



International
Standard

ISO 15589-2

**Oil and gas industries including
lower carbon energy —
Cathodic protection of pipeline
transportation systems —**

**Part 2:
Offshore pipelines**

*Industries du pétrole et du gaz y compris les énergies à faible
teneur en carbone — Protection cathodique des systèmes de
transport par conduites —*

Partie 2: Conduites en mer

**Third edition
2024-02**

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO document should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document was prepared by Technical Committee ISO/TC 67, *Oil and gas industries including lower carbon energy*, Subcommittee SC 2, *Pipeline transportation systems*, in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 219, *Cathodic protection*, in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

This third edition cancels and replaces the second edition (ISO 15589-2:2012), which has been technically revised.

The main changes are as follows:

- in [Clause 6](#), recommendations for isolating joints have been expanded;
- in [Clause 7](#), NOTES to [Table 1](#) and text in [7.4](#) have been updated to avoid discrepancies with [Figure 2](#); coating breakdown factors have been revised for errors left in the previous edition and less conservative values for some coating systems have been selected based on feedback from the industry;
- in [Clause 8](#), NOTES and guidance on the design of the system have been updated including recommendations for buried pipelines; anode utilization factors have been expanded to cover additional anodes types;
- in [Clause 9](#), [Table 6](#) has been updated to reflect anode compositions in line with current industry practices and other standards;
- in [Clause 10](#), additional references have been provided for guidance on core dimensions and position as well as testing for quality control of anode electrochemical properties;
- in [Annex A](#), additional anode resistance formulae have been provided to cover different anode types.
- [Annex B](#) has been modified to present the NORSOK method as a requirement, with an alternative method given for information.
- [Annex C](#) has been updated as informative and the test method replaced with references to current test methods in line with current industry practice.

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- The previous Annex E has been removed and replaced by additional guidance on quality control testing of anodes in [10.10](#).
- In the updated [Annex E](#) (Interference), additional references for alternating current interference have been added.

A list of all parts in the ISO 15589 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

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Introduction

Pipeline cathodic protection is achieved by the supply of sufficient direct current to the external pipe surface, so that the steel-to-electrolyte potential is lowered on all the surface to values at which external corrosion is reduced to an insignificant rate.

Cathodic protection is normally used in combination with a suitable protective coating system to protect the external surfaces of steel pipelines from corrosion.

This document can also be used for offshore pipelines outside the petroleum, petrochemical and natural gas industries.

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Oil and gas industries including lower carbon energy — Cathodic protection of pipeline transportation systems —

Part 2: Offshore pipelines

1 Scope

This document specifies requirements and gives recommendations for the pre-installation surveys, design, materials, equipment, fabrication, installation, commissioning, operation, inspection and maintenance of cathodic protection (CP) systems for offshore pipelines for the petroleum, petrochemical and natural gas industries as defined in ISO 13623. Flexible pipelines, in-field flowlines, spools and risers are included in this document. Subsea production and injection equipment and structures are not included in this document.

This document is applicable to carbon steel, stainless steel and flexible metallic pipelines in offshore service.

This document is applicable to retrofits, modifications and repairs made to existing pipeline systems.

This document is applicable to all types of seawater and seabed environments encountered in submerged conditions and on risers up to mean water level.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 630, *Structural steels*

ISO 1461, *Hot dip galvanized coatings on fabricated iron and steel articles — Specifications and test methods*

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

ISO 8501-1, *Preparation of steel substrates before application of paints and related products — Visual assessment of surface cleanliness — Part 1: Rust grades and preparation grades of uncoated steel substrates and of steel substrates after overall removal of previous coatings*

ISO 9606-1, *Qualification testing of welders — Fusion welding — Part 1: Steels*

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

ISO 15607, *Specification and qualification of welding procedures for metallic materials — General rules*

AWS D1.1/D1.1M, *Structural Welding Code — Steel*

EN 10025 (all parts), *Hot rolled products of structural steels*

EN 10204:2004, *Metallic products — Types of inspection documents*

ASTM D1141, *Standard Practice for Preparation of Substitute Ocean Water*

DNV-RP-B401, *Cathodic Protection Design*

NACE TM0190, *Standard Test Method — Impressed Current Test Method for Laboratory Testing of Aluminium Anodes*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 8044 and the following apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

- ISO Online browsing platform: available at <https://www.iso.org/obp>
- IEC Electropedia: available at <https://www.electropedia.org/>

3.1

anode sled

anodes installed on a structure and connected to the pipeline by a cable

3.2

closed-circuit potential

anode potential while electrically linked to the pipeline to be protected

3.3

coating breakdown factor

f_c
time-dependent factor to address increasing current requirements due to coating breakdown based on the ratio of current density required to polarize a coated steel surface as compared to a bare steel surface

3.4

cold shut

horizontal surface discontinuity caused by solidification of the meniscus of the partially cast anodes as a result of interrupted flow of the casting stream

3.5

driving voltage

difference between the pipeline/electrolyte potential and the anode/electrolyte potential when the cathodic protection is operating

3.6

electric field gradient

change in electrical potential per unit distance through a conductive medium, arising from the flow of electric current

3.7

electrochemical capacity

ϵ
total amount of electric charge that is produced when a fixed mass (usually 1 kg) of anode material is consumed electrochemically

Note 1 to entry: Electrochemical capacity is expressed in ampere hours.

3.8

final current density

current density required to repolarise pipeline at the end of the CP design life

Note 1 to entry: Final current density is expressed in amperes per square metre.

3.9

hydrogen-induced stress cracking

HISC

cracking due to a combination of load and hydrogen embrittlement caused by the ingress of hydrogen formed at the steel surface due to the cathodic polarization

3.10

IR drop

voltage due to any current, measured between two points of the metal of the pipe or two points of the electrolyte, such as seawater or seabed, in accordance with Ohm's law

Note 1 to entry: IR drop and *electric field gradient* (3.6) are related terms.

3.11

master reference electrode

reference electrode, calibrated with the *primary calibration reference electrode* (3.15), used for verification of reference electrodes that are used for field or laboratory measurements

3.12

mean current density

estimated average cathodic current density for the entire lifetime of the pipeline

Note 1 to entry: Mean current density is expressed in amperes per square metre.

3.13

protection potential

structure-to-electrolyte potential for which the metal corrosion rate is considered as insignificant

3.14

pitting resistance equivalent number

PREN

number, developed to reflect and predict the pitting resistance of a stainless steel, based on the proportions of Cr, Mo, W and N in the chemical composition of the alloy

3.15

primary calibration reference electrode

reference electrode used for calibration of *master reference electrodes* (3.11)

3.16

remotely-operated vehicle

ROV

underwater vehicle operated remotely from a surface vessel or installation

[SOURCE: ISO 14723:2009, 4.32]

3.17

riser

part of an offshore pipeline, including any subsea spool pieces, that extends from the seabed to the pipeline termination point on an offshore installation

[SOURCE: ISO 13623:2017, 3.1.20, modified — "including any subsea spool pieces" has been added.]

3.18

utilization factor

μ

fraction of the anodic material weight of a galvanic anode that can be consumed before the anode ceases to provide the minimum required current output

3.19

pipeline lifetime

period that includes pipeline service life, and any prior or subsequent period planned by the operator

4 Symbols and abbreviated terms

4.1 Symbols

ΔE_A	electrolytic potential drop
ΔE_{Me}	metallic potential drop
μ	utilization factor
A	anode exposed surface area
A_c	total surface area
A_w	cross-sectional area of the pipe wall
C	anode cross-sectional perimeter
D	pipeline outer diameter
d	pipeline wall thickness
ΔE	driving voltage
D_i	pipeline internal diameter
E_0	pipe-to-electrolyte potential shift at anode
E_a	design closed-circuit potential of the anode
E_c	design protection potential
E_x	pipe-to-electrolyte potential shift at a distance x
f_c	coating breakdown factor
f_{cf}	final coating breakdown factor
I_0	current flowing onto the pipe at anode
I_{af}	individual current output at the end-of-life
I_c	current demand
i_c	current density
I_{cf}	current demand at the end of life
I_{cm}	mean current demand
I_f	end-of-life individual anode current output
I_x	current flowing onto the pipe at a distance x
L	anode length
L_d	distance between anodes
L_m	half the distance between drain points
m	net anode mass

m_a	individual net anode mass
n	number of anodes
r	anode radius
R_0	pipe-to-electrolyte insulation resistance
R_a	anode resistance /total circuit resistance
R_{af}	anode resistance at end of life
R_L	linear electrical resistance of the section of the pipeline
R_t	transverse resistance
S	arithmetic mean of anode length and width
t_{dl}	design life, expressed in years.
α	attenuation constant for the pipeline
ε	electrochemical capacity
ρ	environmental resistivity
ρ_{Me}	pipe material resistivity

4.2 Abbreviated terms

AC	alternate current
CAT	cold-applied tape
CE	carbon equivalent
CP	cathodic protection
CRA	corrosion-resistant alloy
CSE	saturated copper electrode (Cu/CuSO ₄)
DC	direct current
EPDM	ethylene propylene diene monomer
FBE	fusion-bonded epoxy
HSS	heat-shrinkable sleeve
ICCP	impressed current cathodic protection
MIC	microbially induced corrosion
PE	polyethylene
PP	polypropylene
PREN	pitting resistance equivalent number
PU	polyurethane

ROV	remotely-operated vehicle
SCE	saturated calomel electrode (KCl)
SMYS	specified minimum yield strength
SRB	sulphate reducing bacteria
TSA	thermally sprayed aluminium
3LPE	three-layer polyethylene
3LPP	three-layer polypropylene

5 General

5.1 Competence assurance

Personnel who undertake the design, supervision of installation, construction, installation supervision, commissioning, supervision of operation, measurements, monitoring and supervision of maintenance of cathodic protection systems shall have the appropriate level of competence for the tasks undertaken.

Competence of cathodic protection personnel to the level appropriate for tasks undertaken should be demonstrated by certification in accordance with prequalification procedures such as ISO 15257, or by any other equivalent scheme.

5.2 Conformity

A quality system and an environmental management system should be applied to assist conformity with the requirements of this document.

NOTE ISO 29001 gives sector-specific guidance on quality management systems and ISO 14001 gives guidance on the selection and use of an environmental management system.

6 Cathodic protection system requirements

6.1 General

The CP system shall be designed to prevent external corrosion over the pipeline lifetime and to:

- provide sufficient current to the pipeline to be protected and distribute this current so that the selected criteria for CP are effectively attained on the entire surface;
- provide a design life of the CP system commensurate with the required life of the protected pipeline, or to provide for periodic rehabilitation of the anode system;
- provide adequate allowance for anticipated changes in current requirements with time;
- ensure that anodes are installed where the possibility of disturbance or damage is minimal;
- provide adequate monitoring facilities to test and evaluate the system's performance.

The CP system shall be designed with due regard to environmental conditions and neighbouring structures.

Electrical isolation of offshore pipelines protected by galvanic anodes from other pipelines, structures, subsea facility or floaters that are protected by impressed-current systems shall be evaluated for adverse interaction between the two systems. An assessment shall be performed to identify the cathodic protection system of these facilities and review the electrical connectivity with the proposed pipeline to ensure no detrimental effects on each side related to inadequate or excessive polarization. Offshore pipelines shall be

isolated from other unprotected or less protected structures, which can drain current from the pipeline's CP system. If stray current problems are anticipated due to interaction between offshore pipelines and other structures, providing electrical continuity of the pipelines to the other structures can be considered.

CP systems of adjacent pipelines or structures shall be verified to be compatible such that current drain from one system into an adjacent system does not adversely affect the performance of either CP system.

The pipeline CP design shall take into account the pipeline installation method, the types of pipeline and riser, and the burial and stabilization methods proposed. Guidance is given in [Annex F](#).

The CP system based on galvanic anodes shall be designed for the lifetime of the pipeline system using the calculation procedure given in [Annex A](#).

The design of the CP system shall document what allowances have been made for the effects of water velocity and erosion effects (e.g. from entrained sand silt or ice particles).

Installation of permanent test facilities should be considered, taking into account specific parameters such as pipeline length, water depth and underwater access related to the burial conditions.

ISO 15589-1 should be used for the cathodic protection of short lengths of offshore pipelines and their branches that are directly connected to cathodically protected onshore pipelines.

6.2 Selection of CP systems

6.2.1 General

CP shall be achieved using either galvanic anodes or an impressed-current system. Galvanic anodes shall be connected to the pipe, either individually or in groups

Galvanic anodes are limited in current output by the anode-to-pipe driving voltage and the electrolyte resistivity. Generally, anodes are attached directly to the pipe as bracelets. Sleds or mattresses of anodes can also be placed at regular intervals along the pipeline. For these cases, an attenuation check in accordance with [Annex B](#) shall be conducted to ensure the full length of pipeline is protected.

Some pipelines can be protected by anodes located at each end. Typically, this type of installation is used on inter-platform pipelines. Anodes for the pipeline can be attached to the platform if the pipeline is electrically connected to the platform. For this case, an attenuation check in accordance with [Annex B](#) shall be conducted to ensure the full length of pipeline is protected.

Items that shall be considered in selecting the system to be used are covered in [6.2.2](#).

6.2.2 System selection considerations

Selection of the CP system shall be based on the following considerations:

- magnitude of the protective current required;
- resistivity of the seawater;
- availability and location of suitable power sources for impressed-current systems;
- existence of any stray currents causing significant potential fluctuations between pipeline and earth that can preclude the use of galvanic anodes;
- effects of any CP interference currents on adjacent structures that can limit the use of impressed-current CP systems;
- limitations on the space available, due to the proximity of foreign structures, and related construction and maintenance concerns;
- future development of the area and any anticipated future extensions to the pipeline system;

- cost of installation, operation and maintenance;
- reliability of the overall system;
- integrity of other pipelines and/or structures existing in the same area that can be affected by impressed-current systems unless proper measures are taken to prevent these effects.

NOTE Impressed-current systems can be preferred on short pipelines which terminate at platforms that have impressed-current systems installed or where an impressed-current system is operated from the shore. Impressed-current systems can also be preferred as a retrofit system on pipelines with galvanic anode failures, excessive anode consumption, operation beyond original design life or excessive coating deterioration. Impressed current can also be the preferred method for high-resistivity water.

