

Cathodic protection measurement techniques

The European Standard EN 13509:2003 has the status of a
British Standard

ICS 25.220.40; 77.060

National foreword

This British Standard is the official English language version of EN 13509:2003.

Attention is drawn to the fact that BS 7361-1:1991, *Cathodic protection — Part 1: Code of practice for land and marine applications*, provides general information on cathodic protection. Note that BS 7361-1:1991 will eventually be withdrawn when all the CEN standards relating to cathodic protection currently being prepared are published.

The UK participation in its preparation was entrusted to Technical Committee GEL/603, Cathodic protection, which has the responsibility to:

- aid enquirers to understand the text;
- present to the responsible international/European committee any enquiries on the interpretation, or proposals for change, and keep the UK interests informed;
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English version

Cathodic protection measurement techniques

Techniques de mesures applicables en protection
cathodique

Messverfahren für den kathodischen Korrosionsschutz

This European Standard was approved by CEN on 27 December 2002.

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Foreword

This document (EN 13509:2003) has been prepared by Technical Committee CEN/TC 219 "*Cathodic protection*", the secretariat of which is held by BSI.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by November 2003, and conflicting national standards shall be withdrawn at the latest by November 2003.

This European Standard should be considered as a basic document developing general measurement techniques applicable for the protection of buried or immersed metallic structures.

Annexes A, B, C, D, E, F, G, I, J and K are informative.

Annex H is normative.

This document includes a Bibliography.

According to the CEN/CENELEC Internal Regulations, the national standards organizations of the following countries are bound to implement this European Standard: Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, Malta, Netherlands, Norway, Portugal, Slovakia, Spain, Sweden, Switzerland and the United Kingdom.

Introduction

This European Standard describes the principles of the different methods of measurement used to assist in the design of the cathodic protection system of a buried or immersed metallic structure, for the verification of its effectiveness and finally for its optimum operational conditions.

It deals in particular with the measurement of the structure to electrolyte potential, which indicates whether or not the cathodic protection criterion for the structure is met.

Apart from specifying the factors, which may influence the measurement of the potential, this European Standard describes the different techniques possible and their suitability in various situations.

Further, this European Standard provides parameters to be controlled and measurements to be carried out (potential, potential gradient, current and resistance measurements) to ensure the correct functioning of the cathodic protection system and its effectiveness for the entire structure.

Several measurement methods described in general terms in the body of the standard are explained in more detail in annexes. These methods differ from one another to account for differences in type or state of the structure, the local environment and the degree of accuracy selected.

Measurements on buried structures that are not easily accessible e.g. pipe networks in urban areas are difficult to implement and interpret. To take measurements without the full knowledge of the problems associated with the measurement technique renders the interpretation of the measurements difficult and leads to incorrect decisions.

One of the clauses of this European Standard therefore outlines the difficulties encountered when measuring structure to electrolyte potentials, and suggests several methods of measurement that take into account, or avoid, these difficulties.

Based on knowledge and experience, the most suitable measurement techniques can be selected as described in this European Standard.

In order to achieve effective and efficient cathodic protection, measurements should be performed by trained, experienced and responsible personnel.

Instrumentation used for measurement should be kept in good working order and should be subjected to periodical calibration and safety checks.

1 Scope

This European Standard deals with the cathodic protection against corrosion of buried or immersed metallic structures, detailing the measuring methods to be used for assessing the effectiveness of cathodic protection as well as the measurements and measures taken to monitor cathodic protection during operation.

Throughout the text, the measurement techniques are described primarily for pipelines.

However, they are sufficiently general to apply to other kinds of buried or immersed (except offshore) structures.

General principles with regard to cathodic protection are described in EN 12954. Other measurement methods specific to particular cases are described in other European Standards e.g. prEN 50162.

2 Normative references

This European Standard incorporates by dated or undated reference, provisions from other publications. These normative references are cited at the appropriate places in the text, and the publications are listed hereafter. For dated references, subsequent amendments to or revisions of any of these publications apply to this European Standard only when incorporated in it by amendment or revision. For undated references the latest edition of the publication referred to applies (including amendments).

EN 12954:2001, *Cathodic protection of buried or immersed metallic structures — General principles and application for pipelines*

EN ISO 8044:1999, *Corrosion of metals and alloys — Basic terms and definitions (ISO 8044:1999)*

3 Terms, definitions and symbols

3.1 Terms and definitions

For the purposes of this European Standard the following terms and definitions apply. For other terms and definitions related to corrosion refer to EN ISO 8044:1999 and to cathodic protection refer to EN 12954:2001.

3.1.1

anode backfill

material with a low resistivity, which may be moisture-retaining, immediately surrounding a buried anode for the purpose of decreasing the effective resistance of the anode to the electrolyte

3.1.2

backfill

see anode backfill

3.1.3

bond

metal conductor, usually of copper, connecting two points on the same or on different structures usually with the intention of making the points equipotential

3.1.4

buried structure

any metal construction built or laid beneath ground level or built on ground level and then covered with earth

3.1.5

calomel reference electrode

reference electrode consisting of mercury and mercurous chloride in a solution of potassium chloride

3.1.6

cathodic protection system

entire installation, including active and passive elements, that provides cathodic protection

3.1.7

cell current

current flowing in a corrosion cell

3.1.8

coating defect

deficiency in the protective coating (e.g. holidays, porosity)

3.1.9

coating resistance or structure to soil resistance (R_{co})

electrical resistance between a coated metal and the electrolyte expressed in ohms. It is determined largely by the size and number of coating defects, coating pores and the electrolyte resistivity

3.1.10

copper/saturated copper sulphate reference electrode

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

3.1.11

coupon

representative metal sample used to quantify the extent of corrosion or the effectiveness of applied cathodic protection

3.1.12

d.c. traction system

electrical traction system powered by direct current

NOTE If these systems have the return circuit earthed at more than one point or are not completely isolated they can generate stray currents, which may cause corrosion damage.

3.1.13

d.c. industrial plant

electrical system, other than a traction system, powered by direct current

NOTE If these systems use the earth as a part of the return circuit, they can generate stray currents, which may cause corrosion damage. Cathodic protection systems use the earth as a part of the circuit.

3.1.14

electrolyte

liquid, or the liquid component in a medium such as soil, in which electric current flows by the movement of ions

3.1.15

electrolyte resistivity (ρ)

the specific electric resistance of the electrolyte assuming that the electrolyte is homogeneous

NOTE Usually expressed in Ωm .

3.1.16**equalising currents**

currents that flow between areas of different polarisation after switching off the protection current. Equalising currents can be a source of error in measuring IR free potentials

3.1.17**external potential test probe**

installation comprising a coupon with an associated reference electrode to provide structure to electrolyte potential measuring facilities devoid of IR drop errors

3.1.18**foreign anode**

see Foreign Electrode

3.1.19**foreign cathode**

see Foreign Electrode

3.1.20**foreign electrode**

foreign electrode is either a foreign anode or a foreign cathode. A foreign anode is a metal or a conductive material in contact with the structure under consideration which has a more negative potential than the structure and a foreign cathode is a metal or a conductive material in contact with the structure under consideration, which has a more positive potential than the structure

3.1.21**foreign structures**

any neighbouring structure other than the structure that is under consideration

3.1.22**galvanic anode**

anode that provides cathodic protection current by means of galvanic action

3.1.23**holiday**

defect in a protective coating at which metal is exposed to the environment

3.1.24**immersed structure**

any metal construction, or part of a construction laid in a liquid environment such as fresh water (rivers, lakes), brackish water (estuaries), or sea water

3.1.25**insulated flange**

flanged joint between adjacent lengths of pipe in which the nuts and bolts are electrically insulated from one or both of the flanges and the gasket is non-conducting, so that there is an electrical discontinuity in the pipeline at that point

3.1.26**interference**

any change of the structure to electrolyte potential, which is caused by foreign electrical sources

3.1.27**IR drop**

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

3.1.28

IR free potential ($E_{\text{IR free}}$)

structure to electrolyte potential measured without the voltage error caused by the IR drop due to the protection current or any other current

3.1.29

isolating joint

electrically discontinuous connection between two lengths of pipe, inserted in order to provide electrical discontinuity between them, e.g. monobloc isolating joint, insulated flange

3.1.30

measuring electrode

electrode with a stable potential in a given electrolyte used to determine the potentials of a structure in that electrolyte. The potential of a measuring electrode in a given electrolyte has to be determined with respect to a reference electrode

3.1.31

measuring point

point at which the actual measurement takes place. In the case of structure to electrolyte potentials this refers to the location of the reference electrode

3.1.32

off potential (E_{off})

structure to electrolyte potential measured immediately after synchronous interruption of all sources of applied cathodic protection current

3.1.33

on potential (E_{on})

structure to electrolyte potential measured with the cathodic protection current flowing

3.1.34

permanent reference electrode

permanently buried or immersed reference electrode designed for a long life and installed close to the structure

3.1.35

polarisation

change in the potential of an electrode (e.g. structure) as the result of current flow to or from that electrode

3.1.36

potential gradient

difference in potential between two separate points in the same electric field

3.1.37

potential test probes

see External Potential Test Probe

3.1.38

protected structure

structure to which cathodic protection is effectively applied

3.1.39

protection current (I_p)

current made to flow into a metallic structure from its electrolytic environment in order to effect cathodic protection of the structure

3.1.40**protection potential**

structure to electrolyte potential for which the metal corrosion rate is acceptable

3.1.41**silver/silver chloride electrode**

measuring electrode consisting of silver, coated with silver chloride, in an electrolyte containing chloride ions

3.1.42**silver/silver chloride reference electrode**

reference electrode consisting of silver, coated with silver chloride, in an electrolyte containing a fixed concentration of chloride ions

3.1.43**standard hydrogen electrode**

reference electrode, used as a standard in laboratories, consisting of an inert metal, such as platinum, in an electrolyte containing hydrogen ions at unit activity and saturated with hydrogen gas at one standard atmosphere

3.1.44**structure**

metallic construction, whether coated or not, which is in contact with an electrolyte (e.g. soil, water)

NOTE The structure can represent a construction of great length, such as a pipeline, pipe networks, and underground electric cables, or well casings as well as construction on a smaller scale such as piles, sheet pilings, tanks or other underground constructions.

