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Cathodic protection of steel in concrete

Protection cathodique de l'acier dans le béton

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Contents

Page

Foreword ..... **v**

Introduction ..... **vi**

1 Scope **1**

2 Normative references **1**

3 Terms and definitions **2**

4 General **3**
- 4.1 Quality management 3
- 4.2 Persons 3
- 4.3 Design 3

5 Structure assessment and repair **4**
- 5.1 General 4
- 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 5
- 5.7 Reinforcement electrical continuity 5
- 5.8 Steel/concrete potential 5
- 5.9 Concrete electrical resistivity 5
- 5.10 Repair 6
  - 5.10.1 General 6
  - 5.10.2 Concrete removal 6
  - 5.10.3 Reinforcement preparation 6
  - 5.10.4 Concrete reinstatement 6
- 5.11 Cementitious overlay 7
- 5.12 New structures 7

6 Cathodic protection system components **8**
- 6.1 General 8
- 6.2 Anode systems 8
  - 6.2.1 General 8
  - 6.2.2 Conductive coating anode systems 9
  - 6.2.3 Activated titanium anode systems 10
  - 6.2.4 Titania ceramic anodes 11
  - 6.2.5 Conductive cementitious anodes 11
  - 6.2.6 Embedded galvanic anodes 11
  - 6.2.7 Surface-mounted galvanic anodes 12
  - 6.2.8 Buried and immersed anodes 12
- 6.3 Monitoring sensors 14
  - 6.3.1 General 14
  - 6.3.2 Portable reference electrodes 15
  - 6.3.3 Other sensors 15
- 6.4 Monitoring instrumentation 16
  - 6.4.1 General 16
  - 6.4.2 Digital meters 16
  - 6.4.3 Data loggers 16
- 6.5 Data management system 17
- 6.6 Direct current cables 18
- 6.7 Junction boxes 19
- 6.8 Power supplies 19
- 6.9 Transformer-rectifiers 19

7 Installation procedures **21**
- 7.1 Electrical continuity 21

7.2 Performance monitoring system ... 21
7.3 Connections to steel in concrete ... 22
7.4 Concrete repairs associated with the cathodic protection components ... 22
7.5 Surface preparation for anode installation ... 22
7.6 Anode installation ... 23
7.7 Connections to the anode system ... 23
7.8 Anode overlay, surface sealant or decorative coating application ... 23
7.9 Electrical installation ... 24
7.10 Testing during installation ... 25

8 Commissioning ... **25**
8.1 Visual inspection ... 25
8.2 Pre-energizing measurements ... 25
8.3 Initial energizing of impressed current systems ... 26
8.4 Initial adjustment of impressed current systems ... 26
8.5 Initial performance assessment ... 27
8.6 Criteria of protection: Interpretation of performance assessment data ... 28

9 System records and documentation ... **29**
9.1 Quality and test records ... 29
9.2 Installation and commissioning report ... 29
9.3 Operation and maintenance manual ... 30

10 Operation and maintenance ... **30**
10.1 Intervals and procedures ... 30
10.2 System review ... 31
10.3 System review report ... 31

Annex A (informative) **Principles of cathodic protection and its application to steel in concrete** ... **32**

Annex B (informative) **Design process** ... **40**

Annex C (informative) **Notes on anode systems** ... **47**

Annex D (informative) **Notes on reference electrodes** ... **52**

Bibliography ... **56**

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 of the voluntary nature of standards, 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 www.iso.org/iso/foreword.html.

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

This third edition cancels and replaces the second edition (ISO 12696:2016), which has been technically revised.

The main changes compared to the previous edition are as follows:

— the scope has been revised to clarify that, in order to comply with this document, it is necessary for the cathodic protection system to have sufficient monitoring provisions to demonstrate that the system meets the criteria of protection specified in 8.6;

— subclause 8.6 has been revised;

— Annex A has been revised and its figures have been updated;

— Clause A.7 has been moved to the new Annex D and a new Clause A.7 “Benefits of cathodic protection current when criteria in 8.6 are not fully met” has been added;

— Annex B has been revised completely;

— a new clause, Clause C.5 “Hybrid anodes”, has been added;

— a new annex, Annex D “Notes on reference electrodes”, has been added;

— the references in the whole document have been revised.

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

Introduction

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

As 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 ISO 12696:2016 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 specified 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 in this document. See EN 14038-1:2016[10] and EN 14038-2:2020[11] for information on electrochemical treatments.

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 that a detailed design and specification for materials, installation, commissioning and operation will be prepared by experts and experienced persons.

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 carbon steel reinforcement and prestressed reinforcement embedded in the concrete. It is applicable to uncoated steel reinforcement and to organic-coated steel reinforcement. It is not applicable to reinforced concrete containing electrically conductive fibres (e.g. carbon or steel).

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

This document is only applicable to the applications of cathodic protection to steel in concrete which are designed with the intention to, and can be demonstrated to, meet the criteria of protection specified in 8.6. This requires the provision of sufficient performance monitoring systems as specified in 6.3 to all parts of the structure intended to be protected, in order to assess the extent to which the criteria in 8.6 are met.

This document does not apply to galvanic anodes or systems applied into patch repairs to reduce the effects of 'incipient anodes'. This document does also not apply to any form of cathodic protection systems or other electrochemical treatments that either cannot meet the requirements of 8.6 or are not provided with the performance monitoring systems (see 6.3) that are necessary to assess whether the criteria of protection specified in 8.6 are met.

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.

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

ISO 15257, *Cathodic protection — Competence levels of cathodic protection persons — Basis for a certification scheme*

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 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 supply 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)*

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*

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 terminology databases for use in standardization at the following addresses:

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

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

3.1
zone
part of a cathodic protection system

Note 1 to entry: Anode systems can be divided into separate zones to supply current to a fully continuous reinforcement mesh. Alternatively, a single anode zone can supply current to separate, electrically isolated, zones within the reinforcement system. Zones can 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 that promotes the retention of moisture

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

4 General

4.1 Quality management

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. For further information, see Annex B.

NOTE ISO 9001 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 either appropriate visual, mechanical or electrical testing, or all, and all testing shall be documented.

All test instrumentation shall have valid calibration certificates traceable to National or International standards concerning calibration.

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

4.2 Persons

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 persons 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 either the fields of electrochemistry, concrete technology, civil or structural engineering and cathodic protection engineering, or all.

Persons 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. ISO 15257 specifies a suitable method which may be utilized in the assessement of the competence of cathodic protection persons.

The competence of cathodic protection persons to the appropriate level for tasks undertaken should be demonstrated by certification in accordance with ISO 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 and document 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.

The detailed design shall be undertaken by persons who meet the requirements of 4.2. Annex B gives respective information about the design. Annex B provides information for the detailed design which should be undertaken by persons who meet the requirements of 4.2. If ISO 15257 is used to demonstrate their competence, they shall be certificated to Level 4 or above in the sector 'reinforced concrete structures'.