6.3 Isolating joints

Isolating joints should be considered at the following locations:

- at connections to onshore pipelines or onshore receiving facilities;
- at connections to pipelines that require different protection criteria;
- between cathodically protected pipelines and non-protected facilities or less protected facilities;
- between pipeline systems (or structures) protected by impressed current and galvanic anodes;
- at connections between pipelines and appurtenances constructed from dissimilar metals (e.g. pumps and valves).

Electrical isolation of submarine pipelines from onshore electrical earthing systems is essential for effective cathodic protection offshore and onshore. This isolation shall be provided using electrically isolating joints.

Where offshore submarine pipeline CP is provided using galvanic anodes and onshore sections of the pipeline are protected using either impressed current or galvanic anodes, electrical isolation is necessary in order to enable the onshore section to be subject to the performance assessment as in ISO 15589-1. This requires the measurement of IR free pipe/soil potentials on the pipeline. As current flowing to the onshore pipeline from offshore galvanic anodes cannot be interrupted, it is necessary to electrically isolate the onshore pipeline from the offshore pipeline. This is to permit the onshore pipeline CP system to be adequately performance assessed.

This isolation shall be provided using electrically isolating joints. These isolating joints are best located at the landfall or on the seaward side of any emergency shut down valves. They should be located on the seaward side of any electrical or control piping connections to the onshore pipeline, to avoid such connections short circuiting the CP current and negating the effectiveness of the isolation joints.

NOTE 1 If these requirements for isolation joints are not followed, there is a considerable threat that cathodic protection effectiveness be severely impaired and that significantly costly remedial work be necessary in order to maintain pipeline integrity.

If isolating joints are used, they shall be designed in accordance with ISO 15589-1 and installed to ensure long-term integrity and shall be positioned to allow easy access for inspection and maintenance.

ISO 15589-1 requires that monolithic isolation joints be used wherever possible, for all electrical isolation requirements. Unless these joints are exposed to unplanned forces, they have been shown to be much more reliable than the use of insulating gaskets, sleeves and washers in a conventional flange. Due to the impact of isolation failure on pipeline integrity, monolithic isolation joints should be used at the interfaces between offshore and onshore pipelines.

NOTE 2 NACE SP0286-2007, "Electrical Isolation of Cathodically Protected Pipelines", provides information on the design and application of monolithic isolation joints.

7 Design parameters

7.1 General

The design of a pipeline CP system shall be based on:

- detailed information on the pipeline to be protected, including material, length, wall thickness, outside diameter, pipe-laying procedures, route, laying conditions on the sea bottom, temperature profile (operating and shut in) along its whole length, type and thickness of corrosion-protective coating(s) for pipes and fittings, presence, type and thickness of thermal insulation, mechanical protection and/or weight coating;
- environmental conditions, including diurnal and seasonal variations, such as seawater salinity, temperature and resistivity, tides and seabed resistivity along the whole length of the pipeline;
- burial status (extent of backfilling after trenching or natural burial) and soil resistivity;
- design life of the system;
- information on existing pipelines in close proximity to or crossing the new pipeline, including location, ownership and corrosion-control practices;
- information on existing CP systems (platforms, landfalls, subsea structures, etc.) and electrical pipeline isolation;
- availability of electrical power, electrical isolating devices, electrical bonds;
- construction dates, start-up date (required for hot lines);
- presence of fittings, J-tubes, risers, clamps, wyes, tees and other appurtenances;
- performance data on CP systems in the same environment.

If CP performance data for similar environments is not available (e.g. when moving into deeper water), data on the seawater characteristics (dissolved oxygen, salinity, pH, sea currents, and fouling) shall be obtained as these can affect cathodic polarization and calcareous deposit formation. For these situations, the required information shall be obtained from field surveys and/or corrosion test data including the following:

- protective current requirements to meet applicable criteria;
- electrical resistivity of the electrolyte, including seasonal changes if relevant;
- pipe burial depth (if buried) and identification of exposed span lengths and locations;
- water temperature at the seabed;
- oxygen concentration at the seabed;
- water flow rate at the seabed, including seasonal changes if relevant;
- seabed topography.

When reviewing operating experience for existing CP systems, the following should be considered:

- electrical continuity;
- electrical isolation;
- external coating integrity;
- deviation from specifications;
- maintenance and operating data.

Design procedures for the CP based on galvanic anode systems shall be in accordance with [Annex A](#).

7.2 Protection potentials

7.2.1 Potential criteria

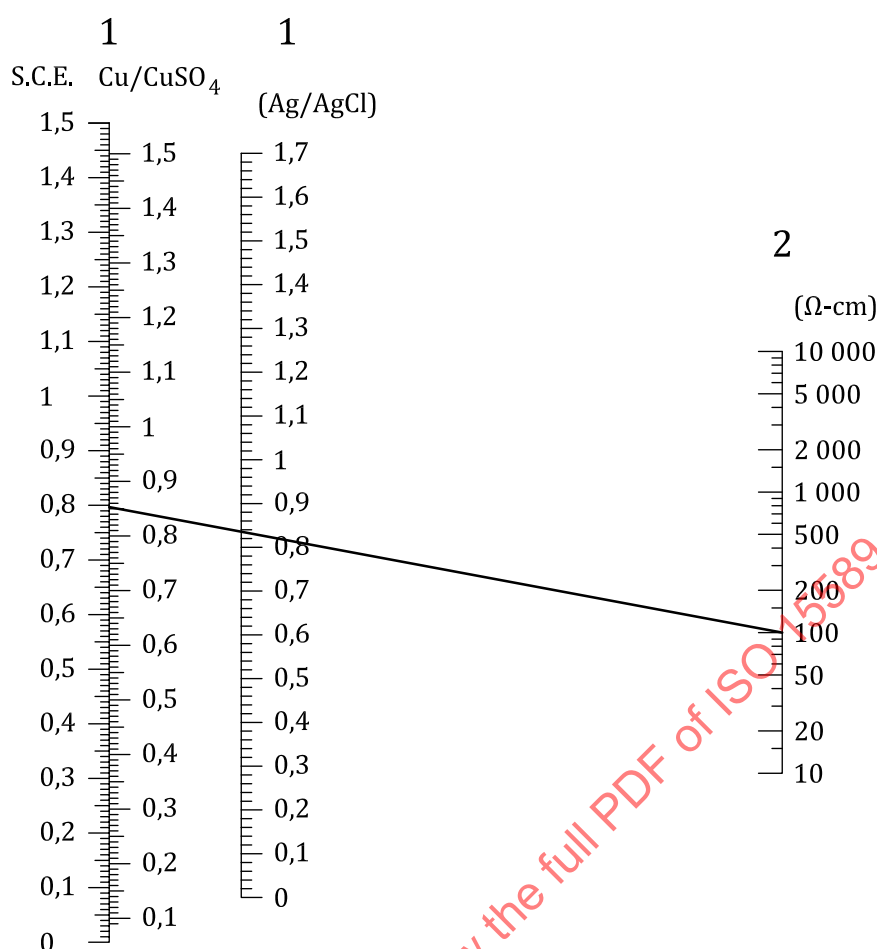
To ensure that adequate CP of a pipeline is being achieved, the measured potential shall be in accordance with [Table 1](#).

NOTE The effectiveness of CP or other external corrosion-control measures can be confirmed by direct measurement of the pipeline potential. However, visual observations of progressive coating deterioration and/or corrosion, for example, are indicators of possible inadequate protection. Physical measurements of a loss of pipe wall thickness, using divers, or using internal inspection devices such as intelligent pigs, can also indicate deficiencies in the level of corrosion protection.

Table 1 — Potential criteria

Materials	Minimum negative potential V	Maximum negative potential ^a V
Carbon steels		
Immersed in seawater	-0,80	-1,10 ^b
Buried	-0,90 ^f	-1,10 ^b
Austenitic stainless steels^g		
PREN $\geq 40^c$	-0,30 ^d	-1,10
PREN $< 40^c$	-0,50 ^d	-1,10
Duplex stainless steels	-0,50 ^d	e
Martensitic stainless (13 % Cr) steels	-0,50 ^d	e
The potentials are referenced to a silver/silver chloride reference electrode (Ag/AgCl/seawater) which are equivalent to an SCE reference electrode, in 30 Ω ·cm seawater.		
^a These negative limits also ensure negligible impact of CP on pipeline coatings.		
^b Where pipeline systems are fabricated from high-strength steel (SMYS > 550 MPa), the most negative potential that can be tolerated without causing hydrogen embrittlement shall be ascertained.		
^c $F_{PREN} = w_{Cr} + 3,3(w_{Mo} + 0,5w_W) + 16w_N$, where F_{PREN} is the PREN; w_{Cr} , w_{Mo} , w_W and w_N are the mass fractions of Cr, Mo, W and N in the stainless steel respectively, expressed in per cent.		
^d For stainless steels, the minimum negative potentials apply for aerobic and anaerobic conditions.		
^e Depending on the strength, specific metallurgical condition and stress level encountered in service, these alloys can be susceptible to hydrogen embrittlement and cracking. If a risk of hydrogen embrittlement exists, then potentials more negative than -0,8 V should be avoided. See also 7.2.2 .		
^f This covers the possibility of SRB activity and/or high pipeline temperature ($T > 60$ °C).		
^g If a metallurgical structure is not fully austenitic, these stainless steels can be susceptible to hydrogen-induced stress cracking (HISC) and potentials more negative than -0,9 V are considered high and should be avoided, unless testing has proven a different limit is applicable.		

The potential of the Ag/AgCl/seawater reference electrode is dependent upon the concentration of chloride ions in the electrolyte, and hence the seawater resistivity. If the chloride concentration and hence the resistivity is known to differ significantly from that of ordinary seawater (typically 3,5 % and 30 Ω ·cm respectively), the protection potential criteria shall be adjusted in accordance with [Figure 1](#).

**Key**

- 1 potential, in negative volts
2 resistivity, in $\Omega \cdot \text{cm}$

Figure 1 — Nomogram for the correction of potential readings made with the Ag/AgCl/seawater electrode in waters of varying resistivity against the SCE and Cu/CuSO₄ (sat) reference electrodes^[17]

EXAMPLE If brackish water of 100 $\Omega \cdot \text{cm}$ resistivity exists at the pipeline potential measurement site, the least negative potential for the effective corrosion-protection electrode is -0,84 V and not -0,80 V as given in [Table 1](#), with reference to the Ag/AgCl/seawater reference electrode.

SCE are seldom used due to its Hg content. Cu/CuSO₄ electrodes should not be used in seawater as contamination by chlorides shifts the potential.

Alternative reference electrodes for specific conditions are given in [D.4.2](#).

7.2.2 HISC evaluation

HISC is a non-ductile mode of failure caused by an interaction between stresses, hydrogen produced by the cathodic protection system and a susceptible material. A special assessment shall be carried out to ensure that the risk of HISC is minimized. All load contributions causing stress and strain shall be included.

For duplex stainless steels, DNV-RP-F112^[9] may be used to assess acceptable stresses and strains.

Fillet welds, doubler plates or aluminothermic welds should not be used directly on high-strength carbon steels (SMYS > 550 MPa), martensitic or duplex stainless steel materials. For martensitic or duplex stainless steel pipelines, installation of galvanic anode cables should be performed to special pipe joints consisting of carbon steel internally clad with CRA or made of other CRA materials which are not susceptible to HISC.

7.2.3 Thermally sprayed aluminium

If a component with thermally sprayed aluminium is cathodically protected at potentials more negative than $-1,15$ V, the thermally sprayed aluminium can suffer corrosion as a consequence of the build-up of alkali at the metal/electrolyte interface. A polarized potential more negative than $-1,15$ V should not be used unless previous test results or operating experience indicate that no significant corrosion will occur.

TSA coating has a corrosion potential more negative than $-0,950$ V (Ag/AgCl/seawater). Unless corrosion of the TSA coating is accounted for in the design, CP for TSA coated surfaces should be designed to provide a protection potential more negative than this.

7.3 CP system design life

The design life of the pipeline CP system shall cover the pipeline lifetime. However, the possibility of future life extension or future pipeline connections should be recognized at the design stage. Provisions should be made to accommodate possible future events and this can include revised coating breakdown criteria and/or incorporating facilities for future anode retrofits.

7.4 Design current densities for bare steel

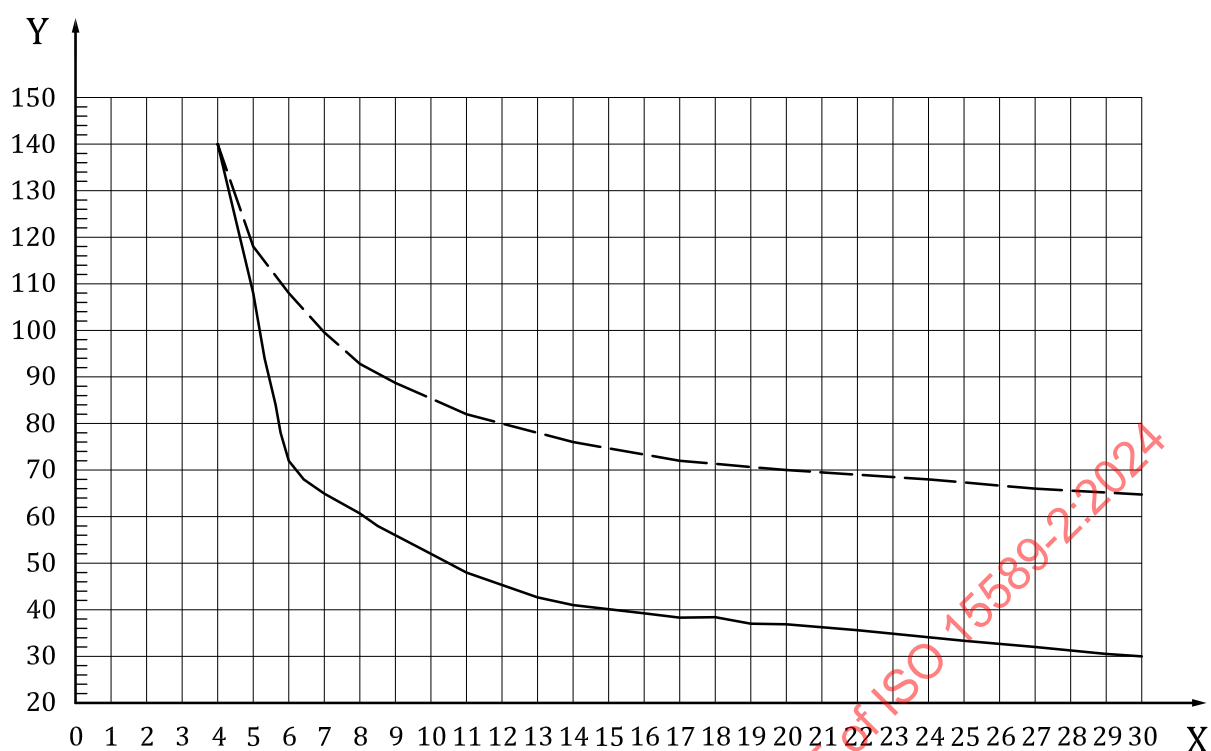
7.4.1 General

The design current densities depend upon the seawater temperature, the oxygen content, the seawater velocity, microbially induced corrosion (MIC) and the ability to build up protective calcareous films on bare metal surfaces.

