INTERNATIONAL STANDARD

ISO 22858

First edition
2020-08

Corrosion of metals and alloys — Electrochemical measurements — Test method for monitoring atmospheric corrosion

Corrosion des métaux et alliages — Mesures électrochimiques — Méthode d'essai pour la surveillance de la corrosion atmosphérique

Reference number
ISO 22858:2020(E)

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Published in Switzerland

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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).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

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 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.

Introduction

The purpose of this document is to provide instructions on the use of electrochemical sensors for monitoring atmospheric corrosion. These sensors are used to measure thin film electrolyte conductance, corrosion current or coating condition over long periods. This method permits the instantaneous evaluation of corrosion current that can be related to specific environmental conditions in real time. The instantaneous corrosion current measurements are not accessible using electrical resistance sensors or mass loss techniques. The technology described in this document complements other standard techniques for assessing atmospheric corrosion such as mass loss coupons, electrical resistance sensors or coated test panels (see ISO 8407 and ISO 4628-8). These continuous records of material condition can be useful for studying atmospheric corrosion, evaluating materials or managing assets[21][22][23][24][25][26][27][28][29].

This document was developed based on ANSI/NACE TM0416-2016.

This document is relevant to alloy and coating manufacturers and users in transportation, chemical process, energy and infrastructure applications.

Corrosion of metals and alloys — Electrochemical measurements — Test method for monitoring atmospheric corrosion

1 Scope

This document specifies a test method for atmospheric corrosion measurements, using two-electrode electrochemical sensors.

It is applicable to measurements of the corrosion rate of uncoupled metal surfaces (i.e. "free" corrosion rate), galvanic corrosion rate, conductance of thin film solutions and barrier properties of organic coatings. It specifies electrochemical sensors that are used with or without organic coatings. The sensors are applicable to corrosion measurements made in laboratory test chambers, outdoor exposure sites and service environments.

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 4618, *Paints and varnishes — Terms and definitions*

ISO 4628 (all parts), *Paints and varnishes — Evaluation of degradation of coatings — Designation of quantity and size of defects, and of intensity of uniform changes in appearance*

ISO 8044, *Corrosion of metals and alloys — Vocabulary*

ISO 9223, *Corrosion of metals and alloys — Corrosivity of atmospheres — Classification, determination and estimation*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 4618, ISO 4628 (all parts), ISO 8044, ISO 9223 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
electrical resistance sensor
device for measuring corrosion involving measurement of the ratio of the potential difference along a conductor and the current through the conductor

Note 1 to entry: ISO 15091:2019, 3.1, defines "electrical resistance" as the "ratio of the potential difference along a conductor and the current through the conductor".

3.2
electrochemical sensor
device for measuring corrosion involving anodic and cathodic reactions

Note 1 to entry: ISO 8044:2020, 4.1, defines "electrochemical corrosion" as "corrosion involving at least one anodic reaction and one cathodic reaction".

3.3
electrode digit
single finger of an *interdigitated electrode* (3.5)

3.4
corrosion penetration
distance between the corroded surface of a metal and the original surface of the metal

Note 1 to entry: ISO 8044:2020, 3.11, defines "corrosion depth" as the "distance between a point on the surface of a metal affected by corrosion and the original surface of the metal".

3.5
interdigitated electrode
electronic conductors interlocked like fingers

3.6
sensor range
upper and lower measurement values

3.7
sensor span
difference between maximum and minimum measurement values

3.8
solution resistance
ratio of electrode potential increment to the corresponding current increment dependent on solution

3.9
thin film conductance
solution layer current transport capacity

Note 1 to entry: ISO 15091:2019, 3.3, defines "conductance" as the "reciprocal of the resistance".

3.10
zero-resistance ammeter
instrument used for current measurement between two electrodes with no potential drop between them

4 Summary of sensors

The atmospheric corrosion measurements are made using three types of sensors to measure: a) free corrosion current, b) galvanic corrosion current and c) surface conductance.

Electrochemical sensors for atmospheric corrosion shall have a planar gage area. They are composed of two metallic electrodes separated by a dielectric material that electrically isolates the electrodes (see Figures A.1 and A.2). The electrochemical sensors have interdigitated electrode geometries and may be produced using composite laminate or thin film processes (see Annex A). The sensor gage area is defined as the area of the electrodes exposed to the environment.

5 Free corrosion current sensor

5.1 Free corrosion current sensor description

Free corrosion rate measurements are obtained using two-electrode sensors that may have a variety of alloys, geometries and excitation techniques[22][23][24][25][27]. Two-electrode sensors for the measurement of free corrosion rate may be made from any alloy of interest. Both electrodes of the free corrosion current sensor shall be constructed of the same alloy. The electrical excitation of sensors shall be done by applying a voltage between the two electrodes. Voltage may be applied using a potentiostat or other electronic device designed to apply a controlled potential. During measurements, the voltage between the two electrodes is controlled and the current response recorded. Between measurements, the two electrodes of the sensor may be electrically shorted. The corrosion current measurement range and span will be dependent on the expected corrosion rates of the given sensor alloy in the environment.