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 (for further information, see Annex B).

These investigations shall include, but shall not be limited to, those given 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 can 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 can permit significant water penetration, and which can 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, the 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 is adequate for the particular anode system envisaged, and to identify dense regions of steel or reinforcement which can require high current density per square meter of concrete. Shielding of the steel to be protected, caused by embedded metal meshes, metal fibres or plates, plastic sheets or non-conductive repair materials, which can 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 can be less significant if the anode system comprises 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 size, distribution, laps and continuity. The last shall then be proven on site by measuring either the electrical resistance or potential difference, or both, 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 size, distribution, laps and 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 reinforcing 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 any other 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 References [12], [13] and [14] 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 of concrete resistivity found on the structure.

NOTE References [14] and [15] 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 5.10.

NOTE Installation of cathodic protection to an existing structure can 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.

5.10.2 Concrete removal

Any repair material detrimental to the performance of the cathodic protection (CP) system shall be broken out.

For example, predominantly epoxy-based repair materials have very high resistivity values and can shield reinforcement within or behind them from cathodic protection. Concrete reinforced with metallic fibres can have very low electrical resistivity and the fibres can 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 can contact the anode system or that can 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 can corrode and can 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. However, the designer shall consider the impacts of any significant corrosion products on the steel surface on the bonding of concrete repairs to the reinforcement.

NOTE Retained corrosion products are likely to be high in chlorides. If these coincide with voids in the concrete repairs these areas are likely to continue to corrode.

The designer shall consider the effect of primers or coatings used as part of the repair system, having consideration for the possible shielding of CP current from the steel to which, or behind which, the primers or coatings are applied.

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. 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 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 is that of an aged material (age > 20 years), whereas the electrical resistivity of the repair material reflects the properties at a relatively young age; it is anticipated that there is a significant ageing effect over time. Also, measurements made in the laboratory on prisms do 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 6.2.3.2, following a 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). Bond strength between the existing concrete and overlay shall be tested according to EN 1542. A series of tests shall consist of three single tests. The average bond strength shall be greater than 1,5 MPa for all test series and greater than 1,0 MPa for all single tests. For example, bond strength should be tested with one test series for each started 100 m^2.

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 can significantly exceed that of the 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. 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.

The potential between the anode and reinforcement/steel (cathode) shall be monitored to detect short-circuits.

5.12 New structures

In the case of a new structure, if cathodic protection as a preventive system (cathodic prevention) 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 reinforcing 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 prevention system;

d) in the case of 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. Monitoring of potential between anode and reinforcement/steel (cathode) shall be used to detect any 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 can be interrogated and displayed by portable instrumentation or by 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 can be used without monitoring systems or methods to measure their performance. Such systems do not comply with this document.

6.2 Anode systems

6.2.1 General

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.

For anodes embedded into or applied to the surface of the concrete, the maximum short-term current density at the anode surface shall not exceed 220 mA/m^2 and the maximum long-term current density at the anode surface shall not exceed 110 mA/m^2. These values may only be exceeded if the designer can demonstrate and document within the design report that a higher current density can be reliably accommodated within the design life of the cathodic protection system for that combination of anode material, its cementitious surround and its method of installation (e.g. a mesh anode within an overlay, a ribbon or ribbon mesh anode within slots or chases, or discrete anodes within drilled holes). The anode manufacturer's recommended current densities shall not be exceeded.

Either the design or the selection, or both, 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 use in cathodic protection of steel in concrete, as the anodes must 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 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 either laboratory testing, trials or past projects, or all.

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, either extended or accelerated, or both, field trials prior to commercial non-trial applications.

NOTE 3 There is an established test method for accelerated life testing of mixed metal oxide coated titanium anodes embedded in concrete, ISO 19097-1[5]. There is also a procedure for comparative testing of carbon based conductive-coating anodes[16].

Anode systems used for the protection of steel in buried or immersed concrete are detailed in EN 12954[9], EN 12495[7], ISO 15589-2[4], ISO 12473[2] and ISO 19097-2[6] and ISO 13174[3].

6.2.2 Conductive coating anode systems

6.2.2.1 Conductive coatings

These coatings are used as impressed current anodes.

The anode system shall comprise a conductive coating containing carbon and a series of conductors (current distributors) 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, for example, 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 current distributors shall be demonstrated by trials or past projects to enable the design anode performance to be achieved. The spacing of current distributors 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 current distributors, 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 either the wet or dry, or both, film thickness requirements to achieve the required dry film conductivity.

See Annex C for further information.

6.2.2.2 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, subject to the requirements of being able to monitor the performance of the CP system as in this document.

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, a top-coating with suitable properties 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.

6.2.3 Activated titanium anode systems

6.2.3.1 General

These anodes are used as impressed current anodes.

The anode system shall comprise a substrate of titanium[17] 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 mixed metal-oxide-coated titanium (MMO/Ti) anodes or inert anodes.

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

NOTE 2 A suitable test procedure is given in ISO 19097-1[5] for anodes encased in concrete and ISO 19097-2[6] for buried and immersed anodes

6.2.3.2 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 or spraying the concrete, and shall ensure that there are no short-circuits between anode and reinforcement/steel.

See Annex C for further information.

6.2.3.3 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.

6.2.3.4 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.

6.2.4 Titania ceramic anodes

See Annex C for further information.

6.2.5 Conductive cementitious anodes

Galvanic systems shall be wired to enable current interruption between the anode and the cathode for monitoring purposes in accordance with the requirement of this document.

See Annex C for further information.

6.2.6 Embedded galvanic anodes

These consist of zinc anodes in an activating encapsulation.

NOTE 1 Galvanic anodes can be used to enhance the durability of localized patch repairs and, in particular, to limit the likely acceleration of corrosion rate around patch repairs (sometimes called the ‘incipient anode effect’). These systems are not typically subject to performance monitoring and are not addressed in this document.

NOTE 2 Galvanic anodes can be used more extensively in a structure and if provision is made to include performance monitoring provision into the system such that the requirements of 8.6 can be demonstrated and if one or more of the criteria of 8.6 a), b) or c) are met, such systems are addressed in this document.

Anode types consists of zinc encased in proprietary activating encapsulation with connections to the reinforcing bar (rebar). One or more galvanic anodes are installed within the concrete repair, or into drilled or cored holes in, or surrounding the concrete repair and are attached to the reinforcement.

Other anode types consist of a “string” of zinc anodes in a proprietary activating encapsulation to be embedded into drilled or cored holes within the concrete repair or surrounding undamaged parent concrete, which are then attached to the reinforcement either directly or via monitored cable connection for assessment purposes.

Galvanic systems shall be wired to enable current interruption between the anode and the cathode for monitoring purposes in accordance with the requirement of this document.

See Annex C for further information.

6.2.7 Surface-mounted galvanic anodes

6.2.7.1 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 the 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.