NOTE 1 In theory, three values of current density are significant: the initial, mean and final current densities, which refer to the current density required to polarize the pipeline within a reasonable period of time (i.e. 1 to 2 months, initial), the current density necessary to maintain the polarization (mean), and the current density necessary for an eventual repolarization which can occur close to the end of the pipeline life (final), e.g. after a heavy storm. For a coated pipeline, the initial current density is never the critical constraint in the design, so it is not considered further in [Annex A](#). Pipelines are located on the seabed and depolarization in storms has not been found to have a significant effect, so the same current density value can be used for the mean and final current densities. This can be inapplicable to pipelines with uncoated field joints.

If it is decided for a specific location that a higher final current density needs to be considered in the design because of storms, a value which is 20 mA/m^2 above the mean value for that temperature may be used.

For most applications in water depth of less than 500 m, the design current densities are dependent only on the seawater temperature, and the current densities for non-buried pipelines should be assessed from [Figure 2](#).

**Key**

X seawater temperature, °C

Y current density, mA/m²**Figure 2 — Mean current density range for non-buried bare steel pipelines**

In [Figure 2](#), the lower current-density curve may be used where there are no significant changes in oxygen content from surface to seabed, with build-up of protective calcareous films, and low to moderate seabed currents (up to 2 knots).

If no other data are known, the upper curve in [Figure 2](#) should be used.

NOTE 2 Calcareous deposits, formed on the exposed surfaces of the pipeline by the application of CP current, reduce the current density required to maintain protective potentials and also improve current distribution. Pipeline coatings also favour the formation of a dense calcareous deposit, because the initial current density is rather high when defects are formed in the coating. However, the solubility of potential film-forming calcareous deposits is dependent on temperature, and colder waters can disallow the formation of protective calcareous deposits or can require higher initial current density to achieve polarization.

NOTE 3 The lower curve was published in Reference [19]. This curve is based on test and field data from many platform and pipeline locations world-wide, collected over a number of years. The upper curve is a conservative curve fit of the data published in DNV-RP-B401 and ISO 13623 and, especially for deep waters, is generally accepted by operators and represents the highest current density values reported normally for seawater saturated with oxygen. The required current density values for a given field lie somewhere between these two extremes.

At temperatures below 4 °C, the mean design current density shall be 140 mA/m², unless otherwise specified, as limited data are available for temperatures below 4 °C.

If the seawater temperature profile along the pipeline route is not known, the required current density shall be based upon the minimum seabed temperature measured, which is usually the temperature at the deepest location along the pipeline route.

If the seawater temperature profile along the pipeline route is known, the curves in [Figure 2](#) should be used with the averaged seawater temperatures to obtain current densities for each pipeline section. If the annual average seawater temperature varies by more than 5 °C over the pipeline length, the pipeline length should be split up into separate sections that cover intervals of no more than 5 °C each. The averaged seawater

temperature should be used for each section. The design current densities discussed above are applicable for CP of bare carbon steel and stainless steel (austenitic, martensitic and duplex).

Current densities may alternatively be based on field measurements or data from facilities installed in the same general geographical location.

EXAMPLE There are specific locations where higher and lower current densities have been reported. These have been related to significant changes in oxygen content with depth, and/or significant seabed currents (see [Table 2](#)).

Table 2 — Examples of design current densities for specific locations

Location	Water depth m	Seawater temperature °C	Mean current density mA/m ²	Comment
US West Coast	> 500	10 to 12	90	moderate current flow
Cook Inlet	all depths	2	380	high seabed currents
Australia	> 500	12 to 18	90	large seasonal temperature variation
Norwegian Sea	> 1 000	−1 to 4	200	cold deep conditions
Offshore Brazil	> 300		130	temperature to be considered

7.4.2 Splash zone

For risers in the splash zone, current densities selected shall be 10 mA/m² higher than for the equivalent riser or pipeline below the splash zone (at the same temperature).

NOTE Splash zone depths vary by location; for example, in the North Sea, splash zones typically extend down to −10 m, whereas in the South China Sea, the splash zones typically extend down to −1 m.

7.4.3 Buried pipelines

For pipelines fully buried in sediments (trenched and naturally buried) or artificially covered (e.g. rock dumping), a design current density (mean and final) of 20 mA/m² should be used, irrespective of seawater temperature, oxygen content or depth.

7.4.4 Thermally sprayed aluminium coated pipelines

For TSA a current density of 0,01 A/m² is used.

7.4.5 Elevated temperatures

Pipelines operating with temperatures in excess of 25 °C on the outside metallic surface of the pipe require an adjustment to the design current density. The design current densities shall be increased by 1 mA/m² for each degree Celsius of the metal/environment above 25 °C up to 100 °C.

The corresponding increase for TSA coated steel is 0,2 mA/m² per degree Celsius.

NOTE Increasing water temperature decreases oxygen solubility. Increasing temperatures also accelerate the corrosion rate.

7.4.6 Current drains

If subsea facilities are connected to the pipeline CP system, the current drain to subsea structures, wellheads, manifolds and well casing shall be included in the design, unless they are provided with a separate CP system. An allowance should be included in the total design current requirements to compensate for the current load imposed by the well casings below the mudline. The typical design current for wells should be between 5 A and 8 A per well.

7.5 Coating breakdown factors

The current demand of a coated pipeline increases with time as the coating deteriorates. Enough cathodic protection capacity should be provided to maintain protection as the coating deteriorates.

These coating breakdown factors shall be applied to calculate the bare metal surface areas of the coated pipe for mean conditions and at the end of the design life respectively (see [Annex A](#)). Mean and final coating breakdown factors shall be calculated as follows.

The mean coating breakdown factor, $\bar{f}_c$, is given by [Formula \(1\)](#):

$$\bar{f}_c = f_i + (0,5\Delta f \times t_{dl}) \quad (1)$$

The final coating breakdown factor, f_f , is given by [Formula \(2\)](#):

$$f_f = f_i + (\Delta f \times t_{dl}) \quad (2)$$

where

f_i is the initial coating breakdown factor at the start of pipeline operation;

Δf is the average yearly increase in the coating breakdown factor;

t_{dl} is the design life, expressed in years.

The coating breakdown factors given in [Tables 3](#) and [4](#) should be considered. Coating breakdown factors for pipeline coatings not included in [Tables 3](#) and [4](#) shall be fully documented.

NOTE 1 Typical parameters f_i and Δf are given in [Table 3](#) (for pipelines without concrete weight coating) and [Table 4](#) (for pipelines with concrete weight coating), which address combinations of the most common coating systems used for corrosion prevention or thermal insulation. The coating breakdown factors given refer to both seawater exposed pipelines and pipelines buried in the seabed.

NOTE 2 The coating breakdown factors are based on coating quality being in accordance with the various parts of ISO 21809 or with other commonly applied industry standards specifying an equal level of quality coatings. The coating breakdown factors include some allowance for damage to pipeline coatings during fabrication, handling, transportation, installation or operation such as third-party damage (e.g. anchors, trawl gear). However, they do not include allowance for extreme damage or for field joints intentionally left uncoated.

If extreme damage (due to trawling or drilling activities) or uncoated field joints are anticipated, the affected surface area shall be estimated and included in design calculations as bare metal surface ($f_c = 1$), or increase the coating breakdown factors in [Tables 3](#) and [4](#). In this case, initial current demand needs to be considered too. Coating breakdown factors are not applicable for TSA, see [7.4.4](#).

Table 3 — Coating breakdown factors, f_c , for pipelines without concrete weight coating

Factory-applied coating type	Field joint coating type	f_i	Δf
Fusion-bonded epoxy (FBE)	Heat-shrinkable sleeves (HSS ^a)	0,080	0,003 5
	FBE	0,060	0,003
Three-layer coating systems including epoxy, adhesive and polyethylene (3LPE)	HSS ^a	0,009	0,000 6
	FBE	0,008	0,000 5
	Multilayer coating including epoxy and PE (e.g. moulded, HSS ^a or flame spray)	0,007	0,000 5
^a HSS can be used with or without primer.			

Table 3 (continued)

Factory-applied coating type	Field joint coating type	f_i	Δf
Three-layer coating systems including epoxy, adhesive and polypropylene (3LPP)	HSS ^a	0,008	0,000 5
	FBE	0,008	0,000 5
	Multilayer coating including epoxy and PP (e.g. HSS ^a , hot tapes, moulding or flame spray)	0,007	0,000 3
Heat insulation multilayer coating systems including epoxy, adhesive and/or PE, PP or PU	Thick multilayer coating systems including epoxy, adhesive and/or PE, PP, PU, HSS ^a or a combination of these products.	0,002	0,000 1
Thick coatings: elastomeric materials (e.g. polychloroprene or EPDM) or glassfibre-reinforced resins	Thick elastomeric materials or glassfibre-reinforced resins	0,002	0,000 1
Flexible pipelines	Not applicable (mechanical couplings)	0,002	0,000 1

^a HSS can be used with or without primer.

Table 4 — Coating breakdown factors, f_c , for pipelines with concrete weight coating

Factory-applied coating type	Field joint infill	Field joint coating type	f_i	Δf
Asphalt or coal tar enamel	no	Cold-applied tapes (CAT ^a) or heat-shrinkable sleeves (HSS) over a wire-brushed surface to St 3	0,045	0,002 5
		Cold-applied tapes (CAT ^a) or heat-shrinkable sleeves (HSS) over a blast-cleaned surface to Sa 2 ½	0,040	0,002 0
	yes	CAT ^a	0,030	0,001 5
		HSS	0,020	0,000 8
Fusion bonded epoxy (FBE)	no	HSS	0,045	0,002 5
		FBE	0,035	0,002 0
	yes	HSS	0,040	0,002 0
		FBE	0,030	0,001 5
Three-layer coating systems including epoxy, adhesive and polyethylene (3LPE)	no	HSS or FBE,	0,008	0,000 5
		Multilayer coating including epoxy and PE (e.g. HSS, or flame spray)	0,007	0,000 3
	yes	HSS or FBE	0,004	0,000 2
		Multilayer coating including epoxy and PE (e.g. HSS or flame spray)	0,004	0,000 2
Three-layer coating systems including epoxy, adhesive and polypropylene (3LPP)	no	HSS or FBE	0,007	0,000 3
		Multilayer coating including epoxy and PP (e.g. HSS, moulded or flame spray)	0,005	0,000 2
	yes	HSS or FBE	0,004	0,000 2
		Multilayer coating including epoxy and PP (e.g. HSS, moulded or flame spray)	0,004	0,000 2

^a CAT should be applied with primer.

For heat insulation covered with concrete coating, the values for heat insulation in [Table 3](#) should be used.

8 Galvanic anodes

8.1 Design of system

The galvanic anode system shall be designed by locating properly shaped and sized anodes along the pipeline such that sufficient current is delivered to the pipeline to maintain the required potentials throughout the design life.

NOTE 1 Normally, the CP system consists of bracelet anodes distributed at regular intervals along the pipeline.

Design calculations for the CP systems shall demonstrate that the anodes give the pipeline the necessary current to meet the current density requirements. The anodes shall deliver sufficient current to meet the mean and final design current demands.

NOTE 2 The weight and shape of individual anodes can be limited by anode manufacturing and handling constraints.

If anode sleds are used, alternative methods for distribution and connection to the pipeline should be considered.

The spacing between bracelet anodes shall be determined together with the number of anodes. The spacing shall be close enough to maintain an adequate protection in the event of mechanical or electrical loss of a single anode. This can be satisfied by ensuring the distance between effective anodes is less than the attenuation length calculated in accordance with [Annex B](#) or other mathematical modelling accepted by the pipeline operator. In cases where anode mass is the driver for the anode spacing, compensation for mechanical or electrical loss of a single anode should be considered for the whole pipeline. In any case, anode spacing should not exceed 300 m unless documented by attenuation calculations.

Design approach for anode sleds cathodic protection systems is the same except that the attenuation shall be calculated based on all anodes on the sled rather than an individual anode. It is not necessary to consider a complete loss of the anode sled. However, adequate redundancy on the connection system/cable (to the pipeline) shall be provided since the risk of losing connection in these systems is higher risk than the risk of losing an anode (sleds).

For short pipelines, anodes may be installed at each end of the pipeline if it can be demonstrated by mathematical calculations or modelling that CP can be achieved. Typically, this type of installation is used on inter-platform pipelines. Anodes for the pipeline can be attached to the platform if the pipeline is electrically connected to the platform. Attenuation calculations shall be carried out in accordance with [Annex B](#) for these installations to determine whether it is feasible to protect the mid-point of the pipeline using anodes located at the ends.

Extra anodes should be placed on the portion of the pipeline that is near a structure, platform or shore approach. A factor of 2 should be included in the calculated design current demand for the first 1 000 m in the absence of specific information

NOTE 3 The reasons for adding extra anodes include, but are not limited to:

- increased risk of pipeline coating damage due to dropped objects and vessel anchors;
- possibility of an increased current drain;
- likelihood that the pipeline potential is more negative than that on the platform, so that the pipeline anodes near the structure will also provide current to the platform.

All these factors increase current output from the anodes and reduce anode life.

Anodes and anode supports shall be designed to avoid any sharp edges or corners or protruding assemblies which can be hazardous to personnel (see also [Annex E](#)). This latter requirement particularly applies to diving operations conducted near anode installations.

