
**Corrosion of metals and alloys —
Determination of AC corrosion —
Protection criteria**

*Corrosion des métaux et alliages — Détermination de la corrosion
occasionnée par les courants alternatifs — Critères de protection*

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Contents

Page

Foreword.....	v
Introduction.....	vi
1 Scope.....	1
2 Normative references.....	1
3 Terms and definitions.....	1
4 Cathodic protection persons competence.....	5
5 Assessment of the AC influence.....	5
5.1 General.....	5
5.2 Assessment of the level of interference.....	6
6 Evaluation of the AC corrosion likelihood.....	6
6.1 Prerequisite.....	6
6.1.1 General.....	6
6.1.2 AC voltage on the structure.....	7
6.2 AC and DC current density.....	7
6.2.1 General.....	7
6.2.2 AC current density.....	7
6.2.3 High cathodic DC current density.....	7
6.2.4 Low cathodic DC current density.....	8
6.2.5 Current ratio " I_{ac}/I_{dc} ".....	8
6.2.6 Soil resistivity.....	8
6.3 Corrosion rate.....	8
6.4 Pipeline coatings.....	8
6.5 Evaluation of the metal loss.....	9
7 Acceptable interference levels.....	9
8 Measurement techniques.....	9
8.1 Measurements.....	9
8.1.1 General.....	9
8.1.2 Selection of test sites.....	9
8.1.3 Selection of measurement parameter.....	10
8.1.4 Sampling rate for the recording of interference levels.....	10
8.1.5 Accuracy of measuring equipment.....	10
8.1.6 Installation of coupons or probes to calculate current densities.....	10
8.2 DC potential measurements.....	10
8.3 AC voltage measurements.....	11
8.4 Measurements on coupons and probes.....	11
8.4.1 Installation of coupons or probes.....	11
8.4.2 Current measurements.....	12
8.4.3 Corrosion rate measurements.....	12
8.5 Pipeline metal loss techniques.....	13
9 Mitigation measures.....	13
9.1 General.....	13
9.2 Construction measures.....	13
9.2.1 Modification of bedding material.....	13
9.2.2 Installation of isolating joints.....	13
9.2.3 Installation of mitigation wires.....	14
9.2.4 Optimization of pipeline and/or powerline route.....	14
9.2.5 Power line or pipeline construction.....	14
9.3 Operation measures.....	14
9.3.1 Earthing.....	14
9.3.2 Adjustment of cathodic protection level.....	15
9.3.3 Repair of coating defects.....	15

10	Commissioning	16
10.1	Commissioning	16
10.2	Preliminary checking	16
10.2.1	General	16
10.2.2	Coupon AC voltage and current startup	17
10.2.3	Verification of effectiveness	17
10.2.4	Installation and commissioning documents	17
11	Monitoring and maintenance	18
Annex A (informative)	Simplified description of the AC corrosion phenomenon	19
Annex B (informative)	Coupons and probes	21
Annex C (informative)	Coulometric oxidation	26
Annex D (informative)	Influence of soil characteristics on the AC corrosion process	27
Annex E (informative)	Other criteria that have been used in the presence of AC influence	28
Annex F (informative)	Parameters to take into account to choose a DC decoupling device	32
Annex G (informative)	Method to determine the reference electrode location to remote earth	34
Annex H (informative)	Simultaneous measurement on coupon current densities with high rate	36
Bibliography		38

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 156, *Corrosion of metal and alloys*.

This second edition cancels and replaces the first edition (ISO 18086:2015), of which it constitutes a minor revision. The changes compared to the previous edition are as follows:

- references cited informatively (EN 13509 and EN 15257) have been moved from [Clause 2](#) to the Bibliography;
- in [Clause 7](#), the two instances of the phrase “AC current density” have been changed to “AC average current density”.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

This document has incorporated criteria and thresholds together with experience gained from the most recent data. Various countries have a very different approach to the prevention of AC corrosion depending primarily on the DC interference situation. These different approaches are taken into account in two different ways:

- in the presence of “low” on-potentials, which allows a certain level of AC voltage (up to 15 V);
- in the presence of “high” on-potentials (with DC stray current interference on the pipeline for instance), which requires the reduction of the AC voltage towards the lowest possible levels.

This document also gives some parameters to consider when evaluating the AC corrosion likelihood, as well as detailed measurement techniques, mitigation measures, and measurements to carry out for the commissioning of any AC corrosion mitigation system. [Annex E](#) proposes other parameters and thresholds that require further validation based on practical experiences.

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Corrosion of metals and alloys — Determination of AC corrosion — Protection criteria

1 Scope

This document specifies protection criteria for determining the AC corrosion risk of cathodically protected pipelines.

It is applicable to buried cathodically protected pipelines that are influenced by AC traction systems and/or AC power lines.

In the presence of AC interference, the protection criteria given in ISO 15589-1 are not sufficient to demonstrate that the steel is being protected against corrosion.

This document provides limits, measurement procedures, mitigation measures, and information to deal with long-term AC interference for AC voltages at frequencies between 16,7 Hz and 60 Hz and the evaluation of AC corrosion likelihood.

This document deals with the possibility of AC corrosion of metallic pipelines due to AC interferences caused by conductive, inductive or capacitive coupling with AC power systems and the maximum tolerable limits of these interference effects. It takes into account the fact that this is a long-term effect, which occurs during normal operating conditions of the AC power system.

This document does not cover the safety issues associated with AC voltages on pipelines. These are covered in national standards and regulations (see, e.g., EN 50443).

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 8044, *Corrosion of metals and alloys — Basic terms and definitions*

ISO 15589-1, *Petroleum, petrochemical and natural gas industries — Cathodic protection of pipeline systems — Part 1: On-land pipelines*

IEC 61010-1, *Safety requirements for electrical equipment for measurement, control, and laboratory use — Part 1: General requirements*

EN 50443, *Effects of electromagnetic interference on pipelines caused by high voltage AC electric traction systems and/or high voltage AC power supply systems*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 8044 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <http://www.electropedia.org/>

3.1

AC electric traction system

AC railway electrical distribution network used to provide energy for rolling stock

Note 1 to entry: The system can comprise the following:

- contact line systems;
- return circuit of electric railway systems;
- running rails of non-electric railway systems, which are in the vicinity of and conductively connected to the running rails of an electric railway system.

3.2

AC power supply system

AC electrical system devoted to electrical energy transmission, which includes overhead lines, cables, substations and all apparatus associated with them

3.3

AC power system

AC electric traction system (3.1) or *AC power supply system* (3.2)

Note 1 to entry: Where it is necessary to differentiate, each *interfering system* (3.6) is clearly indicated with its proper term.

3.4

copper/copper sulfate reference electrode

CSE

reference electrode consisting of copper in a saturated solution of copper sulfate

3.5

AC voltage

voltage measured to *earth* (3.9) between a metallic structure and a reference electrode

3.6

interfering system

general expression encompassing an interfering high voltage *AC electric traction system* (3.1) and/or high voltage *AC power supply system* (3.2)

3.7

interfered system

system on which the *interference* (3.15) effects appear

Note 1 to entry: In this document, it is the *pipeline system* (3.8).

3.8

pipeline system

system of pipe network with all associated equipment and stations

Note 1 to entry: In this document, pipeline system refers only to metallic pipeline system.

Note 2 to entry: The associated equipment is the equipment electrically connected to the pipeline.

3.9

earth

conductive mass of the earth, of which the electric potential at any point is conventionally taken as equal to zero

[SOURCE: IEC 60050-826]

3.10**operating condition**

fault-free operation of any system

Note 1 to entry: Transients are not to be considered as an operating condition.

3.11**fault condition**

non-intended condition caused by a short-circuit to *earth* (3.9), the fault duration being the normal clearing time of the protection devices and switches

Note 1 to entry: A short circuit is an unintentional connection of an energized conductor to earth or to any metallic part in contact with earth.

3.12**conductive coupling**

coupling that occurs when a proportion of the current belonging to the *interfering system* (3.6) returns to the system *earth* (3.9) via the *interfered system* (3.7) or when the voltage to the reference earth of the ground in the vicinity of the influenced object rises because of a fault in the interfering system and the results of which are conductive voltages and currents

3.13**inductive coupling**

phenomenon whereby the magnetic field produced by a current carrying circuit influences another circuit

Note 1 to entry: Coupling is quantified by the mutual impedance of the two circuits. The results of which are induced voltages and, hence, currents that depend on, for example, the distances, length, inducing current, circuit arrangement and frequency.

3.14**capacitive coupling**

phenomenon whereby the electric field produced by an energized conductor influences another conductor

Note 1 to entry: Coupling is quantified by the capacitance between the conductors and the capacitances between each conductor and the *earth* (3.9). The results of which are *interference* (3.15) voltages into conductive parts or conductors insulated from earth. These voltages depend, for example, on the voltage of the influencing system, distances and circuit arrangement.