3.1.45**structure to electrolyte potential (also called electrode potential)**

difference in potential between a structure and a specified reference electrode in contact with the electrolyte at a point sufficiently close to, but without actually touching the structure

3.1.46**test probe**

see External Potential Test Probe

3.1.47**test station**

installation that provides measuring and test facilities for the buried structure. Such installations will include cabling and structure connections

3.1.48**zinc electrode**

measuring electrode made from sufficiently pure zinc

3.2 Symbols

I	Current
E	Potential
R	Resistance
J	Current density
U	Voltage
a	Year
a.c.	Alternating current
d.c.	Direct current

E_{Ag}	Metal to electrolyte potential with respect to a silver/silver chloride Electrode
E_{Cu}	Metal to electrolyte potential with respect to a copper/saturated Copper sulphate reference electrode
$E_{IR \text{ free}}$	IR free potential
E_{KCl}	Metal to electrolyte potential with respect to a silver/silver Chloride/saturated potassium chloride reference electrode
E_n	Free corrosion potential
E_{off}	Off potential
E_{on}	On potential
E_p	Protection potential
E_{Hg}	Metal to electrolyte potential with respect to a Mercury/calomel/saturated potassium chloride reference electrode
E_H	Metal to electrolyte potential with respect to a standard hydrogen reference electrode
E_{Zn}	Metal to electrolyte potential with respect to a zinc electrode
I_p	Protection current
I_s	Stray current
R_{co}	Coating resistance (Ω)
T	Temperature
t	Time
ρ	Resistivity ($\Omega.m$)

4 Buried structure to electrolyte potential

Criteria for cathodic protection are generally based on the value of the structure to electrolyte potential. Measurement of the potential is therefore necessary in order to assess the effectiveness of the cathodic protection. This subclause describes different potential determination methods.

4.1 Electrical equipment

The type and use of the instrument for measurement should be suitable for the prevailing electrical and environmental conditions (see annex H).

Instrumentation used for measurement shall be kept in good working order and shall be subjected to periodical calibration and safety checks.

4.2 Potential measurement

Since only bare metal (e.g. at the coating holidays) is likely to suffer significant corrosion, the measurement, indicating whether or not the protection potential E_p is fulfilled, would have to be made right on the metal/electrolyte phase boundary, e.g. metal/soil boundary (see EN 12954).

As this is not technically feasible, other techniques shall be applied to assess the effectiveness of cathodic protection. The most suitable one has to be selected on the basis of the local conditions in the field, e.g. coating type and quality, soil resistivity and presence of stray currents.

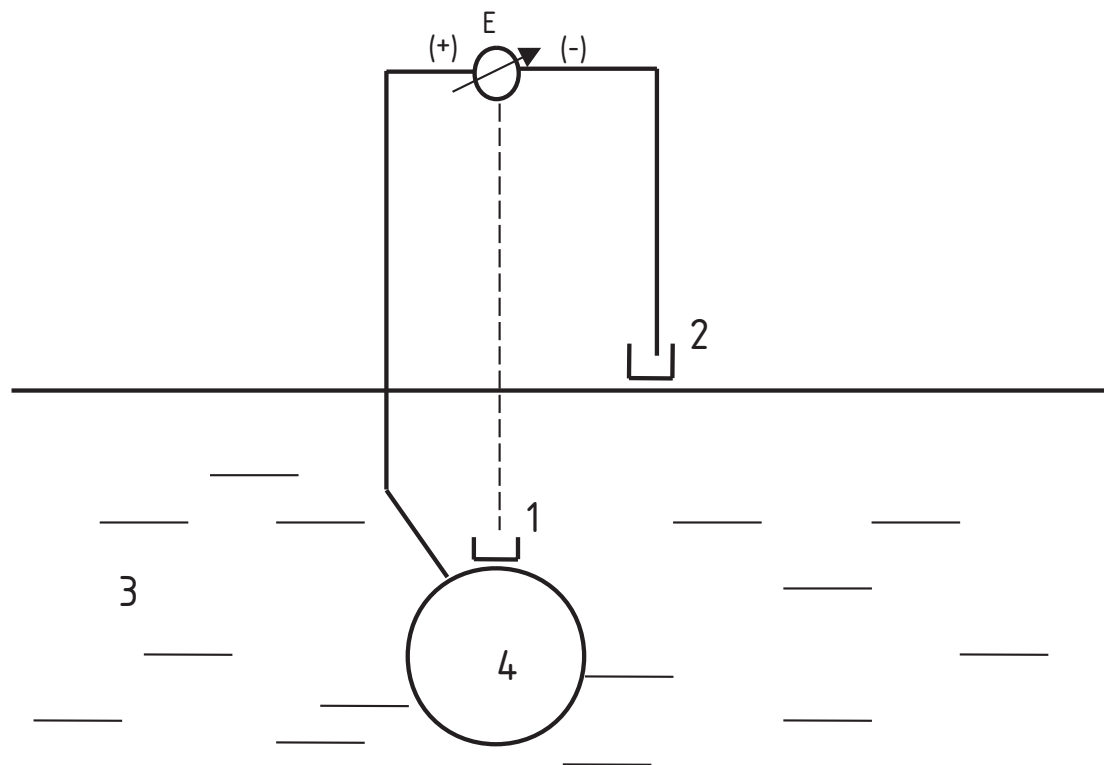
Generally, structures to electrolyte potentials are measured using a reference electrode placed on the soil surface (see Figure 1). Potential values of various normally used reference and measuring electrodes with respect to the standard hydrogen electrode are listed in annex A.

Saturated calomel electrode shall not be used in soil or water because, among other things, the risk of leakage of mercury from the electrodes.

In case of disbonded coating, potential measurement may give incorrect indications ¹.

4.3 Factors influencing the potential measurement

Figure 1 shows locations of reference electrodes for structure to electrolyte potential measurements.



Key

- 1 and 2 Reference electrode locations
- 3 Soil
- 4 Pipe

Figure 1 — Possible locations of reference electrodes for measurement of structure to electrolyte potentials

¹ Where water flows between a loose coating and the structure surface, the potential measured is not representative of the electrochemical phenomena that occur under the disbonded coating.

Disregarding minor errors, which are negligible in practice, the structure to electrolyte potential corresponds to the potential difference between the structure and the reference electrode at location (1), positioned in the immediate vicinity of the bare metal of the structure (e.g. at a coating defect of a coated structure). Since in practice, it is in most cases not possible to place the reference electrode so close to the metal of the structure, the structure to electrolyte potential is therefore measured as the potential difference between the structure and the reference electrode positioned at location (2).

In the presence of currents in the soil between (1) and (2), however, placing the reference electrode at location (2) will cause the measurement to be affected by errors. The value measured in this way differs from the value, which theoretically would be measured against the reference electrode positioned at location (1). The difference between the two potential measurements is equal to the algebraic sum of all the ohmic voltage drops (IR drops) in the soil between locations (1) and (2) due to currents flowing in the environment.

$$E_{(2)} - E_{(1)} = \sum IR \text{ drops}$$

Table 1 lists the different currents, which may cause IR drops.

In the case of cathodic protection currents from the structure's own protective systems, the potentials measured at location (2) are generally more negative than the potential at location (1). In low resistivity soils the IR drop caused by these currents may reach several tens of millivolts, while in high resistivity soils it may reach a few volts.

In the case of equalising currents, cell currents and stray currents, the potentials measured at location (2) may either be more negative or more positive than the potential at the location (1), according to the sense of currents. In soil, equalising currents and cell currents may cause IR drops of up to a few tens of millivolts and stray currents from d.c. traction systems may cause IR drops of up to a few tens of volts.