5.2 Sensor geometry

The separation distance between the electrodes should be no more than 300 μm (see Figures A.1 and A.2). A high electrode digit length to width ratio minimizes the contribution of edge effects that distort current and potential distributions, and small width electrodes support a more uniform active measurement area under varying environmental conditions. An example length to width ratio is 10 and an example electrode digit width is 2 mm. Geometry and sensing areas for each electrode should be the same.

5.3 Uniform corrosion current measurement

5.3.1 Use and conditions for uniform corrosion measurements

For alloys that undergo uniform corrosion, such as a low alloy steel, polarization resistance may be obtained and free corrosion rate estimated by means of the Stern-Geary equation (see ISO 17475, ISO/TR 16208 and ASTM G59-97). For a simple equivalent circuit model of a two-electrode sensor, the polarization resistance may be approximated as half of the real impedance at a low frequency (see Annex B). This assumes that the solution resistance is small relative to the polarization resistance. This assumption may not be valid at low levels of corrosive contaminants or for very thin or discontinuous solution layers. Uniform corrosion measurements should be validated with mass loss or other coupon tests for environments classified as low corrosivity outdoor (C1) or medium corrosivity indoor (IC 3) or less (see ISO 9223, ISO 9224, ISO 9226 and ISO 11844-1). High solution resistance could result in an underestimation of corrosion rate. Polarization resistance shall be determined using the methods given in 5.3.2 to 5.3.4.

5.3.2 Method 1 — Sine wave excitation

The current response may be measured using a voltage sine wave excitation. The amplitude should be less than 30 mV. The excitation frequency shall be low enough, typically from 0,01 Hz to 10 Hz, to obtain a reasonable estimate of the polarization resistance. This method may require verification that the selected frequency yields, or correlates to, polarization resistances obtained using a full electrochemical impedance scan (see ISO/TR 16208 and ASTM G102-89).

5.3.3 Method 2 — Triangle wave excitation

The current response may be measured using a triangle wave voltage excitation with an amplitude not greater than 30 mV. The excitation signal shall have a ramp rate from 0,05 mV/sec to 10 mV/sec. This method may require verification that the selected waveform produces polarization resistances that correlate to those obtained using potentiodynamic scan methods (see ISO 17475 and ASTM G59-97).

5.3.4 Method 3 — Potential step excitation

The current response may be measured using potential steps and holds. A sufficient number of steps shall be used to obtain a linear fit to the voltage versus current response data over a potential range no greater than ±30 mV[22]. For each step, the hold time should be sufficient to obtain a steady-state current measurement. For each step, the current shall be measured after the hold time and be an average of multiple readings. This method may require verification that the selected excitation produces polarization resistances that correlate to polarization resistances obtained using potentiodynamic scan methods (see ASTM G59-97).

5.4 Localized corrosion current measurement

For alloys that corrode by localized mechanisms, such as aluminium alloy pitting, the impedance should be measured for a given sine wave voltage excitation, and the amplitude should be less than 30 mV. The impedance may be either the real component or modulus. The excitation frequency shall be within the range of 0,01 Hz to 10 Hz. In the case of localized corrosion processes, a constant of proportionality that empirically relates the measured impedance to the corrosion current is needed to make absolute estimates of corrosion rate.

5.5 Free corrosion rate and total free corrosion for sensors without coatings

5.5.1 Free corrosion current and current density

Free corrosion current density shall be reported as microampere per square centimetre (μA/cm²). Current density shall be calculated using the free corrosion current and the area of one electrode. If one electrode is smaller, then the smallest electrode area shall be used. See Formula (1).

$$i_{\text{corr}} = \frac{I_{\text{corr}}}{A} \quad (1)$$

where

i_{corr} is the free corrosion current density, expressed as microampere per square centimetre (μA/cm²);

I_{corr} is the free corrosion current, expressed as microampere (μA);

A is the electrode area, expressed as square centimetre (cm²).

5.5.2 Free corrosion penetration rate

The free corrosion rate may also be converted to free corrosion penetration rate, but this shall only be done for alloys with uniform corrosion and shall not be used for alloys with localized corrosion such as pitting or intergranular corrosion. See Formula (2):

$$r_{\text{t}} = K_1 \cdot \frac{i_{\text{corr}}}{\rho} \cdot W_{\text{e}} \quad (2)$$

where

r_{t} is the corrosion penetration rate of a metal, expressed as micrometre per year (μm/a);

K_1 is a constant of proportionality equal to 3,27, expressed as micrometre gram per microampere centimetre year ((μm · g)/(μA · cm · a)) (see ASTM G102-89);

ρ is the density of the metal, expressed as kilogram per cubic metre (g/cm³);

W_{e} is the atomic weight of the metal divided by the valence of the oxidized metal atom, this is used as a dimensionless quantity (see ASTM G102-89).

