International Standard

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Galvanic anodes for cathodic protection in seawater and saline sediments

Anodes galvaniques pour la protection cathodique dans l'eau de mer et les sédiments salins

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Foreword

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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 156, *Corrosion of metals and alloys*, 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).

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

Introduction

This standard defines the minimum requirements for the galvanic anode quality levels and verification procedures.

The anticipated performance of the cast galvanic anodes for use in seawater and saline mud or sediment is determined by their composition, anode dimensions and the quality of their manufacture.

In addition, the document provides guidance and recommendations related to the environmental impact.

Galvanic anodes for cathodic protection in seawater and saline sediments

1 Scope

This document defines requirements and gives recommendations for the chemical composition, electrochemical properties, physical tolerances and test and inspection procedures for cast galvanic anodes of aluminium, magnesium and zinc-based alloys for cathodic protection in seawater, saline sediment and brackish water.

Information on salinity ranges can be found in Annex A.

The requirements and recommendations of this document can be applied to any available anode shape for cast anodes, e.g. trapezoid, circular, half-spherical cross sections, bracelet type.

Whilst other metals, such as soft iron, can be used as galvanic anode material to protect more noble metals than iron and steel, these are not covered in this document.

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 (all parts), *Structural steels*

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

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*

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

ISO 10474:2013, *Steel and steel products — Inspection documents*

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

ISO 15609-1, *Specification and qualification of welding procedures for metallic materials — Welding procedure specification — Part 1: Arc welding*

3 Terms and definitions

For the purposes of this document, the following terms and definitions 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 consumption rate

mass consumption rate

amount of anode material consumed for a current output of one ampere during one year

Note 1 to entry: The anode consumption rate is expressed in kilograms per amp year [kg/(A·y)].

3.2

batch

group of anodes all produced from a single furnace cast

Note 1 to entry: Multiple batches of different anodes can be produced from a single cast.

3.3

bracelet anode

anode shaped as half-shells (annular castings) to be positioned on tubular items

Note 1 to entry: Two half-shell castings fit together to become a bracelet anode. These are typically used for submarine pipelines and occasionally used for marine structure tubulars.

Note 2 to entry: Bracelet anodes can be fabricated as half or part shell castings with the structural core within the casting, or as cast segments with only the supporting core within the casting and the structural steel elements external to the castings. Segmental bracelets comprise individual castings attached to external steel bands to fit around the pipeline or tubular structure.

3.4

cast

charge

heat

single furnace load with a unique, analysed chemical composition from which anodes are produced

3.5

closed circuit potential

potential of an electrode measured with respect to a reference electrode or another electrode when a current is flowing in the circuit

3.6

cold shut

surface discontinuity in the cast anode alloy caused by solidification of a portion of a meniscus during the progressive filling of a mould, which is later covered with more solidifying metals as the molten metal level rises

Note 1 to entry: Cold shuts often occur remote from the point of pour.

3.7

crack

imperfection produced by a local rupture in the solid state, which can arise from the effect of cooling or stresses

3.8

driving voltage

voltage between the galvanic anode to electrolyte potential and the structure to electrolyte potential

Note 1 to entry: For design purposes, the driving voltage refers to the difference between the closed-circuit potential of the anode and the design protective potential of the structure. This value is used to determine the maximum available anode current for a given circuit resistance.

3.9

electrochemical capacity

total amount of electric charge that is produced when a fixed mass of anode alloy is consumed electrochemically

Note 1 to entry: Electrochemical capacity is expressed in ampere hours per kg (A·h/kg).

Note 2 to entry: This represents the practical amount of charge per unit mass available, which is less than the theoretical, Faradaic value.

Note 3 to entry: An alternative, not preferred, term is alloy capacity.

Note 4 to entry: Electrochemical capacity is not a material constant but can vary with electrolyte conditions.

3.10
electrochemical property
property of potential and electrochemical capacity that characterises a galvanic alloy and can be assessed by quantitative tests

3.11
flush mounted anode
anode fitted to a structure with one face in contact with or very close to the structure

3.12
free-running test
electrochemical test where potential and current are not controlled

3.13
gas hole
blow hole, channel or porosity produced by gas evolution during solidification or entrapped air

Note 1 to entry: Gas holes can indicate:

- contamination of the mould or core prior to casting;
- poor mould or insert design;
- casting process permitting entrapped air during the pour.

3.14
gross mass
mass of a cast anode, including the mass of the steel core and any integral attachments on completion of casting

3.15
insert
core
structural item over which the anode is cast and which supports the alloy and can be used to connect the anode to the structure requiring protection

Note 1 to entry: The insert (core) is generally made of steel. Its design helps determine the utilization factor of the anodes.

3.16
ladle sample
specimen taken from the molten metal

3.17
net mass
mass of cast anode, excluding the mass of the steel core and any integral attachments on completion of casting

Note 1 to entry: Net mass represents the mass of the galvanic alloy material and is used in cathodic protection design.

3.18
nominal value
designated or intended value

Note 1 to entry: Examples of nominal values are length, width and mass.

3.19
non-metallic inclusions
particles of oxides and other refractory materials entrapped in liquid metal during the melting or casting sequences

3.20
pitting
localised corrosion resulting in cavities extending from the surface into the metal

3.21
polarization
change in the potential of an electrode as a result of current flow to or from that electrode

3.22
shrinkage depressions
natural concave surfaces which can be produced when liquid metal is allowed to solidify in a mould without the provision of extra liquid metal to compensate for the reduction in volume that occurs during the liquid and liquid–solid (solidification) contractions on cooling the liquid-solid transformation

3.23
stand-off anode
anode which is offset a certain distance from the object on which it is positioned

3.24
surface morphology
description of the features or structure of the anode surface

3.25
undercutting
formation of subsurface cavities which can be caused by pitting corrosion or inter-granular corrosion

3.26
utilization factor
fraction of the galvanic alloy mass in an anode which can be used for cathodic protection current before the galvanic material is no longer supported by the core or the anode can no longer deliver the minimum required current

Note 1 to entry: Utilization factor is generally expressed numerically (e.g. 0,80) and is dependent on the detailed anode design and location of the insert.

Note 2 to entry: Utilization factor is critical in the determination of anode mass requirements for a cathodic protection design.

3.27
void
lack of bond between the steel core and the cast alloy of an anode that can be formed by movement of the anode core in the mould as the alloy solidifies

4 Symbols and abbreviations

4.1 Symbols

y	year
E	anode consumption rate, kg/(A·y)
Q	electrochemical capacity of the alloy, A·h/kg
CE	carbon equivalent

4.2 Abbreviations

CP	cathodic protection
EPD	environmental product declaration
ITP	inspection and test plan
LCA	life cycle assessment
QC	quality control

5 Competence of personnel

It is the responsibility of personnel performing the design of the anode and the anode core to ensure that the anode, including its core, is suitable to deliver the utilization factor, see Clause 7. Those responsible for the core design shall have the appropriate level of competence for the tasks undertaken. Those responsible for all other aspects of the anode manufacture, inspection and testing shall also have the appropriate level of competence for the tasks undertaken. These should be the subject of the necessary training, assessment and documentation by the anode manufacturer to ensure that the requirements of this document are met.

NOTE Competence of CP personnel to the appropriate level for tasks undertaken can be demonstrated by certification in accordance with ISO 15257 or by another equivalent prequalification procedure.

6 Galvanic anode materials and their properties

6.1 General

In this document, alloys used for galvanic anodes in seawater or saline sediment shall be based on aluminium (Al), magnesium (Mg) or zinc (Zn). The performance, and therefore the suitability of a particular alloy for a specific application, depends on the composition and characteristics of both the anode alloy, the electrolyte and operation conditions of the polarized anode.

The performance of an anode alloy will vary in different environmental conditions. The performance data shall include the electrochemical capacity in ampere-hours per kilogram (A·h /kg), and the closed-circuit anode to electrolyte potential of a working anode measured against a calibrated standard reference electrode (see 6.3 and Annex D).

Each anode shall be uniquely marked by hard stamping with the cast number during production. Other markings can be added by agreement between purchaser and manufacturer and may include for example, a manufacturer identification, an alloy designation, anode mass and a sequential production number within the cast. Marking should be by hard stamping on the anode surface located where it is visible when the anodes are stacked or palleted for storage or delivery.

6.2 Anode alloy composition

The performance of an alloy is dependent on the specific alloy composition. Variations in composition from established specifications can result in variations in activation, resistance to passivation, electrochemical capacity and corrosion surface morphology. Some elements are known to have a detrimental effect on anode performance and their content is normally subject to strict control.

The most common galvanic anode generic compositions for aluminium, magnesium and zinc-based anode alloys are given in Annex C.

Strict control of the alloy chemical composition, both alloying elements and impurities, is essential and shall be carried out on each cast.

A minimum of two samples from each cast (ladle sample) shall be taken for chemical analysis. The samples shall be taken in the beginning and at the end of casting from the pouring stream. The sample shall be taken at the beginning of the first cast and at the end of the second cast, then in the beginning of the third cast and so on. The samples shall be analysed to verify the required chemical composition. All samples shall be identified with the cast number. All anodes from that particular cast shall be similarly identified with the cast number (see 6.1).

The samples shall be analysed to prove conformity with the agreed chemical composition limits of the alloy being produced. Additional sample(s) may be taken and stored for future determination of chemical composition.

