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Cathodic protection of steel in concrete (ISO 12696:2016)

National foreword

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The UK participation in its preparation was entrusted to Technical Committee GEL/603, Cathodic protection.

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European foreword

This document (EN ISO 12696:2016) has been prepared by Technical Committee ISO/TC 156 "Corrosion of metals and alloys" in collaboration with Technical Committee CEN/TC 219 “Cathodic protection” the secretariat of which is held by BSI.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by June 2017, and conflicting national standards shall be withdrawn at the latest by June 2017.

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

This document supersedes EN ISO 12696:2012.

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Endorsement notice

The text of ISO 12696:2016 has been approved by CEN as EN ISO 12696:2016 without any modification.

Contents

Page

Foreword .... **v**

Introduction .... **vi**

1 Scope **1**

2 Normative references **1**

3 Terms and definitions **2**

4 General **2**
- 4.1 Quality management systems 2
- 4.2 Personnel 3
- 4.3 Design 3

5 Structure assessment and repair **3**
- 5.1 General 3
- 5.2 Records 4
- 5.3 Visual inspection and delamination survey 4
- 5.4 Chloride analysis 4
- 5.5 Carbonation depth measurement 4
- 5.6 Concrete cover and reinforcement location 4
- 5.7 Reinforcement electrical continuity 4
- 5.8 Steel/concrete potential 5
- 5.9 Concrete electrical resistivity 5
- 5.10 Repair 5
  - 5.10.1 General 5
  - 5.10.2 Concrete removal 5
  - 5.10.3 Reinforcement preparation 6
  - 5.10.4 Concrete reinstatement 6
- 5.11 Cementitious overlay 6
- 5.12 New structures 7

6 Cathodic protection system components **7**
- 6.1 General 7
- 6.2 Anode systems 8
  - 6.2.1 Conductive coating anode systems 8
  - 6.2.2 Activated titanium anode systems 9
  - 6.2.3 Titania ceramic anodes 11
  - 6.2.4 Conductive cementitious anodes 11
  - 6.2.5 Embedded galvanic anodes 11
  - 6.2.6 Surface-mounted galvanic anodes 11
  - 6.2.7 Buried and immersed anodes 11
- 6.3 Monitoring sensors 13
  - 6.3.1 General 13
  - 6.3.2 Portable reference electrodes 14
  - 6.3.3 Other sensors 14
- 6.4 Monitoring instrumentation 15
  - 6.4.1 General 15
  - 6.4.2 Digital meters 15
  - 6.4.3 Data loggers 15
- 6.5 Data management system 16
- 6.6 Direct current cables 17
- 6.7 Junction boxes 18
- 6.8 Power supplies 18
- 6.9 Transformer-rectifiers 18

7 Installation procedures **20**
- 7.1 Electrical continuity 20
- 7.2 Performance monitoring system 20

7.3 Connections to steel in concrete ... 21
7.4 Concrete repairs associated with the cathodic protection components ... 21
7.5 Surface preparation for anode installation ... 21
7.6 Anode installation ... 22
7.7 Connections to the anode system ... 22
7.8 Anode overlay, surface sealant or decorative coating application ... 22
7.9 Electrical installation ... 23
7.10 Testing during installation ... 23

8 Commissioning ... 24
8.1 Visual inspection ... 24
8.2 Pre-energizing measurements ... 24
8.3 Initial energizing of impressed current systems ... 25
8.4 Initial adjustment of impressed current systems ... 25
8.5 Initial performance assessment ... 25
8.6 Criteria of protection: Interpretation of performance assessment data ... 26
8.7 Adjustment of protection current for impressed current systems ... 28

9 System records and documentation ... 28
9.1 Quality and test records ... 28
9.2 Installation and commissioning report ... 28
9.3 Operation and maintenance manual ... 29

10 Operation and maintenance ... 29
10.1 Intervals and procedures ... 29
10.2 System review ... 30
10.3 System review report ... 30

Annex A (informative) **Principles of cathodic protection and its application to steel in concrete ... 31**

Annex B (informative) **Design process ... 37**

Annex C (informative) **Notes on anode systems ... 41**

Bibliography ... 46

Foreword

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

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents 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).

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. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

The committee responsible for this document is ISO/TC 156, *Corrosion of metals and alloys*.

This second edition cancels and replaces the first edition (ISO 12696:2012), of which it constitutes a minor revision with the following changes:

— figures for MnO_2, NaOH (0,5 M) in Table A.1 have been updated;

— general editorial corrections throughout the document.

Introduction

This document applies to cathodic protection of steel in concrete, with the concrete atmospherically exposed, buried or immersed.

Because the criteria of protection for steel in buried or immersed concrete are those applicable to cathodic protection of steel in atmospherically exposed concrete, this revision of EN 12696:2000 incorporates cathodic protection of steel in buried and immersed concrete. The provision of cathodic protection current can often be more economically provided to steel in buried and immersed concrete by using buried or immersed anode systems detailed in International Standards for buried and immersed steel structures, rather than the anode systems that are suitable for applications to steel in atmospherically exposed concrete. Therefore, reference is made to other International Standards in this respect while the cathodic protection performance criteria for steel in concrete are defined in this document for all exposures.

There are other electrochemical treatments intended to provide corrosion control for steel in concrete. These techniques include re-alkalization and chloride extraction and are not incorporated into this document. CEN/TS 14038-1:2004 and CEN/TS 14038-2:2011 have been published.

Cathodic protection of steel in concrete is a technique that has been demonstrated to be successful in appropriate applications in providing cost effective long-term corrosion control for steel in concrete. It is a technique that requires specific design calculations and definition of installation procedures in order to be successfully implemented. This document does not represent a design code for cathodic protection of steel in concrete, but represents a performance standard for which it is anticipated, in order to comply with this document, a detailed design and specification for materials, installation, commissioning and operation will be prepared.

Cathodic protection of steel in concrete

1 Scope

This document specifies performance requirements for cathodic protection of steel in cement-based concrete, in both new and existing structures. It covers building and civil engineering structures, including normal reinforcement and prestressed reinforcement embedded in the concrete. It is applicable to uncoated steel reinforcement and to organic-coated steel reinforcement.

This document applies to steel embedded in atmospherically exposed, buried, immersed and tidal elements of buildings or structures.

NOTE 1 Annex A gives guidance on the principles of cathodic protection and its application to steel in concrete.

NOTE 2 This document, while not specifically intended to address cathodic protection of steel in any electrolyte except concrete, can be applied to cathodic protection of steel in other cementitious materials such as are found, for example, in early 20th century steel-framed masonry, brick and terracotta clad buildings. In such applications, additional considerations specific to these structures are required in respect of design, materials and installation of cathodic protection; however, the requirements of this document can be applied to these systems.

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.

EN 1504 (all parts), *Products and systems for the protection and repair of concrete structures — Definitions, requirements, quality control and evaluation of conformity*

EN 14629, *Products and systems for the protection and repair of concrete structures — Test methods — Determination of chloride content in hardened concrete*

EN 14630, *Products and systems for the protection and repair of concrete structures — Test methods — Determination of carbonation depth in hardened concrete by the phenolphthalein method*

IEC 60502-1, *Power cables with extruded insulation and their accessories for rated voltages from 1 kV (Um = 1,2 kV) to 30 kV (Um = 36 kV) — Part 1: Cables for rated voltages of 1 kV (Um = 1,2 kV) and 3 kV (Um = 3,6 kV)*

IEC 60529, *Degrees of protection provided by enclosures (IP Code)*

IEC 61140, *Protection against electric shock — Common aspects for installation and equipment*

IEC 61558-1, *Safety of power transformers, power supplies, reactors and similar products — Part 1: General requirements and tests*

IEC 61558-2-1, *Safety of power transformers, power supplies, reactors and similar products — Part 2-1: Particular requirements and tests for separating transformers and power supplies incorporating separating transformers for general applications*

IEC 61558-2-2, *Safety of power transformers, power supplies, reactors and similar products — Part 2-2: Particular requirements and tests for control transformers and power supplies incorporating control transformers*

IEC 61558-2-4, *Safety of transformers, reactors, power supply units and similar products for supply voltages up to 1 100 V — Part 2-4: Particular requirements and tests for isolating transformers and power supply units incorporating isolating transformers*

IEC 61558-2-13, *Safety of transformers, reactors, power supply units and similar products for supply voltages up to 1 100 V — Part 2-13: Particular requirements and tests for auto transformers and power supply units incorporating auto transformers*

IEC 61558-2-16, *Safety of transformers, reactors, power supply units and similar products for voltages up to 1 100 V — Part 2-16: Particular requirements and tests for switch mode power supply units and transformers for switch mode power supply units*

IEC 62262, *Degrees of protection provided by enclosures for electrical equipment against external mechanical impacts (IK code)*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 8044 and EN 1504 (all parts) and the following apply.

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

— IEC Electropedia: available at http://www.electropedia.org/

— ISO Online browsing platform: available at http://www.iso.org/obp

3.1
zone
part of a cathodic protection system

Note 1 to entry: Anode systems may be divided into separate zones to supply current to a fully continuous reinforcement mesh. Alternatively, a single anode zone may supply current to separate, electrically isolated, zones within the reinforcement system. Zones may comprise an individual anode zone for each reinforcement zone or exposure condition. As the current provision to each of the zones in each of these alternatives can be separately measured, all of them are generically called “cathodic protection zones” and specifically “anode zones” or “cathode zones”.

3.2
humectant
hygroscopic material, i.e. a substance that promotes the retention of moisture

Note 1 to entry: It may be applied to the surface of a galvanic anode to keep the concrete-anode interface moist.

4 General

4.1 Quality management systems

The design, the installation, the energizing, the commissioning and the long-term operation of all of the elements of cathodic protection systems for steel in concrete shall be fully documented.

NOTE ISO 9000 constitutes a suitable quality management systems standard which can be utilized.

Each element of the work shall be undertaken in accordance with a fully documented quality plan.

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

Each stage of the installation, energizing, 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 European standards concerning calibration.

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

4.2 Personnel

Each aspect of the cathodic protection system design, installation, testing of the installation, energizing, commissioning and long-term operational control shall be under the supervision of personnel with appropriate qualifications, training, expertise and experience in the particular element of the work for which they are responsible.

NOTE Cathodic protection of steel in concrete is a specialist multidiscipline activity. Expertise is required in the fields of electrochemistry, concrete technology, civil and/or structural engineering and cathodic protection engineering.

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. EN 15257 specifies a suitable method which may be utilized for assessing the competence of cathodic protection personnel.

The 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.

4.3 Design

This document does not represent a design code, but is a performance standard.

Cathodic protection systems for steel in concrete shall be the subject of detailed design.

The design shall, as a minimum, include the following:

a) detailed calculations;

b) detailed installation drawings;

c) detailed material and equipment specifications;

d) detailed method statements or specifications for installation, testing, energizing, commissioning and operation;

e) structures containing prestressing shall be assessed for their susceptibility to hydrogen embrittlement and for risk of stray currents.

Annex B lists items that should be considered in the detailed design.

5 Structure assessment and repair

5.1 General

For cathodic protection (or cathodic prevention) of new structures, see 5.12.

The assessment of an existing structure, including its material condition, its structural integrity and whether and how to repair it, shall be performed in accordance with EN 1504 (all parts).

When cathodic protection is proposed as the repair/protection method, or part of it, for a structure, additional investigation shall be undertaken in order to

a) confirm the suitability of cathodic protection, and

b) provide system-design input information. See Annex B.

These investigations shall include, but shall not be limited to, those in 5.2 to 5.10.

5.2 Records

All available drawings, specifications, records and notes shall be reviewed to assess the location, quantity, nature (e.g. normal, galvanized, epoxy-coated, prestressed) and continuity of the reinforcement and any additional steel, the constituents and quality of the concrete.

The available information shall be confirmed and supplemented by site survey and laboratory tests, as specified in 5.3 to 5.8.

5.3 Visual inspection and delamination survey

Visual survey data shall be collected to ascertain the type, causes and extent of defects, and any features of the structure or its surrounding environment, which could influence the application and effectiveness of cathodic protection. Areas which have been previously repaired, and the repair methods and materials, shall be identified.

All areas of the structure which require to be cathodically protected shall be checked for delamination of the concrete cover.

Defects, such as cracks, honeycombing or poor construction joints, which could permit significant water penetration, and which could in turn impair the effectiveness or durability of the cathodic protection system, shall be recorded.

Where necessary, the inspection and survey of buried or immersed elements will be facilitated by excavation and or cofferdams.

5.4 Chloride analysis

If required, values and distributions of the chloride content of the concrete shall be determined in accordance with EN 14629.

5.5 Carbonation depth measurement

If required, distribution of carbonation depths shall be measured in accordance with EN 14630.

5.6 Concrete cover and reinforcement location

Concrete cover distribution and embedded steel and reinforcement size and position measurements shall be carried out in order to assess whether the anode/cathode spacing will be adequate for the particular anode system envisaged, and to identify dense regions of steel or reinforcement which may require high current density. Shielding of the steel to be protected, caused by embedded metal meshes, metal fibres or plates, plastic sheets or non-conductive repair materials, which could impair the efficiency of cathodic protection, shall be assessed. Possible short-circuits between reinforcing steel and impressed current anodes shall be assessed.

For buried or immersed structures or zones, the concrete cover may be less significant if the anode system is to comprise anodes buried or immersed and located some distance from the structure.

5.7 Reinforcement electrical continuity

Drawings of reinforcement and other steel elements shall be checked for continuity which shall then be proven on site by measuring the electrical resistance and/or potential difference between bars in locations remote from each other across the structure. Testing shall be as specified in 7.1 for the purpose of confirming cathodic protection feasibility and providing design information. This shall include at least an assessment of the following on a representative basis:

a) electrical continuity between elements of the structure within each zone of the cathodic protection system;

b) electrical continuity of reinforcement within elements of the structure;

c) electrical continuity of metallic items, other than reinforcement, to the reinforcement itself.

At the subsequent repair and installation stage, reinforcement and other steel electrical continuity shall be further checked in accordance with the methods, and to the extent specified in 7.1.

5.8 Steel/concrete potential

Representative areas, both damaged and apparently undamaged, shall be surveyed for reinforcement/steel corrosion activity, using portable reference electrodes conforming to 6.3.2. Measurements shall be taken, preferably on an orthogonal grid, at a maximum spacing of 500 mm.

NOTE 1 It is not necessary to carry out a steel/concrete potential survey of the entire structure. It is appropriate to survey, in more detail, those areas where reference electrodes are planned to be permanently installed, in order to place them in most anodic and other suitable locations.

Continuity of the reinforcement and steel within any steel/concrete potential survey area is essential and shall be checked, using the method in 7.1 before the steel/concrete potential survey.

Measurements in any areas identified as delaminated, in the survey specified in 5.3, should be interpreted with caution, because delamination can produce readings inconsistent with the level of corrosion of the reinforcement or other embedded steel.