Methods are available for obtaining corrosion mass loss and penetration rate for alloys that use alloy equivalent weight and densities, but these methods are outside the scope of this document (see ASTM G102-89).

5.5.3 Free corrosion mass loss rate

Free corrosion current density measurement may be converted to mass loss corrosion rate. See Formula (3):

$$r_{corr} = K_2 \cdot i_{corr} \cdot W_e \quad (3)$$

where

r_{corr} is the corrosion mass loss rate of metal, expressed in grams per square metre year (g/(m^2 · a));

K_2 is a constant of proportionality equal to 3,268, expressed as gram square centimetre per microampere square metre year ((g · cm^2)/(μA · m^2 · a)).

5.5.4 Total free corrosion mass loss and corrosion penetration

Time-based measurements of free corrosion current or corrosion rate may be integrated to obtain estimates of total charge passed or total mass loss, respectively. Total charge or mass loss shall be expressed in coulombs per square metre (C/m^2) or grams per square metre (g/m^2), respectively. Measures of thickness loss may also be reported as micrometres (μm), but shall only be reported for alloys with uniform corrosion. Total mass loss obtained from the sensor should be compared to the mass loss of specimens produced from the same alloy as the sensor (see ISO 8407).

5.6 Free corrosion current and total charge for sensors with coatings

5.6.1 Use and conditions for free corrosion measurements with coatings

For use with coatings, the sensor should be mounted to form a planar surface that is greater than the sensor gage area along each edge (see Figures A.1 and A.2). This may be achieved by casting, potting or mounting the sensors.

The sensor responses are dependent on coating properties and coating defect area. The sensor response may change during the test as the coating degrades. Therefore, the sensor response is not a measure of uniform conditions over the complete gage area of the sensor.

5.6.2 Free corrosion current for a coated sensor

For a coated free corrosion sensor, the current should be measured for a given sine wave voltage excitation and the amplitude should be less than 30 mV. The excitation frequency shall be within the range of 0,01 Hz to 10 Hz.

Current shall be expressed as microamps (μA).

5.6.3 Free corrosion total charge for a coated sensor

Time-based measurements of current may be integrated to obtain estimates of total charge passed. Total charge shall be expressed as coulombs (C).

5.7 Free corrosion sensor preparation

5.7.1 Considerations for free corrosion sensor surface preparation

The free corrosion sensors shall be prepared and cleaned as specified by the sensor supplier. Mechanical surface preparation should be avoided for thin film sensing elements. Composite laminate sensors with sufficient electrode thickness, approximately greater than 1 mm, may be mechanically finished using abrasives such as 600-grit sandpaper.

5.7.2 Free corrosion sensors without coatings

For sensors used without coatings, the sensors shall be cleaned to remove soluble organic and inorganic contaminants. Cleaning chemicals and processes shall be compatible with the sensor electrode and dielectric materials.

5.7.3 Free corrosion sensors with coatings and surface treatments

5.7.3.1 Coatings and surface treatments for use with free corrosion sensors

A broad range of protective coatings and surface treatments can be used with the electrochemical sensors. A general description of the use of electrochemical sensors with an organic coating system is given in 5.7.3.2 to 5.7.3.4. The system can consist of a chemical pretreatment, primer and topcoat. Besides paints and coatings, other materials that can be applied to the sensors are chemical pretreatments, volatile corrosion inhibitors and protective oils or compounds.

5.7.3.2 Organic coating

Sensors to be used with organic coatings can be prepared using typical etching, cleaners and pre-treatment processes. Coating performance is strongly dependent on surface cleanliness and preparation. Some high temperature and cleaning process steps may damage the sensor electrodes. It is recommended that sensor resistance to cleaning and pretreatment processes be verified prior to coating tests. The sensors should be visually inspected after each step of the coating process.

5.7.3.3 Coating application and processing

Sensors used to test coatings should be processed, as much as possible, like actual parts. Coatings can be applied by spray, brush or dipping processes. Masking shall be used to protect the electrical contacts and connectors from the coating processes. Heat-cured coatings can be applied to the sensors, but resistance of the sensor to cure temperatures shall be verified. Coatings should be applied and cured according to the manufacturer's specifications. Specific coating properties such as dry film thickness, adhesion and curing should be tested on witness panels processed at the same time as the sensor electrodes.

