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Assessment of the effectiveness of cathodic protection based on coupon measurements

Evaluation de l'efficacité de la protection cathodique par mesurages sur coupon

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Foreword

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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).

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

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Assessment of the effectiveness of cathodic protection based on coupon measurements

1 Scope

This document specifies requirements for the design, installation, positioning, sizing, use and maintenance of coupons for the assessment of the effectiveness of cathodic protection (CP) of buried and immersed metallic structures, such as pipelines, in the case of normal operation as well as AC and DC interference conditions.

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

EN 50162, *Protection against corrosion by stray current from direct current systems*

3 Terms and definitions

For the purposes of this document, the following terms and definitions 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
complex structure
system comprising the *structure* (3.13) to be protected connected to one or more foreign electrodes and/or crossing multiple connected electrodes or passing close or through steel-reinforced concrete

3.2
electrolyte
medium in which an electric current is transported by ions

Note 1 to entry: Electrolyte is synonymous with soil, backfill and water.

3.3
polarization
change of an electrode [e.g. *structure* (3.13) and/or *coupon* (3.14)] potential caused by current flow

Note 1 to entry: Current flow results in *concentration polarization* (3.4) and *activation polarization* (3.5).

3.4
concentration polarization
portion of an electrode [*structure* (3.13) and/or *coupon* (3.14) *polarization* (3.3)] produced by electrolyte concentration changes resulting from the passage of a current through an *electrolyte* (3.2)

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3.5
activation polarization
change of an electrode [e.g. *structure* (3.13) and/or *coupon* (3.14)] potential due to charge transfer

3.6
depolarization
loss of *polarization* (3.3) of an electrode [e.g. *structure* (3.13) and/or *coupon* (3.14)] potential subsequent to current interruption

Note 1 to entry: Loss of *concentration polarization* (3.4) of an electrode (e.g. structure or coupon) is > 10^{-2} s up to seconds, hours or days. Only a small fraction of concentration polarization is usually lost within 0,1 s after current interruption in most cases. The time constant for build-up and depolarization of *activation polarization* (3.5) of an electrode is from 10^{-4} s to 10^{-3} s. Therefore, usually all activation polarization is lost within 0,1 s after current interruption.

3.7
IR drop
voltage, due to any current, developed in an *electrolyte* (3.2) such as soil, between the reference electrode and the metal of the *structure* (3.13), in accordance with Ohm's Law ($U = I \times R$)

3.8
IR-free potential
$E_{\text{IR free}}$
electrode [e.g. *coupon* (3.14)] to *electrolyte* (3.2) potential measured without the voltage error caused by the *IR drop* (3.7) due to the protection current or any other current

3.9
instant-off potential
E_{off}
electrode [e.g. *structure* (3.13) and/or *coupon* (3.14)] to *electrolyte* (3.2) potential measured very quickly (typically < 0,3 s) after an interruption of all sources of applied cathodic protection current with the aim of approaching an *IR-free potential* (3.8)

Note 1 to entry: The delay between the current interruption and measurement will affect the measured value and whether there is a decay of *concentration polarization* (3.4) and/or *activation polarization* (3.5).

3.10
on-potential
E_{on}
electrode [e.g. *structure* (3.13) and/or *coupon* (3.14)] to *electrolyte* (3.2) potential measured while the cathodic protection system is energized

3.11
over-polarization
over-protection
achievement of the *structure* (3.13) to *electrolyte* (3.2) potentials that are more negative than required for the control of corrosion and that can damage coatings, increase AC corrosion rate or, particularly for high yield strength steels, enhance the tendency to crack

3.12
spread resistance
ohmic resistance through a coating defect or *coupon* (3.14) to remote earth or from the exposed metallic surface of a coupon towards earth

Note 1 to entry: This is the resistance that controls the DC or AC current through a coating defect or an exposed metallic surface of a coupon for a given DC *on-potential* (3.10) or AC voltage. It comprises the metal resistance, the polarization resistance and the resistance within the coating defect as well as the contribution of the earth resistance.

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3.13
structure
metallic structure intended to receive cathodic protection

3.14
coupon
metal sample of defined dimensions and shape made of a metal equivalent to the metal of the *structure* (3.13)

Note 1 to entry: For the purpose of this document, the coupon is connected to the external surface of, and immersed in the *electrolyte* (3.2) adjacent to, the structure being protected by cathodic protection.

Note 2 to entry: Special kinds of *probes* (3.15) and coupons (examples of which are given in the annexes) are also considered part of the coupon definition (hence covered by this document) to the extent that they are intended to reflect structure coating defects, and thus act as a representative metal sample used to quantify the extent of corrosion or the effectiveness of applied cathodic protection.

3.15
probe
device incorporating a *coupon* (3.14) that provides measurements of parameters to assess the effectiveness of cathodic protection

Note 1 to entry: In this document, the term "coupon" is used as a synonym for both coupons and probes.

3.16
electrical resistance probe
ER probe
device that provides measurements of metal loss by comparison of the calibrated resistance value of a piece of metal with known physical characteristics

Note 1 to entry: Refer to Annex A for information on ER probes.

3.17
stray current
current flowing through paths other than the intended circuits

[SOURCE: ISO 8044:2020, 4.14, modified — "corrosion" has been deleted from the end of the term, and "impressed current corrosion caused by" has been deleted from the start of the definition.]