NOTE 4 Further information on galvanic anodes is given in EN 12496^[10].

8.2 Selection of anode material

The alloy selected shall be one that has given a satisfactory performance under similar field conditions, or in long-term laboratory and field trials in a simulated environment. Although not mandatory, a test method to qualify the electrochemical performance of galvanic anodes can be found in Section 10 of DNV-RP-B401, see [Annex C](#).

Unless otherwise documented, aluminium anodes should not be used below 0,5 ‰ (mass/volume) salinity.

Zinc anodes should not be used at temperatures exceeding 50 °C unless their performance is supported by appropriate test data that confirms satisfactory performance. Intergranular corrosion and/or a reduction in electrochemical capacity are the main problems for zinc anodes at elevated temperatures.

The galvanic anode alloys developed for marine applications have been specifically conceived to perform in seawater with an alkaline pH, high salinity and a significant content of oxygen. For some areas, the seawater and mud conditions can be very different, such as being totally anaerobic with large concentrations of SRBs and sulphides. In addition, the salinities can be low. This can be of importance for anode selection. Long term testing in appropriate environments should be considered and suitable test procedures agreed.

NOTE 1 Aluminium and zinc alloys are the materials most often used as galvanic anodes on pipelines. Typical compositions are respectively given in [9.4](#) and [9.5](#).

NOTE 2 Aluminium alloy anodes have decreased electrochemical efficiency at elevated temperatures. Certain aluminium alloy compositions can be unsuitable at elevated temperatures.

NOTE 3 The behaviour of certain aluminium alloys can be adversely affected by burial in seabed mud, particularly if the current output remains low.

NOTE 4 Aluminium alloys containing magnesium can suffer ageing with a loss of mechanical properties.

8.3 Electrochemical properties

For design purposes, the values quoted in [Table 5](#) should be used. Alternative values for the electrochemical capacities of galvanic anodes may be used if the data are properly documented by testing as detailed in [Annex C](#). The electrochemical properties shall be documented for the relevant anode operating temperatures.

Table 5 — Design values for galvanic anodes

Anode type	Anode surface temperature ^a	Immersed in seawater		Buried in seawater sediments	
		Potential	Electrochemical capacity	Potential	Electrochemical capacity
		Ag/AgCl/seawater	ε	Ag/AgCl/seawater	ε
	°C	mV	A·h/kg	mV	A·h/kg
Aluminium	< 30	– 1 050	2 000	– 1 000	1 500
	60	– 1 050	1 500	– 1 000	800
	80 ^b	– 1 000	900	– 1 000	400
Zinc	< 30	– 1 030	780	– 980	750
	> 30 to 50 ^c			– 980	580

Electrochemical capacity for a given alloy is a function of temperature and anode current density. Reference is made to [Annex A](#) for guidance on CP design for variations in anode current densities.

For non-buried pipelines, the anode surface temperature should be taken as the external pipeline temperature and not the internal fluid temperature.

^a For anode surface temperatures between the limits stated, the electrochemical capacity shall be interpolated.

^b For aluminium anodes, the anode performance values are only applicable up to anode surface temperature shall not exceed of 80 °C unless the performance has been demonstrated in tests and has been documented.

^c For zinc anodes, the anode performance values are only applicable up to anode surface temperature of 50 °C unless satisfactory performance has been demonstrated in tests and has been documented.

Pipelines which are rock-dumped shall be considered as buried in seawater sediments.

The design values in Table 5 are applicable to seawater with a typical salinity of 3,5 ‰ (mass/volume. For salinities below 1,2 ‰ (mass/volume, the design values given for anodes buried in sediments should be used.

NOTE 1 The electrochemical capacity can be lower for aluminium in brackish water than in ocean seawater.

For buried pipelines the following apply:

- for non-insulated pipelines the anode surface temperature shall be taken as the internal fluid temperature;
- for insulated pipelines, or when anodes are thermally isolated from the pipeline, the anode surface temperature shall be calculated.

For pipelines or pipeline section where incomplete self-burial is expected, the base case is to design as the pipeline and anodes are freely sea water exposed when internal fluid temperature is equal to or below 25 °C.

For pipelines with internal fluid temperature above 25 °C, the design shall be determined by the most conservative of the following cases:

- a) pipelines and anodes either fully exposed to sea water (0 % burial);
- b) fully buried (100 % burial).

NOTE 2 Anode compositions which have been qualified for one set of operating conditions (e.g. low temperature, unburied) can be unsuitable for use under other conditions (e.g. high temperature, buried).

8.4 Anode shape and utilization factor

The internal diameter of a bracelet anode should be determined by the outside diameter of the pipe and the thickness of coatings applied. Tolerances of the outer diameter of pipe and coating thickness should be taken into account.

Depending on the pipeline installation method, the anodes can be susceptible to damage. This concern is critical when the anodes pass over a stinger as the pipeline leaves the lay barge.

For non-weight-coated pipelines, anodes with either tapered shoulders or taper cones should be used to reduce the risk of the anodes catching on the stinger rollers.

For weight-coated pipelines, the thickness of anodes should match the thickness of the weight coating, such that the anodes will roll smoothly over the stinger rollers.

NOTE A variety of galvanic anode designs are available for attachment to the pipeline. Semi-cylindrical bracelets with tapered and square shoulders are available for use on small- and medium-diameter pipelines. For larger-diameter pipelines where semi-cylindrical anodes would be impractical, segmented designs are available. For special circumstances, anodes can sometimes be cast directly onto the pipe.

The core shall be designed to maintain electrical integrity with the anode body for the full design life of the anode.

Anodes shall be designed in such a way that a utilization factor, μ , is assured. The insert shall be designed in order to deliver the utilization factor in the CP design premise. Subject to the design of the inserts being able to deliver it, the following utilization factors may be used:

- bracelet anodes = 0,80;
- slender anodes = 0,90 maximum;
- short flush mounted anodes = 0,80;
- long flush mounted anodes = 0,85;
- stand-off anodes = 0,90.

Flush-mounted anodes are classified as short or long based on their length (L) to width (b) and length to thickness (d) ratios as follows:

- long flush-mounted anode = $L \geq 4b$ and $L \geq 4d$;
- short flush-mounted anode = $L < 4b$ and $L < 4d$.

The position of the anode insert within the body of the anode material shall be such that the remaining anode weight at the end of the design life is fully supported by the steel core and be electrically connected to pipeline so that the specified utilization factors are achieved.

In bracelet and flush-mounted anodes the insert should be placed as close as possible to the surface of the anode that will be adjacent to the structure (typical distance 8 mm to 10 mm). The anode material below the insert shall not be considered utilizable. In some cases, a utilisation factor of 0,8 is not achievable and this should be reflected in the CP design.

8.5 Electrical considerations

The electrical connection between the pipeline and the anode is generally made by a bonding wire or direct welding of the anode core to the pipeline. The bonding wire can be attached by a variety of methods, including aluminothermic welding and pin brazing. The attachment method shall be compatible with the requirements of the pipe lay method and the metallurgy of the pipeline steel (see 7.2.2).

Anode core extensions of bracelet half-shells are generally oriented in the longitudinal direction of the half-shell and at the mid-point of the half-shell cross-section. Anode core extensions, usually a flat steel bar, should be fully welded to the core and the dimensions should be compatible with the pipe dimensions and material.

9 Galvanic anode manufacturing

9.1 Pre-production test

The detailed anode design shall include anode drawings showing shape and dimensions with tolerances. Prior to fabrication of the anodes, a pre-production test shall be carried out at the foundry to ascertain that all moulds, cores, casting equipment and other components are in accordance with applicable standards, governing drawings, dimensions, tolerances, inspection procedures and data sheets.

At least one of the anode cast assemblies should be inspected destructively in accordance with 10.9.

Other types of procedure qualification may be considered.

9.2 Coating

Bracelet anodes should be coated on the sides facing the pipeline and the concrete weight coating. The coating applied to the anode faces should be an immersion-grade two-component epoxy with a minimum thickness of 100 μm . Coating sides of other anode types should also be considered.

The exposed (external) surface of the anode shall be free from coating.

9.3 Anode core materials

Anode cores shall be fabricated from weldable structural steel plate/sections in accordance with to the EN 10025 series, the ISO 630 series, or equivalent standards. Anode core materials to be welded to the pipeline shall be compatible with the pipeline material or structural elements to which it is attached, and

the carbon equivalent (CE) shall not exceed the CE value of the pipeline material, or maximum 0,45. The CE value shall be calculated using [Formula \(3\)](#).

$$w_{CE} = w_C + w_{Mn}/6 + (w_{Cr} + w_{Mo} + w_V)/5 + (w_{Ni} + w_{Cu})/15 \quad (3)$$

where the symbols with the elements as subscripts represent the mass fractions of the corresponding elements.

If the full chemical composition is not reported, the alternative w_{CE} value of [Formula \(4\)](#) may be used.

$$w_{CE} = w_C + w_{Mn}/6 + 0,04 \quad (4)$$

NOTE In the industry, the symbols for the elements (i.e. CE, C, Mn, Cr, Mo, V, Ni and Cu) are used directly in some documents to represent the mass fractions of the corresponding elements.

The material certificate for the anode cores shall meet the requirements of EN 10204:2004, 3.1, or equivalent.

Welding of steel anode cores shall be in accordance with the relevant requirements of AWS D1.1/D1.1M or technically equivalent standards. Welding shall be performed by welders qualified according to ISO 9606-1 or AWS D1.1/D1.1M or technically equivalent standards. Qualification of welding procedures shall be in accordance with the requirements of ISO 15607, AWS D1.1/D1.1M, or technically equivalent standard.

Anode core steel for aluminium anodes shall be blast-cleaned to Sa 2½ in accordance with ISO 8501-1 prior to casting and maintained until casting commences.

Anode core steel for zinc anodes shall be blast-cleaned to the minimum standard Sa 2½ in accordance with ISO 8501-1 or galvanized according to ISO 1461 or equivalent. Rust discoloration and/or visual surface contamination of zinc-coated surfaces shall not be permitted. The degree of cleanliness shall be maintained until casting.

9.4 Aluminium anode materials

The aluminium anode material shall be Al-Zn-In alloy. The chemical composition of the anodes shall be formulated and demonstrated to meet the potential and electrochemical capacity requirements of the project design. Typical chemical compositions are given in [Table 6](#), but specific alloys have been developed with optimum performance which have smaller composition ranges, within the limits below. Other compositions may be used if testing demonstrates that they meet the required anode electrochemical properties for the project design.

Table 6 — Typical chemical composition of aluminium anode materials

Element ^a	Mass fraction range <i>w</i> (%)	
	Typical alloy limits A	Typical alloy limits B
Zn	3,0 to 5,5	4,75 to 5,75
In	0,016 to 0,040	0,016 to 0,020
Ga	-	-
Fe	0,09 max	0,06
Si	0,10 max	0,08 to 0,12
Cu	0,005 max	0,003 max
Cd	0,002 max	0,002 max

Table 6 (continued)

Element ^a	Mass fraction range <i>w</i> (%)	
	Typical alloy limits A	Typical alloy limits B
Other impurities (each)	0,02 max	0,02 max
Other impurities (total)	0,1 max	0,05 max
Al	Remainder	

Alloy A is generally used in offshore applications in temperate waters.

Alloy B is generally used for cold deep conditions (see [Table 2](#)).

Further details on anode compositions are in EN 12496 (being replaced by ISO 9351).

9.5 Zinc anode materials

A typical chemical composition known to perform well in many conditions is given in [Table 7](#).

Table 7 — Typical chemical composition of zinc anode materials

Element	Mass fraction	
	min. %	max. %
Cu	—	0,005
Al	0,10	0,50
Fe	—	0,005
Cd	0,025	0,07
Pb	—	0,006
Zn	Remainder	

Other compositions may be used if testing demonstrates that they meet the required anode electrochemical properties. EN 12496 (being replaced by ISO 9351) gives alternative compositions for zinc anodes. Caution should be exercised when any element falls outside the specified range, as anode performance may be less than the design requires.

10 Galvanic anode quality control

10.1 General

A quality control procedure shall be followed to ensure that the requirements in this clause are met.

10.2 Steel anode cores

All welds shall be visually inspected.

Required surface finish shall be verified by visual inspection immediately prior to casting.

10.3 Chemical analysis of anode alloy

Two samples from each heat shall be taken for chemical analysis. The samples shall be taken in the beginning and at the end of casting from the pouring stream. For smaller alloying furnaces (max. 500 kg), it is acceptable to take one sample per heat. The sample shall be taken at the beginning of the first heat and at

the end of the second heat, then in the beginning of the third heat and so on. The samples shall be analysed to verify the required chemical composition.

Anodes from heats whose chemical composition do not meet the required chemical composition shall be rejected.

10.4 Anode mass

Individual anode castings of each type shall have a net mass within ± 3 % of the nominal net mass for anode castings with total mass above 50 kg. For anode castings below 50 kg, the mass tolerances shall be ± 5 % unless otherwise agreed between the end user and the relevant parties.

At least 10 % of the total number of anode castings shall be weighed to confirm conformity with this requirement. If agreed between the end user and the relevant parties, the weighing can be done in groups, which gives an average individual weight.

The total net mass of anodes shall not be less than the nominal value. A maximum value can be agreed between the end user and the relevant parties.

10.5 Anode dimensions and straightness

10.5.1 Slender anodes

The anode dimensions and straightness for slender anodes shall conform to the following:

- anode length shall be within ± 3 % of the nominal length or ± 25 mm, whichever is smaller;
- anode mean width shall be within ± 5 % of the nominal mean width;
- anode depth shall be within ± 10 % of the nominal mean depth;
- the diameter of cylindrical anodes shall be within $\pm 2,5$ % of the nominal diameter;
- the straightness of the anode shall not deviate by more than 2 % of the anode nominal length from the longitudinal axis of the anode.

At least 10 % of the total number of anodes shall be checked to confirm conformity with these requirements.

10.5.2 Bracelet anodes

Each bracelet anode length shall be within ± 3 % of the nominal length or ± 25 mm, whichever is smaller.

The anode internal diameter shall conform to the following dimensional tolerances:

0 / +4 mm for pipeline diameters	≤ 300 mm
0 / +6 mm for pipeline diameters	> 300 mm and ≤ 610 mm
0 / +1 % for pipeline diameters	> 610 mm

The dimensional tolerance on the anode thickness shall be ± 3 mm.