5.7.3.4 Coating scribe defect

Coating defects may be produced on free corrosion sensors using a mask, scribe tool or rotary cutting tool (see ISO 4628-8 and ASTM D1654-08). The defects should be oriented transverse to the interdigitated electrodes, and can be oblique or normal to the sensor length (see Figure A.1). One or more defects may be applied to each sensor.

Coating defects can be formed by masking the sensor using thin strips of tape that extend across the full width of the sensor.

Mechanical scribing of thick composite laminate electrodes can be done using standard manual or automated methods for coated panels (see ISO 4628-8 and ASTM D1654-08). Mechanical scribing shall not be performed on deposited or thin film electrodes. Scribes shall fully penetrate the coating to the substrate and have a uniform width of exposed metal that should be 0,5 mm to 1,5 mm. After scribing, the impedance shall be assessed to demonstrate that the electrodes are not electrically shorted by metal smearing or debris in the scribe (see 5.8.3.2). If an electrical short is detected, the scribe should be cleaned with a fine grit silicon carbide sandpaper (800 to 1 000 grit) or with an abrasive file.

5.8 Specification and inspection — Free corrosion sensors

5.8.1 Visual inspection

Sensors should be inspected prior to sensor processing and before use in atmospheric corrosion tests. Sensors shall be visually inspected for any irregularities such as defects or pores in the dielectric materials, damage to the electrodes, irregular geometry, electrode defects, surface contaminants or other sensor-to-sensor anomalies that could affect performance and consistency of results.

5.8.2 Sensor range and span

The nominal expected range and span for the sensors should be established for the expected test conditions either theoretically or experimentally before conducting exposure tests.

5.8.3 Electrical verification tests

5.8.3.1 Continuity test

Continuity between the gage area of the electrodes and sensor connector shall be checked. Care should be taken not to scratch or otherwise damage the test surface during this measurement.

5.8.3.2 Electrical resistance test

Resistance measurements between the two electrodes of the interdigitated electrode sensor shall be made on the as-produced or as-received sensors and shall be repeated again immediately prior to testing after preparation is complete. The resistance should be measured using a multimeter. This test is done to ensure that the two electrodes are electrically isolated from each other prior to use. The resistance shall be greater than 100 MΩ. Resistance measurements shall be performed in environmentally controlled conditions with a RH less than 50 % and a temperature between 20 °C and 27 °C.

5.8.4 Corrosion verification tests

Sensor operation may be verified by immersing in different corrosivity salt solutions (see ISO 11845). Solution chemistry and concentration should be selected based on expected sensor use. Free corrosion sensors shall be immersed in salt solution at a known temperature and excited using the excitation methods of 5.3 or 5.4. Sensors used to verify performance should not be reused for atmospheric testing.

The time between exposure and testing should be noted. The time should be sufficient for the corrosion sensor to reach a steady-state condition. Test conditions may be application specific. The solution chemistry, concentration and temperature shall be recorded. Three conditions should be tested that produce sensor response in each third (low, medium and high) of the desired corrosion rate range.

6 Galvanic corrosion current sensor

6.1 Galvanic corrosion current sensor description

Galvanic corrosion current measurements are obtained using two-electrode sensors with the electrodes connected together using either: a) a zero-resistance ammeter, or b) a precision resistor (see Figures A.1 and A.2)[21][23][24][26][29]. The preferred technique for measuring galvanic corrosion is the zero-resistance ammeter method. Two-electrode sensors for the measurement of galvanic corrosion may be fabricated from any alloys of interest. The electrodes of the two-electrode sensor shall be constructed of dissimilar materials to form a galvanic couple. Galvanic current range will depend on the alloys, cathode and anode areas and environment. Spans for current measurements should be selected based on these factors. The galvanic corrosion measurement range and span will depend on the expected galvanic corrosion rates for the given sensor alloys and environment.

6.2 Sensor geometry

The separation distance between the electrodes and the electrode digit length to width ratio should be as described by 5.2. The geometry of the electrodes and cathode to anode area ratio will influence the spatial distribution and magnitude of the galvanic current. The area ratio may be selected based on the known cathode and anode areas for a particular application.

6.3 Galvanic corrosion current measurements

6.3.1 Methods for galvanic corrosion current measurement

Electrical measurement of the galvanic current may be done using either of two methods:

a) zero-resistance ammeter (see 6.3.2);

b) precision resistor measurements (see 6.3.3).

6.3.2 Method 1 — Zero-resistance ammeter

Galvanic sensor excitation shall be done using a zero-resistance ammeter that applies a current to control the potential difference between the electrodes of the galvanic couple to zero. The current required to achieve this potential control is the galvanic current.

During the time interval between active zero-resistance ammeter measurements, the two electrodes of the sensor shall be controlled to the same potential or electrically shorted.