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4 Assessment of CP effectiveness

The assessment of the effectiveness of CP in accordance with ISO 15589-1 is based on an IR-free potential measurement. The determination of the IR-free potential on the cathodically protected structure is only possible based on combined direct current voltage gradient and close-interval potential survey measurements. This method is called "intensive measurement" and is described in EN 13509. This method requires, however, significant measurable voltage gradients associated with individual coating defects in order to allow for a reliable assessment of their IR-free potential and demonstrating conformity to ISO 15589-1. As a consequence, the determination of IR-free potential and demonstrating conformity to ISO 15589-1 is no longer possible on today's structures with high-quality coating systems. While it is still possible to determine instant-off potentials on many structures and use this reading as an approximation to the IR-free potential in certain cases, the increasing level of AC interference is preventing the separation of the earthing systems connected through decoupling devices from the cathodically protected structures for safety reasons. Similarly, in the presence of DC interference conditions, the determination of both IR-free potentials and instant-off potentials is not possible. As a consequence, on an increasing number of structures neither IR-free potentials nor instant-off potentials can be determined in order to demonstrate conformity to ISO 15589-1. The only remaining technology for demonstrating effectiveness is the use of coupons that are connected to the structure under investigation. The use of coupons is further required by ISO 18086. The determination of the effectiveness of CP under AC interference is only possible based on a current density measurement

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on coupons. The validity and accuracy of data obtained on coupons depend on a number of factors, such as location, geometry and bedding conditions. This document provides guidance on these aspects.

5 Application principles

5.1 IR-free potential measurements

The traditional coupon measurement technique has been used to demonstrate conformity of the coupon polarization, which is taken to be representative of the structure coating defects in accordance with the requirements of ISO 15589-1. There are several situations where the use of coupons is a feasible alternative to IR-free potential measurements directly on the structure. In particular, when accurate measurements directly on the structure itself are problematic. Examples include:

- in areas affected by traction stray currents and telluric currents;
- when dealing with the CP of complex structures;
- interference caused by two or more cathodically protected structures crossing or sharing the same right-of-way;
- interference between both parts of an isolating joint for a structure protected by two different CP systems one on each side of the joint;
- effects from equalizing currents from adjacent coating defects: the coupon may be regarded as one single coating defect exposed in the chemistry of the soil exactly where the coupon has been buried, whereas measurements on the structure may include a range of coating defects exposed in varying individual soil chemistries leading to the formation of potential differences and varying current demand;
- in areas where the CP is applied using several CP sources, and it is not possible or economically practical to synchronously turn off these CP sources.

EN 13509, EN 50162, ISO 18086 and ISO 15589-1 allow for the use of coupons in such instances.

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5.2 DC and AC currents and current densities

The use of coupons allows for an assessment of current densities in order to demonstrate conformity to ISO 18086 and EN 50162.

The DC current consumed by a coupon is primarily used for assessing the significance of DC stray current interference. EN 50162 describes a procedure for the demonstration of effectiveness of CP based on current density. This involves measuring the DC current throughout a period of typically 24 h. From these measurements, a period is defined in which no interference is present (e.g. hours during the night when trains do not operate). This period is used as the reference value and the measure of the reference current under normal CP. Based on the analysis of these currents, an assessment of the effectiveness of CP under DC interference is performed.

Apart from the risk of corrosion due to DC stray current interference, the DC current density is also important in the evaluation of effectiveness of CP under AC interference in accordance with ISO 18086. Excessive cathodic DC current can produce alkalinity near a coating defect to the extent where this electrolysis (leading to the production of current conducting OH^- ions) considerably increases the conductivity of the soil adjacent to the coating defect, thus lowering the spread resistance of this coating defect and increasing the corrosion rate under AC interference.

The AC current density has become a significant tool in the determination of the effectiveness of CP under AC interference in accordance with ISO 18086. Essentially, the AC current density associated with a coating defect with given surface is the result of the AC voltage on the structure at the position of the coating defect divided by the spread resistance of the coating defect. As the spread resistance and the AC current density cannot be measured directly at coating defects on structures, ISO 18086 requires

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a 1 cm^2 coupon for measuring the coupon current and calculating the current density for evaluation of the effectiveness of CP under AC interference.

5.3 Spread resistance

In relation to coupons, the spread resistance is the ohmic resistance from the exposed metallic surface of the coupon towards remote earth. This is the resistance that controls the DC or AC current through a coating defect for a given DC or AC voltage. Determining the spread resistance on coupons allows for assessing acceptable on-potentials (DC) and AC voltages.

5.4 Corrosion rate measurements

Various types of coupons and probes have been designed for the purpose of quantifying corrosion and the corrosion rate. Examples are weight loss coupons, perforation probes and ER probes. Refer to Annex A for more details.

6 Design considerations

6.1 General

The coupon design should reflect the purpose of the coupon measurement. The purpose may be:

— a detailed and comprehensive assessment of the CP effectiveness;

— an assessment of the effectiveness of CP under DC interference;

— an assessment of the effectiveness of CP under AC interference.

The information obtained with coupons depends on the geometry and size of the coupon. In the case of assessing the effectiveness of CP, the critical aspects are associated with insufficient cathodic current. In that case, a coupon with a design that results in a highest relative spread resistance, e.g. Figure 1 a), represents a worst case. In contrast, the most critical conditions in the case of AC and DC interference occur on small coating defects with a design that results in lowest spread resistance, e.g. Figure 1 c). As a consequence, these influencing parameters shall be considered. The fundamental concept of a coupon is the mimicking of a coating defect on the structure. These coating defects can have various shapes and sizes. Therefore, the coupon geometry should be adapted to an assumed coating defect geometry and size present on the structure. The relevant parameters are discussed in the following clauses.