3.15**interference**

phenomenon resulting from *conductive, inductive or capacitive coupling* (3.12, 3.13, 3.14) between systems, which can cause malfunction, dangerous voltages, *damage* (3.17), etc.

3.16**disturbance**

malfunction of a piece of equipment that loses its capability to work properly for the duration of the *interference* (3.15)

Note 1 to entry: When the interference disappears, the *interfered system* (3.7) starts working properly again without any external intervention.

3.17**damage**

permanent reduction in the quality of service that can be suffered by the *interfered system* (3.7)

Note 1 to entry: A reduction in the quality of service could also be the complete cancellation of service.

EXAMPLE Coating perforation, pipe pitting, pipe perforation, permanent malfunction of the equipment connected to the pipes.

3.18

danger

state of the influenced system that is able to produce a threat to human life

3.19

interference situation

maximum distance between the *pipeline system* (3.8) and AC power system for which an *interference* (3.15) is to be considered

3.20

interference voltage

voltage caused on the *interfered system* (3.7) by the *conductive, inductive or capacitive coupling* (3.12, 3.13, 3.14) with the nearby *interfering system* (3.6) between a given point and the *earth* (3.9) or across an insulating joint

3.21

IR drop

voltage due to any current, developed in an electrolyte such as the soil, between the reference electrode and the metal of the structure, in accordance with Ohm's Law ($U = I \times R$)

3.22

IR-free potential

$E_{IR-free}$

pipe to electrolyte potential measured without the voltage error caused by the *IR drop* (3.21) due to the protection current or any other current

3.23

off-potential

E_{off}

pipe to electrolyte potential measured after interruption of all sources of applied cathodic protection current with the aim of approaching an *IR-free potential* (3.22)

Note 1 to entry: The delay before measurement varies according to circumstances.

3.24

on-potential

E_{on}

pipe to electrolyte potential measured while the cathodic protection system is continuously operating

3.25

spread resistance

ohmic resistance through a coating defect to *earth* (3.9) or from the exposed metallic surface of a *coupon* (3.26) towards earth

Note 1 to entry: This is the resistance which controls the AC or DC current through a coating defect or an exposed metallic surface of a coupon for a given AC or DC voltage.

3.26

coupon

metal sample of defined dimensions made of a metal equivalent to the metal of the pipeline

3.27

probe

device incorporating a *coupon* (3.26) that provides measurements of parameters to assess the effectiveness of cathodic protection and/or corrosion risk

4 Cathodic protection persons competence

Persons who undertake the design, supervision of installation, commissioning, supervision of operation, measurements, monitoring and supervision of the maintenance of cathodic protection systems shall have the appropriate level of competence for the tasks undertaken.

EN 15257 or the NACE Cathodic Protection Training and Certification Programme constitute suitable methods of assessing and certifying the competence of cathodic protection personnel.

The competence of cathodic protection persons to the appropriate level for tasks undertaken should be demonstrated by certification in accordance with prequalification procedures such as EN 15257, the NACE Cathodic Protection Training and Certification Programme, or any other equivalent scheme.

5 Assessment of the AC influence

5.1 General

This document is applicable to all metallic pipelines and all high voltage AC traction systems and high voltage AC power supply systems and all major modifications that can significantly change the AC interference effect.

The effects are the following:

- danger to people who come in direct contact or contact through conductive parts with the metallic pipeline or the connected equipment;
- damage of the pipeline or to the connected equipment;
- disturbance of electrical/electronic equipment connected to the pipeline.

Electrical/electronic systems installed on a pipeline network shall be chosen such that they will neither become dangerous nor interfere with normal operating conditions because of short-term voltages and currents, which appear during short circuits on the AC power system.

Long-term AC interference on a buried pipeline can cause corrosion due to an exchange of AC current between the exposed metal of the pipeline and the surrounding electrolyte.

This exchange of current depends on an AC voltage of which the amplitude is related to various parameters such as the following:

- configuration of AC power line phase conductors;
- presence and configuration of the earthing conductor;
- distance between the AC power line/traction system and the pipeline;
- current flowing in the AC power line/traction system phase conductors;
- average coating resistance of the pipeline;
- thickness of the coating;
- soil resistivity;
- presence of earthing systems;
- voltage of the AC railway system or the AC power line system.

5.2 Assessment of the level of interference

Calculations can be carried out (e.g. in accordance with EN 50443) by mathematical modelling to determine the earthing requirements necessary to maintain touch voltages within acceptable safe levels. Their results can also be used to determine voltages necessary to reduce the AC corrosion likelihood.

During the design phase of new influencing systems (electricity power line or railway line) or a new influenced system (pipelines), an estimation of the level of AC voltage on the pipeline should be calculated. Calculations can be carried out by mathematical modelling to determine the level of voltage produced on the pipeline. In the case of existing structures, field measurements can also be used as an option to calculation.

According to the results of calculations or field measurements, relevant mitigation measures should be installed on the influencing systems and/or the influenced system to achieve the relevant AC voltage to reduce the AC corrosion likelihood (see [Clause 7](#)).

Guidance on calculating the AC voltage on a structure caused by an AC power system was published in Reference [8]. The algorithm determines the worst-case conditions for the input parameters used for the calculation.

Due to inconsistent load demands on AC power systems, the magnitude of operating currents in power lines varies. The fluctuations depend on daily and seasonal changes. Input data for calculation purposes should be based on the realistic operating conditions or the maximum power load of the influencing system.

NOTE Carrying out calculations with input data based on both approaches helps to estimate the range between both results and to choose the right method.

6 Evaluation of the AC corrosion likelihood

6.1 Prerequisite

6.1.1 General

The AC voltage on a pipeline is the driving force for the AC corrosion processes taking place on the steel surface at coating defects. Among other things, corrosion damage depends on the AC current density, level of DC polarization, defect geometry, local soil composition and resistivity (see [Annex D](#)).

Basically, there are three different approaches to prevent AC corrosion: to limit the AC current flowing through a defect, to control the cathodic protection level, and to ensure that any coating remains defect free. These approaches are not mutually exclusive.

The evaluation of AC corrosion likelihood should be performed by the evaluation of some or all of the following parameters:

- AC voltage on the structure;
- on-potential;
- IR -free potential;
- AC current density;
- DC current density;
- AC/DC current density ratio;
- soil resistivity;
- corrosion rate.

[Annexes B, C and E](#) provide further information.

6.1.2 AC voltage on the structure

The acceptable AC voltage thresholds (see [Clause 7](#) and [Annex E](#)) depend on the chosen strategy to prevent AC corrosion. Hence, a given interference situation on the pipeline can influence the decision regarding the applicable strategy.

6.2 AC and DC current density

6.2.1 General

The AC and DC current density on a coating defect controls both the cathodic protection level and AC corrosion process. Therefore, it is a more reliable parameter for the evaluation of the AC corrosion likelihood than the on-potential or the AC voltage. However, in contrast to the voltages present on the pipeline, the current density cannot be readily determined. In principle, the current density can be calculated from the spread resistance and the geometry of the coating defect and the AC voltage. This calculation is generally not possible since the geometry of the coating fault and its surface area are generally not known. Moreover, the application of cathodic protection can significantly change the spread resistance and therefore, the current density at a given voltage.

The current density can only be estimated by means of coupons or probes. When evaluating the AC corrosion likelihood by means of a coupon or probe, it is important to consider the limitations of this technique. The calculation of the current density based upon the metallic coupon or probe surface area and on the current measured on a coupon or probe, the current is averaged over the entire coupon or probe surface. However, the current distribution on the coupon or probe can vary depending on its geometry. Typically, current densities at the edges of the coupon or probe are larger than the current averaged over the entire surface. Moreover, the often-observed formation of chalk layers can decrease the effective coupon or probe surface area. Again, this effect results in an under estimation of the current density.

6.2.2 AC current density

The AC current density results in anodic and cathodic charge transfer. A detailed explanation of the charge transfer process is given in [Annex A](#). This current can be consumed in charging of the double layer capacitance at the steel surface, in the oxidation of hydrogen (resulting in a decreasing pH), in the oxidation of corrosion products, and in the oxidation of the metal. The oxidation of the metal results in corrosion. Generally, an increasing AC current density results in a larger amount of metal oxidation and higher corrosion rates. However, the anodic current is not the only current that can affect the corrosion process. Cathodic current can reduce oxide layers formed and increase the pH on the metal surface.

High AC current densities do not necessarily cause AC corrosion if the charge passed through the metal surface can be consumed in reactions other than metal oxidation and oxide film reduction. This is the case in the presence of low cathodic DC current densities. As a consequence, the judgment of the AC corrosion likelihood based on the AC current density requires the additional consideration of the cathodic DC current density.

