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Cathodic protection of harbour installations

Protection cathodique des installations portuaires

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Foreword

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

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 13174 was prepared by the European Committee for Standardization (CEN) Technical Committee CEN/TC 219, *Cathodic protection*, in collaboration with Technical Committee ISO/TC 156, *Corrosion of metals and alloys*, in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

ISO 13174 cancels and replaces EN 13174:2001, which has been technically revised.

Introduction

Cathodic protection is applied, sometimes in conjunction with protective coatings, to protect the external surfaces of steel harbour installations and appurtenances from corrosion due to seawater, brackish water, saline mud or soil fill.

Cathodic protection works by supplying sufficient direct current to the immersed external surface of the structure to change the steel to electrolyte potential to values where corrosion is insignificant.

The general principles of cathodic protection in seawater are detailed in ISO 12473. The general principles of cathodic protection in soils are detailed in EN 12954.

Cathodic protection of harbour installations

1 Scope

1.1 General

This International Standard defines the means to be used to ensure that cathodic protection is efficiently applied to the immersed and driven/buried metallic external surfaces of steel port, harbour, coastal and flood defence installations and appurtenances in seawater and saline mud to provide protection from corrosion.

1.2 Structures

This International Standard specifies cathodic protection of fixed and floating port and harbour structures. This includes piers, jetties, dolphins (mooring and berthing), sheet or tubular piling, pontoons, buoys, floating docks, lock and sluice gates. It also specifies cathodic protection of the submerged areas of appurtenances, such as chains attached to the structure, when these are not electrically isolated from the structure.

This International Standard is to be used in respect of cathodic protection systems where the anodes are exposed to water or saline mud. For buried areas, typically in soil or sand filled areas behind piled walls or within filled caissons, which may be significantly affected by corrosion, specific cathodic protection design and operation requirements are defined in EN 12954, the anodes being exposed to soils.

This International Standard does not cover the cathodic protection of fixed or floating offshore structures (including offshore loading buoys), submarine pipelines or ships.

This International Standard does not include the internal protection of surfaces of any components such as ballast tanks, internals of floating structures flooded compartments of lock and sluice gates or the internals of tubular steel piles.

1.3 Materials

This International Standard covers the cathodic protection of structures fabricated principally from bare or coated carbon and carbon manganese steels.

As some parts of the structure may be made of metallic materials other than carbon steels, the cathodic protection system should be designed to ensure that there is a complete control over any galvanic coupling and minimize risks due to hydrogen embrittlement or hydrogen-induced cracking (see ISO 12473).

This International Standard does not address steel reinforced concrete structures (see ISO 12696).

1.4 Environment

This International Standard is applicable to the whole submerged zone in seawater, brackish waters and saline mud and related buried areas which can normally be found in port, harbour, coastal and flood defence installations wherever these structures are fixed or floating.

For surfaces which are alternately immersed and exposed to the atmosphere, the cathodic protection is only effective when the immersion time is long enough for the steel to become polarized. Typically, effective cathodic protection is achieved for all surfaces below mid tide.

For structures such as sheet steel and tubular steel piles that are driven into the sea bed or those that are partially buried or covered in mud, this International Standard is also applicable to the surfaces buried, driven and exposed to mud which are intended to receive cathodic protection along with surfaces immersed in water.

Cathodic protection may also be applied to the rear faces of sheet steel piled walls and the internal surfaces of filled caissons. Cathodic protection of such surfaces is specified by EN 12954.

This International Standard is applicable to those structures which are, or may be in the future, affected by "Accelerated Low Water Corrosion" (ALWC) and other more general forms of microbial corrosion (MIC) or other forms of so-called "concentrated corrosion" associated with galvanic couples, differential aeration and other local corrosion influencing parameters

NOTE Information is available in BS 6349-1:2000, Clause 59 and CIRIA C634 (see Bibliography)

1.5 Safety and environment protection

This International Standard does not address safety and environmental protection aspects associated with cathodic protection to which national or international regulations apply.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 12473, *General principles of cathodic protection in sea water*

EN 12496, *Galvanic anodes for cathodic protection in seawater and saline mud*

ISO 12696, *Cathodic protection of steel in concrete*

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

EN 13509, *Cathodic protection measurement techniques*

EN 50162, *Protection against corrosion by stray current from direct current systems*

3 Terms and definitions

For the purposes of this document, the terms and definitions in ISO 12473 and the following apply.

3.1
accelerated low water corrosion
ALWC
localised corrosion generally found on the sea side at or just below the LAT level of structures, but can be present at all immersed levels

Note 1 to entry: This phenomenon is associated with microbiologically influenced corrosion (MIC) and generally quiescent conditions. (See CIRIA C634.) Corrosion rates, without cathodic protection, can be as high as 2 mm/side/year and the corrosion is typically localized as large, open pitting

3.2
atmospheric zone
zone located above the splash zone, i.e. above the level reached by the normal swell, whether the structure is moving or not

3.3
buried zone
zone located under the mud line or in soil or fill

3.4
cathodic protection zone
that part of the structure which can be considered independently with respect to cathodic protection design

3.5
coating breakdown factor
F
ratio of cathodic current density for a coated metallic material to the cathodic current density of the bare material

3.6
driving voltage
difference between the structure/electrolyte potential and the anode/electrolyte potential when the cathodic protection is operating

3.7
HAT
level of highest astronomical tide

3.8
immersed zone
zone located above the mud line and below the extended tidal zone or the water line at a draught corresponding to the normal working conditions

3.9
LAT
level of lowest astronomical tide

3.10
MTL
mean tide level (also known as MSL mean sea level or MWL mean water level)

3.11
microbial corrosion
corrosion associated with the action of micro-organisms present in the corrosion system

Note 1 to entry: Also called microbiologically influenced corrosion (MIC).

3.12
ROV
remotely operated vehicle

3.13
piling
foundation, tubular or sheet steel element forming part or whole of a harbour structure

3.14
splash zone
the elevation of the structure which is intermittently wet and dry due to the wave action just above the HAT

3.15
submerged zone
zone including the buried zone, the immersed zone, the transition zone and the lower part of the tidal zone under the MWL
See Figure 1.

3.16
transition zone
zone located below LAT and including the possible level inaccuracy of the structure installation which is affected by a higher oxygen content due to normal swell or tidal movement

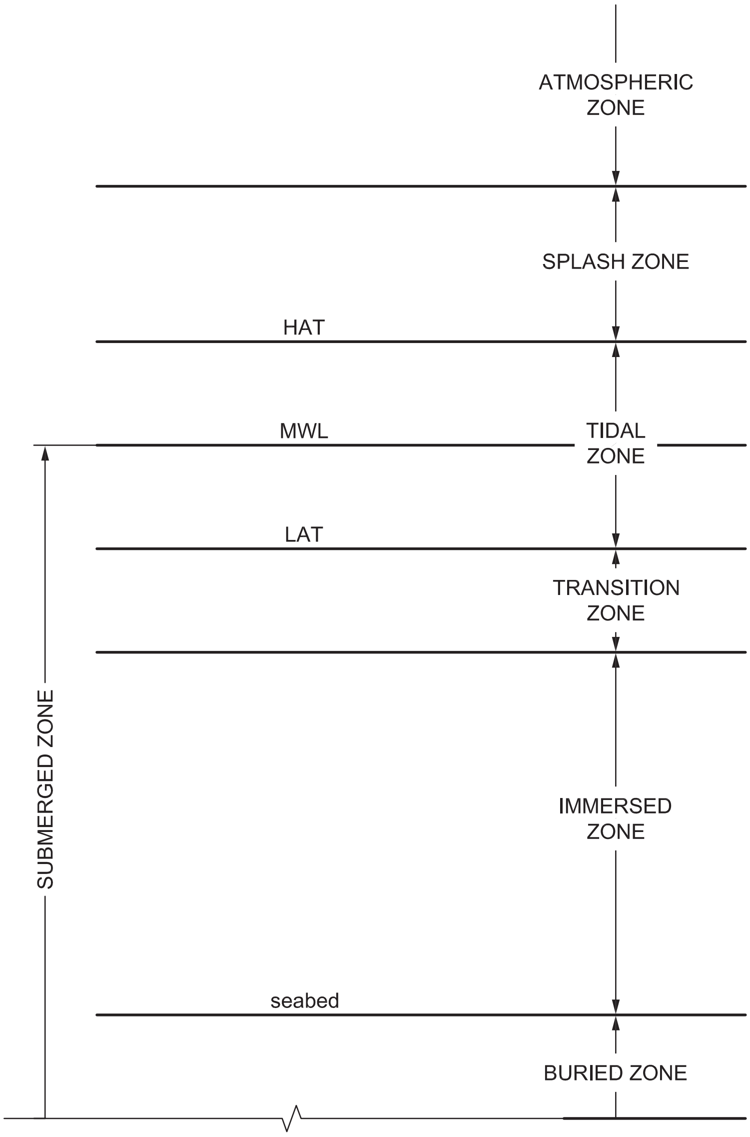


Figure 1 — Schematic representation of levels and zones in seawater environment

4 Competence of personnel

Personnel who undertake the design, supervision of installation, commissioning, supervision of operation, measurements, monitoring and supervision of maintenance of cathodic protection systems shall have the appropriate level of competence for the tasks undertaken. This competence should be independently assessed and documented.