Galvanic systems shall be wired to enable current interruption between the anode and the cathode for monitoring purposes in accordance with the requirement of this document.

See Annex C for further information.

6.2.7.2 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.

Galvanic systems shall be wired to enable current interruption between the anode and the cathode for monitoring purposes in accordance with the requirement of this document.

See Annex C for further information.

6.2.8 Buried and immersed anodes

6.2.8.1 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 and as described in EN 12495[7], EN 12954[9], ISO 12473[2] and ISO 15589-2[4] can 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 reinforced 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.

In order to comply with this document any such buried or immersed anode application shall meet the requirements for monitoring and achievement of criteria (see 8.6).

6.2.8.2 Immersed concrete structures

6.2.8.2.1 Galvanic anodes

For immersed concrete structures, immersed or buried galvanic anodes, comprising alloys of aluminium-zinc-indium, zinc or magnesium alloys, can be used as described in EN 12495[7]. 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 depends on the current demand, the (soil or water) electrolyte resistivity, the structure size and shape 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.

6.2.8.2.2 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[7], may be used.

The number, size, capacity and location of impressed current anodes depends 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 can result in local over-polarization.

6.2.8.3 Buried concrete structures

6.2.8.3.1 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[9], may be used.

Anodes are normally 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 is 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 depends 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.

6.2.8.3.2 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[9], may be used. Anodes are normally 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 depend 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 sufficient sensors at representative points over the entire structure / in each anode zone to be protected in order to demonstrate if the criteria of performance in 8.6 are met. The designer shall consider the sample regime for monitoring against the corrosion risk, size of structure, exposure and likely variance in conditions. The final monitoring scheme shall enable the performance across the entire protected structure to be assessed.

The cathodic protection system performance shall be determined by measuring the steel/concrete potential, using reference electrodes (for further information, see Annex D).

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

NOTE 2 Other sensors, such as potential decay electrodes, current density coupons, macro-cell probes, can 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 can be unstable. In instances of significant temperature changes, all electrodes change their electrode potential. In some such circumstances, it can 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. Saturated calomel electrodes include mercury which is a hazard to health and the environment; local regulations can preclude the use of calomel electrodes either on site or in the laboratory. This document does not provide guidance on safety aspects.

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 (for further information, see Annex D).

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 calibrated with respect to a pair of clean and fully maintained laboratory or mapping electrodes in order to demonstrate the electrode potential accuracy as stated in 6.3.1 at the beginning and end of each site application.

NOTE Suitable portable reference electrodes include gel-filled, double-junction Ag/AgCl/0,5 mol/l KCl.

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) and the most negative limits in 8.6] 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 can be used to determine the potential change (during “on and off switching”) over a limited period of time, 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

Coupons and macro-cells are optional additional monitoring sensors.

Where used, coupons 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. The designer shall ensure that any structural implications of such action have been addressed.

Current density coupons 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.

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, for impressed current systems, the operating condition of the direct current power supply.

NOTE Monitoring instrumentation can 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 International 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 ±5 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 to be identified.

NOTE Data loggers can be used to collect data from both sensors and direct current power supplies. Data loggers can 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 current power supplies, and so forth, 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 battery, alternating current mains or via the network cable, as appropriate.

Interconnection into a network shall be in accordance with relevant national or International 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 can 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 can 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 (e.g. inspection dates, changes in system operation).

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) can 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 manufactured from copper or titanium and shall be colour-coded according to their function.

NOTE 1 The following colours are preferred:

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

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

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

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

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

— 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 in 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. The 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 cross-linked polyethylene (XLPE) are likely to be suitable for long-term use. Insulation of very chemically resistant materials such as Kynar can be considered, but these have disadvantages of cost and of 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.

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, can 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 can 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 International 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 DC 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 either national or international standards, or both.

EXAMPLE Via an appropriately rated, double-pole neutral linked switch fuse or circuit breaker and residual current device.

The main 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 series 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 1 Facilities to link this system to the control signals from data logging equipment can 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 2 Facilities can be used for measurement of:

— steel/concrete potential with respect to potential decay probes;

— 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 3 Permanently installed digital panel meters can be used to measure the data required in items a) to c). Calibration checks on a regular basis are necessary. If permanently installed meters are used, the provisions for using portable calibrated meters for the same measurements can be provided.

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, for example, “+ ANODE” and “– STEEL”.

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

Light emitting diodes (LEDs) 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.

All AC input, DC output and monitoring circuits shall, when necessary, be provided with protection devices to prevent damage to the equipment by surges due to electrical faults or lightning. The protection devices shall provide appropriate current and surge time periods and shall not degrade the function of the protected circuits.

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 International 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 measuring the resistance using a current of minimum 250 mA for a period of minimum 0,5 s. The acceptance criteria for such testing shall be stable values and a resistance less than 1,0 Ω measured at the end of the applied current pulse, confirmed by 0 V residual voltage measured 0,1 s after the applied current is interrupted.

If there is an electrolytic component in the measuring circuit then resistance measurements using a DMM can produce unreliable results. In these circumstances, resistance measurements should use four wire type instruments or ohmmeters that are unaffected by polarization caused by other instrument passing DC current to achieve the resistance measurement.

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 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, for impressed current systems, its power supply output voltage and output current and for all systems its steel/concrete potential using a minimum of two reference electrodes (see 6.3.1) permanently embedded at representative locations.

NOTE 1 Each zone can 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 can be either manual, electronically data-logged or electronically data-transmitted, or all.

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 can 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 can 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, for example, 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 given in 5.11 [see EN 1504 (all parts)].

NOTE 1 Cathodic protection conductive coatings generally require a minimum of preparation to leave a maximum of cement paste and minimal exposure of aggregate and can be as specified in the coating product specification and the cathodic protection system specification.

NOTE 2 Cementitious overlays for cathodic protection anodes generally require a greater degree of preparation to leave a particular degree of cleanliness and surface roughness and can be as specified in the overlay product specification or overlay design 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 12495[7], EN 12954[9], ISO 12473[2] and ISO 15589-2[4]. 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 prevents 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 and galvanic anodes systems which require isolation monitoring.

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 and water evaporation of either the anode or the overlay, or both.

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 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 6.2.3.2 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 (see 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 can 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 can 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[37].

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;

   NOTE 2 Local regulations can apply.

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 3 In locations where there is high risk of damage, cables can be embedded into concrete or can 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, either whose construction or installation, or both, 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 4 Connections inside water-resistant or sealed boxes constructed and installed with an environmental protection rating above the worst-case external environmental exposure can utilize copper or brass threaded or proprietary connection assemblies.

f) it shall be permissible for anode/cable connections for anodes, for example, 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, for example, 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 5 The electrical characteristics required of the low voltage direct current circuits of cathodic protection systems can render full conformity to international (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 can 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;

d) insulation checks for anodes in adjacent zones.

