BRITISH STANDARD

BS 7361-1:
1991

Cathodic protection —

Part 1: Code of practice for land and marine applications —

(formerly CP 1021)

Committees responsible for this British Standard

The preparation of this British Standard was entrusted by the General Electrotechnical Standards Policy Committee (GEL/-) to Technical Committee GEL/109, upon which the following bodies were represented:

Association of Consulting Engineers
British Gas plc
British Railways Board
British Telecommunications plc
Corrosion Control Engineering Joint Venture
Department of Energy (Energy Technology)
Department of Trade and Industry (National Physical Laboratory)
Electricity Supply Industry in England and Wales
General Council of British Shipping
Institute of Petroleum
Institution of Corrosion Science and Technology
Institution of Electrical Engineers
Institution of Gas Engineers
Institution of Water and Environmental Management
Lloyd’s Register of Shipping
Ministry of Defence
Pipeline Industries Guild
United Kingdom Offshore Operators Association
Water Companies Association
Water Services Association of England and Wales

This British Standard, having been prepared under the direction of the General Electrotechnical Standards Policy Committee, was published under the authority of the Standards Board and comes into effect on 28 June 1991

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Foreword

This Part of BS 7361 has been prepared under the direction of the General Electrotechnical Standards Policy Committee. It represents a revision of CP 1021:1973, which is withdrawn.

Cathodic protection is a means of preventing the corrosion of most metals wherever they are in contact with a mass of water or moist materials. It should not, however, be inferred that cathodic protection, wherever applicable, is necessarily advantageous. Unless the need for cathodic protection is already established, every case should be carefully examined and an evaluation made of the economic advantage of cathodic protection, compared with other methods of avoiding or reducing corrosion, such as sheathing or coating, the use of other materials of construction etc. Included in the assessment should be the cost and consequences of allowing the expected corrosion to proceed. This may be possible, for example, in the case of steel pilings, while entirely ruled out in the case of high pressure pipelines.

This Part of BS 7361 covers good up-to-date practice and contains both guidance on general principles and detailed information on the cathodic protection of particular types of structure or plant, excluding those involved in off-shore applications. Even where sufficient evidence based on actual installations has not been obtained to enable detailed information to be given, it should not be assumed that cathodic protection is unsuitable if there is sufficient economic incentive. Lack of evidence has also prevented firm guidance being given at several points in this Part of BS 7361, notably on the test methods needed to avoid excessive error due to potential drop through the electrolyte when the effectiveness of cathodic protection is being assessed by measuring the potential of the metal relative to a reference electrode.

Attention is drawn to the importance of considering any measures necessary to prevent corrosion during the early stages of the design of structures and possible future extensions. Design to prevent corrosion, for example by selection of materials, avoidance of unsuitable shapes or combinations of metals, or by using metal spraying or protective coatings is important, but is outside the scope of this standard. The corrosion protection of iron and steel in this context is covered by BS 5493.

This revision has been occasioned by developments in a variety of industries since 1973, as well as increasing sophistication in the associated measuring techniques. Whilst the main body of the first edition has been found to be sound, detailed changes have been required throughout the document, and additional experience in areas such as pipe coatings, anode materials and the cathodic protection of reinforcing steel in concrete, and methods of assessing cathodic protection, has necessitated the introduction of new text. Despite further consideration by the committee no change is proposed to the 20 mV criterion for limiting corrosion interaction.

A major area for cathodic protection is that concerned with off-shore applications. The scale of this work and the size of the corresponding text to cover it requires the preparation of Part 2 of this standard and this is intended to be accomplished by participation in corresponding work that has been initiated in Europe under the aegis of CEN.

It has been assumed in the drafting of this British Standard that the execution of its recommendations is entrusted to appropriately qualified and experienced people, for whose guidance it has been prepared.

Compliance with a British Standard does not of itself confer immunity from legal obligations. In particular attention is drawn to the following regulations:

Electricity (Factories Act) Special Regulations 1908 and 1944
Health and Safety at Work etc. Act 1974
Pipelines Act 1962 — Repeals and Modifications Regulations 1974
The IEE Wiring Regulations. Regulations for electrical installations, published by the Institution of Electrical Engineers (subsequently referred to as the IEE Wiring Regulations) are not statutory, but compliance may satisfy the requirements of certain statutory regulations. It is advisable therefore to comply with these regulations where appropriate.

Summary of pages

This document comprises a front cover, an inside front cover, pages i to viii, pages 1 to 110, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

Section 1. General

1.1 Scope

This Part of BS 7361 covers the applications of cathodic protection for which principles of use have been established, i.e. the prevention of the corrosion of buried or immersed metalwork and the internal protection of containers for aqueous liquids. It does not deal with the cathodic protection of off-shore structures.

The code indicates general circumstances in which the application of cathodic protection is likely to be economical as a method of corrosion prevention. It covers general principles, their application, the special problems arising in the protection of particular types of structure, the safeguarding of neighbouring structures, electrical measurements, the commissioning, operation and maintenance of cathodic protection systems, and safety aspects. Off-shore applications are to be covered in Part 2 (see foreword).

NOTE 1 Where detail of equipment is shown in the figures, the purpose is to assist in the reading of the text by indicating typical arrangements. The figures are not intended to establish preferred types of equipment. Similarly, any dimensions shown are to provide an indication of size, not to establish preferred dimensions.

NOTE 2 The titles of the publications referred to in this code are listed on the inside back cover. The titles of related British Standards are listed in Appendix B for information.

NOTE 3 The numbers in square brackets in the text refer to numbered references in Appendix C.

1.2 Definitions

For the purposes of this Part of BS 7361 the definitions given in BS 4727 apply together with the following.

1.2.1
anaerobic

the lack of free oxygen in the electrolyte adjacent to a metal structure

1.2.2 anodes

1.2.2.1
anode

the electrode through which direct current enters an electrolyte

1.2.2.2
cantilever anode

an anode formed and supported as a cantilever

NOTE This type of anode is used particularly for the impressed current protection of the inner surfaces of containers for liquids.

1.2.2.3
continuous anode

a long flexible anode

1.2.2.4
sacrificial anode

an anode used to protect a structure by galvanic action

NOTE Previously termed "galvanic anode" or "reactive anode".

1.2.2.5
anode backfill

a low-resistance moisture-retaining material immediately surrounding a buried anode for the purpose of decreasing the effective resistance of the anode to the soil

1.2.2.6
anodic area

that part of a metal surface which acts as an anode

1.2.3
blistering (of paint film)

the formation of swellings on the surface of an unbroken paint film by moisture, gases, or the development of corrosion products between the metal and the paint film

1.2.4 bonds

1.2.4.1
bond

a piece of metal conductor, either solid or flexible, usually of copper, connecting two points on the same or on different structures, to prevent any appreciable change in the potential of the one point with respect to the other

1.2.4.2
continuity bond

a bond designed and installed specifically to ensure the electrical continuity of a structure

NOTE This may be permanent or temporary. In the latter case it is used to connect two sections of a structure which would otherwise be disconnected during a modification or repair.