NOTE 2 ASTM C876, RILEM TC 154 report (2003)[9] and Concrete Society Technical Report 60[10] provide guidance with respect to steel/concrete potential measurements and interpretation.

5.9 Concrete electrical resistivity

The impact of variations in concrete resistivity on the cathodic protection system shall be considered. There is no firm guidance on limits of electrical resistivity with respect to cathodic protection, but the designer shall consider whether full protection can be achieved where required for the ranges and absolute values of concrete resistivity found on the structure.

NOTE RILEM TC 154 Report (2000)[11] and Concrete Society Technical Report 60[10] provide guidance with respect to concrete electrical resistivity measurements and interpretation.

5.10 Repair

5.10.1 General

All operations comprising repair shall be performed in accordance with EN 1504 (all parts), except where stated otherwise in this subclause.

NOTE Installation of cathodic protection to an existing structure may be associated with other forms of repair work, such as strengthening, patching or coating, as determined in accordance with EN 1504 (all parts). In this subclause, the term “repair” signifies reinstatement of the damaged/deteriorated concrete to provide an uninterrupted path for the flow of cathodic protection current prior to the installation of cathodic protection, as well as reinstatement at locations where concrete has been removed to provide access to reinforcement and other steel, to install cable connections and monitoring sensors, etc.

5.10.2 Concrete removal

All repair materials from previous installations with significantly different electrical resistivity from the parent concrete shall be broken out.

Typically, these repair materials with an electrical resistivity outside the range of approximately half to twice that of the parent concrete, when measured under the same conditions as the parent concrete, should be removed in order to allow relatively uniform current distribution to reinforcement. For example, predominantly epoxy-based repair materials will have very high resistivity values and may shield reinforcement within or behind them from cathodic protection. Concrete reinforced with metallic fibres may have very low electrical resistivity and the fibres may form an electrical short-circuit path between the anode and the steel.

For impressed-current cathodic protection systems, any tying wire, nails or other metal components visible on the concrete, that might contact the anode system or might be too close to the anode for optimum anode/cathode spacing, shall be cut back and the concrete shall be repaired.

NOTE Any metallic objects electrically isolated from the cathodic protection cathode circuit may corrode and may require to be electrically bonded to the reinforcement or removed.

The removal of physically sound chloride-contaminated or carbonated concrete prior to applying cathodic protection is not necessary.

5.10.3 Reinforcement preparation

Any loose corrosion product particles shall be removed from the exposed reinforcement or other steel to ensure good contact between the steel and the repair material, but there is no need to clean the reinforcement or other steel, to be embedded in concrete, to bright metal.

Neither insulating nor resistive primers or coatings shall be used.

5.10.4 Concrete reinstatement

Concrete reinstatement shall be in accordance with EN 1504 (all parts), except where stated in this subclause.

Concrete shall be reinstated using cementitious materials. Repair materials containing metal (either fibre or powder) shall not be used, especially in the case of impressed current systems. The electrical resistivity characteristics and mechanical properties of the repair materials shall be compatible with the original concrete. Proprietary curing membranes shall not be used prior to subsequent anode installation over the repair area. Alternative curing methods shall be used.

The electrical resistivity of concrete repair materials shall be similar to that of the parent concrete.

NOTE Typically, these repair materials will have an electrical resistivity within the range approximately half to twice that of the parent concrete when measured under the same conditions as the parent concrete. However, the electrical resistivity of the parent concrete will be that of an aged material (age >20 years), whereas the electrical resistivity of the repair material will reflect the properties at a relatively young age; it is anticipated that there will be a significant ageing effect over time. Also, measurements made in the laboratory on prisms will not represent the conditions of the structure. A good quality repair made with materials known to be compatible with cathodic protection installations has been found to be more important than arbitrary resistivity limits.

5.11 Cementitious overlay

For cathodic protection systems employing anode systems as outlined in 6.2.2.2, following repair as specified in 5.10, and anode installation in accordance with 7.5, 7.6 and 7.7, a cementitious overlay shall be applied over appropriate types of installed anode. All materials and application methods shall be in accordance with EN 1504 (all parts). The average bond strength between the existing concrete and overlay shall be greater than 1,5 MPa and the minimum shall be greater than 1,0 MPa.

If the substrate concrete cohesive strength fails at lower values than 1,5 MPa average and 1,0 MPa minimum, the use of a cementitious overlay may be inappropriate.

Overlay application may be combined with concrete repair.

The electrical resistivity of anode overlays may exceed twice that of parent concrete subject to the anode within the overlay being able to pass its design current at the design voltage, in an overlay of this resistivity, in all atmospheric and exposure conditions applicable to the structure.

The selected material, thickness and placement method shall be compatible with each other, with the anode material and the exposure of the structure.

The potential between the anode and reinforcement/steel (cathode) shall be monitored to detect short-circuits. Curing membranes shall be removed from the parent concrete/substrate or shall have sufficiently degraded to avoid adversely influencing the performance of the cathodic protection system.

5.12 New structures

In the case of a new structure, if cathodic protection as a preventive system is to be included in the original construction, the following issues shall be assessed in the design, specification and construction procedures, in addition to the requirements of the remainder of this document and of the standards governing the design and construction of the new structure:

a) provision and checking of reinforcement/steel electrical continuity, in accordance with 7.1;

b) adequate securing and protection of monitoring sensors and all cables and their connections, to avoid damage or disturbance during concrete placement and vibration;

c) connection, location or insulation of other metallic fixtures, fixings or other items, so as to avoid undesirable influences from the cathodic protection system;

d) in the case of impressed current anodes cast into the concrete structure, provision of sufficient rigid insulating spacers and attachments to secure the anodes in position and prevent the creation of short-circuits during concrete placement and vibration. The potential monitoring between anode and reinforcement/steel (cathode) shall be used to detect short-circuits during concrete placement.

6 Cathodic protection system components

6.1 General

The cathodic protection system shall include an anode system intended to distribute the cathodic protection current to the surfaces of the embedded steel to be protected. Impressed current cathodic protection systems shall further incorporate positive and negative direct current cables between the anode and the steel, respectively, and the DC power supply, which is the source of the cathodic protection current.

For galvanic anode systems, direct permanent metallic connections shall be provided between the anode and the steel, except where monitoring that requires current interruption is installed.

Reference electrodes, other electrodes and other sensors are key elements of cathodic protection systems and constitute the performance monitoring system within cathodic protection systems. The data from the electrodes and sensors may be interrogated and displayed by portable instrumentation or permanently installed instrumentation of either the automatic or manual type.

The entire cathodic protection system shall be designed, installed and tested to be suitable for its intended life in its intended environment.

Both impressed current and galvanic anode cathodic protection systems require monitoring provisions in order to determine the performance and comply with this document.

NOTE Galvanic anode systems may be used without monitoring systems or methods to measure their performance. Such systems do not comply with this document.

6.2 Anode systems

See Annex C.

The anode system shall be capable of supplying the performance required by the cathodic protection design (see 4.3). The anode system's calculated or anticipated life shall be sufficient for the design life incorporated into the design, with, where necessary, planned maintenance or replacement of the anode system or parts of the system at periods designated in the design.

For anodes embedded into or applied to the surface of the concrete, the anode current density shall conform to the design and shall not exceed such values resulting in a performance reduction of either

a) the concrete at the anode/concrete interface, or

b) the anode, during the design life of the anode.

The design and/or the selection of the anode material shall consider likely variations in cathode current density requirements, steel distribution, concrete electrical resistivity and any other factors likely to result in uneven distribution of current demand or current discharge from the anode and the possibility of this resulting in an early failure of isolated parts of the anode system.

NOTE 1 A variety of anode systems have been developed, tested and demonstrated in long-term field applications to be suitable for use embedded in concrete or applied to the concrete primarily (but not exclusively) in the cathodic protection of steel in atmospherically exposed concrete. The requirements for such anodes are unique for usage of cathodic protection in concrete, as the anodes have to be installed or applied and distributed across the concrete surface or within the concrete, as required, to meet the design distribution and magnitude of current. The anode is therefore in close contact with the highly alkaline concrete pore water. In operation, the anodic electrochemical reactions at the anode/concrete interface are oxidizing, producing acidity.

NOTE 2 The anode systems described in this document are in two categories. Anode systems which have been in use for a minimum of 5 years and which have extensive, generally successful, track records are covered in 6.2.1 and 6.2.2. It is not intended that the use of other, perhaps newer or less well proven, anode materials is to be precluded as this would restrict the necessary and advantageous development of new, possibly improved, anode materials. Anodes are listed non-exclusively in Annex C.

It is likely that new and effective anode materials will be developed for cathodic protection of steel in concrete. It is not the purpose of this document to preclude their use. It is recommended that the use of any anode should only be undertaken where performance can be demonstrated by laboratory testing, trials and/or past projects.

It is suggested that new anode materials for cathodic protection of steel in concrete should be the subject of rigorous laboratory testing and, wherever possible, extended and/or accelerated field trials prior to commercial non-trial applications.

NOTE 3 There is an established test method for accelerated life testing of anodes embedded in concrete, NACE/TM 0294[12] and for organic-based conductive-coating anodes.[13]

Anode systems used for the protection of steel in buried or immersed concrete are detailed in European Standards EN 12473, EN 12954, EN 12495, EN 12474 and ISO 13174.

6.2.1 Conductive coating anode systems

6.2.1.1 Organic coatings

These coatings are used as impressed current anodes.

The anode system shall comprise an organic conductive coating (solvent based or water soluble, containing a carbon conductor) and a series of conductors (primary anodes) fixed to the concrete surface or integrated into the coating, in order that the conductors can distribute current within the coating. The conductors shall be of material able to resist anodic reactions, e.g. platinum-coated or platinum-clad titanium or niobium which may be copper cored, or mixed metal-oxide-coated titanium.

The combination of conductive coating and primary anodes shall be demonstrated by trials or past projects to enable the design anode performance to be achieved. The spacing of primary anodes within the conductive coating shall be such that it can be calculated or demonstrated that the variation in anode current output attributable to the resistance, within the coating, between primary anodes, does not exceed ±10 % of the average current output measured as a ±10 % voltage drop.

The particular application technique selected shall be demonstrated by trials or past projects to enable the design anode performance to be achieved.

The adhesion of the coating to the concrete, subject to appropriate surface preparation and the above application technique, shall be suitable to achieve the full design life of the anode system.

Data shall be provided determining the wet and/or dry film thickness requirements to achieve the required dry film conductivity.

See Annex C for further information.

6.2.1.2 Thermally sprayed metallic coatings

The anode system shall comprise a thermally sprayed metallic coating of Zn, Al-Zn, Al-Zn-In or Ti.

The Zn coatings are used both as impressed current anodes and as galvanic anodes; the Al-Zn and Al-Zn-In alloy anodes are used as a galvanic anode. Ti is used as an impressed current anode with a catalytic spray to lower the anode-to-concrete interfacial resistance.

When thermal sprayed metallic coatings are used as galvanic anodes, they may be applied directly to the reinforcement/steel where it is exposed, as well as predominantly to the sound concrete surface.

A humectant may be applied to thermal sprayed metallic coatings used as galvanic anodes to enhance their performance.

To avoid atmospheric corrosion and prolong the lifetime of the anode, an organic top-coating may be applied to the thermal sprayed metallic layer.

The combination of metallic coating and connectors shall be demonstrated by trials or past projects to enable the design anode performance to be achieved.

The particular application technique selected shall be demonstrated by trials or past projects to enable the design anode performance to be achieved.

The adhesion of the coating to the concrete, subject to appropriate surface preparation and the above application technique, shall be suitable to achieve the full design life of the anode system.

Data shall be provided for determining the application process requirements to achieve the required film thickness and conductivity.

Metallic connectors (of Cu, Cu-Zn-alloys, Ti or steel) mechanically bonded to the concrete surface shall be installed prior to metallic coating application.

See Annex C for further information.

6.2.2 Activated titanium anode systems

6.2.2.1 General

These anodes are used as impressed current anodes.

The anode system shall comprise a substrate of titanium[14] and an electrocatalytic coating containing oxides of platinum group metals, platinum, iridium or ruthenium along with oxides of titanium, zirconium and tantalum, together with anode/cable connections and a cementitious overlay or surround.

NOTE 1 These anodes are frequently described as MMO/Ti anodes (mixed metal-oxide-coated titanium) or dimensionally stable anodes (DSA).

The coating composition and thickness, or mass per unit area, shall be demonstrated by trials and/or laboratory testing to enable the design anode performance to be achieved.

NOTE 2 A suitable test procedure is NACE/TM 0294.[12]

6.2.2.2 Surface installed

The activated titanium shall take the form of a mesh or grid, distributed in accordance with the cathodic protection system design, on the concrete surface. Titanium connectors shall be spot welded to the mesh or grid to distribute current to all component parts of the anode and to facilitate electrical connections to the anode. Where anode/cable connections are to be incorporated into the cementitious overlay, they shall be of a type and installed in a manner that can be demonstrated by trials or past projects to enable the design anode and anode/cable connection performance to be achieved.

Non-metallic fixings shall be utilized to facilitate the fixing of the anode material to the surface of the concrete or to reinforcement/steel prior to pouring the concrete, and shall ensure that there are no short-circuits between anode and reinforcement/steel.

See Annex C for further information.

6.2.2.3 Installation into recesses in cover concrete

The anode shall take the form of solid or mesh titanium strips or grids complete with the electrocatalytic coating, suitable for recessing into grooves cut into the cover concrete, or be activated titanium strips and grids with non-metallic fixings to facilitate installation onto exposed reinforcement prior to concrete placement.

The size and distribution of the strips or grids shall conform to the cathodic protection system design and the maximum anode current density.

See Annex C for further information.

6.2.2.4 Embedded within the structure

Activated titanium shall be embedded within the structure in one of the following ways:

a) electrocatalytically coated titanium in the form of strip, mesh, grid or tubes shall be embedded into a cementitious repair mortar in holes drilled into the concrete;

b) anodes of a similar form or platinum-coated titanium rods shall be used in conjunction with a conductive graphite-based backfill;

c) anodes of a similar form shall be cast into new construction for cathodic prevention or into concrete repairs for cathodic protection.

Where a backfill (e.g. graphite) is part of the anode system, its operating current density based upon the dimensions of the hole drilled in the concrete, and the anode current density within the backfill shall conform to the cathodic protection system design (see 4.3) and shall be limited to values which can be demonstrated by trials or past projects to enable the requisite anode, backfill and anode/cable connection performance to be achieved. Where graphite backfill is utilized, the graphite shall be considered as the anode in calculating the minimum anode/reinforcement or other steel spacing.

See Annex C for further information.

6.2.3 Titania ceramic anodes

See Annex C for further information.

6.2.4 Conductive cementitious anodes

See Annex C for further information.

6.2.5 Embedded galvanic anodes

These consist of zinc anodes in an activating encapsulation.