At least 10 % of the total number of anodes shall be checked to confirm conformity with these requirements.

Anodes shall be free from excessive bowing or twisting. The anode casting shall not deviate by more than 2 % of the anode nominal axial length from the longitudinal axis of the anode. At least one completely assembled bracelet anode shall be fitted. This shall be verified by fitting an agreed number of bracelet assemblies to a full-length former or by an equivalent method. The external diameter shall not exceed the summation of tolerances given above.

10.6 Anode core dimensions and position

Tolerances on the anode core position within the anode shall be subject to agreement prior to fabrication, to conform with utilization factor requirements, and should be part of the fabrication quality plan. Anode core protrusions and any other critical dimensions shall be measured and shall conform to specified requirements. EN 12496^[10], NACE SP 0387^[28] and NACE SP 0492^[27] provide guidance on acceptable tolerances for anode steel core location within cast anodes. Tolerances and core design should be agreed in order to deliver the utilisation factor and structural requirements of the design.

10.7 Anode surface irregularities

10.7.1 Slender anodes

Slender anodes shall be inspected visually to confirm conformity with the following requirements:

- shrinkage depressions shall not exceed 10 % of the nominal depth of the anode material to the anode core, as measured from the plane of the anode surface to the bottom of the depression;
- in the topping-up area, the maximum shrinkage shall not be more than a 10 mm depth measured from a straight edge across the topping-up face and not more than 0,5 % of the gross anode volume; any additional topping-up materials or casting surface irregularities shall be fully bonded to the bulk anode material;
- cold shuts shall not exceed a depth of 10 mm and/or extend over a total length of more than three times the width of the anode;
- all protrusions that are hazardous to personnel during handling shall be removed.

10.7.2 Bracelet anodes

Bracelet anodes shall be inspected visually to confirm conformity with the following requirements:

- shrinkage depressions shall be <10 % of the thickness of the anode as measured from the uppermost corner to the bottom of the depression. Shrinkage depressions that expose the anode core are not acceptable;
- in the topping-up area, the maximum shrinkage shall not be more than 10 mm measured from a straight edge across the topping-up face and not more than 0,5 % of the gross anode volume. Any additional topping-up materials or casting surface irregularities shall be fully bonded to the anode material;
- any cold shuts shall be <10 mm depth and/or extend over a total length of < 150 mm;
- all protrusions that are hazardous to personnel during handling of the anode(s) shall be removed.

10.8 Cracks

10.8.1 General

All anodes shall be inspected for cracks.

NOTE Cracks can occur while cooling during the casting of galvanic anode bracelets because of the different coefficients of expansion of the anode and the core. These cracks are not detrimental, provided they do not converge in a manner that allows loss of anode material.

No treatment shall be applied to grind, peen, or in any other manner dress cracks before inspection and checks.

Zinc anodes shall be free from visible cracking without the aid of magnification.

Cracks may be accepted in aluminium anodes provided the cracks do not cause any mechanical failure during installation, transportation or service of the anode. The combination of cracks and lack of bond to the

anode core and cracks in the area where the anodes are not fully supported by the anode core shall not be accepted. For aluminium, the cracking criteria given in [10.8.2](#) and [10.8.3](#) shall apply.

10.8.2 Aluminium slender anodes

The following cracking criteria shall apply:

- for sections of anode material not fully supported by the anode core, no visible cracks shall be permitted without magnification;
- cracks within the section of an anode supported by the anode core are not acceptable if the length is > 100 mm and/or the width > 1 mm;
- cracks penetrating to the steel anode cores or through the anode are not permitted;
- a maximum of 10 cracks per anode with small dense cracks counting as one and cracks $< 0,5$ mm wide not counted.

Longitudinal cracks are not permitted.

10.8.3 Aluminium bracelet anodes

The following cracking criteria shall apply:

- for sections of anode material not fully supported by the anode core, no visible cracks shall be permitted without magnification;
- cracks penetrating to the steel anode cores or through the anode are not permitted;
- cracks with a length of > 100 mm or > 50 % of the anode diameter (whichever is greater) and/or width > 3 mm are not acceptable.

Provided the above is satisfied, the following cracks are acceptable in transverse direction:

- cracks with a length of ≤ 50 mm or ≤ 20 % of the anode diameter, whichever is less, and a width < 3 mm;
- cracks with a length of 50 mm to 200 mm or between 20 % and 50 % of the anode diameter, whichever is less, and a width < 1 mm;
- cracks with a length of 50 mm to 200 mm are limited to two per half-bracelet or four per anode.

Cracks in the longitudinal direction shall be < 100 mm in length or < 20 % of anode length, whichever is less, and/or ≤ 1 mm in width.

10.9 Internal defects, destructive testing

The number and method of selection of anodes to be destructively tested (sectioned) within each anode type/size shall take into account anode design, the total number of anodes, and the pre-production test requirements (see [9.1](#)).

If an anode does not meet the requirements below, an additional anode shall be subjected to destructive testing. If this does not satisfy the specified requirements, the whole anode lot shall be rejected or other actions taken as agreed prior to fabrication.

Slender anodes should be sectioned transversely at 25 %, 33 % and 50 % of the nominal length, or at other agreed locations for a particular anode design. The cut faces, when examined visually without magnification, shall conform to the following criteria.

- Gas holes and porosities shall be limited to maximum 2 % of the total cut surface area, and maximum 5 % of any individual cut surface area. No cavity shall exceed 1 cm^2 .

- Non-metallic inclusions shall be limited to maximum 1 % of the total cut surface area and maximum 2 % of any individual cut surface area. No non-metallic surface shall exceed 1 cm².
- Lack of bond (voids) shall be limited to maximum 10 % of the total tubular anode core circumference and maximum 20 % of the circumference for any individual cut.

Bracelet anodes should be sectioned transversely by cuts at 25 % and 50 % of the nominal length, or at other agreed locations for a particular anode design. The cut faces, when examined visually without magnification, shall conform to the following criteria.

- Gas holes and porosities shall be limited to maximum 2 % of the total cut surface area, and maximum 5 % of any individual cut surface area. No cavity shall exceed 1 cm².
- Non-metallic inclusions shall be limited to maximum 1 % of the total cut surface area and maximum 2 % of any individual cut surface area. No non-metallic surface shall exceed 1 cm².
- Lack of bond (voids) adjacent to the anode core shall be limited to maximum 10 % of the total anode core perimeter and maximum 20 % of any individual cut.

The conformance of the anode core position within the anode body in accordance with the design drawings shall be confirmed by physical measurement on the cut faces.

Other types of procedure qualification may be considered based on agreement between the end user and the relevant parties.

10.10 Electrochemical quality control testing

The following shall be assessed:

- closed-circuit potential;
- electrochemical capacity;
- corrosion pattern (uneven consumption, intergranular attack, passivity, etc.).

One set of tests shall be carried out for each 15 t of anodes produced. The electrochemical test data shall be reported.

Testing shall be carried out in natural seawater or in artificial seawater in accordance with ASTM D1141.

The test shall be conducted using the procedure described either in DNV-RP-B401 Section 9 or in NACE TM0190.

Test results shall meet the acceptance criteria in [Table 8](#). For other testing procedures, acceptance criteria shall be documented in the test procedure.

Table 8 — Recommended acceptance criteria for electrochemical performance (production quality testing)

Anode type	Minimum electrochemical capacity A·h/kg	Closed-circuit potential (at end of testing) mV (Ag/AgCl seawater)
Aluminium	2 500	– 1 050
Zinc	780	– 1 030

If the specified requirements are not met, re-tests shall be carried out on three specimens from each heat that failed to meet the requirements. Failure of any of these three specimens to meet the specified requirements shall lead to rejection or other actions taken as agreed prior to fabrication of all anodes from the heat(s) involved.

The tested anode sample surface shall not show any signs of passivity or intergranular attack.

11 Galvanic anode installation

All welding procedures and welders qualification for the attachment of anodes to pipelines shall be in accordance with the relevant requirements of AWS D1.1/D1.1M or equivalent.

NOTE The above does not override the pipeline fabrication requirements which can mandate standards to be met for the welding of attachments to the pipeline.

Bracelet anodes shall be bolted on, or welded to, the pipeline.

For bracelet anodes mounted on pipe joints that are concrete-weight-coated, electrical contact between the concrete reinforcement and the anodes shall be avoided by providing a gap, typically of 25 mm, at each end of the anode. Gaps between bracelet anode half-shells and between half-shells and the concrete shall be filled with non-conductive mastic or similar compound.

Anode installation shall be carried out in such a way that damage to the pipeline coating is minimized.

After installation of the anode-to-pipe connection, the pipeline coating shall be repaired using a compatible coating material.

The anode-to-pipeline connection shall be designed to ensure adequate mechanical strength and electrical continuity and to prevent damage to the pipe at the point of connection.

A detailed anode-to-pipeline connection design shall be included as one of the detailed anode design drawings. Welding of cable connections shall not be carried out on bends or within 200 mm from pipeline welds.

For aluminothermic welding of cables, the welding procedure shall be such that copper penetration into the pipeline material shall be less than 1 mm and local pipeline hardness shall remain within the requirements given in the pipeline specification.

Aluminothermic weld charges should not be greater than 15 g. If cables larger than 16 mm² need to be attached, the cores shall be separated into a number of smaller strands, each measuring less than 16 mm² and welded separately.

Aluminothermic welding should not be carried out on corrosion-resistant alloy pipelines. Alternative methods such as pin brazing, soft soldering, adhesive bonding or friction welding may be used, provided that the detailed procedure and performance are reliable and properly documented.

All items to be protected by CP shall be electrically connected and should have a welded or brazed connection to an anode. All bolted or clamped components with a surface area exceeding 1 m² shall have an all-welded or brazed connection to an anode. For all bolted or clamped assemblies without an all-welded or brazed electrical connection, it shall be verified that the electric resistance is less than 0,1 Ω in accordance with a procedure accepted by the operator/end user. The pipeline coating on contact surfaces shall be removed prior to making the connection.

Cables shall be copper-cored and shall be insulated and sheathed to withstand the prevailing chemical and mechanical conditions. The minimum conductor size for measurement cables shall be 4 mm². Cables shall be sized such that no excessive voltage drops occur which reduce the capacity of the system.

If the contact is made by using current-carrying copper cables welded or brazed at each end, these shall be stranded and have a minimum cross-section of 16 mm² and brazed to the cable shoe. At least two cables per anode shall be installed. For half-shell anodes, two half-shells shall be considered as a single anode.

When electrical continuity is achieved by direct welding of core extensions, a doubler pad should be pre-installed on the pipeline to avoid detrimental effects of the fillet welds and the external coating.

For pipelines coated with thick insulating coating systems, the anodes may be placed on the outside of the coating and electrical connection may be made to a steel bracket with a doubler pad arranged to provide a surface for the attachment which is flush with the outer diameter of the insulating coating.

After the attachment process, the area shall be coated with a compatible coating system.

Typically, anodes are attached directly to the pipeline and installed onshore/on the vessel. Underwater installation of anodes should only be utilized in exceptional cases (e.g. the retrofit of a CP system or the use of remote anode assemblies).

Bolted connections with set screws or friction welding may be considered for the electrical connection of anode retrofit systems.

12 Impressed-current CP systems

12.1 Current sources and control

NOTE Impressed-current systems utilize a DC power supply as the current source. Statutory requirements can apply for its design, installation and operation.

Separate negative connections shall be installed for each pipeline to be protected, independent of any negative connection to the platform or any land-based installation. Negative connections shall be terminated in a control box. There shall be a facility to regulate and measure the protective current to each pipeline.

The control of the DC power supply current output can be manual or automatic. In the first case, either current or voltage control may be used, while automatic control shall be based on potential readings from fixed reference electrodes. Alarm functions indicating excessive voltage/current load on anodes and/or too negative or too positive protection potentials should be included.

The current output from individual anode/anode bank should each be independently adjustable.

12.2 Impressed-current anode materials

Anode material should be any of the following:

- mixed metal oxides or platinum on a substrate of titanium, niobium or tantalum;
- graphite;
- high-silicon cast iron;
- magnetite;
- precious metal;
- steel.

Other impressed-current materials can be used in specific applications if they are reliable and properly documented. For land-based CP systems which are designed to protect offshore pipelines, alternative anode materials may be used if they are reliable and properly documented in accordance with ISO 15589-1.

NOTE The anode material and substrate determine the maximum operating voltage and anodic current density that can be utilized. Impressed-current materials suffer deterioration, the magnitude of which is dependent on the anodic current density and the applied voltage.

12.3 System design

WARNING — During operation of CP systems, chlorine gas can develop at anode surfaces and hydrogen gas can develop at cathode surfaces. To avoid any health and safety hazards, design and operation shall avoid any detrimental build-up of the gases.

Impressed-current anodes are generally located at one or both ends of submerged pipelines. The current output shall be sufficient to protect the pipeline to the mid-point for systems operating from both ends.

The high current output can result in overpolarization of the pipeline nearest the impressed-current anodes or nearest the negative connection point to the pipeline (drain point). Current attenuation calculations

should therefore be conducted to verify that mid-point protection can be achieved without overprotecting the ends for systems operating from both ends (see [Annex B](#)).

The total current capacity of the impressed-current CP shall be at least 1,25 times the total demand of the pipeline calculated as described in [Annex A](#).

To account for both uneven current distribution and a higher risk of anode malfunction compared to galvanic anode systems, the design of the impressed-current CP system shall include redundancy with respect to the number of anodes.

Impressed-current anodes and cables shall be designed to withstand all expected forces during installation and operation. Anodes shall be designed so that they can be replaced either from the surface or subsea by diver or ROV.

Where anodes are mounted within 1,5 m of the support structure, a non-conductive coating or sheet (minimum 1 mm thickness), i.e. a dielectric shield, shall be applied to the adjacent support surface.

NOTE 1 This precaution is to prevent excessively negative potentials. Typically, shields of prefabricated glass-fibre-reinforced sheets of epoxy resin are used and can be an integral part of the anode assembly or fastened to the object with an epoxy resin. Alternatively, liquid-applied coatings such as glass-flake-reinforced epoxy or polyester can be applied.