NOTE Reference electrodes and rectifier circuits can be damaged by insulation checks. Reference electrodes can 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 4).

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 either diver or camera, or both) 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 adversely affects 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 either any electronic data logging or data transmitting facility installation, or both, 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 can 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 and Clause 10 should incorporate recording 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 normally corresponds 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 and electrode potential values shift in a positive direction, they shall be investigated to determine any requirements for either additional testing or remedial works, or both.

8.4 Initial adjustment of impressed current systems

The cathodic protection system shall be energized to a level of current estimated to enable the system to meet its initial performance objectives (as specified in the design documents) and then, after polarization, to meet the criteria of performance in 8.6. See the following Note 1 and Note 2.

NOTE 1 This can be a precalculated level of current (e.g. a particular cathode current density) or it can 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 can 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 can 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 energization although, if a slow polarization energizing policy (low initial current) is adopted, full polarization can 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” 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” potential measurements, sufficient time shall be allowed before measurement to avoid any transient voltage arising from switching surges, capacitance or resistance effects that 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 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 can be very slow and can extend to weeks. In the extreme, oxygen availability at the steel can possibly not be sufficient to maintain passivity of the steel/concrete interface and the potential can “rest” at a relatively negative value. In these conditions, potential decay can possibly not be a practical protection criterion and an ‘absolute potential criterion’ as 8.6 (a) can be required to be used.

NOTE 3 Potential shift (see 8.4, Note 1) can 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 can 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 4 During measurement of “Instantaneous OFF” potentials, it can be necessary to switch the direct current power circuit off and on to facilitate sequential measurements steel/concrete potentials at a number of embedded reference 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 5 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 slow data collection and risk depolarization during the off period.

The initial performance assessment shall be undertaken, as a minimum, using the performance monitoring systems as specified in 6.3 and shall be applied to all parts of the structure as is necessary to assess whether the criteria of protection as specified in 8.6 are met in all parts of the structure fitted with cathodic protection components.

8.6 Criteria of protection: Interpretation of performance assessment data

The data collected in accordance with 8.5, shall be reviewed and interpreted in accordance with the requirements of 8.6 by persons competent in cathodic protection as specified in 4.2. When ISO 15257 is used to demonstrate the competence of the persons, they shall be certificated to Level 3 or above in the steel in concrete sector, as specified in that document for assessment in accordance with the requirements of 8.6 with respect to the negative limit and criteria of 8.6, a), b) or c).

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

NOTE 1 Prestressing steel can be sensitive to hydrogen embrittlement even at potentials less negative than −900 mV 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 high yield steel (>550 N/mm^2) or prestressing steel, the safe potential limit shall have been determined and documented as part of the design.

NOTE 2 Prestressing steel that is corroded can possibly not have a safe potential limit and it is not ensured to be possible to provide cathodic protection to it in a safe manner.

The performance assessment shall be in accordance with the following criteria of protection for steel in concrete. For any structure, any representative steel in concrete location shall meet any one of the criteria given in 8.6, a) to c):

a) an "Instantaneous OFF" potential more negative than −720 mV with respect to Ag/AgCl/0,5 mol/l 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.

These criteria apply to all types of cathodic protection system applied to steel in concrete.

NOTE 3 It is not necessary to meet more than one item of 8.6, a), b) or c).

NOTE 4 Criteria a), b) and c) are supported by published papers. They are proven as a practical series of criteria of performance to indicate adequate polarization which leads to the maintenance or re-establishment of protective conditions for the steel within the concrete.

NOTE 5 As an investigative criterion it can be considered, by persons competent in cathodic protection as specified in 4.2, certificated to Level 4 or above in the steel in concrete sector of ISO 15257 (or equivalent), 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 mol/l KCl. This steel potential across the structure indicates steel is passive.

NOTE 6 These criteria, as discussed in items 8.6, 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 can be avoided by locating reference electrodes and other sensors away from concrete repairs wherever possible.

NOTE 7 Variations in conditions such as tidal effects, stray current, temperature and moisture etc. can cause significant changes to the measured potentials. This can have consequences for the interpretation of the data and whether it satisfies the criteria in items 8.6, a), b) and c).

NOTE 8 For structures, such as buried, immersed or coated structures, where oxygen availability within the concrete is limited, the criteria given in items 8.6, b) and c) cannot 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 cannot 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, then steps shall be undertaken to increase the protection current, in order to meet the criteria of protection as detailed in a), b) or c) above.

If the criteria are not met, the requirements of this document are not met and the system cannot be stated to comply with this document. It should be noted, however, that in certain circumstances (such as older systems or structures where remedial options were limited/constrained) where a system does not meet the criteria, there can be some benefits to structure durability. Such systems do not meet the requirements of this document, but additional assessment techniques, outside the scope of this document, can be brought to bear when deciding what action to take. Such assessments shall be undertaken under the guidance of persons certificated to ISO 15257 Level 4 or above in the reinforced concrete sector or have equivalent training, qualifications and experience. See Annex A.7.

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 persons responsible for the design, supervision and commissioning of the cathodic protection system and their respective responsibilities;

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

c) all measurements and test data taken before and while the system is energized and during the initial system performance assessment, together with the performance assessment data used and the interpretation of the data; a detailed assessment, on a zone by zone basis of if the system is likely to be able to perform as intended; if not, detailed recommendations shall be provided for investigation or remedial measures;

d) a record of the "as-left" operating conditions of the system;

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

NOTE Other documents can 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) either a list of the major components of the cathodic protection system with data sheets and the source(s) of spare parts or maintenance for these components and for the overall system, or both;

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

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

NOTE Other information can also be included if 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, dependent 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, deliberate mechanical or electrical damage.

Those systems provided with electronically data logged or electronically data transmitted performance monitoring systems can 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 and 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) The function check comprises:

1) confirmation that all systems are functioning;

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

3) assessment of data.

b) The performance assessment comprises:

1) a measurement of "Instantaneous OFF" polarized potentials;

2) a measurement of potential decay;

3) a 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) an assessment of data;

6) an 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-month intervals. Typically, the performance assessment shall be undertaken at 3-month intervals in the first year of operation and, subject to satisfactory performance and review at 6-month to 12-month 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 can 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 intervals of a maximum of 12 months:

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

b) a performance assessment in accordance with 10.1 b);

c) a visual inspection of the cathodic protection system;

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

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

f) 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.

Typically, the system review, and its report shall be undertaken and prepared annually.

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.

Concrete is a porous material with moisture in the pores even when exposed to the atmosphere. Despite the presence of moisture and oxygen at the steel surface, corrosion rates are usually depressed to a negligible level by the alkalinity of the pore water. The pore water is a mix of alkaline compounds, predominantly a saturated solution of calcium hydroxide $Ca(OH)_2$, with sodium and potassium hydroxides, with excess solid $Ca(OH)_2$ available. The pH at the steel surface is generally in excess of 12,5. At this pH, steel reacts with oxygen to form a dense, protective oxide that passivates the steel. Corrosion does not occur unless this passive layer is broken down. The passive layer is a dynamic oxide which sustains itself as long as the alkalinity is present and the oxide is uncontaminated.