NOTE Spark emission spectrometry is an appropriate method of analysis in a production environment but requires regular calibration against known and certified reference alloy samples.

Where a small holding furnace is used to continue topping up the cooling and solidifying anode after pouring from the main furnace has ceased, the holding furnace shall be supplied from the same cast as in the main furnace. A sample should be taken from the holding furnace for chemical analysis to ensure that the composition remains within limits.

The chemical composition of all samples analysed shall be documented. Anodes from casts which do not meet the required chemical composition shall be rejected.

6.3 Electrochemical properties

Cathodic protection (CP) is electrochemical in nature. The anode material's electrochemical properties are primary factors in cathodic protection design and therefore shall be documented.

These properties are:

- closed circuit potential;
- practical electrochemical capacity.

These properties can vary with electrolyte conditions. They can also vary over time, even when exposed to constant conditions. This is due to the corrosion products and layers of marine growth that form on the anode surface as well as variations in current demand. Caution should be exercised when considering these parameters for CP-specific design purposes (see 6.4.2).

NOTE 1 ISO 15589-2 and References [11] and [12] give further information on the impact of capacity variations of temperature and environment on cathodic protection design for pipelines.

NOTE 2 Due to self-corrosion, all anode materials have a practical electrochemical capacity lower than the capacity calculated by considering the theoretical electrical equivalence determined by Faraday's Law (i.e. some of the anode mass is consumed through self-corrosion, not current supply, and is not available for cathodic protection). The practical electrochemical capacity is used in cathodic protection design.

6.4 Electrochemical testing

6.4.1 General

There are two principal reasons for carrying out electrochemical tests: to determine alloy electrochemical performance and to conduct production quality control. Testing can also be carried out for research purposes, but such tests are generally customised and not considered in this document.

The principal methods of electrochemical testing are described in Annex D.

6.4.2 Performance testing

To determine alloy performance, there is no substitute for prolonged field testing of alloys in practical situations. Experience with different anode applications can be drawn upon, where possible.

In some cases, there are no reliable historical or laboratory data relating to the performance of a specific anode alloy composition range in a particular environment. In these cases, electrochemical testing shall be carried out to indicate the relevant alloy closed circuit potential and electrochemical capacity.

Long-term laboratory test procedures shall be selected to best represent the expected operating conditions (including electrolyte, temperature and anode current density). These test procedures shall be carried out over a period that is long enough to provide a realistic assessment of alloy performance in a practical application.

The test period should not be less than one year. One year is a relatively short period compared to most CP design lives. See Annex D.

A long-term test to an agreed common procedure can be used to qualify alloys for specific purposes. It can be useful to rank alloys on a relative scale. A related procedure is described in Reference [11].

These laboratory tests produce alloy performance data. However, these data only reflect the particular test parameters used in the test, e.g. exposure period, temperature and anode current density and its variation over time. Free running tests have current density variations in time, but galvanostatic tests cannot show risk of passivation. Even data from long-term free running tests should be used with caution, since it is possible they do not reflect the particular application intended. In addition, it is not necessarily safe to adopt the test results for CP design in all applications (see Annex D).

Samples for electrochemical testing should be representative of the specified alloy composition range, the process route and the target chemical analysis.

Where performance tests are to be used to determine anode alloy performance properties for design purposes, they should be conducted by or witnessed, assessed and approved by an independent certified authority. The certified authority shall be experienced in and accredited to conduct the tests they are assessing. The accreditation shall be by a national accreditation body.

6.4.3 Short-term testing for quality control

The objectives of short-term quality control (QC) tests are very different from those of the long-term tests described in 6.4.2. Short-term tests are designed to produce measurable results in a relatively short period consistent with production release and delivery requirements. This is performed by adopting relatively high anode current densities, which can lie outside reasonable expectations of actual anode applications. These tests are primarily intended to demonstrate consistency of production within a particular alloy chemical compositional range.

Data from such short-term quality control tests shall not be relied on for system design or be interpreted as an indicator of the long-term performance of the alloy.

Short-term tests for quality control should be carried out to an agreed standardised procedure. Suitable tests in common use are those described in References [11] and [13] (see also Annex D). For anode production quality control, short-term high current density tests should be carried out on each charge of production or otherwise at a frequency to be agreed and consistent with the contract delivery requirement. Acceptance criteria for quality control testing shall be agreed. Test results should form part of the contract documentation.

Other short-term tests for QC purposes, such as closed-circuit potential tests, may be carried out by agreement.

6.5 Anode consumption rate

The anode consumption rate for a galvanic alloy anode is expressed in kilograms per ampere year (kg/(A·y)) and is the total amount of anode material consumed in practice for a current output of one ampere during one year. Like electrochemical capacity (see 6.4.2), all anode materials have a practical consumption rate different from their theoretical consumption rate. In this case, the anode consumption rate is higher than that calculated by Faraday’s Law.

The anode consumption rate and the current capacity are related by:

$$E \cdot Q = 8\,760$$

where

E	is the anode consumption rate (kg/(A·y));
Q	is the electrochemical capacity (A·h/kg);
8 760	is the number of hours in one year.

7 Anode design and acceptance criteria

7.1 General

The chemical composition of any alloy used for galvanic anodes shall be specified by either the CP designer or the purchaser. The corresponding electrochemical properties shall be determined and documented against defined test procedures (see 6.4).

The anodes, including cores and associated supports, shall be designed to give the specified performance during fabrication, transport, installation and operation. The dimensions and shape of the anodes, their steel core and any integral extensions shall be designed to withstand the mechanical forces that can act on the anodes, e.g. waves, currents, pile driving or vibration. For all anodes, the anode and anode core dimensions shall be designed to be compatible with the proposed installation method and any structural material requirements. However, the steel core shall be designed to support the anode alloy for its full design life consistent with the utilization factor appropriate for the anode design.

Anodes shall not be manufactured without cores or inserts.

In subsea areas where divers or remote operated vehicles are likely to operate, stand-off type anodes should be provided so that the support cores protrude through the end-faces of the anode. This is to reduce the danger of entangling wires, ropes, umbilical cables, etc.

For open moulds, over-pouring to fill shrinkage depressions shall be kept to a minimum. All pouring of molten anode alloy shall be finished smooth before the surface of the cast anode solidifies. The surface of the anode may be kept in a liquid state for a while by applying heat, for example, from gas burners, but once solidified, no re-melting shall be allowed, not even to fill shrinkage depressions. The term "shrinkage depression" also applies to the free surface area of an open mould casting, where the final solidification occurs and where, before final solidification, additional molten alloy can be added to top up any shrinkage depressions to maintain final mass and dimension requirements.

NOTE The term "shrinkage depression" can also apply to the concave surfaces produced when liquid metal is solidified in a closed mould in such a manner that the area is not “fed” by the liquid metal provided by the mould design.

The exposed (external) surfaces of the anode shall not be subject to any coating except for flush mounted and bracelet anodes where the anode surface facing, and immediately adjacent to the structure surface to be protected, should be coated.

The manufacturers shall produce anode castings in which the presence of defects, such as shrinkage depressions and cracks, shall conform to the limits specified in Annex B.

Physical tolerances of anodes shall be confirmed in accordance with the requirements of Annex B. An inspection and test plan (ITP) shall be agreed upon between anode producer and purchaser before commencing anode casting. The ITP shall define all requirements to the production, including alloy composition, testing, dimensions etc., and which level of inspection the purchaser requires during the production. An example of an ITP is given in Annex F.

7.2 Chemical composition

Galvanic anode alloys can have reduced ductility due to their inherent mechanical properties and/or the nature of the as-cast material. This should be considered when designing anode shape and size. Alloying additions commonly used to strengthen aluminium, zinc and magnesium engineering castings shall not be used for galvanic anodes because of their detrimental effect on electrochemical properties. Annex C provides limits for some of these detrimental elements in various galvanic alloys.

7.3 Electrochemical properties

Anode design is a compromise between the current required from an anode and the net mass of the as-cast anode.

Anode alloy electrochemical capacity is a primary factor in determining the anode net mass requirements of a CP design. The correct value of anode alloy electrochemical capacity appropriate for any particular application of cathodic protection is of paramount importance (see 6.3, 6.4.2 and Annex D).

The closed-circuit potential determines the driving voltage between the anode and the protected structure. The driving voltage and the anode to electrolyte resistance (ohmic resistance) of the anode are used to determine the available current at various stages of the anode life.

NOTE Standard anode resistance formulae for various anode shapes are included in many other CP design standards such as ISO 13174, EN 17243, ISO 15589-2, ISO 24656 and Reference [11].

For applications in seawater outside a salinity range between 30 g dissolved salts/kg seawater (30 ‰) and 35 g dissolved salts/kg seawater (35 ‰), the electrochemical properties, capacity and potential should be determined. Some indications are available in Reference [14] but detailed assessments and testing should be completed prior to selection of anode shape and composition limits.

7.4 Anode shape

Anode shape is determined by many factors including the shape or nature of the object to be protected, for example, pipeline, subsea structure with confined spaces etc. CP specifications advise on the preferred or possible configurations of anodes required in those circumstances.