Anode cables shall have a steel armour or shall be adequately protected by routing within a dedicated conduit. Provisions for repairs to and replacement of cables shall be incorporated in the design.

NOTE 2 Restrictions for routing of cables in hazardous areas can apply.

Platinum- or gold-coated titanium, niobium, and tantalum should be used for electrical contacts exposed to seawater.

Pipelines protected by impressed current shall be electrically isolated at both ends from adjacent structures/pipelines. Isolating joints should be located above water at a location suitable for inspection and maintenance. If interference effects from adjacent structures or pipelines are considered, connections for testing and remedial provisions shall be installed. See ISO 21857.

When impressed-current systems are used, fixed reference electrodes shall be installed to verify adequate CP of the pipeline and shall include potential monitoring in the area closest to the anode, i.e. to verify there is no overpolarization. Critical areas where diver or ROV inspection is prevented shall have fixed reference electrodes.

NOTE 3 Reference electrodes are typically installed near the ICCP connection point to the pipeline instead of across the whole length of the pipeline.

Since fixed reference electrodes have a limited life, procedures for maintenance and on-line calibration should be established.

Positive and negative cables shall not be placed in a common conduit.

To evaluate the performance of the CP on offshore pipelines protected by an impressed-current system, measuring cables and test points shall be installed at each end of the pipeline if direct contact is not possible.

At isolating joints, two cables shall be connected to each side of the joint or flange. The cables shall be separately terminated in one test post or junction box with suitable facilities to install direct or resistive bonds. To enable reproducible monitoring, the test box should be installed in a convenient, safe location close to the riser, where there is vertical access to the seawater for riser-drop cell surveys.

12.4 Manufacturing and installation considerations

Manufacturing of impressed-current anodes, subsea electrical connectors and dielectric shields shall be performed according to an approved quality control system. Any welding or brazing of cables shall be carried out according to a recognized procedure.

12.5 Mechanical and electrical considerations

The electrical connection between the anode lead cable and the anode body shall be made watertight and mechanically sound.

Cable and connection insulating materials shall be resistant to chlorine, hydrocarbons and other deleterious chemicals.

Care shall be taken to provide suitable mechanical protection for both the anode and its connecting cable. On suspended systems, the individual anodes or anode strings should be equipped with winches or other retrieval means as a damage-preventing measure during severe storms or for routine inspection and maintenance, and the implications of a loss of protection during these periods should be assessed.

NOTE 1 Impressed-current systems are more critical with respect to mechanical damage than galvanic anode CP systems because relatively few anodes are involved, each of which discharges a substantial amount of protective current. The loss of an anode or any negative return cable can seriously reduce system performance.

The following methods of installing fixed-type impressed-current anodes may be applied:

- Anodes may be bottom-installed on the ocean floor by mounting them on specially designed concrete sleds for stability. This minimizes the possibility of the anodes becoming covered with mud or silt.
- Anodes may be installed at the lower ends of protective vertical steel pipe casings or conduits attached to the platform. Casings should be attached to above-water platform members and supported at repeating members below water. The anodes should be lowered through the casings (which protect the anode lead wires) and be allowed to extend below a termination fitting at the bottom of each casing. This method provides a means of anode retrieval or replacement using the anode cable, without diver assistance. Marine growth or corrosion scale can make anode retrieval difficult or impossible. The top of the anode casing should be sealed with a removable cap to prevent any debris going down the casing.
- Anodes with essentially flat configuration-mounted, isolating-type holders may be attached directly to submerged platform members or to auxiliary structural members, such as vertical pipes, which can be removed for anode retrieval without diver assistance.
- Anodes may be installed on submerged platform members using offset steel structural support attached to the platform members. In this case, diver assistance is required for anode replacement.
- Anodes may be installed into the ocean floor in trenches to prevent damage from anchors or trawling.

Simple, rugged, easily maintained impressed-current equipment shall be used. The system can be based on manual, constant current or automatic potential control rectifiers.

NOTE 2 Because conditions at an offshore location seldom vary, except for weather-related factors, manually adjustable oil-cooled rectifiers with both AC and DC overload protection are commonly used.

There can be a delay of several months to a year or more between the time a pipeline is laid until permanent electrical power becomes available on the platform. Adequate CP of the pipeline (e.g. interim CP by galvanic anodes) for the interim period shall be provided.

Interference current corrosion on other pipelines and steel structures and reinforcement of concrete structures shall be assessed. Further guidance is given in [Annex E](#). See ISO 21857.

13 Documentation

13.1 Design, manufacturing and installation documentation

The documentation for as-built systems shall cover the following:

- description of the basis of the CP design with reference to project specifications, codes and standards;
- calculations of surface areas to be protected and currents demanded including coating breakdown factors;

- final design anode calculations including anode mass, dimensions, resistance, numbers and performance;
- drawings, including anode distribution, detailed anode design, manufacturing and installation;
- anode cable attachment report;
- CP survey report;
- electrical continuity report;
- CP commissioning report.

The final documentation shall contain the engineering drawings and equipment lists updated to “as-built” status, and certification covering anode manufacturing and testing.

The following additional documentation shall be included for impressed-current systems:

- DC power supply documentation, including capacity, control and alarm facilities and circuit drawings;
- detailed drawings of anodes, reference electrodes, subsea connectors, cable terminations and dielectric shields;
- procedures for fastening anodes, reference electrodes and dielectric shields, if applicable;
- documentation of impressed-current anode performance;
- drawings showing location of anodes and reference electrodes;
- detailed drawings of cables and electrical isolating joints, if applicable;
- drawings of cable protection conduits;
- documentation of potential-monitoring system.

A schedule of materials to be used for the installation of the CP system shall be issued, listing the specified materials in the quantities required to construct the CP system.

Construction details and installation procedures for the CP system shall be provided.

13.2 Commissioning procedures

For galvanic anode systems, commissioning generally only requires the pipeline potentials to be measured in order to ensure the minimum protection levels have been achieved. More detailed testing may also be performed including calculations of anode current densities by voltage gradient measurement and any other testing required by the design. Commissioning activities are subject to agreement between the owner and CP system installation contractor.

For impressed-current systems the commissioning procedures shall include:

- testing of pipeline isolation where present;
- energizing CP hardware;
- measurement of adequate protection levels (see [Annex D](#));
- interference testing, if applicable (see ISO 18086 and ISO 21857).

13.3 Operating and maintenance manual

For impressed-current systems, an operating and maintenance manual shall be provided containing:

- a description of the system and system components;
- a commissioning report;

- drawings for as-built components/systems;
- manufacturer/supplier documentation;
- potential criteria for the system;
- a monitoring plan, including procedures, schedules and equipment for each type of monitoring facility installed on the pipeline;
- guidelines for the safe operation of the CP system;
- maintenance procedures.

All items except the guidelines for the safe operation are applicable for galvanic anode systems.

14 Operation, monitoring and maintenance of CP systems

14.1 General

Details of inspection and monitoring shall be performed in accordance with [Annex D](#). Details of interference are given in [Annex E](#). See ISO 21857.

14.2 Monitoring plans

A monitoring plan shall be written as part of the design.

The monitoring plan should consider the following:

- required types of measurement, such as pipe-to-seawater potentials, anode potentials, anode current outputs, visual inspection of anode dimensions, pipeline isolation testing, etc.;
- locations at which measurements are to be carried out;
- any permanent monitoring facilities;
- required monitoring installations and equipment to carry out such surveys;
- description of the techniques to be used, such as monitoring by divers, ROVs, trailing wires, towed fish, etc.; this description shall also include methods for accurately locating the pipeline, and the construction-phase requirements concerning the acquisition of navigation data for this purpose;
- frequency of each type of measurement.

This plan shall be part of the operating and maintenance manual.

14.3 Repair

Remedial measures shall be implemented if periodic surveys and inspections reveal that protection no longer meets the design criteria. In such cases the installation of additional anodes can be required.

Continuity cables can be attached to the pipeline by mechanical fixing devices or by welding to an approved procedure (e.g. friction welding). Electrical resistance of such connections should be less than 0,1 Ω .

NOTE Mechanical fixing devices have been found to be less reliable, but can be simpler to install.

Future inspections should include checks on all retrofitted galvanic anodes which rely upon mechanical contact with the pipeline for electrical continuity (e.g. the measurement of potential on both the anode and the pipeline immediately adjacent to the attachment point).

Annex A (normative)

Galvanic anode CP design procedures

A.1 General

[Annex A](#) specifies the detailed design procedures of CP systems based on galvanic anodes.

A.2 Subdivision of pipeline

Pipelines may be divided into sections where changes in conditions, such as water depth, operating temperature or burial, can give rise to variations in design current density.

A.3 Surface area calculations

For each pipeline section, the surface areas to receive CP shall be calculated separately where conditions cause different current requirements.

Components to be connected electrically to the pipeline, such as risers, expansion loops, tie-in spools, valves and tees, shall be included in the surface area calculations, if this equipment shall be protected by pipeline anodes.

A.4 Current demand calculations

From the pipeline dimensions and the coating selected, the mean current demand (I_{cm}) and the final demand (I_{cf}) shall be calculated separately from [Formula \(A.1\)](#).

$$I_c = A_c \times f_c \times i_c \quad (A.1)$$

where

- I_c is the current demand for a specific pipeline section calculated for mean and final conditions, in amperes;
- i_c is the current density, selected for mean and final conditions (see [7.4](#)), in amperes per square metre;
- f_c is the coating breakdown factor determined for mean and final conditions (see [7.5](#));
- A_c is the total surface area for a specific pipeline section, in square metres.

A.5 Selection of anode type and dimensions

The type of anode shall be determined from fabrication, installation and operational considerations.

The internal diameter of bracelet anodes shall be determined from the nominal outside diameter of the pipe and should consider the specified coating thickness, pipe diameter tolerances and pipe ovality.

For pipeline bracelet anodes mounted flush with the concrete coating, the thickness of the concrete coating layer shall be taken into account when determining the overall dimensions of the anode.

The anode dimensions shall be sufficient to meet the required current demand at the end of the design life.

A.6 Total anode mass calculations

The total net anode mass required to maintain CP throughout the design life shall be calculated for each section of pipeline in accordance with [Formula \(A.2\)](#).

$$m = I_{\text{cm}} \times t_{\text{dl}} \times \frac{8\,760}{\mu \times \varepsilon} \quad (\text{A.2})$$

where

m is the total net anode mass, for the specific pipeline section, in kilograms;

I_{cm} is the mean current demand for the specific pipeline section, in amperes;

t_{dl} is the design life, in years ([7.3](#));

ε is the electrochemical capacity of the anode material per kilogram ([8.3](#)), in ampere hours;

μ is the utilization factor ([8.4](#)).

A.7 Calculation of anodes, dimensions and net mass

The final dimensions and net mass of the individual anodes shall be optimized, by carrying out a number of re-iterative calculations, using [Formulae \(A.3\)](#) to [\(A.7\)](#).

The total net anode mass is given by [Formula \(A.3\)](#).

$$m = n \times m_{\text{a}} \quad (\text{A.3})$$

where

n is the number of anodes to be installed on the specific pipeline section;

m is the total net anode mass, in kilograms, for the specific pipeline section [from [Formula \(A.2\)](#)];

m_{a} is the individual net anode mass, in kilograms.

The minimum number of anodes n shall be determined considering the maximum allowable anode spacing (see [8.1](#)). For bracelet anodes, anode spacing is set at a fixed number of field joints. For sled anodes, the anode spacing is usually set at an easily defined spacing (e.g. the calculated spacing may be 1 187 m but a spacing of 1 000 m is selected).

NOTE 1 The anode manufacturers usually have standard-size moulds available for specific line sizes. Although [Formula \(A.3\)](#) is correct, in practice n and m_{a} are selected using [Formula \(A.4\)](#).

$$m > n \times m_{\text{a}} \quad (\text{A.4})$$

The required end-of-life individual anode current output, I_{f} , shall be calculated from [Formula \(A.5\)](#).

$$I_{\text{f}} = \frac{I_{\text{cf}}}{n} \quad (\text{A.5})$$

where

I_f is the required end-of-life individual anode current output, in amperes;

I_{cf} is the total current demand for the protection of the specific pipeline section at the end of life, in amperes;

n is the number of anodes to be installed on the specific pipeline section.

For a given anode size and mass, the actual individual anode current output at the end of life, I_{af} , is calculated from [Formula \(A.6\)](#).

$$I_{af} = \frac{E_c - E_a}{R_a} \quad (\text{A.6})$$

where

I_{af} is the actual end-of-life individual current output, in amperes;

E_a is the design closed-circuit potential of the anode, in volts (see [Table 5](#));

E_c is the design protection potential, in volts, i.e. minimum negative potential (see [Table 1](#));

R_a is the total circuit resistance, which is assumed to be equivalent to the anode resistance, in ohms (see [A.8](#)).

For determining the end-of-design-life anode-to-seawater resistance, the anodes shall be assumed to be consumed to an extent given by their utilization factor. The approximate anode dimensions corresponding to this degree of wastage shall be used in the anode resistance formula for R_a (see [A.8](#)).

To provide the required current, the actual anode current output shall be greater than or equal to the required current output, see [Formula \(A.7\)](#):

$$I_{af} \geq I_f \quad (\text{A.7})$$

[Formulae \(A.4\)](#) to [\(A.7\)](#) should be used to optimize the number, size and individual mass of the anodes to be used. For anodes that meet the criteria of [Formulae \(A.4\)](#) and [\(A.7\)](#), an economic optimization may be carried out considering anode fabrication and installation cost.