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.

The chloride ion “competes” with the hydroxyl ion and when present in sufficient concentration at the steel/concrete interface, breaks down the protective passive oxide and allows the formation of non-protective, large volume oxides. Once the chloride content of the pore water exceeds a threshold value then the passive oxide layer breaks down.

The carbon dioxide molecule is acidic. It neutralises the alkalinity in the concrete, precipitating solid calcium carbonate in the pores and reducing the pH from over 12,5 to about 8,0. The passive layer starts to break down at about pH 11,0, again leading to the formation of non-protective, large volume oxides.

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 indicated by 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, corrosion can result in cracking and delamination of the covering concrete which can 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 onto 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, galvanic anodes are applied to, or embedded into the concrete and connected 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 to the reinforcement/steel.

The concrete, through its pore solution, provides the electrolyte to allow current flow and the associated ionic movement. The change of steel/concrete potential is measured with respect to reference electrodes which are embedded in the concrete or placed on the surface of the concrete and used, in conjunction with a suitable voltmeter and connections to the reinforcement/steel, to measure steel, concrete and 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 different 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 can be applied early 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. If the cathodic protection anode system is on the surface, or within the cover concrete, through which the contamination migrates to the steel, the negative polarization achieved also limits or prevents migration of the chloride ions to the steel, thereby, preventing them from depassivating the steel. 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 in sufficient quantities and depassivation has not yet occurred.

The other case is in older structures with corroding steel, when cathodic protection is often 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} (see Figure A.2). 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.

There are two authoritative reports on criteria for cathodic protection published by NACE. The first is a literature survey of cathodic protection criteria, the second discusses the 100-mV depolarization criterion. The literature survey is concerned with buried and submerged pipelines and makes no mention of steel in concrete. The 100-mV criterion report discusses the theory of corrosion control and the application of the 100 mV criterion to buried and submerged structures and contains a section devoted to steel in concrete.

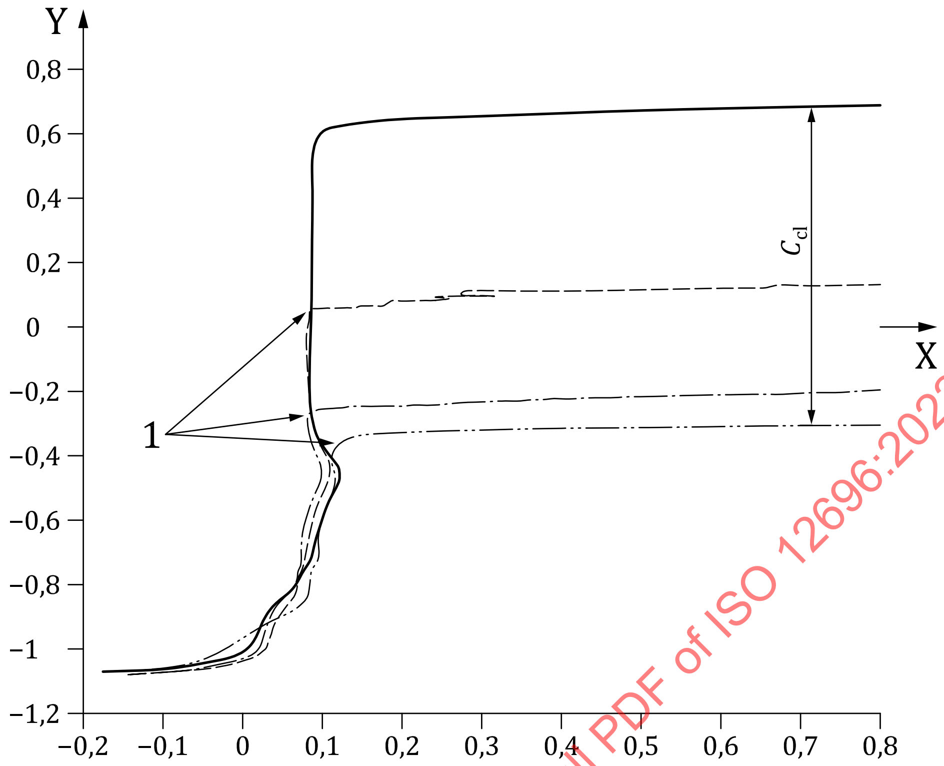
One of the earliest papers that defined what a cathodic protection system is trying to achieve was given in a paper by Mears and Brown. They said that "it is necessary to polarise the cathodes in the corrosion cell to the open circuit potential of the local anodes in order to obtain complete cathodic protection". This is why the current moves the steel potential negative, to move the more easily polarized cathodes toward the potential of the less easily polarized anodes. Any negative movement of the cathodic areas on the steel toward the corroding anodic areas on the steel reduces the rate of corrosion.

This was confirmed by Bartholomew et al.[33] who conducted experiments on steel in damp sand with different levels of chloride contamination to determine the amount of current and polarization required to control corrosion. The results were discussed in Reference [34]. It is important to understand that the results of these tests in damp sand illustrate the principle of the link between corrosion, chloride content, polarization and current density. The results should not be transposed directly to steel in concrete.

Reference [22] used theory and field results to produce a series of curves relating potential shift with unpolarised corrosion rate for different applied current densities for steel in concrete that is not oxygen limited (water-saturated).

The long-term beneficial effects of applying cathodic protection current are confirmed by the fact that intermittent cathodic protection has been found to provide protection in the absence of current for significant periods of time.

Figures A.1 to A.3 illustrate these factors. These figures are illustrative anodic potentiodynamic scans of steel in alkaline solution where the steel is initially stripped of its oxide film. They do not necessarily accurately represent steel in concrete.