1.2.4.3
drainage bond

a bond to effect electric drainage

1.2.4.4
remedial bond

a bond installed between a primary and a secondary structure in order to eliminate or reduce corrosion interaction

1.2.4.5
resistance bond

a bond either incorporating resistors or of adequate resistance in itself to limit the flow of current

1.2.4.6
safety bond

a bond connecting the metallic framework or enclosure of electrical apparatus with earth, in order to limit its rise in potential above earth in the event of a fault, and so reduce the risk of electric shock to anyone touching the framework or enclosure

1.2.4.7
bond resistance

the ohmic resistance of a bond including the contact resistance at the points of attachment of its extremities

1.2.5
carbonation

the chemical reaction between atmospheric carbon dioxide and the calcium hydroxide present in Portland cement

1.2.6
cathode

the electrode through which direct current leaves an electrolyte

1.2.7
cathodic area

that part of a metal surface which acts as a cathode

1.2.8
cathodic disbonding

the failure of adhesion between a coating and a metallic surface that is directly attributable to cathodic protection conditions and that is often initiated by a defect in the coating system, such as accidental damage, imperfect application or excessive permeability of the coating

1.2.9
cathodic protection

a means of rendering a metal immune from corrosive attack by causing direct current to flow from its electrolytic environment into the entire metal surface

1.2.10
cell

a complete electrolytic system comprising of a cathode and an anode in electrical contact with an intervening electrolyte

1.2.11
conductor

a substance (mainly a metal or carbon) in which electric current flows by the movement of electrons

1.2.12
corrosion

the chemical or electrochemical reaction of a metal with its environment, resulting in its progressive degradation or destruction

NOTE This standard is concerned with corrosion by electrochemical action.

1.2.13
corrosion product

the chemical compound or compounds produced by the reaction of a corroding metal with its environment

1.2.14
corrosion interaction

the increase or decrease in the rate of corrosion, or the tendency towards corrosion, of a buried or immersed structure caused by the interception of part of the cathodic protection current applied to another buried or immersed structure or current from other sources

NOTE 1 For convenience, also referred to as "interaction".

NOTE 2 Also known as "corrosion interference".

1.2.15
crossing point

a point where two buried or immersed structures cross each other when viewed in plan

1.2.16
current density

the current per unit geometrical area of the protected structure, coated and uncoated, in contact with the electrolyte

1.2.17
dielectric shield

a protective covering of insulating material applied to a painted structure in the immediate vicinity of an anode to prevent the paint being stripped by alkali produced by the high current density at the steel surface close to the anode

NOTE This is usually applied to a ship's hull.

1.2.18
differential aeration

the unequal access of air to different parts of a metallic surface

NOTE This often results in the stimulation of corrosion at areas where access of air is restricted.

1.2.19 drainage

1.2.19.1
electric drainage

a means by which protection of an underground or underwater metallic structure against electrochemical corrosion is achieved by making an electrical connection between the structure and the negative return circuit (rail, feeder, busbar) of a d.c. electric traction system

NOTE For convenience, also referred to as "drainage".

1.2.19.2
forced drainage

a form of drainage in which the connection between a protected structure and a traction system includes an independent source of direct current

1.2.19.3
polarized electric drainage

a form of drainage in which the connection between a protected structure and a traction system includes a unidirectional device or devices such as a rectifier or a relay and contactor

NOTE For convenience, also referred to as "polarized drainage".

1.2.19.4
drainage tests

tests in which current is applied for a short period, usually with temporary anodes and power sources, in order to assess the magnitude of the current needed to achieve permanent protection against electrochemical corrosion

1.2.20
driving potential (of a sacrificial anode system)

the difference between the structure/electrolyte potential and the anode/electrolyte potential

1.2.21
earth (1)

the conducting mass of earth or of any conductor in direct electrical connection therewith

NOTE The conducting mass of earth also includes expanses of natural water.

1.2.22
earth (2)

a connection, whether intentional or unintentional, between a conductor and the earth

1.2.23
earth (3)

to connect any conductor with the general mass of earth

1.2.24
electrode

a conductor of the metallic class (including carbon) by means of which current passes to or from an electrolyte

1.2.25
electrolyte

a liquid, or the liquid component in a composite material such as soil, in which electric current flows by the movement of ions

1.2.26
electronegative

the state of a metallic electrode when its potential is negative with respect to another metallic electrode in the system

1.2.27
electropositive

the state of a metallic electrode when its potential is positive with respect to another metallic electrode in the system

1.2.28
electro-osmosis

the passage of a liquid through a porous medium under the influence of a potential difference

1.2.29
galvanic action

a spontaneous chemical reaction which occurs in a system comprising a cathode and an anode in electrical contact and with an intervening electrolyte, resulting in corrosion of the anode

1.2.30
groundbed

a system of buried or submerged electrodes connected to the positive terminal of an independent source of direct current, in order to lead to earth the current used for the cathodic protection of a buried or immersed metallic structure

1.2.31
grounding cell

two electrodes of zinc or other sacrificial material that are separated by insulating spacers and packaged in a low-resistivity backfill material

NOTE These provide, for surges and alternating currents, a low-resistance path between sections of a structure and from structure to earth but drain only a small direct current from the cathodic protection system.

1.2.32
holiday

a defect in a protective coating at which metal is exposed

NOTE This may, in some cases, be as small as a pinhole.

1.2.33
hydration (of cement)

the chemical and physical reactions between cement and water from which the material derives its strength

1.2.34
impressed current

the current supplied by a rectifier or other direct-current source (specifically excluding a sacrificial anode) to a protected structure in order to attain the necessary protection potential

1.2.35
instantaneous-off potential

the structure/electrolyte potential measured immediately after the synchronous interruption of all sources of applied cathodic protection current

1.2.36 joints

1.2.36.1
isolating joint

a joint or coupling between two lengths of pipe, inserted in order to provide electrical discontinuity between them

1.2.36.2
insulated flange

a flanged joint between adjacent lengths of pipe in which the nuts and bolts are electrically insulated from one or both of the flanges and the jointing gasket is non-conducting, so that there is an electrical discontinuity in the pipeline at that point

1.2.37
interaction test

a test to determine the severity of corrosion interaction between two buried or immersed structures

1.2.38
ion

an atom, or group of atoms, carrying a positive or negative electrical charge

1.2.39
joint cathodic protection scheme

a scheme in which different structures, usually separately owned, are bonded together and protected by a common cathodic protection installation

1.2.40
passivity

the state of the surface of a metal or alloy susceptible to corrosion where its electrochemical behaviour becomes that of a less reactive metal and its corrosion rate is reduced

NOTE This is generally the result of protective film formation.