One anode type consists of a disk of zinc encased in proprietary activating mortar with connections to the reinforcing bar (rebar) attached. One or more galvanic anodes are attached to the reinforcement in a concrete repair. The anode will corrode and provide current which may be sufficient to protect an area around the patch repair.

Another anode type allows a “string” of zinc anodes in proprietary activating mortar to be embedded in cored holes in the concrete.

See Annex C for further information.

6.2.6 Surface-mounted galvanic anodes

6.2.6.1 Zinc mesh in overlay

This anode is designed for splash and tidal zone applications. It consists of an expanded zinc metal sheet or mesh, mechanically fixed and grouted to the prepared concrete surface. It may use a permanent form (or jacket) containing an expanded mesh zinc anode which is clamped to a concrete pile in the splash and tidal zone. This is filled with a cementitious grout. Cast zinc anodes may be attached below the low-water line.

See Annex C for further information.

6.2.6.2 Adhesive zinc-sheet anode

A “glue on” anode system has been developed that can be applied directly to a prepared concrete surface. The adhesive is a hydrogel, as used in attaching electrodes to the skin for medical applications. The anode is supplied in rolls of adhesive covered zinc sheet and is attached to the structure. The rolls are then soldered together and attached directly to the steel.

See Annex C for further information.

6.2.7 Buried and immersed anodes

6.2.7.1 General

For structures that are either buried or immersed, anodes do not have to be in direct physical contact with the concrete. Traditional anode systems, for example, as used in cathodic protection schemes for buried and immersed pipelines, tanks, marine structures, etc. and as described in EN 12473, EN 12954, EN 12495 and EN 12474 may be used. In these cases, the anodes are located away from the structure but are buried or immersed in the same electrolyte in which the steel in concrete structure is buried or immersed.

The type of anode composition, shape, location and method of installation varies for the different systems and also varies between buried and immersed conditions. Further information is given in Annex C.

NOTE The Bibliography provides additional sources of data on the design and application of buried and immersed anodes that can be applied to supplying cathodic protection (or cathodic prevention) current to steel in buried or immersed concrete structures.[10][11]

6.2.7.2 Immersed concrete structures

6.2.7.2.1 Galvanic anodes

For immersed concrete structures, galvanic anodes, comprising alloys of aluminium–zinc–indium, zinc or magnesium alloys, may be used as described in EN 12495. Aluminium-based alloys are only suitable for saline water conditions. In very low resistivity environments or if magnesium alloys are used, particular consideration shall be given to acceptable negative potential limits (see 8.6).

The number, size, capacity and location of galvanic anodes will be dependent on the current demand, the (soil or water) electrolyte resistivity, the structure size and shape, and shall be designed to ensure uniform current distribution and polarization to the structure.

Electrical connections between the anode and the steel in the concrete may be by direct welding of anode supports to the steel (either during construction of the structure or after excavation to expose the steel with suitable concrete repair following welding) or by the use of an integral anode cable fixed to a suitable contact point(s) on the steel.

6.2.7.2.2 Impressed current anodes

Impressed current anodes with long-established track records in buried or immersed applications, including high-silicon iron (with chrome in chloride environments), mixed metal-oxide-coated titanium, platinized titanium or platinized niobium mounted either on the concrete structure or located some distance from the structure (as remote anodes), as described in EN 12495, may be used.

The number, size, capacity and location of impressed current anodes will be dependent on the current demand, the (soil or water) electrolyte resistivity, the structure size and shape, and shall be designed to ensure uniform current distribution and polarization to the structure.

Where anodes are fixed directly to the structure, a dielectric shield may be required between the anode and the concrete to prevent excessive current entering the concrete immediately adjacent to the anode, which could result in local over polarization.

6.2.7.3 Buried concrete structures

6.2.7.3.1 Galvanic anodes

For concrete structures buried in soil (including foundations, storage tanks and concrete pipelines), galvanic anodes with long-established track records in buried applications based on zinc or magnesium alloys, as described in EN 12954, may be used.

Anodes will normally be located a short distance from the structure and placed in a suitable chemical backfill (typically a mix of gypsum, bentonite and sodium sulfate).

Electrical connection between the anode and the steel in the concrete structure shall be via an integral anode cable to a junction or test box, with a corresponding connection cable from the steel in the structure to the junction/test box.

The selection of zinc or magnesium alloys will be dependent on soil resistivity and the required current output from the anodes. In very low resistivity soils or where magnesium alloys are used, particular consideration shall be given to acceptable negative potential limits (see 8.6).

The number, size and location of anodes will be dependent on the current demand from the structure, the structure geometry and the soil resistivity. For longitudinal structures (e.g. pipelines) in particular, attenuation along the structure length shall be considered in the determination of anode spacing.

6.2.7.3.2 Impressed current anodes

Impressed current anodes with long-established track records in buried or immersed applications, including high-silicon iron (with chrome in chloride environments), mixed metal-oxide-coated titanium, platinized titanium or platinized niobium (with or without a copper core) located in groundbeds some distance from the structure, as described in EN 12954, may be used. Anodes will normally be installed in a conductive backfill (typically calcined petroleum coke) and may be located either as single anodes or grouped to form horizontal or vertical groundbeds (anode groups).

The number, size, capacity and location of impressed current anodes and groundbeds will be dependent on the current demand from the structure, the structure size and geometry, and the soil resistivity. The design shall take into account requirements for ensuring uniform current distribution and polarization over the structure, as well as available space/right of access where large-size groundbeds are located some distance from the concrete structure. For longitudinal structures (e.g. pipelines) in particular, attenuation along the structure length shall be considered in the determination of spacing between groundbeds and between the structure and the groundbeds.

6.3 Monitoring sensors

6.3.1 General

In order to determine the performance of the cathodic protection, a monitoring system shall be incorporated. The monitoring system shall incorporate sensors at representative points over the entire structure/anode zone to be protected.

The cathodic protection system performance shall be determined by measuring the steel/concrete potential, using reference electrodes.

NOTE 1 Suitable reference electrodes for permanent embedding in concrete include double junction Ag/AgCl/KCl and Mn/MnO_2/0,5 M NaOH electrodes.

NOTE 2 Other sensors, such as potential decay electrodes, current density coupons, macro-cell probes, etc., may also be used in conjunction with reference electrodes.

NOTE 3 In some environments, such as in the presence of bromides, iodides or ionizing radiation, Ag/AgCl/KCl electrodes may be unstable. In instances of significant temperature changes, all electrodes will change their electrode potential. In some such circumstances, it may be necessary to utilize potential decay probes only.

Reference electrodes are used to measure absolute potential values, as in 8.6. Their own electrode potential shall be accurate and stable with respect to a standard electrode.

NOTE 4 This is typically expressed in theory with respect to a standard hydrogen electrode but is more frequently measured in the laboratory with respect to a saturated calomel electrode.

Reference electrodes shall have an electrode potential within ±10 mV of their theoretical value and any batch of reference electrodes shall all have electrode potentials within ±5 mV of their calibration certificates.

Reference electrodes shall be calibrated with respect to a pair of clean and fully maintained laboratory or mapping electrodes in order to demonstrate the above electrode potential accuracy prior to installation. Electrode installation may be improved by precasting electrodes into shrinkage-compensated cementitious mortar and ensuring intimate bonding between the mortar and the porous plug of the electrode.

All sensors shall be sufficiently robust for installation and permanent exposure in highly alkaline conditions.

The cables and cable connections to sensors shall be similarly robust and alkaline resistant and acid resistant if in contact with, or close to, the anode system.

6.3.2 Portable reference electrodes

Portable reference electrodes shall be reference electrodes designed to be used either directly on the concrete surface or in conjunction with Luggin probes.

Portable reference electrodes to be used directly on the concrete surface shall have an integral, but replaceable, sponge for contact with the concrete.

Portable reference electrodes shall be supplied with a calibration certificate and shall be stored, maintained and handled in full accordance with the manufacturer's instructions. Portable reference electrodes shall be checked against a known laboratory standard reference electrode, or similar, at the beginning and end of each site application.

NOTE 1 Suitable portable reference electrodes include gel-filled, double-junction Ag/AgCl/0,5 M KCl and saturated calomel electrodes (in a non-glass housing) (SCE).

NOTE 2 Calomel electrodes may not be suitable for site use for health and safety reasons as they contain mercury. Cu/saturated $CuSO_4$ electrodes (CSE) are not recommended for use on concrete surfaces due to the high risk of significant errors if copper sulfate leaks onto the concrete surface.[15]

6.3.3 Other sensors

6.3.3.1 Potential decay probes

Potential decay probes shall not be used to measure absolute steel/concrete potential [as specified in 8.6 a)] or long-term potential decay beyond 24 h.

NOTE 1 Potential decay probes are sensors enabling the measurement of steel/concrete potential, but do not have the reversible stability of their own half-cell potential in order to be classified as a reference electrode. They may be used to determine the potential change (during "on and off switching") over a limited time period, typically a maximum of 24 h.

NOTE 2 Suitable potential decay probes for permanent embedding in concrete include graphite and activated titanium.

6.3.3.2 Coupons and macro-cell probes

Coupons and macro-cells are optional additional monitoring sensors.

Where used, coupons and macro-cell probes shall be manufactured from steel of similar composition to the structure-reinforcing steel and shall either be of rugged construction suitable for permanent embedding in concrete or be constructed by isolating and instrumenting existing reinforcement which is already in place.

Macro-cell probes shall be encased in chloride-rich mortar cylinders. The chloride content of the cylinders (with respect to the mass of the cement) shall be at least five times the average chloride content of the structure concrete (with respect to the mass of the cement) and exceed the maximum chloride content at the depth of reinforcement.

Current density coupons or macro-cell probes may be used to estimate the local current density collected on the steel cathode; for this application, the coupon shall be of a known surface area.

NOTE Macro-cell probes can also be used to confirm that local active corrosion sites ("hot spots") receive sufficient current from the cathodic protection system to control corrosion. This is indicated by a reversal of the net current flow between the macro-cells and the main reinforcement after the cathodic protection system has been energized.

6.3.3.3 Luggin probes (electrolytic bridge)

Luggin probes shall comprise an ionic conductive medium within a rigid or semi-rigid insulation material. All materials shall be suitable for being permanently embedded in concrete and shall be prevented from completely drying out.

NOTE Luggin probes or similar devices can be used to enable the potential of embedded steel deep within a structure to be determined using a portable reference electrode.

6.4 Monitoring instrumentation

6.4.1 General

Monitoring instrumentation shall be used to interrogate monitoring sensors installed to determine the performance of the cathodic protection system and the operating condition of the direct current power supply.

NOTE Monitoring instrumentation may comprise manual devices, portable data loggers or permanently installed data loggers. Instrumentation is principally required to measure direct current voltages. If coupons or macro-cell probes are incorporated or other measurements are required, then other specialist instrumentation is necessary.

All instrumentation shall be constructed in accordance with relevant national or European Standards relating to electronic and measurement equipment and shall be provided with a valid calibration certificate. All equipment shall be handled, installed, commissioned and operated in accordance with the manufacturer's recommendations.

6.4.2 Digital meters

Voltmeters for measuring sensors and direct current power supplies shall have a minimum resolution of 1 mV, an accuracy of ±1 mV or better and an input impedance of greater or equal to 10 MΩ.

Analogue meters shall not be used.

Current flow between coupons or macro-cell probes and reinforcement shall be measured using a zero resistance ammeter or other suitable device of such accuracy and resolution that the current is measured to an accuracy of better than ±1 % of the value measured.

NOTE Depending on the coupon or macro-cell probe size and their environment, the currents can range from tens of microamperes to hundreds of milliamperes.

6.4.3 Data loggers

6.4.3.1 General

Data loggers shall have suitable multi-channel input or multiplexers to enable all channels selected for data logging to be measured and recorded.

Data loggers shall operate under a real date-time clock which shall be included in all measurement units. Data loggers shall have a minimum input impedance of 10 MΩ and a resolution of at least 1 mV in a range of at least 2 000 mV and an accuracy of ±5 mV or better.

Data loggers shall be supplied with software allowing test locations, sensors, direct current power systems, anode zones, etc. to be identified.

NOTE Data loggers can be used to collect data from both sensors and direct current power supplies. Data loggers may be either portable or permanently installed.

6.4.3.2 Portable data loggers

Portable data loggers shall be suitable for rough handling and temporary exposure to the site environment. Connection of portable data loggers to test boxes, direct currrent power supplies, etc. shall be by suitable connector(s) and cable, as appropriate.

6.4.3.3 Permanently installed data loggers

Permanently installed data loggers shall be located in an enclosure suitable for the environment and climate conditions at the site, in accordance with 6.7 and 6.9.

Permanently installed data loggers shall be hardwired to relevant sensors, direct current power supplies, etc. Instrumentation cable connections shall be in accordance with 6.6.

NOTE 1 Permanently installed data loggers can be operated independently, on a network or via a modem link. The power supply can either be alternating current mains or via the network cable, as appropriate.

Interconnection into a network shall be in accordance with relevant national or European Standards and the network manufacturer's recommendations.

Each permanently installed data logger shall have a unique identification reference number.

NOTE 2 Permanently installed data loggers can operate as either passive or active systems. If passive, they collect data only when instructed by a system controller. If active, they can be programmed to collect data for selected intervals. Either they may transmit all data or transmit summary data (e.g. mean, maximum, minimum, standard deviation, over a selected period) on request or automatically.

It is recommended that access to permanently installed data loggers either directly or via a network shall be secured, requiring at least the need for a user-defined password in order to prevent unauthorized access. Industry standard data-transfer security and communications protocols should be considered according to the location of the installed network.

6.5 Data management system

A data management system shall be provided to collate, order, sort and present the performance data arising from the cathodic protection system.

NOTE 1 This may be either a manual (paper) system or a computerized data-based management system or a combination of both.

The system shall contain the following data as a minimum:

a) anode-zone layouts;

b) sensor type and location;

c) direct current power unit rating;

d) initial (pre-commissioning) sensor readings;

e) commissioning data;

f) sensor data obtained since commissioning (at time intervals conforming to Clause 10);

g) direct current power supply output data since commissioning;

h) event record (i.e. inspection dates, changes in system operation, etc).

Sensor data obtained and recorded shall be compatible with, and sufficient to enable conformity to, the selected performance criterion given in 8.6 to be assessed.

Computer database management systems shall be provided with full documentation. Facilities for automatic data back-up and archive shall be incorporated.

The system shall be capable of presenting data/information in both tabular and graphical form.

NOTE 2 Data superimposed on mimic diagrams (schematic plans and sections) may also be used.

The system shall be capable of identifying data points outside pre-set (user definable) limits on request.

6.6 Direct current cables

Single-core cables shall be colour coded according to their function.