Nevertheless, there is an empirically determined lower limit for the AC current density below which the probability for AC corrosion is extremely low (see [Clause 7](#)).

6.2.3 High cathodic DC current density

A high DC current density results in more negative cathodic protection levels and the formation of a high pH at the pipeline surface. However, the formation of a high pH-value, the decrease of the spread resistance, and the increased reduction of surface oxide films can result in an acceleration of the corrosion rate under simultaneous AC interference. Nevertheless, a sufficiently high DC current density can prevent any anodic metal oxidation and therefore, the occurrence of AC corrosion.

[Annexes A](#) and [E](#) give detailed explanations about this process.

6.2.4 Low cathodic DC current density

A low DC current density results in a limited increase of the pH value at the metal surface, does not significantly change the spread resistance, and has less reductive effect on metal oxides on the pipeline surface. Therefore, the AC corrosion likelihood significantly decreases with decreasing DC current densities. However, low DC current densities can result in an insufficient level of cathodic polarization of the metal surface, as stated in ISO 15589-1.

[Annexes A](#) and [E](#) give detailed explanations about this process.

6.2.5 Current ratio " $I_{a.c.}/I_{d.c.}$ "

High DC current densities, depending on the AC current density, can result in both high and low AC corrosion rates. Hence, the ratio of the two current densities may be used to assess the corrosion likelihood. As long as the ratio is below a certain threshold (see [Annex E](#)), no AC corrosion can occur since metal oxidation in the anodic half wave is prevented. The key advantage of using the ratio as an indicator of corrosion likelihood is that the uncertainties regarding the condition of the metal surface (e.g. formation of a chalk layer) are eliminated since the precise metal surface area is not required for the calculation.

6.2.6 Soil resistivity

The AC corrosion process is controlled by the current density on a steel coating defect, which depends on the voltage at the location and the spread resistance. The spread resistance is influenced by the soil resistivity. The following soil resistivity parameters have been determined by experience in terms of AC corrosion risk:

- below 25 $\Omega.m$: very high risk;
- between 25 $\Omega.m$ and 100 $\Omega.m$: high risk;
- between 100 $\Omega.m$ and 300 $\Omega.m$: medium risk;
- above 300 $\Omega.m$: low risk.

For further guidance on the effect of soil composition on AC corrosion risk, [Annex D](#) gives more detailed information.

6.3 Corrosion rate

A direct way of evaluating the AC corrosion likelihood is by determining the corrosion rate on a probe (see [8.4.3](#)). This allows complex interference situations to be assessed on the basis of the actual measured corrosion rate. The principles of the electrical resistance (ER) probe concept are described in [Annex B](#).

6.4 Pipeline coatings

AC corrosion can only take place on metal surfaces that are in contact with the surrounding soil. The AC current passing through the metal/soil interface results in oxidation of the metal. By providing a holiday-free coating, the risk of AC corrosion is greatly reduced.

NOTE This method is limited by the fact that it is very difficult in practice to ensure that there are no coating defects on a pipeline.

6.5 Evaluation of the metal loss

Metal loss measurement tools, such as internal inspection, can be used to verify the effectiveness of the applied mitigation measures on new pipelines and to identify if any external metal loss has occurred on existing pipelines without mitigation.

NOTE The resolution in terms of width and depth of the in-line inspection (ILI) tool is a crucial parameter to be considered to detect metal loss (such as AC corrosion).

7 Acceptable interference levels

The design, installation, and maintenance of the cathodic protection system shall ensure that the levels of AC voltage do not cause AC corrosion. Since the conditions vary for each situation, a single threshold value cannot be applied.

This is achieved by reducing the AC voltage on the pipeline and current densities as specified below.

- As a first step, the AC voltage on the pipeline should be decreased to a target value, which should be 15 V rms or less. This value is measured as an average over a representative period of time (e.g. 24 h).
- As a second step, effective AC corrosion mitigation can be achieved by meeting the cathodic protection potentials defined in ISO 15589-1:2015, Table 1, and:
 - maintaining the AC average current density (rms) over a representative period of time (e.g. 24 h) to be lower than 30 A/m² on a 1 cm² coupon or probe; or
 - maintaining the average cathodic current density over a representative period of time (e.g. 24 h) lower than 1 A/m² on a 1 cm² coupon or probe if AC average current density (rms) is more than 30 A/m²; or
 - maintaining the ratio between AC current density ($J_{a.c.}$) and DC current density ($J_{d.c.}$) less than 5 over a representative period of time (e.g. 24 h).

NOTE Current density ratios between 3 and 5 indicate a small risk of AC corrosion. However, in order to reduce the corrosion risk to a minimum value, smaller ratios of current density than 3 would be preferable (see [Annex E](#)).

Further information is provided in [Annex E](#).

Effective AC corrosion mitigation can be also demonstrated by measurement of the corrosion rate.

8 Measurement techniques

8.1 Measurements

8.1.1 General

This clause covers techniques related to the measurements of the parameters identified in [Clause 5](#).

NOTE It is important that personnel are aware of the safety issues relating to measurements on pipelines subjected to interference by AC systems (steady-state and fault condition).

Only instruments and cables with a sufficient isolation level as specified in IEC 61010-1 shall be used.

8.1.2 Selection of test sites

AC voltage should be measured at test posts during a general assessment and detailed and comprehensive assessment of the effectiveness of the cathodic protection (see ISO 15589-1). Additional measurements shall be carried out during a representative period of time (see [Clause 7](#)) at sites where

the pipeline operator (or the responsible body acting in his/her place or on his/her behalf) suspects that there might be a risk of AC corrosion. Such areas should include the following:

- areas where the soil resistivity is low (e.g. lower than 25 $\Omega\cdot\text{m}$);
- areas where casings are filled with substances with low resistivity properties (e.g. bentonite);
- areas with highest AC interference levels;
- areas where AC corrosion has previously taken place;
- areas where local DC polarization conditions can favour AC corrosion, such as areas with cathodic DC stray current interference or areas where high levels of cathodic protection are present (see 6.2.3);
- areas where internal inspection tools have detected external metal loss.

At a later stage, the test sites can be restricted to particular positions where the initial analysis has indicated a sustained likelihood of AC corrosion.

8.1.3 Selection of measurement parameter

The measurements to be carried out should take into account the parameters described in [Clause 6](#) and be in accordance with [Clause 7](#).

8.1.4 Sampling rate for the recording of interference levels

The measurement sampling rate shall be consistent with the type of interference. High voltage power system interference can typically require a sampling rate in the order of minutes, whereas AC or DC railway interference can require a sampling rate in the order of seconds.

8.1.5 Accuracy of measuring equipment

The instruments used for measuring any voltages (AC or DC) shall be suitable.

NOTE Conditions are set out in EN 13509.

The accuracy of the measuring equipment is only one amongst several factors contributing to the uncertainty of the measurement.

8.1.6 Installation of coupons or probes to calculate current densities

In order to calculate current densities (see [Clause 7](#)), the use of coupons or probes is necessary (see [8.4](#)).

8.2 DC potential measurements

DC potential measurements and associated instrumentation are given, for example, in EN 13509.

Guidance on the accuracy of potential measuring equipment is given in [Annex H](#).

When measuring DC potentials in conjunction with AC interfered pipelines, the following factors can cause uncertainty in the measurement.

- a) The E_{off} potential measurements on a pipeline are generally dependent on the filter characteristics of the voltmeter and the time after disconnection of the current source before the reading is taken.
- b) DC decoupling devices such as capacitors and diodes can influence DC potentials and DC potential measurements. The reliability of measurements of E_{off} potentials on the structure itself by interruption techniques can be affected by the time constants and discharge characteristics introduced by such devices.
- c) IR -free potential measurements are affected by the induced AC voltage.

- d) In general (regardless of the measurement technique), the *IR*-free potential is shifted to a more positive value and the DC current density is increased by the superimposed AC voltage. This reflects the effect of the AC voltage on the DC polarization.

The above effects are generally more significant factors than the accuracy of the voltmeter itself regarding the uncertainty of the measurement.

NOTE Additional interference sources causing *IR* drops, as well as possible measuring techniques, are given in EN 13509:2013, Table 1.

8.3 AC voltage measurements

AC voltage measurements are used to determine the level of AC interference.

For this purpose, measurements shall be made using a data logging device programmed to measure the AC voltage in sufficiently short enough intervals (see 8.1.4) to capture the steady-state long-term interference.

AC voltage measurements are made with reference to earth. [Annex G](#) gives a method to determine the reference electrode location to earth.

AC voltage measurement methods are further described in EN 50443, with reference to appropriate standards and guidelines.