Other important factors to be taken into account when deciding on anode size and shape are:

- anode distribution, which determines the extent of protection of the structure and therefore the number and size of the anodes;
- alloy cover over core, which determines the initial mass of the anode and any propensity to cracking of the as-cast anode, in addition to the end of life current output;
- anode current output, which is calculated using Ohm's Law from a knowledge of driving voltage and anode to electrolyte resistance.

There are formulae for the calculation of anode to electrolyte (seawater) resistance. All require a knowledge of the electrolyte resistivity which is governed by the seawater salinity.

Most marine CP applications are in waters with a salinity from 30 g dissolved salts/kg seawater (30 ‰) to 35 g dissolved salts/kg seawater (35 ‰) or their sediment. For CP applications outside this salinity area, the full range of salinity shall be determined over full tidal and annual variations and the impacts of these on the anode performance shall be determined by specialists. This covers areas in which salinity is known to be widely variable such as the Baltic, Caspian and Black Seas. Annex A provides information on ocean salinity.

7.5 Physical properties

The physical and dimensional tolerances shall meet the anode design requirements. Any specific tolerances required by any CP design shall be agreed between purchaser and manufacturer. These tolerances shall be clearly marked on an approved drawing.

Physical and dimensional tolerances that can be used as default parameters are given in Annex B.

No anode or its steel core shall have any defect either on its surface or within its body that affects the transportation, installation and future performance of the anode. Any protrusions either on the anode body or insert surfaces shall be examined and removed if potentially a safety hazard.

7.6 Anode core materials

Anode cores shall be fabricated from weldable structural steel tubes/plates/sections in accordance with the ISO 630 series, the EN 10025 series with a maximum carbon equivalent (CE) value of 0,45. For circular hollow sections, ASTM A106 and API 5L may apply.[15], [16]

The CE value shall be calculated using Formula (1):

$$CE = \%C + \frac{\%Mn}{6} + \frac{\%Cr + \%Mo + \%V}{5} + \frac{\%Ni + \%Cu}{15} \tag{1}$$

where,

C is carbon;

Mn is manganese;

Cr is chromium;

Mo is molybdenum;

V is vanadium;

Cu is copper.

If the full chemical composition is not reported, the alternative CE Formula (2) may be used.

$$CE = \%C + \frac{+\%Mn}{6} + 0{,}04 \tag{2}$$

The material certificate for the anode cores shall meet at least the requirements for a declaration of compliance with the order (document type 2.1) as defined in ISO 10474:2013, 4.1.

For all fabrication welding of steel anode cores, welding procedures shall be in accordance with relevant requirements of ISO 15607 and ISO 15609-1.

NOTE 1 Reference [17] constitutes an acceptable equivalent.

Welds shall be performed by welders qualified in accordance with ISO 9606-1.

NOTE 2 Reference [17] constitutes an acceptable equivalent.

100 % visual inspection of the cores shall be carried out prior to casting.

For zinc or magnesium anodes, the steel cores can be bare steel or hot dip galvanised steel. In this case, hot dip galvanising shall be in accordance with ISO 1461.

Zinc electroplated coatings according to ISO 2081 do not provide a true steel-zinc inter-metallic bond and should not be used.

NOTE 3 Small vessel zinc anodes cast onto zinc electroplated steel cores are used but can result in an uncertain performance.

Visible surface contamination of the blast-cleaned or zinc-coated surface are not permitted. When bare steel cores are used, they shall be blast cleaned to the grade Sa 2½ as defined in ISO 8501-1.

For aluminium anodes, the steel core shall be grit blast cleaned at a minimum to the grade Sa 2½ as defined in ISO 8501-1 before casting. The surface roughness Ra shall be a minimum of 75 µm. Galvanised or zinc electroplated cores shall not be used.

Shot or sandblasting shall not be used.

NOTE 4 A zinc coating on an insert within an aluminium anode has an exothermic reaction between the aluminium and the zinc/iron interface and with possible significant safety threats to casting personnel. Both zinc and steel are dissolved during casting with possible modification of the alloy chemical composition and damage to the mechanical properties of the steel core.

Rust discoloration and/or visible surface contamination of the cores before anode casting shall not be accepted.

7.7 Cable connections to anodes

Where anodes are to be connected to the structure using cables, as opposed to direct welding of the core to the structure, the cable shall be selected to provide a robust mechanical connection with low contact resistance and low total voltage drop. The cable should be copper cored, multi-stranded and insulated or insulated and sheathed with a material suitable for long term seawater exposure. Cable size depends on the specific application, but a minimum copper core size of 16 mm^2 is recommended. Larger copper core cross-section areas and further mechanical protection can be required for anodes and connections made in more dynamic environments, or where voltage drops require this. Cable insulation and sheathing properties can also be influenced by flexibility requirements during anode installation.

A detailed cable-to-structure connection procedure is not part of the anode design and should be detailed in the CP design.

Cable connection to the anode shall be mechanically sound using a proven connection method such as brazing. If cable lugs are used, they shall be correctly sized for both cable and stud and hexagonally crimped and brazed or silver soldered. Where possible, the connection should be sealed using a suitable high build coating, setting mastic or encapsulation suitable for the environment of the application.

Where connection is by cable, the use of multiple cables is recommended to provide a degree of redundancy in case of cable damage.

8 Environmental impact

All cathodic protection systems, whether galvanic anode cathodic protection or impressed current cathodic protection, have an impact on the environment and sustainability. Methods of identifying these impacts include environmental product declarations (EPD) and life cycle assessment (LCA). Information on these and other information relevant to galvanic anodes is given in Annex E.

It is recommended that an EPD for the galvanic anodes be requested by the purchaser, with pre-defined impact categories and analysis covering raw material acquisition, production, use, recycling/re-use, waste treatment, transport and energy supply (see Annex E).

The product declaration of anodes can then be included in the environmental impact of the cathodic protection system (LCA). This includes its design, manufacturing application, operation and maintenance, and all components of the system. The entire cathodic protection system as well as the structure to be protected should be optimised to minimise the environmental impact.

Some factors pertaining solely to galvanic anodes can be significant when considering environmental and sustainability impacts. This includes anode geometry and chemical composition.

Anode geometry determines the current available from an anode. Correct anode sizing and distribution can in many cases result in fewer anodes required for a specific system design. Reducing the system overall anode mass requirement reduces the environmental impact.

Anode chemical composition can be tailored to reduce the impact of any constituents on the environment (see Annex C), for example by minimizing cadmium content in zinc anodes for fishing tanks.

Responsible sourcing is recommended. This requires information on origin of ore (preventing felling of forests including rain forests) and environmental data of metals used in alloys.

The direct impact of metal emissions into the surrounding seawater or sediment from dissolving galvanic anodes has been investigated.[18][19][20][21][22][23][24] However, no conclusive evidence has been published to date supporting any measurable or significant adverse impacts of metal salts in the marine environment or on marine organisms.

Annex E provides further information.

Annex A
(informative)

Seawater

This document is applicable to anodes in seawater. It is also applicable to anodes in brackish water and saline sediments.

Marine waters, or "seawater", are those of the oceans or seas. The salinity of fully saline seas is generally between 30 g of dissolved salts/kg of seawater (30 ‰) to 35 g of dissolved salts/kg of seawater (35 ‰), but some sources quote 34 ‰ to 36 ‰.

Brackish seas or waters, typically diluted by fluvial flows from rivers, have salinity in the range of 0,5 ‰ to 29 ‰.

Metahaline seas have a salinity range from 36 ‰ to 40 ‰. Their salinity is derived from the ocean and the salinity does not vary much over time. Examples are Shark Bay, Western Australia and Exuma Cays, the Bahamas.

Some bodies of water have wide variations of salinity with time. These variations are generally due to flora and fauna in the water.

Most cathodic protection applications are in oceans or seas with salinity of 30 ‰ to 35 ‰.

One exception is the Baltic Sea, which ranges from approximately 3 ‰ in its north, approximately 4 ‰ in the Gulf of Finland, and approximately 7 ‰ near the Gulf of Riga. These values can be subject to substantial variation with time and are subject to stratification. The Kattegat, between Denmark and Sweden, is "normal" seawater, but the transition is marked at the Great Belt (Storebaelt) bridge and into the Lubeck and Rostock coast. The salinity around Bornholm is reported at approximately 8 ‰ at the surface and 16 ‰ at depth. There are other issues in the Baltic; much of the bed is anoxic with significant H_2S.

The Caspian varies from an extreme low salinity of approximately 1 ‰ in the north, where the Volga discharges, to between 12,5 ‰ and 13,5 ‰ in the south. There is a restricted area, the Garabogazköl Basin, where the salinity is reported as 300 ‰.

The Black Sea varies from approximately 17 ‰ in the east to approximately 38 ‰ at the Bosphorus, with significant variations with depth and anoxic conditions and H_2S reported at depth.

Annex B
(normative)

Physical tolerances for galvanic anodes

B.1 General

Galvanic anodes within the context of this document are manufactured for specific purposes, i.e. to satisfy the requirements of a cathodic protection design. Therefore, the design of the anode is critical in allowing fulfilment of the CP design intention. The physical and dimensional tolerances shall be consistent with the anode design requirements. Any specific tolerances required by any particular CP design shall be agreed between the purchaser and the manufacturer. To prevent confusion between anode manufacturer and purchaser (and any intermediate inspector), a clear indication of the anode design detail is essential. The established practical method for this is to produce an engineering drawing of the anode which includes dimensions and masses with tolerances and material specifications which can be agreed by all parties before manufacture.