1.2.41 pH

1.2.41.1
pH value

a logarithmic index for the concentration of hydrogen ions in an electrolyte

NOTE See **A.1**.

1.2.41.2
acid

containing an excess of hydrogen ions over hydroxyl ions

1.2.41.3
alkaline

containing an excess of hydroxyl ions over hydrogen ions

1.2.41.4
neutral

containing equal concentrations of hydrogen ions and hydroxyl ions

1.2.42
pitting

a non-uniform corrosion of a metal whereby a number of cavities, not in the form of cracks, are formed in the surface

1.2.43
polarization

change in the potential of an electrode as the result of current flow

1.2.44
polarization cell

a device inserted in the earth connection of a structure that drains only a small current from the source used to provide cathodic protection for the structure, but provides a low resistance path to currents from high d.c. voltages and all a.c. voltages carried by the structure

1.2.45
protection current

the current made to flow into a metallic structure from its electrolytic environment in order to effect cathodic protection of the structure

1.2.46
protection potential

the more negative level to which the potential of a metallic structure, with respect to a specified reference electrode in an electrolytic environment, has to be depressed in order to effect cathodic protection of the structure

1.2.47
protective coating

a dielectric material adhering to or bonded to a structure to separate it from its environment in order to prevent corrosion

1.2.48
reaction (anodic, cathodic)

a process of chemical or electrochemical change, particularly taking place at or near an electrode in a cell

1.2.49
redox potential

the potential taken up by a platinum electrode with respect to a reference electrode

NOTE See **A.2**.

1.2.50 reference electrodes

1.2.50.1
reference electrode

an electrode the potential of which is accurately reproducible and which serves as a basis of comparison in the measurement of other electrode potentials

NOTE Sometimes termed a "half cell".

1.2.50.2
calomel reference electrode

a reference electrode consisting of mercury and mercurous chloride (calomel) in a standard solution of potassium chloride

1.2.50.3
copper/copper sulphate reference electrode

a reference electrode consisting of copper in a saturated copper sulphate solution

1.2.50.4
silver/silver chloride reference electrode

a reference electrode consisting of silver, coated with silver chloride, in an electrolyte containing chloride ions

1.2.50.5
standard hydrogen electrode

a reference electrode consisting of an electro-positive metal, such as platinum, in an electrolyte containing hydrogen ions at unit activity and saturated with hydrogen gas at 1 atm

1.2.50.6
sensing electrode

a permanently-installed reference electrode used to measure the structure/electrolyte potential and to provide a reference signal to control the protection current of an automatic impressed current system

1.2.51
saponification

the chemical process of forming a soap; more particularly a deterioration by softening of paint films caused by the action of aqueous alkali on fatty-acid constituents of the film

1.2.52
stray current

current flowing in the soil or water environment of a structure and arising mainly from cathodic protection, electric power or traction installations, and which can pass from the environment into the structure and vice versa

NOTE Stray *alternating* current is not considered in depth in this standard (see **3.8.4**).

1.2.53 structures

1.2.53.1
protected structure

a structure to which cathodic protection is applied

1.2.53.2
unprotected structure

a structure to which cathodic protection is not applied

1.2.53.3
primary structure

a buried or immersed structure cathodically protected by a system that may constitute a source of corrosion interaction with another (secondary) structure

1.2.53.4
secondary structure

a buried or immersed structure that may be subject to corrosion interaction arising from the cathodic protection of another (the primary) structure

1.2.54
structure/electrolyte potential

the difference in potential between a structure and a specified reference electrode in contact with the electrolyte at a point sufficiently close to (but without actually touching) the structure to avoid error due to the voltage drop associated with any current flowing in the electrolyte

NOTE Similar terms such as metal/electrolyte potential, pipe/electrolyte potential, pipe/soil (water) potentials etc., as applicable in the particular context are also used.

1.2.55
sulphate-reducing bacteria

a group of bacteria found in most soils and natural waters, but active only in conditions of near neutrality and freedom from oxygen, which reduce sulphates in their environment with the production of sulphides

1.2.56
utilization factor

that proportion of anode material on an anode that may be consumed before the anode ceases to provide a current output as required in the design

1.3 Exchange of information

The application of cathodic protection externally to buried or immersed objects causes direct current to flow through the soil or water and this may accelerate the corrosion of other buried structures or plant. Therefore the owners of any other structure or plant near the cathodic protection installation and/or protected structure should be consulted, as discussed in section 9. This does not apply to plant protected internally by cathodic protection. There are also possibilities of electrical interference with telecommunication circuits and of causing false operation of railway signalling circuits (see **9.3.6**).

Cathodic protection equipment may give rise to certain hazards, particularly in areas where there are flammable liquids or gases. In such cases, consultation between the installer and owner is necessary. Where the equipment is required to be flameproof, the relevant provisions of BS 5345 apply.

1.4 Quality and performance of equipment

The quality and standard of performance of the components of a cathodic protection system should be not inferior to those specified in the appropriate British Standard.

In addition to the standards referred to in the text of this code, relevant British Standard specifications and codes of practice are listed in Appendix B.

Section 2. General principles

2.1 Introduction

This section covers the electrochemical aspects of corrosion and cathodic protection as an aid to the understanding of the rest of this code. There is, inevitably, some over-simplification. A number of reference books dealing with the subject are included in the bibliography (see references [1] to [11]).

2.2 Behaviour of buried or immersed metals in the absence of cathodic protection

2.2.1 The nature of metal corrosion

When a metal corrodes in contact with an electrolyte, neutral atoms pass into solution by forming positively charged ions. Excess electrons are left in the metal. The process is shown for iron in equation 1.

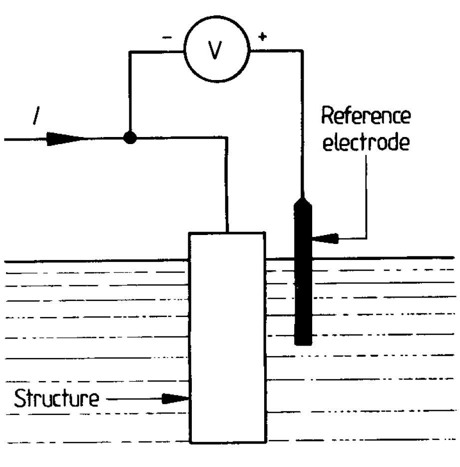
$$\mathrm{Fe} \longrightarrow \mathrm{Fe}^{++} + 2\mathrm{e}^{-} \qquad (1)$$

Thus corrosion is accompanied by the flow of an electric current from metal to electrolyte due to the movement of positive ions into the electrolyte and of electrons into the metal. Any area at which current flows in this direction is referred to as an anodic area, and the reaction is called an anodic reaction. The metallic ions may react with negative ions in the electrolyte to give insoluble corrosion products (for example, rust in the case of steel). Such reactions do not materially affect the corrosion process except where insoluble corrosion products are able to stifle further corrosion attack (see **2.2.4**).