NOTE 1 The following colours are preferred:

a) brown (or alternatively red) from positive DC power to anode/cable connection;

b) black (or alternatively grey) from negative DC power to reinforcement steel/cable connection;

c) grey (or alternatively black) for monitoring test (reinforcement connection for monitoring) cable.

NOTE 2 Negative DC power and monitoring test cables may be of the same colour if of different sizes, for example:

a) blue for reference electrode cable (not red or black);

b) yellow or other colour (not brown, red, grey, black or blue) for other monitoring sensors.

Multi-core cables shall be colour or number coded.

All cables shall be identified in junction boxes and at their points of connection to monitoring equipment and power supplies. The identification shall be by proprietary cable markers and the identification shall be fully detailed (i.e. any code explained) in each junction box, monitoring unit and power supply unit. The identification and the cable colours shall be fully documented on the as-built drawings and manuals (see 9.2).

Cables shall meet the following requirements:

a) carry the design current +25 % within permissible temperature increases allowed under IEC 60502-1, as appropriate to the maximum environmental temperatures;

b) limit the voltage drop at 125 % of the designed maximum current in the cathodic protection system circuit to a value compatible with the power supply voltage output and the anode/cathode voltage requirements and provide uniform zone current distribution.

Zone anode current density shall be designed to be uniform to within 10 % of the nominal anode current density at all locations within the zone; cable and anode volt drops should be calculated and designed to ensure such uniformity.

Minimum core sizes of multi-core cables for mechanical purposes, with all cables encapsulated in concrete, or in conduit or trunking shall be as follows:

— DC positive and negative supplies 1,0 mm^2;

— monitoring cable 0,5 mm^2;

— data networking in accordance with network standards.

If single-core cables are used, the minimum core size for mechanical purposes shall be 2,5 mm^2.

All cable cores shall have a minimum of seven strands.

All cables shall have a minimum of a single layer of insulation and a single layer of sheathing which shall conform to IEC 60502-1. The selection of insulation and sheath shall take due account of the proposed installation and functional requirements. Cable to be installed in contact with anode material shall be suitable for long-term exposure to acidic conditions, typically pH = 2, and those to be installed in concrete for long-term exposure to alkaline conditions, typically pH = 13.

NOTE 3 Cables with insulation or sheaths of polyvinyl chloride (PVC), ethylene propylene rubber (EPR) or chloro-sulfonated polyethylene (CSP) or other rubbers are unlikely to be suitable for long-term use in pH 2 to pH 13. Cables with insulation and sheaths of XLPE are likely to be suitable for long-term use. Insulation of very chemically resistant materials such as Kynar may be considered, but these have disadvantages of cost and a tendency to crack at low temperatures and they require particular care with respect to large minimum bend radii.

6.7 Junction boxes

Junction boxes shall be rated in accordance with IEC 60529 and IEC 62262 to render appropriate protection against the environment, taking into account the type of connections made within the box and the worst case external environmental and mechanical exposure to which the box is to be subjected.

It is recommended that all junction boxes should be non-metallic and conform to IEC 60529 classification IP 66 or better when exposed to external environments.

6.8 Power supplies

Where mains electrical power is used, the direct current power supply shall be provided by a transformer-rectifier or a switch mode rectifier.

NOTE Other types of supply, such as diesel, wind or turbine generators, may be used to generate alternating current as a supply to a transformer-rectifier. Controlled direct current supplies can be generated directly by thermoelectric or solar generators and wind or turbine generators may be used with rectification to provide a supply to intermittently charged battery systems which supply current to DC controllers.

All power supplies shall be constructed in accordance with relevant national or European Standards relating to electronic and measurement equipment and shall be provided with a valid calibration certificate. All equipment shall be handled, installed, commissioned and operated in accordance with the manufacturer’s recommendations.

Power supplies may be integrated with monitoring instrumentation and communication facilities (see 6.4) in order to provide remote monitoring of d.c power supply parameters and the cathodic protection system performance (see 8.6). This integrated monitoring and power supply system may provide for remote control of the power supply direct current output.

6.9 Transformer-rectifiers

The transformer-rectifier unit shall be continuously rated, self-contained and suitable for the environment in which it is to operate.

The unit shall be housed in a robust enclosure suitable for wall or floor mounting, as applicable. The enclosure shall provide protection against the worst case environment in accordance with IEC 60529.

The incoming alternating current supply shall be terminated in accordance with the electricity supplier’s requirements and national and/or European Standards.

NOTE 1 For example, via an appropriately rated, double-pole neutral linked switch fuse or circuit breaker and residual current device.

The mains transformer shall be an isolating transformer conforming to IEC 61558-1, IEC 61558-2-1, IEC 61558-2-2 and IEC 61558-2-4 continuously rated and suitable for connection to the low voltage alternating current supply. The transformer-rectifier output shall not exceed 50 V DC with a ripple content not exceeding 100 mV RMS with a minimum frequency of 100 Hz.

Equipment, which does not conform to the relevant parts of IEC 61558 because it is required by environment or service to operate above an ambient temperature of 30 °C or to utilize oil or forced air cooling, shall in all other aspects conform to IEC 61558-1, IEC 61558-2-1, IEC 61558-2-2 and IEC 61558-

2-4. Equipment utilizing auto transformers shall conform to IEC 61558-2-13 and equipment utilizing switch mode power supplies shall conform to IEC 61558-2-16.

The rectifier shall conform to appropriate national or International Standards with suitable alternating current and direct current surge protection. Rectifiers shall be rated for continuous operation at the specified outputs with a peak inverse voltage of at least 600 V. Varistors shall be compatible with the rectifier peak inverse voltage levels. The direct current circuits shall be separated from those of any other system (e.g. the incoming alternating current supply). For cathodic protection systems placed in locations accessible to persons or animals, and where preventative measures, such as barriers, obstacles or electrical insulation, are not provided, the output from the transformer rectifier unit shall not exceed 24 V DC with a ripple content not exceeding 100 mV RMS. This shall specifically apply to cathodic protection of reinforced concrete structures and buildings where conductive-coating anode systems are used.

The output shall be controlled to provide stepless (<0,1 % of full range) constant voltage, constant current or potentiostatic control from zero to full rated output.

A direct current relay system interrupting the output shall be provided to facilitate “instantaneous off” potential measurement [see 8.6 a)].

NOTE 2 Facilities to link this system to the control signals from data logging equipment may be provided.

Facilities shall be provided to enable portable instrumentation to be used for measurement of the following:

a) output voltages;

b) output currents (by voltage drop across a shunt resistor with an accuracy of ±0,5 % or better);

c) steel/concrete potential with respect to the reference electrodes.

NOTE 3 Facilities may be used for measurement of:

a) steel/concrete potential with respect to potential decay probes;

b) coupon or probe/reinforcement current.

The function and rating of all sockets and the multiplying factor of all shunts shall be clearly marked. All fuses shall be labelled with circuit designation and fuse characteristics.

NOTE 4 Permanently installed digital panel meters may be used to measure the data required in items a) to c). Calibration checks on a regular basis are necessary.

A minimum of one positive and one negative terminal for cable connections shall be provided. All output terminals shall be fully insulated from any metal within the box.

The connectors shall be clearly marked, e.g. “+ ANODE” and “− STEEL”.

It is recommended that the positive and negative terminals should be of different sizes in order to avoid transposition of cables.

LEDs (light emitting diodes) or other means of indicting alternating current power supply “on” and direct current output “operating” shall be provided.

For equipment with multiple transformer-rectifiers or multiple channels, each transformer-rectifier and channel shall be fully identified and shall conform to this subclause.

Tests shall be conducted at the manufacturer’s works to demonstrate full functional conformity and fitness for purpose. The tests shall be arranged to represent realistic on-site working conditions and the results shall be fully documented and shall constitute part of the permanent records for the works.

All electrical tests shall be carried out in a manner prescribed by the relevant national or European Standards.

7 Installation procedures

7.1 Electrical continuity

Unless alternative testing procedures and criteria have been selected in the design, the electrical continuity between reinforcing bars or elements of steel in concrete shall be tested by a direct current reverse polarity resistance measurement technique, by measuring the resistance using a direct current resistance instrument and then reversing the polarity of the test leads, or by a direct current potential difference measurement technique. The acceptance criteria for such testing shall be stable values and a resistance less than 1,0 Ω. All steel exposed during concrete repairs or other works shall be continuity tested, and any bar or component tested failing the test shall be continuity bonded to ensure long-term resistance of 1,0 Ω or less. At additional representative locations in each unit or discrete part of the structure, sufficient reinforcement and any other embedded steel shall be exposed and tested at selected locations to determine the general level of electrical continuity of the reinforcement/steel.

Alternatively, a potential measurement technique may be used with a fixed-location reference electrode used to measure steel/concrete/electrode potential connected to one reinforcement bar or element of steel and then, without moving the reference electrode, connecting to another steel bar or element. The acceptance criteria shall be stable potential measurements with a difference of less than 1 mV when connections are made to the two steel bars or elements.

Continuity testing and bonding, as necessary, shall be applied to all steel exposed during concrete repairs.

The continuity testing results, all available construction drawings, the nature of the structure and its construction shall be assessed in order to determine whether additional reinforcement/steel should be exposed for testing and possible bonding.

All ancillary steel fixed to or part of the concrete structure (e.g. embedded steel beams, bearings, drainage pipes) either shall be continuity tested as above and bonded if required or shall be bonded in accordance with 7.3.

Electrical contact shall be prevented between reinforcement or ancillary steel and the anode system of any impressed current cathodic protection system.

Attention should be given to the location, removal or insulation of steel in the surface of concrete particularly if conductive coatings (including conductive overlays or sprayed zinc impressed current) anodes are to be used. Contact between an impressed current anode and such steel will either result in short-circuits between anode and reinforcement causing a failure of that cathodic protection zone or in corrosion of isolated steel.

7.2 Performance monitoring system

Each zone of the impressed cathodic protection system or at representative areas for systems with galvanic anodes shall be provided with the means necessary to monitor its power supply output voltage and output current and its steel/concrete potential using a minimum of two reference electrodes (6.3.1) permanently embedded at representative locations.

NOTE 1 Each zone may also be provided with potential decay probes to monitor potential decay, with corrosion coupons to measure anodic or cathodic current density on parts of the reinforcement/steel or with other methods to measure or assess corrosion rate or extent of cathodic protection. The data collection system may be manual, electronically data logged and/or electronically data transmitted.

The permanently installed performance monitoring system shall be located so that representative data can be assessed at typical intervals in accordance with Clause 10.

NOTE 2 This assessment may involve manual data collection, recording data collection with portable equipment or locally, area networked/modem linked, permanently installed data logging systems.

The extent and locations of deployment of the permanently installed performance evaluation system shall be in accordance with the design. The areas addressed shall include the following:

a) high probability to corrosion or under-protection;

b) high probability to excessive protection;

c) high corrosion risk or activity.

NOTE 3 The data from or the performance of permanently installed reference electrodes, coupons or other sensors, are likely to be adversely affected or rendered non-representative by placement in or adjacent to concrete repairs incorporating reinforcement or other embedded steel.

Reference electrodes and other sensors shall not be placed in, or close to, concrete repairs unless there are no alternative locations. In the vicinity of the sensor, concrete surrounding the steel shall remain undisturbed. Typically reference electrodes should, if possible, be placed a minimum of 500 mm from concrete repairs which incorporate steel.

Permanently installed reference electrodes, and other sensors that can be calibrated prior to installation, shall be calibrated.

7.3 Connections to steel in concrete

Each zone of the cathodic protection system shall be provided with multiple (a minimum of two) negative connections of cables to reinforcement/steel for the cathodic protection current and a minimum of one test connection to the reinforcement/steel for measurement of steel/concrete potentials with respect to permanent or portable electrodes.

The electrical continuity between all negative connections and test connections of each individual zone shall be tested and shall be 1,0 Ω or less. If this requirement is not initially achieved, additional reinforcement/steel exposure for testing and bonding shall be undertaken in accordance with 7.1.

NOTE Continuity between the negative connections of different zones of a cathodic protection system may be required in accordance with the particular design.

The cable connections to the reinforcement and steel shall be made by methods providing a long-term cable/reinforcement or steel resistance of less than 0,01 Ω.

7.4 Concrete repairs associated with the cathodic protection components

Any concrete repairs associated with the installation of performance monitoring system electrodes, other sensors and the connections to steel in concrete shall be undertaken using methods and materials conforming to Clause 5 and EN 1504 (all parts).

7.5 Surface preparation for anode installation

The concrete surfaces intended to receive installation of anode material, e.g. conductive coatings or activated titanium mesh within a cementitious overlay, shall be prepared so as to present, as a minimum, a clean, non-friable surface and in order that the substrate to overlay adhesion shall be as in 5.11 [(see EN 1504 (all parts)].

Cathodic protection conductive coatings generally require a minimum of preparation to leave a maximum of cement paste and minimal exposure of aggregate and should be as specified in the coating product specification and the cathodic protection system specification.

Anodes installed for the protection of steel in buried or immersed concrete may themselves be buried or immersed and may be quite remote from the structure, as in EN 12473, EN 12954, EN 12495 and EN 12474. In these applications, the concrete surface needs no surface preparation. However, the surface may require excavation for visual inspection and confirmation that there are no coatings or water-proofing membranes applied to the concrete surface which would prevent the passage of cathodic protection current to the steel in the concrete.

7.6 Anode installation

The anode system shall be installed by methods and under controlled environmental conditions which can be demonstrated by trials or past projects to enable the requisite anode performance to be achieved. The anode system shall be installed in accordance with the design method statements or specification for installation.

Particular attention shall be given to the avoidance of short-circuits between the anode system and any reinforcement steel, ancillary metallic components or reinforcement of tie wire or debris steel in the concrete for impressed current systems.

After conductive coating or cementitious overlay or embedded anode applications, the atmospheric conditions and concrete surfaces shall be maintained at temperatures and humidity or moisture levels necessary to ensure proper curing/solvent loss/water evaporation of the anode and/or overlay.

Prior to application of any overlay, surface sealant or decorative coating over the anode systems, the anode/cathode resistance and potential difference shall be measured in order to determine whether short-circuits have been established and, if so, they shall be detected and corrected before further work for impressed current systems or galvanic systems or anode zones that require isolation for monitoring purposes.

7.7 Connections to the anode system

Each zone of the impressed current cathodic protection system shall be provided with multiple positive cable/anode connections such that the failure of any one anode/cable connection shall not significantly impair the performance of the cathodic protection system in that zone.

The failure of any one anode/cable connection in a zone should not reduce the local zone anode current density by more than 10 % of the nominal anode current density at any location within the zone; anode/cable connections should be designed and located and also cable and anode volt drops should be designed to ensure such uniformity.

The anode/cable (or anode to reinforcement in galvanic anode applications) connection system shall be of a type and installed to such standards, as can be demonstrated by trials or past projects to enable the requisite anode and anode/cable connection performance to be achieved.