Once the requirements for the anode are agreed, procedures can be adopted to ensure that the drawing requirements are met in full. A practical method for this is for the manufacturer to develop an inspection and test plan (ITP), or quality control plan, which can be followed by both the manufacturer and the purchaser (see 6.1). This annex describes the minimum physical and dimensional tolerances for manufacture which, in the absence of otherwise agreed values, can be used for verification of the agreed physical characteristics of the manufactured anode.

A project specific ITP shall be agreed between manufacturer and purchaser for each individual project. An example of an ITP is included in Annex F.

NOTE In Clause B.3, reference is made to stand-off and slender flush mounted and bracelet anodes. Stand-off anodes have inserts which allow them to be installed some distance from the surface to which they are attached. These can be relatively short anodes or long slender anodes, which can be defined as $L \geq 4r$, where L is the anode length and $r=(c/2)\pi$, where c is the circumference of the non-circular section of the anode and r is the effective radius of the anode. All these anode configurations can have different dimensional and physical tolerances.

B.2 Anode mass

Individual anode castings with nominal net mass above or equal to 50 kg shall have a net mass within ±3 % of the required nominal net mass.

For castings with required nominal net mass below 50 kg, the tolerances shall be ±5 %. A sample of not less than 10 % of the total number of inserts for the anode type being produced shall be weighed and the average mass calculated. Anode net mass is determined as the as-weighed casting mass (gross mass or weight) less the average mass of the insert.

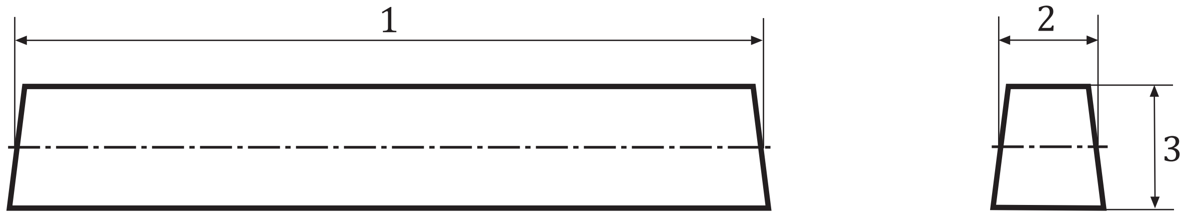
Castings may be weighed either individually or in batches. Batch weighing can be undertaken by agreement between the manufacturer and the purchaser. In this case, a representative number of anodes shall be weighed with a minimum of 10 % of the total number of castings of each type being weighed.

The total net mass of anode castings for a determined delivery order can be agreed as the minimum total mass necessary to deliver the full CP design life and performance. In such cases, the purchaser and the manufacturer should agree on the limits on the minimum mass requirement, e.g. 51 kg + 1,53 kg (3 %) or +3,06 kg (6 %) / −0 kg. The minus 0 kg may be appropriate if the number of anodes to protect a single structure is low.

The total net mass of anode castings shall not be less than the nominal value and should be no more than 2 % above for an agreed contractual delivery requirement.

B.3 Anode dimensions and straightness

Figure B.1 shows anode dimensions which are subject to controlled tolerances.



Key

1	anode mean length
2	anode mean width
3	anode depth

Figure B.1 — Sketch showing anode mean length, anode mean width and anode depth

B.3.1 Stand-off and slender flush mounted anodes

Dimensions shall conform to the following:

— Anode mean length to be ±3 % of nominal length or ±25 mm, whichever is smaller.

Anode length is a prime determinant in anode to electrolyte resistance, and thus anode current output. The purchaser or anode designer may specify the minimum anode length necessary to deliver the full design life and performance. In such cases, the purchaser and the manufacturer should agree on the limits on the minimum length, either by specifying the acceptable tolerances including a zero negative tolerance where appropriate, e.g. 2 000 mm ± 25 mm or −0 + 50 mm.

NOTE Anode length is commonly specified as a mean length to recognise that the anode end profile may be tapered to accommodate casting requirements.

— Anode mean width should be ±5 % of nominal mean width.

— Anode depth should be ±10 % of nominal mean depth.

— The diameter of cylindrical anodes should be ±2,5 % of nominal diameter.

— The straightness of the anode shall not deviate more than 2 % of the anode nominal length or 25 mm, whichever is smaller from the longitudinal axis of the anode. A small amount of warpage is acceptable if it does not adversely affect the anode installation.

— A minimum of 10 % of the total number of anodes shall be inspected and measured to confirm conformity with these requirements.

B.3.2 Bracelet anodes

Dimensions shall conform to the following:

— the mean length of the anode casting shall be ±3 % of nominal length or ±25 mm, whichever is smaller, unless agreed between the purchaser and the manufacturer.

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 tolerances on the anode thickness shall be ±3 mm.

For bracelet anodes fabricated from multiple cast anode segments welded onto bracelet steel bands, the dimensional tolerances of the individual anode casting as described in B.3.1 can be applicable. However, due to the possible variations in segmented bracelet design, tolerances should be agreed between the purchaser and the producer.

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

Anodes shall be free from excessive bowing or twisting. This shall be verified on a completely assembled bracelet by fitting to a full-length former or by any other agreed method. The external diameter should at no point exceed the summation of the tolerances given above.

B.4 Steel core

The location of the anode core or insert dictates the effective anode utilization, which is an important factor in the CP design. Therefore, the cross-section dimensions of the anode core and its location in the anode section shall comply with the agreed anode manufacturing drawing (see Clause B.3).

Half shell anode cores that contain two circumferential straps should have longitudinal tie-bars between them to support the alloy between the straps.

The tolerances for the position of the core within the anode section for any particular project shall be agreed between the manufacturer and the purchaser and unless otherwise agreed shall be for the following:

- flush mounted anodes ±5 mm of the nominal location;
- stand-off type anodes ±10 % of the nominal anode design depth or ±5 % of the nominal anode design mean width;
- for half-shell bracelet anodes, tolerances on the location of the core within the casting shall be agreed prior to manufacture and may include a zero-negative tolerance.

The core position within the anode section shall be confirmed by measurement on the cut faces. This is described in Clause B.7.

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 utilization factor of 0,8 is not achievable and this should be reflected in the CP design.

Anode core protrusions are critical for the installation of the anode and tolerances on fixing centres. Any other specified critical dimensions shall be agreed and measured on samples of all anodes of each type and shall conform to specified requirements. For bracelet anodes, this can also be verified for a completely assembled bracelet by fitting of an agreed number of assemblies to a full-length former or by any other agreed method.

B.5 Anode surface irregularities

All anodes shall be inspected visually to confirm the following requirements are met:

- Shrinkage depressions shall not exceed 10 % of the nominal thickness or depth of the anode, as measured by a gauge from a straight edge across the depression in all positions.
- 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 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 with 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 (for stand-off and flush mounted anodes) or more than 150 mm (for bracelet anodes).
- All protrusions that are hazardous to personnel during handling, and any sharp edges, shall be removed.

B.6 Cracks in cast anode material

B.6.1 General

All anodes shall be inspected visually to confirm conformity with the requirements in Clause B.5. No treatment shall be applied to grind, peen or in any other manner dress cracks before inspection and checks. Magnesium anodes shall be free from cracking visible to the naked eye.

Even with good foundry practice, particular aluminium anode alloy compositions can suffer a degree of cracking.

Cracks can occur while cooling during the casting of aluminium or zinc anodes because of the different coefficients of expansion of the anode and the core. These cracks are generally fine (< 0,5 mm wide) and relatively short. They are not detrimental provided they do not converge in a manner to allow loss of anode alloy material.

Small cracks in the final topping up area of open castings, such as trapezoidal cross section stand-off and flush mounted anode, are not detrimental to the structural integrity of the anode and need not be considered.

Small cracks in aluminium and zinc anodes can be accepted provided the cracks would not cause any mechanical failure during installation, transport or service of the anode. The combination of cracks and lack of bond to the core is detrimental. Visible cracks in the area where the anode material is not wholly supported by the core shall not be accepted.

Cracks penetrating to the steel core or penetrating through the anode are not permitted.

A sample size of anodes to be inspected shall be agreed between the purchaser and the producer. Those with cracks exceeding the limits in Clause B.6 shall be rejected. If more than 5 % of the agreed sample size is rejected, the purchaser and the producer shall review the sample size and possibly increase it.

B.6.2 Stand-off slender and flush mounted anodes

Cracks which follow the longitudinal direction of long slender anodes shall not be accepted.

- For transverse cracks within the section of an anode alloy wholly supported by the core, the following acceptance criteria shall be applied. Longitudinal cracks are not permitted except for fine cracks (< 0,5 mm wide) in the final “topping-up” metal.
- Transverse cracks of maximum length 200 mm are permitted in any single casting surface if their width does not exceed 2 mm and if there are no more than 10 cracks per anode. Small dense cracks shall be considered one crack. Cracks of 0,5 mm width or less shall not be included in the crack count. Full circumferential cracks shall not be permitted.
- For sections of cast galvanic anode material not wholly supported by the anode insert, no cracks visible without magnification shall be permitted.

Acceptable cracks as defined in B.6.2 shall be limited to 10 per casting.