6.3.3 Method 2 — Precision resistor

Galvanic current shall be determined by measuring the voltage drop across a precision resistor that connects the two alloys of the galvanic couple. Knowing the voltage drop (V) and the value of the precision resistor (R), the galvanic current (I_g) may be calculated using Ohm's Law: ($I_g = V/R$). The resistor produces a voltage difference between the anode and cathode. The resistance should be as low as possible, while still allowing the current measurement to meet the galvanic current range and precision requirements. The resistance should be between 10 ohms to 100 000 ohms with a tolerance of 0,01 %[31][32].

Between measurements, the two electrodes of the sensor shall be electrically connected through the precision resistors.

6.4 Galvanic corrosion rate and total galvanic corrosion without coatings

6.4.1 Galvanic corrosion current

Galvanic corrosion current density (i_g) shall be reported as microampere per square centimetre (µA/cm^2). Current density will be measured using the area of the anode.

6.4.2 Galvanic corrosion rate for mass loss and corrosion penetration

Galvanic corrosion current density may be converted to mass loss rate using Formula (3) as described in 5.5.3. Galvanic mass loss rate shall be expressed as grams per square metre year (g/(m^2 · a)). Galvanic corrosion penetration rate may be expressed in micrometre per year (µm/a) using Formula (2) (see 5.5.2), but shall only be reported for alloys that uniformly corrode and shall not be reported for alloys with localized corrosion such as pitting or intergranular corrosion.

6.4.3 Total galvanic corrosion mass loss and corrosion penetration

Time-based measurements of galvanic corrosion rate may be integrated to obtain estimates of total mass loss. Total mass loss shall be expressed as grams per square metre (g/m^2). Measures of thickness loss may also be reported as micrometre (µm), but shall only be reported for alloys with uniform corrosion.

6.5 Galvanic corrosion rate and total galvanic corrosion with coatings

6.5.1 Use and conditions for galvanic corrosion measurements with coatings

For use with coatings, the galvanic corrosion sensors should be mounted to form a planar surface that is greater than the sensor gage area along each edge (see Figures A.1 and A.2). This may be achieved by casting, potting or mounting the sensors.

The galvanic corrosion sensor responses are dependent on coating properties and coating defect area. The sensor response will change during the test as the coating degrades. Therefore, the measured galvanic corrosion rate is not a measure of the anodic current over the complete anode gage area of the sensor.

6.5.2 Galvanic mass loss corrosion rate for a coated sensor

Galvanic corrosion shall be reported as galvanic current and shall be measured as microampere (μA). Galvanic corrosion current measurements may be converted to galvanic mass loss corrosion rate (see 5.5.3 and ASTM G102-89). Galvanic mass loss rate shall be expressed as grams per year (g/a).

6.5.3 Total galvanic mass loss for a coated sensor

Time-based measurements of galvanic corrosion rate may be integrated to obtain estimates of total charge passed or total mass loss. Total charge or mass loss shall be expressed as coulombs (C) or grams (g), respectively.

6.6 Galvanic corrosion sensor preparation

6.6.1 Considerations for galvanic corrosion sensor preparation

The galvanic corrosion sensors shall be prepared and cleaned as specified in 5.7.

6.6.2 Galvanic corrosion sensors without coatings

For sensors used without coatings, the galvanic corrosion sensors shall be cleaned as described in 5.7.2.

6.6.3 Galvanic corrosion sensors with coatings and surface treatments

A broad range of protective coatings and surface treatments can be used with the galvanic corrosion sensor. The preparation methods described in 5.7.3 shall be followed.

6.7 Specification and inspection — Galvanic corrosion sensors

6.7.1 Visual, span and range inspection

Sensors should be inspected prior to sensor processing and before use in atmospheric corrosion tests according to the methods described in 5.8.1 and 5.8.2.

6.7.2 Electrical verification tests

6.7.2.1 Continuity test

Continuity between the gage area of the electrodes and sensor connector shall be checked according to 5.8.3.1.

6.7.2.2 Electrical resistance test

Resistance measurements between the two electrodes of the interdigitated electrode sensor shall be checked according to 5.8.3.2.

6.7.3 Corrosion verification tests

Sensor performance may be verified by methods described in 5.8.4.

7 Thin film conductance sensors

7.1 Conductance sensor description

Conductance measurements are used to measure moisture and contaminants on the sensor surface[30]. The conductance measurement is indicative of conditions that promote corrosion.

Interdigitated two-electrode sensors produced from noble metals and alloys, such as gold, shall be used for surface conductance measurements.

7.2 Sensor geometry

The separation distance between the electrodes and digit length to width ratio should be as described by 5.2.

7.3 Surface conductance measurement method

The electrical excitation of sensors shall be done by applying a voltage signal between the two electrodes. During measurements, the relative potential between the two electrodes is controlled and the current response recorded. Current range will depend on the electrode area, excitation voltage and environment. Spans for current measurements used to determine conductance should be selected based on these factors. The conductance measurement range and span will be dependent on the expected contaminant composition and amount deposited on the sensor surface.