NOTE 1 EN 15257 constitutes a suitable method of assessing and certifying competence of cathodic protection personnel which may be utilized.

NOTE 2 Competence of cathodic protection personnel to the appropriate level for tasks undertaken should be demonstrated by certification in accordance with EN 15257 or by another equivalent prequalification procedure.

5 Design basis

5.1 Objectives

The objective of a cathodic protection system is to deliver sufficient current to each part of the structure and appurtenances and to distribute this current so that the steel/water potential of each part of the structure is within the limits given by the protection criteria (see 5.2).

Steel/water potentials should be as uniform as possible over the whole structure. This may be achieved only if distribution of the protective current over the structure during normal service conditions allows. Uniform levels of cathodic protection may be difficult to achieve in some areas or parts of structures such as chains, for which a supplementary cathodic protection system may be considered if it is intended to attempt to provide full cathodic protection to them.

The cathodic protection system for a fixed or floating structure belonging to harbour installations may be combined with a coating system, even though some appurtenances, such as chains, may not benefit from the use of coatings. Extensive coating damage may also occur to buried areas of piles and steel sheet pile walls which are driven into position during installation.

Dielectric shields may be used in conjunction with anodes; particularly impressed current anodes, to minimize the risk of local over-protection and to improve the distribution of current from the anodes.

The cathodic protection system should be designed either for the life time of the structure or for a period corresponding to a planned maintenance or (if applicable) dry-docking interval. Alternatively when it is not feasible to design the cathodic protection system for the life of the structure or if dry-docking is not possible, the system should be designed for easy replacement of cathodic protection components, typically using divers or a ROV.

The above objectives should be achieved by the design of a cathodic protection system using impressed current or galvanic anode systems or a combination of both.

The design, the installation, the energising, the commissioning, the long-term operation and the documentation of all of the elements of cathodic protection systems shall be fully recorded.

Each step shall be undertaken in accordance with a fully documented quality plan.

NOTE ISO 9001 constitutes a suitable Quality Management Systems Standard which may be utilized.

Each stage of the design shall be checked and the checking shall be documented.

Each stage of the installation, energising, commissioning and operation shall be the subject of appropriate visual, mechanical and/or electrical testing and all testing shall be documented.

All test instrumentation shall have valid calibration certificates traceable to national or International Standards of calibration.

The documentation shall constitute part of the permanent records for the works.

5.2 Cathodic protection criteria

The criteria for cathodic protection are detailed in ISO 12473.

The criterion for protection of steel in aerobic seawater is a polarized potential more negative than −0,80 V measured with respect to silver/silver chloride/seawater reference electrode (Ag/AgCl/seawater reference electrode). This corresponds approximately to + 0,23 V when measured with respect to pure zinc electrode (e.g. alloy type Z2 as defined in EN 12496) or + 0,25 V when measured with respect to zinc electrode made with galvanic anode alloy types Z1, Z3 or Z4 as specified in EN 12496.

The criterion for protection of steel in anaerobic environments in seawater and sea bed muds which contain active sulfate reducing bacteria or support other microbial corrosion (MIC) species, including those associated with Accelerated Low Water Corrosion (ALWC), is a polarized potential more negative than −0,90 V measured with respect to silver/silver chloride/seawater reference electrode (Ag/AgCl/seawater reference electrode).

A negative limit of −1,10 V (Ag/AgCl/seawater reference electrode) is generally recommended to prevent coating disbondment and/or increase in fatigue propagation rates.

Where there is a possibility of hydrogen embrittlement of steels or other metals which may be adversely affected by cathodic protection to excessively negative values, an additional less negative potential limit shall be defined and observed. If not enough documented for a given material, this specific negative potential limit shall be determined relative to the metallurgical and mechanical conditions by mechanical testing at the limit polarized potential. For conventional steels, this limit is −1,10 V (Ag/AgCl/seawater reference electrode). Refer to ISO 12473 for more details.

These values also apply to steel in brackish waters but the errors due to variations in salinity when using Ag/AgCl/seawater reference electrodes shall be corrected when necessary as detailed in 6.3.4. The recommended metal/water potential limits for a range of metals and alloys in seawater are listed in ISO 12473.

NOTE The protection criteria and limit values are polarized potentials without IR errors. IR errors, caused by cathodic protection current flowing though resistive electrolyte and surface films on the protected surface, are generally considered insignificant in marine applications. Potential measurements using “Instant OFF” techniques or “coupon Instant OFF” techniques may be necessary in applications described in this International Standard to demonstrate the achievement of the above protection criteria (see EN 13509). Particular attention should be given to this in brackish waters and mud applications or close to impressed current anodes.

5.3 Design parameters

5.3.1 General

The design of a cathodic protection system should be made in order that each structure subdivision and anode zone is supplied with the cathodic protection current necessary to provide cathodic protection to meet the criteria in 5.2 for all service conditions.

5.3.2 Structure subdivision

Structures to be protected should be divided into different cathodic protection zones, which can be considered independently with respect to cathodic protection design, although they may not necessarily be electrically isolated.

NOTE 1 For a non-floating structure such as a dolphin, the area of piling can be divided into two main cathodic protection zones: the immersed or wetted cathodic protection zone and the buried cathodic protection zone. This division is related to the different current demands of the two zones. The high current demand of the immersed or wetted cathodic protection zone is due to the velocity of water movement, salinity, oxygen content and temperature. In the buried cathodic protection zone the current demand will be reduced due to the environment.

NOTE 2 For buoys, a single zone is generally considered sufficient to cover the immersed body of the buoy and the influenced part of the mooring chain(s).

5.3.3 Description of cathodic protection zone

Each cathodic protection zone may consist of several components, the parameters of which should be fully described including material (steel, cast iron, etc.), surface area and coating characteristics (type, lifetime and coating breakdown factor).

5.3.4 Service conditions

The design of the cathodic protection system(s) depends on service conditions which include lifetime, environment and operating conditions.

— Lifetime: Either the whole design life of the structure or the planned maintenance period(s) should be used.

— Environment: The seawater, sea bed, or estuarine environment properties to which the structure is exposed should be established (see ISO 12473 and Annex A).

— Operating conditions: The cathodic protection design normally considers only the static conditions of the structure because the durations when dynamic conditions prevail are generally negligible.

5.4 Electrical current demand

5.4.1 General

The current density for each component shall be selected to achieve the protection criteria specified in 5.2 for the conditions outlined in 5.3.

The current demand of each metallic component of the structure is the result of the product of its surface area exposed to the electrolyte multiplied by the selected current density (see Annex A).

5.4.2 Protection current density for bare steel

The selected current density may not be the same for all components of the structure as the materials, coatings, environment and service conditions may be variable.

The selection of design current densities should be based on experiences gained from similar structures in a similar environment or from specific tests and measurements.

NOTE 1 The current density depends on the kinetics of electrochemical reactions and varies with parameters such as the protection potential, surface condition, seawater resistivity, dissolved oxygen in seawater, seawater velocity at the steel surface, temperature.

For optimising the design, the following should be specified:

— initial current density necessary to achieve initial polarization of the structure;

— maintenance current density necessary to maintain polarization of the structure;

— final current density for possible repolarisation of the structure, e.g. after severe storms or cleaning operations.

NOTE 2 As the initial polarization preceding steady-state conditions is normally short compared to the design life, the average current density over the lifetime of the structure is usually very close to the maintenance current density.

If the structure has established ALWC or microbial corrosion the initial current density necessary for polarization may be greater than that necessary to polarize steel unaffected by microbial corrosion. In addition, the time to reach steady-state polarization may be considerably extended by the presence of previously active ALWC/microbial corrosion colonies. The design of cathodic protection of structures affected by ALWC shall take these factors into account (see Annex A).

The (average) maintenance current density shall be used to calculate the minimum mass of galvanic anode material or the capacity (anode current output x life) of impressed current anodes necessary to maintain cathodic protection throughout the design life. The initial or final current density values will normally determine the peak current output of the cathodic protection system; for galvanic anode systems the anode numbers and shape will generally be determined by these parameters and for impressed current systems the maximum output rating of anodes and power supplies will generally be determined by these parameters.

Typical values of current densities as used for bare steel are given in Annex A.

5.4.3 Protection current density for coated steel

The cathodic protection system may be combined with suitable coating systems. Effective coatings can significantly reduce current density and improve the current distribution over the surface. The cathodic protection design shall reflect the increase in current demand as the coating deteriorates.

Coatings are not necessary for effective cathodic protection.

The reduction of necessary current density for coated steel compared with bare steel may be in a ratio of 100 to 1 or even more. However, the current density will increase with time as the coating deteriorates.