B.6.3 Bracelet anodes

For any sections of cast anode alloy not wholly supported by the core, cracks visible without magnification shall not be accepted.

Anodes, in which cracks are visible without magnification, shall be rejected if crack dimensions exceed the following limits:

- longitudinal cracks exceeding 100 mm or 20 % of the bracelet length, whichever is greater and with a maximum width of 1 mm;
- circumferential cracks exceeding 200 mm in length or 50 % of the bracelet outer diameter, whichever is greater provided the crack width is < 1 mm;
- circumferential cracks exceeding 100 mm in length or 50 % of the bracelet outer diameter, whichever is greater provided the crack width is < 3 mm;
- cracks exceeding 3 mm width;
- cracks penetrating to the steel core or through the cast anode.

Anodes with cracks not within the section of an anode wholly supported by the core shall be rejected.

Acceptable cracks as defined in B.6.3 shall be limited to two per half shell.

Acceptance criteria for other sizes of cracks should be dependent upon core and anode design and agreed between the purchaser and the manufacturer.

B.7 Internal defects and 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 any pre-production trials. These shall be agreed between the purchaser and the producer.

If any anode does not meet the requirements in Clause B.7, or requirements agreed between the purchaser and the producer and documented in the ITP (see example of ITP in Annex F), an additional anode shall be subjected to destructive testing. If this does not satisfy specified requirements, the whole anode batch should be rejected or other actions taken as agreed prior to fabrication.

Slender and flush mounted anodes selected for examination shall be sectioned transversely by single cuts at 25 %, 33 % and 50 %, of nominal length, or at other agreed locations for a particular anode design.

Bracelet anodes selected for examination shall be sectioned transversely by single cuts at 25 % and 50 % of nominal length, or at other agreed locations for a particular anode design.

The cut faces, when examined visually without magnification, shall meet the following criteria:

- Gas holes and porosities shall be limited to maximum 2 % of the total cut surface areas, and maximum 5 % of any individual cut surface area; no cavity shall exceed 1 cm^2 in a single transverse section.
- Non-metallic inclusions shall be limited to maximum 1 % of the total cut surface areas and maximum 2 % of any individual cut surface area; no non-metallic inclusion shall exceed 1 cm^2.
- Lack of bond (voids adjacent to the core) shall be limited to maximum 10 % of the total anode core perimeter in all cut sections and maximum 20 % of the perimeter for any individual cut.

For non-tubular cores and half-shell bracelet castings, the limits may be otherwise agreed between the manufacturer and the purchaser.

B.8 Reporting

The purchaser and the producer should agree on the requirements for all the inspections and testing outlined in Annex B as well as the details of the required reporting of the data and presenting of any photographic records. These can be integrated with other quality related data into a formal data book for the production or batches of production.

Annex C
(informative)

Composition and performance properties for galvanic anodes

C.1 Aluminium alloys

C.1.1 Anode material

Aluminium alloys for use in seawater and saline sediment normally contain zinc and small amounts of indium as an activator. However, there is a wide range of alloy compositions. Some alloys are non-proprietary. Some are or were proprietary and are or were covered by national and/or international patents. The different compositions are aimed at modifying the properties of the anodes primarily to optimise specific anode performance properties.

Compositions for some of the common aluminium anode alloys are given in Table C.1, with aluminium being the balance. These alloy ranges are not necessarily optimised for performance.

Aluminium-zinc-indium-magnesium anode compositions are not recommended for large offshore anodes, for anodes with large cross section cores or where the anode can be subject to high stress levels in service, e.g. by tidal flows or storms.

The aluminium-zinc-indium anode alloys within the generic compositions A 1, A 2 and A 3 have the longest track record. There are many individual specifications for composition within these generic alloys. However, the zinc content is usually in the range 2,5 % and 5,0 % and the indium content around 0,02 %. Residual impurities, such as iron and copper, should be kept to a minimum. However, due to raw materials and production methods, the iron content can be the most difficult to control. For long-term applications, the iron content shall be less than 0,09 %, but some purchasers require lower limits. The limits of all elements in these alloys are important and can be optimised with the above ranges for specific environments.

All impurities should be kept as low as possible, including spurious impurities not being tested in routine analysis, otherwise potential and capacity can be adversely affected. Therefore, it is recommended to undertake a short-term electrochemical testing according to 6.4.3. Historically, anode alloys beyond the composition ranges in Table C.1 have been found to passivate (i.e. form a stable protective film on the anode surface), which prevents further anode dissolution and hence provision of current for cathodic protection. Anode alloys not within the generic limits in Table C.1 should not be used unless they are supported by long term (> 1 year, see Annex D) free running tests under environmental and current density conditions that closely replicate the planned use of the anodes.

The indium activated aluminium anode alloys (A 2 and A 3) have proved to be suitable for applications in marine sediments, i.e. covered with sediment.

Aluminium alloys are only applicable for environments with salinity greater than 5 g dissolved salts/kg seawater (mass fraction 0,5 % or salinity 5 ‰), i.e. typically in seawater/brackish water environments with resistivity of less than 2 Ω m.

Table C.1 — Chemical composition for aluminium anodes in % of mass fraction

Elements	Alloy A 1	Alloy A 2	Alloy A 3	Alloy A 4	Alloy A 5
Zn	2,0 to 6,0	3,0 to 5,5	4,75 to 5,75	0,15 max.	0,3 to 0,8
In	0,010 to 0,030	0,016 to 0,040	0,016 to 0,020	0,005 max.	0,018 to 0,040
Ga	–	–	–	0,092 to 0,110	0,04 to 0,10
Fe	0,12 max.	0,09 max.	0,06 max.	0,08 max.	0,08 max.
Si	0,12 max.	0,10 max.	0,08 to 0,12	0,10 max.	0,10 max.
Cu	0,006 max.	0,005 max.	0,003 max.	0,005 max.	0,003 max.
Cd	0,002 max.	0,002 max.	0,002 max.	–	0,002 max.
Other impurities (each)	0,02 max.	0,02 max.	0,02 max.	0,02 max.	0,02 max.
Other impurities (total)	0,1 max.	0,1 max.	0,05 max.	0,05 max.	0,05 max
Al	remainder	remainder	remainder	remainder	remainder

NOTE 1 Alloy A 1 is generally used for marine applications.

Alloy A 2 is generally used for offshore applications.

Alloy A 3 is generally used for deep- and cold-water applications.

Alloy A 4 is an alloy used for low driving voltage applications.

Alloy A 5 is an alloy used when lower levels of zinc are preferred or required.

NOTE 2 Alloy A 4 is an alloy designed for low driving voltage applications (e.g. for use with high strength steels) and has not been widely used. See References [25], [26] and [27] for more information on this alloy.

NOTE 3 The ranges of indium in Table C.1 have an essential role in aluminium anode performance and electrochemical capacity. Indium is the “activator” within the alloy. Lower indium results in anode prone to passivation. Higher indium concentrations result in high self-corrosion and lower the electrochemical capacity.

NOTE 4 Alloy A 5 is a proprietary alloy subject to international patent (EP no. 20204306.3)[28] and has been developed in response to environmental concerns.

NOTE 5 Alloys based on aluminium-zinc-magnesium-indium (Al-Zn-In) have also been used for ship CP applications. However, Al-Zn-In alloys that contain Mg can suffer from age hardening at ambient temperatures and cracking, particularly when high residual stresses in the anode are a consequence of the casting procedure. This can be brought about by anodes with large steel core cross sections compared with the cast alloy cross section.

NOTE 6 Alternative alloys based on aluminium-zinc-tin (Al-Zn-Sn) are subjected to heat treatment to achieve effective activation and can suffer inter-granular corrosion and slow activation at low temperatures (i.e. 5 °C). Al-Zn-Sn alloys are no longer commonly used; they have not been included in Table C.1.

NOTE 7 Alternative alloys based on aluminium-zinc-mercury (Al-Zn-Hg) are no longer used due to environmental restrictions.

In partially closed and flooded spaces where seawater replenishment is inadequate or uncertain, the use of Al based anodes risks significant acidification (reduced pH) with detrimental effect on the anode performance and CP efficacy. In such situations, the use of zinc-based anodes is recommended according to ISO 24656.

C.1.2 Electrochemical properties

The electrochemical properties for aluminium based alloys vary depending on the specific alloy composition, metallurgical condition, operating temperature, operating anodic current density and the operating environment.

The actual properties and operational conditions for an alloy should be determined and documented by testing in accordance with the requirements of 6.4. Indicative values for the typical generic alloy compositions shown in Table C.1 are given in Table C.2 in normal operation conditions in open seawater at ambient temperature and with a nominal anode current density of approximately 1 A/m^2.

Table C.2 — Typical properties of aluminium anodes in normal operation conditions

Alloy type	Environment	Closed circuit potential Ag/AgCl/seawater reference electrode V	Electrochemical capacity A·h/kg	Anode consumption rate kg/(A·y)
Alloy A 1	Seawater	−1,09	2 500	3,5
Alloy A 2	Seawater	−1,09	2 500	3,5
	Marine sediments	−1,05	2 000	4,4
Alloy A 3	Seawater	−1,09	2 500	3,5
	Marine sediments	−1,05	2 000	4,4
Alloy A 4	Seawater	−0,83	1 500	5,8
Alloy A 5	Seawater	−1,09	2 500	3,5

NOTE 1 The typical closed-circuit potential, capacity and anode consumption rates shown are consistent with published worldwide results for alloys tested to the 12-month qualification procedure of References [11] and [29] (DNV type test results). These tests are carried out on specific alloy compositions within the ranges quoted in Table C.1 and not for the full range of generic compositions in Table C.1. Annex D gives further information on the implications of testing.