Between measurements, the two electrodes of the sensor should be electrically shorted.

The current response shall be measured using sine wave voltage excitation. Excitation frequency shall be within the range of 0,1 kHz to 1,000 kHz for conductance sensors used in the bare condition.

The excitation signal shall be a voltage sine wave with amplitude between the two electrodes of not more than 50 mV. The conductance shall be measured as the ratio of the current to voltage. The conductance shall be measured as Siemens (S).

7.4 Surface conductance sensor preparation

For sensors used without coatings, conductance sensors shall be cleaned as described in 5.7.2.

7.5 Specification and inspection — Conductance sensor

7.5.1 Visual, span and range inspection

Sensors should be inspected prior to sensor processing and before testing according to the methods described in 5.8.1 and 5.8.2.

7.5.2 Electrical verification tests

7.5.2.1 Continuity test

Continuity between the gage area of the electrodes and sensor connector shall be checked according to 5.8.3.1.

7.5.2.2 Electrical resistance test

Resistance measurements between the two electrodes of the interdigitated electrode sensor shall be checked according to 5.8.3.2.

7.5.3 Conductive solution verification tests

Sensor performance may be verified in standard conductivity solutions at a constant temperature. Sensors used to verify performance shall not be reused for atmospheric testing.

Test conditions may be application specific. Solution chemistry, concentration and temperature shall be recorded. It is recommended that three conditions be tested that produce sensor response in each third (low, medium and high) of the stated sensor conductance measurement range.

8 Coating barrier property sensors

8.1 Coating barrier property sensor description

Coating impedance measurements with interdigitated, noble metal, two-electrode sensors are used to measure barrier properties of coatings applied to the sensor. The impedance measurements for coatings are dependent on coating properties, moisture and contaminants. The sensors described in Clause 7 shall be used to make impedance measurements to assess coating barrier properties. For coating tests, the sensors should be flush mounted to form a planar surface that is greater than the sensor gage area along each edge (see Figures A.1 and A.2). This may be achieved by casting, potting or mounting the sensors.

8.2 Coating barrier property measurements

The impedance measurement range and span required for coating barrier properties will depend on the coating, electrode area and test environment. The electrical excitation of sensors shall be done by applying a voltage signal between the two electrodes. During measurements, the relative potential between the two electrodes is controlled and the current response recorded.

Between measurements, the two electrodes of the sensor should be electrically shorted.

The current response shall be measured using voltage sine wave excitation. Single or multiple frequency measurements may be used to characterize coating condition. Excitation frequency may include the range from 0,1 Hz to 100 kHz. The sine wave excitation signal shall have a voltage amplitude between the two electrodes of not more than 50 mV. The impedance shall be measured as the ratio of the voltage to current. The coating impedance shall be measured as ohms (Ω).

8.3 Coating barrier property sensor preparation

8.3.1 Sensor preparation for coating

Sensors to be used with organic coatings shall be prepared as described in 5.7.3.2 and 5.7.3.3.

8.3.2 Coating test condition

The coating barrier property sensors shall only be tested with intact coatings with no applied artificial defects.

8.4 Specification and inspection — Coating barrier property sensor

8.4.1 Visual, span and range inspection

Sensors should be inspected prior to sensor processing and before testing according to the methods described in 5.8.1 and 5.8.2.

8.4.2 Electrical measurements

8.4.2.1 Continuity test

Continuity between the gage area of the electrodes and sensor connector shall be checked according to 5.8.3.1.

8.4.2.2 Resistance test

Resistance measurements between the two electrodes of the interdigitated electrode sensor shall be checked according to 5.8.3.2.

8.4.3 Sensing system impedance verification tests

The measurement system impedance should be verified using load resistances applied to the measurement circuit. It is recommended that three resistances be tested that produce the measurement system response expected for each third (low, medium and high) of the expected sensor impedance measurement range.

9 Atmospheric testing with electrochemical sensors

9.1 Types of atmospheric tests

The electrochemical sensors can be used in laboratory tests, outdoor exposures and service environments.

9.2 Test arrangement

The sensors should be arranged and oriented using the same practices used for other standard test panels (see ISO 8565 and ISO 9226).

9.3 Test duration

The longevity of an electrochemical sensor will depend on the corrosivity of the environment, presence of a coating, coating defects and durability of the sensing elements.

9.4 Sensor selection

The sensor selection should consider the expected laboratory test or exposure environment severity (see ISO 9223 and ISO 11844-1).

It may be necessary to run preliminary tests to verify that the sensors have the longevity and measurement range required for the given environment.