For harbour installations cathodic protection of bare steel may present a lower full life cost than cathodic protection of coated steel. Corrosion protection above the mid tide level is not possible by cathodic protection; coatings may be necessary above the mid tide level to deliver the required structure design life or aesthetics.

An initial coating breakdown factor related mainly to mechanical damage occurring during the fabrication and installation of the structure should be included in the design. A coating deterioration rate (i.e. an increase of the coating breakdown factor) should be selected to take into account the coating ageing and possible mechanical damage occurring to the coating during the design life of the cathodic protection system which should itself be related to the lifetime of the structure or corresponding to the dry-docking or maintenance period(s).

These values are strongly dependent on the actual coating selection, surface preparation, coating application, construction and operational conditions.

Due to possible interactions between the cathodic protection and the coating, all coatings to be used in combination with cathodic protection should be tested beforehand to establish that they have acceptable resistance to cathodic disbondment.

Guidelines for the values of coating breakdown factors (f_c) are given in Annex A.

The current density needed for the protection of coated steel is equal to the product of the current density for the bare steel and the coating breakdown factor.

$$J_c = J_b \cdot f_c$$

where

J_c is the protection current density for coated steel, in amperes per square metre;

J_b is the protection current density for bare steel, in amperes per square metre;

f_c is the coating breakdown factor which varies with time due to ageing and mechanical damage:

$f_c = 0$ for a perfectly insulating coating.

$f_c = 1$ for a bare structure.

This formula should be applied for each individual component or zone as defined in 5.3 where the coating, or the current density for bare steel, may be different.

5.4.4 Protection current demand

The current demand shall be calculated to optimize the mass and size of galvanic anodes, or the capacity of impressed current systems. The protection current demand $\boldsymbol{I}_{\mathbf{e}}$ of each component (element) of the structure to be cathodically protected is equal to:

$$I_e = A_e \cdot J_{ce}$$

where

A_e is the surface area of the individual zone, in square metres;

J_{ce} is the individual protection current density for the component considered, in amperes per square metre.

The protection current demand I_Z of each cathodic protection zone is therefore equal to the sum of current demand of each component included in the cathodic protection zone:

$$I_z = \sum^{z} I_e$$

where I_e is the protection current demand of each component included in the cathodic protection zone, in amperes.

NOTE 1 For current demand determination, the full range of astronomical tide should be considered but it is normal to consider the immersed zone of the cathodic protection (CP) system to extend from mean sea level (mid tide) to sea bed. In the design of galvanic anode systems, due to their ability to increase current output as the structure/electrolyte potentials become less negative and due to the averaging effect of high and low tides on current demand, the area used in the calculation of I_e above may be limited to the area below mean sea level (MSL). In the design of impressed current systems, due to their need to be sized for the maximum current demand, the area used in the calculation of I_e above may include the area to HAT.

NOTE 2 For sheet steel piled walls without cathodic protection of the rear face, allowances should be made if the anodes are placed at locations where current will flow to the rear faces. Particular consideration should be given to ends of sheet steel piled walls which are not connected to other cathodically protected piles. See Annex A.

NOTE 3 Allowances should be made for metallic components connected to the structure which may receive some cathodic protection current, such as electrical earthing systems or utility service pipes (water and gas). See Annex A.

An estimate of the current demand of chains which are not electrically insulated from the structure should be made and added to I_Z when applicable. This is necessary to ensure an efficient cathodic protection design, even if the potential achieved on the chains (and their protection) will depend on the actual quality of the electrical continuity between the chains and the structure, and between the links of each chain.

Current demand determination calculations shall include steel items such as fenders and ladders which are part of the structure and within the submerged zones of the structure.

5.5 Cathodic protection systems

Two types of cathodic protection systems are used:

— impressed current,

— galvanic anode.

Sometimes a combination of both systems is used (hybrid).

The choice of the most appropriate system depends on a series of factors (see ISO 12473).

NOTE In general, for harbour installations, galvanic anode systems are preferred for their proven reliability, simple robust construction, low maintenance requirements and minimal interaction with berthed vessels. Impressed current systems are preferred only for those structures that will be provided with a dedicated cathodic protection monitoring, control and maintenance resource, which have available electrical power and generally to those where there is a high current demand. Harbours in brackish water may require impressed current systems if the water resistivity is frequently above that in which galvanic anodes can operate reliably and effectively. It is recommended that the structure Owner/Operator is appraised of the full life personnel demands and costs of cathodic protection monitoring, control and maintenance during the choice between galvanic anode systems and impressed current systems. For the protection of the rear face of sheet steel piled walls and caisson internals impressed current can be both reliable and the most practical system.

For a cathodic protection system using galvanic anodes, the size and shape of the anodes shall be determined using Ohm's law.

$$I_a = \frac{\Delta U}{R}$$

where

I_a is the anode current output (A);

ΔU is the driving voltage (V);

R is the circuit resistance (Ω).

The circuit resistance is assumed to be approximately equal to the electrolyte resistance, which is called "anode resistance" as the cathode (structure) resistance to the electrolyte is generally very small.

The anode resistance is a function of the resistivity of the anodic environment and of the geometry (form and size) of the anode. Empirical formulae may be used for the evaluation of the anode resistance such as those given in B.1.

For an impressed current system, the direct current (DC) output voltage of the power source shall be higher than the sum of the voltage drops in all the components of the circuit; cables, electrolyte (generally considered as the anode resistance) and the anode/cathode back EMF (i.e. the potential difference between anode and cathode in the electrolyte without current).

The voltage between anode and electrolyte should not exceed a maximum acceptable value depending on the material of the anode.

NOTE Recommended figures for maximum acceptable voltages are given in Annex C.

Minimum anodic current densities may be necessary in some cases (see Annex C).

The number and location of the anodes shall produce, as far as practicable, an electrical current distribution achieving the protection potential level over the whole steel structure surface.

If the anodes are grouped in arrays and close to each other, mutual interference between anodes should be considered when calculating the anodic resistance.

Calculations can be performed using computer numerical modelling based on finite elements or boundary elements methods; these are normally only justified in particularly complex or novel applications.

All components of the cathodic protection system should be installed at locations where the probability of disturbance or damage is minimised.

5.6 Electrical continuity

Structures to be protected shall be electrically continuous, otherwise each part of the structure, such as individual piles, shall be fitted with their own galvanic anode system or impressed current negative return. Bonding of steel-piled structures, jetties or berthing dolphins should, where possible, be designed as an integral part of the structure. The bonding system may comprise steel reinforcing bars of an electrically suitable size, welded between components cast into concrete piles caps or decking. To ensure good electrical continuity, the elements should be welded together or alternatively an external system of bonding should be used. Where relative movement between two parts of the structure is expected, e.g. at expansion joints and fenders, bonds need to be flexible. If cathodic protection is required for appurtenances, such as mooring dolphins, then electrical bonding to the principle structure should be ensured by appropriate means (which may be submarine cables) but this can be avoided if the appurtenances (e.g. mooring dolphins) are protected by independent cathodic protection systems.

The electrical resistance of the bonding should be low enough to achieve protection of the structures connected.

The electrical continuity shall be reliable and permanently maintained to ensure its continuous long term effectiveness. Where welding is used for continuity provision. care shall be taken to avoid adverse effects on the mechanical properties of the elements being welded.

For buoys and other moored structures with their own independent cathodic protection systems, their design shall make appropriate current provisions for the chains.

NOTE No particular continuity provision for anchor chains is generally required

The method of attachment of the anodes to the structure is governed by their type and application but low resistance electrical contact shall be maintained throughout the operating life of galvanic anodes. The design of the attachments shall be in accordance with the design code for the structure if any. These requirements may affect the design of the anode insert (see Annex D).

5.7 Interactions

A structure may be permanently or temporarily connected to other neighbouring structures. Each structure should be fitted with its own cathodic protection system which should be checked before electrically connecting it to any other structure.

If temporarily connected foreign structures are not fitted with their own cathodic protection system, the steel/seawater potentials of the structure being protected should be measured to confirm that the cathodic protection is at an acceptable level during the period of connection.

Measurements should be taken to ensure that there are no deleterious effects of electrical stray current on the protected structure and that the cathodic protection system of the protected structure does not adversely affect adjacent structures (see EN 50162).

Interaction testing is not normally required in respect of ships due to their normal mobility. However, if a ship is laid up or is berthed for long or repeated periods alongside steel quays or jetties it is recommended that interaction testing should be undertaken to demonstrate that both the ship or the adjacent Port and Harbour structures are not adversely affected by the cathodic protection systems of either the ship or the structure. Adjacent structures fitted with cathodic protection should not have their protection levels changed beyond the levels indicated in 5.2 by the adjacent ship cathodic protection system. Ships, boats or structures not fitted with cathodic protection should not have their corrosion potentials changed by more than +20 mV by any adjacent cathodic protection system (see EN 13509 and EN 50162).

Any changes to ship, boat or structure/electrolyte potentials greater than the above specified value shall be investigated and corrected by agreed remedial actions based on negotiation with the party operating the cathodic protection system causing the interaction.