Key

X log i (i is the electric current density) [A/m^2]

Y measured potential, $E_{Ag/AgCl/0,5\ mol/l\ KCl}$ [V]

1 pitting potential, E_{pit} [V]

C_{Cl} concentration of chloride [mol/l]

——— 0 mol/l Cl

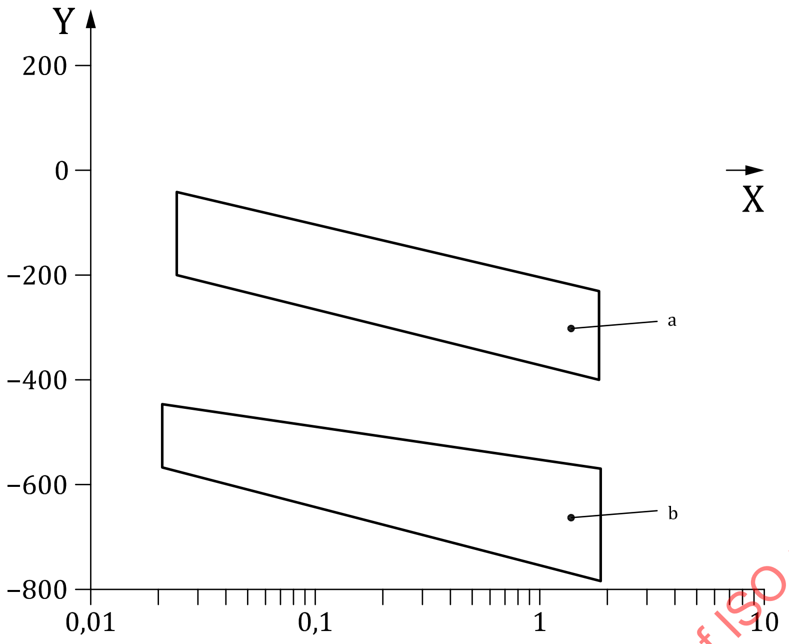
– – – – 0,02 mol/l Cl

—·— 0,2 mol/l Cl

—··— 2 mol/l Cl

NOTE These curves were produced at a polarization scan rate of 1 mV/s after sample preparation by polishing the steel electrode, placing it into quartz sand. It was flooded with sat. $Ca(OH)_2$ at different chloride content (2 mol/l, 0,2 mol/l, 0,02 mol/l and 0 mol/l) and was preconditioned by applying a cathodic current of 1 A/m^2 for 1 h. Slower scan rates and different preconditioning produce different data.

Figure A.1 — Laboratory examples of the anodic behaviour of steel in the presence of different levels of chloride



Key

X concentration of chloride, C_{Cl} [mol/l]

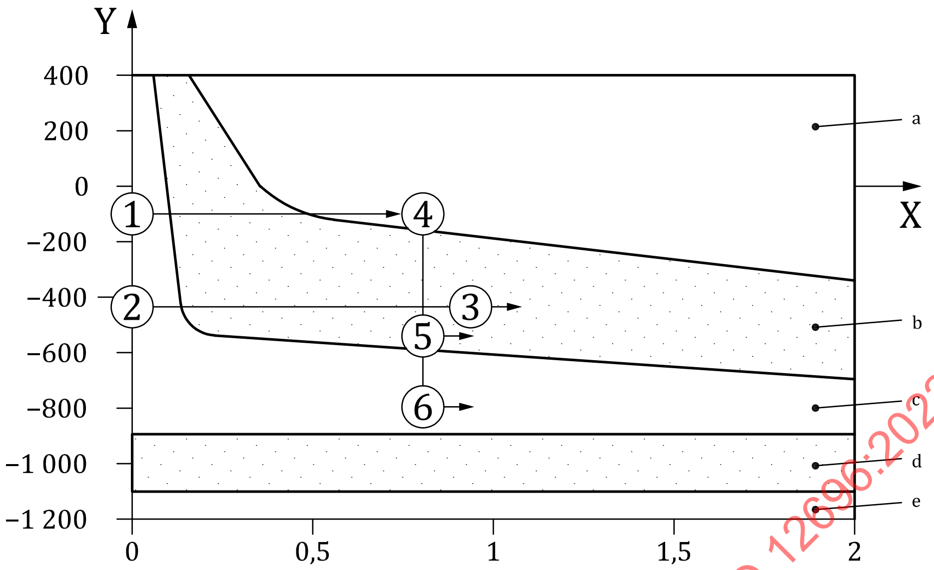
Y measured potential, $E_{Ag/AgCl/0,5\ mol/l\ KCl}$ [V]

a Pitting potential, E_{pit} [mV].

b Protection potential, E_{prot} [mV].

NOTE All values are indicative.

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[18]



Key

X w_{Cl} (cement) [%]

Y measured potential $E_{Ag/AgCl/0,5\ mol/l\ KCl}$ [mV]

1 → 2 → 3 cathodic prevention (see Note 1)

1 → 4 → 6 cathodic protection restoring passivity (see Note 2)

1 → 4 → 5 cathodic protection reducing corrosion rate (see Note 3)

a Pitting initiates and propagates.

b Pitting does not initiate but propagates.

c Pitting does not initiate or propagate.

d Hydrogen embrittlement risk to high-strength steels.

e Reduction of steel/concrete bond.

NOTE 1 Cathodic prevention may be applied from the beginning of structure life at 1.

NOTE 2 Cathodic protection applied only after corrosion has initiated at 4. Polarization to 6 (area c) restores passivity.

NOTE 3 Cathodic protection applied only after corrosion has initiated at 4. Polarization to 5 (area b) reduces corrosion, new pitting does not initiate but existing pits do propagate.

NOTE 4 All values are indicative.

Figure A.3 — Schematic illustration of the evaluation paths of the pitting potential versus chloride content in percentage by mass of cement in steel/reinforcement surface during service life[18]

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 can 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 results in reduction in oxygen content at the steel surface under normal exposure conditions, which is accelerated under the application of cathodic protection. Where oxygen depletion occurs, the potential becomes very negative and the current required for cathodic protection is 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 is 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 versus Ag/AgCl/0,5 mol/l KCl. Prestressing steel can 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 either incorrectly designed or operated, or both, 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 versus Ag/AgCl/0,5 mol/l 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 [19]).

Prestressing steel inside ducts cannot be provided with cathodic protection with anodes located outside the ducts.

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 Benefits of cathodic protection current when criteria in 8.6 are not fully met

The performance criteria for effective cathodic protection are specified in 8.6. If none of these are met, then the system cannot be stated to comply with this document.

It should be noted, however, that in certain circumstances (such as older systems or structures where remedial options were limited/constrained) a system that may not meet the criteria may bring benefit to the structure. While not conferring "full cathodic protection", a degree of corrosion rate reduction, or reduction in corrosion pit propagation can be achieved if the steel/concrete potential is shifted in a negative direction.

The structure owner can wish to have expert assistance to estimate what benefits in reduction in the rate of deterioration of the structure this partial cathodic polarization can deliver and if additional assessment techniques can be used to inform what action, if any, to take. NACE SP008-2018-SG[20] and NACE TR21463-2020[21] describe techniques that may be used to evaluate the condition of the structure. Such assessments should be undertaken under the guidance of personnel certificated to ISO 15257 Level 4 or above in the reinforced concrete sector or have equivalent training, qualifications and experience.

The passing of current from concrete into steel brings about several electrochemical changes at the steel/concrete interface. The current is carried from the anode to the steel via the concrete pore water in the form of charged calcium, sodium and potassium ions (Ca^{2+} Na^{+} and K^{+}) moving towards the steel while negatively charges ions move away from the negatively charged steel, such as the chloride ion (Cl^{-}) and the hydroxyl ion (OH^{-}) which are generated by the cathodic reaction [see Formula (A.1)] and which are present in the existing concrete pore solution.