NOTE 2 The electrochemical capacity values shown are the practical current capacity values for optimised composition aluminium alloys and incorporate an allowance for self-corrosion of the alloy. No further efficiency allowance is necessary.

NOTE 3 It has not been possible to find reported performance data for Alloy A 1, A 4 and A 5 in marine sediments.

NOTE 4 Values shown in Table C.2 are based on specific operating conditions and are not appropriate for CP design in all circumstances.

The practical electrochemical capacity for a specific Al-Zn-In alloy should be confirmed based on either long-term performance tests of at least 12 months carried out by an independent authority or from long-term practical experience. Short-term tests are likely to give higher capacity values (i.e. will indicate a higher electrochemical capacity closer to the theoretical Faraday capacity) due to the higher current density applied to the anode alloy test sample compared to anodes in service. Where long-term performance data are not available, caution should be exercised in selecting values for design purposes. Annex D gives further guidance on testing.

The aluminium alloy anodes in Table C.2 shall have been subjected to long-term testing. Long term testing can be run according to DNV-RP-B401:2021, Section 10[11] or equivalent (see 6.4.2). The average capacity results of this test should be in excess of 2 500 Ah/kg with a spread within a tolerance range of ± 150 Ah/kg for the individual samples tested and a closed circuit potential of −1,08 V or more negative with respect to Ag/AgCl/seawater for all samples tested. If the production composition limits are maintained very close to the composition of the alloy originally tested in the long-term tests, these long-term test data are reproduceable. This requires the composition to be within a smaller compositional range than in Table C.1.

Test procedures and the implications of their results are described in 6.4 and Annex D.

Electrochemical capacity for all aluminium-based alloys reduces significantly at higher operating temperatures. For example, electrochemical capacity for alloys A 1 and A 2 drop approximately linearly from 2 500 A·h/kg at 25 °C to 500 A·h/kg at 80 °C. This is equivalent to a change in anode consumption rate of 3,5 kg/(A·y) at 25 °C to 17,5 kg/(A·y) at 80 °C. In saline sediment, at elevated temperatures, the capacity values is lower than those indicated for seawater (see ISO 15589-2 and Reference [12]).

Environments such as brines, seawater of varying salinity or marine sediments, with or without hydrogen sulfide (H_2S), result in variations in aluminium anode alloy performance properties. Specific testing should be completed to determine appropriate application parameters.

C.2 Zinc alloy

C.2.1 Anode material

Zinc based anodes are widely used for shipping applications. They are also used for offshore structures, but their higher density can lead to weight limitations. Zinc anodes do not require a chloride environment to operate and can be used in brackish and fresh water applications, or where there is a risk of acidification using aluminium anodes. There is a wide range of alloy compositions available. The different compositions are intended to optimise specific performance properties.

Some alloy compositions are proprietary to specific to a producer and/or subject to international patents.

Chemical compositions of typical zinc anode alloys are given in Table C.3, with zinc being the balance.

All impurities should be kept as low as possible, including spurious impurities not being tested in routine analysis, otherwise potential and capacity can be adversely affected. Therefore, it is recommended to undertake a short-term electrochemical testing, according to 6.4.3.

Table C.3 — Chemical composition for zinc anodes in % of mass fraction

Elements	Alloy Z 1	Alloy Z 2	Alloy Z 3	Alloy Z 4	Alloy Z 5
Al	0,1 to 0,5	0,005 max.	0,10 to 0,20	0,10 to 0,25	0,10 to 1,00
Cd	0,025 to 0,07	0,003 max.	0,04 to 0,06	0,001 max.	0,001 max.
Fe	0,005 max.	0,0014 max.	0,0014 max.	0,002 max.	0,005 max.
Cu	0,005 max.	0,002 max.	0,005 max.	0,001 max.	0,005 max.
Pb	0,006 max.	0,003 max.	0,006 max.	0,006 max.	0,005 max.
Sn	–	–	0,01 max.	–	0,005 to 1,00
Mg	–	–	0,50 max.	0,05 to 0,15	–
Others	0,10 max.	0,005 max.	0,10 max.	0,10 max.	0,10 max.
Zn	remainder	remainder	remainder	remainder	remainder

NOTE 1 Alloy Z 1 is equivalent to the alloys noted in MIL-DTL-18001 (2013)[30] or to ASTM B418, Type I.[31]

NOTE 2 Alloy Z 2 is of term “high purity zinc” and is equivalent to the alloys noted in ASTM B418, Type II.[31]

NOTE 3 Alloy Z 4 is a proprietary alloy that has been developed for use at elevated temperatures.

NOTE 4 Alloy Z 5 has been used in seawater but not widely.

Alloy Z 4 and alloy Z 5 can be used when a low cadmium alloy is needed.

C.2.2 Electrochemical properties

The electrochemical properties for zinc-based alloys vary depending on the specific alloy composition and the operating environment. Generally, zinc alloys are only applicable at temperatures up to 50 °C. Above this temperature, zinc alloys Z 1 and Z 3 can suffer from inter-granular corrosion, especially when buried in saline sediment. Some proprietary alloys have been developed that can operate successfully at higher temperatures up to 85 °C. At higher temperatures (> 70 °C), zinc anodes in low chloride environments can exhibit potential reversal with steel.[32]

The electrochemical capacity values shown are the practical capacity values for zinc alloys. These values incorporate an allowance for self-corrosion of the alloy. No further efficiency allowance is necessary.

The actual properties and operational conditions for an alloy should be determined by testing in accordance with Annex D. Typical values of electrochemical properties for alloy compositions shown in Table C.3 are given in Table C.4.

Table C.4 — Typical electrochemical properties of zinc anodes at ambient temperatures (5 °C to 25 °C)

Alloy type	Environment	Closed circuit potential Ag/AgCl/seawater reference electrode V	Electrochemical capacity A·h/kg	Anode consumption rate kg/(A·y)
Alloy Z 1	Seawater	−1,03	780	11,2
	Marine sediment	−0,99	750	11,8
Alloy Z 2	Seawater	−1,00	760	11,5
Alloy Z 3	Seawater	−1,03	780	11,2
Alloy Z 4	Seawater	−1,03	780	11,2
	Marine sediment	−0,98	710	12,3
Alloy Z 5	Seawater	−0,94	780	11,0
NOTE 1 Alloy Z 4 was developed for use at elevated temperatures.				
NOTE 2 It has not been possible to find published long-term performance test result for alloy Z 4 or alloy Z 5.				

Alloys Z 1 and Z 3 should not be used at temperatures above 50 °C in sediments.[32]

C.3 Magnesium alloy

C.3.1 Anode material

Magnesium-based anodes can be required in brackish or fresh water where their high driving voltage is required to provide practical current output, or in seawater where rapid polarization is desired. Magnesium anodes can be used in seawater. However, aluminium and zinc alloys are often the first choice where there is a naturally low seawater resistivity. Magnesium anodes can be designed for long-term use in seawater if the anode shape, anode resistance, total circuit resistance and the anode-to-structure spacing are specifically selected for such applications.

There are two generic groups of magnesium alloys used in cathodic protection as shown in Table C.5, with magnesium being the balance. These are classified as high potential and low potential grades. Several low potential grade magnesium alloy specifications are available. High potential magnesium alloys are more applicable to higher resistivity waters and saline muds. Low potential magnesium is more commonly used for seawater, medium-to-lower resistivity waters and higher temperature applications.

The propensity for magnesium alloys to self-corrode in seawater means that anode specification, manufacturing techniques and application are critical. Magnesium anodes should not be wet stored before installation.

Table C.5 — Chemical compositions for magnesium anodes in % of mass fraction

Elements	High potential alloy	Low potential alloy (H-1)	
	M 1	Grade A	Grade B
Al	0,01 max	5,3 to 6,7	5,3 to 6,7
Zn	–	2,5 to 3,5	2,5 to 3,5
Mn	0,50 to 1,3	0,15 min	0,15 min
Fe	0,03 max.	0,003 max	0,003 max
Cu	0,02 max.	0,02 max	0,05 max
Si	–	0,10 max	0,30 max
Ni	0,001 max.	0,002 max	0,003 max
Others	Total: 0,30 max.	Total: 0,30 max.	Total: 0,30 max.
Mg	remainder	remainder	remainder

NOTE 1 Alloy M 1 is equivalent to the anodes noted in ASTM G97:2018.[33]

NOTE 2 Alloys H-1, grade A and B are equivalent to the anodes noted in ASTM B843:2018.[34]

NOTE 3 The high driving potentials available when operating in seawater increase generation of hydrogen gas compared to aluminium and zinc.

All impurities should be kept as low as possible, including spurious impurities not being tested in routine analysis, otherwise potential and capacity can be adversely affected.

In both cases, residual impurities naturally occurring in the magnesium shall be controlled to limit polarization and self-corrosion. Manganese is added to isolate iron impurities by the formation of iron compounds and make the anode potential more negative.