A.8 Anode resistance formulae

Individual anode resistance shall be calculated as follows:

a) for bracelet anodes and short flush mounted anodes, see [Formula \(A.8\)](#):

$$R_a = 0,315 \times \frac{\rho}{\sqrt{A}} \quad (\text{A.8})$$

b) for long slender stand-off anodes, see [Formula \(A.9\)](#):

$$R_a = \frac{\rho}{2 \times \pi \times L} \times \left(\ln \frac{4L}{r} - 1 \right) \quad (\text{A.9})$$

c) for short slender stand-off anodes, see [Formula \(A.10\)](#):

$$R_a = \frac{\rho}{2 \times \pi \times L} \times \left(\ln \left(\frac{2L}{r} \times \left(1 + \sqrt{1 + \left(\frac{r}{2L} \right)^2} \right) \right) + \frac{r}{2L} - \sqrt{1 + \left(\frac{r}{2L} \right)^2} \right) \quad (\text{A.10})$$

d) for long flushed mounted anodes, see [Formula \(A.11\)](#):

$$R_a = \frac{\rho}{2S} \quad (\text{A.11})$$

where

R_a is the anode resistance, which is assumed to be equivalent to the total circuit resistance, in ohms;

ρ is the environmental resistivity, in ohm metres;

L is the length of the anode, in metres;

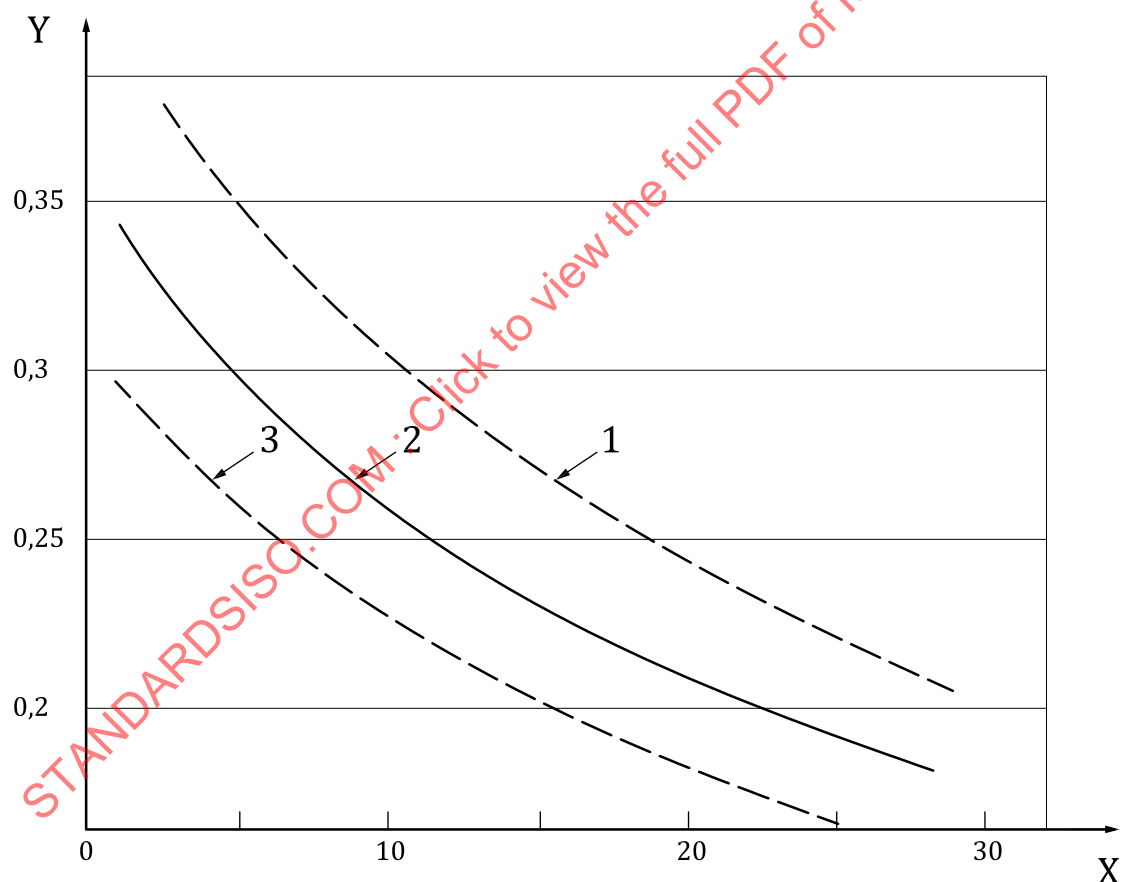
r is the radius of the anode, in metres;

A is the exposed surface area of the anode, in square metres;

S is the arithmetic mean of anode length and width, in metres.

Anode resistance increases due to interference when groups of anodes are placed in close proximity. To compensate for close proximity between anodes, the calculated resistance (initial and final) shall be increased by multiplying it by a factor corresponding to the reduction in active anode surface.

Figure A.1 shows typical variations of resistivity with temperature for salinity of 3 % to 4 %.



Key

- X temperature, °C
- Y seawater resistivity, ρ , $\Omega \cdot \text{m}$
- 1 salinity 3,0 %
- 2 salinity 3,5 %
- 3 salinity 4,0 %

Figure A.1 — Seawater resistivity as a function of temperature for salinities 3,0 % to 4,0 %

For anodes exposed to seabed environments, the resistivity should be assessed by measurements or previous experience. If no data are available, 1,5 $\Omega\cdot\text{m}$ should be used.

For non-cylindrical anodes, the radius, r , in [Formula \(A.9\)](#) shall be calculated from [Formula \(A.12\)](#).

$$r = \frac{C}{2\pi} \quad (\text{A.12})$$

where

r is the radius of the anode, in metres;

C is the anode cross-sectional perimeter, in metres.

Other anode resistance equations may be validated by theory and/or testing.

A.9 Design adjustments for varying conditions

The coating breakdown factor, f_c , and the electrochemical capacity, ε , used in the typical CP design assume that the operating conditions for the pipeline do not vary over the life of the pipeline. If this assumption is not correct, the values used in [Formulae \(A.1\)](#), [\(A.2\)](#) and [\(A.6\)](#) are not constants, but vary as the operating conditions change. The impact of these varying conditions upon the CP design may be evaluated by repeating the design calculations at the extremes of the expected conditions. If the difference between the two anode designs is small, the most conservative design should be used. However, if the number of anodes required by the two designs is significantly different, a design that addresses these changes may be developed.

EXAMPLE 1 For high-temperature pipelines installed several years before the start of production, cathodic current requirements during the period prior to start-up are less due to the cooler temperature.

EXAMPLE 2 For buried flowlines that can experience increasing operating temperatures as water production increases later in its operating life, cathodic current requirements are much less during the initial period of production than in the later high-temperature period. Since the anode operating temperature can change with time, the electrochemical capacity can vary as the temperature increases.

EXAMPLE 3 Pipelines with exceptional coating quality and a high cathodic current density requirement, such as deepwater insulated lines, can require such small amounts of current that the anode current density of a conventional anode bracelet design is below 1 000 mA/m². The electrochemical capacity of aluminium alloys is not a constant value at anode current densities below 1 000 mA/m².

Anode electrochemical capacity is usually tabulated as high and low temperature values at anodic current densities in excess of 1 000 mA/m². For normal operating temperatures less than 50 °C and anode current densities over 1 000 mA/m², this variation may be ignored.

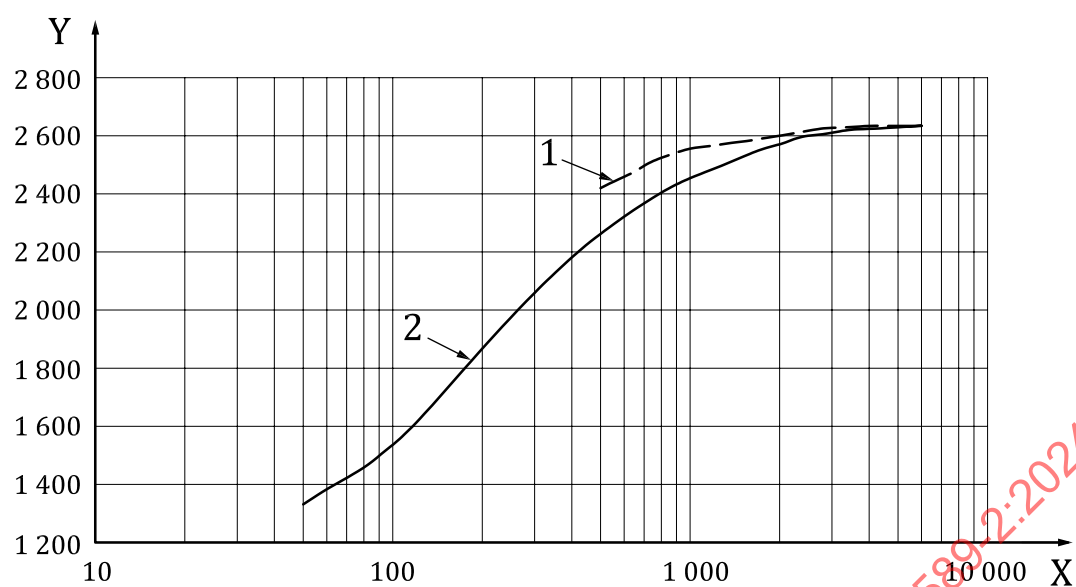
NOTE Examples 2 and 3 listed above describe applications that fall either outside the normal anode operating envelope or where the operating conditions change over the life of the anode (as an example, see [Figure A.2](#) which gives curves of anode electrochemical capacity versus anode current density for two specific temperature ranges). In these situations, the anode electrochemical capacity, ε , changes over the life of the pipeline.

To account for these changing conditions, a single value for the anode electrochemical capacity may not be appropriate in [Formula \(A.2\)](#). If variable electrochemical capacities are envisaged, then [Formula \(A.2\)](#) should be revised by [Formula \(A.13\)](#).

$$m = \frac{A_c \times 8\,760}{u} \int_t i_c \times f_c \times \frac{1}{\varepsilon} dt \quad (\text{A.13})$$

where i_c , f_c and ε are not constant values but vary over the design life of the pipeline.

Information about ε as a function of temperature and/or current density may be obtained in accordance with [Annex C](#). Normally, these calculations are performed as numerical integrations using a spreadsheet that allows the annual value for m to be calculated and then summed over the life of the pipeline.



Key

- X anode current density, mA/m²
Y anode electrochemical capacity, A·h/kg
1 $T = 2\text{ °C}$
2 $T = 25\text{ °C to }28\text{ °C}$

Figure A.2 — Aluminium anode performance in seawater at low current densities

Annex B (normative)

Attenuation of protection

B.1 General

Once the number, size and spacing of the anodes have been determined in accordance with [Annex A](#), an approximate check on the suitability of the anode distribution can be carried out using attenuation formulae. Using these formulae, it is possible to obtain an indication of the distribution of the pipe-to-electrolyte potential and the current flowing onto the pipeline a function of the distance from the drain points (i.e. anodes).

B.2 NORSOK procedure

The procedure given in this clause shall be used for determining the maximum distance between anodes.

Reference [\[15\]](#) provides further information for this method. Using this method, the maximum voltage drop, or the maximum distance between anodes, is calculated by assuming that the whole area with coating breakdown is located halfway between the anodes. Accordingly, all CP current shall be assumed to enter half-way between anodes.

The voltage drop (or potential increase) between two anodes for a CP design based on anodes equally distributed along the pipeline should be calculated using [Formula \(B.1\)](#).

$$\Delta E_{Me} + \Delta E_A = \frac{L_d^2 \times \rho_{Me} \times i \times f_{cf} \times D}{4 \times d \times (D - d)} + R_a \times i \times \pi \times D \times f_{cf} \times L_d \quad (B.1)$$

where

ΔE_A is the IR drop due to transporting the current from anode to cathode, electrolytic potential drop (V);

ΔE_{Me} is the IR drop due to transporting the current in the pipe wall, metallic potential drop (V);

R_a is the anode resistance (Ω);

ρ_{Me} is the resistivity of the pipe wall material ($\Omega \text{ m}$);

L_d is the distance between anodes (m);

i is the current density (A/m^2);

f_{cf} is the final coating breakdown factor (see [7.5](#));

D is the pipeline outer diameter (m);

d is the pipeline wall thickness (m).

For anodes distributed along a pipeline, loss of one anode shall be taken into account when calculating the maximum distance between the anodes; see also [8.1](#).

For a CP design with anode banks located at the pipeline ends only, the voltage drop (or potential increase) between the two anode banks should be calculated using [Formula \(B.2\)](#).

$$\Delta E_{\text{Me}} + \Delta E_{\text{A}} = \frac{L_d^2 \times \rho_{\text{Me}} \times i \times f_{\text{cf}} \times D}{4 \times d \times (D - d)} + \frac{R_{\text{a}} \times i \times \pi \times D \times f_{\text{cf}} \times L_d}{2} \quad (\text{B.2})$$

[Formula \(B.2\)](#) is valid only if the pipeline section and the anode pipe joints are unaffected by other installations at the pipeline ends. If this condition is not fulfilled and such structures can draw current from the anodes, then the last part of [Formula \(B.2\)](#), which represents the voltage drop from the anode, shall be further developed to account for such effects. A special assessment of the anode voltage drop shall also be made when the pipeline is protected from anodes on a structure at the pipeline end. In cases where end mounted anodes are used in combination with anodes or anode spools along the pipeline, a combination of [Formula \(B.1\)](#) and [Formula \(B.2\)](#) shall be used.

[Formula \(B.3\)](#) can be used to calculate the distance between two anodes for design based on anodes distributed along the pipeline.

$$L_{\text{max}} = \frac{-R_{\text{af}} \cdot i_{\text{cf}} \cdot \pi \cdot D \cdot f_{\text{cf}} + \sqrt{(R_{\text{af}} \cdot i_{\text{cf}} \cdot \pi \cdot D \cdot f_{\text{cf}})^2 + \frac{\rho_{\text{Me}} \cdot i_{\text{cf}} \cdot f_{\text{cf}} \cdot D}{d \cdot (D - d)} \cdot \Delta E}}{\frac{\rho_{\text{Me}} \cdot i_{\text{cf}} \cdot f_{\text{cf}} \cdot D}{2 \cdot d \cdot (D - d)}} \quad (\text{B.3})$$

where:

L_{max} is the maximum distance between pipeline bracelet anodes (m);

R_{af} is the anode resistance or anode bank resistance at final condition (Ω);

i_{cf} is the final current density (mA/m^2);

D is the linepipe outer diameter (m);

f_{cf} is the final coating breakdown factor;

ρ_{Me} is the specific resistivity of linepipe material ($\Omega \text{ m}$);

d is the linepipe wall thickness (mm);

ΔE is the driving voltage (mV).