8.4 Measurements on coupons and probes

8.4.1 Installation of coupons or probes

Coupons or probes should be installed so that they are representative of the pipeline conditions. The following points should be considered.

- The coupon or probe should be installed in the same soil or backfill as the pipeline itself.
- The coupon or probe geometry (size, shape, coating thickness, angle between coating and simulated coating defect) influences the spread resistance and should be taken into consideration. The measurements with respect to the criteria defined in [Clause 7](#) have to be carried out on a 1 cm² coupon surface area.
- The coupon or probe should not cause or receive any electrical interference from adjacent coupons or coating faults on the pipeline, unless this is part of the purpose of monitoring.
- The coupon or probe should have and maintain effective electrical contact with the surrounding soil, unless lack of contact is part of the purpose of monitoring. During the installation process, the soil around the coupon or probe should be compacted to prevent settlement and voids forming around the coupon or probe. These voids could result in loss of full contact between the coupon or probe surface and the surrounding soil.

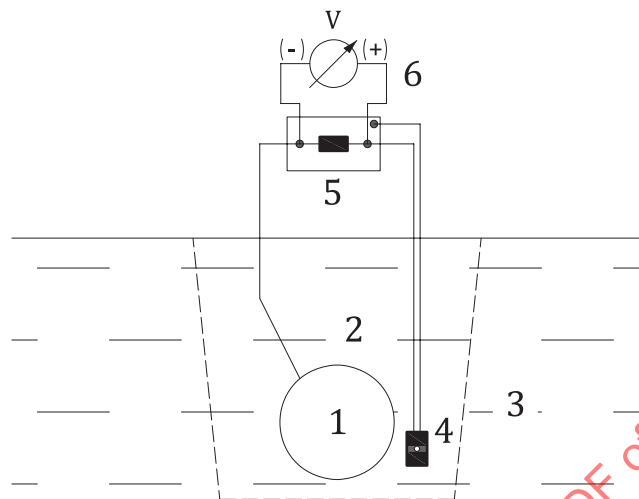
Coupons or probes can be installed by a number of different methods, such as:

- during construction of the structure under investigation;
- during excavation activities for investigation of the structure;
- by augering (see [Annex B](#)).

The installation method selected depends on site access, the type of soil to be excavated, the cost involved and the availability of an electrical connection to the structure.

8.4.2 Current measurements

Coupon or probe currents (AC or DC) can be measured by the voltage drop across a series resistor (see [Figure 1](#)). For both AC and DC current measurements, the value of the series resistor should be sufficiently low to avoid significant disturbance of the system. For field measurements, this is typically in the range of $10\ \Omega$ for a $1\ \text{cm}^2$ coupon or probe.



Key

- 1 pipe
- 2 backfill
- 3 native soil
- 4 coupon or probe
- 5 series resistor or internal shunt resistor of ammeter
- 6 voltmeter

Figure 1 — Coupon or probe test post with series resistor for current measurements

One connection between the coupon or probe and the pipe is essential to ensure cathodic protection and the ability to take cathodic protection measurements, while a second connection makes measurements easier, more reliable and eliminates the effect of voltage loss in the current carrying conductor.

8.4.3 Corrosion rate measurements

Various types of corrosion rate measurements have been described in the annexes of this document.

The following three general types of corrosion rate measurements can be applied:

- weight loss measurements;
- perforation measurements;
- ER measurements.

Weight loss measurements require the installation of pre-weighed coupons. After some time of operation (months to years), the coupon is excavated. If it is brought to a laboratory for cleaning, inspection and weighing, this should be carried out in accordance with the procedure described in ISO 8407. The primary advantage of the procedure is that the visual inspection provides detailed information of the corrosion topography, maximum, as well as the average corrosion rate. The primary disadvantage is that the coupon provides no information until it is excavated.

Perforation measurements are made on special perforation probes (see [Annex B](#)). A signal is generated when the corrosion process has perforated the wall thickness of the coupon. The primary advantage is

that the maximum (localized) corrosion depth is registered without having to excavate the probe. The primary disadvantage is that this information is not available until the coupon is perforated.

ER measurements require the installation of ER probes (see [Annex B](#)). Corrosion is detected by the increase of the ER of the coupon when corrosion progressively decreases the thickness of the coupon. The primary advantage of this technique is that the average corrosion rate can be followed continuously and used to optimize cathodic protection levels. The primary disadvantage is that the localized corrosion rate is detected with less accuracy until the probe is perforated.

AC corrosion processes have also indirectly been identified by the coulometric oxidation of corrosion products (see [Annex C](#)).

8.5 Pipeline metal loss techniques

Internal inspection tools can be used to verify locations of metal loss. If the measurement accuracy and position accuracy are sufficient, then an estimate of the corrosion rate can be made (see [6.4](#)).

9 Mitigation measures

9.1 General

AC corrosion can be mitigated by using construction and operation measures. The following subclauses describe measures that can be used individually or in combined application.

9.2 Construction measures

9.2.1 Modification of bedding material

As specific bedding material condition can affect the AC corrosion likelihood, the soil condition is of special importance.

This mitigation measure can be implemented at the stage of pipeline installation by bedding it in sand.

Nevertheless, a full embedding status of the pipeline cannot be ensured during operation as the sand could be drained, eluted or mixed with other soil strata, which decreases the effect of the original protection method.

9.2.2 Installation of isolating joints

The AC voltage on a pipeline can be reduced by installing isolating joints at suitable positions in the pipeline thus, electrically interrupting the longitudinal current path along the pipeline. The effect of this method depends on the reduction of interfering proximity lengths.

NOTE The location of isolating joints can also depend on the presence of DC stray currents.

The isolating joint locations can be determined during design using simulating models (see Reference [\[8\]](#)).

This method can be beneficial where there are extensive parallel routings or high soil resistivities (e.g. greater than 500 $\Omega \cdot m$). In the case of high soil resistivity, the dimensions of the earthing system to mitigate the induced AC interference can be significant.

The position of isolating joints should take into account the continuity/discontinuity of AC and/or DC current distribution along the pipeline.

9.2.3 Installation of mitigation wires

Interference can also be modified by the installation of an insulated wire in close proximity but not connected to the pipeline and between powerline and pipeline. The insulated wire is also earthed at each extremity. This method should not be used as it is considered to be a more effective measure to prevent short-term interference rather than a method to reduce long-term interference.

In any event, bare wires shall not be used because they can have an adverse effect on coating defect surveys in the case of a coating defect on the pipeline.

9.2.4 Optimization of pipeline and/or powerline route

The AC interference situation on a pipeline mainly depends on the proximity and parallel routing between a pipeline and high voltage power lines. A mitigating effect on the AC voltage status can be achieved by increasing the distances between the pipeline and powerline routes.

This requirement often contradicts with the general obligation of joint common “energy corridors” to minimize environmental impacts.

9.2.5 Power line or pipeline construction

The geometric arrangement of phase conductors or an earthing wire on power line towers will have an effect on the magnitude of the induced voltage on the pipeline and needs to be considered during power line or pipeline construction.

9.3 Operation measures

9.3.1 Earthing

9.3.1.1 General

Mitigating the interference situation by installing earthing systems is a most commonly used method.

Usually, horizontally installed or vertically installed earthing systems are used. The decision on which system to use depends on the local soil resistivities and the local access conditions. The earthing system should have sufficiently low enough impedance to achieve the required AC corrosion protection criteria for induced voltage. Typically, the impedance will need to be less than 10 Ω , although typical configurations require significantly lower values of impedance.

9.3.1.2 Direct earthing

Direct connection of earthing systems to the pipeline is not recommended, particularly if the earthing system is made of copper but also zinc or magnesium. The following are the disadvantages of direct connection.

- An increased demand on the cathodic protection system has to be considered in addition to the protective pipeline cathodic protection current demand.
- The off-potential measurement readings can be misleading.
- Cathodic protection effectiveness can be compromised. If this is the case, particular attention should be paid to detrimental galvanic cells (e.g. an earthing system made of copper connected to the pipeline system).
- When magnesium electrodes are used to discharge AC, they might have a short life.
- There is a tendency for zinc or galvanised steel wires in soil used as earthing system to become more anodic with time. Thus, the earthing system can consume more cathodic protection current with time, which will be detrimental to the pipeline corrosion protection system.

- Due to the application of cathodic protection current, direct earthing system might be covered by a calcareous layer, which can have, with time, an adverse effect on its effectiveness to mitigate AC corrosion.

9.3.1.3 Indirect earthing of the pipeline via DC decoupling devices

To avoid disadvantages due to direct bonding, earthing systems are commonly not directly bonded to the pipeline but connected via decoupling devices, which provide an electrical path for the AC current from the pipeline to earth while simultaneously blocking DC current.

The DC decoupling devices should not interfere with the normal cathodic protection system operation as well as the monitoring of the cathodic protection effectiveness and the touch voltage protection on the pipeline.