NOTE 1 If a ship is laid up or berthed for long periods adjacent to a quay or jetty which is itself protected with cathodic protection, it is recommended that cathodic protection interaction testing should be undertaken to determine the effects on the ship's hull of the adjacent cathodic protection system.

NOTE 2 It is not normal practice when designing cathodic protection of harbours to consider electrical continuity bonds between ships or boats and the jetties or quays at which they berth.

NOTE 3 Electrical bonding between ships or boats and the jetties or quays at which they berth may be mandatory for safety reasons. However electrical isolation is recommended by organisations such as IMO and International Chamber of Shipping (see Bibliography).

NOTE 4 Galvanic anode systems for the protection of jetties or quays will normally have a minimal interaction effect on berthed ships or boats even when they are not bonded together. If the vessel has its own cathodic protection system any interaction effects from the jetty or quay cathodic protection system will be further reduced.

Impressed current systems for the protection of jetties or quays may cause interaction effects to adjacent berthed vessels; the current rating and location of impressed current anodes for the protection of the jetty or quay should be selected to minimize possible interaction effects to adjacent vessels. This will generally result in the use of multiple anodes of relatively low current output located close to the structure being protected and as remote as possible from the vessels using the berths.

6 Impressed current systems

6.1 Objectives

An impressed current system provides protection using direct current (DC) delivered by connecting the steel structure to the negative terminal of an adjustable DC power source and the anodes to the positive terminal of the DC power source.

The electrical current output delivered by the DC power source is controlled during the lifetime of the cathodic protection system to obtain and maintain the protection potential level over the whole steel surface of the structure.

6.2 Design considerations

Cathodic protection designs, including monitoring systems or provisions, shall be documented detailing the design parameters, structural/mechanical integrity and ability to withstand worst case storm/wave/propeller wash conditions for all immersed or tidal zone equipment, surface area calculations, anode current output and life calculations including cable volt drop and current rating calculations for impressed current systems along with detailed specifications for the cathodic protection materials, their installation (including installation and general arrangement drawings), testing, commissioning and performance verification. The documentation shall be updated to "as built" as necessary until the satisfactory completion of commissioning and performance verification demonstrating compliance with the cathodic protection criteria in 5.2 and shall then be maintained as part of the health and safety record for the structure.

Design guidance is provided in Annexes A, B, C and D.

The design calculations and specifications should include detailed information on the following:

- design basis,
- size of equipment,
- general arrangement of the equipment,
- specification of equipment, e.g. DC source, anodes, connection cables, terminations, protection devices, measurement electrodes,
- installation specifications,
- monitoring and maintenance specification.

Impressed current systems for harbour structures usually include one or more variable DC power source(s), several anodes, several negative connections and a number of fixed reference electrodes with appropriate monitoring provisions. For some installations, portable reference electrodes may be used.

DC power sources with automatic potential control should be used when the environment conditions, in particular tide levels, flow rates and varying dilution of seawater with fresh water, the structure configuration and service conditions cause significant and frequent variations of the current demand necessary to maintain polarization.

Each cathodic protection zone (see 5.3.2) may be protected by a dedicated system. A multi-zone control system may be necessary in specific areas presenting particular situations, to optimize the current distribution to the cathodic protection demand. Protection of the rear face of sheet steel piled walls or the internals of caissons should be by separate cathodic protection zones from those for steel exposed to the sea.

A dielectric shield is usually used on the structure or incorporated into the mounting of close fitted impressed current anodes to prevent local over-protection and improve the current distribution to the cathode.

The total maximum current demand (I_Z) for the protection of a cathodic protection zone of the structure should be calculated using formulae according to 5.4, with the most severe service conditions as described in 5.4.2 using the highest breakdown factor for the design life considered (see 5.4.3).

To compensate for a less efficient current distribution (a small number of higher current anodes compared with a galvanic anode system), the cathodic protection system should be designed to be able to provide 1,1 to 1,5 times the calculated total maximum current demand, depending on the geometry and the coating of the structure:

$$I_t = (1{,}1 \text{ to } 1{,}5) \cdot I_z$$

6.3 Equipment considerations

6.3.1 Direct current power source

The DC power source shall be able to deliver the total maximum current (I_t) for the zone it is intended to protect.

The output voltage should take into account the resistance of the electric circuit (cables, anodes and back e.m.f.) and the maximum recommended operating voltage of the anodes.

For platinum coated anodes, the magnitude of AC ripple shall be limited to 100 mV RMS (Root Mean Square) and its frequency should be not lower than 100 Hz to limit impact on the wear rate. (See Annex C.)

The DC power source should be able to deliver sufficient electrical current to maintain the cathode potential within the set range even at peak current demand. (See 5.4.2 and Annex A.)

DC power sources with automatic potential control should be able deliver an electrical current (constant or variable) when one of the reference electrodes used for the control of the DC power source leads to a structure/electrolyte/electrode potential value less negative than the set positive limit (refer to 5.2 for the protection criteria).

This type of DC power source should also be able to deliver little or no electrical current when all the reference electrodes used for the control of the DC power source lead to potential readings more negative than the set negative limit. Under normal operating conditions the DC power source should operate at a stable current output delivering stable polarization levels and only increase or decrease the current output as the environmental conditions change the current demand.

There should be devices to limit the output current to a preset value.

DC power sources with output current limitation circuits should have an effective shut-down in the event of an external short circuit.

6.3.2 Anodes

Anodes should be either suitable for the life of the structure or replaceable. Anodes used for impressed current systems are generally of the “inert type”. They are normally made of titanium, niobium or tantalum with a thin layer of platinum or mixed metal oxides which makes possible the discharge of electric current.

Lead silver semi-inert anodes can also be used, provided that the initial anode current density is sufficient to generate and maintain a conductive PbO_2 film (see Annex C). The performance of lead silver anodes may be affected adversely in deep water (>30 m) or waters of low oxygen.

Chromium silicon iron semi-inert anodes may be used provided that the maximum anode current density is not higher than 30 A/m^2.

Typical electrochemical characteristics of impressed current anodes are given in Annex C.

Generally impressed current anodes are of high current output and a small number are used compared to galvanic systems. Therefore, the loss of an anode may significantly reduce the performance of the system. The anode assembly and its attachment should be designed to have a high resistance to mechanical damage.

All possible precautions shall also be taken to avoid any direct electrical contact (short circuit of the cathodic protection circuitry) between the anodes and the structure.

It is usually a requirement to fit a cofferdam for floating structures to facilitate the entry of the anode supply cable into the interior of the structure in a manner which ensures the mechanical integrity and water-tightness of the floating structure.

The number, size and location of anodes should be determined to be able to deliver the electrical current distributed by the DC power source to which the anodes are connected in a uniform manner to all parts of the structure intended to receive cathodic protection.

It may be advantageous in some situations to use computer modelling based on finite elements or boundary elements calculation methods and/or model testing and/or a trial installation on part of the structure to demonstrate that current distribution is uniform enough to provide everywhere the protection level.

Anodes shall not be located in areas where they can interfere with the normal operation of the structure. They should not be installed in high stress areas or areas subject to high fatigue loads such as butts or seams. They should not be located in areas where they could be damaged (by accidentally dropped objects or by craft coming alongside, anchor chains or cables). Their mechanical design shall allow to withstand the most rigorous environmental conditions (wave, current, propeller wash) anticipated during the life of the cathodic protection system.

6.3.3 Dielectric shields

Dielectric shields shall be used when impressed current anodes are directly installed flush or less than 1 m from the structure.

Materials selected shall be resistant to chemicals produced at the anodes.

Factory or site applied coatings, fibreglass reinforced plastic, prefabricated plastic or elastomeric sheets can be used on the structure or the anode support provisions adjacent to the anodes. Materials bonded to the structure shall be resistant to cathodic disbonding.

The design of the cathodic protection system should anticipate the possible deterioration and ageing of shielding materials and devices to obtain the desired life of the system.

NOTE The dielectric shields should be sized in order that the minimum distance between the anode and the structure steel is generally at least 0,5 m and as necessary in order that any conventional coating does not suffer cathodic disbondment and the structure materials do not suffer hydrogen damage at maximum anode current output. This matter may necessitate detailed testing and/or modelling and will be determined in part by the properties of the coating and the structure construction materials.

6.3.4 Reference electrodes

Reference electrodes are used to measure the steel to seawater potential and are generally used to control the electrical current delivered by impressed current cathodic protection systems. Electrodes are generally either zinc or silver/silver chloride/seawater reference electrodes (see ISO 12473). Zinc electrodes are more robust whereas silver/silver chloride/seawater reference electrodes are more accurate.

All precautions shall be taken to avoid any direct electrical contact between the electrodes and the structure. Similarly, precautions shall be taken to avoid any leakage of water through any structure penetration provided for the electrode. It is usually necessary to fit a cofferdam for floating structures to facilitate the entry of the electrode cable into the interior of the structure in a manner which ensures the mechanical integrity and water-tightness of the floating structure.