6.2 Geometry of the defect

The case of a coating defect with vertical side walls is shown in Figure 1 a). This represents the case where the coating was locally damaged resulting in parallel walls going through the coating. The resistance of the electrolyte within the defect gives a contribution to the spread resistance and results in a homogeneous current distribution on the metal surface. This type of coupon, see Figure 1 a), is least sensitive to the total surface area in the case of large values of z/y. The value y represents the diameter of the coating defect and z represents the coating thickness. The reason for this is the parallel current distribution caused by the constrained electrical field. The calculated average current density is identical to the current density on the edges of the coupon. This configuration represents a conservative assessment of the effectiveness of CP, since typical coating defects do not have vertical parallel sides and permit higher average current densities on the steel within the coating defect.

In Figure 1 c), another extreme case of a coating defect represented by a coupon is shown. In this case, the coupon was constructed with the metal surface flush with the encapsulating coating surface. A large increase of the current density is observed at the edges next to the coating. This edge effect can result in a local increase of the current density of up to a factor of 10, compared to the average current density. This is a result of the non-parallel current distribution and the absence of a constrained electrical field.

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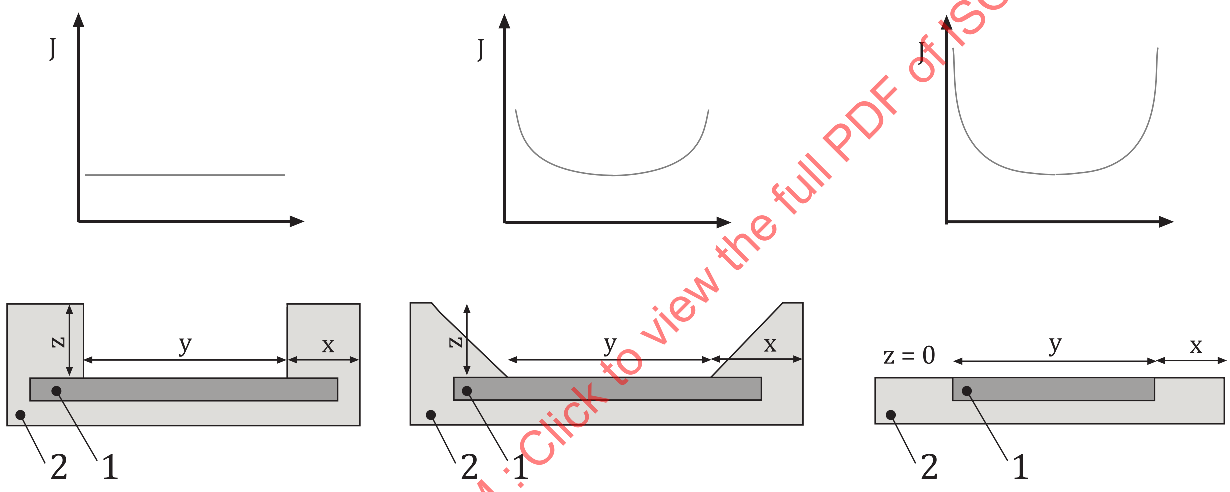
When high current densities are associated with high corrosion rates (in the case of DC and/or AC interference), locally increased metal loss is observed resulting in a heterogeneous metal loss. The corrosion rate is significantly higher with the type of coupon indicated in Figure 1 c) compared to the one shown in Figure 1 a). The calculated average current density in Figure 1 c) underestimates the maximum current densities present at the edges of the metal surface. Similarly, using probes that permit the determination of the average metal loss underestimates the maximum corrosion rate taking place in the case of Figure 1 c) on the edges. If the structure coating thickness is low (e.g. fusion bonded epoxy coatings), the coupon type in Figure 1 c) is relatively representative of structure coating defects.

The case in Figure 1 a) is conservative for conventional E_{off} measurements for the assessment of the effectiveness of CP (measured values may be less negative than in reality). In contrast, the case in Figure 1 c) is conservative for AC corrosion investigations, since it results in the lowest possible spread resistance and highest local current densities; the coupon geometry in Figure 1 c) will indicate higher AC corrosion rates than expected on a coating defect of the same size on the structure.

Figure 1 b) illustrates a compromise that may be used in all cases based on the avoidance of excessively conservative data of the geometry in Figure 1 c) in the case of AC and/or DC interference. Similarly, in the case of an assessment of CP effectiveness, the Figure 1 a) geometry is excessively conservative.



a) Coating defect with vertical side walls

b) Coating defect with angled side walls

c) Metal surface flush with encapsulating coating surface

Key

1 metal plate
2 coating
J current density
x insulated coupon surface adjacent to the bare steel surface
y coating defect diameter
z coating thickness

Figure 1 — Examples of different coupon geometries and the corresponding current density distribution

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6.3 Dimension of the coupon base plate

The lateral dimension of the coupon non-metallic encapsulation mimicking the structure coating is relevant for the spread resistance and correspondingly for the current density. This is because the encapsulation (such as the coated structure) restricts the CP current flow in the electrolyte. In Figure 1 a) to c), x represents the width of insulated coupon surface adjacent to the bare steel surface and y represents the coating defect diameter. In the case of a defect on a structure, this width x would correspond to the coating extending around the defect. This value is typically quite large. Detailed analysis has shown[5] that the effect of the width x is negligible when x is at least three times y (the

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diameter of the steel surface of the coupon). If x is smaller, the current density on the coupon will be increased compared to that of an identical coating defect on the structure.

6.4 Surface area of the coupon

Generally, increasing the coupon size results in smaller average current density since the spread resistance decreases linearly with increasing y and the current density decreases linearly with the surface area (i.e. $0{,}25 \cdot \pi \cdot y^2$). As a consequence, the current density is typically underestimated when the coupon surface area is chosen larger than the maximum defect size present on the structure. For this reason, in the case of AC corrosion, the use of 1 cm^2 has been established as a standard dimension in ISO 18086. Contrarily, the use of 1 cm^2 to 100 cm^2 coupon surfaces may be indicated for investigating the effectiveness of CP. The size of the coupon shall be adapted to the coating defects expected on a given structure. It is important to note that it is not possible to prove the effectiveness of CP on a poorly coated structure with large coating defects based on a measurement on a 1 cm^2 coupon with a defect geometry represented in Figure 1 c), since the current density and the polarization will be significantly increased compared to the one on larger coating defects on the structure.

