BS EN 15112:2006

External cathodic protection of well casings

The European Standard EN 15112:2006 has the status of a British Standard

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October 2011

ICS 23.040.99; 77.060

British Standards

National foreword

This British Standard was published by BSI. It is the UK implementation of EN 15112:2006. It partially supersedes BS 7361-1:1991. BS 7361-1:1991 "*Cathodic protection — Part 1: Code of practice for land and marine applications*", which provides general information on cathodic protection, will be withdrawn when all the CEN standards relating to cathodic protection currently being prepared are published.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.

A list of organizations represented on GEL/603 can be obtained on request to its secretary.

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External cathodic protection of well casings

Protection cathodique externe des cuvelages de puits

Äußerer kathodischer Korrosionsschutz von Bohrlochverrohrungen

This European Standard was approved by CEN on 19 June 2006.

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Foreword

This document (EN 15112:2006) 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of an identical text or by endorsement, at the latest by January 2007, and conflicting national standards shall be withdrawn at the latest by January 2007.

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

Introduction

Gas, oil and water well casings are usually cemented for the proposes of anchoring the pipes in the borehole and isolating the various geological layers from each other. This is necessary to avoid liquid exchanges between these.

Steels in contact with the cement are in a passivation status and, thus, protected from any kind of external corrosion, except if the cement contains chloride ions. However, it is not always possible to obtain a continuous cementation on all the external steel surfaces. These bare residual surfaces may be in contact with more or less aggressive layers. Furthermore, these surfaces may constitute electrochemical cells with the cemented metallic parts. The anodic areas, which are the poor cemented parts, correspond to corrosion areas.

In general, external corrosion effects are rare, particularly on recent wells, since most of them are well cemented. However, borehole cementation programmes sometimes result in cementation failures, and studies have shown that, corrosion phenomena being progressive, the mean time for the appearance of leaks is dependent on different factors such as geological formation, thickness of the layers and of the steel casing.

Experience has also shown that the situation may be significantly improved by applying external cathodic protection to wells.

Environmental aspects with regard to gas, oil or water wells should be considered when deciding on whether or not to apply cathodic protection.

1 Scope

This European Standard specifies methods used to evaluate the external corrosion hazards of well casings, as well as cathodic protection means and devices to be implemented in order to prevent corrosion of the external part of these wells in contact with the soil.

This European Standard applies to any gas, oil or water well with metallic casing, whether cemented or not.

However, in special conditions (shallow casing: e.g. 50 m, and homogeneous soil), EN 12954 can be used to achieve the cathodic protection and assess its efficiency.

This European Standard also describes techniques allowing determination of the current required for protection and ensuring correct operation of the cathodic protection devices installed.

2 Normative references

The following referenced documents are indispensable for the application 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.

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

EN 60079-10, *Electrical apparatus for explosive gas atmospheres — Part 10: Classification of hazardous areas (IEC 60079-10:2002)*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in EN 12954 and the following apply (see also Figure 1).

3.1
casing (or well casing)
heavy steel pipe string used to line a borehole from the ground surface, and secured in the formations generally by cementing

NOTE Casing is generally externally cemented over its total depth or over a length sufficient to obtain anchoring and stability between the production or storage zone and the ground surface or other intermediate layers.

This pipe string allows:

- to prevent the ingress of fluid from upper strata;
- to keep the hole from collapsing due to the pressure of the geological layers crossed;
- to isolate the inside part of the well from the surrounding soil;
- to continue drilling to the production or storage zone;
- to drive down the tubing string from the surface to the production or storage zone.

There may be two or more strings of casing, one inside the other, in a single well:

- surface casing: casing that extends from the surface to a depth sufficient to avoid any entering of surface waters or earth into the well;
- intermediate casing: casing set from the ground surface down to an intermediate depth. This intermediate depth is situated between the surface casing shoe and the production or storage zone;
- production casing: casing that extends through the surface casing and intermediate casing to the production or storage zone. The extremity of the production casing can be at the top or bottom of this zone.

3.2
cellar
excavation at ground surface, intended for housing the wellhead and safety shut-off devices.

EXAMPLE safety valves

3.3
cementation
process, and its result, which ensures the anchoring of well casing in the borehole and the tightness between different geological levels.

NOTE In the same time, this cementation can mitigate corrosion

3.4
centralizer
device constituted by a set of metallic blades which are fitted around the pipes of a string to keep them centred, either in the open hole (hole drilled in the ground), or inside pipes of larger diameter in which the considered string is installed. This device can also be used to ensure electrical continuity between the two concentric pipe strings

3.5
completion
process, and its result, which consists of fitting a well with the tubing to allow well operation in accordance with the applicable codes of practice and safety rules

3.6
flow-line
pipe connecting a well to a station

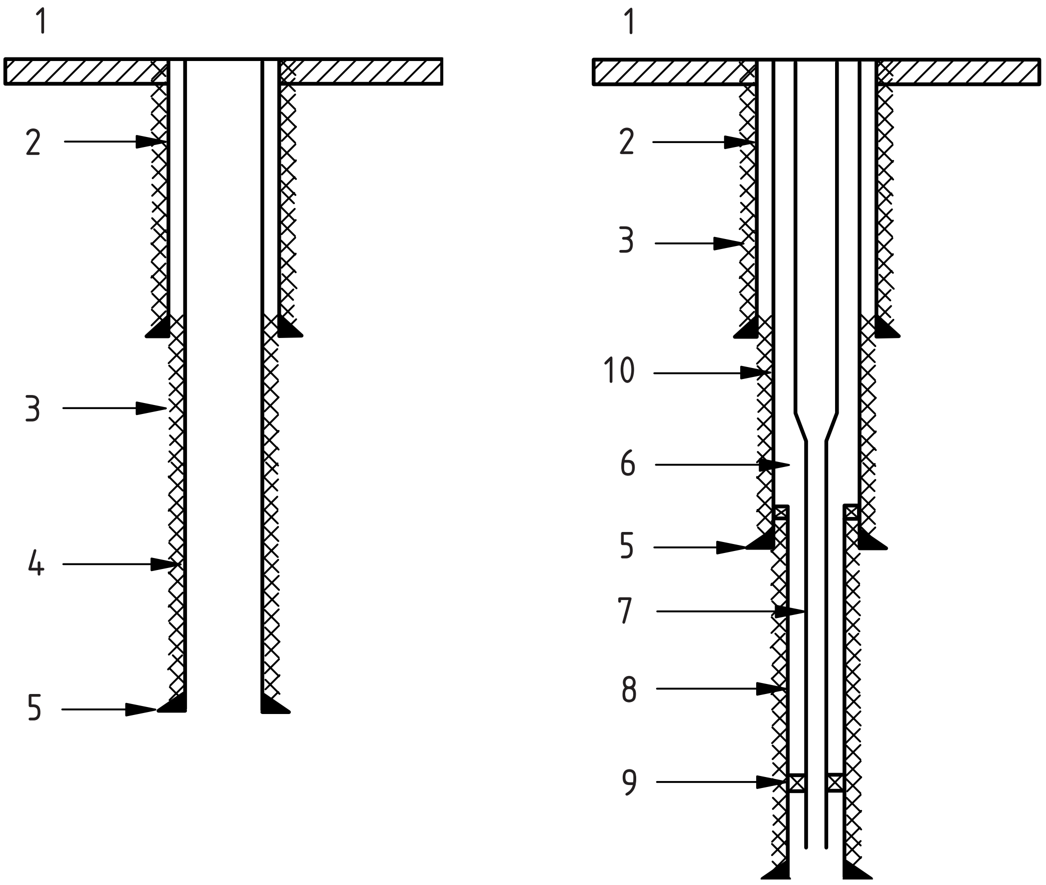
3.7
liner (bottom hole)
pipe having the same function as the casing but hung inside a casing (or another liner) and not at the wellhead like a conventional casing

3.8
packer (production)
device ensuring tightness of a pipe annulus. The production packer seals the annulus between the tubing and the production casing or liner

3.9
shoe
cylindrical element attached to the lower part of the casing, and allowing to place the casing in the borehole (guide shoe). If equipped with a valve, it makes easier the borehole cementation (cementing shoe)

3.10
tubing (production tubing)
pipe string, with its additional equipment, inside the production casing to allow the flow of oil, gas or water between the production or storage zone and the ground surface

3.11
wellhead
device installed at the top of the well, designed to hang the different pipe strings and to ensure tightness between the various annular spaces. The wellhead is fitted with valves to allow access (pressure monitoring, sampling) to the different annuli. Such fitted wellhead allows well operation and the intervention on the different components of the well. This device allows a good electrical continuity between all the pipe strings



Key

1 ground surface
2 surface casing
3 cementation
4 production casing
5 shoe
6 production annulus
7 tubing
8 liner (bottomhole)
9 packer (production)
10 intermediate casing

Figure 1 — Typical well completion equipment

4 Description and assessment of corrosion risks

4.1 General

Corrosion may occur on the external surface of well casings.