For all currents from foreign sources a distinction should be made, as to whether the potential gradient caused by these currents is nearly constant with distance in the vicinity of the structure to be protected (case of remote source) or not (case of nearby source). In addition, currents from foreign sources, which fluctuate rapidly with time, should be differentiated from those, which are constant with time. The burial depth of the structure also influences the IR drop.

Table 1 — Currents causing IR drops between the structure being protected and the reference electrode at location (2) in Figure 1 and examples of possible measuring techniques for determining the IR free potential for each type of current

Item No.	Type of current	Possible measuring techniques, e.g.	Subclause
1.	<i>Currents specific to the system</i>		
1.1	Protective current	Off potential measurement External potential test probe	4.4.2.1 4.4.2.4
1.2	Equalising current	Intensive measurement technique External potential test probe	4.4.2.3 4.4.2.4
1.3	Cell current (remote foreign electrodes)	Intensive measurement technique External potential test probes	4.4.2.3 4.4.2.4
2.	<i>Currents from remote foreign sources</i>		
2.1	Not fluctuating with time, e.g. protective currents, equalising or cell currents	Intensive measurement technique External potential test probes	4.4.2.3 4.4.2.4
2.2	Fluctuating with time, e.g. from d.c. traction systems, d.c. industrial plants, telluric current	Special off potential measurement Intensive measurement technique External potential test probes	4.4.2.2 4.4.2.3 4.4.2.4
3.	<i>Currents from nearby foreign sources</i>		
3.1	Not fluctuating with time, e.g. protective currents, equalising or cell currents	External potential test probes	4.4.2.4
3.2	Fluctuating with time, e.g. from d.c. traction systems or d.c. industrial plants	Special off potential measurements External potential test probes	4.4.2.2 4.4.2.4

4.4 Potential measurement techniques

4.4.1 Measuring technique including IR drop (on potential measurement)

Potential measurements conducted while the protective current is on are referred to as "on potential measurements". The values obtained (on potentials E_{on}) contain various unknown IR drops (see 4.2), which can change with time and position of the reference electrode. The readings do not reflect the potential at the metallic electrolytic phase boundary.

On potential measurements are mostly used for monitoring cathodic protection, particularly where stray currents from d.c. traction systems occur. In this case, in order to obtain meaningful values, on potentials should be recorded over a period of time consistent with the interference level and variation over time (see prEN 50162).

4.4.2 Measuring techniques to determine IR free potentials ($E_{ir\ free}$)

The following subclauses describe techniques, which may be applied to evaluate the IR free potential. They are differentiated by the type of current causing the IR drop (Table 1).

4.4.2.1 Off potential measurements (instantaneous off potential technique)

The instantaneous off potential technique may be used to eliminate IR drops caused by protective current (Table 1, item 1.1) where equalising currents, cells currents due to foreign anodes or foreign cathodes and stray currents are not present. The values obtained are referred to as off potentials, E_{off} .

For the steel/soil system, the potential measured against the reference electrode at location (2) in Figure 1 within one second after the protective current is switched off is usually sufficiently accurate. Depolarisation may occur relatively quickly for some metal/electrolyte systems, e.g. lead/soil, and for some steel structure where cathodic protection has been newly applied or the structure is bare. The current reduction technique described in annex B may be used in such cases.

The ratio between the "on" and "off" switching periods shall be chosen to avoid significant depolarisation. In this way, the longer the measurement campaign duration is (e.g. 24 h), the higher the ratio between the "on" and "off" periods shall be.

Close Interval Potential Survey (CIPS) described in annex C takes on/off pipe to soil potential measurements at regular intervals (about 1 to 2 m) along the pipe.

4.4.2.2 Special off potential measurements

In areas with stray currents from d.c. traction systems (Table 1, item 2.2 and 3.2), the off potential measurement technique may also be applied during intervals in which the d.c. traction system is not in operation. Based on these measurements, annex E describes the special off potential measurement technique, which helps to assess the effectiveness of cathodic protection in areas affected by stray currents.

4.4.2.3 Intensive measurement technique

The intensive measurement technique may be used to cover IR drops caused by currents noticed in Table 1, item 1.2 to 2.2 (equalising currents, cell currents, and, fluctuating or not fluctuating currents from remote foreign sources).

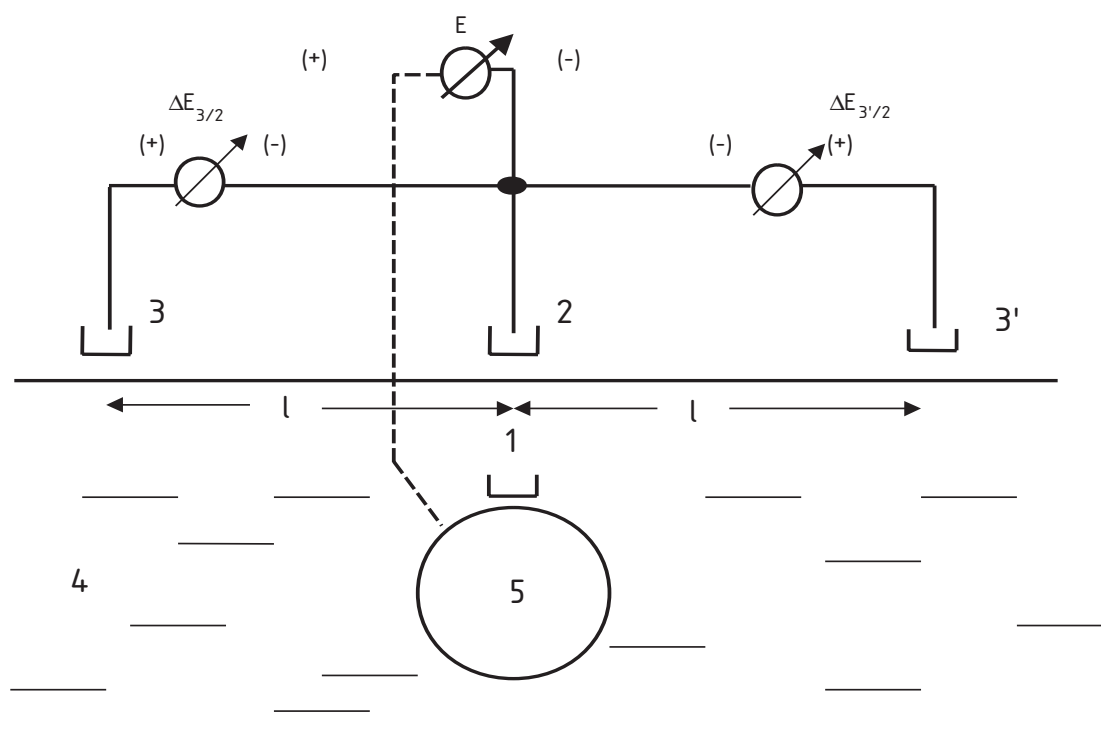
The intensive measurement technique measures simultaneously pipe to soil potentials and associated horizontally opposed potential gradients. The technique identifies coating defects and enables calculation of IR free potentials at the defects.

This technique can be applied only if the structure is within the linear part of the potential gradient caused by the foreign current (remote) source, i.e. where the potential gradients are constant with distance.

Intensive measurements are made to determine the IR free potential ($E_{\text{IR free}}$) at coating holidays detected by various methods (see annex D).

The technique involves measuring the pipe to electrolyte potentials, E_{on} and E_{off} , between the pipe and the reference electrode at location (2) in Figure 2 as well as the potential gradients, ΔE_{on} and ΔE_{off} , as the potential differences between the reference electrodes at locations (2) and (3). The readings obtained at appropriate distances along the pipeline route allow determining the IR free potential according to annex F. If the protection potential, E_p , is met at the largest coating holidays, it may generally be assumed that all other nearby holidays will be cathodically protected.

NOTE Location 3' is used to verify if potential gradients around the pipe are not symmetrical which can indicate the presence of foreign current source (as defined in Table 1, item 2.2), and/or heterogeneity of soil.



Key

- 1, 2, 3, 3' Reference electrode locations
- 4 Soil
- 5 Pipe

Figure 2 — Locations (1), (2), (3) and (3') of reference electrodes for measurement of structure to electrolyte potentials and potential gradients on, for example, a buried pipeline, via intensive measurement technique

The distance l between electrodes at location (2) and (3) should be selected to cover the total extent of the gradient.

4.4.2.4 Potential measurements for pipelines with external potential test probes or coupons

The potential measurement with external potential test probe or coupons may be used to cover IR drops caused by all currents noticed in Table 1 (protective current, equalising currents, cell currents, and fluctuating or not fluctuating currents from remote or nearby foreign sources).

External potential test probes will yield information on the IR free potential even in cases where the on or off potential measurement technique or the intensive measurement technique cannot be applied due to local conditions: (e.g. non conducting soil cover or greatly varying burial depth, new pipelines without holidays, fluctuating currents to Table 1, Item 2.2, or unavoidable contacts with foreign structures etc., where synchronous measurements of the variables relevant to the intensive measurement technique are not possible).