When using a coupon for a specific application, these effects shall be taken into account. They significantly affect the spread resistance, the resulting current density and the level of polarization. Depending on whether the coupon is used to demonstrate the effectiveness of CP, protection against interference from DC traction systems or AC corrosion, different designs are required. With respect to the effectiveness of CP, the design should reflect the highest possible spread resistances as obtained with the geometry in Figure 1 a) or Figure 1 b) in conjunction with a value for x that is larger than three times y. In contrast, the assessment with respect to AC and/or DC interference conditions low spread resistances are more critical corresponding to the geometry in Figure 1 c).

6.5 Other types of coupon geometries

The above description highlights the effects associated with plate-shaped coupons. However, the same basic principles apply to other geometries, such as rod-shaped coupons. Values of x that are significantly smaller than y will result in decreased spread resistance and typically increased current densities.

7 Monitoring purpose — Selection of installation sites

7.1 General

The selection of the installation sites shall include the following aspects:

— a detailed and comprehensive assessment of the CP effectiveness;

— an assessment of the effectiveness of CP under DC interference;

— an assessment of the effectiveness of CP under AC interference.

7.2 Detailed and comprehensive assessment of CP effectiveness

For a detailed and comprehensive assessment of CP effectiveness, the coupons may be installed in locations along the structure that may vary in soil resistivity, soil chemistry, moisture content, current density, coating condition and temperature. Examples of such locations are:

— the top of a dry, rocky hill;

— a low-lying wet valley;

— a mid-span between CP current sources;

— the suction and discharge of compressor stations;

— the casings.

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The coupon should be located close to the structure to ensure that the soil conditions are similar at the coupon surface and at the nearby structure surface. The design of the coupon shall be adopted according to the coating system and coating condition of the structure. For the CP assessment, coupons shall be electrically connected to the structure. In order to ensure that the protection criterion is met, it can be useful to install coupons in locations where the access of CP current could be difficult. Typically, these are areas where the protection criterion can be difficult to obtain. Examples of such conditions with compromised CP effectiveness are:

— in high or very low soil resistivity;

— within casings;

— in the presence of high DC stray current.

In conditions and locations where it is not possible to place coupons close to the structure in the same backfill, it may be acceptable to place coupons somewhat remote from the structure, in a selected backfill.

To demonstrate a detailed and comprehensive effectiveness of CP in accordance with ISO 15589-1, IR-free potentials shall be measured. This is possible based on the following requirements.

— Measuring the off-potential immediately after disconnecting the coupon from the structure. For demonstrating the effectiveness of CP, taking measurements after 0,3 s in accordance with ISO 15589-1. However, to minimize depolarization effects causing the measured IR-free potential to become more positive, is can be necessary to be commence measurements within a shorter period after the disconnection of the coupon. The measurement period shall be at least the time period of the AC cycle measured locally on the structure caused by various interference sources. This typically corresponds to 16,7 ms in the case of 60 Hz, 20 ms in the case of 50 Hz, and 60 ms in the case of 16,7 Hz interference. Optimum coupon IR-free potential measurements shall commence within 0,1 s after interrupting the current and shall measure for at least one AC cycle. This type of measurement allows for assessing concentration polarization.

— For demonstrating the absence of over-polarization, ISO 15589-1 requires measurements using a “fast data logger or oscilloscope”. The data logger shall be sufficiently “fast” in the range of 1 ms to permit the measurements as detailed above. Similarly, such a high time resolution is required for the assessment of the effects of AC interference on the IR-free potential. These high data acquisition rates allow for the assessment of concentration polarization and activation polarization. Inductance and capacitance of the measurement circuit needs careful evaluation to ensure plausible data in the case of such fast measurements. This typically includes the use of shielded cables and high precision switching devices.

— Calculation of the IR-free potential based on the determined spread resistance and the on-potential. This measurement allows for an assessment of the polarization caused by concentration polarization and activation polarization in absence of AC interference. In the case of AC interference, the assessment of the contribution of the activation polarization requires the use of the fast-measured IR-free potential.

— Placing the reference electrode very close to the coupon surface thereby minimizing contributions of the spread resistance and stray currents in the soil to the IR-error. This allows for the direct assessment of the IR-free potential and eliminates all contributions from other voltage gradients in the ground caused by foreign constant and time-variant interferences.

An installation example for the assessment of the effectiveness of CP is given in B.1.

7.3 Assessment of CP effectiveness under DC interference conditions

For the evaluation of the risk of DC stray current corrosion, the coupons shall be placed at any location where DC stray current causes inacceptable levels of interference. In the presence of stray currents created by DC traction systems, the influences produced along the structure can significantly change during the design life. To avoid any corrosion at cathodically protected structures caused by stray

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currents, the requirements of ISO 15589-1 and EN 50162 with respect to IR-free potentials shall be permanently met. To demonstrate this requirement, the measurements shall be performed during a representative period of time. The sufficient period of time shall cover all normal variations created by time-variant DC interference. For this purpose, a data logger shall be installed for measuring IR-free potentials according to 7.2.

Additionally, EN 50162 allows the assessment of effectiveness of CP under DC interference conditions based on current measurements. Examples for the assessment of effectiveness of CP under DC interference conditions are given in Annex C. An example of using coupons for mitigating DC interference is shown in C.2.

NOTE EN 50162 provides guidance on the assessment of DC stray current interference.