The predominant cathodic reaction at the steel is:

$$\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^- \tag{A.1}$$

When corrosion is due to chloride attack, the negative charge on cathodic steel repels negatively charged chloride ions. This has been demonstrated in practice by comparing chloride profiles of areas of a bridge subject to marine salt spray with and without impressed current cathodic protection applied. This is of course the principle behind the process of electrochemical chloride extraction which uses higher currents over a short period to re-passivate the steel and drive chlorides away from and ideally out of the concrete.

Where corrosion is due to carbonation, the generation of hydroxyl ions by the cathodic reaction at the steel surface [see Formula (A.1)] increases the pH toward the level at which the passive oxide film becomes stable again. This is the principle behind the process of electrochemical realkalization which uses high currents over a short period to re-passivate the steel.

The consequence of the removal of chlorides from the steel surface, and of the generation of hydroxyl ions by the cathodic reaction is that the passive layer can re-form and the steel becomes protected from damaging levels of corrosion.

In atmospherically exposed concrete (when the corrosion process is not limited by a restriction of the rate at which oxygen in the air reaches the steel), an apparent steel corrosion rate has been estimated by inserting the applied current density and steel potential shift into the Butler Volmer formula. This is a nonlinear polarization technique and is not considered to be accurate or secure. If this technique is used, it does not constitute an additional criterion to assess compliance with this document.

Passive steel is indicated by a corrosion rate of less than 1 mA/m^2 when determined by linear polarization techniques. A falling trend in corrosion rate combined with a rising trend in depolarised corrosion potential (i.e. movement of the potential towards less negative values) is also a sign that protection is being achieved. However, field measurement of corrosion current with portable instrumentation applied to steel in concrete is difficult and prone to inaccuracies. To use this technique on cathodically protected, or partially protected, steel reinforced structures requires them to be fully depolarised and, although possible, cannot be practical. This technique, if used, is not an additional criterion to assess compliance with this document.

It can be appropriate to assess the residual corrosion risk and to assess its impact on the structural integrity and the residual service life. The structure owner, based upon expert advice, can determine that it is not necessary to meet the CP criteria and to accept the ongoing corrosion risk.

Annex B
(informative)

Design process

B.1 General

In 4.1, it is required that each stage of the design shall be checked and the checking shall be documented.

In 4.2, it is required that persons 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. ISO 15257 specifies a suitable method which may be utilized for assessing the competence of cathodic protection persons. 8.6 requires that when ISO 15257 is used to demonstrate the competence of the persons, they shall be certificated to Level 4 or above in the steel in concrete sector, as specified in ISO 15257.

In 4.3 it is required that cathodic protection systems for steel in concrete shall be the subject of detailed design.

The design shall, as a minimum, include and document 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.

In 6.1, it is required that the entire cathodic protection system shall be designed, installed and tested to be suitable for its intended life in its intended environment.

B.2 Concept CP design process

CP systems should, prior to installation, be the subject of detailed design. The design should be based on sufficient survey of the structure and assessment of the data in order to sufficiently inform all the design and subsequent installation and operation steps in the CP process.

It is normal for structural surveys or assessments to be undertaken to confirm that the structure is suitable for its intended function and life; this is not part of the CP assessment or design process and is normally undertaken by experienced structural specialists and experts in the type of structure being considered.

CP is often incorporated into concrete repair and may be incorporated into structural strengthening works. In these applications, close integration and liaison is required between relevant specialist persons at all stages of design, materials selection, works execution and CP commissioning. All component parts and processes should be compatible.

The design process is typically a staged process as follows:

a) a confirmation that either the deterioration of the structure or the anticipated or possible future deterioration within the design life of the structure is due to corrosion, typically caused by chlorides and can be mitigated by CP;

b) a determination from the client, owner or operator, of the requirements for the service life of the structure and life of the CP system, or parts of the CP system, within the service life;

c) a confirmation that the structure is suitable for the application of cathodic protection. Subclause 5.10.3 requires that the designer shall consider the effect of primers or coatings applied to reinforcement;

d) in particular that the concrete does not contain prestressing or post tensioning steel that can have been subject to corrosion and can be at risk of hydrogen induced stress cracking (HISC) if cathodic protection is applied. In this case, specialist investigation and testing beyond the scope of the EN 1504 series and this document are recommended, before a determination that CP can be safely applied. Subclause 8.6 requires that for high yield steel (>550 N/mm^2) or prestressing steel the safe potential limit shall have been determined by testing and be documented as part of the design. It notes that prestressing steel that is corroded can possibly not have a safe potential limit;

e) an assessment of the chloride content and profiles, the reinforcement cover, steel/concrete (half-cell) potential survey data (including a partial assessment of steel reinforcement electrical continuity), distribution of surface water on and water saturation within the structure; 5.9 requires that the designer shall consider whether full protection can be achieved, where required, for the ranges of concrete resistivity found on the structure; in addition to informing future current density requirements, these data inform the selection of suitable anode types;

f) an assessment of the exposure conditions of the structure, and any predicted changes to these, that can influence the suitability of the available anode options, the necessity or otherwise of anode overlays and the type and location of DC power supplies and cable management systems;

g) an assessment of the safe access to the structure, including issues such as traffic management and temporary supports needed during the works and subsequent operation, inspection and maintenance of the structure and the CP system, that can influence the suitability of the available anode options, the necessity or otherwise of anode overlays and the type and location of DC power supplies;

h) any weight or aesthetic limitations of the structure that can influence the suitability of the available anode, overlay and cable management options;

i) the availability of AC mains power or the practicalities of alternative power sources.

At this stage, the designer should be able to determine if CP is appropriate and what form it should take. It is then necessary to consider in detail the particular parts of the structure, with their variations in steel reinforcement disposition, variations in accessibility for installation of steel cathode connections, anodes, performance assessment sensors and their associated cables, cable management, power supplies in order to determine the general concept and key component types of the CP system.