9.5 Sampling time interval

The sampling interval shall be selected based on the expected rate of change of the exposure conditions. For cyclic laboratory testing, a five-minute interval may be suitable. For outdoor testing under ambient weather, conditions a 15-min to one-hour interval may be suitable. When selecting sampling time interval and total test time, the file size should be considered.

9.6 Date and time information

All data shall be time and date stamped using Coordinated Universal Time (UTC) conventions. Formats described in ISO 8601-1 should be used. Clocks shall be verified versus UTC prior to initiating a test. Clock precision and accuracy for the specific electronics should be stated as part of the system specifications and reporting.

10 Test report

10.1 Test report guidance

Guidance is given for reporting sensor information, results and environmental parameters in Annex C (see ASTM G33-99 and ASTM G107-95).

10.2 Sensor information

The type of sensor used shall be identified: free corrosion, galvanic corrosion, conductance or coating barrier property. Reporting shall include sensor-specific information, including sensor serial number, sensor materials, geometry and electrode areas. Sensor output spans and data sampling rates shall be stated. The methods used to determine free corrosion and galvanic corrosion shall be identified (see 5.3, 5.4 and 6.3). Excitation signal parameters shall be given for all corrosion, conductance and barrier property sensors used.

10.3 Surface preparation

Surface preparation processes, products and materials shall be reported along with any observations related to the sensor inspection, condition, cleaning, pretreatment and coating. The application of artificial coating defects shall be reported.

10.4 Test description

Reporting shall include the type of test, start date, end date and duration. Reporting shall include notes on any irregular conditions that may affect the results of the test. If environmental and quality control data (mass loss, collection rates, chemistry, etc.) are collected during the exposure tests, these data should be included or referenced.

10.5 Sensor inspection

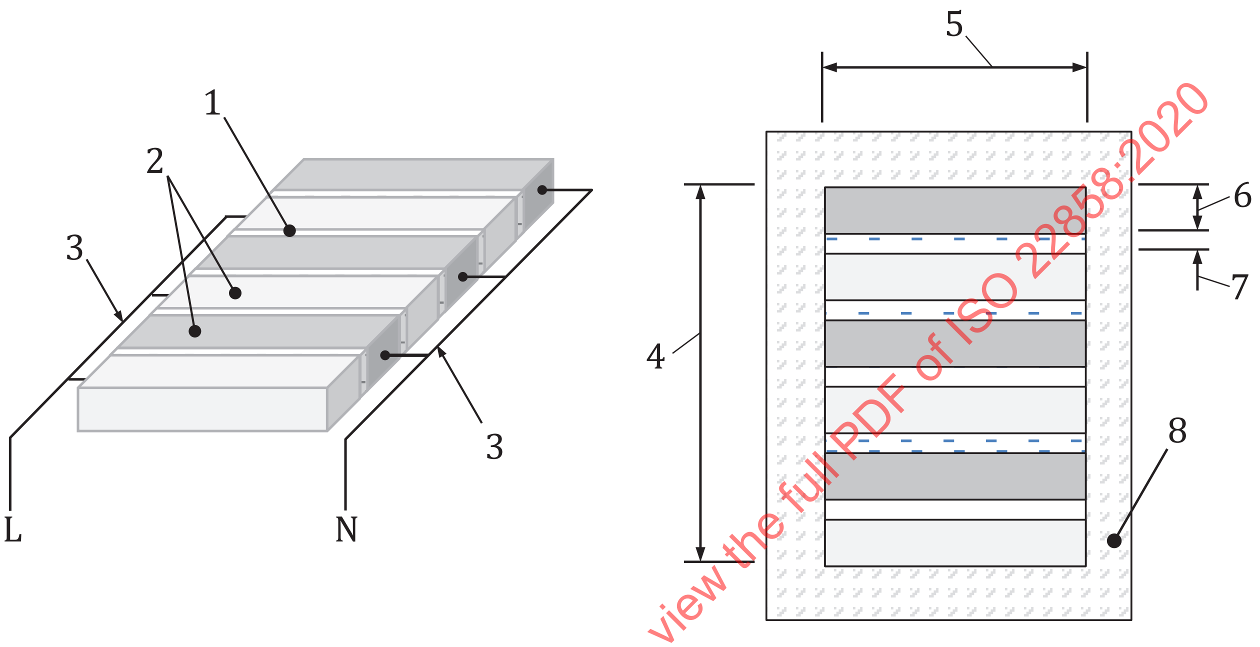
Sensors shall be visually inspected after testing and images should be obtained to document the corrosion and coating condition on the sensors. Coating defects shall be assessed in accordance with ISO 4628 (all parts). Sensor degradation that could affect the performance and consistency of results should be noted, such as a localized attack at interfaces between the dielectric materials and electrode alloys (see Figure A.1).