This corrosion, if not controlled, may lead to harmful damage such as losses of products, water, gas or oil, damage to the well and its completion (internal equipment), damage to the environment, for instance in allowing exchange between different geological formations. There is also the possibility of harm for people living near such installations.

The risks of corrosion should be considered in order to decide if cathodic protection shall be applied to the structure.

4.2 Description of corrosion risks

In general, for technical reasons, well casings should be covered by cement. In such conditions steel is passive, its potential is uniform under the cement and the corrosion hazards are reduced. In this case, cathodic protection should not be necessary.

In fact, due to the heterogeneity of the soils which are crossed during drilling and specifically due to the heterogeneity of the mechanical properties of these soils, it is not always possible to guarantee that a continuous cement layer covers the whole steel surface. Because of this non-homogeneous cement layer, some parts of the casing surface are in contact with the external medium. Macro-electrochemical cells (steel/cement and steel/medium) are then established and this results in a corrosion of the anodic parts of the cells (steel in the medium).

If there is no isolating joint between the well and surface piping, such detrimental macro-cells may also appear between the casing and the bare or poorly coated parts of the buried structure surface which become the anodic parts of the macro-cell.

Corrosion caused by the currents generated by macro-cells is more severe where soil layers with low resistivity are crossed.

Risks of corrosion damage shall be considered particularly where:

- the designed service life is long (depending on location, operational conditions);

- the procedure and execution of the cementation results in areas not or incorrectly cemented;

- there are stray current sources;

- the geological layers crossed are of a different nature.

4.3 Corrosion risk assessment

The previous information is only intended to provide a general idea on the corrosion risks involved.

Usually, a corrosion risk is assessed by measuring the structure-to-electrolyte potential. However, these potential measurements require installation of a reference electrode in the electrolyte in the immediate vicinity of the metal. For a well casing, access is limited to the upper part of the well and it is thus impossible to perform any measurement on the deep borehole.

During drilling, samples of drill cuttings should be checked and recorded at regular depths, particularly if their make up changes, to assess corrosivity and composition if the strata changes.

As an alternative to the above method, another way could be to carry out an accurate analysis of the electric log surveys which have been recorded in the open borehole.

Another approach consists in establishing whether current coming from the outside environment (ground) enters in or, conversely, exits from the casing, by using the method known as voltage drop profile (Annex A), which allows this determination by following the direction and intensity of currents circulating in the casing along the well.

This method allows localization of all areas where there is corrosion. Furthermore, according to the voltage drop observed, it is possible to assess the importance of the current intensity exiting from the casing, which determines the rate of corrosion. Nevertheless, this method is difficult to implement.

If available, the usual logs performed after borehole cementation can be usefully analysed to ascertain quality and homogeneity of the borehole cementation, especially in the areas with low electrical resistivity.

5 Prerequisites for application of cathodic protection

5.1 General

The requirements defined in EN 12954 shall be met. However, it should be taken into account that the well casing is bare and in contact with the soil in the borehole through the cement.

5.2 Electrical continuity

If a well is to be cathodically protected, a number of precautions shall be taken during completion. In addition to the external parts in contact with the borehole cementation or the soil, for which protection is required, the well generally includes other parts which are not in contact with the surrounding soil. The latter comprise the production string and all or part of intermediate and production casings depending on the type of completion, operation mode, the depth and the diameter.

It is necessary to avoid current flow through an electrolyte located in the annular space, since it could cause corrosion. Annular spaces which are not cemented are generally filled with a liquid which may be brine, mud water and so on. Under such conditions, current flow through the electrolyte shall be prevented by the use of bonds between each string.

Therefore it is necessary:

- to establish metallic bonds to ensure perfect electrical continuity of each casing part, at upper (wellhead) and lower (shoe) levels, and

- to install metallic centralisers where geological layers may promote a flow of current into the casing.

5.3 Electrical isolation

5.3.1 General

In principle, there should be no electrical continuity between the well to be protected and the foreign structures and particularly the flow-line. For this purpose, an isolating joint is installed between the well and its flow-line.

In this case, a special attention shall be given to avoid undesirable electrical shunts which may be caused by metallic bonds due to the small diameter pipes which are used for well control and safety devices.

Another problem may appear when the fluid or a part of the fluid conveyed in the flow-line is a low-resistivity electrolyte. An internal corrosion risk may exist due to a possible voltage drop between both sides of the isolating joint. In such a case, the isolating joint shall be internally coated with a suitable and electrically isolating material. Moreover, the internal coating shall be:

- applied over a suitable length to reduce the corrosion rate to an acceptable level;
- only applied on the side with the most negative potential.

5.3.2 Particular situations

It may be sometimes necessary to ensure electrical continuity (direct or resistive) between the well to be protected and neighbouring structures, typically the flow-lines.

- Such may be the case for some wells remote from any electrical current source. A method to allow the well cathodic protection consists in the use of the flow-line as a return conductor by short circuiting the isolating joint. Then, the protection is carried out on both structures. However, as both structures have very different coating resistances, it can be necessary to fit the bond of the isolating joint with a resistor.
- Such may be also the case if the well is subject to the influence of stray currents. The bonding of the isolating joint (with or without resistor) can sometimes allow the installation of a drainage on the flow line to mitigate the influence of the stray currents.
- Wells have very low resistance against earth. A device to protect the isolating joint against over voltages should be installed if such a risk exists.

In some cases, it may be impossible to insulate the well from foreign structures. Such is the case for offshore platforms where wells are always connected to the main structure.

5.4 Cathodic protection equipment

Considering the low resistance to earth of the casing and its length, it is generally only possible to obtain protection down to the well shoe by use of impressed current even when borehole cementing is of good quality.

Offshore, where it is difficult to obtain potentials more negative than - 1,00 V measured with an Ag / AgCl / sea water reference electrode at the wellhead, whatever the platform protection method, the borehole cementing needs to be of very good quality to protect the entire casing.

For installations affected by stray currents, suitable equipment (e.g. resistive drainage bonds) shall be considered.

Whatever the method selected, the equipment shall be chosen and provided in accordance with EN 12954.

5.5 Groundbed

To allow the protective current to reach the lower extremity of the well, the groundbeds should be at a sufficient distance from the casing in order to obtain a good current distribution. The distance depends on:

- soil resistivity along the well casing;
- amount of protective current (dimensions of the well casing and cementing quality);
- depth of the well casing.

5.6 Safety requirements

The national and local safety rules and procedures concerning gas, crude oil and water drilling installations, shall be complied with.

These rules and procedures concern surface installations, wells and equipment related to these structures. They may cover the following:

- electrical insulation;
- permanent or temporary earthing;
- perfect electrical continuity throughout the installations to avoid any sparking risk, even during maintenance and workovers;
- materials and equipment;
- classified hazardous areas, according to EN 60079-10, where it is possible to install cathodic protection equipment both with regard to access to the wellhead and any explosion risk.

A close co-operation between specialists on safety and cathodic protection shall be established to comply with the safety rules as well as cathodic protection requirements (assurance of its correct installation and operation, as well as absence of influence risks for neighbouring buried metallic parts which are not protected by means of cathodic protection).

6 Design of the cathodic protection

6.1 General

In general, design of the cathodic protection of a structure includes as a first step the definition of the minimum initial of protective current demand required to meet the basic criterion for cathodic protection $\mathbf{E} \leq \mathbf{E_p}$’ as defined in the European Standardization (see EN 12954).