This technique consists of achieving IR free potential measurement by measuring off potential with the use of external potential test probe or coupon.

Example of typical external potential test probe and coupons are shown in annex G.

The distance between the reference electrode and the coupon should be as small as possible to enable a more accurate coupon to electrolyte potential measurement than when the reference electrode is placed at the ground surface. In this way the measurement is less influenced by stray current, which cause IR drops.

This technique is particularly useful if the structure is within the non-linear part of the potential gradient (where potential gradients are not constant with distance) caused by a (nearby) foreign current source.

The location of the external potential test probe shall be determined on the basis of detailed knowledge of the source of d.c. currents and soil homogeneity. The external potential test probe is placed preferably in the soil near the structure to avoid measuring errors caused by the heterogeneity of the soil e.g. in the same backfill as the structure.

To optimise the accuracy of measurement there should be no exchange of current between the coupon and the pipe, more precisely between the coupon and an adjacent coating defect or adverse effect from potential gradients when the coupon is disconnected from the pipe.

The external potential test probe is connected to the pipeline through a test station. In homogeneous soils, the pipeline could be regarded as cathodically protected over a short distance from the external potential test probe, if the protection potential, E_p , for the external potential test probe is met.

External potential test probe readings are only applicable to pipeline coating holidays not larger than the exposed surface area of the external potential test probe. An external test probe may also be used to determine whether the current is flowing to or away from the structure.

5 Immersed structure to electrolyte potential

If the basic principle concerning the potential measurements of an immersed structure is identical with that which is used for buried installations, the aqueous medium (fresh water, brackish or sea water) poses specific problems connected both with the measuring equipment employed and the difficulties in locating and reaching the surfaces to be checked.

5.1 Electrical equipment

The measuring equipment employed shall have the same electrical qualities as for buried structure measurements. In low resistivity waters it may be necessary, when measuring potential gradients, to have a measurement range in the order of 10 mV.

The electrodes used for potential measurements in an aqueous medium are listed in annex A.

5.2 Potential measurements

To carry out the potential measurements of the immersed parts of the structures, it is necessary to use one or more test stations.

5.2.1 Direct potential measurement methods

Direct potential measurements may be made if either of the following is used:

- A single test station above water situated on the part of the structure above the water, or distributed test stations fixed under water. The measuring electrode may be installed permanently or lowered from a vessel or installed by a diver and shall be in the correct position with respect to the structure.

- A temporary connection made by a measuring technician, for instance a diver, who establishes an electrical contact with the structure and carries out the measurements. This method may be used for structures, which have not been equipped with permanent test stations.

In these cases the same principles and similar methods may be applied as for buried structure measurements (see clause 4).

5.2.2 Indirect potential measurement method

This method may be used when it is desirable to carry out a continuous check of the structure to electrolyte potential.

For this purpose it is necessary to carry out a direct potential measurement according to subclause 5.2.1. The local potentials may then be determined by adding up the potential gradients measured between two reference electrodes, which are moved upon the immersed part of the structure (see Bibliography, reference 2 and 4).

6 Other measurements

6.1 Current measurements (d.c.)

Current can be measured/determined as follows:

- 1) With an ammeter e.g. at rectifier connections or at bonded isolating joints.
- 2) (In the case of pipelines) by determining the voltage drop between two test stations at a suitable distance from each other and the electrical resistance of the pipeline between the test station connections (see annex I, Figure 2). A variant of this method is to measure the current that is needed to reduce the voltage drop between the test stations to zero.
- 3) By determining the voltage drop across a shunt.
- 4) With a clamp/clip type ammeter.

The type and use of instrument for measurement should be suitable for the prevailing electrical and environmental conditions (see annex I).

6.2 Isolating joints

The ineffectiveness of an isolating joint may be due to different causes: a defective isolating joint itself, a contact between the structure under protection and an installation with a metallically conductive connection to the unprotected side, and, in the case of pipelines carrying electrolytic solutions, a degradation of the internal coating.

To determine the effectiveness of installed isolating joints, there are various measuring procedures that may be applied:

- **Structure to electrolyte potential measurements:** Structure to electrolyte potentials are measured on both sides of the isolating joint. If the potentials on both sides are different the isolating joint could be effective. However, a partly defective isolating joint may not be noticed since in this case the potential on both sides of the joint may also be different.

- **Resistance measurements:** These shall be carried out with an alternating current resistance meter. Direct current resistance meters give false indications due to polarisation effects.

The interpretation of resistance measurements at installed isolating joints is difficult because in the measuring circuit the resistance of the structures to earth and, in the case of pipelines carrying electrolytic solutions, the internal resistance of the pipeline to the electrolyte are parallel to the resistance of the isolating joint. So a low resistance is not always an indication that the isolating joint is defective (see annex J).

- **Impressed current tests:**

- * **Method 1:** To check the working of an isolating joint, current is impressed on the structure on one side of the isolating joint, possibly via a switcher. If the potential on the other side does not change or if it changes in the opposite direction (interference effect), the isolating joint is effective.
- * **Method 2:** The current through a bond across an isolating joint is measured. If there is no current, the isolating joint is defective. However, a partly defective isolating joint may not be noticed since in this case the current in the bond may not be zero (see annex K).

- **Audio frequency generator measurements:** These shall be carried out by injecting a suitable audio frequency on one side of the isolating joint, e.g. by a conventional pipe locator, and tracing the signal.

In case of doubt, a combination of two or more of the methods mentioned above can provide more certainty.

6.3 Foreign structures

Where possible contact between the protected structure and other metallic structure such as sleeves (casing), well casings and sheet piling may exist, this can be detected by measuring structure to electrolyte potential on both structures. Test stations may be installed to facilitate these measurements.

If necessary, the metallic separation can be verified by additional structure to electrolyte potential and/or resistance measurements and/or impressed current testing between the two structures. The same measurement techniques as described in 6.2 may be used (see also annex K).

6.4 Coating

The coating condition is related to the number and size of the coating defects.

Some methods to detect these coating defects are described in annex D.

There are also various methods that are used to make an evaluation of the average coating conditions by the measurement of potentials and currents and performing a calculation. Some formulae are in regular use and it is a matter of preference which formula is used (one formula can be found in the Bibliography, reference 4).

Annex A

(informative)

Table A.1 - Electrodes for Potential Measurements in Soil and/or Aqueous Media

Electrode	Phase constitution	Symbols commonly used for potential measurement	E_H^{**} (V)	Usual Application	Remarks
REFERENCE ELECTRODE					
Saturated calomel electrode	Hg/HgCl/KCl saturated	E_{Hg}^* E_{SCE}	+ 0,25	Laboratory	Soil and water for specific applications
Saturated silver/silver chloride electrode	Ag/AgCl/KCl saturated	E_{KCl}^* E_{SSE}	+ 0,20	Laboratory water	Soil for specific applications
Copper/saturated Copper sulphate electrode	Cu/CuSO ₄ saturated	E_{Cu}^* E_{CSE}	+ 0,32	Soil	Water only for short exposure time
MEASURING ELECTRODE					
Ag/AgCl electrode	Ag/AgCl/ sea water	E_{Ag}^*	+ 0,25	Sea water	Can be used in brackish water with a potential variation from + 0,25 (sea water) up to + 0,35*** (fresh water) Should be periodically verified
Zinc/sea water electrode	Zn/sea water	E_{Zn}^*	- 0,78	Sea water	After 2 days of immersion
* These symbols are used in European Standards ** E_H is the potential of the reference or measuring electrode with respect to the standard hydrogen electrode. Example: Protection potential for carbon steel : $E_{p,H} = -0,53V$; $E_{p,Cu} = -0,85V$ *** These potentials change with the chloride ion concentration; the variation is about 60 mV for each 10-fold change in concentration. The environmental impact of mercury (calomel electrode) has to be taken in account according to national regulation.					

Annex B (informative)

Current reduction technique

The current reduction technique is used to determine the structure to electrolyte potential when the instantaneous off potential technique described in 4.4.2.1 is difficult to carry out because of rapid depolarisation of the structure.

In this technique the protective current (I_p) is not switched off but only reduced to a value (I_{red}) chosen in such a way that the structure depolarisation cannot occur too quickly. Only the IR drops developed in the electrolyte should change according to the current. The ratio of the currents is given by:

$$x = \frac{I_{red}}{I_p} \quad \text{B.1}$$

where $0 < x < 1$

The ON potential corresponding to $I_{(p)}$ is noted E_{on} .

The Instantaneous potential corresponding to I_{red} is noted E_{red} .

In such conditions the structure to electrolyte potential (E) calculated by extrapolation is given by:

$$E_{IRfree} = \frac{E_{red} - x \cdot E_{on}}{1 - x} \quad \text{B.2}$$

It can be verified that for $x = 0$ the equation B.2 includes the off potential measurement.

