ground resistance of some ohms. The strips can be placed in the same trench with the grounded pipeline, but to prevent the adverse influence of earthing strips on coating fault measurements, their installation is recommended longitudinally to the pipeline in some meters apart.

Grounding of the pipeline as a mitigation measure can be done as:

- direct
- indirect.

Direct grounding system is done by directly connecting pipeline and grounding electrode via cables at the test post. Using direct grounding system increases output current value of CP rectifier because grounding electrodes behave like coating defects.

Indirect grounding system operates with a separating unit. The unit is an electric device (Kirk cell, semiconductors, dischargers, capacitors unit etc.) which provides electric separation between the pipeline and the grounding. Some units may be controlled by the induced voltage, in such a way, that the groundings are connected only, when the induced a.c. voltage reaches a certain level. Increasing this level e.g. due to a.c. voltage influence, the unit allows to ground a pipeline sufficiently.

In some systems these units may be sampled synchronously with the protecting rectifiers in order to measure the classical on and off potentials on the pipeline. Some of the above-mentioned types of separating units can effect pipeline location procedures due to discharging of a.c. signal current to the grounding.

6.4. Compensation of induced a.c. voltage

6.4.1. Full compensation of induced a.c. voltage

Reduction of induced voltage may be achieved by introducing a.c. voltages E_1 and E_2 into the connection between pipeline and earth electrodes R_{a1} and R_{a2} respectively (fig. 6.3) having a phase shift $\varphi=180°$ compared to the a.c. voltage pipeline/soil at the location of installation.
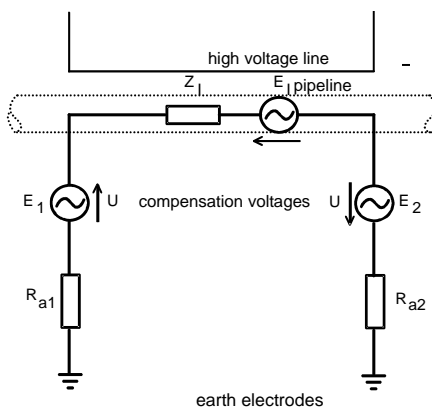

Fig. 6.3 Equivalent circuit (simplified) of a high voltage interfered pipeline with equipment for a.c. voltage compensation

Based on the simplifying conditions $R_{a1}=R_{a2}=R_a$ and $E_1=E_2=E$, it is $U=U_1=U_2$ and:

$$U = \frac{E_L + E\,Z_L / R_a}{2 + Z_L / R_a}$$

In case of U=0, which corresponds to a complete compensation of induced voltage it is:

$$E = -E_L \frac{R_a}{Z_L}$$

If E_1 and E_2 are adjusted in this way a complete compensation of the induced voltage is possible. The current to be provided by the a.c. sources E_1 and E_2 shall be:

$$I = \frac{E_L}{Z_L}$$

For practical applications the power P, required from E_1 and E_2 is of importance. Under the simplifying conditions mentioned above it is:

$$P = E I = -E_L \frac{R_a}{Z_L} \frac{(-) E_L}{Z_L} = E_L^2 \frac{R_a}{Z_L^2}.$$

This means that the required power increases proportional to the square of induced voltage and also increases with decreasing impedance per unit length. The following considerations should indicate the order magnitude of power required.

Example 1
4 km parallel routing of pipeline DN 800 with high voltage line. The induced electric field strength is assumed to be 15 V/km yielding a total voltage E_L = 60V across the interfered pipeline section. The impedance per unit length is $Z_{L'}$ = 0.5 Ω/km; i.e. the impedance of the interfered section is Z_L = 2 Ω. The ground resistances R_{a1} and R_{a2} are assumed to be 2 Ω each. The power P required from one compensation equipment then is 1800W.

Example 2
20 km parallel routing of pipeline DN 300 with high voltage line. The induced electric field strength is assumed to be 15 V/km yielding a total voltage E_L = 300V across the interfered pipeline section. The impedance per unit length is $Z_{L'}$ = 0.73 Ω/km; i.e. the impedance of the interfered section is Z_L = 14.6 Ω. The ground resistances R_{a1} and R_{a2} are

assumed to be 2 Ω each. The power P required from one compensation equipment then is approximately 850W.

In such ideal cases a complete compensation of induced a.c. voltage along the complete pipeline, i.e. also outside the section of parallel routing will be possible.

As in practice the geometry of proximity generally does not correspond to these ideal assumptions, it has to be taken into account that a complete compensation will not be achievable. That is why we can hardly expect compensation with Ua.c.= 0. Furthermore the power required will be extraordinarily high in case of short but highly interfered pipeline sections.