Surface variations in performance are created by alloy elements including manganese and iron compounds causing cathodic sites and self-corrosion.

Increased anode efficiencies are achieved by specifying the correct alloy composition and the best processes for casting and controlled cooling.

Controlled cooling of the casting has been seen to reduce grain size, since it creates more Mg/Al compounds interspersed with the Fe/Mn compounds, thus reducing self-corrosion due to the presence of fewer cathodic sites.

Cooling in a furnace, in air or in uncooled moulds is not recommended, as these produce large grain size with wide variation throughout the casting, in particular with larger anode castings.

NOTE The purest production route for magnesium production is electrolytically from seawater. Magnesium is also manufactured by a thermal smelting process. Some recycling of magnesium products produces suitable input material for low potential magnesium. Anodes produced from magnesium from the thermal smelting process can exhibit variable performance characteristics.

Alloys produced in electric induction furnaces have a better natural mixing process than those from gas fired furnaces. Smaller grain sizes are produced by casting into moulds, subject to casting size, than from extruding magnesium.

C.3.2 Electrochemical properties

Magnesium based alloys have a higher operating voltage (typically −1,5 V vs. Ag/AgCl/seawater or −1,7 V vs. Ag/AgCl/seawater, dependent on alloy type) than aluminium and zinc alloys but have a lower electrochemical capacity – and higher consumption rate – due to self-corrosion.

Typical values of electrochemical properties for alloy compositions shown in Table C.5 are given in Table C.6.

Table C.6 — Typical electrochemical properties of magnesium anodes at ambient temperatures (5 °C to 25 °C)

Alloy type	Environment	Open circuit potential Ag/AgCl/seawater reference electrode V	Closed circuit potential Ag/AgCl/seawater reference electrode V	Electro-chemical capacity A·h/kg	Anode consumption rate kg/(A·y)
Alloy M 1	Seawater	−1,65 to −1,73	−1,45 to −1,70	1 100	7,3
Alloys H-1	Seawater	−1,45 to −1,55	−1,40 to −1,50	1 100	7,3
NOTE The electrochemical capacity values shown are the practical capacity values for magnesium alloys and incorporate the high self-corrosion (corresponding to approximately 50 %) of the alloy. No further efficiency allowance is necessary.					

The practical electrochemical capacity can be considerably lower than that shown in Table C.6 based on composition and manufacturing methods and when operating at low current densities or over extended operating periods.[35] Efficiency values as low as 20 % have been recorded during testing.[36]

Magnesium anode electrochemical properties cannot be accurately predicted from composition alone. Documented short-term potential and capacity determinations at predicted current densities and under conditions similar to those in which the anode will be subjected should be considered for each batch or series of batches of anodes with the same minor impurities and microstructure.

Annex D
(informative)

Description of various electrochemical tests

D.1 General

There are two principal reasons for carrying out electrochemical tests: testing for production quality control and testing to determine alloy electrochemical performance.

The purpose of production quality control testing is to determine that alloy heats produced to the same chemical composition specification give consistent and reproducible results. The requirement for the test is to give consistent results from tests using practical and reproducible test parameters, such as current density, temperature and test period, which are chosen to allow multiple tests to be carried out without special measures such as elevated temperature. The test should be conducted over a short period of time since the release of anodes for delivery from production can depend on the results. Short-term testing does not provide reliable data regarding long-term alloy electrochemical capacity or operating potential. The results from such tests should not be used for design purposes.

Performance tests require a very different set of test parameters since they are intended to determine alloy performance in actual or simulated exposure conditions. This requires a particular environment, test period and anode current density to determine a meaningful result.

However, the electrochemical properties of galvanic anodes are not a material constant. It is very important to recognise that the actual test parameters used in either test will have an effect on the test outcome. This is less important in short-term quality control tests since, provided the same test parameters are always used, the results can be useful to fulfil the aims of the test as described above.

A primary requirement of any test is that it should give useful results within the defined period of the test. The function of an anode alloy is to provide protective current over relatively long periods, so the test parameters shall be a compromise to make the test both useful and meaningful.

There are three established methods of test to determine galvanic anode electrochemical properties. These are galvanostatic, free running and potentiostatic. This annex describes the general principles of these tests. It also considers the effect on test results of some of the parameters used in the accepted test procedures and highlights where the interpretation of test results should be very carefully considered if the tests are to be truly meaningful.

D.2 Galvanostatic tests

In this test, the galvanic anode is exposed to a defined constant current density. During the exposure, the anode potential is recorded; after the exposure, the anode capacity is calculated from the sample weight loss and aggregated current over the test period (ampere-hours). The galvanostatic test can be performed at different current densities (0,003 A/m^2 to 10 A/m^2). It is possible to change the anode current density at different times during the test by changing the applied current. The exposure to a constant current density on the anode does not represent a real-life situation for a galvanic anode where the anode current density can vary greatly during the service life. Passivation effects can therefore not be studied in this test.

The electrochemical capacity of aluminium anodes is reduced at low current densities. At low current densities, significant scatter can be obtained which can invalidate the results.

NOTE 1 Examples of galvanostatic test procedures are Reference [37], the DNV-RP-B401[11] test for quality control of aluminium and zinc-based anode alloys and Reference [33] for magnesium anode alloys in bentonite.

Reference [33] is the only established test method for magnesium. The data from such testing indicates variances in performance in bentonite, but the correlation of these data with performance in seawater should be used with caution.

NOTE 2 These short-term tests do not provide a definitive measure of long-term anode performance. These tests are generally only used as part of a quality control procedure (as described in 6.4.3) or as a pre-screening procedure.

Galvanostatic testing can be used for long-term testing but requires continuous current and potential monitoring in order to determine practical results over a long period. For this reason, free-running tests are more often used to determine alloy performance.

D.3 Free-running tests

In this test, the galvanic anode is connected to a steel cathode and the polarization behaviour is produced by the galvanic couple effect under given conditions. The free running test can therefore represent a simulation of the galvanic anode in some practical situations. During the test exposure, the current and the anode potential should be continuously recorded since the aggregated current in ampere hours is required to calculate alloy electrochemical capacity. However, over prolonged testing periods, it is possible to manually monitor current and potential; current can be averaged over short periods if the exposure conditions are stable. The test is suitable for long term performance data assessment and gives data on practical electrochemical capacity and anode potential. The anode potential can give information on passivity.

In a free-running test, the anode current is not controlled. In long-term tests, the current reduces as the cathode polarizes and calcareous film builds up on the cathode surface. The calcareous deposit is a layer consisting primarily of a mixture of calcium carbonate and magnesium hydroxides deposited on surfaces being cathodically protected in seawater due to the increased pH adjacent to the protected surface.

The anode current density is controlled by the anode/cathode surface area ratio. This shall be chosen with care to obtain measurable consumption within the test period and be of practical significance in relation to the intended application of the anodes.

If the area of the cathode is too small or if calcareous deposits reduce the cathodic current to a value that is too low, the anodic current may be reduced to near zero. The cell arrangements, sample size, cathode distribution and exposure conditions can therefore be critical in free-running tests.

NOTE A method currently used for long-term testing is given in Reference [11].

The nature of the free running test necessarily determines the range of anode current densities that are of practical value for determination of meaningful data. It is possible that this does not reflect the actual conditions envisaged in any application of the anode. For example, a test result obtained with relatively high current density can adequately reflect an offshore application in open seawater but not be appropriate for an anode buried partially in sediment whether at ambient or elevated temperature. Caution should be exercised when using the test data from any particular test for CP design purposes (see 6.4.2).

With adapted cell arrangements, the free running test can be used as a screening test to give data on electrochemical capacity, anode potential and on tendencies to passivate in a variety of envisaged applications. It can also be used to qualify alloys for practical applications provided the limitations of this test as described above are recognised.

D.4 Potentiostatic tests

In this test, the anode is exposed at a given defined value of potential. The potentiostatic test is suited for establishing tendencies to passivity. Such tendencies can be observed in a free-running test, but not with a galvanostatic test.

In a practical situation, a galvanic anode operates with a relative stable potential, while the current can vary significantly. However, the operating potential is not always known and the potential set in the test can give an unrealistic current output. Therefore, for potentiostatic testing to determine the alloy electrochemical capacity, experience or detailed knowledge of the operating potential is necessary.

The preferred approach is to conduct tests over a range of potentials.

D.5 Effect of other test parameters

The tests described in this annex are designed for zinc and aluminium anodes to be used in seawater. Both short-term quality control tests in current practice use either natural or substitute seawater according to ASTM D1141 24[38] (but without trace heavy metal additions). Natural seawater is not defined and can vary according to geographic location and seasonal factors. One important factor is to ensure continuous oxygenation of the test solution. This requires either mechanical aeration directly into the test cell or some form of electrolyte circulation with external aeration. At coastal test locations, a “once through” natural seawater system can be used. However, over a long test period, this can introduce other seasonal variations, such as temperature change.

Seawater temperature does affect electrochemical performance. However, temperature differences within the range 15 °C to 30 °C have no significant effect on consistency of results in the tests described in this annex. For long-term performance tests however, the temperature of the electrolyte can fall below this range and vary seasonally. This is important when comparing long-term laboratory test results from around the world, even when the tests are carried out to the standard procedure outlined in Reference [11], which allows temperatures in the range 7 °C to 20 °C.