However, as mentioned above (Clause 4) it is impossible to verify that the basic criterion for cathodic protection of well casings is correctly fulfilled along the entire structure to be protected.

Consequently, to begin the study of cathodic protection of a well, it is necessary to use methods and measurement procedures specific to this type of structure.

The methods described hereafter allow the determination of the currents required for cathodic protection. Other methods, based on specialist experience, may be used, if they are documented and can lead to a comparable result.

6.2 Voltage drop profile method

This method, as mentioned in 4.2 for corrosion risk assessment and described in Annex A, may be used to determine the protective current to ensure effective cathodic protection. The aim of this method is to make sure that all segments of the voltage drop profile have a positive slope which means that the entire structure no longer has anodic areas.

For this purpose a temporary cathodic protection station has to be installed. The temporary groundbed should be far away from the well to allow a good repartition of the current. Groundbed selection shall take account of safety, particularly electrical hazards, for the personnel in charge of tests and also for the structure under test.

For a chosen protective current, the voltage drop is recorded along the entire well in accordance with the procedure described in Annex A.

If the protective current used during this test is not sufficient (Annex A, Figure A.2, case B), the voltage drop, recorded at each measuring point with the measuring tool shows negative slope segments. These represent those areas which remain anodic. This is always the case if the voltage drop shows negative values.

If the protective current used during the test is sufficient (Annex A, Figure A.2, case C), all segments of the curve of potentials have a positive slope. The entire well structure is cathodic. In some cases, the test may be performed again with a lower current to determine the minimum protection current which makes the entire structure cathodic.

6.3 Polarisation curve method

The principle and performance of this method are described in Annex B.

From a test cathodic protection installation, a protection current is injected. For this purpose a temporary cathodic protection station can be used (see 6.2). At the end of a defined time period, when the structure to electrolyte potential becomes stable, the structure-to-electrolyte potential value of the casing E_{off} at the ground surface is recorded (see 7.1).

After this first measurement, the current is increased by a pre-defined increment and maintained at the new value over the same time period. This procedure is repeated until a sufficient number of adjustments have been made to the applied current to enable line II of the curve to be drawn in Figure B.1. Once the curve is plotted, the tangents to the two linear parts I and II (see Figure B.1) are used to determine the minimum current which ensures that the well casing is considered to be cathodically protected.

6.4 Mathematical approach based on a field test

Even the mathematical calculation in Annex C is presented for two concentric pipes (see C.5); it may be applied using computer means where casings consist of several concentric pipes. It allows expressing the casing potential shift at ground surface as well as protection current, according to the:

- well features (length, section, thickness, steel resistivity);
- contact resistance with environmental medium (structure-to-soil resistance);
- minimal potential shift expected at the lower extremity (shoe).

Well protection is considered to be achieved over its whole length if the potential shift, related to the free corrosion potential E_N, calculated at the lower extremity of the well is at least equal to 300 mV.

A current injection test is performed; the current injected and the potential at the top of the well are recorded. When transferred in the equation system of Annex C, these two values allow the determination of the protection current to be adopted for the well.

This method is very easy to implement with a maximum of two concentric casings. It leads to determination of excess values of the required current protection. Indeed, it does not take into consideration the electrochemical polarisation phenomena which progressively appear on the well metal surface. It may be used for the whole well life to establish, whenever required, the optimum protection current adjustment.

6.5 Simulation of the cathodic protection for a well

Cathodic protection for a well can be simulated by numeric methods in order to determine how protection current is distributed on the external surface along the casing, depending on the characteristics of the geological layers, on the electrochemical interface between the steel and the cementation (polarisation curves of steel in cementation) and on ohmic characteristics of the columns.

These numeric methods also allow the potential values all along the casing to be predicted.

NOTE The simulation can be associated with field measurements in order to verify its agreement and to adjust the required current.

7 Measurement of the well-casing-to-soil potential at the wellhead

7.1 General

A general indication of protection level is given by measuring the well-casing-to-soil potential at the wellhead in compliance with requirements of EN 12954. However, as mentioned in Clause 6, the voltage drop profile method and polarisation curve method give a more precise assessment of cathodic protection effectiveness.

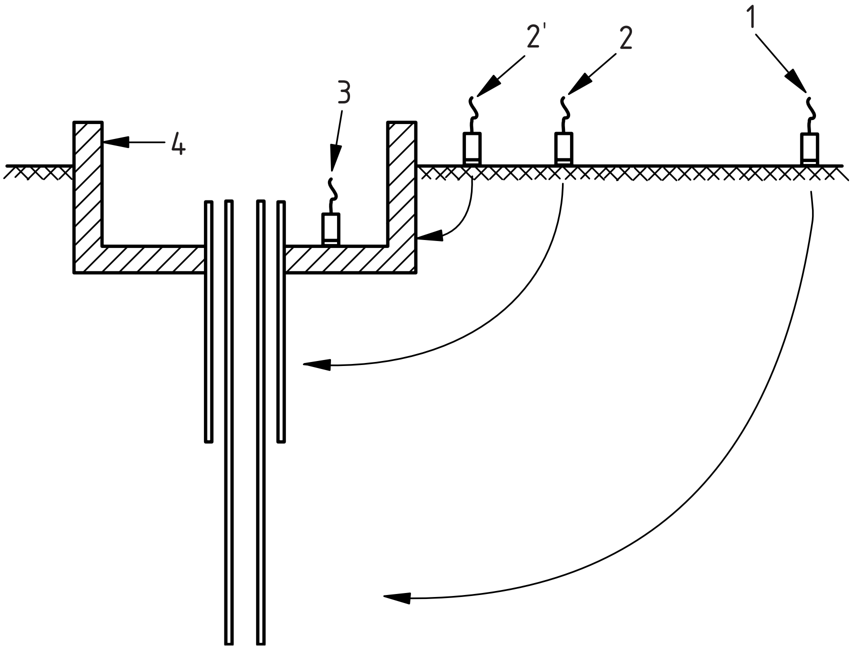
Considering the fact that the well is a structure with a very low resistance to earth value (cementing is a conductive coating) and that potentials measured are influenced by the presence of installations buried at ground surface (e.g. cellar, concrete foundations, various piping), specific provisions, such as those defined below, are sometimes used for potential measurements.

7.2 Measuring points

The potential should be measured using a measuring electrode located at remote earth from the well (approximately 50 m to 100 m, see case 1 of Figure 2) and from any other buried installations, and outside of the influence of the groundbed. The potential determined at this measuring point corresponds to a mean value for the whole well casing or its upper part, depending on the total depth and the geological strata.

If the electrode is located inside the cellar (case 3 of Figure 2), potential measurement reflects a mixed potential of the rebar and the part of the casing inside the cellar if in electrical contact. If there is no electrical contact between rebar and casing, the measurement of the potential of the well is not representative either.

If the electrode is located outside and near the cellar (cases 2 and 2' of Figure 2), potential measurement is not representative of the potential of the well, due to an electrical contact between rebar and casings, or a too close proximity of the surface casing.



Key

1, 2, 2' and 3 measuring electrode connected to the producing casing

4 cellar

Figure 2 — Measuring points

The potential may be measured at wellhead by comparing it with that of a metallic coupon (for example a pipe element installed in the soil a few metres away from the wellhead, and permanently connected to the casing by an insulated cable). This coupon may be provided with or without its own measuring electrode.

7.3 Method used for potential measurement - Interpretation

The well casing potential to be measured is the off potential.

When the protection current is switched off, the related ohmic voltage drop (IR drop) in the soil disappears immediately.

Generally depolarisation is relatively slow due to the particular medium (borehole cementation) around the casing. However, it may be related to the cathodic protection operating conditions.

If rapid depolarisation is observed, for instance 100 mV within 5 min after current is switched off, this may indicate insufficient cathodic protection and/or the presence of equalising currents between casing parts which are differently polarized.

If the 100 mV depolarisation takes longer (for instance 1 h or more), and if the potential then corresponds to the selected protection criterion (see 6.1), the well casing is considered to be cathodically protected.