For the determination of the factor x in equation B.2 it is important to carry out current measurements, which is not always feasible. Yet, it can be noted that the value of x can be also determined by the ratio of transversal potential gradients.

$$x = \frac{I_{red}}{I_p} = \frac{\Delta E_{red}}{\Delta E_{on}} \quad \text{B.3}$$

with :

$$\begin{aligned} \Delta E_{red} &= E_{red} - E_{IRfree} \\ \Delta E_{on} &= E_{on} - E_{IRfree} \end{aligned}$$

The gradients ΔE_{on} and ΔE_{red} are measured at the surface of the soil above the structure and at the same time of the potential measurements (E_{on} and E_{red}).

In such conditions, the structure to electrolyte potential is given by:

$$E_{\text{IRfree}} = E_{\text{red}} - \frac{E_{\text{on}} - E_{\text{red}}}{E_{\text{on}} - \Delta E_{\text{red}}} \Delta E_{\text{red}} \quad \text{B.4}$$

By using the equation B.4, there is no need for current measurements to determine the structure to electrolyte potential.

This method cannot be used in presence of stray currents.

Annex C **(informative)**

Above ground surveys used to measure pipe to soil potential along a buried pipeline

Close Interval Potential Survey (CIPS)

The most enduring method of assessing the effectiveness of cathodic protection is by the measurement of pipe-to-soil potentials.

Although test posts are distributed along the length of the pipeline there is always the possibility that the cathodic protection may be ineffective at some point between test posts.

Close Interval Potential Surveys take pipe-to-soil potential measurements at intervals of about 1 to 2 m. The measurement is associated with a time and a distance, so that the location of the measurement can always be resolved. For this the operator unwinds behind him over a long distance a very fine electric wire (disposable or not) connected to the pipeline via a test station.

In order to achieve a realistic pipe-to-soil potential the IR drop should be reduced to an insignificant level. To do this it is important to synchronously interrupt the sources of applied d.c. current to the pipeline that effect the potential of the pipeline at the specific location of the measurement. Synchronous interruption can be achieved by the use of synchronized cyclical switchers.

This method cannot be used in presence of stray currents.

There is a wide range of proprietary devices available for taking the close interval pipe-to-soil potentials with varying degrees of accuracy. Whichever measurement system is chosen it should have the ability to either be synchronized to the switchers, or have the ability to accurately select the time at which a reading is taken.

Data is usually presented as a graph showing on and off potentials against distance.

Annex D (informative)

Above ground surveys used to assess the coating condition and to locate coating defects

Coating defects can be located either by a.c. or d.c. signal measurements. Two of the most well known are Pearson (a.c.) and D.C.V.G. (d.c.). These are described below.

NOTE Poor results can be obtained if ground contact of the pipeline is not sufficient.

Pearson Survey

The Pearson Survey depends upon the injection of an alternating frequency signal onto a buried pipeline that can be detected by an above ground detection system that is specially configured to receive signals at the injected frequency.

The selection of the frequency will depend upon the type of coating that the buried pipeline has.

The Pearson Survey system detects the signals that are emitted from the buried structure. The strength of the emitted signal will vary according to location and size of coating defects.

The transmitter is usually connected to the pipeline via an existing test post. In some cases the transmitter signal can be induced into the pipe, which obviates the necessity for a test post connection.

The survey is conducted by two operators walking along the route of the pipeline, one behind the other. The distance between them depends on the diameter of the pipeline and can be 6 m to 12 m.

As the leading operator approaches a coating defect the signal will gradually increase and peak as he passes over the defect. The signal will gradually reduce to a null when the defect is midway between the two operators.

Direct Current Voltage Gradient Survey (DCVG)

DCVG surveys are carried out on buried pipelines to locate and assess the severity of coating defects.

The system works by the application of a cyclically switched d.c. current to the pipeline and measurement of the magnitude and direction of the voltage gradients in the soil.

Either an existing or a temporary impressed current system is used as a source of d.c. current to the pipeline. The d.c. source is interrupted cyclically, usually about 0,66 s off and 0,33 s on. This provides a rapidly pulsing d.c. source that can be easily identified with an analogue millivoltmeter.

Special measurement instruments are required that are able to respond to the rapidly changing voltage. The analogue instrument is centre zeroed so that the direction, as well as the magnitude, of the pulsing d.c. voltage can be measured.

The d.c. voltage gradients are measured by placing reference electrodes on the ground about 1 m to 1,5m apart. The operator usually walks parallel to the pipeline, placing the reference electrodes on the ground about every 2 m, and observing the analogue instrument indication.

When the d.c. current flows to a coating defect the potential gradient in the soil will change, becoming greater as the defect is approached, and decreasing to zero when the epicentre of the coating defect is mid-way between the two reference electrodes.

There are many variations that can be applied in the field, and the correct interpretation of the measured data is dependent upon the competence of the operator.

General remark

Depending on local conditions and the structure itself, it is possible to apply:

- Methods, which are modifications of Pearson Survey and DCVG methods;
- Other principles such as induction or attenuation of alternative frequency signal.

Annex E

(informative)

Special off potential measurements in stray currents areas

In the presence of stray currents, off potential measurements for determining IR free potentials can only be performed for an adequate period of time in the absence of railway traffic (e.g. during the night). The influence of equalising and/or cell currents is taken into consideration when fixing the base value.

The following technique involving on and off potential measurements helps to assess the effectiveness of cathodic protection in areas affected by stray currents.

Potential measurements should be performed as follows:

- On potential should be recorded over a period of time consistent with the interference level (e.g. 24 h) at those measuring points, which are most critical from a cathodic protection point of view.
- The off potential measurements should be performed at the same measuring points for a suitable period of time when there is no railway traffic. The off potential values obtained should be considered as the base values.

At these measuring points a more negative value than the protection potential, E_p , should be maintained by the cathodic protection system (see EN 12954).

At the measuring points a more negative value than the protection potential, E_p , should be maintained (see EN 12 954).

Corresponding on potential values shall be taken into account to satisfy the following requirement:

The on potential values recorded over a period of time consistent with the interference level (24 hours) should always be more negative than the on potential value measured when there is no railway traffic, even in the presence of stray currents.

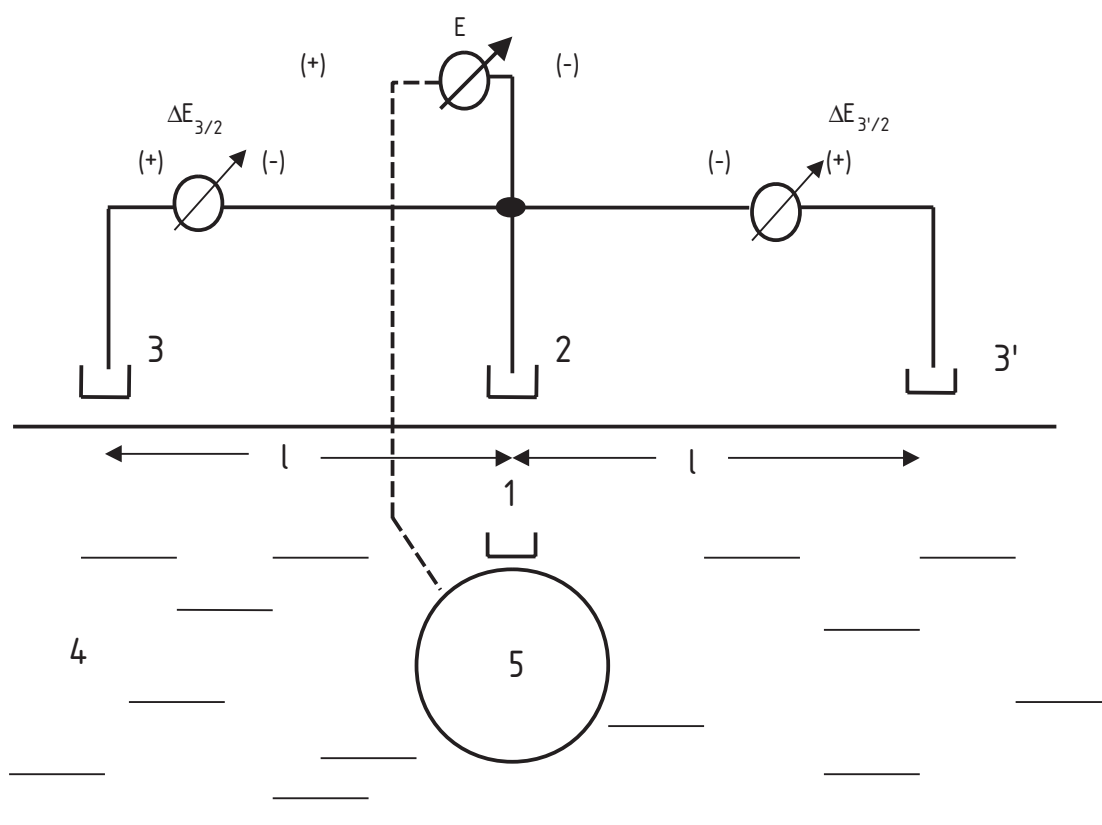
The potential at the most critical measuring points shall be verified from time to time throughout the life of the structure.