The DC leakage current for the selected decoupling devices should be taken into consideration when determining the cathodic protection current demand for the pipeline to be cathodically protected.

The most common device used for this is an electrolytic capacitor. It can be equipped with other electronic devices (in parallel or in series) for safety reasons, for protecting it from surge current and for specific applications.

[Annex F](#) gives information to assist in the selection of the correct device to install.

9.3.1.4 AC compensation method

If it is not possible to achieve a low resistance earth or if the AC voltage is not sufficiently lowered, the decoupling device can be replaced by an AC compensation device.

This device compensates the AC voltage by imposing a counter phase AC current on the pipeline and, thereby, generating an artificially zero resistance earth.

9.3.2 Adjustment of cathodic protection level

Adjustment of the cathodic protection level is a method that can be used to mitigate the AC corrosion risk on pipeline by meeting the criteria defined in [Clause 7](#). The adjustment can consist of either of the following:

- controlling the cathodic protection level towards a more negative level to meet the criterion defined in [Clause 7](#) ($J_{a.c.}/J_{d.c.} > 5$);
- controlling the cathodic protection level towards less negative level to meet the criterion defined in [Clause 7](#) ($J_{d.c.} < 1 \text{ A/m}^2$).

9.3.3 Repair of coating defects

The AC corrosion likelihood exists on interfered pipelines especially for small sized coating defects in low resistivity soils (e.g. lower than $25 \Omega.m$). Those sections with coating defects can be surveyed with suitable measurement techniques as described in EN 13509.

In order to obtain sufficient resolution, the measurement setup should be optimized (increased voltage used for detection and increased resolution of the voltmeter) according to the conditions of the pipeline (depth, severity of coating defect).

If an unacceptable AC corrosion risk exists on a section of a pipeline despite all the mitigation measures, all coating defects should be excavated and repaired. This is only economically feasible for well-coated pipelines.

This method should be combined by measurements on the pipeline to evaluate the AC corrosion risk.

A repetition of the measurements to establish a defect-free coating condition might be necessary on a regular basis.

10 Commissioning

10.1 Commissioning

Although AC mitigation systems are not cathodic protection systems, they should be generally commissioned in the same manner as cathodic protection systems as detailed in ISO 15589-1.

It is possible that there will be AC voltages at test facilities and exposed sections of pipeline and, while these might not be a hazard in themselves, they could cause an involuntary reaction that could be hazardous. Safety precautions shall be taken if there is any risk of unacceptable levels of touch potential (see, e.g., EN 50443).

10.2 Preliminary checking

10.2.1 General

Ensure that appropriate safety precautions are in place.

Before any mitigation devices are connected to the pipeline, a series of measurements should be carried out at various locations to establish the existing levels of AC interferences. Selected locations shall include the areas known to experience high levels of interference (see [Clause 7](#)) and should include areas that are not considered to suffer from high levels of interference. Interference levels could change adversely when the mitigation measures are applied. A data logger system is recommended for voltage, current and potential measurements because they should be made over a sufficient period of time (at least 24 h) to accommodate diurnal variations and the measurements made at different locations should be synchronised.

The following measurements should be made and compared with the design or performance values:

- design checks:
 - resistance to earth of the installed earthing system;
 - pipe to soil AC voltage and on-potentials at selected locations;
- installation checks (before having connected any earthing systems):
 - functionality of the mitigation devices;
 - cathodic protection transformer-rectifier settings (if an impressed current system is used);
 - if suitable probes and coupons have been installed, then the following additional measurements can be made:
 - corrosion rate;
 - spread resistance;
 - coupon on- and off-potential and current;
 - coupon AC voltage and current;
- commissioning checks (after having connected any earthing systems):
 - pipe to soil AC voltage and on- and off-potentials at selected locations;

- if suitable probes and coupons have been installed, then the following additional measurements can be made:
 - corrosion rate;
 - coupon on- and off-potential and current.

10.2.2 Coupon AC voltage and current startup

The startup should be carried out accordingly as below, unless the requirements given in EN 50443 are exceeded with mitigation devices disconnected.

- Carry out the data logging and measurement procedures during the installation and commissioning checks before commencing any startup procedures.
- Check touch potentials by measurement. If there are unacceptable levels of touch potential, then suitable precautions shall be taken (see EN 50443).

Connect the mitigation device to the earthing system via the pre-arranged connection, then connect the other terminal of the mitigation device to the pipeline. Repeat this procedure for all mitigation devices.

10.2.3 Verification of effectiveness

The effectiveness of the mitigation system can be demonstrated by showing that criteria defined in [Clause 7](#) are achieved. The same measurements as those conducted during commissioning can also be made (see [10.2.2](#)).

Measurements should be performed on pipelines or sections of them where unacceptable AC influence is suspected or can be expected based on map observation, calculation or routine measurements. These measurements should be performed, in the first instance, at all test points, cathodic protection stations, insulating joints and casings, and wherever an accessible measurement cable is connected to the pipeline or section.

A coupon or probe could be used at the areas identified as being at a high risk of AC corrosion to determine the current density and/or the corrosion rate (see [8.4](#)).

Additionally, the effectiveness of the mitigation system can also be determined by a reduction in corrosion rate, since this accurately represents the total effectiveness of the applied cathodic protection system as well as the AC mitigation system.

10.2.4 Installation and commissioning documents

After the completion of the commissioning checks, a file of documents shall be prepared. The following information should be provided:

- as built drawings of the installation;
- design documentation, which should include the detailed specification of any devices installed;
- results of data logging and potential measurements before the connection of the mitigation system;
- results of data logging and potential measurements after the connection of the mitigation system;
- recommendations for long-term monitoring of the induced AC levels and their impact on the external corrosion of the pipeline (this can include remote monitoring and coating defect surveys);
- an operation and maintenance manual.

These documents should be retained by the pipeline operator or the responsible body for the integrity of the pipeline system.

11 Monitoring and maintenance

AC measurements and controls should be integrated into the routine monitoring of cathodic protection systems and included in the maintenance procedures.

In the areas where the interference from AC systems is known, the maintenance procedures should include:

- measurements of AC voltage;
- measurements of on-potential;
- measurements of on-potential and/or off-potential and AC voltage on coupons or probes;
- AC and DC current densities on coupons or probes;
- measurements of corrosion rate on probes;
- measurements of AC and DC current on existing DC decoupling devices through all earthing systems;
- measurements of the ER of the earthing systems.

Measurements shall be made in accordance with [Clause 8](#) and on selected test points. Measurement frequencies shall be in accordance with those given in ISO 15589-1. As the corrosion risk is higher on a pipeline with an AC voltage, the operator shall pay special attention to the frequency at which measurements are taken and how the measurements are performed.

Annex A (informative)

Simplified description of the AC corrosion phenomenon

A.1 Cathodically protected pipeline

The cathodic protection of pipelines forces current to enter the pipeline through the metal surface in contact with soil where the coating is damaged. This current prevents corrosion from taking place by removing oxygen from soil and eliminating potential differences along the pipeline. Moreover, the cathodic current results in the increase of the alkalinity on the steel surface.

A.2 Cathodically protected pipeline with AC voltage

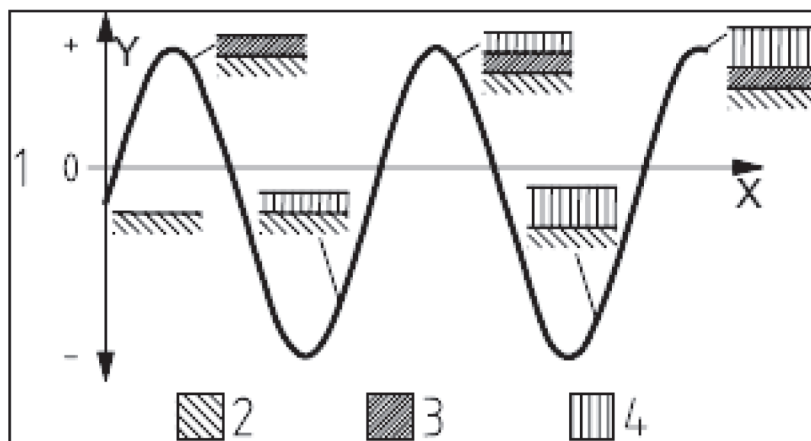
A.2.1 Description of the phenomena

When an AC voltage is present on a cathodically protected pipeline, current will flow through the metal surface at defects in the coating. The amount of current flowing depends on the AC voltage and the impedance of the system. During the cathodic half wave, the amount of current entering the steel surface and, therefore, the rate of the cathodic reactions on the metal surface generally increases. During the anodic half wave of the AC voltage, the current will leave the metal surface if the AC voltage is sufficiently large. A current leaving the metal surface is associated with oxidation reactions and can, therefore, cause corrosion.