In the event that anode banks are located at the pipeline ends only, [Formula \(B.4\)](#) can be used as basis for the calculations. The formula gives the maximum anode spacing between the anode banks.

$$L_d = \frac{-R_{\text{af}} \cdot i_{\text{cf}} \cdot \pi \cdot D \cdot f_{\text{cf}} + \sqrt{(R_{\text{af}} \cdot i_{\text{cf}} \cdot \pi \cdot D \cdot f_{\text{cf}})^2 + 4 \cdot \frac{\rho_{\text{Me}} \cdot i_{\text{cf}} \cdot f_{\text{cf}} \cdot D}{d \cdot (D - d)} \cdot \Delta E}}{\frac{\rho_{\text{Me}} \cdot i_{\text{cf}} \cdot f_{\text{cf}} \cdot D}{d \cdot (D - d)}} \quad (\text{B.4})$$

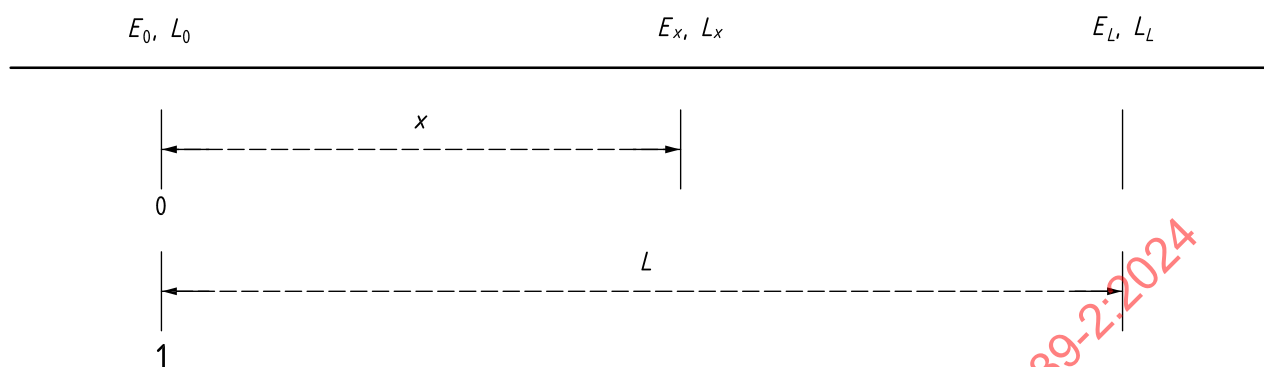
[Formula \(B.4\)](#) is only directly valid if the pipeline section and the anode banks are unaffected by other installations at the pipeline ends. If this condition is not fulfilled and such structures can draw current from the anodes, the last part of the equation, which describes voltage drop from the anode, shall be further developed to reflect this situation. Also, if the pipeline is protected from anodes on a structure at the pipeline end, a special assessment of the anode voltage drop is needed.

In cases where end mounted anodes are used in combination with anodes or anode spools along the pipeline, a combination of [Formula \(B.3\)](#) and [Formula \(B.4\)](#) should be used.

B.3 Alternative method

The procedure given in this clause may be used for checking the suitability of the anode distribution.

Figure B.1 provides an illustration of the potential and currents as a function of the distance from the drain point.



Key

1 drain point

NOTE The symbols used in this figure are defined in [Formulae \(B.5\)](#) and [\(B.6\)](#).

Figure B.1 — Drain point definition

For a pipeline with multiple drain points (anodes) at a uniform spacing of $2L$, the potential, E_x , and current, I_x , at any distance x from the anode shall be calculated using [Formulae \(B.5\)](#) and [\(B.6\)](#):

$$E_x = E_0 \times \frac{\cosh \alpha (L - x)}{\cosh \alpha L} \quad (\text{B.5})$$

$$I_x = I_0 \times \frac{\sinh \alpha (L - x)}{\sinh \alpha L} \quad (\text{B.6})$$

where

E_0 is the pipe-to-electrolyte potential shift at the drain point (anode), in volts;

E_x is the pipe-to-electrolyte potential shift at a distance x from the drain point, in volts;

I_0 is the current flowing onto the pipe at the drain point (anode), in amperes;

I_x is the current flowing onto the pipe at a distance x from the drain point, in amperes;

L is half the distance between drain points, in metres;

α is the attenuation constant for the pipeline section and is equal to $\sqrt{\frac{R_L}{R_t}}$;

is the linear electrical resistance of the section of the pipeline, in ohms per metre, and is given by:

$$R_L = \frac{\rho}{A_w} ;$$

R_t is the leakage or transverse resistance, in ohm metres, and is equal to $\frac{R_0}{\pi D_o}$;

R_0 is the pipe-to-electrolyte insulation resistance, in ohm square metres;

ρ is the specific resistance of the pipeline material, in ohm metres;

D_o is the outer diameter of the pipeline, in metres;

A_w is the cross-sectional area of the pipe wall, in square metres.

A value for the insulation resistance R_0 should be selected based upon practical experience and consider the following:

- type of coating;
- exposure conditions such as to seawater or seabed sediments;
- design life of the pipeline and anticipated progressive reduction in coating resistance over the design life;
- pipeline installation method and projected extent of coating damage.

The linear electrical resistance of the section of the pipeline R_L may be calculated from [Formula \(B.7\)](#):

$$R_L = 4L_m \cdot \frac{\rho}{\pi(D_o^2 - D_i^2)} \quad (\text{B.7})$$

where

D_o is the outer diameter of the pipeline, in metres;

D_i is the inner diameter of the pipeline, in metres;

L_m is half the distance between the drain points, in metres.

Alternatively, values for the electrical resistance for standard pipe sizes may be obtained from tables in ISO 13623.

Annex C (informative)

Performance qualification testing of galvanic anode materials

C.1 General

This annex provides a procedure for laboratory testing for determining performance values for galvanic anodes in a given environment as a qualification of the anode alloy.

The performance of galvanic anode materials may also be validated by field experience, either by using data from monitored anodes or by dedicated field-testing of full-size anodes.

Performance qualification testing is typically carried out for new (nominal) anode compositions and/or foundry, and whenever there is a need to verify anode material performance.

C.2 Testing

Long term performance of an anode alloy may be evaluated by testing in accordance to DNV-RP-B401 Section 10.

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Annex D (normative)

CP monitoring and surveys

D.1 General

A number of methods may be employed to monitor the effectiveness of offshore pipeline CP. The level of monitoring shall be commensurate with the criticality and condition of the pipeline, and minimum requirements of regulations.

A post-installation survey should be carried out within 12 months of pipeline installation in accordance with [D.6.1](#).

Further surveys should be considered based on:

- CP design and anode performance in accordance with this document;
- results from the initial survey;
- reported excessive anode consumption;
- presence of coating damage which may result in breakdown factors larger than those given in [Tables 3](#) and [4](#);
- potential interference with/from neighbouring pipelines and structures, if applicable, in accordance with ISO 18086 and ISO 21857.

If the pipeline is to remain in service beyond its original design life, then at least one potential survey shall be performed within the last 5 years of the design life of the CP system (see [D.6.2](#)).

D.2 Topside potential monitoring

Measurements of potentials applied to pipeline risers may be carried out by using a simple portable reference electrode and a conventional voltmeter. The voltmeter negative terminal shall be connected to the riser above the water line, and the positive terminal to the reference electrode. The reference electrode shall be lowered into the water alongside and, to ensure accuracy, as close as possible to the riser. Potentials shall be recorded at different depths determined from markers attached to the reference electrode cable.

NOTE 1 Motion of the water and loss of visual contact with the reference electrode reduces measurement accuracy. However, accuracy can be restored if a diver is employed to ensure good positioning of the reference electrode.

When divers or ROVs are used for measuring potential, specially designed contact probes shall be used (see [D.4.3](#)). Electrical contact between the riser and host structure shall be checked prior to reading potentials.

NOTE 2 The potential of risers can be influenced by the host structure if in electrical contact with the host structure. However, the potential of the riser is not necessarily a good indicator of the potential profile along the whole pipeline.

The potential on short pipelines running between two platforms may be modelled using attenuation equations, and the worst-case potential value predicted from the potentials measured at the extremities. Potential measurements shall be carried out at intervals along the pipeline for verification of model reliability.

D.3 Visual inspection

Visual inspection of unburied sections should be carried out when necessary to check the condition of the pipe, coating and CP system. The type of data to be gathered during the inspection shall be documented prior to the inspection and be appropriate for the needs of the pipeline.

NOTE Direct visual inspection by divers or ROV cameras can disclose deficiencies of a CP system, such as damaged or missing anodes, damaged cables, excessive anode consumption. Apparent corrosion damage or rust discoloration can be another sign of under-protection. Low anode consumption can indicate passivation, and heavy calcareous deposits close to the anodes can indicate overprotection.

Galvanic anode surfaces should be cleaned before any physical measurements of anode dimensions are taken.

D.4 Potential measurements

D.4.1 General

Potential measurements should be taken to assess the performance of the CP system in accordance with this document.

The objective of potential measurements is to determine the actual potential at the pipe-to-seawater interface with respect to a reference electrode, such that the effectiveness of CP can be assessed. Acceptance criteria are given in [Table 1](#) and may be converted for different reference electrodes as detailed in [D.4.2](#). Normally, it is difficult to measure pipe-to-seawater potentials directly, as bare steel is not usually available. In such cases, indirect potential measurements should be considered.

Potential measurements should also be taken at galvanic anodes to obtain information on their performance.

When CP is achieved using impressed-current systems, the potential shall be measured with the protective current applied.

NOTE 1 The value includes the voltage drop across the steel/water interface, and also includes the voltage drop in the seawater between the reference electrode and the pipe.

In most circumstances, except near impressed-current anodes, the voltage drop in the seawater may be taken as zero.

Test equipment shall be maintained and periodically calibrated. Reference electrodes shall be routinely calibrated against a standard laboratory-grade reference electrode.

Reference electrodes shall be positioned as close to the pipeline as practical, in particular for measurements of anode potentials with large voltage drops in the seawater adjacent to the anode. In these cases, the IR drop shall be compensated for when interpreting the measured anode potential in terms of the true anode potential.

Electrical safety shall be observed when divers work on pipelines protected by an impressed-current CP system.

The steel/sea water potential shall be measured to determine whether a structure is adequately protected. For such measurements, connections shall be made to both the structure and the electrolyte.

NOTE 2 The connection to the structure is a simple metallic one but, for the connection to the electrolyte, a metal conductor is introduced into the electrolyte. This conductor introduces its own electrode potential, which inevitably becomes included in the measured value. This situation can be resolved by using a conductor of reproducible and defined electrode potential; this is called a reference electrode. Irrespective of the type of reference electrode used, it is essential that it be placed very close to the metal surface as the measurement of the potential difference between the metal surface and the electrolyte can be considerably affected by the potential drop produced by the protection current as it flows through the surrounding electrolyte to the structure. This effect, known as the IR drop, has the effect of making the measured potential more negative than the actual potential at the metal/electrolyte interface. The IR drop is dependent on electrolyte resistivity and is particularly relevant to buried structures. The resistance of any coatings also has an effect.

D.4.2 Reference electrodes

Reference electrodes such as the saturated calomel electrode or various silver/silver chloride electrodes with different concentrations of KCl electrolyte may be used as master reference electrodes. Two electrodes in the same assembly, to give an on-line cross-calibration, should be considered for potential-monitoring devices.

NOTE 1 Saturated calomel electrodes or silver/silver chloride/potassium chloride electrodes are not often used for monitoring and controlling cathodic protection systems in seawater because they are insufficiently robust for field use. Reference electrodes used more often in the field are silver/silver chloride/seawater electrodes or high-purity or anode-alloy-specification zinc electrodes. These electrodes are considered sufficiently accurate for most practical purposes even if the electrolyte is not fully defined and reproducible. The silver/silver chloride/seawater (Ag/AgCl/seawater) electrode is the most widely used electrode for seawater applications, particularly in conjunction with portable monitoring equipment.

Other reference electrodes that may be used in place of the Ag/AgCl/seawater reference electrode are described below, with the respective protection potentials for carbon steel equivalent to the $-0,80$ V versus Ag/AgCl/seawater criterion.

- a) Saturated copper/copper sulfate reference electrode (CSE). The least negative potential measured against this electrode shall be $-0,85$ V. This electrode is more commonly employed for determining the level of protection on onshore pipelines and is not sufficiently stable in seawater for long-term immersion in this environment. It is not recommended for use in seawater.
- b) High-purity metallic zinc electrode. "High purity" (ASTM B418, type II, or EN 12496, alloy type Z2) or a zinc alloy used for anode manufacturing (US Mil Spec A-18001K or EN 12496, alloy type Z1 or Z3) have a moderately stable potential in seawater and are sometimes used as a reference electrode. However, zinc electrodes are less accurate than silver/silver chloride reference electrodes, and are mostly used in permanent monitoring applications. For permanent installations, a small anodic current should pass through the surface to keep it clean and active. The least negative potential for effective CP of carbon steel versus the zinc/seawater electrode is $+0,25$ V.
- c) Saturated calomel reference electrode (SCE). This electrode comprises mercury and mercurous chloride in a saturated solution of potassium chloride. The least negative potential for effective CP of low-alloy steel is $-0,78$ V. This electrode is not normally used for site surveys and is more suitable for laboratory applications. This electrode is being replaced due to environmental concerns.
- d) Saturated silver/silver chloride (Ag/AgCl/saturated KCl). This electrode is similar to the silver/silver chloride/seawater electrode, except that the silver/silver chloride is immersed in a saturated solution of potassium chloride and the potential is not affected by the salinity (or resistivity) of the seawater. The least negative potential for effective CP of low-alloy steel using this electrode is $-0,76$ V. As with SCE, the saturated silver/silver chloride electrode is more suitable in laboratory applications.

Reference electrodes used in the field shall be periodically checked with a master reference electrode having a valid calibration certificate. The master electrode shall be calibrated periodically with a minimum frequency of once a year to a primary calibration reference electrode.

Reference electrodes such as the saturated calomel electrode or various silver/silver chloride electrodes with different concentrations of KCl electrolyte may be used as master reference electrodes.

NOTE 2 A standard hydrogen electrode (SHE) is an electrode used for reference on all half-cell potential reactions. This electrode considers the fugacity coefficient for hydrogen gas and the activity coefficient for H^+ ions but is practically impossible to manufacture.

D.4.3 Contact probes

Potential measurements may be made above water using a conventional voltmeter connected to the reference electrode via a cable, and a second cable from the metal tip of the contact probe to the negative