The location of the reference electrodes is very important, particularly when used to control the system.

Electrodes should be installed at locations where the potential of the structure may become outside the protection criteria range.

NOTE 1 Ag/AgCl/seawater reference electrodes are only accurate in undiluted seawater with a salinity of 3,5 %. If used in water of other salinity the values indicated will be in error. Reference electrodes should be stable to their theoretical potential to within ±10 mV. Zinc is generally used as a reference electrode but its potential with respect to Ag/AgCl/seawater in clean seawater varies between −1060 and −1000 mV (for zinc electrodes made from Types Z1, Z3 or Z4 according to prEN 12496) and this range may increase if the electrolyte is contaminated or fouled. The range will be less if the electrode is maintained clean, for example, by passing a small anodic current continuously through the electrode and interrupting it before measurement. Alternatively the electrode can be used as a controlling electrode with a low impedance circuit so that the function maintains the electrode clean in service.

NOTE 2 In diluted (estuarine) conditions, a Ag/AgCl/0,5M KCl reference electrode should be used which does not vary with salinity.

6.3.5 Cables and terminations

All connecting cables shall withstand the expected mechanical and chemical conditions and shall be fitted with support and protection to avoid any mechanical damage that could occur in service, including the most arduous environmental conditions (wave, current, propeller wash, etc.) anticipated during the design life of the cathodic protection system.

The electrical termination between the anode cable and the anode shall be watertight, chemically resistant and mechanically robust.

The cable and termination insulation materials shall be resistant to their environmental conditions (nascent chlorine, high pH, seawater, hydrocarbons and other chemicals).

When determining the cross-section of the cable conductor, it is necessary to take into account the voltage drop for the length of cable under consideration.

The specified maximum current rating for a given size of cable shall not be exceeded.

For potential measurements, dedicated cables shall be used. These cables should be protected with a metallic screen from any electrical or radio frequency interference to the measured potential signals.

6.3.6 Impressed current anode installation

All anodes shall withstand the expected mechanical and chemical conditions and shall be fitted with support and protection to avoid any mechanical damage that could occur in service, including the most arduous environmental conditions (wave, current, propeller wash, etc.) anticipated during the design life of the cathodic protection system.

NOTE Impressed current anodes are vulnerable to mechanical damage and particular attention should be given to this aspect in the design and installation.

7 Galvanic anode systems

7.1 Objectives

The objective of a galvanic anode system is to deliver sufficient current to protect those parts of the structure selected for protection and to distribute this current such that the cathodic protection criteria detailed in 5.2 are met for the designed life of the system.

For a galvanic anode system, current shall be provided by a metal (e.g. alloys of aluminium, zinc or magnesium) of more electro-negative potential than the item to be protected.

7.2 Design

The design shall be documented and, as a minimum, include the following:

a) detailed calculations (current demand, anode mass, dimensions, quantity and location)

b) detailed installation drawings

c) detailed material specifications

d) detailed method of achieving anode/structure continuity and calculation for design of fixings

e) detailed method statements or specification for installation, testing, commissioning and operation

f) acceptance criteria for the completed system.

NOTE Annexes A, B and D details items that should be considered in the design

7.3 Materials

Galvanic anodes shall be in accordance with EN 12496 and the design objectives (see 5.1).

The electrochemical properties of the anodic material should be documented or determined by appropriate tests.

The information required includes:

— the driving voltage to polarized steel, i.e. the difference between closed circuit anode potential and the positive limit of the protection potential criterion,

— the practical electrical current capacity (A h/kg) or consumption rate (kg/A yr),

— the susceptibility to passivation,

— the susceptibility to intergranular corrosion.

7.4 Location of anodes

The galvanic anodes shall be distributed to ensure the whole surface is polarized to within the recommended limits (see 5.2). It may be advantageous in some situations to use computer modelling based on finite elements or boundary elements calculation methods and/or model testing.

Galvanic anodes shall not be located in areas where they can interfere with the normal operation of the structure. They should not be installed in high stress areas or areas subject to high fatigue loads. They should not be located in areas where they could be damaged (by accidentally dropped objects or by craft coming alongside, anchor chains or cables).

7.5 Installation

7.5.1 Electrical continuity

Electrical continuity of the elements of the structure to be protected and their respective galvanic anodes shall be ensured during construction or, for post construction applications of cathodic protection, by the provision of continuity bonds. Continuity shall be achieved through either metallurgical (e.g. welded, brazed) or bolted bonds or by reliable intimate contact between piles demonstrated to exist during the commissioning of the system. Continuity shall be assessed for long term reliability.

NOTE 1 For sheet steel piles, electrical continuity should be provided by continuity welds between all adjacent sheet piles. For tubular piles, electrical continuity may be established by continuity straps welded between piles or by cross-beams between the piles or individual galvanic anodes may be installed on each pile. While continuity bond welds may not be structural their quality should comply with recognized welding standards and procedures.

NOTE 2 Continuity may be achieved by bonding piles to steel concrete reinforcing bars in the deck slab.

7.5.2 Anode installation

The method of attachment of the anodes to the structure depends on their type and application but low resistance electrical contact shall be maintained throughout the operating life of the anodes.

Galvanic anodes should be attached to the structure:

— either by continuous welding of their steel insert to the structure in such a manner that stresses are minimised at the weld location

— or by welding of their steel insert to separate support brackets which have been connected to the structure by continuous welding

— or by bolting of their steel insert to separate support brackets which have been connected to the structure by continuity welding..

All welding (underwater and atmospheric) associated with anode attachments and continuity bonding shall be undertaken in accordance with pre-qualified procedures and personnel

Alternative methods of anode attachment shall be pre-qualified.

Galvanic anodes may also be buried or immersed at a distance from the structure to be protected. Electrical continuity between the structure and the anode should be provided by with a suitably sized insulated cable protected against possible environmental and mechanical damage for the life of the system..

7.5.3 Testing during Installation

Testing in accordance with the quality plan (5.1) shall include the following:

Confirmation of as-found conditions compared to the design (dimensions of structure, bed depth, etc.)

Confirmation of the location of each anode as checked during construction or after positioning and the method of anode installation.

8 Commissioning, operation and maintenance

8.1 Objectives

The objectives of the commissioning, operation and maintenance of the cathodic protection system are:

— to confirm that the cathodic protection system installation and its function are in accordance with the intentions of the design and meets the criteria specified in 5.2,

— to ensure that the cathodic protection system continues to perform in accordance with the design and that the structure remains satisfactorily protected from corrosion over the life of the system.

All measurements shall be in accordance with EN 13509.

8.2 Commissioning: galvanic systems

For galvanic systems, a survey of polarized potentials shall be undertaken within 3 months of completion of the installation. The survey shall be undertaken using a portable reference electrode to supplement any permanent monitoring provisions installed. The survey shall ensure that the criteria in 5.2 selected at design stage are met at representative locations. For example, for a plain sheet piled wall, potential measurements should be undertaken at three elevations (e.g. MWL, midway between MWL and sea bed and at the sea bed level) in seawater at regular intervals along the installation (e.g. at 5 m spacing).

NOTE Ag/AgCl/seawater reference electrodes should only be used in undiluted seawater with a salinity of 3,5 %. If used in brackish water the values indicated will be in error and a Ag/AgCl/0,5M KCl reference electrode should be used (see 6.3.4).

The potential of steel shall be measured using a high impedance voltmeter connected to a reference electrode which shall be located as close as possible to the steel surface to be monitored. See 5.2 with respect to criteria and IR drop errors.

8.3 Commissioning: Impressed current systems

8.3.1 Visual inspection

The cathodic protection system and all its components shall be subject to a complete visual inspection confirming that all components and cables are installed properly, are labelled where appropriate and protected from environmental, human or animal damage.

8.3.2 Pre-energising measurements

Prior to energising measurements shall be made and recorded in accordance with the quality plan (5.1) and shall include the following:

a) Potential of steel/seawater with respect to permanently installed reference electrodes

b) Proving of any electronic data logging and/or data transmitting facility installation as part of the performance monitoring system.

8.3.3 Initial energising

The cathodic protection system shall be energised in accordance with the design requirements for initial polarization. Measurements shall be made and recorded in accordance with the quality plan (5.1) and shall include the following:

a) The potential of the steel/seawater with respect to all permanently installed reference electrodes

b) Confirmation of polarity. If any steel/seawater potential values shift in a positive direction they shall be investigated and immediately remedied

c) The output voltage and current of all dc power supplies providing current to the cathodic protection systems

d) If applicable the individual anode currents measured at the transformer-rectifiers or junction boxes.

8.3.4 Performance assessment

For impressed current systems, a survey of IR-free potentials (Instant Off, coupon Instant Off, or reference electrode close to the structure) shall be undertaken within 3 months of completion of the installation. The survey shall be undertaken using a portable reference electrode to supplement any permanent monitoring provisions installed. The survey shall ensure that the criteria in 5.2 selected at design stage are met at representative locations. For example, for a plain sheet piled wall, potential measurements should typically be undertaken at three depth increments in seawater at 5 m horizontal spacing along the wall.