In each individual zone, the electrical resistance of all anode/cable connections shall be tested and compared with calculated values for the particular anode type and distribution. Data shall be assessed to determine whether additional testing or additional anode/cable connections are required.

A 100 % visual inspection shall be undertaken of the anode system, including all related cables and cable connections, prior to application of any coating or overlay.

7.8 Anode overlay, surface sealant or decorative coating application

Any requisite anode overlay, surface sealant or decorative coating shall be applied by methods and under controlled conditions which can be demonstrated by trials or part projects to enable the requisite anode and overlay, sealant or coating performance to be achieved and in accordance with the design method statements or specification for installation.

For cathodic protection systems employing anode systems as outlined in 6.2.2.2, following repair as specified in 5.10, and anode installation in accordance with 7.5, 7.6 and 7.7, a cementitious overlay shall be applied over appropriate types of installed anode. All materials and application methods shall be in accordance with EN 1504 (all parts). The average bond strength between existing concrete and overlay shall be greater than 1,5 MPa and the minimum shall be greater than 1,0 MPa, or the test failure shall be within the existing concrete. Overlay application may be combined with concrete repair (5.10).

NOTE If the substrate concrete cohesive strength fails at lower values than 1,5 MPa average and 1,0 MPa minimum, the use of cementitious overlay may be inappropriate.

7.9 Electrical installation

All electrical installation works shall be undertaken in accordance with international (or other applicable national) electrical safety standards.

NOTE 1 The electrical power supply for the cathodic protection system may be provided by transformer-rectifier(s) powered by an electrical supply from a mains voltage distribution system.

The direct current and monitoring cables of a cathodic protection system are all classified as "extra low voltage" (ELV) in accordance with IEC 61140.

In addition to the particular requirements of the cathodic protection system, the following electrical safety measures shall be applied to all installations:

a) mains voltage cables shall be electrically isolated and separated from low voltage direct current cables in accordance with local regulations;

b) cables shall be uniquely identified at the direct current power supply, at any junction box and at their point of connection;

c) cables shall be adequately supported and protected from environmental, human and animal damage;

   NOTE 2 In locations where there is high risk of damage, cables may be embedded into concrete or may be protected by steel wire armouring.

d) except for the cable connections covered in item f), cable connections shall only be made at locations in enclosures or junction boxes;

e) connections inside boxes, whose construction and/or installation renders their environmental protection rating below the worst case external environmental exposure, including boxes with non-sealed conduit entries, shall be made by methods suitable for long-term water immersion;

   NOTE 3 Connections inside water resistant or sealed boxes constructed and installed with an environmental protection rating above the worst-case external environmental exposure may utilize copper or brass threaded or proprietary connection assemblies.

f) it shall be permissible for anode/cable connections for anodes, e.g. activated titanium mesh, which are to be permanently embedded in an overlay material to be installed without junction boxes if the anode/cable connection and its method of electrical/mechanical/moisture sealing can be demonstrated by trials or past projects to enable the requisite performance to be achieved;

g) anode systems for which there is no overlay or electrical barrier to prevent direct human or animal contact, e.g. conductive coating, shall be limited to a supply voltage of 24 V DC with a maximum ripple content of 100 mV RMS;

h) equipment shall be marked with all relevant electrical safety/testing/maintenance markings in accordance with national and International Standards.

NOTE 4 The electrical characteristics required of the low voltage direct current circuits of cathodic protection systems may render full conformity to European (or national) electrical safety standards inappropriate in one respect; the normal requirement for isolation between all power circuits and the safety earth. This is due to the negative pole of the cathodic protection circuit (the steel reinforcement or embedded steel) often being electrically earthed (connected to the safety earthing or lightning protecting system), thus, preventing the normal requirement for isolation between all power circuits and earth.

7.10 Testing during installation

Testing in accordance with the quality plan (see Clause 4) shall include the following for the cathodic protection system:

a) polarity checks for all circuits (the results shall be unambiguous);

b) continuity checks for all circuits, (the results of which shall demonstrate individual circuit resistance values within ±10 % of those calculated from cable and component values);

c) insulation checks for all circuits of impressed current systems and at the monitoring areas of galvanic systems, which may have to be undertaken prior to connections to either anode or reinforcement/steel, and which shall demonstrate the electrical isolation of DC positive cables from DC negative cables.

NOTE Reference electrodes and rectifier circuits may be damaged by insulation checks. Reference electrodes may be damaged by continuity checks. The intended low resistance between anode and reinforcement/steel and between adjacent zones anode or cathode circuits renders conventional electrical circuit insulation and continuity testing inappropriate (see 7.9, Note 5).

The mains voltage electrical power supply system and the transformer-rectifier(s) providing low voltage DC to the cathodic protection system shall be tested and documented for electrical safety in accordance with international and national electrical safety standards.

8 Commissioning

8.1 Visual inspection

The cathodic protection system and all its component parts shall be subjected to a complete visual inspection (for buried or embedded elements, before backfilling or concreting, for immersed elements by diver and/or camera) confirming that all components and cables are installed properly, labelled where appropriate and protected from environmental, human or animal damage.

8.2 Pre-energizing measurements

Prior to energizing, measurements shall be made and recorded in accordance with the quality plan (see Clause 4) and shall include the following for the cathodic protection system:

a) potential of steel/concrete with respect to permanently installed reference electrodes and potential decay probes. Measurements shall be taken at low (about 10 MΩ to 20 MΩ) and high (about 500 MΩ to 1 000 MΩ) input impedance to determine whether the contact resistance of the reference electrode or sensor to the concrete will adversely affect the performance of the electrode or sensor;

   The difference in potential between low-impedance and high-impedance measurements should generally be less than 10 mV.

b) potential of steel/concrete with respect to portable reference electrodes at any location determined in the design method statements or specifications;

c) potential of steel/concrete with respect to the anode system;

d) any baseline data from additional sensors installed as part of the performance monitoring system;

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

For structures significantly affected by variable environmental factors, such as tide, temperature, surface wetting, fluctuating stray current, etc., consideration should be given to the recording of steel/concrete potential data over periods sufficient to record the effects of the variable environment; this may typically be 24 h. If significant potential changes are detected, these should be considered when determining whether all data measurements in subsequent monitoring in 8.4, 8.5, 8.7 and Clause 10 should incorporate recoding data over extended periods.

8.3 Initial energizing of impressed current systems

The system shall not be energized until the concrete of a new construction and any cementitious overlay has been adequately cured or any conductive coating has achieved adequate solvent release/cure.

NOTE For new constructions, this period normally corresponds to 28 d after placement at 20 °C (or longer at lower temperatures), for cementitious overlays this period normally corresponds to 14 d after placement at a temperature of 20 °C. For conductive coatings, this period will normally correspond to 48 h with adequate ventilation.

The cathodic protection system shall be energized initially at low current (about 10 % to 20 % of design current). Measurements shall be made and recorded in accordance with the quality plan (see Clause 4) and shall include the following:

a) the potential of the steel/concrete with respect to all permanently installed reference electrodes and with respect to portable reference electrodes at any location determined in the design method statements or specification;

b) the output voltage and current values of all direct current power supplies providing current to the cathodic protection systems;

c) confirmation that the polarity of all values conform to the quality plan and design and that the steel/concrete potentials, measured with respect to all permanently installed reference electrodes, potential decay probes and to any portable electrode locations measured, shift in a negative direction from the values measured in accordance with 8.2 a) and b). If any steel/concrete/electrode potential values shift in a positive direction, they shall be investigated to determine any requirements for additional testing and/or remedial works.

8.4 Initial adjustment of impressed current systems

The system shall be energized to a level of current estimated to enable the cathodic protection system to meet its performance objectives. See Notes 1 and 2.

NOTE 1 This may be a precalculated level of current (e.g. a particular cathode current density) or it may be based upon the response of the system when first energized (e.g. to achieve a negative potential shift of 200 mV or more measured with the current “ON”). Alternatively, the system may be polarized for a short time and then adjusted to a potential shift of approximately 50 mV measured “Instantaneous OFF”.

NOTE 2 Slow polarization at a relatively low current density may be beneficial to long-term performance.

The system shall be operated at these initial settings of current which shall be maintained prior to initial performance assessment, for a sufficient period to achieve significant polarization.

NOTE 3 The period is typically between 7 d and 28 d after initial energizetion although, if a slow polarization energizing policy (low initial current) is adopted, full polarization may require longer than 28 d.

8.5 Initial performance assessment

After the period of initial polarization (see 8.4), the initial performance assessment shall be undertaken in accordance with the quality plan. This assessment shall include the following:

a) measurement of output voltage and current supply to each zone of the cathodic protection system and the calculation therefrom of circuit resistance;

b) measurement of “Instantaneous OFF” (IR free) potentials (measured between 0,1 s and 1 s after switching the direct current circuit open) at all permanently installed reference electrodes and any other locations indicated in the quality plan a short period after switching open the direct current power supply circuit to the cathodic protection system;

After switching “OFF” for “Instantaneous OFF” (IR free) potential measurements, sufficient time shall be allowed before measurement to avoid any transient voltage arising from switching surges, capacitance or resistance effects that would affect the measured values. This waiting period shall be sufficiently short to avoid significant depolarization.

Typically, measurements of "Instantaneous OFF" are taken between 0,1 s and 0,5 s after switch "OFF", but appropriate values will vary from system to system and with the extent/period of polarization. The measurement period (for digital "counting") should be sufficiently short to avoid significant depolarization during the measurement period, but of sufficient length not to degrade the accuracy or noise rejection capability of the measurement system. While the typical measurement periods are between 0,1 s and 0,5 s, calibration and other instrumentation calculation steps may dictate a longer period than this between subsequent measurements.

c) measurement of potential decay after switching the cathodic protection direct current supply to constant open circuit. The period of potential decay and the intervals for measurements of steel/concrete/electrode potentials shall be as indicated in the quality plan;

NOTE 1 Typical periods of decay are 4 h to 25 h with measurements taken at some or all of 0,5 h, 1 h, 2 h, 3 h, 4 h, 23 h, 24 h and 25 h after switch "OFF", as appropriate, to determine the extent of potential decay and the rate of any ongoing decay at the end of the selected period.

NOTE 2 For buried (particularly those buried in wet conditions or impermeable clays) and immersed structures and for atmospherically exposed structures that incorporate a surface coating that limits oxygen availability within the concrete, potential decay may be very slow and may extend to weeks. In the extreme, oxygen availability at the steel may not be sufficient to maintain passivity of the steel/concrete interface and the potential may "rest" at a relatively negative value. In these conditions, potential decay may not be a practical protection criterion.

Potential shift (see 8.4, Note 1) may be equivalent to potential decay, but only if the initial potential ("natural" or "as found" from which the potential shift is measured) is determined immediately before energizing the cathodic protection system and if this value is not affected by stray current. Particular caution should be exercised if potential shift measurements are used as a protection criterion on buried, immersed, water saturated or coated structures as the "natural" or "as found" potential may be subject to very significant negative potential changes as oxygen is depleted within the concrete. Negative potential shifts of 200 mV to 300 mV are quite possible due to oxygen depletion without the application of cathodic protection.

d) measurement of parameters from all other sensors installed as part of the performance monitoring system;

e) measurement of "ON" steel/concrete potentials (including IR drop) if required in the quality plan.

NOTE 3 During measurement of "Instantaneous OFF" potentials, it may be necessary to switch the direct current power circuit off and on to facilitate sequential measurements of a number of steel/concrete/electrodes.

The off:on time ratio of any such switching regime used for "Instantaneous OFF" potential measurements shall be a minimum of 1:4.

NOTE 4 Typical values for manual data collection are 3 s off, 12 s on. For electronic data collection, it is advantageous to link the data logging system to the switching system, in order that measurement waiting periods and measurement periods are accurately related to the instant of switch off. Longer switching periods would slow data collection and risk depolarization during the off period.

8.6 Criteria of protection: Interpretation of performance assessment data

The data collected in accordance with 8.5 shall be reviewed and interpreted in respect of the following or such criteria as modified by the particular requirements of the structure, its environment or developing expertise in respect of criteria of protection for steel in concrete.

No instant off steel/concrete potential more negative than −1 100 mV with respect to Ag/AgCl/0,5 M KCl shall be permitted for plain reinforcing steel or −900 mV for prestressing steel.

NOTE 1 Prestressing steel may be sensitive to hydrogen embrittlement and, due to the high tensile loading, failure can be catastrophic. It is essential that caution is exercised in any application of cathodic protection to prestressed elements. For galvanic systems using zinc anodes, the degree of excessive polarization is naturally limited and this should normally be sufficient to keep the steel/concrete potential below the potential limit of −900 mV vs. Ag/AgCl/0,5 M KCl.

For any structure, any representative steel in concrete location shall meet any one of the criteria given in items a) to c):

a) an "Instantaneous OFF" potential more negative than −720 mV with respect to Ag/AgCl/0,5 M KCl;

b) a potential decay over a maximum of 24 h of at least 100 mV from "Instantaneous OFF";

c) a potential decay over an extended period (typically 24 h or longer) of at least 150 mV from the instant off subject to a continuing decay and the use of reference electrodes (not potential decay probes) for the measurement extended beyond 24 h.

NOTE 2 It is not necessary to meet more than one item of a), b) or c).

NOTE 3 In systems where activated titanium anodes are used, the steel/concrete potential limit (−1 100 mV or −900 mV), as above, may be verified by measurement of the anode/concrete potential and the transformer-rectifier output voltage, taking account of cable volt drop values.

NOTE 4 Criteria, a), b) and c) are not necessarily supported by theoretical considerations, but are a non-exhaustive, practical series of criteria to indicate adequate polarization which will lead to the maintenance or re-establishment of protective conditions for the steel within the concrete.

NOTE 5 As an investigative criterion it may be considered appropriate to seek a steel/concrete potential in a fully depolarized structure after the cathodic protection system has been switched off for a long period (typically 7 d or longer) less negative than −150 mV with respect to Ag/AgCl/0,5 M KCl.

NOTE 6 These criteria, as discussed in items a), b) and c), can be disrupted by the presence of concrete repairs encompassing reinforcement or other steel within 0,5 m of the point of measurement of potential. This should be avoided by locating reference electrodes and other sensors away from concrete repairs wherever possible.

NOTE 7 The criteria given in items b) and c) may be invalidated by variations in temperature, and moisture content. Such variations, themselves, can be the cause of significant changes in steel/concrete potentials.

NOTE 8 For structures, such as buried, immersed or coated structures, where oxygen availability within the concrete is limited, the criteria given in items b) and c) may not be practical due to the very slow rate of depolarization, as detailed in 8.5, Note 2. Similarly, as detailed in the paragraph below Note 2 in 8.5, potential shift measurement may not be equivalent to potential decay over a limited time period and changes in the "natural" or "as found" due to oxygen depletion can lead to serious errors in assessment of potential shift.