7.4 Assessment of CP effectiveness under AC interference conditions

For the evaluation of the effectiveness of CP under AC interference, the coupons shall be installed wherever the criteria for AC corrosion likelihood are expected to be exceeded, as indicated by increased AC voltages, low soil resistivities and possible over-polarization. The areas with low soil resistivity and more negative on-potentials result in an increased AC corrosion risk based on ISO 18086, since they contribute to low-spread resistances and high-current densities. The current densities typically increase with decreasing defect size. For coupons used to assess AC corrosion, the defect surface area is typically 1 cm^2, since larger defects will exhibit lower current densities and can overestimate the effectiveness of corrosion protection under AC interference. Additionally, the access of the current to a small defect is influenced by its geometry. The adjacent coating, its thickness and the geometry of the coupon shall reflect the expected defect geometry on the structure to obtain the most representative results. Wherever possible, the coupon should be installed on the lower part of the structure, since there the humidity of the soil is higher and, therefore, the soil resistivity is naturally lower. Further guidance for the assessment of effectiveness of CP under AC interference conditions is given in B.2. Examples of concepts for addressing combined interference conditions are given in Annex C.

NOTE ISO 18086 provides guidance on the assessment of AC interference.

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8 Installation procedures

The installation of coupons should be made in such a manner that the representative behaviour is maintained to the greatest possible extent. The following aspects shall be considered in this context:

a) the coupon should be permanently installed, ideally in the same soil or backfill as the structure itself; if this is not possible, a replacement soil with conservative behaviour can be used;

b) the coupon geometry and associated spread resistance should reflect the purpose of the monitoring;

c) the coupon should not cause or receive any electrical interference from adjacent coupons or coating defects, unless this is part of the purpose of monitoring;

d) the coupon should have and maintain an intimate contact to the surrounding soil, unless a lack of contact and poor bedding condition is part of the purpose of monitoring;

e) if a permanent installation of the coupon is not possible, the effect of a limited polarization time on the obtained data with respect to corrosion protection, over-polarization and AC corrosion should be assessed; it shall be ensured that the temporary coupon is sufficiently polarized during the limited exposure time in order to demonstrate effectiveness of CP.

Intimate contact shall be maintained between the coupon surface and the surrounding environment. During the installation process, the soil around the coupon shall be compacted to prevent settlement and air voids forming around the coupon. These voids could result in loss of full contact between the coupon surface and the surrounding soil. The possible loss of contact because of soil movement caused by freezing or subsidence of the backfill material around the coupon shall be considered and minimized during installation, unless a lack of contact/poor bedding condition is part of the purpose of monitoring.

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A loss of contact between soil and coupon can usually be excluded when the coupon's surface is oriented upward. In contrast, a loss of contact can be mimicked by orienting the coupon surface downward.

Coupons may be installed by a number of different methods, including:

— excavation activities during the structure investigation;

— installation of the coupon during construction of the structure under investigation;

— hand digging;

— auguring;

— vacuum excavation;

— use of an underground access box to limit excavation work for easier installation and later removal of coupon.

NOTE Access boxes usually consist of cement or plastic rings that allow direct access to the soil. They are usually closed and exhibit direct cable connections.

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

9 Commissioning of coupons

9.1 Preliminary checking

Before connecting the coupon to the structure, the following measurements should be performed:

— corrosion potential of the coupon;

— potential of the permanent reference electrode (if present) against a portable reference electrode;

— spread resistance of the coupon (e.g. by measuring the resistance between coupon and pipe with a AC resistance meter);

— in cases of ER probes, the initial values of the electrical resistance of the built-in metal elements shall be recorded;

— soil resistivity near the coupon, if possible (e.g. with a soil box during installation or a resistivity calculation based on the spread resistance).

9.2 Start up

After connecting the coupon to the structure, the following measurements should be performed:

— coupon AC current;

— coupon DC current;

— on-potential;

— coupon IR-free potential;

— in cases of ER probes, the initial values of the electrical resistance of the build-in metal elements, under the influence of the AC current;

— checking of the remote monitoring system, if present.

In addition, the spread resistance of the coupon (e.g. by measuring the resistance between the coupon and pipe with an AC resistance meter) can be assessed.

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9.3 Measurement of the settled parameters

Once the coupon has sufficient ground contact and after a suitable polarization period, the coupon parameters (see 9.2) should be checked.

9.4 Installation and commissioning documents

After the successful installation of the coupon, the following documents can be prepared:

— installation date, as well as documents detailing the type of coupon and the dimensions of the coupon parameters;

— as-built layout documents showing the position of the coupon; additionally, other information can be collected such as the orientation of the coupon (e.g. upward by 45° or horizontally downward), the precise relative position to the pipe (vertical and lateral) and, if possible, the position relative to the position within the original backfill (e.g. in the backfill, 10 cm from native soil);

  NOTE When the location of the coupon can be readily assessed in the field (e.g. due to an underground access box), the as-built layout documents are not required.

— results of all measurements carried out before and after commissioning;

— description of the installation with details and references to materials as well as information useful for the correct operation and maintenance, e.g. frequency of system checks.

The final data are the basis for subsequent system checks to be performed on the coupon arrangement. Results of relevant measurements carried out before, during and after commissioning shall be filed and retained. The relevant data are the parameters listed above.

9.5 Frequency of coupon measurement

The frequency of the measurement depends on the requirements with respect to a detailed and comprehensive assessment, i.e. typically every three years in accordance with ISO 15589-1. Annex C gives examples of continuous coupon measurements based on remote monitoring and control systems.