The current leaving the metal surface can cause charging of the double layer capacitance, oxidation of hydrogen where present and corrosion products (e.g. reduced by the cathodic protection current), and oxidation of the pipeline steel. If the pH-value is sufficiently high (above 10), this oxidation of the pipeline steel can result in the formation of an oxide film. In contrast, current entering the metal surface can result in the charging of the double layer capacitance, reduction of oxygen, formation of hydrogen and reduction of oxidized corrosion products. Furthermore, the oxide film formed during the anodic half wave can at least partly be electrochemically reduced.

Empirically it has been observed that both very high and very low DC current densities can prevent AC corrosion. In the case of very high DC current densities, this effect can be associated with the increase of the pH at the steel surface, the resulting decrease of the spread resistance and the increased electrochemical reduction reactions taking place on the steel surface. These effects result in increased AC and DC current densities, larger charges passed during the anodic and cathodic half wave, changes in the solubility of oxidation products of iron and their oxidation state.

A very simplified description of the process taking place during AC corrosion is shown in [Figure A.1](#). During the anodic half wave, the bare metal surface is oxidized resulting in the formation of an oxide film. This is due to the current that leaves the metal surface. During the negative half wave, when the current enters the metal surface, this oxide film is reduced and, therefore, converted into a non-protective rust layer. In the following anodic cycle, a new oxide film grows. Upon reduction of the oxide film, the amount of rust is increased. If this process results in the formation and dissolution of a single oxide layer during every anodic half wave, corrosion rates in the range of 100 mm/year would be obtained. Since such high corrosion rates were only achieved under extreme laboratory conditions, it can be concluded that the formation and/or reduction of the oxide film is, in most cases, only partially taking place.



Key

- 1 AC current present on a coating defect
- 2 metal
- 3 passive film (e.g. Fe_3O_4)
- 4 iron hydroxide [e.g. $\text{Fe}(\text{OH})_2$]
- X time
- Y current

**Figure A.1 — Graph of cathodic protection current with AC influence —
Schematic description of the AC corrosion process with cathodic protection**

A.2.2 Reduction of the AC corrosion rate

Based on this concept, it is possible to discuss several empirical observations. The most efficient way of mitigating AC corrosion is the limitation of AC current density. If this is not possible, other mitigation measures have to be addressed. The AC corrosion process only takes place if the oxide film is formed (at least partly) and dissolved (at least partly). If the formation of an oxide film is prevented by sufficiently high DC current densities at sufficiently low AC current densities, AC corrosion can be stopped. Similarly, AC corrosion can be stopped if the cathodic reduction (dissolution) of the once-formed oxide film is prevented. This is possible by sufficiently limiting the cathodic current density. Additionally, the decreased AC corrosion rate at low DC current densities could be a result of the lower pH-value at the metal surface and the higher spread resistance of the metal surface.

Based on this consideration, it is clear that both high and low DC current densities can prevent AC corrosion. This has to be taken into account in the discussion of threshold values since there are two fundamentally different concepts of prevention of AC corrosion. The concept allows the explanation of the relevance of the various thresholds, such as the existence of a critical ratio between AC and DC current density and of a critical AC current density.

Annex B (informative)

Coupons and probes

B.1 Use and sizes of coupons and probes

B.1.1 Use of coupons or probes

AC voltage on a pipeline can cause corrosion in normal operating conditions of the AC source (power line or railway line). This AC voltage may be induced or flowed on the pipeline from AC power sources.

The AC corrosion risk can be evaluated by measurements on coupons or probes installed on the pipeline. They can be installed permanently or temporarily. So, measurements made with coupons or probes can be compared to criteria defined in this document.

The AC corrosion risk can also be evaluated by corrosion rate measurements on coupons or probes. The corrosion rate can be measured by the ER probe technique or by visible corrosion on a "removable" coupon, which is buried near the pipeline. This last kind of coupon is usually used when other techniques do not provide results that can be compared to the criteria.

B.1.2 Sizes of coupons or probes

Most of the time, AC corrosion is observed on pipelines with an efficient coating with only small coating defects.

At a given potential, current density (AC and DC) is higher on small coating defects. For this reason, it is preferable to use small surface area coupons or probes to perform AC measurements (e.g. $U_{a.c.}$ and $I_{a.c.}$).

AC current density studies and measurements are made with circular coupons or probes with 1 cm² exposed surface area. For AC interference measurements, the 1 cm² surface area has been adopted as a universal standard.

B.2 Installation of buried coupons and probes

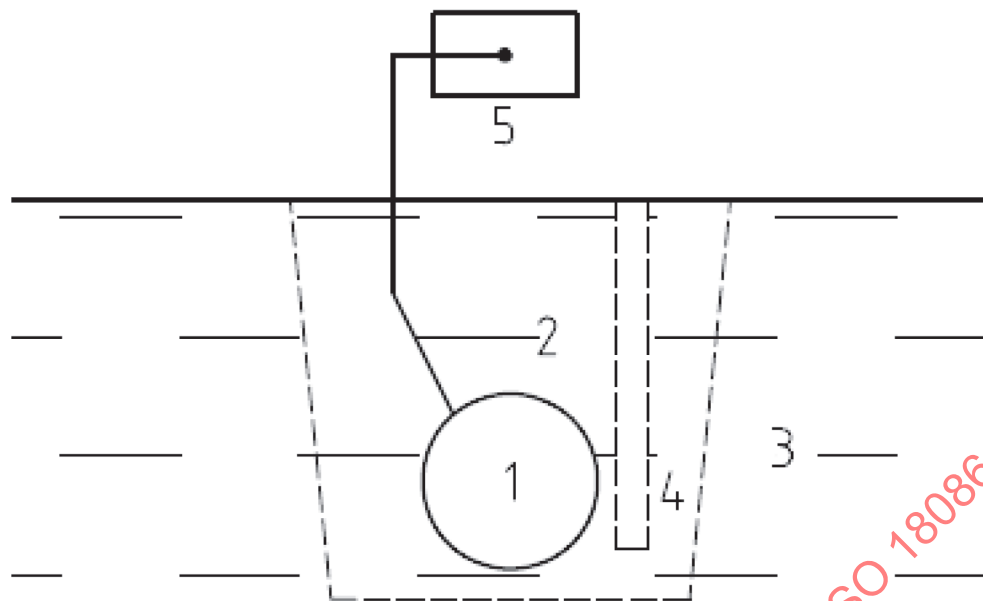
B.2.1 General

This subclause gives a typical procedure for the installation of coupons or probes by an augering technique.

B.2.2 Before installing the coupon or probe

Locate and identify all buried structures including piping, tanks and cables prior to the installation of any coupons or probes. Select a point to auger, while taking proper precautions not to damage the coating or structure when auguring. Preferably, the backfill zone should be known in advance (see [Figure B.1](#)). Make a mark (e.g. on the test post) defining a depth of zero.

Drill a hole using an auger (or an equivalent method) preferably to the pipe invert level to install a coupon or probe. The hole should be installed about 20 cm from the pipeline. While collecting the soil, record the nature of any different soil layer/types (top layers, middle layers, bottom layers, etc.) in order to be able to relocate the soil profile upon completion of the hole. It is of particular importance to refill the bottom layer soil that would be present around the pipeline when the coupon or probe is installed.



Key

- 1 pipe
- 2 backfill
- 3 native soil
- 4 augered hole
- 5 test post

Figure B.1 — Drilled hole next to a pipeline

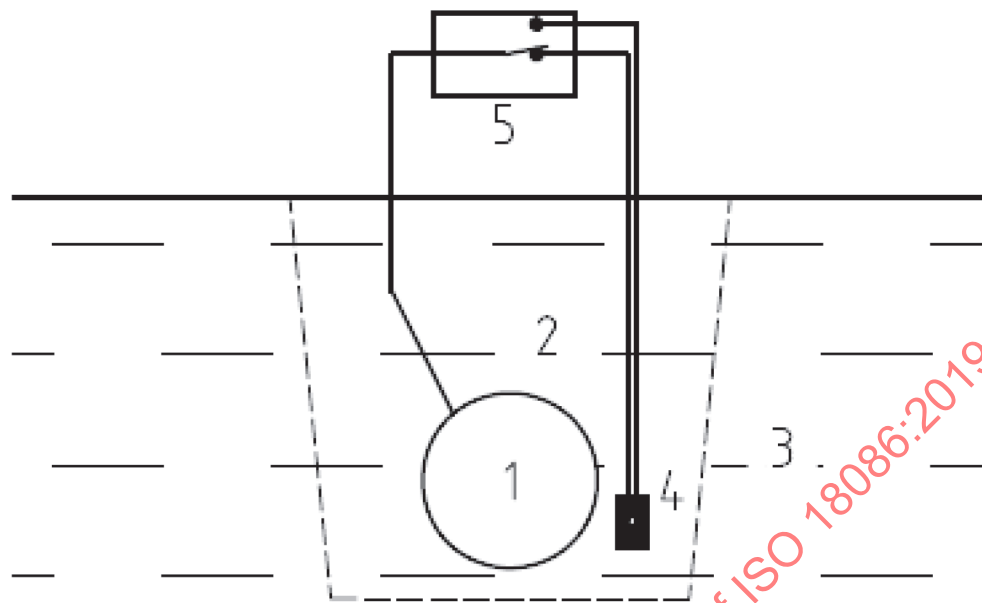
If desired for a characterization of the soil type, it is advisable to use some of the excavated soil to perform soil resistivity testing in a soil box, to determine the soil moisture content, to conduct an acid droplet test for the presence of calcium carbonate or to obtain a sample for further analysis. The detailed soil analysis can be conducted in a laboratory.