If the interpretation of the performance assessment data in accordance with 8.6 indicates that criteria for protection are achieved, no further measures are necessary. If they are not achieved with galvanic anode systems where it is not possible to increase current to the steel, then a further assessment of corrosion risk shall be made. If a corrosion risk is identified, then steps shall be taken to increase the protection current, by supplementing the galvanic anode system, to minimize this risk.

NOTE 9 In atmospherically exposed concrete (when the corrosion process is not limited by the rate at which oxygen in the air reaches the steel), the steel corrosion rate may be estimated by inserting the applied current density and steel potential shift into the Butler Volmer formula. The applied current density may be obtained from the current delivered from a small segment of the anode system and an estimate of the steel potential shift is given by the steel potential decay measured at the same anode segment. See Reference [16].

NOTE 10 Passive steel is indicated by a corrosion rate of less than 2 mA/m^2 and preferably less than 1 mA/m^2. A falling trend in corrosion rate combined with a rising trend in corrosion potential is also a sign that protection is being achieved.

NOTE 11 Actions to take if a corrosion risk is identified include turning the galvanic system into an impressed current system (if this is possible), installing more galvanic anodes or applying a temporary electrochemical treatment (using the galvanic anodes, if possible) and a temporary power supply. The options available will depend on the galvanic anode system used.

8.7 Adjustment of protection current for impressed current systems

If the interpretation of the performance assessment data in accordance with 8.6 indicates that the criteria of protection are achieved, no immediate measures are necessary, subject to the requirements of Clause 10. If the criteria of protection are not achieved or are judged to be at risk of not being achieved in the future, further adjustments of the current output shall be made, to be followed, a minimum of 28 d thereafter, by repeated performance assessments, as specified in 8.5 and 8.6.

NOTE It is emphasized that long-term polarization arising from long-term cathodic protection will result in a reduction in the requirement for current and a reduction in the rate of potential decay occurring when switching off the system.

9 System records and documentation

9.1 Quality and test records

The quality plan, the quality documents arising therefrom, the visual inspection and the test results shall all form part of the permanent records of the installation of the system.

9.2 Installation and commissioning report

An installation and commissioning report for the cathodic protection system shall be prepared and shall incorporate, as a minimum, the following:

a) a general description of the works, the parties associated with the works [e.g. client, design engineer, supervising engineer, contractor, subcontractor(s)] and the key personnel responsible for the design, supervision and commissioning of the cathodic protection system and their respective responsibilities;

b) a copy of the method statements and/or specification and drawings in accordance with which the system was installed and commissioned indicating all deviations or variations therefrom and a copy of the design data calculations [see 4.3 a)] if available;

c) a detailed description of the installation and commissioning works including key dates;

d) as-built drawings detailing the installation and its components in sufficient detail to facilitate all future requirements for inspection, maintenance, and reconstruction of the system and its major components;

e) all measurements/test data taken before and while the system was energized and during the initial system performance assessment, together with the performance assessment data used and the interpretation of the data;

f) a record of the “as-left” operating conditions of the system;

g) a copy of the permanent records (specified in 9.1);

h) recommendations for any revisions to the cathodic protection system.

NOTE Other documents may also be included as considered necessary.

9.3 Operation and maintenance manual

An operation and maintenance manual for the cathodic protection system shall be prepared and shall incorporate, as a minimum, the following:

a) a detailed description of the system and a set of the “as-built” drawings;

b) details of recommended routine maintenance and inspection intervals and procedures (see Clause 10);

c) recommended intervals and procedures for future performance assessments and the interpretation of the data therefrom;

d) proformas or computer data formats for all recommended routine maintenance, inspection and performance assessment activities;

e) error finding procedures for errors within the cathodic protection electrical power supply (alternating current and direct current), and for short-circuits and open circuits in the cathodic protection system;

f) maintenance/repair procedures for the electrical power supply equipment, any data logging/control equipment and the anode system with any overlay, sealant or decorative coating;

g) a list of the major components of the cathodic protection system with data sheets and the source(s) of spare parts and/or maintenance for these components and for the overall system;

h) all information, passwords and protocols required for the long-term connection to and operation of any monitoring and control system.

NOTE Other information may also be included as considered necessary.

10 Operation and maintenance

10.1 Intervals and procedures

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

NOTE 1 The intervals and procedures for routine inspection and testing vary from one cathodic protection system to another, dependant upon the structure type, the cathodic protection system type, the reliability of power supplies (impressed current systems), the reliability of the galvanic anode in that environment and the vulnerability to accidental or deliberate mechanical or electrical damage.

Those systems provided with electronically data logged or electronically data transmitted performance monitoring systems may require less frequent physical inspection, as routine testing can be undertaken automatically.

It can be considered to extend the intervals between routine inspection and testing if no errors, damage or significant variation in system performance are indicated by successive inspections/tests.

NOTE 2 Long periods of satisfactory operation result in significant polarization and repassivation of the steel in concrete.

Routine inspection procedures shall be as follows:

a) **Function check: To comprise the following:**

   1) confirmation that all systems are functioning;

   2) measurement of output voltage and current to each zone of the impressed current cathodic protection system;

3) assessment of data;

b) **Performance assessment: To comprise the following:**

1) measurement of "Instantaneous OFF" polarized potentials;

2) measurement of potential decay;

3) measurement of parameters from any other sensors installed as part of the performance monitoring system;

4) a full visual inspection of the cathodic protection system;

5) assessment of data;

6) adjustment of current or voltage output for impressed current systems.

All inspections and testing shall be in accordance with Clause 8.

Typically, the function check shall be undertaken monthly in the first year of operation and, subject to satisfactory performance, thereafter at 3 mo intervals. Typically, the performance assessment shall be undertaken at 3 mo intervals in the first year of operation and, subject to satisfactory performance and review at 6 mo to 12 mo intervals thereafter. After the first year, the visual inspection may be deleted from the performance assessment but should remain in the system review (see 10.2).

At concrete temperatures below 0 °C, potential monitoring may be impossible. The dates for performance monitoring should be selected to avoid measurements at such cold weather.

10.2 System review

The inspection and testing works shall comprise the following at maximum intervals of 12 months:

a) a review of all test data and inspection records since the previous review;

b) performance assessment in accordance with 10.1 b);

c) visual inspection of the cathodic protection system;

d) a review and interpretation of the data generally in accordance with Clause 8;

e) adjustment of the current output if necessary in accordance with Clause 8;

f) preparation of a system review report in accordance with 10.3.

10.3 System review report

The report shall detail the following:

a) the work undertaken;

b) the data collected;

c) data interpretation and recommendations for any changes to the operation and maintenance or system review intervals and procedures;

d) recommendations for any changes to the cathodic protection system.

Annex A
(informative)

Principles of cathodic protection and its application to steel in concrete

A.1 General

Steel in concrete is usually protected against corrosion by passivation of the steel arising from the high alkalinity of the pore solutions within the concrete. A stable oxide layer is formed on the steel surface which prevents the anodic dissolution of iron. The necessity for additional protective measures arises if this stable oxide layer is rendered unstable (if depassivation occurs) due to the ingress of chlorides to the steel/concrete interface or carbonation of the concrete reducing the alkalinity of the pore solution at the steel/concrete interface.

In the case of chloride contamination of concrete, the chloride ions initiate depassivation which leads to corrosion if there is access of oxygen to the remaining passive areas. Depassivation and, hence, corrosion can be obtained by the establishment of a specific steel/concrete potential, the pitting potential E_{pit}. At potentials more positive than E_{pit}, a sharp increase in the iron dissolution rate leads to high corrosion rates in small localized areas of the steel surface whereas, at lower potentials than E_{pit} (i.e. more negative), the corrosion rate decreases. The objective of cathodic protection is to shift the steel/concrete potential into a region where

a) the initiation of corrosion, or

b) if corrosion has already started, the continuation/propagation of corrosion; is so far suppressed that a corrosion failure is unlikely during the lifetime of the structure.

In the case of reinforced concrete, a corrosion failure can include cracking and delamination of the covering concrete which may arise from as little as 50 µm of metal loss from an area of reinforcement or other embedded steel, due to the bursting stresses generated by high-volume corrosion products.

In steel-reinforced concrete structures, cathodic protection can be achieved by polarizing the reinforcement/steel with an “external” current. For this purpose, anodes are surface mounted, painted on to or embedded in the concrete and connected to the positive pole of a direct current power supply in the case of impressed current protection. Alternatively, anodes of zinc or Al-Zn-In are applied to the concrete and connected directly to the reinforcement.

The system cathode is formed by the steel reinforcement/steel. In the case of impressed current, the negative pole of the direct current power supply is connected to the embedded steel/reinforcement. In the case of galvanic anode cathodic protection, the galvanic anode (typically zinc) is connected directly to the reinforcement/steel.

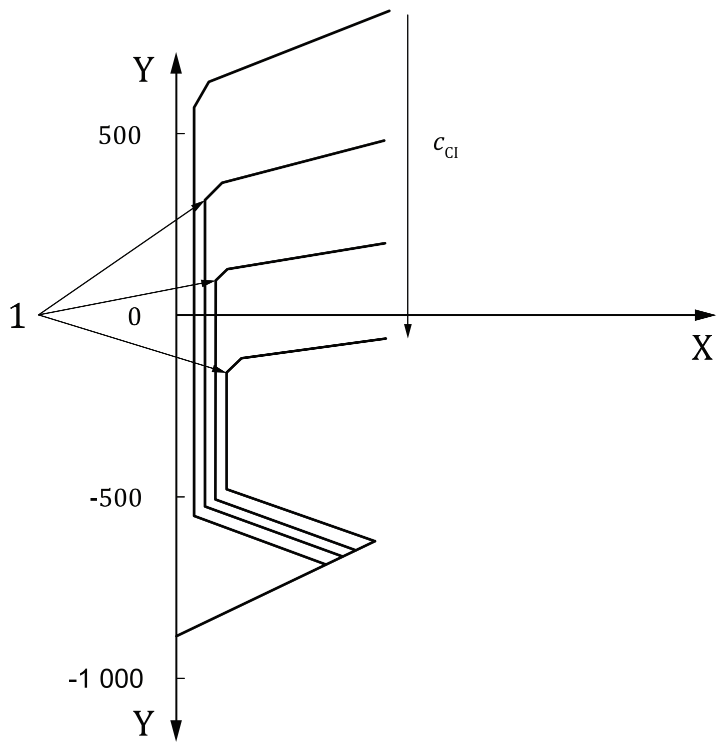
The concrete, in particular the pore solution, provides the electrolyte to allow current flow and the associated ionic movement. The change of steel/concrete potential is indicated by electrodes which are embedded in the concrete or placed on the surface of the concrete and used, in conjunction with suitable instrumentation and connections to the reinforcement/steel, to measure steel/concrete/electrode potentials.

A.2 Criteria for protection

If environmental conditions which favour the occurrence of corrosion of the reinforcement/steel are likely to occur during the lifetime of the structure, or occur during service, cathodic protection is one method of preventing corrosion of steel in concrete. Sufficient corrosion protection is given if specific criteria of protection are met at representative points on the structure. The criteria of protection in this document are based on electrochemical considerations regarding corrosion processes and on practical experience. In practice, two cases are distinguishable. If the aim of cathodic protection is improvement of the corrosion resistance of steel in reinforced and prestressed concrete structures that are expected to become contaminated by chlorides during their service life, a small cathodic polarization of the steel/concrete interface should be applied early on in the service life. This polarization should maintain the steel/concrete potential lower than (more negative than) E_{pit} to prevent the initiation of corrosion. The negative polarization achieved also limits or prevents migration of the chloride ions to the steel, thereby, preventing them from depassivating the steel if the cathodic protection anode system is on the surface through which the contamination will arise. This cathodic protection measure is sometimes called "cathodic prevention" and applies to new structures or structures in service where the chloride ions have not reached the steel and depassivation has not yet occurred.

In older structures with corroding steel, cathodic protection is part of the rehabilitation concept and is aimed to decrease the corrosion rate of the steel from significant to negligible values. For this purpose, the steel/concrete potential should be lowered (made more negative) to values in the range of the protection potential E_{prot}. The corrosion potential E_{corr} and the protection potential E_{prot} are dependent upon environmental conditions (chloride content, pH at local anodic sites, temperature, oxygen content, humidity). Based on the complex interaction of these factors and also practical experience, the definition of one precise protection potential is impossible and also unnecessary for cathodic protection of steel in concrete. It is this complex interaction of factors that dictates that a range of criteria are properly required for cathodic protection of steel in concrete, as is reflected in 8.6.

Figures A.1 to A.3 illustrate these factors.



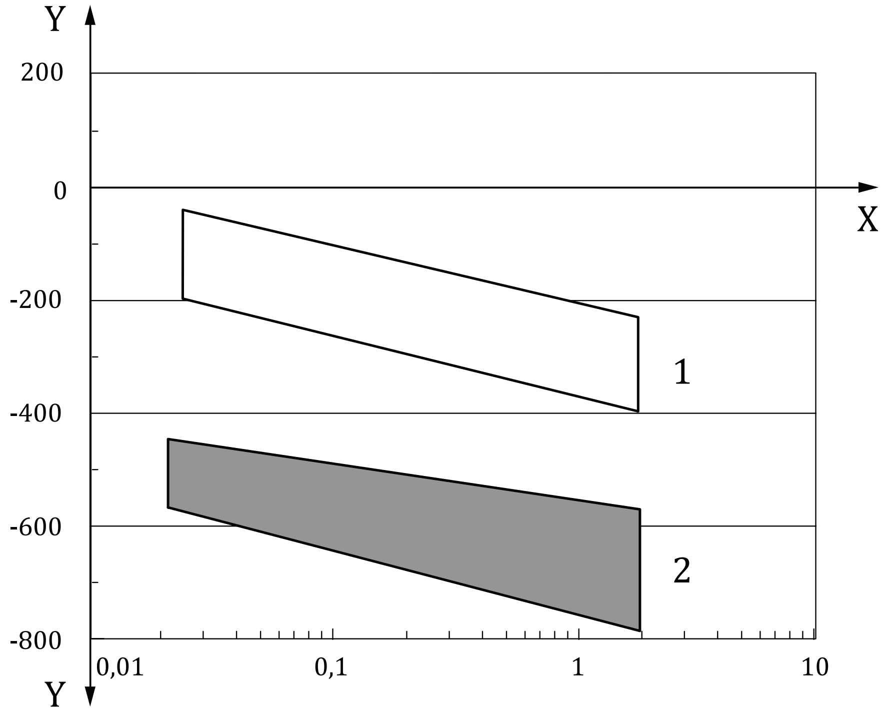
Key

X log *i* (*i* is the electric current)

Y $E_{Ag/AgCl/0,5\ M\ KCl}$ [mV]

1 E_{pit}

Figure A.1 — Schematic illustration of the anodic behaviour of steel in the presence of chloride