The potential at the most critical measuring points should be verified from time to time throughout the life of the structure.

Annex F (informative)

Explanatory note on the use of the intensive measurement technique and the calculation of the IR free potential ($E_{\text{IR free}}$)

The intensive measurement technique involves simultaneous measurements of two or three electrodes, one over the structure and one or two remote. The technique can provide both coating defect location and IR free potential measurement.



Key

- 1, 2, 3, 3' Reference electrode locations
- 4 Soil
- 5 Pipe

Figure F.1 — Locations (1), (2), (3) and (3') of reference electrodes for measurement of structure to electrolyte potentials and potential gradients on, for example, a buried pipeline, via intensive measurement technique

Detection of coating holidays:

Using this method coating holidays are detected where $\Delta E_{\text{on}} - \Delta E_{\text{off}}$ peaks are measured along the pipeline route. The absolute value of $\Delta E_{\text{on}} - \Delta E_{\text{off}}$ depends on many factors and under the same conditions is proportional to the size of a coating holiday. Usually these measurements are carried out at a distance of approximately 5 m along the pipe.

Calculation of the IR free potential:

For $\Delta E_{on} > \text{approx. } 20\text{mV}$, the measured values obtained generally allow calculating the IR drop in the soil between locations (1) and (2) in Figure F.1. Hence, the equation for determining the IR free potential is

$$E_{IRfree} = E_{off} - \frac{\Delta E_{off}}{\Delta E_{on} - \Delta E_{off}} (E_{on} - E_{off}) \quad \text{F.1}$$

- **In the presence of equalising currents (Item 1.2 in Table 1) and cell currents from remote foreign electrodes as defined in Table 1, Item 1.3 (see 4.3.):**

The potential gradients will be approximately symmetrical to the pipeline. Therefore it will be sufficient to determine the potential difference between the reference electrodes at locations (2) and (3) or (2) and (3') for determining the ΔE values.

- **In the presence of currents from remote foreign sources - fluctuating and not fluctuating with time - as defined in Table 1, Item 2, (see 4.3.):**

The potential gradients will be no longer symmetrical. The potential gradients caused by coating holidays will then be the mean values of the potentials between the reference electrodes at locations (2) and (3) and at locations (2) and (3'), arranged symmetrically with the distance 'l' in Figure F.1 being the same on both sides.

$$\Delta E = \frac{1}{2} \cdot (\Delta E_{3/2} + \Delta E_{3'/2}) \quad \text{F.2}$$

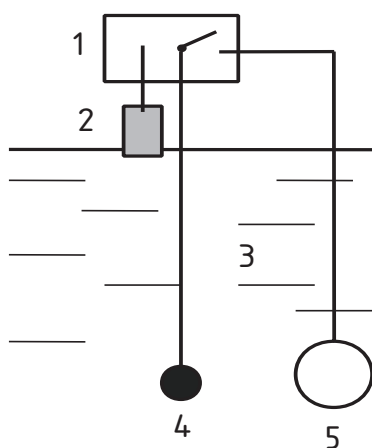
- *In the presence of "current from remote foreign sources - fluctuating with time e.g. d.c. traction systems, industrial plants, telluric current" as defined in Table 1, Item 2.2:*

The E and ΔE readings should be taken simultaneously, both for the "on" and the "off" period.

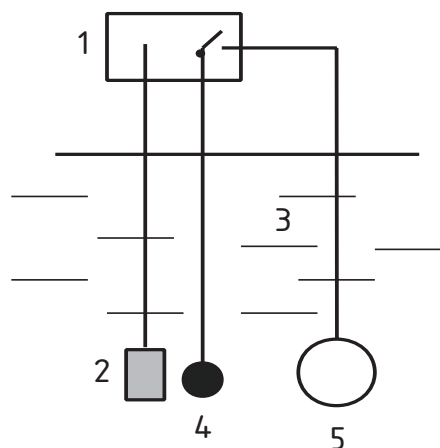
With regard to equation (F.1), it should be noted that unmatched reference electrode potentials may lead to errors when determining IR free potentials.

Annex G (informative)

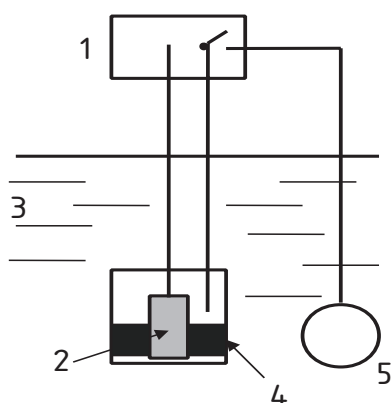
Examples of typical coupons and external potential test probe for pipe



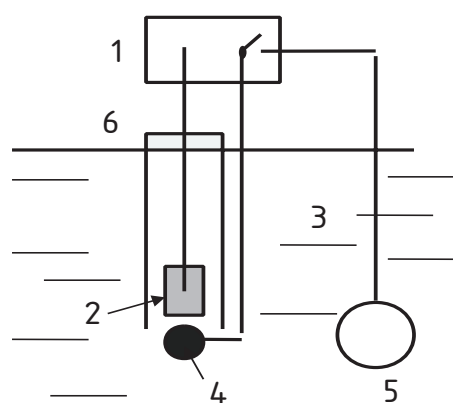
a) Scheme of a coupon with reference electrode on surface



b) Scheme of a coupon with permanent reference electrode



c) Scheme of an external potential test probe



d) Scheme of a coupon with removable reference electrode

Key

- 1 Test post
- 2 Reference electrode
- 3 Soil
- 4 Coupon
- 5 Pipe
- 6 Caps (Figure 'd' only)

Annex H (normative)

Accuracy of potential measuring equipment

It is a fundamental requirement of any measuring instrument that it should not cause unacceptable changes to the circuit being measured. It shall be chosen to be well adapted to the circuit to be measured.

Any measure realized with a measuring instrument comprises the possibility of several errors, which shall be evaluated. They could be:

- Errors due to the internal resistance of the instrument;
- Reading errors with analogue instruments;
- Errors due to the instrument itself and given by the manufacturer of the instrument;
- Errors due to environmental conditions (temperature, hygrometry conditions, presence of magnetic fields.)

VOLTMETERS

There are two kinds of d.c. voltmeters, analogue and digital instruments, both of which can be used in the field for structure potential measurements.

Nevertheless, where fluctuating stray currents affect the soil or the structure to control, it can be preferable to use an analogue voltmeter to follow the potential variations or if necessary to record the latter with an analogue or digital recorder.

Where a.c. interference due for instance to the presence of high voltage electric power lines affects a pipeline, it is possible to read fluctuating or trembling values with analogue d.c. voltmeters or non-consistent values with digital instruments. To avoid this inconvenience, it is recommended to use a digital d.c. voltmeter having a.c. attenuation for 16 and 50 Hz of at least 60 dB.

The intrinsic error of the instrument is the maximal measurement error guaranteed. It can be expressed in two ways according to the type of instrument:

- For an analogue instrument the error is expressed in per cent of the full scale (for an instrument noted class 1,5 the maximal error on a 10 volts scale is 150 mV);
- For a digital instrument the error is expressed in per cent of the reading plus 1 digit, (for a 1 % accuracy instrument, the maximal error on a reading of 1,000 volt is 11V).

The precision of a potential measurement depends also on the input resistance/impedance of the instrument. The value of this resistance should be at least equal to 1 M Ω for potential measurement for underground structures. For low resistivity medium (e.g. brackish or sea water) a lower value is acceptable.

- For analogue d.c. voltmeters the input (or internal) resistance is generally variable and depends on the chosen scale. This resistance expressed in ohm per volt of the full scale can reach 250000 Ω/V in modern instruments. A way to verify the accuracy of an analogue voltmeter is to carry out one measurement with two different scales. The values shall be identical.
- For digital d.c. voltmeters the input impedance, expressed in ohms, is constant. Therefore the accuracy of the measurement is independent of the chosen scale. For modern instruments the input impedance often exceeds 10 M Ω .

Digital voltmeters can produce many readings every second (4 generally). So, there is a risk of a non-consistent reading when measuring a fluctuating potential (reading on peak voltages, off potential at protective current interruption, stray currents...) In this case, it is recommended to repeat the measurement to detect a possible measurement error.

However, the instrument shall be able to make more than one measurement per second to pick up the OFF potential value (as described in 4.4.2.1)

The instrument used for potential measurement should have an accuracy:

- For digital instrument, of less than 1 % of the reading,
- For analogue instrument, of less than 2 % of the full scale deflection (F.S.D.)

REFERENCE AND MEASURING ELECTRODES:

The reference and measuring electrodes should be chosen in agreement with annex A.

They should be constructed in such a manner that their potential is not affected during voltage measurements.