B.2.3 Installation of the buried coupon or probe

Push the coupon or probe into position. If the soil is soft/sandy, push the coupon or probe an additional step down through the undisturbed native soil/backfill. In this case, the soil usually fills out and compacts around the coupon or probe and provides a good electrical connection.

If the soil is harder, it might be necessary to sample an amount of soil from the desired coupon or probe depth and form a “cake” around the artificial coating defect of the coupon or probe, mixed with a small quantity of distilled water prior to positioning in the soil.

Fill back the soil in the drilled hole in the same manner as it was uncovered and compact each small amount of backfill. Arrange the coupon or probe test leads in the test post (see [Figure B.2](#)). Preferably, the coupon or probe should be equipped with a double-wired connection. One connection between the coupon or probe and the pipe is essential to carry out measurements. A second connection makes measurements easier and more reliable.



Key

- 1 pipe
- 2 backfill
- 3 native soil
- 4 coupon or probe
- 5 test post with switch (normally closed)

Figure B.2 — Coupon or probe positioned next to the pipeline and connected through a test post

B.3 ER probes principles

B.3.1 Assessment of the corrosion using the ER probe technique

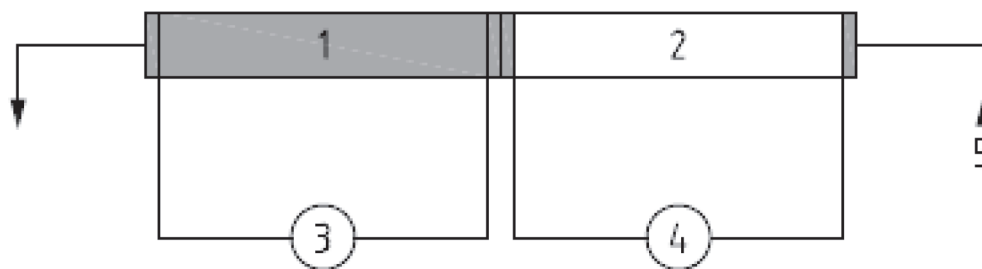
B.3.1.1 General theory

The ER probe technique can be applied for corrosion rate assessment as an alternative to the weight loss coupon. Unlike the weight loss coupon, the ER probe technique does not require excavation and weighing procedures, since a mass loss is assessed by electronic means.

Other probe electrical characteristics, such as AC current density, DC current density, leakage resistance, etc., are also measured on ER probes, as described in [Clause 8](#).

The ER technique measures the change of the resistance of a metal element formed as a coupon. When the metal element suffers metal loss due to corrosion, the ER of the element will increase. Since the resistance of the element also changes due to temperature variations, a second element, which is coated in order to protect it from corrosion, is utilized for temperature compensation. The element exposed to the corrosive environment constitutes the coupon part of the element, whereas the element protected from corrosion by the coating constitutes a reference element (see [Figure B.3](#)). The two are thermally connected in order to efficiently equalize any temperature difference between the two elements.

The resistance values of the two individual elements are usually measured by passing an excitation current through the elements and measuring the voltage generated over the element length caused to the excitation current.

**Key**

- 1 reference element, R_r
- 2 coupon element, R_c
- 3 voltage across the reference element, V_R
- 4 voltage across the coupon element, V_C
- 5 excitation current, I_{exc}

Figure B.3 — Principle of ER probe with excitation current and voltage measurements

B.3.1.2 Specific recommendation for ER probe

Since a high level of AC current can pass through the coupon element, local heating of the coupon element compared with the reference element could be expected. For this reason, ER probes should be disconnected from the pipeline and left in an open circuit condition for a short period of time until thermal equilibrium is reached before the ER measurement is made. This will ensure the best possible assessment of the element thickness.

B.3.2 ER probe application in the field

When using an ER probe, a range of informative indicators (on-potential and/or off-potential, the DC current density, the AC current density and the spread resistance) can be monitored simultaneously. These indicators give valuable information on any cause of corrosion; in the present case, AC corrosion. A typical AC corrosion scenario involves a condition of decrease in the spread resistance throughout time (usually caused by a high level of DC current density), which, in combination with a sufficient AC voltage, creates increasing high levels of AC current density. Eventually, the corrosion rate will increase rapidly to values that are typically significantly higher than 0,01 mm per year.

Using this concept, a pipeline system that is in actual danger of AC corrosion can typically reveal spikes in the ER probe corrosion rates due to changes in the electrical condition. In this manner, by carefully analysing the electrical parameters causing such spikes, the threshold values for corrosion can be deduced and built into the record kept for a particular location, based on the threshold corrosion rate and the threshold protection potentials defined in ISO 15589-1.

The above concept is also applicable for other types of corrosion (e.g. corrosion caused by DC stray current) and makes it a versatile tool.

B.4 Perforation probes

A perforation probe can be used instead of a conventional coupon. The levels of AC and DC interference and the current density can be measured. Additionally, the time when a critical predetermined corrosion depth is reached can readily be determined. Hence, the efficiency of the measures taken to decrease the AC corrosion rate can be verified in the field.

The probe consists of a thin steel plate with a thickness in the range of (0,1 to 1) mm and an internal electrode. The thin steel plate is on one side in contact with the soil and on the other side with an

insulator separating the internal electrode and the steel plate. When corrosion perforates this steel plate, humidity will penetrate into the gas-tight coupon and form a conductive electrolyte between the electrode and the thin steel plate. By a simple resistance measurement between the electrode and the thin plate, the perforation of the coupon can be detected by means of conventional resistance measurement devices. As a consequence, the monitoring of the perforation probe can be readily integrated into a conventional inspection routine or monitored over time. The key advantage is the simple handling and especially the information about the corrosion depth. Hence, information about the depth of the corrosion is provided independent on corroding surface. This is especially important in cases of very local corrosion that penetrates rapidly but with little mass loss.

The main application purpose is to ensure that the threshold values for the current density are met. Since these current values are averaged over the entire probe surface, the actual local current density can be underestimated in the case of the formation of chalk layers on the probe surface. Therefore, the perforation probes provide an additional safety level by giving an alarm value. It is the only coupon that provides information on corrosion depth even in the case of very local corrosion attack.

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Annex C (informative)

Coulometric oxidation

The cathodic protection current results in an increased pH value and in an electrochemical reduction of some of the corrosion products formed on the steel surface from Fe^{3+} to Fe^{2+} . The overall content of iron ions accumulated due to corrosion can be estimated by electrochemical oxidation of Fe^{2+} to Fe^{3+} in the corrosion products. As a consequence, the amount of charge required for oxidation is proportional to the amount of the corrosion product formed over time. The coulometric oxidation can be performed with all types of coupons or probes installed in the field and connected to a cathodically protected pipeline.

By isolating the coupon or probe from the pipeline, a constant anodic current can be applied and the resulting potential can be recorded. The ohmic potential drop can be numerically corrected or the off-potential can be determined by periodically interrupting the current flow. The amount of charge required to polarize the coupon or probe to 0 V against the CSE is used for estimating the mass loss on the coupon or probe. By multiplying the charge in Coulombs with 0,013, the mass loss in grams is obtained. The advantage of the technique is the possibility of determining the extent of corrosion that occurred in the past. Moreover, the further increase in corrosion can be determined by means of repeated coulometric oxidation. The results of the measurements are only reliable if all the corrosion products are electrochemically accessible and if the cathodic protection current is sufficiently high to reduce the corrosion products.

Annex D (informative)

Influence of soil characteristics on the AC corrosion process

D.1 Influence of electrical parameters

The AC current density at a coating defect is essentially determined by the induced AC voltage on the pipeline and the coating fault resistance. Generally, a low coating fault resistance is observed in soil with low specific electrical resistivity resulting in a higher AC corrosion likelihood for a given AC voltage.