10.6 Data storage

The electrochemical sensor data shall be stored in a digital format such as comma separated variable (.csv) text files. The first column of each file will contain a time stamp (UTC). Additional data columns should be added for each sensor being used. Each column will include header information for identification of the data type and units. The digital data can also include environmental measures of sensor surface temperature, air temperature and relative humidity (see ASTM G92-86). Relevant environmental data from other sources, such as time-based records of laboratory test conditions or environmental weather stations, should be included with the digital test records.

Annex A
(informative)

Example images of electrochemical sensors



a) **Isometric view** b) **Top view**

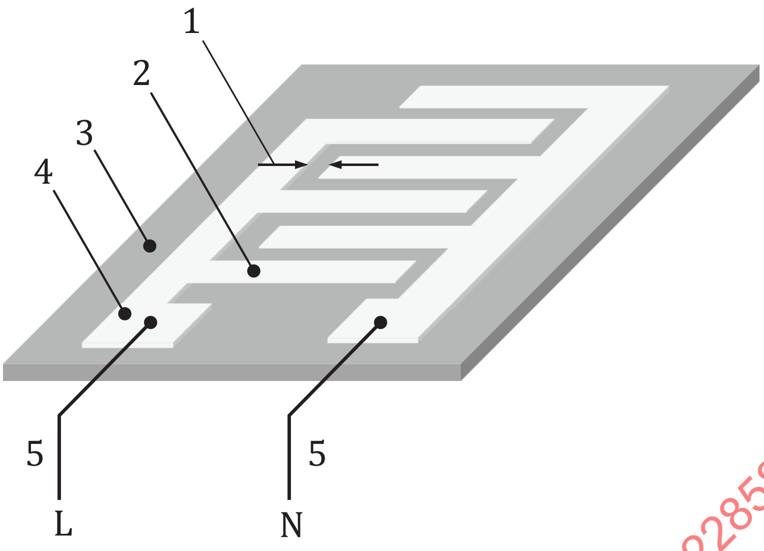
Key

1 dielectric material
2 electrode digit
3 working electrode leads
4 sensor width
5 sensor length
6 electrode width
7 electrode separation distance
8 sensor potting material
L N excitation signal, zero-resistance ammeter or precision resistor

NOTE 1 Each electrode is made of a single alloy or metal, but the two electrodes may be either the same material (free corrosion sensor) or different materials (galvanic corrosion sensor).

NOTE 2 The two electrodes are formed by shorting together every other digit to form the interdigitated electrodes.

Figure A.1 — Illustration of laminated interdigitated two-electrode sensor



Key

1 electrode separation distance

2 electrode digit

3 dielectric substrate

4 electrical contact

5 working electrode leads

L N excitation signal, zero-resistance ammeter or precision resistor

NOTE 1 The two electrodes are formed by patterning the thin film deposit or bonded foil on the dielectric material.

NOTE 2 Each electrode is made of a single alloy or metal, but the two electrodes may be either the same material (free corrosion sensor) or different materials (galvanic corrosion sensor).

Figure A.2 — Illustration of thin film interdigitated two-electrode sensor

Annex B
(informative)

Equivalent circuit analysis for two-electrode measurements

B.1 Polarization resistance theory

The measurement of polarization resistance is for bare sensors only and not for use with coatings and coated sensors. Polarization resistance may be used to calculate the free corrosion current of a metal or alloy using the Stern-Geary equation (see ASTM G59-97), see Formula (B.1):

$$R_{\mathrm{p}} = \frac{(\Delta E)}{(\Delta I)_{\Delta E \to 0}} = \frac{\beta_a \beta_c}{2{,}3 I_{\mathrm{corr}} (\beta_a + \beta_c)}, \text{ or } \frac{\beta}{I_{\mathrm{corr}}}, \text{ so that, } I_{\mathrm{corr}} \propto \frac{1}{R_{\mathrm{p}}} \quad \text{(B.1)}$$

where

R_{p} is the polarization resistance;

ΔE is the change in electrical potential;

ΔI is the change in current;

β_a is the anodic Tafel slope;

β_c is the cathodic Tafel slope;

I_{corr} is the free corrosion current;

β proportionality constant.

B.2 Polarization resistance for two-electrode sensor

Experimentally, the polarization resistance can be obtained by measuring the resistance of a two-electrode circuit with each working electrode fabricated from the same material with equal areas. The simple equivalent circuit for this two-electrode arrangement consists of resistive and capacitive elements (see Figure B.1). The impedance of the equivalent circuit at low frequency excitation and high frequency are shown by Formulae (B.2) and (B.3), respectively.

$$Z_{\omega \to 0} = 2R_{\mathrm{p}} + R_{\mathrm{s}} \quad \text{(B.2)}$$

$$Z_{\omega \to \infty} = R_{\mathrm{s}} \quad \text{(B.3)}$$

where

Z is the impedance;

ω is the frequency;

R_{s} is the solution resistance.