NOTE Ag/AgCl/seawater reference electrodes should only be used in undiluted seawater with a salinity of 3,5 %. If used in brackish water the values indicated will be in error and a Ag/AgCl/0,5M KCl reference electrode should be used (see 6.3.4).

The potential of steel shall be measured using a high impedance voltmeter connected to a reference electrode which shall be located as close as possible to the steel surface to be monitored (see 5.2 with respect to criteria and IR drop errors).

8.3.5 Interaction testing

Interaction testing should be undertaken to demonstrate that adjacent structures are not adversely affected by the cathodic protection system. Adjacent structures fitted with cathodic protection should not have their protection levels changed beyond the levels indicated in 5.2 by the subject new cathodic protection system. Adjacent structures not fitted with cathodic protection should not have their corrosion potentials changed by more than + 20mV by the subject new cathodic protection system (see EN 13509 and EN 50162).

Any changes to the adjacent structure/electrolyte potentials greater than the above shall be investigated and corrected as part of the commissioning procedures for the subject new cathodic protection system.

See also 5.7.

8.4 Operation and maintenance

8.4.1 General

The operation and maintenance and testing intervals and procedures shall be as specified in the operation and maintenance manual (see 9.2 and 9.3) or as subsequently modified based upon performance of the system.

8.4.2 Galvanic anode systems

Periodic performance assessment shall be undertaken.

Typical inspection procedures for sacrificial systems may be as follows.

Following the 3 month commissioning testing in 8.2, further testing should be performed, typically between 9 and 12 months, prior to the end of any defect liability period, and then at intervals of 2 to 5 years subject to performance. This testing should be as detailed in 8.2.

In addition, dependent on the type of structure and location of anodes, a visual inspection of the anodes should be undertaken by diver survey, including a full report and a video record of the work carried out. The survey should assess the consumption of the anodes, check for physical damage to anodes and check that the anodes are visibly secure.

Any damaged or missing anodes should be replaced to ensure that no area of the structure is likely to be under-protected.

8.4.3 Impressed current systems

Routine inspection procedures shall be as follows:

a) Functional check:

Confirmation that all systems are functioning and all outputs are similar to as-left condition of previous performance assessment

b) Performance assessment:

- Measurement of polarized potentials. Impressed current systems can pose a risk to divers and are normally switched off during diving operations in their vicinity. If this is impracticable, divers shall be informed that the system is energised so that the necessary actions can be taken to ensure their safety
- Measurement of parameters from any other sensors installed as part of the performance monitoring system
- Assessment of data
- Adjustment of system outputs or selection of fixed monitoring locations for auto potential systems

c) Inspection periods

Typically the functional check shall be undertaken monthly in the first year and, subject to satisfactory performance, thereafter at 3 month intervals. Typically the performance assessment shall be undertaken at 3 month intervals in the first year and, subject to satisfactory performance and review at 6 to 12 month periods thereafter.

9 Documentation

9.1 Objectives

All information, data and results related to the cathodic protection system should be recorded. This includes all data pertinent to the design, manufacture, installation, commissioning, operation and maintenance recommendations and effectiveness of the cathodic protection system.

The as-built documentation should reflect any changes from the design, either in respect of the as-found conditions or installation.

Commissioning data should include results of surveys conducted before and after energising each cathodic protection system to confirm that it satisfies design criteria and operates effectively, including structure potential measurements to demonstrate that full protection is achieved and any interaction testing of adjacent structures.

9.2 Impressed current system

The following data should be kept for reference and regularly updated, if applicable:

- the design criteria including the design life, environment characteristics (e.g. water salinity range, resistivity), protection criteria, current density requirements and assumed values of anode output currents;
- the design calculations including the calculations of; areas to be protected, current demand, distribution of anodes, cable requirements, power supply requirements, fixings and all other such data

— the number of anodes, their size, specification, description of anodic equipment and connection, effective output current densities and acceptable voltage range, as well as the manufacturer/supplier data and documentation;

— the description and means of attachment of anodes, the composition and location of any dielectric shield (when applicable), as well as the specification, characteristics and attachment method of the connecting cables and cable management system;

— the location of each anode as checked during construction, all deviations from the design location being highlighted and the date of installation; these data should be updated during the life of the structure;

— the location, detailed specification, drawings, and output characteristics of each DC power source with their factory test reports;

— the location, description and specification of any protection, potential control or monitoring device, including reference electrodes, measuring equipment and connecting cables;

— the commissioning results including potential survey data, current and voltage output values of each DC power source, individual anode current and any adjustment made for non-automatic devices;

— the results of any interaction testing of adjacent structures;

— the data recorded during periodic maintenance inspection including protection potential values, DC output values, maintenance data on DC power sources and downtime periods to follow the changes of the protection potential level status of the structure.

— an Operation and Maintenance Manual which shall detail the as-built system, inspection and testing procedures, inspection and testing intervals and provide a fault finding guide. The data detailed above may in addition be incorporated into this volume.

9.3 Galvanic anodes system

The following data should be kept for reference and permanently updated, when applicable:

— design criteria including the design life, the environment characteristics (e.g. water resistivity), the protection criteria, current density requirements, assumed values of anode output currents at different periods and working conditions, and the anodes theoretical efficiency and driving potential;

— the number of anodes, their size, mass, specification, alloy composition, effective consumption rate, and characteristics, as well as the manufacturer/supplier references and documentation;

— the location of each anode as checked during construction, all deviations from the design location being highlighted, the method of attachment and the date of installation; these data should be updated during the life of the structure;

— the location, description and specification of any current or potential control or monitoring device, including type of reference electrode, measuring equipment, and connecting cables;

— the commissioning results including potential survey data;

— the results of periodic maintenance inspection survey data including current and protection potential measurements, equipment and the measuring technique to follow the changes of the protection potential status of the structure.

— an Operation and Maintenance Manual which shall detail the as-built system, inspection and testing procedures, and inspection and testing intervals. The data detailed above may in addition be incorporated into this volume.

Annex A
(informative)

Guidance for current requirements for cathodic protection of harbour installations

A.1 Design current densities for the protection of bare steel in seawater

In the absence of any other documented experience, typical design current densities for protecting bare steel in seawater are given in Table A.1.

Table A.1 — Typical design current densities for protecting bare steel in seawater

Situation	**Current densities** (mA/m^2)					
	Initial value		**Maintenance value**		**Repolarisation value**	
	in poorly aerated waters	in well aerated waters	in poorly aerated waters	in well aerated waters	in poorly aerated waters	in well aerated waters
Conditions with tidal flow less than 0,5 m/s	80 to 100	120 to 150	50 to 65	65 to 80	60 to 80	80 to 100
Conditions with tidal flow more than 0,5 m/s	120 to 150	170 to 200	60 to 80	80 to 100	80 to 100	100 to 130
Conditions with established ALWC or microbial corrosion (MIC)	170 to 200		60 to 100		80 to 130	

If there is established microbial corrosion and/or Accelerated Low Water Corrosion (ALWC), current densities corresponding to these conditions as given in Table A.1 should be applied to the total areas of bare steel in seawater.

When designing impressed current systems, particularly those employing anodes close to the structure, the distribution of current may not be uniform. It is therefore necessary to provide additional current in the design to ensure that those areas remote from the anodes receive the design current densities based on the above. An increase of 10 % to 50 % in applied current may be used; the actual value will be determined by the current distribution. The increase should be applied to both the steel in seawater and the steel in mud (see A.2).

In estuarine conditions, with brackish waters, the above current densities may be applicable to resistivity of up to 2 Ω m. It may be necessary to undertake current drainage tests or laboratory investigations to determine current density requirements in waters for which there is no established cathodic protection historical data.

A.2 Design current densities for the protection of bare steel in saline mud

In the absence of any other documented experience, typical design current densities for protecting bare steel in saline mud are given in Table A.2.

Table A.2 — Typical design current densities for protecting bare steel in saline mud

Description	Current densities (mA/m^2)		
	Initial value	Maintenance value	Repolarisation value
All types of structures in normal saline muds	25	20	20
Conditions with established microbial corrosion	30-50	25-30	25-30

A.3 Values of coating breakdown factors of usual paint systems for the design of cathodic protection systems

The values listed below are based upon coatings widely used in marine environments typically applied to blast cleaned surfaces to a dry film thickness ranging from 250 µm to 500 µm. An assessment of the structure, the coating and the environment should be made to determine the appropriate figures. Particular attention should be paid to coating conditions in the interlocks (clutches) of sheet steel piles. The effects of abrasion should be assessed.

Initial coating breakdown factor:

— 1 % to 2 % in immersed areas

— 25 % to 50 % in driven piled (buried) areas; very dependent on soil conditions and coating selection

— 5 % to 25 % in backfilled areas dependent on the basis of the backfill materials and methods of placement and compaction.