8 Additional cathodic protection equipment

If it is not possible to prevent or remove an electrical contact between the rebar of the cellar and/or the surface casing with the upper part of the well casing, the protection of this upper part may not be achieved in particular when the cellar contains water. In this case, it may be necessary to install locally anodes inside the cellar.

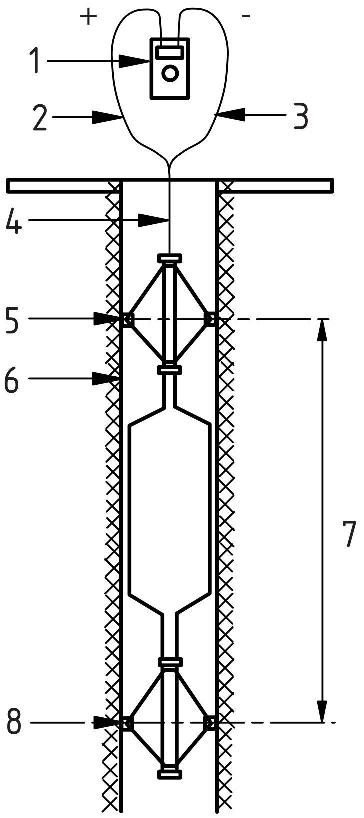
This solution can also be used even if there is no electrical contact when presence of water inside the cellar induces a risk of corrosion.

Annex A
(normative)

Voltage drop profile

A.1 Scope

This method is intended to assess current inputs and outputs by measuring along the casing the voltage drops between two points located at constant distance on the internal surface of the casing (see Figure A.1).



Key

1	voltmeter	2	electrical cable to lower contact knives	3	electrical cable to upper contact knives
4	electrical armoured cable	5	electrical contact of the upper knives with the casing	6	casing
7	length from 3 m to 8 m	8	electrical contact of the lower knives with the casing		

Figure A.1 — Principle of a voltage drop profile measurement

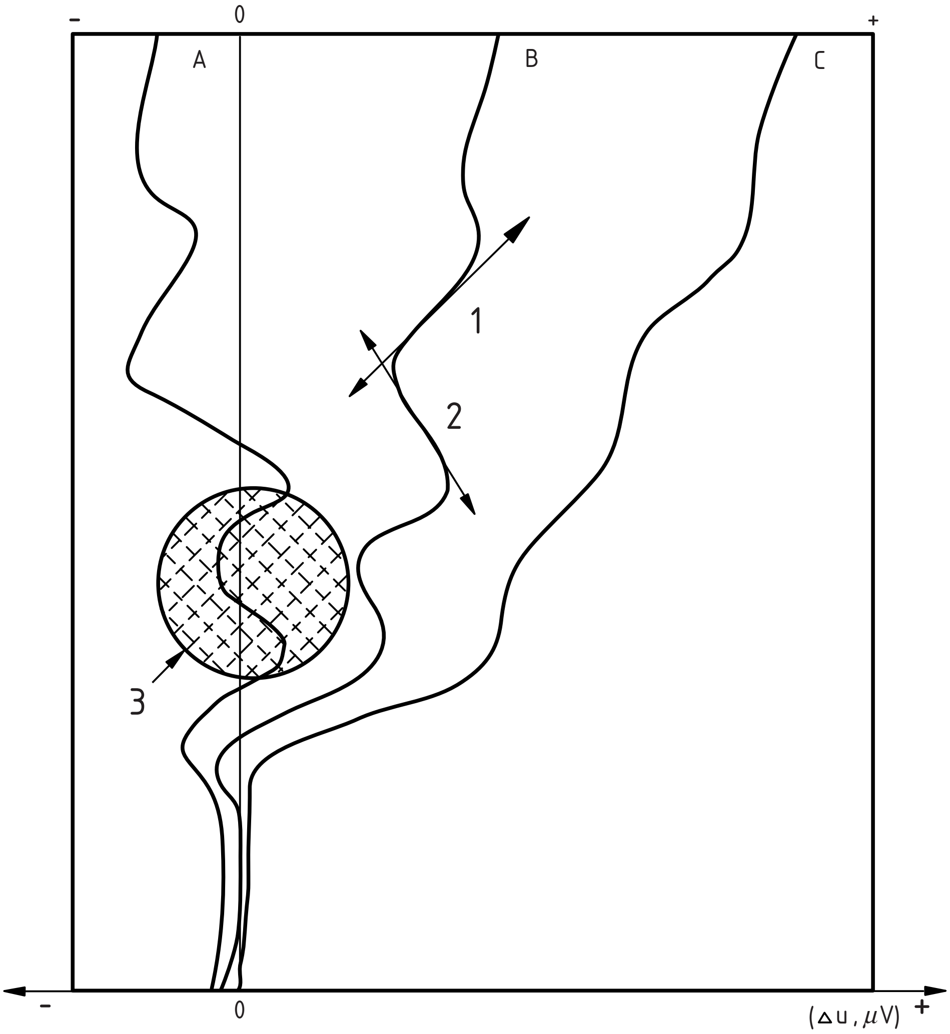
A.2 Principle

An area of corrosion corresponds to current leaving the casing and entering the surrounding electrolyte. These currents are either cell-currents or stray currents. They generate voltage drops in the casing which may be either positive or negative, depending on whether the current is ascending or descending the casing.

Therefore, the method consists of raising from the inside of the casing a tool including two series of knives which ensure a good electrical contact with the casing. These two series of knives are connected to the terminals of a microvoltmeter for measuring direction and magnitude of the voltage drop along the casing.

A.3 Method

The direction and amplitude of the voltage drops, measured as above (see Figure A.2, curves A and B), are analysed in order to locate the areas of corrosion risk to assess the importance of current outputs and hence the corrosion rate, and determine the current needed for cathodic protection of well casings (see Figure A.2, curves B and C).



Key

ΔU:	voltage drop (micro-volt) in the casing measured with a 8 m long knife-tool
Case A:	applied current = 0 (corresponding to the free corrosion potential)
Case B:	applied current < protection current (corresponding to a partial cathodic protection)
Case C:	applied current = protection current (corresponding to a full cathodic protection)
1:	positive slope (cathodic area)
2:	negative slope (anodic area)
3:	see details in Figure A.3

Figure A.2 — Typical profiles of voltage drop - Interpretation - Determination of anodic areas

NOTE A voltage drop is measured positive (with a current flowing up in the casing) when:

- the voltmeter negative pole is connected to the upper contact knife;
- the voltmeter positive pole is connected to the lower contact knife.

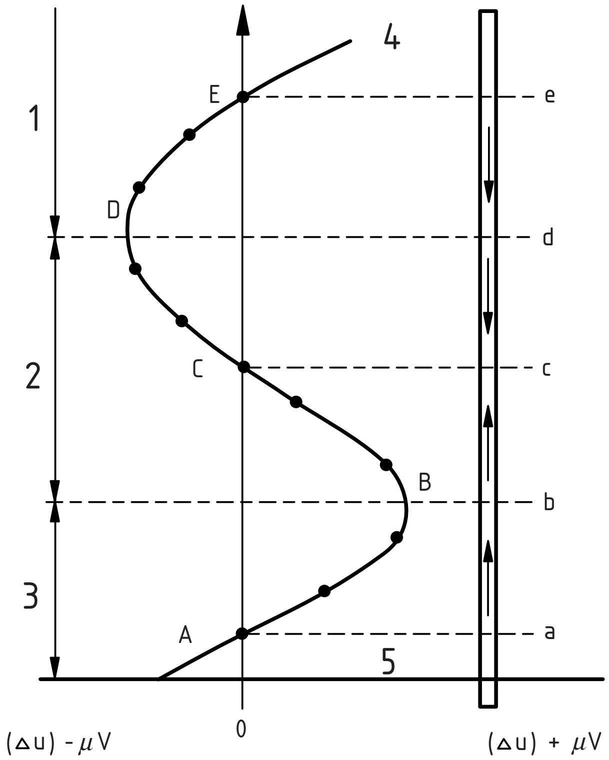
Analysis of the curves

These curves (Figure A.2) are recorded by means of measurements carried out with the specific tool, point after point, from the bottom of the well to the top.

Each point of the curve corresponds to the measurement of a voltage drop.

This voltage drop corresponds to the IR drop in an 8 m length of the casing (if the distance between the contacting knives of the tool is 8 m).