B.3 Detailed CP design process

The detailed stage of the CP should then include but not be limited to:

a) detailed calculation of steel reinforcement (and any other embedded or surface contacted steel) surface areas, paying particular attention to areas of reinforcing laps with higher localized current requirements with associated concrete surface areas;

b) detailed assessment of those surfaces which cannot be accessed for CP system installation and which can require different anode selection(s) to the majority of the structure (e.g. bridge deck 'half joints', complex joints between parts of structures, sections with very deep chloride penetration, which can require embedded discrete anodes when the remainder of the structure can be suitable for surface mounted anodes);

c) selection of the optimum anode type, along with any associated overlay, and zoning of this selection to deliver uniform or appropriate current delivery to reflect variations in steel density (ratio of surface area of steel to surface area of concrete)/distribution and possibly chloride distribution; anode selection is generally made on a combination of life, current density, reliability/track record, exposure and cost assessments; sometimes aesthetics is important;

d) in case of the use of discrete anode or ribbon anode, the maximum distance between anode should be estimated to avoid lack of protection and can be demonstrated by a trial;

e) detailed calculations to determine

— the anode zone size,

— the distribution of any current distributor or current distribution within the anode system, and

— the number and distribution of positive anode/cable connections to demonstrate, through detailed calculations of volt drop in cables, current distributors, in the anode itself that the anode current delivery in the concrete uniformly meets the design requirements and does not vary over the surface of the anode from these requirements by > ±10 %;

f) calculations to determine the number and distribution of negative cable/reinforcement connections and if the steel reinforcement cross-section and distribution, subject to known or assumed quality of bar/bar electrical continuity introduces significant resistance into the CP circuit and to avoid any situation where steel cathode resistance results in cathode current density variations > ±10 % of the design requirements due to volt drop in the steel;

g) determination of optimum cable conductor type (e.g. minimum number of strands), cross-section for current capacity, volt drop and sometimes mechanical durability, insulation and sheathing materials (for chemical and environmental performance in addition to electrical resistance) along with colour coding;

h) calculations of anode positive and steel cathode negative cable resistances between the DC power supply to demonstrate that the cable volt drop is not disproportionate to the available power supply voltage and does not result in variations to anode and cathode current densities over the structure > ±10 % of the design requirements; it is normal good practice to limit cable volt drop to 2 V;

i) selection of reference electrode type(s) along with any other performance assessment sensors to be employed which can be affected by environment, structure function and design life;

j) determination and detailed design of cable management systems, with cables that may be embedded in concrete, mounted on concrete in cable tray or conduits, or buried, which may be routed via junction boxes all of which impacts durability and the electrical properties referenced above;

k) determination of the DC power characteristics required, the extent of data logging and or remote monitoring and remote control and the type of enclosure for these to suit the environment, including effects of impact (including vandalism), water (including flooding), dust; selection of enclosure materials and finish to minimize maintenance requirements for the design life and to suit any aesthetic constraints;

l) determination of AC electrical power requirements, its source and reliability; it can be necessary to compare options for supply on a cost and reliability basis; determination of the requirements, if any, for connections to GSM/internet for remote data logging/control.

B.4 Design documentation

The detailed design should clearly demonstrate and document the following, in a manner that can be independently verified or interrogated by a third party at another time. The detailed design should include the following which may be documented as separate volumes:

a) detailed calculations;

b) an interpretative design report;

c) schematic, general arrangement and detail drawings that should be specific to the structure and proposed system;

d) specifications for materials, installation, testing, commissioning and operation.

Through the above documents the design should, as a minimum, detail and demonstrate the following:

e) the assumed or measured pre-design survey parameters used for the design including, but not limited to, exposure class for structure, chloride content and cover to reinforcement;

f) the parts of the structure to be protected;

g) the chosen scope of protection and zones, including to what depth of reinforcement cathodic protection is intended;

h) the chosen performance monitoring sensors and locations;

i) the chosen approach to cathodic protection and why alternatives have been rejected;

j) the chosen steel cathode current density at what steel levels;

k) the chosen anode current density;

l) details of any specific testing and inspection required to achieve the required protection and service life; this should include testing during installation of the CP system, including steel electrical continuity;

m) details of any specific installation methods required to achieve the required protection and service life;

n) the intended service life of the CP system and reasons for this; the anticipated requirements for replacement of all or parts of the CP system during the intended service life;

o) any assumptions and requirements (e.g. operation and maintenance) required to achieve the above;

p) calculations demonstrating, for all variations of steel density, geometry and exposure condition (on a case-by-case basis), the surface area, and current demand for all representative steel arrangements, including current drain from non-protected supplementary items where appropriate;

q) calculations demonstrating, for all variations of steel density, geometry and exposure condition (on a case-by-case basis), that the designed CP system provides the required protection current from each anode, or anode array, at an acceptable driving voltage;

r) calculations demonstrating, for all variations of steel density, geometry and exposure condition (on a case-by-case basis), that the designed CP system provides the required protection in terms of current distribution between anodes, or anode arrays at an acceptable driving voltage and without producing excessive/unnecessary voltage gradients on the steel surface;

s) calculations demonstrating, for all variations of steel density, geometry and exposure condition (on a case-by-case basis), that the designed CP system performs below the required anode surface current density limits in both the short and long term;

t) calculations demonstrating, the expected current demand to each zone in both short and long term;

u) calculations of cable voltage drops demonstrating, for all variations of steel density, geometry and exposure condition (on a case-by-case basis), that the designed current cable cross-section allows uniform zone anode current density (<10 % variation);

v) calculations to inform the manufacture of DC power supply (TR) equipment in terms of suitable DC current and voltage output;

w) an index of all documents that are used as a basis for the design process;

x) if the system is based on the use of a galvanic anode material or material that can reasonably be depleted during the life-time of the system, the designer should demonstrate that the system comprises suitable and sufficient anode material (mass of material) to satisfy the delivery of the calculated current demand at both start and end of life conditions. The designer should consider the proven anode capacity of the material selected, and its likely utilization in the environment it is intended to function.

The designer may choose to demonstrate compliance with some of the above requirements by use of a temporary or trial CP system. In this case, it is expected that a detailed report will be produced which demonstrates that each of the requirements detailed above can be met by the proposed design.

B.5 Particular guidance related to cathode, anode and monitoring zones

It is necessary to calculate detailed reinforcement and all additional steel surface areas for all parts of the structure. Individual zones should be established within which there is an approximate uniformity of steel surface area relative to the exposed concrete surface area.

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 should be 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 12495[7], EN 12954[9], ISO 12473[2] and ISO 15589-2[4], current distribution from the remote anodes to the steel is 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, along with the selected cathode (steel) current density for the desired level of protection, the CP current requirements should be calculated along with the operating anodic current density on each anode or anode zone.

These values should be used to confirm the anode type, taking into account the factors given in Annex C and select an appropriate overlay material, where the anode is overlaid.

Determine the anode zone size and layout including calculation of locations and spacings of the anode feeder cable and connections to the anode materials 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. Generally, anode current density within a zone should not vary by more than ±5 % above or below the average. Select any current distributor material and cross-section, its distribution and current distributor/“positive cable” connections to provide the required redundancy and to minimize voltage drops in order that the ±5 % variance limit is achieved.

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 ISO 12473[2] and EN 12495[7], 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, for example, mixed metal-oxide-coated titanium (MMO/Ti), it can be 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 can 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.6 Current provision

Using the operating current demand and reserve capacity required, the total current provision should be calculated.

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 is higher with higher chloride content, higher humidity and at higher temperatures. For temperate climates with limited chloride contamination, most applications to existing corroding structures is 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 declines with time.

The reinforcement/steel closest to the anode receives 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 will 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 is 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 [22]). 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.7 Specific design issues for buried and 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 delivery/collection or are shielded to an extent that insufficient current is provided.