Deterioration rate for coatings exposed to Im2 environment (as defined in ISO 12944-2) for various durabilities (as defined in ISO 12944-1):

— 3 % per year low durability coatings

— 1,5 % per year for medium durability coatings

— 0,5 % to 1 % per year for high durability coatings.

A.4 Allowances for current drain

For sheet steel piled walls and similar planar structures, it is often assumed that the surface receiving cathodic protection (the seaward face) can be considered isolated from the rear face. While this may be an acceptable assumption remote from the ends of the structure if galvanic anodes are installed in the submerged section and the piles are driven deep into the sea bed, allowances should be made for current flowing to the rear faces of piles particularly at extremities of sheet steel piled sea walls. Allowances for current flow to rear faces of sheet steel piled sea walls should be increased if remote anodes are employed.

If the rear faces of the piles are themselves protected from corrosion (including microbial corrosion) by a separate cathodic protection system, no current allowance from the front face system is necessary.

Where structures are constructed to be in contact with other metallic structures, sufficient current should be provided in the design for "loss" of current to the adjacent structure. These allowances should include allowances for electrical earthing systems which may be of very low resistance to earth and contain significant copper (or copper and steel in carbonaceous backfill) surfaces in contact with the soil and for any utility pipework (gas or water) that may be connected to the structure and pass either onshore or offshore.

Annex B
(informative)

Anode resistance, current and life determination

B.1 Anode resistance formulae

The formulae given hereafter are generally used. Other formulae may be considered on the basis of documented experience.

Anodes in close proximity will affect the electrical field around adjacent anodes and reduce the current output from anodes. The resistance of an individual anode in an array anode will be increased by the proximity to adjacent anodes.

Closely spaced anodes should be the subject of specific design assessment and their resistance may be determined by using alternate classical resistance to earth formulae, mathematical modelling or direct field measurement.

B.1.1 Slender anodes mounted at least 0,3 m offset from the structure steel surface

If $L \geq 4r$

$$R_\mathrm{a} = \frac{\rho}{2\text{À}L} \times \left[\ln\left(\frac{4L}{r} \right) - 1 \right]$$

if $L < 4\boldsymbol{r}$

$$.\, R_\mathrm{a} = \frac{\rho}{2\pi L} \times \left\{ \ln\left[\frac{2L}{r} \times \left(1 + \sqrt{1 + \left(\frac{r}{2L} \right)^2} \right) \right] + \frac{r}{2L} - \sqrt{1 + \left(\frac{r}{2L} \right)^2} \right\}$$

Simplistically, for anodes mounted closer than 0,3 m offset from the steel surface but more than 0,15 m the resistance can be *assumed* to be R_a x 1,3. This simplification may be improved by mathematical modelling or direct field measurement.

B.1.2 Long-flush mounted anodes on the structure steel surface where length ≥ 4x Width

$$R_\mathrm{a} = \frac{\rho}{2S}$$

B.1.3 Short flat plate or bracelet anodes mounted flush on the structure surface

$$R_\mathrm{a} = 0{,}315 \frac{\rho}{\sqrt{A}}$$

where

R_a is the anode resistance, in ohms,

ρ is the environment resistivity, in ohm metres,

L is the length of the anode, in metres,

r is the radius of the anode (for other shapes than cylindrical, $r = C/2\pi$ where C is the cross-section periphery), in metres,

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

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

B.2 Calculation of the anode resistance at the end of life

The anode resistance will increase with time if consumption of the anode results in dimensional changes. It is necessary for the design to assess the current output capability of the anode at the end of life (see repolarisation current density values in A 1 and A 2 above).

a) **Calculation of end-of-life anode weight**

For all anode shapes:

$$W_{\text{final}} = W_{\text{inital}} \cdot (1 - u)$$

where

W is the net mass of anode alloy (excluding the steel core) in kilograms (kg),

W_{initial} is the initial value,

W_{final} is the final (or end-of-life) value,

u is the utilization factor determined by the portion of anodic material consumed when the remaining anode material cannot deliver the current required (dimensionless). The shape of the anode and the design of the steel core within it will affect the utilization factor, which may be in the range of 0,7 to 0,95.

b) **Calculation of end-of-life anode dimensions**

For slender anodes:

$$L_{\text{final}} = L_{\text{initial}} - (0{,}1 \times u \cdot L_{\text{inital}})$$

where

L is the length of the anode alloy, in metres (m),

L_{initial} is the initial value,

L_{final} is the final (or end-of-life) value.

The depleted anode, with its steel core, is then assumed to be a cylinder with length L_{final} and its cross-sectional area is calculated from the estimate of W_{final} above, the density of the anode alloy and the volume of the anode core within the final length of the anode.

$$X_{\text{final}} = \frac{W_{\text{final}}}{d_{\text{anode}} \cdot L_{\text{final}}} + X_{\text{core}}$$

$$r_{\mathrm{final}} = \sqrt{\frac{X_{\mathrm{final}}}{\pi}}$$

where

X_{final} is the final (or end-of-life) value cross-sectional area of the anode (including the core), in square metres (m^2),

X_{core} is the cross-sectional area of the core, in square metres (m^2),

d_{anode} density of the anode alloy, in kilograms per cubic metre (kg/m^3),

r_{final} final (or end-of-life) anode radius, in metres (m).

Final anode resistance is then determined according to relevant resistance formulae using values of r_{final} and L_{final}, as appropriate.

NOTE This formula will result in a calculated anode length greater than that indicated by the simpler design process in DnV RP B401); accordingly the calculated anode current output will be greater by this design process than that in DnV RP B 401.

For long flush mounted anodes:

As for slender anodes, but assuming that the final shape is a semi-cylinder, hence

$$r_{\mathrm{final}} = \sqrt{\frac{2X_{\mathrm{final}}}{\pi}}$$

For short flush or bracelet anodes:

Assume that the resistance does not change from the initial value.

B.3 Electrolyte resistivity

Cathodic protection designs for port, harbour, coastal and flood protection installations should only be undertaken when the electrolyte resistivity relevant to the anode resistance calculation in B.1 has been correctly measured or assessed.

Electrolyte resistivity is of particular importance in the design of galvanic anode systems as the use of incorrect resistivity data can have significant effect on the calculated anode resistance and then current output. The effect is less critical for impressed current anodes if the design provides for sufficient output voltage variation.

As indicative information, the following resistivity values are typical:

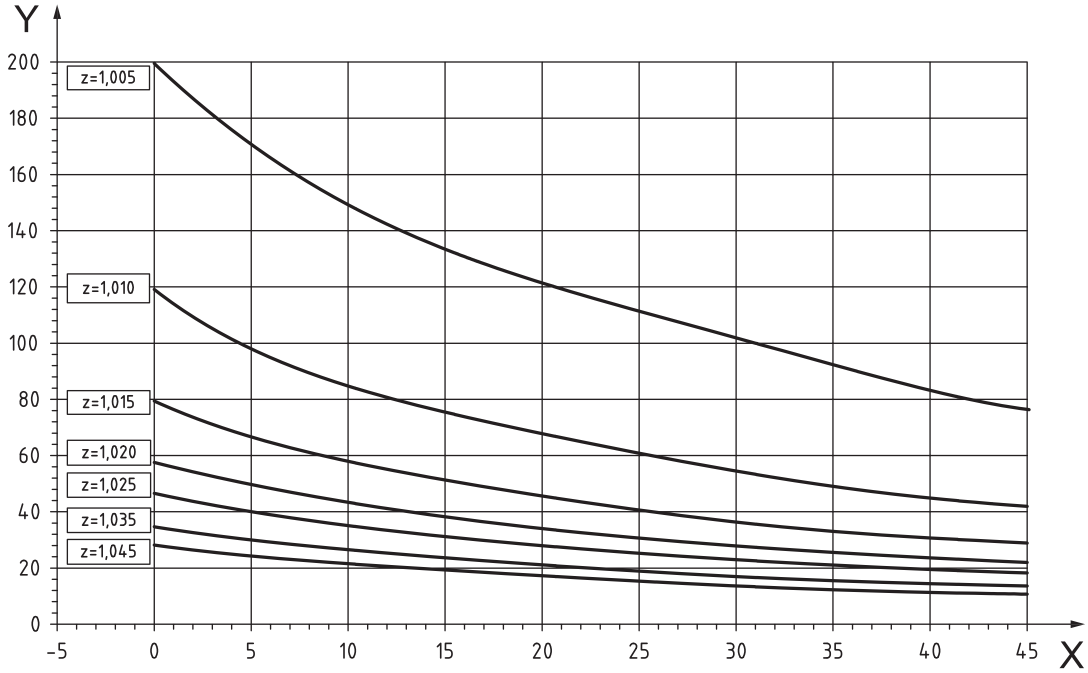
— cold seawater:	0,30 Ω m to 0,35 Ω m	(30 to 35 Ω cm)
— warm seawater:	0,15 Ω m to 0,25 Ω m	(15 to 25 Ω cm)
— saline mud:	0,70 Ω m to 1,70 Ω m	(70 to 170 Ω cm)
— fresh river water	3,00 Ω m to 30,00 Ω m	(300 to 3000 Ω cm)

For brackish water, the resistivity may fluctuate greatly (0,20 Ω.m to 10 Ω.m) depending on the salt content. As these values are so widely divergent the actual values should be measured prior to the design.