The Figure A.3 shows a detailed part of such a curve for a simplified case for which the following explanations are given.



Key

1 cathodic area
2 anodic area
x top of the well casing
y bottom of the well casing

Figure A.3 — Simplified case

It can be said:

- for a constant longitudinal resistance of the casing, if successive voltage drops have increasing values, then currents circulating in the casing are also increasing;

- a positive voltage drop means that the current flowing in the considered length of the casing is going downward;

- a negative voltage drop means that the current flowing in the considered length is going upward.

Analysis of the curve A B (Figure A.4):

- voltage drops are positive: currents in the casing "a – b" flow upward;

- voltage drops regularly increase from A to B: currents flowing upward in the casing increase from "a" to "b" which means that currents are entering the external surface of the casing from the medium.

Conclusion:

- part "a – b" of the casing is cathodic;

- a tangent on the curve A B shows a positive slope.

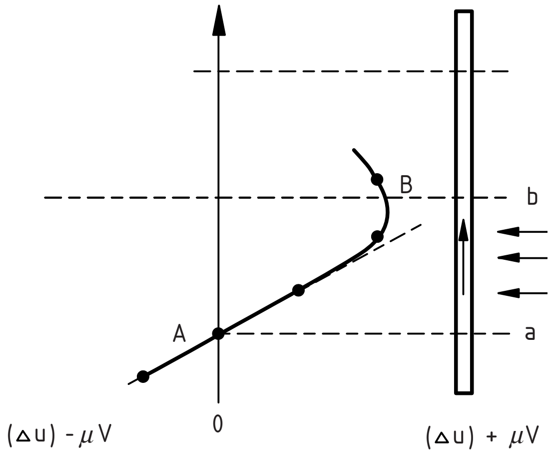


Figure A.4 — Curve A B

Analysis of the curve B C (Figure A.5):

- voltage drops are positive: currents in the casing "b – c" flow upward;

- voltage drops regularly decrease from B to C: currents flowing upward in the casing decrease from "b" to "c" which means that currents are exiting from the external surface of the casing to the medium.

Conclusion:

- part "b – c" of the casing is anodic;

- a tangent on the curve B C shows a negative slope.

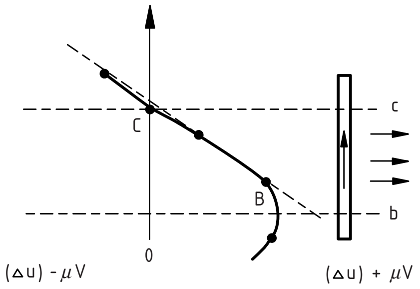


Figure A.5 — Curve B C

Analysis of the curve C D (Figure A.6)

- voltage drops are negative: currents in the casing "c – d" flow downward;

- voltage drops regularly decrease from C to D: currents flowing downward in the casing decrease from "d" to "c" which means that currents are exiting from the external surface of the casing to the medium.

Conclusion:

- part "d – c" of the casing is anodic;
- a tangent on the curve C D shows a negative slope.

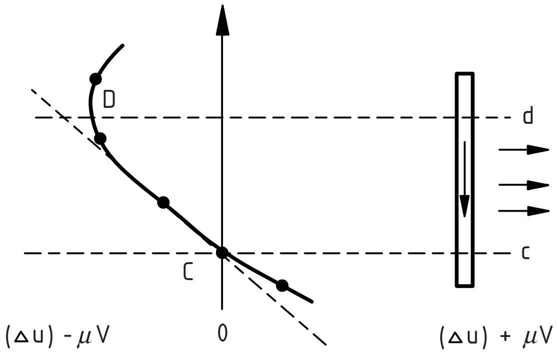


Figure A.6 — Curve C D

Analysis of the curve D E (Figure A.7):

- voltage drops are negative: currents in the casing "d – e" flow downward;
- voltage drops regularly increase from E to D: currents flowing downward in the casing increase from "d" to "e" which means that currents are entering the external surface of the casing from the medium.

Conclusion:

- part "d – e" of the casing is cathodic;
- a tangent on the curve D E shows a positive slope.

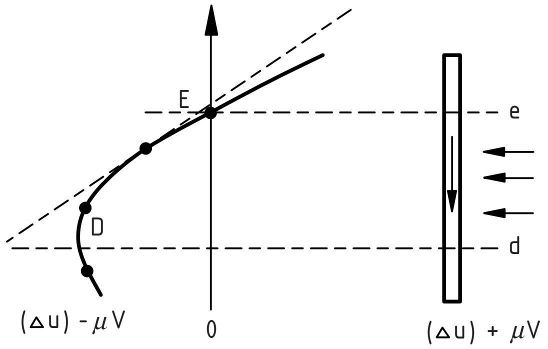


Figure A.7 — Curve D E

A.4 Practical considerations

The range of voltage drop measurements is from 1 μV to 5 000 μV.

The principle of the method requires the internal fluid to be either a gas or a very high resistivity fluid (e.g. fuel oil); otherwise the measuring tool has to be equipped with protective caps in order to avoid any disturbance to the voltage drop measured.

The measurement could be performed by continuous recording while progressively moving the tools. However, the accuracy required and the quality of contacts obtainable between knives and pipe walls are such that the measurements can be carried out only when the tool is stopped. These measurements will last sufficiently to allow either a correct voltage drop stabilisation which is the expression of a good contact, or else an observation (recording) of voltage drop variations if the casing is located in a fluctuating stray current field. The measuring apparatus shall not be affected by any a.c. component in the stray current.

The accuracy of the voltage drop profile depends on three main parameters:

- thickness and nature of the geological strata;
- tool length (knives spacing);
- distance between the measurement locations (pitch).

The tool length (3 m to 8 m) is imposed by the equipment available.

The pitch or distance between two successive measurement locations should be selected so that the possible current output from the casing (anodic areas) can always be detected with certainty at soil seam levels. If the chosen pitch is too large, some thin soil seams may not be covered by the resolution.

If the geological layers are well known (by means of the borehole log), the spacing between two successive measurements can be chosen in relationship to the thickness of the layers. Otherwise, spacing between two successive measurements is about 15 m to 30 m.

The measurement is performed on the inside of the pipe in which the tool is lowered. Therefore, electrical continuity shall be ensured between the concentric casings, for the measurements to be representative of what occurs on the external casing. For this purpose, metallic centralisers shall be fitted at regular and defined intervals along the well.

The value of the voltage drop is affected by the change of the longitudinal resistance of the casing; it is therefore necessary to take into account:

- the changes in pipe wall thickness and/or diameter;
- the type of pipe joints;
- the presence of two or more concentric pipes.

In a field with a homogeneous geological structure, it is considered that a single investigation on a well is representative for the other wells if their cementing quality is comparable.

Annex B
(informative)

Polarisation curve method applied to a well

B.1 Scope

This method is intended to record the well polarization curve E = f (logI), to determine the current demand which is considered to allow a sufficient polarization of the casing.