Overall electric neutrality has to be maintained. For the corrosion reaction to proceed, therefore, the movement of electrons into the metal and positive ions into the electrolyte at the anodic areas has to be counterbalanced by the passage of current from the solution to the metal and the consumption of electrons at other areas, known as cathodic areas. Various reactions can occur at cathodic areas (see **2.2.5**); they are known as cathodic reactions. Thus during the corrosion process, electrons are transferred through the metal from one site on the metal surface to another (electronic conduction) and positive ions are transported through the electrolyte (electrolytic conduction). The current flowing round the circuit is proportional to the corrosion rate. For example, in the case of iron or steel, two electrons are released for each atom going into solution, as shown in equation 1, and a corrosion current of 1 A corresponds to a loss of about 9 kg of metal a year.

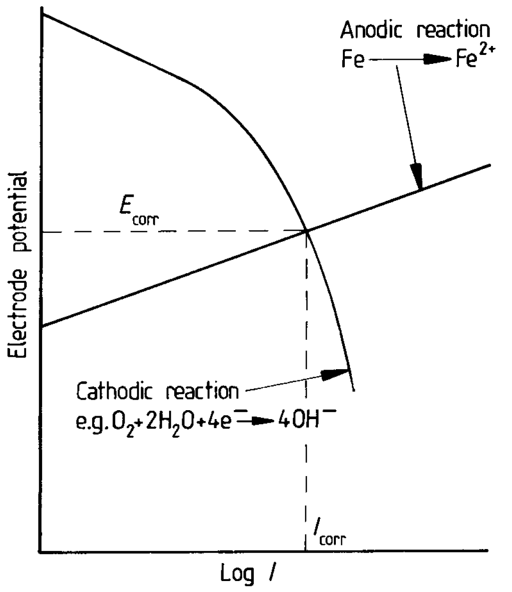
2.2.2 Polarization

The potential difference between any metal and its surrounding electrolyte varies with the density and direction of any current crossing the interface. This variation is referred to as polarization. The potential difference is also dependent on the types of chemical reaction occuring at the metal surface. The metal/electrolyte potential difference may be measured using a reference electrode and the arrangement shown in Figure 1. Since the measured potential difference will also depend on the type of reference electrode which is used (see **10.2.1**), the type of reference electrode should always be stated. The polarization of a metal surface may be conveniently represented by plotting potential against the logarithm of current flowing to or from the metal surface, i.e the degree of polarization of the anodic and cathodic reactions. A schematic representation is shown in Figure 2. Although the current of the cathodic reaction is in the negative direction, it is shown in the figure in the positive direction for convenience. It will be easily seen that at the corrosion potential E_{corr} the anodic and cathodic currents are equal in magnitude and opposite in sign. Hence all the electrons produced by the anodic reaction are consumed by the cathodic reaction, which is the condition existing on a freely corroding metal surface. I_{corr} is the corrosion current at the corrosion potential E_{corr}. From the figure it can be seen that if the potential of the metal can be reduced by external means, the corrosion (anodic) reaction rate will decrease and the cathodic reaction rate will increase. Conversely, the corrosion rate is increased by making the metal more positive.



I is the polarization current

Figure 1 — Arrangement for measurement of structure/electrolyte potential



E_{corr} is the corrosion potential
I_{corr} is the corrosion current

Figure 2 — Schematic polarization curves

2.2.3 Formation of cells

If the potentials of two different metals with respect to an electrolyte are measured with the arrangement shown in Figure 3, and the metal marked A is found to be more negative; when the switch is closed, current will flow in the direction shown by the arrows. Metal A will therefore be the anode and will be corroded, while metal C acts as the cathode.

Commonly used metals and conducting materials are listed below in such order that each normally acts as an anode with respect to all the materials which follow it:

a) magnesium (most electronegative of the materials listed);

b) zinc;

c) aluminium (certain aluminium alloys may be more electronegative);

d) iron and steel;

e) lead;

f) brass;

g) copper;

h) graphite, coke etc. (most electropositive of the materials listed).

Thus, for example, the connection of magnesium to iron results in a cell in which the magnesium acts as an anode and the iron as a cathode.

Cells may also arise due to differing properties of the electrolyte in contact with different parts of the same metal surface. An increased concentration of oxygen tends to make the potential of a metal more positive; thus variation of soil density and porosity is a common cause of corrosion cells. Arrangements giving rise to such cells are shown in Figure 4. The size of the cells may vary greatly. In Figure 4(c), for example, the anodic area may be small. The resultant pitting can, however, lead to rapid penetration of the metal.