The resistivity of water changes significantly with temperature and should be assessed over the full range of normal temperature variations for the particular location. Temperature should be measured at every resistivity determination and reported with the measured data to enable the assessment to be made.

In tidal areas where the water may become more brackish at low water and in areas where fresh water from rivers or surface water runoff may significantly affect the resistivity, the water should be sampled and its resistivity determined. Sampling should be representative of all tidal conditions and all likely extents of fresh water contamination.

The resistivity for different seawater and brackish water densities at different temperatures is shown in Figure B.1



Key

X temperature [°C]

Y resistivity (ρ) [Ω cm]

z seawater density [g/L]

Figure B.1 — Resistivity based on temperature and seawater density (salinity)

B.4 Galvanic anode current output

The current output of a galvanic anode may be determined using Ohm's law.

$$I = \frac{\Delta U}{R}$$

where

I is the current output, in amps,

ΔU is the driving potential, in volts,

R is the circuit resistance, in ohms.

ΔU is generally taken as the potential difference between the polarized potential of the steel (5.2; −0,80 V in non-microbial corrosion/ALWC environments or −0,90 V in microbial corrosion/ALWC environments, all with respect to Ag/AgCl/seawater) and the operating potential of the particular anode alloy in seawater (typically −1,10 V to −1,05 V for Al-Zn-In alloys, −1,05 V to −1,00 V for Zn alloys and between

−1,45 V and −1,65 V for the range of Mg anode alloys all with respect to Ag/AgCl/seawater). These values of anode operating potential may be more positive in saline mud.

Therefore, subject to the characteristics of the particular anode, ΔU will be in the range 0,15 V to 0,20 V for a structure being protected to −0,90 V with respect to Ag/AgCl/seawater from microbial corrosion/ALWC with Al-Zn-In alloy anodes. For a structure being protected to −0,80 V with respect to Ag/AgCl/seawater without a risk of microbial corrosion/ALWC with Al-Zn-In alloy anodes, ΔU will be in the range 0,25 V to 0,30 V.

B.5 Anode life

The anode lifetime (T_{anode}) may be determined using the following formula:

$$T_{anode} = \frac{W_{anode} \cdot u}{E \cdot I_{s,anode}}$$

where

T_{anode} is the effective lifetime of the anode, in years,

W_{anode} is the net mass of anode alloy (excluding the steel core) in kg,

u is the utilization factor determined by the portion of anodic material consumed when the remaining anode material cannot deliver the current demand; the shape of the anode and the design of the steel core within it will affect the utilization factor, which may be in the range of 0,70 to 0,95,

E is the consumption rate of the anode material in the environment considered, in kg/Ay (see EN 12496)

$I_{s,anode}$ is the average (mean) current output of the anode during the lifetime, in amperes.

B.6 Minimum net weight requirement

The minimum total net weight of the anode material required for a cathodic protection zone may be determined from

$$W_{total} = \frac{I_{mean} \cdot T_{design} \times 8760}{Q \cdot u}$$

where

W_{total} is the minimum total net weight of galvanic anode material required, in kilograms (kg),

I_{mean} is the total maintenance current required for the structure, in amperes (A),

u is the utilization factor determined by the portion of anodic material consumed when the remaining anode material cannot deliver the current required (dimensionless); the shape of the anode and the design of the steel core within it will affect the utilization factor, which may be in the range of 0,70 to 0,95,

Q is the practical anode capacity for the anode material in the environment considered, in ampere-hours per kilogram (A·h/kg) (see EN 12496),

8760 is the number of hours in one year (h/y).

T_{design} is the design life of galvanic anode material required, in years (y).

Annex C
(informative)

Typical electrochemical characteristics of impressed current anodes

Typical electrochemical characteristics of anodes used for impressed current systems of harbour installations are given in Table C.1.

Table C.1 — Typical electrochemical characteristics of impressed current anodes

Anode materials	Consumption rate	Maximum current density	Maximum voltage between anode material and electrolyte
	$g \cdot A^{-1} \cdot y^{-1}$	$A \cdot m^{-2}$	V
Platinised titanium	0,004 – 0,012[a]	500 - 3000	8[b]
Platinised niobium	0,004 – 0,012[a]	500 - 3000	50
Platinised tantalum	0,004 – 0,012[a]	500 - 3000	100
Mixed Metal Oxide (MMO) on titanium substrate	0,0005 - 0,001	400 – 1000[c]	8[b]
Lead silver[d]	25 - 100	250 - 300	24
Chromium silicon iron	250 - 500	10 - 30	50

[a] The life of the platinum film may be affected by the electrolyte resistivity, the consumption rate increasing with resistivity. The life of the platinum film can also be affected by the magnitude and frequency of the ripple present in the DC supply. A magnitude lower than 100 mV (RMS) and a frequency not lower than 100 Hz are recommended.

[b] In seawater, the oxide film on titanium may break down if the anode potential exceeds 8V with respect to Ag/AgCl/seawater electrode. Higher voltages may be used with fully platinised or MMO coated anodes or in less saline environments.

[c] In cold seawater the maximum anode current density of Mixed Metal Oxide on titanium substrate anodes should be limited to 100 $A \cdot m^2$ between 0 and 5 °C and 300 $A \cdot m^{-2}$ between 5 and 10°C.

[d] PbO_2 film needs to be formed and maintained by a sufficient anodic current density (typically 100 $A \cdot m^{-2}$ and 40 $A \cdot m^{-2}$ respectively, in aerated seawater). The use of platinum pins in the lead/silver alloy may reduce these minimum values (typically to 50 $A \cdot m^{-2}$ and 20 $A \cdot m^{-2}$ respectively).

Annex D
(informative)

Guidance related to the design process

D.1 Current density values during life

The three design electrical current densities (see 5.4) are considered:

— the maintenance current density is used to determine the mass of the anodes; this current density is necessary to maintain the polarization level of the structure during its design life;

— the initial current density is used to verify that the output current capacity of the new anodes, i.e. their initial dimensions, allows to obtain complete initial polarization of the structure;

— the repolarisation current density is used to verify that the output current capacity of the anodes when they are consumed to their utilization factor, i.e. their final usable dimensions, allows to repolarise the structure after severe storms or marine growth cleaning operations.

D.2 Factors determining galvanic anode current output and operating life

The basic requirements for anodic materials are stipulated in EN 12496.

The environmental impact of alloy metal components released into the electrolyte should be taken into consideration.

The anode current output depends on the resistivity of the environment and on the anode shape and dimensions (see 5.3, 5.5 and Annex B).

The anodic materials exhibit different specific consumption rates when operating in various environments.

Therefore, in a particular environment for a given current output, the anode life duration will depend on the anodic material consumption rate and its mass.

The final current output will be determined by the shape and size of the anode when it is consumed to the full extent determined by its Utilization Factor; for most galvanic anodes this final shape will be determined by the design of the steel core.

The dimensions and number of anodes should be optimised to minimize the total mass of the galvanic anodes, and to provide a protective electrical current greater or equal to the protective electrical current necessary for the permanent protection of the structure during the life of the anodes.

The cathodic protection system shall include sufficient mass of anodic material to be able to supply the (average) maintenance current demand during the design life of the system.

The output current is given by Ohm’s law as explained in 5.5 and Annex B.

The anode life may be determined using the formula given in Annex B.

D.3 Factors determining anode distribution

Anodes should be distributed to minimize interaction effects between anodes (see B.1).

Anodes should be located to minimize their exposure to mechanical damage (for example, within the in-pan of sheet steel piled walls constructed of Z- or U-shaped piles).

Anodes should normally be located below low tide, so that they are always immersed.

Anodes should be located and attached to the structure in a manner that does not result in a reduction in the structural performance of the structure.

Anodes should be located so that there is, as near as is possible, uniform distribution of current from anodes to the structure being protected. For low current output anodes, for example, port and harbour application conventional galvanic anodes for which the individual anode current will be typically < 2 A, if the anodes are distributed in a manner such that each anode is allocated to the local surface area that it is intended to protect, that is directly proportional to the product of the surface area and the current density (i.e. anode/anode distance closer in seawater than in saline mud and closer for bare steel than coated steel), such a simple design process is normally sufficient. This simple approach, providing the additional current (10 – 50 %) indicated in A.1 is included, can also be used for simple impressed current systems using anodes closely mounted to the structure if the individual anode current output is low, typically < 20 A. However, for complex structures or for high current anodes (galvanic or impressed current) a more sophisticated design approach may be necessary. This more sophisticated design approach may include the calculation of attenuation throughout a structure, scale modelling, boundary element or finite element mathematical modelling. Alternatively, past track record, using accurate structure/electrolyte potential surveys from similar structures in similar environments may be used to extrapolate anode distribution for a new, similar structure.

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