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Annex A
(informative)

Special types and procedures of coupons and probes

A.1 Coupons for determination of weight loss and pitting

The coupons are produced from steel plates that are marked, degreased and weighed. After the connection of the cable, the surface is coated except for the area simulating the coating defect. Until installed, it should be stored in a sealed plastic bag containing a drying agent. For cable connections, precautions shall be taken to prevent any contributions of cable connection and disconnection to the mass loss measurement. Typical solutions include a thread in the coupon in combination with a screwed cable connection.

When the coupon is excavated for evaluation, it is advised to collect a sample of the surrounding soil for determination of soil type and resistivity by means of a soil box. Before cleaning the exposed steel surface, a photo should be taken. The coupon is cleaned with fresh water, dried and placed in a plastic bag with a drying agent.

The coating is removed and the cable dissembled. The weight loss is determined by pickling in Clarke's solution (20 g Sb_2O_3 and 60 g $SnCl_2 \times 2H_2O$ per litre concentrated HCl), in accordance with ISO 8407. The pickling is performed in several steps with weighing in-between. The mass loss for each pickling is transferred to a graph, see Figure A.1.

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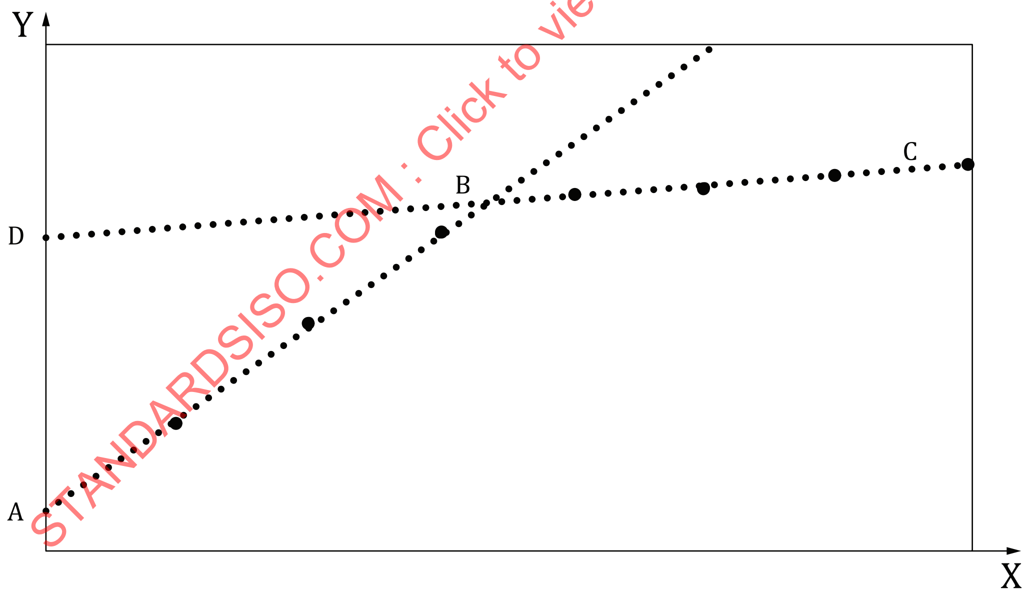

Key

X pickling time

Y mass loss

Figure A.1 — Mass loss curve

The line AB represents the removal of corrosion products. The pickling is repeated until three points on or close to the horizontal line BC are achieved. Until point B, corrosion products still remain on the surface. At point B, the surface is clean from corrosion products and the points between B and C represent the attack on the base metal. The mass loss is extrapolated to the point D on the y-axis, which

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represents the mass loss due to corrosion. The difference in mass loss between the points D and C is a compensation for the mass loss of the base metal during the pickling.

After each pickling, the coupons are rinsed in water, dipped in ethanol and dried in warm air. When the coupons are dry and have achieved room temperature, they are weighed. The pickling is performed at room temperature at periods between 1 min and 10 min depending on how heavily the coupons have been attacked.

The deepest pit within the exposed area should be determined using an optical microscope.

A.2 Perforation probes

The perforation probe can be used as a conventional coupon for regular measurements, but its primary purpose is to give a warning when the deepest corrosion pit reaches a predestined value. The key advantage is the simple handling and especially the information with respect to the corrosion depth. Hence, information about the depth of the corrosion is provided independent of the corroding surface. This is especially important in cases of very local corrosion that penetrates rapidly, but with little mass loss. The monitoring of the perforation probe can be readily integrated into the conventional inspection routine and also remotely controlled.

There are different types of perforation probes, but they are built on the same principle idea. When corrosion penetrates a thin steel plate with a thickness of typically 0,5 mm to 2 mm, this can be detected by a physical measurement, as described below.

The conductive type consists of a thin steel plate and an internal electrode. 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 plate. By a resistance measurement between the electrode and the thin plate, the perforation of the coupon can be detected by means of conventional resistance measurement devices.

The pressurized perforation probe based on pressure surveillance consists of a steel tube connected to a flexible copper tube. Both tubes are covered with a heat shrinkable tube, except for the defect on the steel tube. The copper tube is fitted into a junction box. To the same box, a valve and a manometer are connected, enabling pressurization of the copper/steel tube as well as monitoring the pressure. This measuring device is placed within a plastic container, which is mounted within the test post. When the deepest pit penetrates the wall of the exposed steel surface, the pressure falls, and this is indicated on the manometer.

A.3 ER probes

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 coupon technique does not require excavation for thickness measurement during normal operating conditions and weighing procedures since a mass loss is assessed by electronic means. Other coupon quantities, such as AC current, DC current, spread resistance, etc., can also be measured on ER coupons.

The ER technique consists of measuring the change of the resistance of a metal element formed as a coupon. When the metal element suffers from metal loss due to corrosion, the electrical resistance of the element increases. 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 used for temperature compensation. The element exposed to the corrosive environment constitutes the coupon part element, whereas the element protected from corrosion by the coating constitutes a reference element (see Figure A.2).