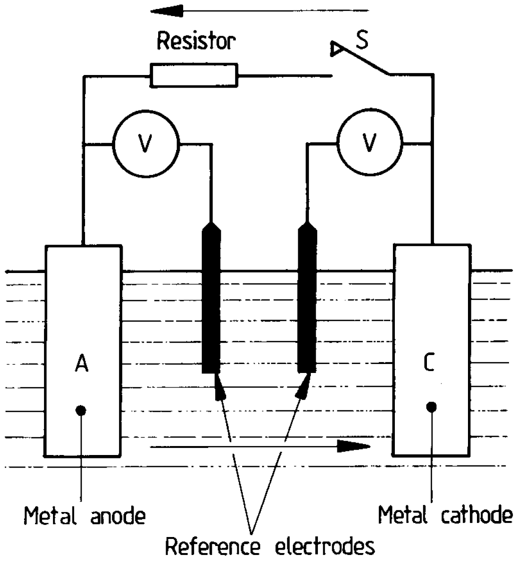


Figure 3 — Formation of a cell

2.2.4 Passivity

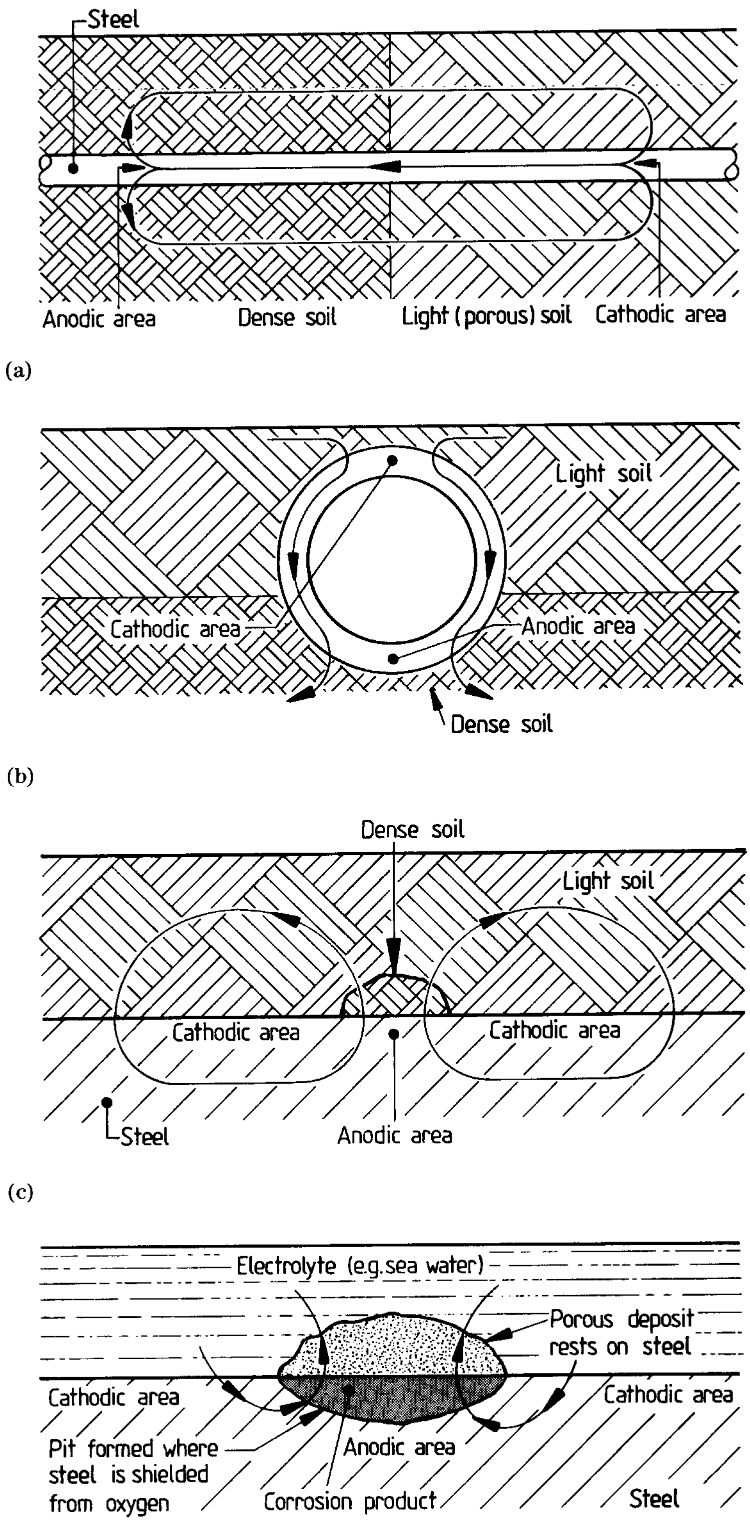
If the corrosion product forms an adherent film on the surface of the metal, further attack may be prevented. The corrosion resistance of stainless steels, for example, is due to protection by oxide films. The metals aluminium, titanium and tantalum also form highly resistant and adherent oxide films which restrict the rate at which metal ions can pass into solution.

2.2.5 Reactions at cathodic areas

Equations 2 and 3 show the most common reactions that occur at cathodes.

$$\underset{\text{Hydrogen ions}}{2\,H^+} + \underset{\text{Electrons}}{2\,e^-} \longrightarrow \underset{\text{Hydrogen gas}}{H_2} \qquad (2)$$

$$\underset{\text{Oxygen}}{O_2} + \underset{\text{Water}}{2\,H_2O} + \underset{\text{Electrons}}{4\,e^-} \longrightarrow \underset{\text{Hydroxyl ions}}{4\,OH^-} \qquad (3)$$



NOTE. Arrows indicate the direction of current flow.

Figure 4 — Cells due to differential aeration

The first of these reactions is favoured by acidity (excess of hydrogen ions) while the second is favoured by the presence of dissolved oxygen and near-neutral conditions. Both tend to make the electrolyte alkaline near the cathode (excess of hydroxyl ions over hydrogen ions: see Appendix A).

In contrast to the anodic reaction (for example equation 1), cathodic reactions do not involve the passage of metal into solution. Hence, in general, corrosion does not occur at cathodic areas. In aerated, near-neutral conditions, the iron ions produced at the anode react with the hydroxyl ions formed at a nearby cathodic site to produce ferrous hydroxide. However, ferrous hydroxide is readily converted to rust in the presence of oxygen, thus the overall reaction which proceeds through a series of intermediate steps is that given in equation 4.

$$4\,\mathrm{Fe} + 3\,\mathrm{O_2} + 2\,\mathrm{H_2O} \rightarrow 2\,\underset{\text{Hydrated ferrous oxide or rust}}{\mathrm{Fe_2O_3.H_2O}} \qquad (4)$$

In practice the rate of corrosion is often determined by the rate at which the cathodic reaction can be maintained. For example, if the relevant reaction is that given by equation 3, replenishment of oxygen may be the controlling factor.

In near-neutral anaerobic soils, sulphate-reducing bacteria give rise to a further type of cathodic reaction and soils of this kind are often particularly aggressive to iron and steel. It is possible by determining pH and redox potential, to assess whether conditions are such that sulphate-reducing bacteria are likely to be active (see Appendix A).

The reactions occurring at cathodes do not directly result in corrosion. It should be noted, however, that the environment of the metal is altered, for example it becomes more alkaline (see above). In the case of aluminium and occasionally lead, corrosion may result. Alkalinity may also cause deterioration of paints and other coatings by saponification. Effects of the cathodic reactions that arise when cathodic protection is applied are listed in **3.8.1**.

2.3 Cathodic protection

2.3.1 Basis of cathodic protection

Corrosion requires the existence of anodic and cathodic areas. The corrosion process in aerated water is shown in Figure 5. If electrons are caused to flow into the structure from an external source, then the positive ions leave the metal surface less readily, but the cathodic process is enhanced.

These principles can be illustrated using polarization curves as shown in Figure 6. If the potential of the metal is reduced by the external supply of electrons from E_{corr} to E_{p}, then the anodic current and hence the corrosion attack will cease and cathodic protection will have been achieved. E_{p} is called the protection potential.

The cathodic current (I_{p}) at the protection potential has to be sustained by the external source in order to maintain cathodic protection. This is achieved by connecting the structure to an auxiliary anode which has to provide the necessary current density to all parts of the surface of the structure which will then become the cathode. If the anode is a material such as magnesium, the current will flow because of the potential difference arising from the cell formed, and the auxiliary anode will be consumed. This type of anode is called a sacrificial anode. Alternatively, the potential difference may be derived from a separate d.c. voltage source. Such an arrangement is termed an impressed current system and allows a wide choice of materials for the auxiliary anode.

These materials are normally chosen so that they are consumed at only a very low rate. Typical figures for the average current density required to maintain the protection potential in particular applications are given in the relevant sections of this code. It is stressed, however, that the average figures provide general guidance only.