B.2 Principle

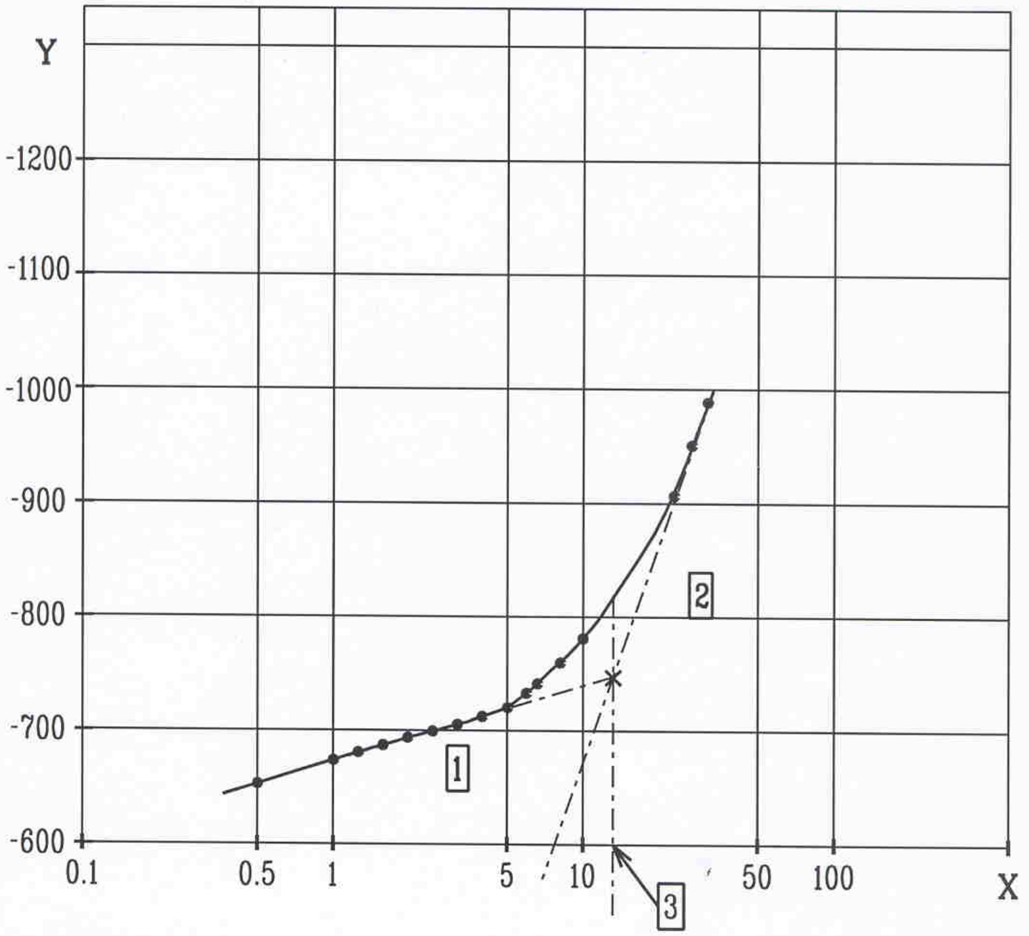
To plot the polarization curve of a well, a polarization test is performed by injecting a cathodic current to the well. After regular defined time periods (usually some minutes), the E_{off} potential, measured versus a reference electrode located remote from the well at ground surface, is recorded and then the injected current is increased by a constant determined quantity. The polarization curve obtained is then plotted in semi-logarithmic coordinates with all the values pairs (E_{off} and log I).

This curve theoretically includes two significantly linear parts (see diagram based on field experiments, in Figure B.1).

Linear part II (which corresponds to the Tafel law: $E = a + b \times \log I$) reports the reduction reactions of the chemical species present in the medium in contact with the metal. In this area, the metal is cathodically protected. The minimum intensity of the current which is considered to allow a sufficient cathodic protection of the well is determined by the abscissa of point 3 of Figure B.1.

Experimental test conditions used to plot the Figure B.1:

- measuring electrode : 50 m from the well;
- time cycle 3 min (2 min 55 s ON - 5 s OFF);
- current increment : 0,5 A each 3 min.



Key

X	current (logarithmic scale), in amperes
Y	off potential versus copper/ saturated copper sulphate reference electrode, in millivolts
1	linear part I
2	linear part II
3	testing protection current

Figure B.B1 — Polarization curve of a well - Determination of the protection current

B.3 Practical considerations

The method is simple to implement and has been derived from methods used in the laboratory. Used on wells, it gives conservative results.

The potential is measured using an electrode located at ground surface, distant enough from the well to be considered as located at the remote earth. The potential is determined with the method known as instantaneous off potential technique. No variation of current (stray current, influence current) should influence the measurements during the period of the field experiment.

The curve requires the test to be conducted with high currents (several times the steady state protective current) before a linear part appears (part II). Therefore, the test rectifier and a temporary groundbed should be planned with sufficient capacity for the current injection and the measurement time cycle should not be modified during the entire test period.

Annex C
(informative)

Determination by calculation of the potential shift at the bottom of the well and the well to soil resistance

C.1 Purpose

This calculation is intended to allow estimation of the potential shift obtained at the bottom of a well on which cathodic protection is applied

It also allows for quantifying an average coating resistance value (r_{co} expressed in ohms square metre) as defined in EN 12954:2001, Clause 3, which represents for an uncoated structure, the electrical contact of the metal with the soil through the cementation.

This calculation may be performed either:

- to determine the base data for cathodic protection design purposes for a non-protected well, or

- to adjust as accurately as possible the protection current of a well fitted with cathodic protection, as the casing polarises.

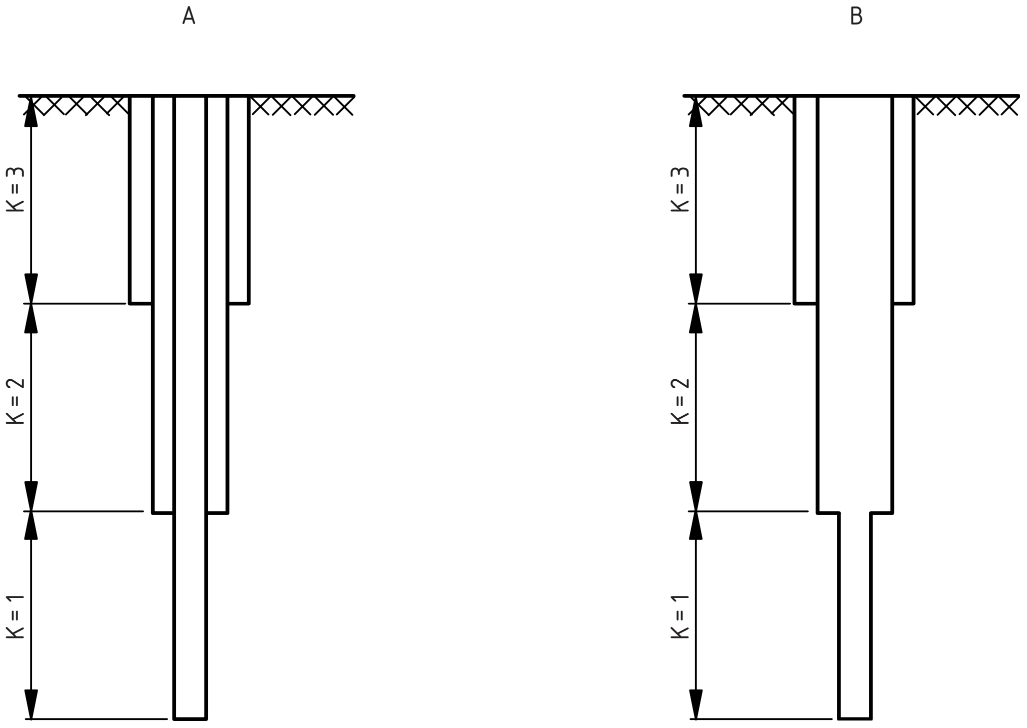
C.2 Principle

Whatever the number of concentric casing strings constituting the casing and their assembly type (examples are given in Figure C.1), the calculation of cathodic protection uses generalised attenuation equations expressing the evolution of potential and currents along the well.

The calculation is carried out, segment by segment, from the bottom of the well to the surface using the equations which are developed in C.4.

A segment is a length of the well along which there is no change of the pipe characteristics, that is to say, no variation in metal cross-section, diameter or number of concentric pipes.

Figure C.1 shows, for two types of well, the segments which need to be considered.



Key

Type A with concentric casing strings and three segments (k1, k2 and k3)

Type B with a liner and three segments (k'1, k'2 and k'3)

Figure C.1 — Examples of casing strings

C.3 Definition of terms and coefficients used in the equations

C.3.1 Symbols and definitions

The following example consists of a segment "k" with a constant external diameter and a constant metallic cross-section (see Figure C.2).