When current is exchanged between the exposed element and the soil, the ER technique should provide a means for temperature compensation due to heating of the exposed element by the current exchange.

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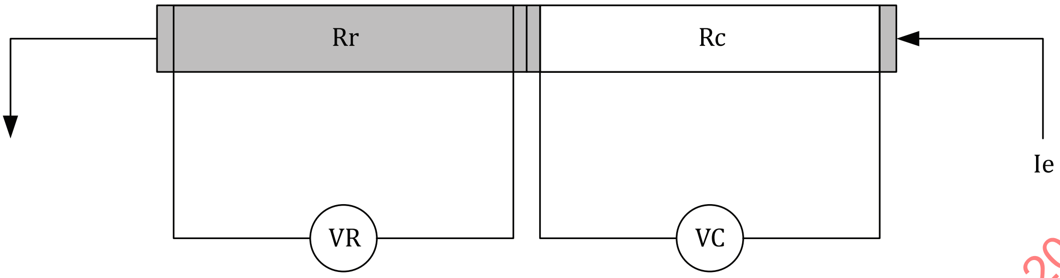
The resistance values of the two individual elements are usually measured by passing an excitation current through the elements and measuring the voltage generated over the element length caused by the excitation current.



Key

Rr	reference element	VR	voltmeter for reference element
Rc	coupon element	VC	voltmeter for coupon element
Ie	excitation current		

Figure A.2 — Principle of ER probe with excitation current and voltage measurement

The thickness of the coupon element at time *t* can be assessed throughout time using the sketched circuit principle. The coupon element thickness at time *t* is then quantified using a mathematical algorithm.

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Annex B
(informative)

Assessment of the effectiveness of CP under any conditions including DC and/or AC interferences

B.1 CP criteria based on the IR-free potentials

Under any conditions, including DC and/or AC interferences, as a first step, CP criteria based on the protection potentials and limiting critical potential provided by ISO 15589-1 shall be met. As these potentials are polarized ones without IR errors, the effectiveness of CP for steel structures can be assessed by coupon instant-off (IR-free) potential measurements.

The measurements shall be taken immediately after the coupon is disconnected from the pipe without interrupting all sources of CP current to the structure. Accurate coupon instant-off potentials can be acquired by placing the reference electrode as close to the coupon as possible to minimize the IR drop due to stray currents. Figure B.1 shows an example of a measuring system for coupon on-potential, coupon instant-off potential, and coupon DC and AC currents on a permanent coupon. A coupon should be installed so as not to shield CP current flowing into the structure. Figure B.1 shows an example of an upwards oriented coupon with the surface area of 1 cm^2 that is installed in a 9 o'clock position of the structure. An on or off-status between the coupon and the pipe is created by operating a solid state relay[6].

It is relatively simple to measure on-potential at each measuring point and AC voltage along the entire structure. On-potential and AC voltage measurements detect the areas of positive (anodic interference) and negative (cathodic interference) potential shifts indicating the risks of stray current interference and over-polarization, respectively, and the point of highest AC interference. At the detected critical points, coupon measurements (instant-off potential and DC and AC currents) can be taken for demonstrating the effectiveness of CP.

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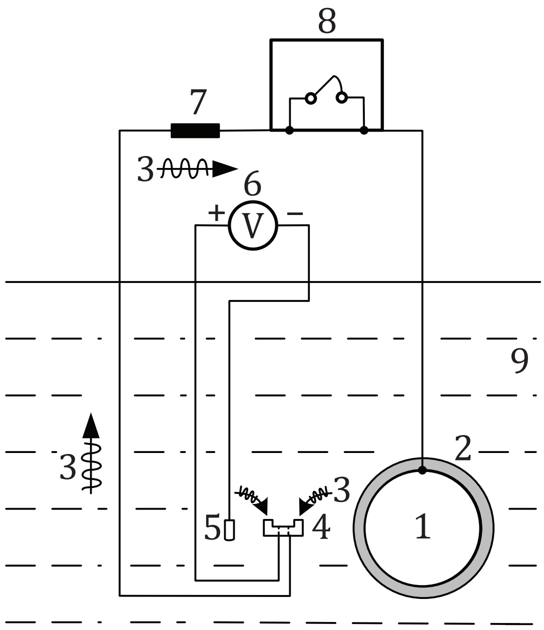

Key

1 structure (ex. pipeline)
2 high resistivity coating
3 CP current and DC/AC stray current
4 coupon
5 reference electrode
6 voltmeter
7 ammeter shunt
8 solid state relay
9 soil

Figure B.1 — Example of a measuring system for coupon on-potential, coupon instant-off potential, and coupon DC and AC currents

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B.2 AC interference

Based on ISO 18086, increased AC and DC current densities cause increased AC corrosion rates. These increased current densities are associated with higher AC voltages and more negative on-potentials. Hydroxides and carbonates of earth alkali cations produce solid precipitates with sometimes increased resistivity, leading to a higher spread resistance and a correspondingly lower AC corrosion rate at the coating defect.

The installation of coupons allows for a direct assessment of these complex interactions and demonstration of effective corrosion protection.

B.3 Real time remote monitoring and control of the rectifiers based on coupon data

In cases of a strong variation of AC and/or DC interferences over time, it can be difficult to control interference phenomena with a fixed setting of the rectifiers. The application of an impressed current cathodic protection (ICCP) system with remote monitoring and remote control of the rectifier based on coupon measurements, such as coupon on-potential, coupon instant-off potential or coupon AC and DC current, can be an effective way of assessing and ensuring effective corrosion protection.