The reference and measuring electrodes should be regularly verified by comparing with reference electrodes specially used for this purpose.

Annex I (informative)

Accuracy of current measurement

Current measurements can be made either by means of direct measurement of a shunt potential or by means of a clamp/clip ammeter to determine the current flow.

The voltage drop due to the current measurement should not exceed 10 mV whether the measurement is a direct one or made by means of an external shunt.

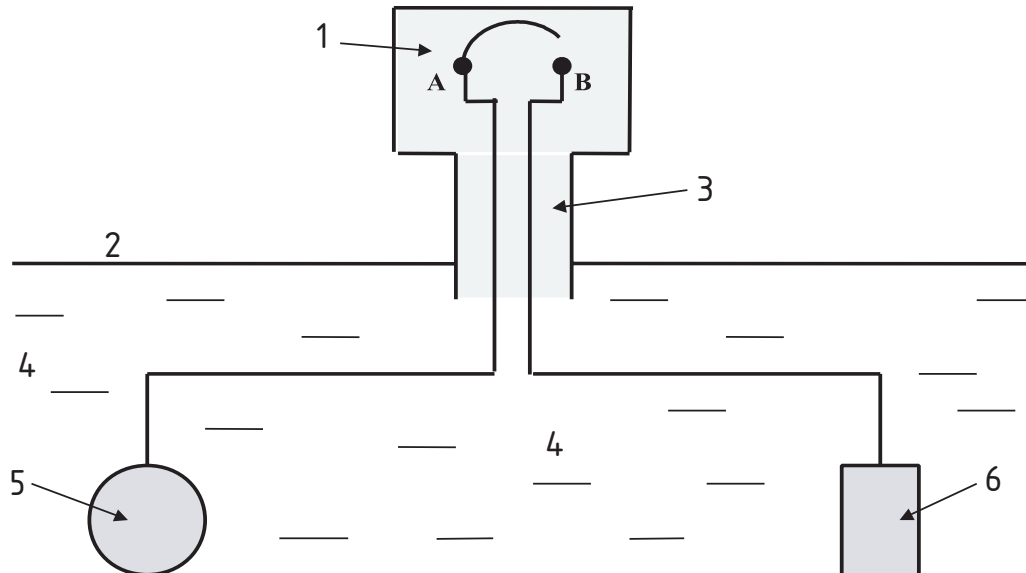
NOTE The selection of the shunt value, whether it is internal or external to the measuring instrument, should take into consideration the likely effect of the inclusion of the shunt resistance in the circuit to be measured.

The accuracy of the measurement should be better than 2,5 %.

Clamp/clip ammeters should be carefully selected and operated to provide acceptable levels of accuracy.

The same considerations for the voltage measuring instrument detailed in annex H should be utilised for shunt potential measurements.

In special circumstances when low current measurements are required to be made in low voltage circuits, then the principles and circuits shown in Figures I.1 and I.2 can be used, providing that there are no stray currents present. Alternatively a zero resistance ammeter can be used.



Key

- 1 Bond
- 2 Ground level
- 3 Test station
- 4 Soil
- 5 Structure (pipeline)
- 6 Secondary structure (Galvanic anode)

Figure I.1 — Method for determining true current flow in very low voltage circuits

Procedure

1. Remove bond between terminals A and B
2. Measure voltage across AB with high impedance millivoltmeter (U_1).
3. Connect ammeter across AB and measure current (I).
4. Measure voltage across AB with ammeter still connected (U_2).

$$\text{True Current} = I \cdot \frac{U_1}{U_1 - U_2} \quad \text{I.1}$$

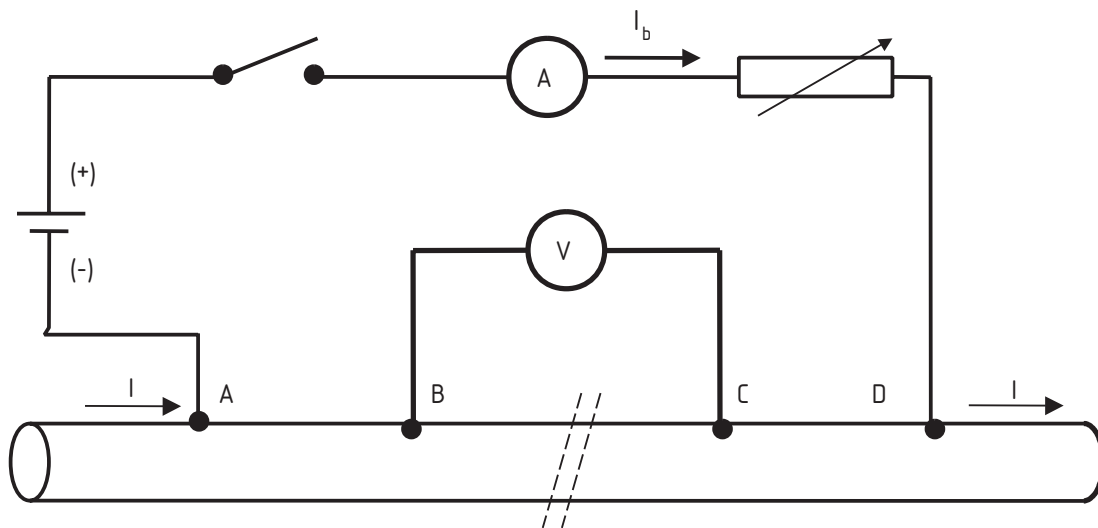


Figure I.2 — Measuring circuit for determining the line current and the longitudinal resistance of a pipeline

Determination for the line current

If current I_b is adjusted to give no deflection on the micro voltmeter, then $I_b = I$.

Determination of longitudinal pipeline resistance

Cables to pipe connection points A and B , and, C and D are located at an interval of minimum 10 cm. Typical values are often chosen between 2 diameters and 5 diameters. The interval between points B and C can reach 100 m.

Current (I_b) is applied to the pipeline section between points A and D using a power source (battery), and the voltage (U) is measured between points B and C . In order to avoid interference caused by other currents flowing through the pipeline as well as contact voltages, the power source is switched on and off and the voltage (ΔU) and the current (ΔI_b) are used for calculation purposes. The longitudinal resistance between B and C is then determined using the following equation:

$$R_{BC} = \frac{\Delta U}{\Delta I_b} \quad \text{I.2}$$

Annex J (informative)

Evaluation of the resistance of isolating joints

When resistance measurements are carried out on installed isolating joints, the measured circuit also includes the resistances/impedances of the structures to earth.

A low resistance is not always an indication that the isolating joint is defective.

The following resulting resistance " R_r " is measured:

$$1/R_r = 1/R_{iso} + 1/(R_{co1} + R_{co2}) \quad \text{J.1}$$

Where: R_r = resulting resistance/impedance.

R_{iso} = resistance of the isolating joint.

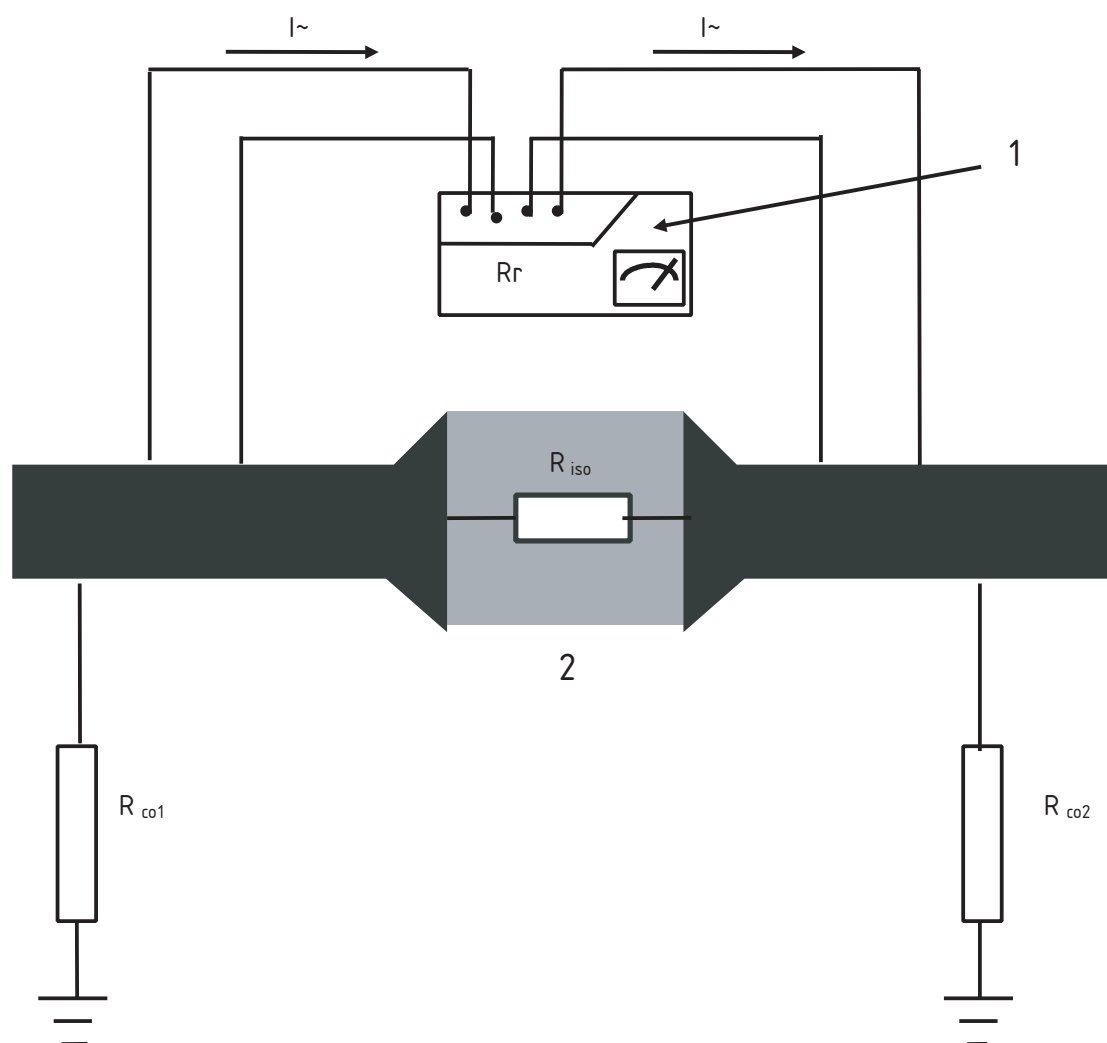
R_{co1} = resistance to earth of the structure on one side of the isolating joint.