Anode grain structure can be a factor in electrochemical performance, particularly electrochemical capacity, because of an anticipated effect of crystal orientation on dissolution rate. This can be more noticeable for short-term tests on as-cast surfaces because of the chill factor on initial solidification and relatively low alloy dissolution in the test. Subsequent anode material metallurgical microstructure is determined by anode size, mould design, cooling rate etc. These factors are expected to vary between different casting techniques and producers. However, the established test procedures in common use (see References [11] and [13]) involve either machining from anodes or separately cast samples. This makes it impossible to assess the effect of anode material metallurgical microstructure, although the position from within the cast anode from which the sample is taken determines the grain size and orientation.

The anode dissolution topography should be visually examined after testing to assess if there is an even corrosion pattern without excessive pitting or undercutting. Visual examination can indicate whether there are any inactive (passive) areas on the sample surface that can have an impact on the test results.

The test period chosen shall produce measurable results with the particular test parameters. It shall also be a practical assessment of either the consistency of alloy production within a manufacturing context for the shorter-term tests or alloy performance for the long-term tests. However, a shorter test period entails high anode current density parameters to produce significantly measurable results. These results are therefore of limited value. Similarly, the period chosen for the long-term test is critical since, particularly in the free-running tests, the test parameters can change with time and therefore the data obtained can be time dependant. This means that performance data obtained after any prolonged test period, even the established test in Reference [11], should be treated with caution for design purposes.

Annex E
(informative)

Environmental impact considerations

E.1 General

All cathodic protection (CP) systems have an environmental and sustainability impact. This includes galvanic anode CP systems, impressed current CP systems, as well as their anodes and associated equipment, whether metals, copper cable, polymeric sheathing, electronics etc. CP systems are often used in conjunction with polymeric coatings, which also have an environmental impact.

Using galvanic anodes that conform to this document ensures the performance of CP systems to protect structures in seawater when designed in accordance with the appropriate CP system standards, e.g. ISO 15589-2, ISO 24656 and EN 17243. This in turn reduces environmental and sustainability impacts whilst still providing CP to the structure.

Legislators and governments expect CP designers to meet increasing numbers of requirements on environmental and sustainability impacts when selecting a CP system and associated materials. This annex is intended to offer guidance and information for the producer and designer of galvanic anodes to minimize adverse environmental impacts and consider sustainable aspects within a functional system.

E.2 UN sustainable development goals

The United Nations has developed 17 sustainable development goals (SDGs), which have been adopted by all Member States. In the development of this document, the following SDGs were identified as relevant:

- Goal 7: Affordable and clean energy;
- Goal 12: Responsible consumption and production;
- Goal 13: Climate action;
- Goal 14: Life below water.

This annex discusses methods for addressing these goals in the production and design of galvanic anodes.

E.3 Minimizing adverse environmental and sustainability impacts from galvanic anodes

E.3.1 Affordable and clean energy

Galvanic anodes contribute to the protection of energy generating assets in many ways. Examples can be offshore wind turbine foundations, condenser protection in conventional power stations, infrastructure protection and transmission systems both onshore and offshore.

Protecting structures against corrosion can be an act of sustainability, since a protected structure lasts longer than an unprotected structure. This is particularly true for CP systems that are robust, reliable and have a low risk of failure. Galvanic anode CP systems designed by competent persons using acknowledged codes and appropriate CP standards represents such a system.

However, some consideration and guidance can be given to further reduce any adverse environmental impacts by considering aspects of design related to the CP system, the design of the anodes used and the alloy composition.

A galvanic anode cathodic protection system is designed such that the anodes supply the current needed over their lifetime. Any excess design current can lead to an overestimation of anode mass with a subsequent unnecessary environmental impact during production. Cathodic protection design standards like ISO 15589-2, ISO 24656, ISO 13174 and EN 17243 outline the minimum recommended design currents for particular applications.

Long, slender anodes deliver a higher current output than shorter, less slender anodes. Optimising the anode geometry results in fewer anodes needed for a specific system design.

Anodes should be distributed as evenly as possible to reflect:

- the metal surface area to be protected in seawater;
- variations in CP current density requirements with depth.

This optimises current consumption from anodes.

E.3.2 Responsible consumption and production

E.3.2.1 Energy consumption in production

Processing any metal from its natural state to a commercially pure metal is highly energy intensive. The alloying constituents of galvanic alloys are no exception. The supply of raw materials of the very high quality and restricted impurity levels needed for galvanic anodes is a specialist supply function. Origin and environmental data should be requested from specialist traders when sourcing raw materials for anode production. For example, this can be environmental data as carbon dioxide equivalent emissions and potential rainforest destruction (see also E.3.2.2).

Anode manufacturing involves the melting of raw materials, alloying and casting into mounds. There are many sources of heat for melting that have differing environmental impacts. The choice of energy supply for manufacture depends on local circumstances but should intend to minimize the environmental impact of the production process and conserving energy. Fabrication of other anode associated materials such as steelwork should also be done as energy efficiently as possible.

E.3.2.2 Environmental product declaration

An environmental product declaration (EPD) is a report that communicates what a product is made of and how it impacts the environment across its entire life cycle. An EPD is defined in ISO 14020:2022, 5.4.1. Requirements, guidance and further information for EPDs are given in ISO 14025.

All manufacturers, designers, owners and operators of CP anodes should develop documented information regarding the environmental impact of the product they are making or using. An anode manufacturer is only able to provide information on environmental impact from sourcing to finished anode.

An EPD typically contains the following:

- global warming potential (Eq. CO_2);
- depletion potential of the stratospheric ozone layer;
- formation potential of tropospheric photochemical oxidants;
- acidification potential of land and water;
- eutrophication potential;
- abiotic depletion potential for non-fossil resources;

— abiotic depletion potential for fossil resources.

NOTE 1 It has not been possible to identify environmental standards specific to the marine sector, but the collection of standards covering construction works can be relevant. EPDs for construction works are typically made according to ISO 14025 and EN 15804.

NOTE 2 When making an EPD, electricity usage can be taken from official statistics recorded by national agencies who publish data on power generation from a mix of sources. This means the average energy consumption is typically used in national calculations. Hence countries with a larger amount of renewable energy are able to document a lower adverse environmental impact compared to countries using fossil fuels when producing anodes for instance.

E.3.3 Climate action

Greenhouse gases comprise carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and fluorocarbons. These gases absorb solar radiation and re-emit it, thus creating the “greenhouse” effect and causing global warming. Carbon dioxide is by far the largest contributor to this process. The main source of carbon dioxide is the use of fossil fuels for heating and power generation, transport and industrial processes.[39][40] For galvanic anodes, the main factors impacting CO_2 emissions are thermal energy use (gas and electricity) during production and transportation during delivery.

From a climate change perspective, any measures to reduce CO_2 emissions should be considered. The source of fuel used to produce heat and electricity during the production of anodes can be significant (see E.3.2.1). This can also depend on the location of the production facility, but power supply companies are able to advise on the mix of generation sources they use.

The objective of cathodic protection is to supply the current needed over the design lifetime. Any excess current or excess mass of (galvanic) anodes can influence the environmental impact. The design should seek to minimise excessive current supply whilst providing the minimum anode mass to achieve the objective. Cathodic protection standards such as ISO 13174, EN 17243, ISO 15589-2 and ISO 24656 outline the minimum recommended design currents for particular applications.

E.3.4 Life cycle assessment

Whilst some attempt can be made to quantify the impact of anodes in terms of production, the true environmental and sustainability impact can only be determined from a life cycle assessment (LCA). The impact analysis can include raw material acquisition, production, use, recycling/re-use, waste treatment, transport and energy supply.

According to ISO 14040, an LCA is defined as the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle. The principles and framework, as well as requirements and guidelines for conducting a life cycle assessment, are described in ISO 14025 and ISO 14040.

E.3.5 Life below water

E.3.5.1 General

A functioning galvanic anode provides protective current by its dissolution. Metal ions are then inevitably released into the marine environment. However, the following are relevant when considering the environmental impact:

a) the concentration of the metal emitted into the environment (seawater and sediment/seabed);

b) the toxicity of the metal emitted.

E.3.5.2 Concentration of dissolved metal

The concentration of ions in the seawater in the vicinity of galvanic anodes highly depends on the seawater state, flow and thereby dilution effect over time. In tanks and harbours where the flow can be restricted, a higher concentration of ions can be expected. The ratio of concentration of ions in water and the concentration of metals in sediment (either as ions, precipitations, absorbed or in complexes) is not known.

The dissolving anode material (aluminium and zinc) can form insoluble precipitates in seawater which can be friable and accumulate in the sediment beneath the anodes in locations where there is little water flow or scour. This is claimed to have been confirmed in studies of aluminium anodes in certain harbours, although the results are inconclusive in terms of environmental impact.[18]

Studies of metal concentrations around offshore wind farms report[41] that the concentrations of the constituents in both water and sediments are largely within the known variability for the North Sea. It is assumed that there is a relatively high dilution effect in the seawaters, which reduces the concentration of alloy metals as such.

However, the amount of metals emitted should in any case be kept at the lowest possible level.

E.3.5.3 Toxicity of metal emission

Whilst studies on anode alloy toxicity when emitted into seawater and saline sediments are limited, there is no definitive conclusion regarding adverse impacts on marine life although studies are ongoing.[41]