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Annex C
(informative)

Examples of instant-off and current density measurements on coupons — Remote monitoring and remote control

C.1 Real-time remote monitoring and control of the rectifier based on IR-free potential measurements in cases of DC interference

The amount of change in coupon instant-off potential readings measured with a reference electrode in the direct vicinity of the coupon is less than that of on-potentials under stray current interference conditions. Therefore, continuous remote monitoring and remote control over the rectifier based on coupon instant-off potential measurements in accordance with EN 50162 can improve the efficiency of the operation of the ICCP system due to the optimized output current of the rectifier[7].

In cases where it is hard to make a clear distinction between anaerobic (immunity environment) and aerobic soils (passivity environment), a coupon instant-off potential of −0,95 V_{CSE} or more negative could be required to control the rectifiers.

Under homogeneous soil conditions that have very high resistivity and are well-aerated, IR-free potentials more positive than −0,85 V_{CSE} could be sufficient. ISO 15589-1 offers the following criteria for aerated soil:

— −0,75 V_{CSE} where soil resistivity is between 100 Ω m and 1000 Ω m;

— −0,65 V_{CSE} where soil resistivity is greater than 1 000 Ω m.

C.2 Real-time remote monitoring and control of the rectifier based on current density measurements in cases of DC interference

The CP level can be evaluated by placing a steel coupon at a critical point, then determining the coupon DC current, which shows entering (protection) and leaving (corrosion) directions as shown in Figure C.1.

With this set up, the constant DC current density averaged over a representative period of time (e.g. 24 h) on the coupon should always be maintained so that the effectiveness of CP is maintained. After confirming the AC interference level is acceptable as defined in ISO 18086, the calculated average DC current density of the coupon is adjusted to the predetermined value. Any decrease in the average coupon DC current density below the preset value will cause the transformer-rectifier current output to increase automatically until a balance is regained. Likewise, any increase in the average DC current density above the predetermined value will cut the current output until a balance is regained.

This approach is only feasible using very rapid response control-circuits and is particularly effective for a structure buried in a stray current exposure area showing the possibly very marked and quick stray current variations.

When a structure is buried under a railroad crossing, and when required during the CP design step, the installation of a coupon should be implemented at the stage of structure laying in the casing pipe. The location of the coupon is very important, particularly when used to control the system. The coupon should be placed just under a railroad crossing where the most intense risks of corrosion and over-polarization are possible. Since the area of influence surrounding the track at the railroad crossing is limited, it is applicable for the installation of shallow groundbed anodes and smaller CP currents, which can result in minimization of the interference effect on foreign metallic structures and AC corrosion risk.

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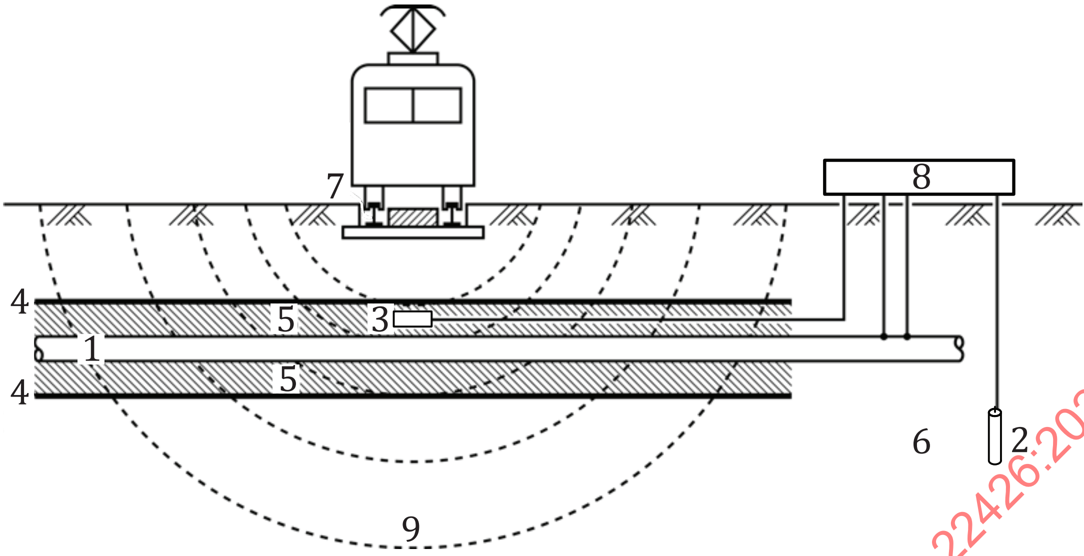

Key

1 structure
2 groundbed anode
3 coupon
4 casing pipe
5 electrolyte
6 soil
7 train equipped with regenerative braking
8 transformer-rectifier
9 equipotential line

Figure C.1 — Coupon DC current density controlled impressed current cathodic protection system[8]

The structure should be evaluated to determine if its CP system is operating properly. The application of a remote monitoring system is very effectual. Items of this remote monitoring system are coupon current density, voltage and current outputs, and the total circuit resistance (= (average voltage output) / (average current output)).

A DC power source with automatic control should be used to maintain a constant coupon DC current density that should be set (e.g. 1 A/m^2).

The DC power source should be able to deliver a sufficient output current instantly when the coupon DC current density becomes below the set value.

This type of DC power source should also be able to cut the output current instantly to mitigate the over-polarization risk when leakage current enters the coupon, with the result that the cathodic current becomes greater than the preset value at the coupon location.

The DC power source shall be equipped with a smoothing circuit (filters), which limits the magnitude of ripple to a value as low as possible. Thereby, the DC power source can maintain a preset constant coupon DC current density very accurately.

The DC power source with output current limitation circuits has an effective shut-down in the event of an external short circuit.

A typical block diagram for a constant coupon DC current density controlled ICCP system is shown in Figure C.2.

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