R_{co2} = resistance to earth of the structure on the other side of the isolating joint.

The resistance of the isolating joint " R_{iso} " is calculated from equation J1.

If direct current is used, the resistance to earth of the structures will change because the structures polarise. To avoid this, alternating current is used.

If the method with two test leads is used, the measured value includes the resistance of the test leads. To eliminate the resistance of the test leads, the method shown in Figure J.1 should be used.



Key

- 1 Four terminals a.c. ohmmeter
- 2 Isolating joint

Figure J.1 — Resistance measurement of an isolating joint with a four terminals a.c. ohmmeter

Annex K (informative)

Current injection test on isolating joints

In order to distinguish between a defective isolating joint itself and short circuiting caused by an unknown metallicity connection, measurements can be carried out in an excavated area with the circuits depicted in Figures K.1 and K.2.

In case of an effective isolating joint, the current is as follows:

$$I_1 = 0 \Rightarrow \Delta U_1 = 0$$

Once the current I is circulating and $\Delta U_1 = 0$, there is a possibility of an external metallic contact.

(Figure K.1)

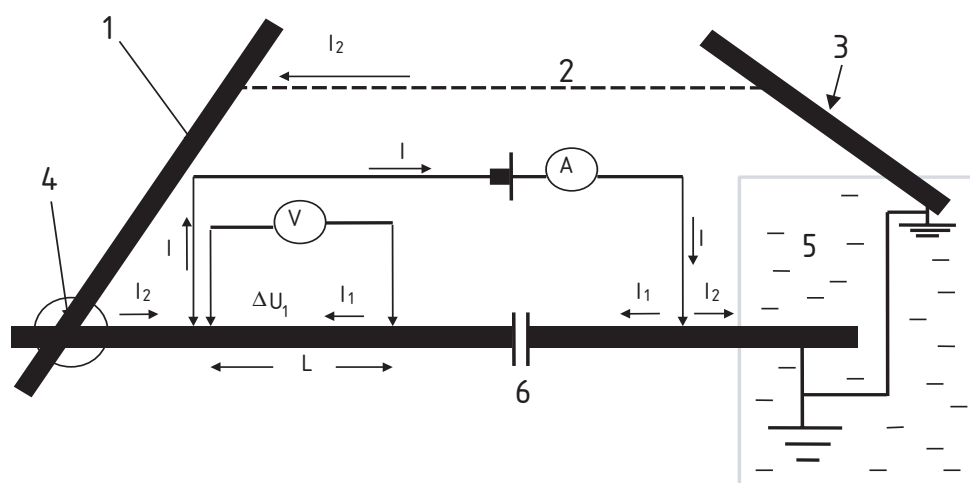
A countercheck to prove that an isolating joint is effective can be made using the circuit depicted in Figure K.2.

The current I_2 shown in the equation K.1 below,

$$I_2 = \frac{\Delta U_2}{R' L} \quad \text{K.1}$$

should then correspond to the injected current I . In such a case, the metallicity connection between the structure under protection and the foreign structure should be identified. In the above equation, R' corresponds to the pipeline's longitudinal resistance per meter.

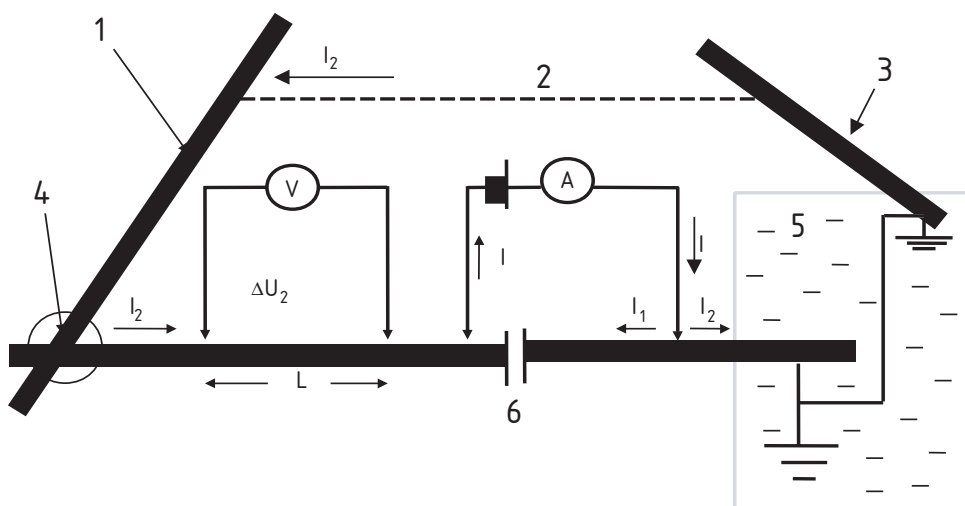
This method can be adapted to confirm the electrical separation between metallic structures.



Key

- 1 Foreign structure
- 2 Unknown electrical path (duct or soil)
- 3 Foreign structure
- 4 Metallically conductive connection
- 5 Soil
- 6 Isolating joint

Figure K.1 — Circuit for checking an excavated isolating joint (inner circuit)



Key

- 1 Foreign structure
- 2 Unknown electrical path (duct or soil)
- 3 Foreign structure
- 4 Metallically conductive connection
- 5 Soil
- 6 Isolating joint

Figure K.2 — Circuit for checking an excavated isolating joint (outer circuit)

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EN 12696, Cathodic protection of steel in concrete.

The following is a non-exhaustive list of different basic European documents known and accepted as good guides for the application of cathodic protection techniques.

[1] Practical guide for cathodic protection
Author: CEOCOR

Edited in 1991 by expert verlag, 71139 Ehningen bei Böblingen, Germany.

Title: Praktischer Leitfaden für den Kathodischen Korrosionsschutz.

Edited in 1991 by AGHTM, 83 Avenue Foch, 75761 Paris Cedex 16, France.

Title: Guide Pratique de la protection cathodique.

[2] Guide of the measuring techniques in cathodic protection
Author: CEOCOR

Edited in 1994 by ÖVGW, A 1015 Vienna, Schuberting 14, Austria.

Title: Leitfaden der Messtechnik für den kathodischen Korrosionsschutz.

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Title: Guide des techniques des mesures en protection cathodique.

[3] Water and gas mains - Corrosion, degradations and protection
Author: Association Générale des Hygiénistes et Techniciens Municipaux (A.G.H.T.M.)

Edited in 1987 by LAVOISIER, 11 rue Lavoisier, 75384 Paris Cedex 08, France

Title: Les canalisations d'eau et de gaz - Corrosion, dégradation et protection.

Edited in 1992 by ELLIS HORWOOD, Market cross house, Cooper Street, P.O.

Box. 19, Chichester, West Sussex 1EB UK.

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[4] Handbook of cathodic protection
Authors: W.v. Baeckmann, W. Schwenk, W. Prinz

Edited in 1989 by VCH Verlagsgesellschaft mbH, 69469 Weinheim, Germany

Title: Handbuch des kathodischen korrosionsschutzes.

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Title: Protezione Catodica

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Authors: G. Bianchi, F. Mazza

Edited in 1980 by MASSON ITALIA EDITORI, via G. Pascoli 55, 20133 Milan, Italy

Title: Corrosione e protezione dei metalli.

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