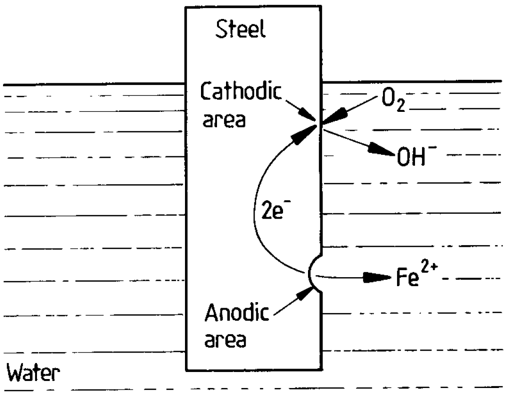
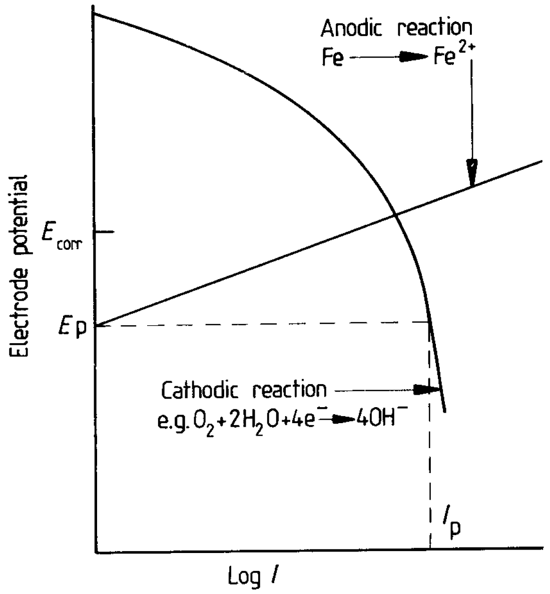


Figure 5 — Anodic and cathodic reactions at a steel surface



E_{corr} is the corrosion potential
E_p is the protection potential
I_p is the protection current

Figure 6 — Relationship between polarization and cathodic protection

2.3.2 Cathodic protection criteria

2.3.2.1 *General*

The potential difference between a metal surface and the electrolyte (soil or water) is normally used as the criterion that satisfactory cathodic protection has been achieved. The minimum values that need to be achieved (the protection potentials) are listed in Table 1. Values more positive than these will allow corrosion to occur. The values depend on the reference electrode used; factors affecting the choice of reference electrode are discussed in **10.2.1**.

In practice the potential may vary considerably over the surface of the metal. It is therefore important in assessing, for example, a cathodic protection installation on a buried pipeline, to ensure that the measurements should enable the least negative metal/soil potential to be located. This will necessitate measuring at a sufficient number of points along the route of the pipeline, taking into account the considerations given in **10.3.2**.

Unless the reference electrode is placed very close to the metal surface, measurement of the potential difference between the metal surface and the electrolyte can be considerably affected by the potential drop produced by the protection current as it flows through the surrounding electrolyte to the structure. This effect, which is often referred to as "IR drop", has the effect of making the measured potential more negative than the actual potential at the metal/electrolyte interface. Unless a method of measurement is used that eliminates or sufficiently reduces the effects of IR drop (see **10.3.2.2**) adjusting the cathodic protection current to the value that gives the relevant protection potential shown in Table 1 may not provide full protection. IR drop is dependent on electrolyte resistivity and is particularly pertinent to buried structures. With a coated structure the resistance of the coating will also have an effect. The instantaneous-off potential method as a means of minimizing IR drop error is rapidly gaining acceptance. However, alternative techniques are likely to be developed, and any technique which can be shown to reduce IR errors to acceptable levels may be employed.

Subject to the above considerations, cathodic protection of a particular metal is achieved by bringing it to the potential shown in Table 1 or to a more negative potential.

Special recommendations relating to particular metals are given in **2.3.2.2** to **2.3.2.6**.

2.3.2.2 *Iron and steel*

As shown in Table 1, a more negative potential is recommended for iron and steel when they are installed in conditions that are likely to become anaerobic, for example clay soils. This is because of the effects of sulphate reducing bacteria.

2.3.2.3 *Stainless steels*

Polarization of stainless steels to excessively negative potentials may result in hydrogen evolution which can cause blistering and loss of mechanical strength.

In many environments, stainless steels will not need protection. In some cases anodic protection is used (see **8.3.2**).

Stainless steels are, however, often susceptible to crevice corrosion. A crevice may be encountered at a riveted or bolted seam for example, or between a metal and a non-metal such as at a gasketed joint. Crevice attack is a particular form of differential aeration corrosion and is most often encountered in a marine environment. It has been found that cathodic protection will significantly reduce the incidence and severity of this form of corrosion. Polarization to potentials given for iron and steel in Table 1 is necessary. It should be noted however that a stainless steel surface may become more susceptible to crevice corrosion attack if it receives cathodic protection for some time and is then disconnected from the cathodic protection system.

Experience has shown that random pitting of stainless steel may not be influenced by cathodic protection, despite the evidence from certain laboratory studies.

2.3.2.4 *Steel in concrete*

Iron and steel that is fully enclosed in sound concrete free from chlorides would not normally require cathodic protection. If steel is only partly enclosed in concrete, the protection potential is determined by the part that is exposed to soil or water as is indicated in Table 1. If cathodic protection is to be applied, for example, because of evidence of chloride intrusion (see **5.1.1**) other criteria may need to be adopted for the steel in concrete. Correct or reliable measurement of the actual steel/electrolyte potential is not always possible and a criterion based on the level of polarization achieved may be more appropriate.

One such system gaining general acceptance [12] is to require as evidence of protection that the instantaneous-off potential (see **10.3.2.3**) should be 100 mV more negative than the fully decayed potential (measured up to 4 h later). The cathodic protection of reinforcing steel in concrete is discussed in section **5**.

2.3.2.5 *Aluminium*

Aluminium may corrode if the potential is made too strongly negative and, for this reason, it is not normally included in cathodic protection schemes. There have been indications that corrosion can be prevented if the potential is maintained between the limits shown in Table 1.

2.3.2.6 *Lead*

In alkaline environments, lead may occasionally be corroded at very negative potentials.