Key

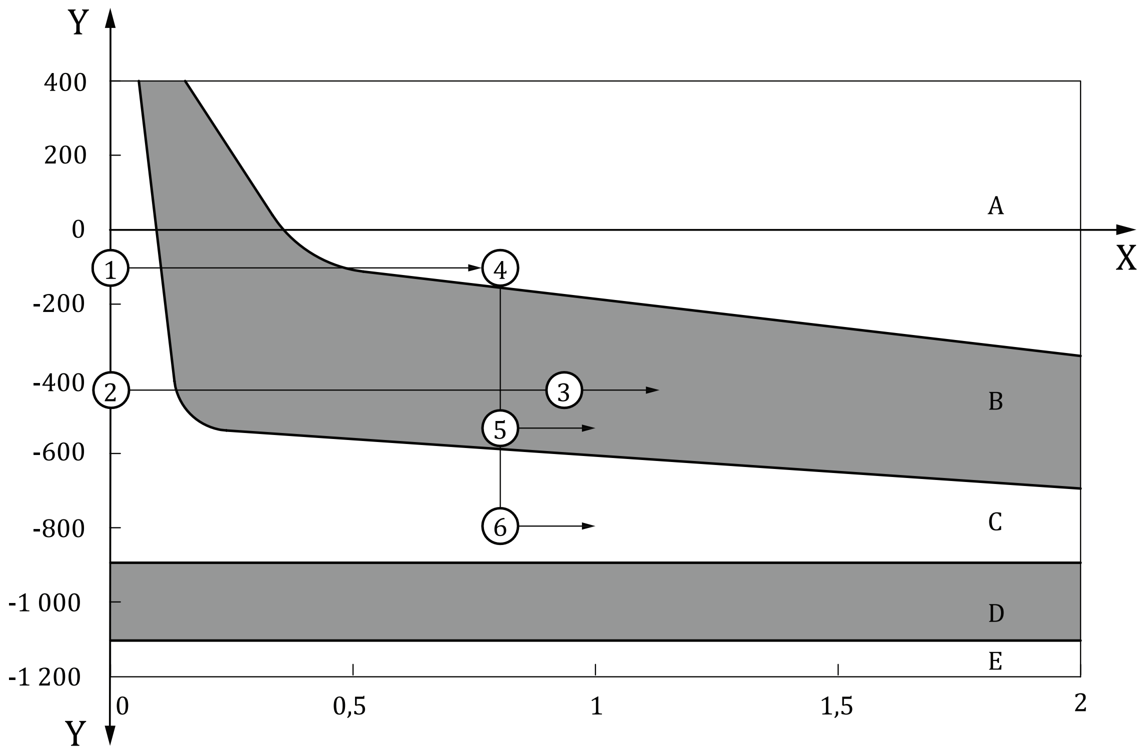
X c_{Cl} [mol/l] (concentration of chlorine)

Y $E_{Ag/AgCl/0,5\ M\ KCl}$ [mV]

1 E_{pit}

2 E_{prot}

Figure A.2 — Values of E_{pit} and E_{prot} measured on steels buried in sand, covered with saturated $Ca(OH)_2$ solution (pH = 12,6) at 20 °C, after Pedeferri[17]



Key

X w_{Cl} (cement) [%]

Y $E_{Ag/AgCl/0,5\ M\ KCl}$ [mV]

NOTE 1 Schematic illustration of evaluation paths of potential and chloride content on steel/reinforcement surface during service life for

— area A: Pitting initiates and propagates;

— area B: Pitting does not initiate but propagates;

— area C: Pitting does not initiate and propagates;

— area D: Hydrogen embrittlement risk to high-strength steels;

— area E: Reduction of steel/concrete bond;

— cathodic prevention (1 → 2 → 3);

— cathodic protection restoring passivity (1 → 4 → 6);

— cathodic protection reducing corrosion rate (1 → 4 → 5).

NOTE 2 Cathodic prevention is applied from the beginning at 1, Cathodic protection only after corrosion has initiated at 4.

Figure A.3 — Pitting potential vs. chloride content in percentage by mass of cement, after Pedeferri[17]

A.3 Current density required for “cathodic prevention” and “cathodic protection”

“Cathodic prevention” current density is approximately one order of magnitude lower than that required for cathodic protection. This is not only because the steel/concrete potentials required for cathodic prevention are less negative than those required for cathodic protection, but also because passive steel is more easily polarized.

Typical cathodic prevention current densities range between 0,2 mA/m^2 and 2 mA/m^2 compared with 2 mA/m^2 to 20 mA/m^2 for cathodic protection on existing corroded structures with uncoated steel. For organic-coated steel, these current densities are reduced further as determined by the coating conductance and the extent of any coating damage. Coating deterioration may continue.

A.4 Cathodic protection for steel in buried or immersed concrete structures

Cathodic protection for steel in buried or immersed concrete follows the same basic principles as for atmospherically exposed concrete described in A.3. The principle difference is that the concrete is likely to become water saturated, which will result in reduction in oxygen content at the steel surface under normal exposure conditions, which will be accelerated under the application of cathodic protection. Where oxygen depletion occurs, the potential will become very negative and the current required for cathodic protection will be reduced.

Hence, the current density required for steel in concrete that is buried or immersed for protection may be, if the concrete is fully water saturated, considerably less than that required for atmospherically exposed concrete. Typical current densities range from 0,2 mA/m^2 to 2,0 mA/m^2 for new structures (before corrosion initiation) in water saturated conditions. For structures that are not fully water saturated and are corroding before the application of cathodic protection, current densities may be as high as those for atmospherically exposed concrete, up to 20 mA/m^2.

The current density is also dependent on whether the concrete is fully immersed or whether one face is exposed to air (e.g. as for tunnels, portions of diaphragm walls, underground storage tanks and where the thickness of the concrete structure is typically less than 0,5 m to 1 m). If this is the case, then a differential concentration (differential oxygen) cell can be created between the fully immersed face and the air exposed face. Where such conditions occur, a higher current density will be required on the immersed portion.

A.5 Prestressing steel and the risk of hydrogen embrittlement

Due to the possible occurrence of hydrogen embrittlement, high-strength steels of the quenched and tempered type should not be exposed to a potential more negative than −900 mV vs Ag/AgCl/0,5 M KCl. Prestressing steel may be sensitive to hydrogen embrittlement and, due to the high tensile loading of prestressing members, failure can be catastrophic. It is essential that caution is exercised in any application of cathodic protection to prestressed elements.

For impressed current systems, high current densities can be provided if the system is incorrectly designed and/or operated and steps should be taken to minimize the risk of excessive polarization to vulnerable steels. For galvanic systems using zinc or aluminium-zinc-indium anodes, the degree of polarization is naturally limited and this normally should be sufficient to keep the steel/concrete potential below the potential limit of −900 mV vs Ag/AgCl/0,5 M KCl. The safe potential limit for pre-corroded prestressing members may be less negative than −900 mV and in applications of cathodic protection involving possibly or known pre-corroded prestressing members, using either impressed current or galvanic anode systems, the safe potential limit should be determined by laboratory testing or other means. See Reference [18].

A.6 Alkali silica reaction

Cathodic protection applied in accordance with this document has been demonstrated to have no influence on alkali silica reaction/alkali aggregate reaction (ASR/AAR).

A.7 Reference electrodes

The MnO_2 reference electrode is a half cell consisting of a compacted mass of MnO_2 in a buffered NaOH solution with a pH of about 13,5 corresponding to normal pore water and, therefore, in chemical balance with the surrounding concrete. The MnO_2 electrode, also known from batteries, has a potential, which is a linear function of pH in the alkaline range. The potential is determined by the MnO_2/MnO_3 equilibrium, manganese metal is not involved. As a naturally occurring mineral, MnO_2 should be expected to be highly stable and this is proved by the long shelf life of alkaline batteries. The diffusion barrier of the MnO_2 reference electrode is a plug of cement paste and this ensures a good bond to the surrounding concrete and also eliminates junction potentials that would be developed.

See Table A.1.

Table A.1 — $AgCl(s) + e^- = >Ag(s) + Cl^-$

Electrode	Potential at 25 °C		Liquid junction	Literature sources
	V vs. NHE	V vs. SCE		
Ag/AgCl, KCl (0,1 M)	0,2881	0,047		Reference [24]
Ag/AgCl, KCl (3 M)	0,210	−0,032		Reference [20]
Ag/AgCl, KCl (3,5 M)	0,205	−0,039	LJ	Reference [22]
Ag/AgCl, KCl (saturated)	0,197	−0,045		Reference [23]
	0,199	−0,045	LJ	Reference [22]
	0,1988	−0,042		Reference [22]
Ag/AgCl, NaCl (3 M)	0,209	−0,035	LJ	Reference [25]
Ag/AgCl, NaCl (saturated)	0,197	−0,047	LJ	Reference [24]
Ag/AgCl, Seawater	0,25	0,01		Reference [26]
MnO_2, NaOH (0,5 M)	0,434	0,190		Reference [21]

Annex B
(informative)

Design process

B.1 Conceptual design

Following feasibility assessment and confirmation of cathodic protection as the optimum protection option for a new structure or the optimum repair option for an existing structure, perform preliminary location and sizing of anode zones, based on factors including, but not limited to

— exposure classifications (buried, immersed, tidal, splash, atmospheric, sheltered, exposed, etc.),

— concrete chloride content,

— concrete resistivity,

— concrete moisture content,

— reinforcement/steel surface area,

— distribution and estimated current demand,

— lifetime requirements,

— service environment,

— weight, or

— installation sequence and constraints.

Give preliminary consideration to anode type, cable routing and possible transformer-rectifier location(s).

B.2 Anode system type and rating

Calculate detailed reinforcement and all additional steel surface areas for all parts of the structure. For zones that are intended to be protected using anodes embedded in the concrete or applied to the concrete surface (typically all atmospherically exposed structures), it is necessary for the local anode current provision to be matched to the local cathode current demand, therefore, calculations are typically made to a detail that determines the steel surface area in each square metre of the structure to enable the appropriate anode system and rating to be applied in each part of the structure. For buried and immersed applications with more remote anodes, subject to the normal design process for the adequate distribution of current to the overall structure, as in EN 12473, EN 12954, EN 12495 and EN 12474, current distribution from the remote anodes to the steel will be able to provide variations in current provision to match the local cathode current demand so there is a lesser need to calculate the local steel reinforcement surface areas with such discrimination.

Using the reinforcement and other steel surface area and distribution and assumed or measured cathodic current density for the desired level of protection, calculate the cathodic current requirements and then the operating anodic current density on each anode. Use this value to confirm the anode type, taking into account the factors given in B.1 to select the overlay material, where appropriate.

B.3 Cathodic protection zones

Plan the anode zone size and layout and calculate the feeder spacing to ensure that local cathode current density requirements are met and to minimize the voltage and anode current density differentials within zones due to anode and cable resistances. Select the primary anode material and cross-section, its distribution and primary anode/“positive cable” connections to provide the required redundancy and to minimize voltage drops.

Different exposure conditions may dictate the use of different zones in the cathodic protection system of a single structure, for example, a hollow, floating reinforced concrete structure may be separated into the immersed zone utilizing immersed anodes in sea water, as detailed in EN 12473 and EN 12495, with the tidal zone protected by a combination of current from the immersed anodes and anodes embedded in the concrete, as detailed in this document, with the splash zone protected by embedded or surface-mounted anodes, as detailed in this document, and the atmospheric zone similarly protected by similar or different embedded or surface-mounted anodes, as detailed in this document.

Different elements of structures may require being combined into single zones: Typical zones for impressed current systems will have current ratings of 0,5 A to 2 A or possibly as high as 5 A if the steel/reinforcement distribution within the zone is uniform. With some anode systems, e.g. mixed metal-oxide-coated titanium (MMO/Ti), it is possible to vary the distribution and grade of anode within a zone in order to match the calculated local current demand and provide uniform cathode (steel) current density within a single complex zone for cathodic protection systems on atmospherically exposed structures or where a distributed anode is required to cope with a high electrolyte resistivity.

Each zone of an impressed current system should be adequately monitored with permanent reference electrodes. There should be typically a minimum of two reference electrodes per zone or one per 100 m^2, whichever is greater. Their locations should be selected to be representative of the entire zone but also to monitor locations where steel density, chloride contamination, environmental exposure or other factors may represent an area of greater risk of corrosion or greater difficulty of protection.

Negative connections to the steel should be similarly typically two per zone minimum or one per 200 m^2, whichever is the greater.

Test connections to the steel should be like the steel negative connections or dedicated one per reference electrode and connected to steel close to the electrode (but not in concrete repairs within 0,5 m of the electrode).

Where potential decay probes are used, similar quantities and location considerations should be used as in respect of reference electrodes.

B.4 Current provision

Using the operating current demand and reserve capacity required, calculate the total current provision.

Typical current demands are 2 mA/m^2 to 20 mA/m^2 (of steel) for steel in chloride contaminated concrete (for cathodic protection) and 0,2 mA/m^2 to 2 mA/m^2 for passive steel in non-chloride contaminated concrete (for cathodic prevention). Current density demand will be higher with higher chloride content, higher humidity and at higher temperatures. For temperate climates with limited chloride contamination, most applications to existing corroding structures will be commissioned at current densities <10 mA/m^2.

Due to polarization (chemical changes at and around the steel/concrete interface), the current demand for cathodic protection will decline with time.

The reinforcement/steel closest to the anode, will receive a higher cathode current density than steel more remote from the anode. In the “typical current demands”, the values given are average values for all the steel in a typical structure. If the design current is (say) 20 mA/m^2 and it is to be delivered to the steel from an anode system embedded in the cover concrete, and if the structure is a wall with two principle layers of reinforcement each comprising vertical and horizontal bars, it is likely that the current density delivered from the anode to the nearest principle layer of steel will be in the range 25 mA/m^2 to 30 mA/m^2 and only some 10 mA/m^2 to 15 mA/m^2 to the furthest principle layer (see Reference [19]). The design should reflect this shielding effect of one layer of reinforcement by another and ensure that all steel receives the current density determined to be necessary for its adequate cathodic protection/cathodic prevention.

B.5 Design issues for buried/immersed concrete structures

When designing cathodic protection for steel in buried/immersed concrete structures, the cathodic protection system type (impressed current or galvanic) should be selected based on considerations of local conditions, current demand, installation and maintenance requirements.

Where anodes/anode groundbeds are located close to the concrete structure, the location and distribution should consider current distribution, ensuring that no areas are subject to excessive current pick up or are shielded to an extent that insufficient current is provided.

The design should ensure that any anode cable is fully supported/protected (by use of conduit or steel armour), suitable for the exposure conditions (direct burial/immersion) and capable of carrying the maximum design current (plus a contingency) with an acceptable level of voltage drop.

Where anodes are fixed directly to the structure weight loading, other structural requirements shall be taken into account.

B.6 Reinforcement connections

Design the connection to the reinforcement or other embedded steel, both for current circuits and for monitoring circuits, and calculate the number and location of connections to provide required redundancy and to minimize voltage drops. Refer to B.5.