D.2 Influence of the electrochemical process

The specific local soil resistivity is controlled by the amount of soluble salts and the soil moisture content. Therefore, significant differences in the coating fault resistance can be observed if the pipeline is above or below the water table level. Additionally, the coating fault resistance is strongly influenced by the electrochemical processes taking place on the bare metal surface, due to the application of cathodic protection current.

The electrochemical reduction of oxygen or the evolution of hydrogen results in an increase of the pH value on the metal surface. Typically, the pH value is above 11 and can reach values of up to 14 or possibly even higher in extreme cases.

D.3 Influence of alkaline ions and cations

The cathodic protection current results in a migration of cations to the metal at the coating fault, which interact with the locally increased pH value. Depending on the soil composition, the coating fault resistance can either increase or decrease over time. Indeed, the following modifications of the soil environment can appear according to the increase of the pH value (i.e. formation of NaOH or CaCO_3).

The earth alkaline ions Ca^{2+} and Mg^{2+} form hydroxides that exhibit a relatively low solubility. With the increase of the pH, their precipitation will take place near any coating holiday. The reaction of these hydroxides with the CO_2 present in the soil results in the formation of calcareous deposits. If a dense calcareous deposit is formed directly on the metal surface at the holiday, the coating fault resistance can significantly increase several orders of magnitude.

While the earth alkaline ions generally increase pore resistance, the alkaline cations Na^+ , K^+ and Li^+ result in the formation of highly soluble hygroscopic hydroxides. As a consequence, a low spread resistance due to the attracted water and high ion concentration is observed. This process can decrease the pore resistance of the metal at a coating fault by up to a factor of 60.

The current density on the metal at a coating fault of a given geometry is, therefore, dependent on the electrical conductivity and the ratio of alkali and earth alkali ions. Moreover, the cathodic current density influences the amount of hydroxide produced and affects, therefore, the local conductivity.

Annex E (informative)

Other criteria that have been used in the presence of AC influence

E.1 General

The criteria presented in this annex, though not widely used, have been successfully applied by some operators. They have defined them either by field and/or laboratory experiments. They are included in this annex for the sake of completeness.

AC values are rms ones. Current densities are measured on a 1 cm² circular coupon or probe.

E.2 On-potential approach

E.2.1 General

The on-potential and the *IR*-free potentials control the level of cathodic protection applied as the driving voltage is defined by the difference between the on-potential and the *IR*-free potentials. The intensity of the cathodic protection current able to reach and polarize the steel surface at a coating defect depends on the driving potential and on the total circuit resistance according to Ohm's law.

The consideration of the corrosion likelihood based on the on-potential is only possible when the chosen concept for AC corrosion prevention is known.

For technical papers related to protection and mitigation measures associated with AC corrosion likelihood on cathodically protected pipelines, see References [4], [5] and [6].

E.2.2 More negative (E_{on}) cathodic protection level

A negative on-potential can result in high cathodic current density, a strong change in the soil chemical composition and spread resistance, and an increased reduction of oxide layers (see [Annex A](#)). AC corrosion can be prevented when applying a sufficiently negative on-potential to avoid any metal oxidation due to the presence of AC interference. As a consequence, the required level of the on-potential is related to the induced AC voltage on the pipeline. The use of more negative on-potentials can be indicated in the presence of DC stray current interference on the pipeline.

E.2.3 Less negative (E_{on}) cathodic protection level

A relatively positive on-potential has only a limited effect on spread resistance. While having no adverse effect on the coating adhesion and resulting in a low hydrogen evolution rate, it can result in insufficient cathodic protection in accordance with the limiting critical potential criteria indicated in ISO 15589-1. The primary advantage of a more positive on-potential is the generally higher acceptable AC voltages. When choosing an AC corrosion prevention system based on a less negative E_{on} cathodic protection level, it might be necessary to install additional cathodic protection stations. Since current flow due to the on-potential depends on the level of the off-potential and also on soil resistivity and defect geometry, it is difficult to judge the AC corrosion likelihood based on the on-potential alone in the case of less negative cathodic protection levels. However, applying an on-potential criterion that is as positive as possible, while still maintaining the off-potentials given in ISO 15589-1, will result in a decreased AC corrosion likelihood.

E.2.4 Criteria

The criteria as defined in ISO 15589-1 should be respected.

Theoretical and practical experiences have shown that the following two methods can be used to solve AC influence problems against steel corrosion.

- First scenario: “more negative” cathodic protection level. In this case, one of the three parameters below, in order of priority, can be applied:

- the following formula should be satisfied: $\frac{U_{a.c.}}{|E_{on}| - 1,2} < 3$;

NOTE –1,2 V against the CSE is the limiting critical potential (see ISO 15589-1). Choosing a more positive value would create a less conservative result in the calculated ratio for given $U_{a.c.}$ and E_{on} values.

- AC current density $< 30 \text{ A/m}^2$;
- $\frac{J_{a.c.}}{J_{d.c.}} < 3$ if AC current density $> 30 \text{ A/m}^2$.

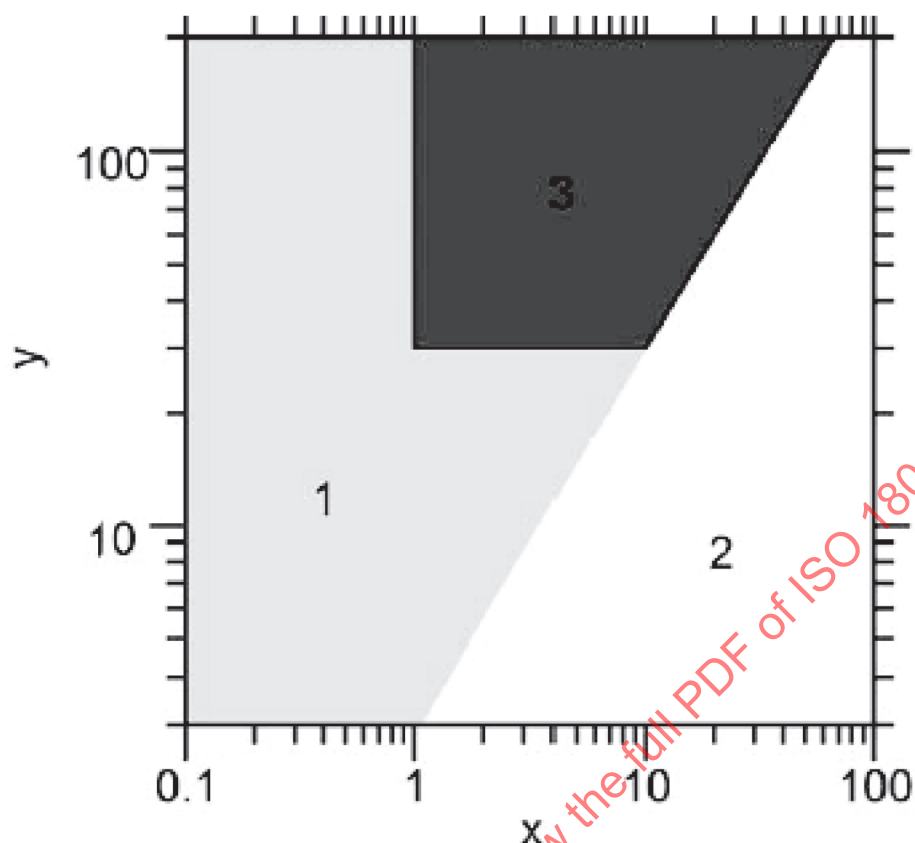
In this case, it is important to ensure that there is no corrosion risk due to cathodic disbondment and no adverse effect from hydrogen evolution.

- Second scenario: “less negative” cathodic protection level. In this case, one of three parameters below, in order of priority, can be used:

- $U_{a.c. \text{ average}} < 15 \text{ V}$ if the average E_{on} is more positive than –1,2 V against the CSE;
- average AC current density $< 30 \text{ A/m}^2$;
- cathodic protection average current density $< 1 \text{ A/m}^2$ if AC average current density $\geq 30 \text{ A/m}^2$.

The AC voltage and DC potential should be determined with the same reference electrode placed at the same location. The electrode is preferably positioned at remote earth. If this is not possible, it will cause a less reliable judgement of the AC corrosion risk.

[Figures E.1](#) and [E.2](#) illustrate limits for scenarios for different AC and DC current densities in terms of AC corrosion likelihood, and also for on-potential and AC voltage in terms of AC corrosion likelihood.



Key

- 1 less negative cathodic protection level
- 2 more negative cathodic protection level
- 3 AC corrosion
- x DC current density (A/m^2)
- y AC current density (A/m^2)

Figure E.1 — Relationship between AC and DC current densities and likelihood of AC corrosion