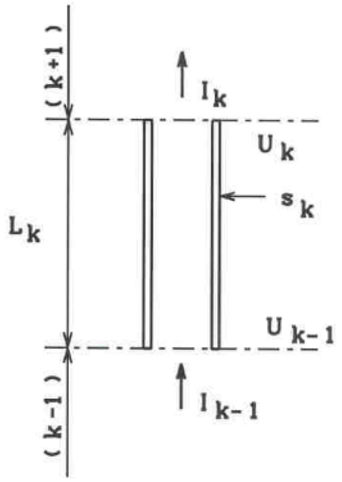
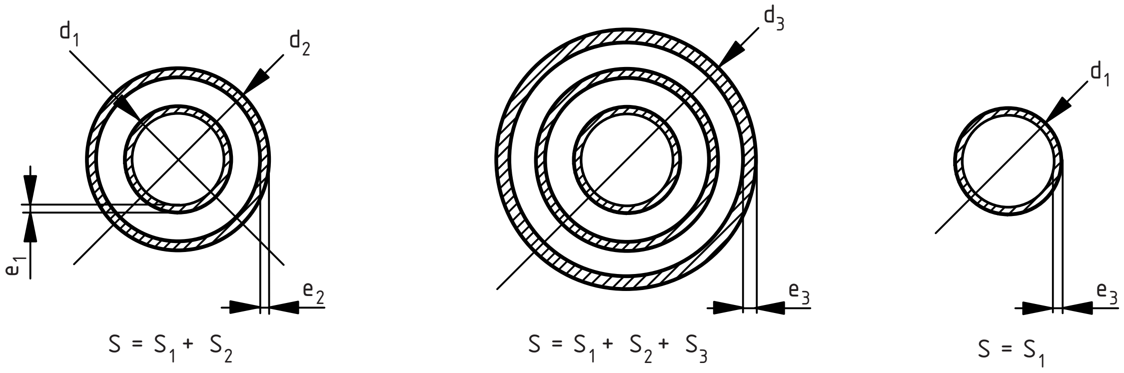
SYMBOL	DEFINITION	UNIT
L_k	length of the segment k	m
dk	nominal diameter of the casing of the segment	m
e_k	thickness of the different concentric pipes, if any	m
Sk	total metal cross section area of the segment (see C.3.2.2)	m²
U	potential shift; variation of the well potential consequential to a protection current	V
U_k	potential shift at the top of the segment k;	V
U_{k-1}	potential shift at the top of the segment (k-1), is also equal to the potential shift at the bottom of the segment (k)	V
U_0	potential shift at the bottom of the well casing when k=0	V
I_k	current coming from segment k and entering segment (k+1)	A
I_{k-1}	current coming from segment (k-1) and entering segment k. NOTE I_0 equals 0.	A
r_{co}	average coating resistance (EN12954)	$\Omega.m^2$
r_k	longitudinal resistance per unit length (see C.3.2.3)  	$\Omega.m^{-1}$
a_k	attenuation factor (see C.3.3.2)	m^{-1}
γ_k	characteristic resistance (see C.3.2.3)	Ω

Figure C.2 — Diagram of a segment "k" of a well

C.3.2 Characteristics of a segment k

C.3.2.1 General



Segment 2, type A or segment 3, type B

Segment 3, type A

Segment 1, types A & B

Figure C.3 — Examples of metal section determination

C.3.2.2 Total cross section of the segment k: S_k

$$S_k = \sum_1^n \pi . d_k . e_k$$ (square metre) (see Figure C.3) (C.1)

n = number of concentric casings in section k

C.3.2.3 Longitudinal resistance per unit length: r_k

For a given segment k

$$r_k = \frac{\rho}{s_k}$$ (ohm per metre) (C.2)

ρ = steel resistivity = 18×10^{-8} Ωm

$$r_k = \frac{18 \times 10^{-8}}{s_k}$$ (ohm per metre)

C.3.3 Coefficients used in the attenuation equations

C.3.3.1 Attenuation factor: a_k

— The attenuation factor depends on the metallic characteristics of the segment and the average coating resistance (r_{co}) of the external casing constituting the segment.

$$a_k = \sqrt{\frac{r_k}{\frac{r_{co}}{\pi \times d_k}}} = \sqrt{r_k \times \frac{\pi \times d_k}{r_{co}}} \quad \text{(1/metre)} \qquad \text{(C.3)}$$

C.3.3.2 Characteristic resistance: γ_k

The characteristic resistance depends on the metallic characteristics of the segment and the average coating resistance (or average structure–to-soil resistance) “r_{co}”.

$$\gamma_k = \sqrt{\frac{r_{co}}{\pi \times d_k} \times r_k} \quad \text{(ohm)} \qquad \text{(C.4)}$$

C.4 Calculation - General attenuation equations

C.4.1 General attenuation equations

The two general attenuation equations for a segment k of a well casing are:

NOTE In order to simplify the following equation, the term "$a_k . L_k$" is replaced by "b_k".

$$U_k = U_{k-1} \times \cosh(b_k) + \gamma_k \times I_{k-1} \cdot \sinh(b_k) \qquad \text{(C.5)}$$

$$I_k = \frac{U_{k-1}}{\gamma_k} \times \sinh(b_k) + I_{k-1} \times \cosh(b_k) \qquad \text{(C.6)}$$

C.4.2 Method for solving the equations system

The calculation is performed starting with the deepest segment (segment 1), according to Equations C.5 and C.6.

For segment 1 (well-bottom) $U_1 = U_0 \times \cosh(b_1)$

$$I_1 = \frac{U_0}{\gamma_1} \times \sinh(b_1)$$

For segment 2 $U_2 = U_1 \times \cosh(b_2) + \gamma_2 \times I_1 \cdot \sinh(b_2)$

$$I_2 = \frac{U_1}{\gamma_2} \times \sinh(b_2) + I_1 \times \cosh(b_2)$$

For segment n (upper part of the well) $U_n = U_{n-1} \times \cosh(b_n) + \gamma_n \times I_{n-1} \times \sinh(b_n)$

$$I_n = \frac{U_{n-1}}{\gamma_n} \times \sinh(b_n) + I_{n-1} \times \cosh(b_n)$$

The resolution of these successive equations systems supposes that:

- the value “r_{co}“ represents an average coating resistance which is the same along the entire length of the well for all segments. The cementation of the casings in the borehole should be considered as homogeneous along the entire length of the well;

- the resistivity of the soil has to be considered as homogeneous all along the entire length of the well because it cannot be taken into account in this type of calculation.

It is easy to demonstrate that the ratio U_n/I_n is independent of the value U_0, the potential shift at the well-bottom.

C.4.3 Calculation procedure

The equations system to solve comprises:

Step 1

All the geometrical and electrical parameters (diameters, length, r_K, s_K) can be determined or calculated from the above equation (C.4.1) according to the type and characteristic of the well.

On the other hand, the attenuation parameters "a_k" and "γ_k"cannot be expressed because they both depend on "r_{co}" which is at this stage an unknown value.

Step 2

A current injection test is performed which makes it possible to measure "I_n" (injected current) and U_n (potential shift at the wellhead noted during the test) and to calculate a measured ratio "U_n/I_n".

Step 3

Determination of the unknown value of "r_{co}".

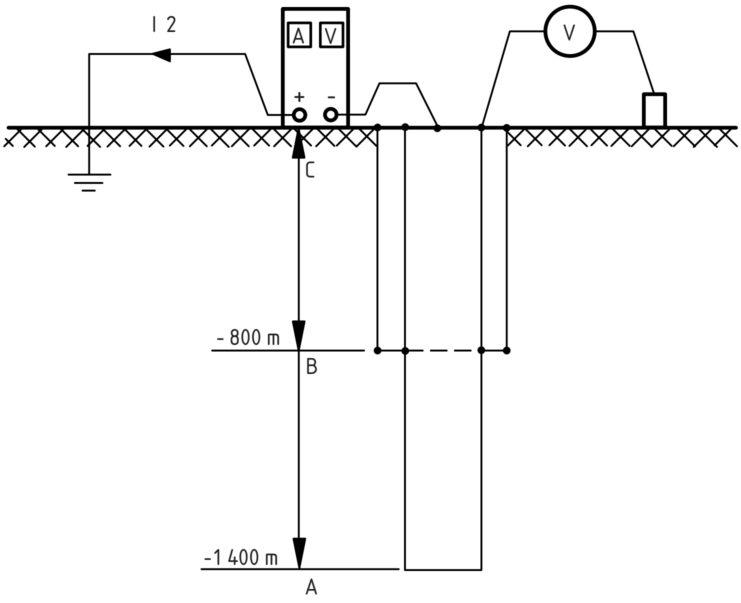
Calculation is achieved, from bottom to top (from segment 1 to segment 2), by setting an arbitrary start value U_0 (for example, $U_0 = 1$). By successive approximations of the value of "r_{co}", the latter is determined (with an acceptable accuracy), to give a ratio U_n/I_n (calculated) equal to ratio U_n/I_n (measured) by the current injection test. A microcomputer becomes necessary when the well has more than two sections of casing.

