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

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.

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)

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.

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.]

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 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.

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 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

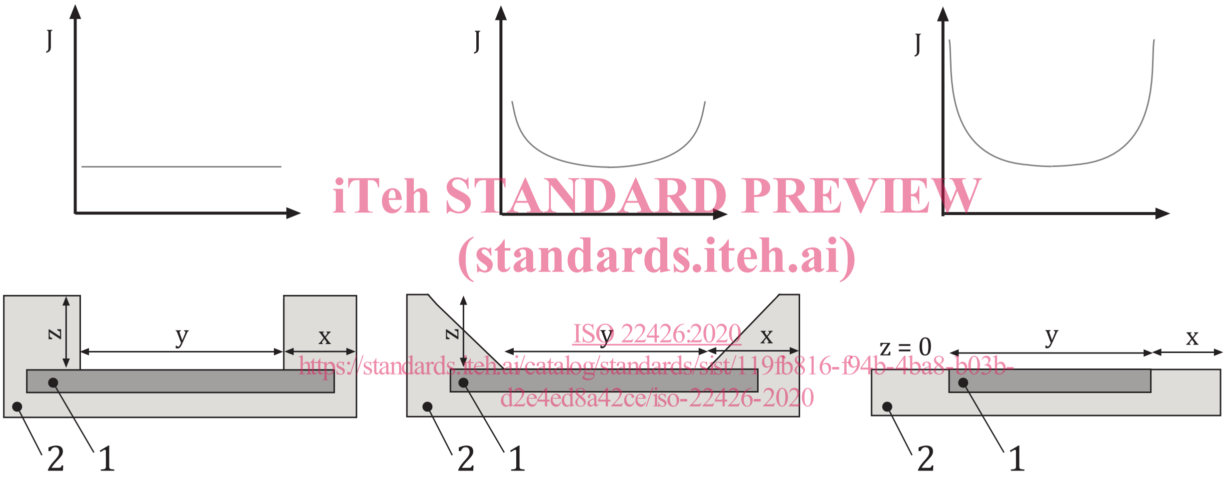
The case of a coating defect with vertical side walls is shown in Figure 1 a). This represents the case where the coating was locally damaged resulting in parallel walls going through the coating. The resistance of the electrolyte within the defect gives a contribution to the spread resistance and results 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.

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

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

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 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.