6.4.2. Partial compensation of induced a.c. voltage

The difficulties of high power consumption may be overcome if the compensation compartments will be connected with the pipeline via diodes as it is shown in fig. 6.4.
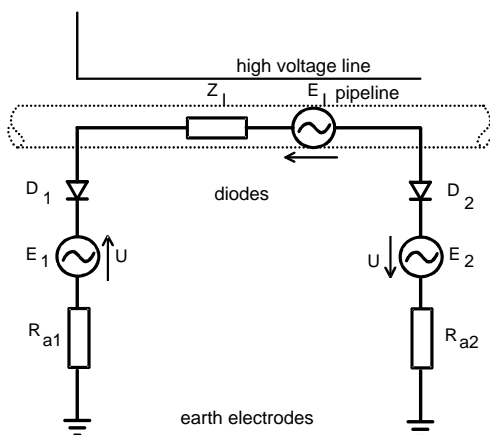

Fig. 6.4   Equivalent diagram (simplified) of a high voltage interfered pipeline with compensation compartments and diodes to compensate for the positive part of induced a.c. voltage

Under these conditions the positive part of the induced ac-voltage is exclusively compensated, thus the consequence will not be a reduction of ac-current density in a coating defect. This method therefore works under the assumption that exclusively the positive part of the a.c. voltage causes corrosion. This principle corresponds to the considerations mentioned in chapter 4.2.2.1.1 where it had been assumed that a.c.

corrosion is successfully mitigated, if the IR-free potential of the coating defect at no time exceeds the protection potential U = -850 mV.

The power consumption of the compensation compartments now corresponds to a simple rectifier, which is adjusted to an output voltage yielding an on potential being in the order of the induced ac-voltage.

The disadvantage of this method clearly is the extremely negative on-potential which is established on the pipeline and which is now fluctuating with the induced a.c. voltage. Especially in case of bituminous coated pipelines this has to be considered from the d.c. interference point of view. In case of high strength steel (X80) this may also be of importance from the hydrogen embrittlement point of view.

6.5. Installation of isolating joints to interrupt longitudinal conductivity of pipeline

In principle a reduction of the induced voltage may be achieved using isolating joints, which are installed to interrupt the conductivity of a pipeline, as the electric field strength in the pipeline is proportional to the length of parallel routing.

If this method is used, the following should be considered:

- installation of the isolating joint within the interfered section of the pipeline reduces the maximum value of induced a.c. voltage, which is proportional to the length of parallel interfered section
- the a.c. voltages on both sides of the isolating joint have a phase shift of 180°. The a.c. voltage measured over the isolating joint is the double of the peak voltage.

A practical example for the installation of isolating joints is the isolation of a branch line from a high voltage interfered main line in order to prevent spreading of a.c. voltage on the branch line.

6.6. Repair of coating damages

PE-coated pipelines have a rate of coating defects of about 1/km or less. With the known coating fault location methods they can be detected and repaired. It is necessary to remember that risk of a.c. corrosion is higher on small defects than on large ones. In order to achieve sufficient protection against a.c. corrosion it has to be verified that no additional defects arise on the pipeline during the following operation. Because perfect coating conditions can not be guaranteed during the whole lifetime of pipeline operation, this measure should be combined with other mitigation measures against a.c. corrosion.

6.7. Exchange of soil in the vicinity of pipeline

The a.c. current density at a coating defect may be reduced by exchanging the low resistivity soil in the vicinity of a pipeline with a high resistivity one (e.g. sand). This is a very costly procedure, especially at existing pipelines and can be taken into account only on very small pipeline sections.

As it is unknown how the chemical composition of the new soil will be altered with time due to the exchange of components with the surrounding "old" soil, the long-term effectiveness of this method is questionable and therefore has to be verified with coupons.

It is very important to remember that, according to soil chemical composition, the hygroscopic salts originating from the reaction of cathodic protection current at small/very small holidays interface may convert intrinsically high resistivity sands into a low resistivity material.

6.8. Use of parallel earthing wire

If a buried earthing wire is located next to the pipeline and not directly connected, it will affect the induced voltage, because part of the electric field will concentrate on the metal earthing wire. It will cause a reduction of ac-voltage induced in the pipeline.

The benefits of this very expensive method are poor in the long-term. Only a 5 % reduction of induced voltage is obtained.

6.9. Mitigation measures summary

Decision making for application of a.c. corrosion mitigation measure assumes that the cheapest solution is that, which guarantees sufficient protection against a.c. corrosion. The following table summarises the different a.c. mitigation measures, together with advantages and disadvantages.

Table 6.1 Mitigation measures summary

Mitigation measure	Advantages	Drawbacks
Increasing CP output current	- low cost - very easy to provide	- only possible in the cases of very low ac-interference
Increasing distance between pipe and high voltage line/electrified railway		- very efficient solution but only possible for newly designed pipes or interfering systems - not possible for existing systems
Arrangement of phase and earth wires of high voltage line		- only possible for newly designed high voltage power lines - solution can only be provided by the electricity company
Earthing of pipeline	- generally good technical solution and cost efficient	- problems may occur in high resistivity soil due to high resistance of groundings
Compensation of ac-voltage		- difficult to settle - high cost of installation and operation
Installation of isolating joints	-good possibility to vary an optimum configuration by calculation and design	- installation requires direct interference with pipeline operation
Repair of coating faults		- requires complementary measures
Exchange of soil in the vicinity of pipeline wall		- disputed behaviour of new backfill over time
Use of earthing wire		- high cost and poor efficiency

7 - References

1 CIGRE Report: Guide on the influence of High Voltage AC Power Systems on Metallic Pipelines - 1995

2 CCITT: Directives concerning the protection of telecommunication lines against harmful effects from electric power and electrified railway lines. Vol III "Capacitive, inductive and conductive coupling: physical theory and calculation methods" - ITU Geneva 1989

3 CEI 9-34 "Effects of electromagnetic interferences caused by a.c. railway contact lines on pipelines. Admissible values and protection measures."

4 AfK Recommendation

5 IGU 1994 Milan - Fault location on pipeline coatings