As an example, this step-by-step procedure is applied in the following subclause on a well with 2 casings.

C.5 Application to a well with two casings

Step 1

The type of the well is illustrated in Figure C.4. The well comprises 2 segments.



Segment k = 1

L_1 = AB = 600 m

d_1 = 245 mm

e_1 = 8,38 mm

Segment k = 2

L_2 = BC = 800 m

d_2 = 340 mm and d_1 = 245 mm

e_2 = 10,03 mm and e_1 = 8,38 mm

The metallic characteristics of the segments and the coefficients to be used in the attenuation equations are presented in the following Table (C.1)

Figure C.4 — Example of a well with 2 casings

Table C.1 - Calculations applied to segments 1 and 2

	Segment 1	**Segment 2**
L (m) d external (m) e (m)	$L_1 = 600$ $d_1 = 0{,}245$ $e_1 = 8{,}38 \times 10^{-3}$	$L_2 = 800$ $d_2 = 0{,}340$ $e_2 = 10{,}3 \times 10^{-3}$
$s = \sum \pi . d . e$ (m^2)	$s_1 = \pi d_1 e_1$ $s_1 = 64{,}5 \times 10^{-4}$	$s_2 = \pi (d_1 e_1 + d_2 e_2)$ $s_2 = 171 \times 10^{-4}$
$r = \frac{18 \times 10^{-8}}{s} \quad (\Omega m^{-1})$	$r_1 = \frac{18 \times 10^{-8}}{s_1} = 27{,}9 \times 10^{-6}$	$r_2 = \frac{18 \times 10^{-8}}{s_2} = 10{,}52 \times 10^{-6}$
$a = \sqrt{r \frac{\pi d}{r_{co}}} \quad (m^{-1})$	$a_1 = \frac{4{,}63 \times 10^{-3}}{\sqrt{r_{co}}}$	$a_2 = \frac{3{,}35 \times 10^{-3}}{\sqrt{r_{co}}}$
$b = a \times L$	$b_1 = \frac{2{,}78}{\sqrt{r_{co}}}$	$b_2 = \frac{2{,}78}{\sqrt{r_{co}}}$
$\gamma = \sqrt{r \times \frac{r_{co}}{\pi d}} \quad (\Omega)$	$\frac{1}{\gamma_1} = \frac{318{,}6}{\sqrt{r_{co}}} = \frac{166}{\sqrt{r_{co}}}$	$\frac{1}{\gamma_2} = \sqrt{\frac{\pi d_2}{r_2 r_{co}}} = \frac{318{,}6}{\sqrt{r_{co}}}$

Step 2: Current injection test

The current injection test performed during 3 min at the wellhead gives:

I_2 (injected current measured after 3 min) : 5,25 A

Potential at the wellhead before injection : - 570 mV ($Cu/CuSO_4$)

off Potential at the wellhead at the end of injection test : - 920 mV ($Cu/CuSO_4$)

Potential shift U_2 = 920 – 570 = : 350 mV

Measured ratio $\frac{U_2}{I_2} = \frac{0{,}350}{5{,}25} =$: 0,066 6 V/A

Step 3: Determination of "r_{co}"

The two equations systems applicable to this well are:

$$\text{A)}\quad \begin{cases} U_1 = U_O \times \cosh b_1 \\ I_1 = \dfrac{U_0}{\gamma_1} \times \sinh b_1 \end{cases} \qquad \text{and B)}\quad \begin{cases} U_2 = U_1 \times \cosh b_2 + \gamma_2\, I_1 \times \sinh b_2 \\ I_2 = \dfrac{U_0}{\gamma_2} \times \sinh b_2 + I_1 \times \cosh b_2 \end{cases}$$

In this elementary case with 2 segments, the 2 equations systems can be treated by replacing in the system B), the values of U_1 and I_1 expressed in the system A). Consequently a new system B') can be written:

$$\text{B')}\quad \begin{cases} U_2 = U_O\,(\cosh b_1 \times \cosh b_2 + (\dfrac{\gamma_2}{\gamma_1}.\sinh b_1 \times \sinh b_2)) \\ \\ I_2 = U_O\,(\dfrac{1}{\gamma_2} \times \cosh b_1 \times \sinh b_2 + (\dfrac{1}{\gamma_1}.\sinh b_1 \times \cosh b_2)) \end{cases}$$

$$\text{The calculated ratio } \frac{U_2}{I_2} = \frac{\cosh b_1 \times \cosh b_2 + (\dfrac{\gamma_2}{\gamma_1} \times \sinh b_1 \times \sinh b_2)}{\dfrac{1}{\gamma_2} \times \cosh b_1 . \sinh b_2 + (\dfrac{1}{\gamma_1} \times \sinh b_1 \times \cosh b_2\,)} = 0{,}066 \text{ (according to step 2)} \tag{C.7}$$

It can be seen that the calculated ratio is independent of the unknown value U_0.

This ratio depends only on the four terms b_1,b_2, γ_1 and γ_2 which all are functions of the term $r_{co.}$ (see Table C.1) Hence the resolution of the above Equation (C.1) will permit to calculate the r_{co} value.

The equation to solve is the following:

$$\frac{\cosh\dfrac{2{,}78}{\sqrt{r_{co}}} \times \cosh\dfrac{2{,}68}{\sqrt{r_{co}}} + 0{,}521 \sinh\dfrac{2{,}78}{\sqrt{r_{co}}} \times \sinh\dfrac{2{,}68}{\sqrt{r_{co}}}}{\dfrac{1}{\sqrt{r_{co}}}(318{,}6 \times \cosh\dfrac{2{,}78}{\sqrt{r_{co}}} \times \sinh\dfrac{2{,}68}{\sqrt{r_{co}}} + 166 \times \sinh\dfrac{2{,}78}{\sqrt{r_{co}}}\ \cosh\dfrac{2{,}68}{\sqrt{r_{co}}}} = 0{,}066$$

It is solved by continual approach giving to "r_{co}" successively arbitrary values. In this case the successive values given to "r_{co}" were:

$r_{co} =$ 150 Ωm^2, 100 Ωm^2, 50 Ωm^2, 80 Ωm^2 and, finally 82 Ωm^2.

The r_{co} value corresponding to this well is 82 Ωm^2.

Step 4: Replacing "r_{co}" in all terms b_1, b_2, γ_1 and γ_2 by

$$\text{B)} \quad \begin{cases} U_2 = U_O \times (1{,}142) \\ I_2 = U_O \times (17{,}023) \end{cases}$$

it is now possible to determine:

- either the potential shift at the well-bottom corresponding to the injection test.

$U_O = \dfrac{U_2}{1{,}142} = \dfrac{0{,}35}{1{,}142} \approx 0{,}3$ V at the bottom, or using the current equation.

$U_O = \dfrac{I_2}{17{,}023} = \dfrac{5{,}23}{17{,}023} \approx 0{,}3$ V (which gives the same result for U_0).

- or the required protective current to obtain a given potential shift at the well-bottom.

To reach U_0 = 0,4 V at the well-bottom for instance, it is necessary to inject a current $I_2 = 0{,}4 \times 17{,}023 \approx 6{,}8$ A.

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[1] EN 13509, *Cathodic protection measurement techniques*

[2] EN 12473, *General principles of cathodic protection in sea water*

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

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

[4] W. von Baeckmann, W. Schwenk, W. Prinz ‘Handbook of Cathodic Corrosion Protection’ 3rd ed. pg. 415-426, Gulf Publishing Company, Houston

[5] C. Compère, D Le Flour, P Chauvot, S. Ghi, M Roche; Simulation of cathodic protection of offshore platform using the PROCOR software: Correlation between experimental results and models; CEFRACOR meeting Aix en Provence, June 2002

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