Table 1 — Minimum potentials for cathodic protection

Metal or alloy	Reference electrode (and conditions of use)			
	Copper/copper sulphate (in soils and fresh water)	Silver/silver chloride/saturated potassium chloride (in any electrolyte)	Silver/silver chloride/sea-water (see note 1)	Zinc/sea-water (see note 1)
	V	V	V	V
Iron and steel				
aerobic environment	– 0.85	– 0.75	– 0.8	+ 0.25
anaerobic environment	– 0.95	– 0.85	– 0.9	+ 0.15
Lead	– 0.6	– 0.5	– 0.55	+ 0.5
Copper-based alloys	– 0.5 to – 0.65	– 0.4 to – 0.55	– 0.45 to – 0.6	+ 0.6 to + 0.45
Aluminium				
Positive limit	– 0.95	– 0.85	– 0.9	+ 0.15
Negative limit	– 1.2	– 1.1	– 1.15	– 0.1

NOTE 1 For use in clean, undiluted and aerated sea-water. The sea-water is in direct contact with the metal electrode.
NOTE 2 All figures have been rounded to the nearest 0.05 V.

Section 3. Application: considerations applicable to most types of structure

3.1 Introduction

This section indicates the range of applications of cathodic protection and presents factors which determine whether it would be economical in particular cases. The general basis of design for cathodic protection systems is described and the general features of materials and equipment are indicated.

3.2 Range of application

Cathodic protection can, in principle, be applied to any metallic structure or plant that is in contact with a mass of soil or water. The application of cathodic protection to metal surfaces that are intermittently immersed, for example due to the action of tides, may also be beneficial.

Economic considerations, however, sometimes restrict the range of application. It may, for example, be uneconomical to protect certain types of existing structure because the cost of making them suitable for cathodic protection is excessive.

The function of the structure or plant under consideration will determine the benefit to be expected by suppressing corrosion. If the consequences of penetration by corrosion are important, for example, hazards due to leakage of a toxic or flammable gas or liquid, or interruption of the operation of a large plant or the failure of a ship's plate, the need to ensure complete reliability will become overriding and complete cathodic protection to the potentials listed in Table 1 would be regarded as economical even under otherwise unfavourable circumstances. However, it should be noted that the first increment of potential fall is more effective in reducing corrosion than the next increment [9] and in some circumstances, e.g. with non-hazardous contents or where a degree of corrosion can be tolerated by the structure, less negative potentials than those listed in Table 1 may be acceptable and/or economical.

Cathodic protection has been applied to a large variety of structures, including pipelines, storage tanks, ships and industrial plant.

3.3 Basis of design

It has been shown in section 2 that cathodic protection is achieved by causing current to flow from the surrounding electrolyte into the structure at all points. The criterion for protection is that the potential of the metal with respect to the electrolyte immediately adjacent to it should be, at all positions, more negative than the appropriate protective potential given in Table 1. The current required to achieve this will vary according to type of structure and environmental conditions as discussed in sections 4 to 8. Figure 7(a) represents, in outline, the components of a cathodic protection system which consists of a buried or immersed anode, a connection to the structure to be protected and, in the case of impressed current systems only, a source of e.m.f.

Current flows in the metallic parts of the circuit in the directions indicated by the arrows and returns through the electrolyte (soil or water) to the protected structure. When the potential drop through the electrolyte and/or the structure is appreciable, the potential change due to the cathodic protection is non-uniform as shown in Figure 7(b). The following factors tend to increase the non-uniformity of the cathodic protection:

a) small separation between the anode and the structure (particularly if the electrolyte resistivity is high);

b) high resistivity of soil or water (particularly if anodes are close to the structure);

c) high current density required to protect the structure;

NOTE 1 The current density will be governed by the quality of the coating, if any, and the availability of oxygen at the surface of the metal or the activity of sulphate-reducing bacteria (see **2.2.5**).

d) high electrical resistance between different parts of the structure;

e) non-uniform coating quality.

NOTE 2 The potential difference between the metal and its environment is liable to be less at a coating defect.

The tendency for the current density to be highest at points nearest the anode may occasionally be an advantage since it is possible to concentrate the effect at a point where it is most needed. For example, when corrosion of iron or steel occurs due to proximity of a more electropositive metal, the attack is often local and only a small proportion of the surface may require protection.

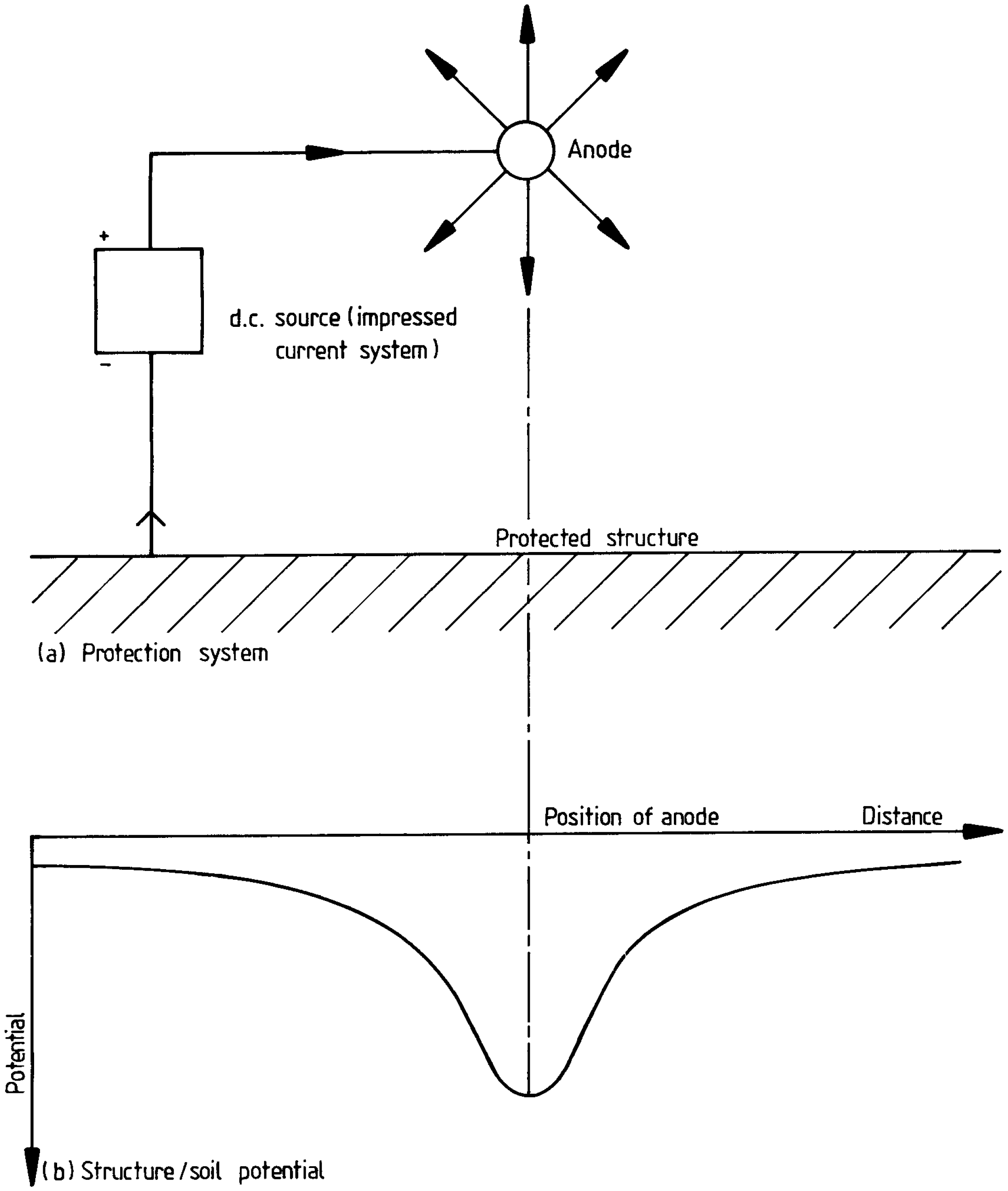


Figure 7 — A cathodic protection system and the distribution of structure/electrolyte potential