B.7 Cabling

Determine the cross-sectional areas and routes for positive and negative cabling for impressed current systems to provide redundancy and to minimize voltage differences, similarly, determine the locations of any junction boxes. Determine the appropriate insulation and sheath materials for the long-term environment.

B.8 Transformer-rectifier/direct current power supply for impressed current systems

Based on operating current and reserve capacity, use circuit resistance to calculate transformer-rectifier output voltage; also determine ancillary transformer-rectifier facilities required for monitoring etc. and to provide direct current supply requirements.

B.9 Monitoring

Determine the type, frequency and positions of sensors and the appropriate instrumentation for the level of monitoring and control required; also determine the data management requirements.

B.10 Documentation

Document the design, specification of materials/components, the installation procedures and layout of the system, along with the quality plan detailing the testing required at various stages of the work and the commissioning procedure. It is important that the design documentation is sufficient to demonstrate the adequacy of the design, that it has been undertaken with sufficient detail to demonstrate adequate current provision and monitoring provision to all parts of the structure requiring cathodic protection/cathodic prevention and that it has been properly checked for accuracy.

Annex C
(informative)

Notes on anode systems

C.1 Conductive coatings for atmospherically exposed concrete

C.1.1 Organic coatings

The coating may be suitable for application by brush, roller or airless spray. Organic coatings have been widely used in North America and Europe for the cathodic protection of steel in atmospherically exposed concrete, in applications to highway structures, buildings and car parks.

Conductive coatings generally operate at a current density of up to 20 mA/m^2 although for short periods (i.e. weeks) current densities of up to 30 mA/m^2 may be sustained without significant damage to the coating or its interface with the concrete. Conductive coatings vary in performance but have a range of anticipated lifetime of 5 years to 15 years if properly applied. They are susceptible to environmental factors and do not withstand continuous wetting. They are not suitable for marine applications unless well above the splash and spray zone and are unlikely to perform well in areas of permanent condensation. They do not withstand wear or abrasion. They may be protected or planned regular recoating may be appropriate in environments where they are subjected to wear or abrasion.

As the coating and its interface with the concrete ages, small defects appear. Isolated defects of typically smaller than 100 mm × 100 mm per m^2 do not affect performance but deterioration may accelerate.

No defects other than pinholes should be observed after installation. Localized defects may rapidly occur after energizing due to local high current density requirements. These can be repaired within a few months of initial energizing and, due to progressive polarization and reduction in localized current demand, these repair areas may perform adequately for the remaining life of the system.

Organic conductive coatings are normally applied to a dry film thickness in the range 0,25 mm to 0,5 mm. The carbon conductor in the coating is consumed by the anodic reaction, but the amount of carbon available should be well in excess of both that required for conduction and the theoretical amounts required for the full lifetime. The normal failure mechanisms are: loss of adhesion and flaking of the coating due to anodic reaction products (acidic) attacking the concrete, or local wetting leading to disbondment.

C.1.2 Metallic coatings

Conductive coatings of thermally sprayed zinc applied by arc or flame spraying may be used as anodes for cathodic protection of steel in atmospherically exposed concrete. Thermally sprayed zinc with a fitting topcoating system has been successfully used as a sacrificial (galvanic) anode. A proprietary aluminium zinc indium alloy is widely used as a galvanic anode. Titanium subsequently activated with a strong oxidizing agent has been used as an impressed current anode in trials. Thermal sprayed zinc anodes are widely used for the protection of steel in atmospherically exposed concrete in North America.

Multiple connectors are used with typically one per 10 m^2.

There is an optimum thickness for metallic zinc applied to concrete which for arc spraying is in the range from 0,10 mm to 0,4 mm. Thicknesses below the optimum thickness result in short life and/or resistive coatings. Applications above the optimum thickness result in poor adhesion to the concrete.

C.2 Activated titanium

Activated titanium anodes, coated with mixed metal oxides, for use embedded into new concrete structures or applied to existing structures. Applications include anodes within overlays, cast into slots or drilled holes or fixed to the surface under GRP casings. In the appropriate form, these anodes can be embedded in new concrete that is then buried or immersed, as well as the more common applications to atmospherically exposed concrete. The life of the coating is determined by its composition and the amount of coating deposited on the substrate, the “coating loading”. Coatings were proprietary and patent protected, but there are now many producers of these “MMO/Ti” anodes.

Test procedures are available for this anode type which enable accelerated testing to demonstrate that the anode life is equivalent to the design life at the maximum design anode current density plus any safety margin determined necessary by the design in respect of possible non-uniform distribution of current.[12]

For all forms of anode of this type, a minimum anode/reinforcement or other steel distance of 15 mm should be maintained.

The titanium substrate may be in the form of an expanded mesh, a strip (solid or expanded), wire, tube, etc., as required by the design and the magnitude and distribution of current. The coatings are proprietary, wholly or in part protected by patents and frequently their composition is not disclosed.

Activated titanium anodes may be operated at current densities of up to 400 mA/m^2 of anode surface area for short periods; the limiting factor is acid attack of the surrounding concrete. Generally, the anode current density is limited by design to a long-term maximum of 110 mA/m^2 but current densities of up to 220 mA/m^2 may be permitted. Dependent upon electrocatalytic coating loading and composition, the calculated life of the anode is in the range 25 years to 100 years. Anode lifetime should be determined considering a non-uniform current distribution.

Surface-mounted activated titanium mesh and grid anodes require cementitious overlays and the surface preparation, pretreatment, design and application of the cementitious overlay is critical to the total performance of the system (see Clauses 6 and 7). Some failures have occurred due to disbondment of the overlay; these failures are generally accepted to be attributable to deficiencies in substrate surface preparation, pretreatment and/or application procedures not related to cathodic protection.

Activated titanium (MMO/Ti) tubular discrete anodes have been used relatively extensively to protect steel in atmospherically exposed concrete, directly cast into mortar in drilled holes. These applications have been designed for operation at anode/mortar current densities of up to 800 mA/m^2, but are unlikely to operate continuously at that level.

MMO/Ti and previously platinized titanium (Pt/Ti) have also been used in discrete anodes as the primary anode/conductor to a graphite paste backfill around the primary anode, filling the holes drilled into the concrete for the anode installation. These applications have operated at carbon paste/concrete current densities of up to 800 mA/m^2.

Uncoated titanium conductor strips used to connect activated titanium anodes and also various discrete anodes may be at risk of corroding by pitting in chloride environments if operated at in excess of approximately 8 V metal/electrolyte potential.

C.3 Other anode systems for atmospherically exposed concrete

C.3.1 Conductive asphalt overlays

This system has a track record of successful long-time use of conductive asphalt overlays in North America, since the late 1970s specifications can be obtained from the Ontario Ministry of Transportation. The system has not been promoted commercially, has not been used extensively outside North America and has not been used since the late 1990s.

C.3.2 Conductive cementitious materials

Conductive cementitious anodes have been containing either granular carbon (in non-proprietary trials) and (in a commercially available proprietary system) carbon fibres with a metallic coating as the conductive medium.

The proprietary system is conductive mortar overlay containing nickel-coated carbon fibres. The system is spray applied to the prepared concrete surface. A protective or cosmetic coating or overlay may also be applied. Conductive mortar overlays generally operate at a current density of up to 20 mA/m^2 although for short periods (i.e. weeks) current densities of up to 30 mA/m^2 may be sustained without significant damage to the conductive mortar or its interface with the concrete.

C.3.3 Conductive ceramic

A conductive titanium oxide ceramic in the form of tubes of varying lengths and diameters is offered as a proprietary probe anode for embedding in holes in the concrete in a cementitious backfill. See C.2.

C.4 Galvanic anodes

C.4.1 Anode for embedding in repairs

A proprietary galvanic anode has been developed to minimize the incipient anode (or ring anode) effect when undertaking concrete repairs in chloride contaminated structures. This is caused by the fact that when an anode develops on reinforcing steel in concrete, particularly due to chloride attack, it provides "natural" cathodic protection to the adjacent steel. When cracking and spalling of the concrete occurs, the anode is repaired and then becomes a cathode. This allows the previously "naturally cathodically protected" adjacent areas to start corroding.

C.4.2 Thermal sprayed metals

See C.1.2.

C.4.3 Adhesive zinc sheet

This consists of rolls of zinc foil typically 0,25 mm thick coated on one side with a proprietary ionic conductive adhesive gel (hydrogel). The anode is applied to a prepared surface and sealed at the edges once applied. It can be coated for protective and decorative purposes.

C.4.4 Zinc mesh within jackets

This consists of an expanded zinc mesh in a permanent glass-reinforced form grouted to concrete piers, piles or columns. It is generally applied in marine exposure conditions.

C.4.5 Discrete anodes

These are similar to the anodes in C.4.1 but are installed in holes cored or otherwise cut in the concrete and wired together.

One proprietary form is a hybrid anode which can be initially energized as an impressed current anode and then left directly connected to the steel as a galvanic anode.

C.5 Anodes for immersed concrete structures

C.5.1 Galvanic anodes

Galvanic anode alloys suitable for immersed concrete structures are described in EN 12496. For seawater and saline waters, anodes of aluminium-zinc-indium, zinc or magnesium can be used. For fresh water applications, only zinc or magnesium anodes are applicable.

The required minimum net mass of the anodes is determined from the total current requirement, anode alloy capacity, design life and anode utilization factor. The size and number of anodes is also determined from the anode current output, which in turn is based on anode shape, electrolyte resistivity and anode operating potential. Details on the procedures for designing galvanic anode system are given in EN 12495 and ISO 13174. Details on anode alloy capacity and operating potential are given in EN 12496.

Galvanic anodes for immersed structures will normally be slender stand-off or hull-mounted type anodes and will normally be installed by direct welding of the anode steel core to the embedded steel. This will require breakout of the concrete to expose embedded steel, welding of the steel core (or welding of a stand-off support), and making good the concrete. An alternative method of fixing connects the anode to electrical contact points (which themselves have been connected to the embedded steel) either directly (using lugs/nuts) or via an integrate anode cable.

If the anode is fixed with one face flush to the concrete, then that face (rear face) should be coated with a suitable coating to prevent excessive current discharge on the rear face.

Anode shapes and fixings should consider forces from wave and current action and should also consider access requirements for divers or remote operated vehicles (rov's), as described in EN 12495 and ISO 13174.

C.5.2 Impressed current anodes

Impressed current anodes suitable for immersed concrete structures typically comprise high-silicon cast iron (with chrome in chloride environments), lead silver alloys (very seldom used in recent years), mixed metal-oxide-coated titanium, platinized titanium or platinized niobium. Impressed current anodes can operate at high-output current densities, ranging from 10 A/m^2 to 30 A/m^2 for silicon-iron-chrome, 200 A/m^2 to 300 A/m^2 for lead silver and up to 1 000 A/m^2 for mixed metal-oxide-coated titanium anodes and up to 3 000 A/m^2 for platinized titanium or niobium anodes.

Impressed current anodes are available in rod, tube or strip form and can be fabricated in a wide range of sizes and shapes. Small rod or single tube anodes rated at 2 A to 5 A each can be fixed directly on or adjacent to a structure to provide localized current, as necessary. Larger anodes (comprising multiple tubes connected together or large-size rods/wires) can be assembled to form remote anodes rated at 50 A to 500 A each, to provide general protection to a large surface area.

The consumption rate for impressed current anodes ranges from 250 g to 500 g a year for high-silicon iron, to 25 g to 100 g a year for lead silver, 0,6 mg to 6 mg a year for mixed metal oxide titanium and 4 mg to 10 mg a year for platinum-based anodes. The consumption rate for platinum anodes is also dependent on salinity, with the rate being approximately an order of magnitude (10×) higher in fresh water compared to seawater conditions.

Cables for impressed current anodes should be suitable for exposed to immersed conditions, be capable of carrying high currents and, at the cable-to-anode interface, be capable of withstanding the aggressive/oxidizing conditions created.

NOTE Cables with insulation or sheaths of PVC, EPR or CSP or other rubbers are unlikely to be suitable for long-term use in proximity to impressed current anodes due to the oxidizing nature of the anodic reaction (acidification, reduction in pH) and in saline conditions, in particular due to the generation of nascent chlorine. Cables with insulation and sheaths of cross-linked polyethylene (XLPE) are likely to be suitable for long-term use in open environments, but may be inadequate in borehole applications or other situations where anodic reaction products are constrained around the cables. Over-sheathing such cables with more chemically resistant materials within these high-exposure areas close to the anodes or in boreholes may be adequate. Insulation using very chemically resistant materials, such as Kynar/HDPE (high density polyethylene), may be necessary, but these have disadvantages of cost and a tendency to crack at low temperatures and they require particular care with respect to large minimum bend radii.

Overall requirements for impressed current anodes for immersed conditions are given in EN 12495 and ISO 13174.

C.6 Anodes for buried concrete structures

C.6.1 Galvanic anodes

For buried concrete structures, traditional galvanic anodes based on zinc or magnesium may be used, as described in EN 12954. The required minimum net mass of the anodes is determined from the total current requirement, anode alloy capacity, design life and anode utilization factor. The size and number of anodes is also determined from the anode current output, which in turn is based on anode shape, soil resistivity and anode operating potential. For high-resistivity soils (typically >100 Ωm), only magnesium alloys will be able to provided effective current output.

Galvanic anodes may be installed directly or in chemical backfill (typically gypsum, bentonite and sodium sulfate) to optimize their performance. Anodes will normally be connected to the embedded steel in the concrete via an integral anode cable. Normal practice is to connect the anode via a junction box or test box to allow the anode current to be measured.

C.6.2 Impressed current anodes

Impressed current anodes for buried steel in concrete typically comprise high silicon cast iron (with chrome in chloride environments), graphite or mixed metal-oxide-coated titanium. Other impressed current anodes can be used including magnetite and scrap iron. Impressed current anodes will be installed either as single anodes or together to form a horizontal or vertical groundbed. The anodes will be embedded in a conductive backfill (typically of calcined petroleum coke) to reduce the resistance to ground (and hence, reduce driving voltage for a desired current output) and to reduce consumption rate on the anode itself.

Outputs for impressed current anode systems can typically range from 1 A to 2 A for single anodes, to typically 5 A to 200 A for horizontal or vertical clustered groundbeds and typically from 10 A to 100 A for deep vertical groundbeds. Selection of the ground bed type will be dependent on the total current requirement, geometry of the structure, access and availability of land for sitting the groundbed. With impressed current anode systems, consideration of the risk of stray current to other structures, including third party structures, should also be taken into account.

Cables for impressed current anodes should be suitable for exposed to buried conditions, be capable of carrying high currents and, at the cable-to-anode interface, be capable of withstanding the aggressive/oxidizing conditions created (see C.5.2, Note).

General details for impressed current anodes for buried structures are given in EN 12954.

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