Normally, however, the whole of the metal surface is to be protected and non-uniformity, as shown in Figure 7(b), is uneconomical because some parts of the surface receive more current than is required to attain the protection potential. Moreover, since the potential should, generally, not be made too strongly negative for the reasons given in **3.8.1**, it may be impossible to compensate for poor initial design by increasing the current and thereby making the potential more negative. Additional anodes will therefore be needed and, in the case of protection by impressed current on extensive structures, this will also entail the provision of additional sources of e.m.f. Thus, if the use of cathodic protection is envisaged, a first step is to consider whether the structure or plant can be designed, or modified if it already exists, in such a way as to make the installation of cathodic protection more economical. These aspects are discussed further in **3.4**. Consideration should also be given to the correct placing of anodes both as regards separation from the structure and their distribution over the surface. When structures such as pipelines are being protected with impressed current, considerations such as the availability of power supplies may, however, have an important bearing on the design.

The two systems for cathodic protection, sacrificial anodes and impressed current, are described in **3.5** and **3.6** and their characteristics are compared in **3.7**. It is sometimes possible to make use of current flowing in the soil due to the operation of traction systems (see **4.6**). Sometimes a structure is protected by a combination of a sacrificial anode system and an impressed current system operating together. This may be called a hybrid system.

Economical design of a structure or plant and its associated cathodic protection system entails striking the best possible balance between factors which affect the initial cost (effectiveness of structure coating, electrical conductance between sections of the structure or plant, extent and position of the anode system, number of separate units etc.) and factors which affect the running cost, notably the power required and frequency of replacement of anodes. There are, in addition, certain considerations which relate only to particular types of structure (see sections 4 to 8). For example, in the cathodic protection of ships' hulls or of pumps, consideration should be given to the hydraulic drag arising from the installation of anodes. In the case of buried structures, possible effects of the direct current flowing in the soil on other structures in the vicinity may also have an important effect on the economics of the scheme (see section 9). There are also some secondary effects of cathodic protection which need to be taken into account (see **3.8.1**).

3.4 Design or modification of structures to be protected

3.4.1 Electrical continuity

It may be necessary to install continuity bonds between different sections of the structure or plant to be protected before cathodic protection is applied. The resistance of these should be sufficiently low to ensure that the potential drop due to the passage of the protective current through the structure is small. In the case of impressed current installations, it may be economical to improve connections between different parts of the structure, even though metallic connections already exist, in order to reduce the total resistance.

It should be noted that if the structure is not metallically continuous, part of the protection current flowing in the electrolyte towards a protected section may pass through isolated sections of the structure. Corrosion may be accelerated where such currents are discharged from the metal and return to the electrolyte (see section 9). This accelerated corrosion could be internal where conducting fluids are being conveyed in pipelines.

3.4.2 Protective coatings

The function of a coating is to reduce the areas of metal exposed to the electrolyte (soil or water). By this means it is possible to reduce greatly the current density required for cathodic protection. The fact that the current is spread more uniformly may reduce the number of points at which cathodic protection need be applied (see also **3.3**).

A coating should, ideally, have a high electrical resistance and be continuous, i.e., there should be few “holidays”. It should be resistant to any chemical or bacterial action to which it might be exposed, and should withstand all temperature variations to which it may be subjected; no blisters should exist and the coating should adhere strongly to the surface to be protected; it should have satisfactory ageing characteristics and adequate mechanical strength. Ability to resist abrasion may be important in some applications.

Coatings may take the form of paints, epoxy or similarly based resins, or of thermoplastic materials such as polyethylene (PE) or polyvinyl chloride (PVC) either sintered, extruded or in sheet form. Enamels of coal-tar or bitumen reinforced with inorganic fibres, and petroleum wax impregnated fabric tapes are also used. The most suitable form of coating depends on the type of structure and its environment; more particular information is given in sections 4 to 8. In deciding upon the type of coating to be used, the aim should be to achieve overall economy in the combined cost of the protected structure and of the initial and running costs of the protection schemes. Due regard should be paid to the life expected of the structure and to the economics of repairing the coating should this become necessary.

In the case of buried structures, a secondary but important function of the coating is to reduce the current flowing thereby reducing the potential gradients in the surrounding soil and thus decreasing interaction with neighbouring buried structures (see **9.3.4**).

The protection current, particularly if strongly negative potentials are used, may produce sufficient alkali to affect the coating adversely (see **2.2.5**). The extent to which coatings are alkali resistant is therefore important in some applications. This is further discussed in **3.8.1** and, in relation to particular applications, in sections 4 to 8. It is, however, possible to give only general information in respect of coatings. If, in a particular case, the coating performance is critical, it would be desirable to determine the properties by test beforehand (see for example BS 3900-F10 and BS 3900-F11).

Useful information on coatings for iron and steel structures is to be found in BS 5493.

Concrete cannot be considered to be a substitute for an insulating coating and such a coating should be provided in addition wherever possible.

3.4.3 Electrical isolation

It often happens that a well-coated structure, to which cathodic protection could be applied economically, is connected to an extensive and poorly coated metallic structure the protection of which is not required or would be uneconomical.

In this situation, the well-coated structure should be isolated before applying cathodic protection to it. In the case of coated pipelines for example, the inclusion of isolating joints at terminal installations is normally considered to be essential.

A further application is the isolation of a section of a structure to prevent or reduce excessive effects on neighbouring structures due to interaction (see **9.3.5**). If the isolated section is so placed that the required continuity of the structure is interrupted, this should be restored using insulated cable.

It may, on occasion, be desirable to shunt an isolating joint by means of a resistor. For example, by choosing an appropriate value for the resistor, it might be possible to adjust the current so that it is sufficient to protect the relevant section of the structure but is insufficient to cause unacceptable interaction on nearby structures.

Isolating joints are sometimes required as part of the safety precautions at oil terminal jetties (see **12.7.9**). They should not be installed in above-ground situations where concentrations of flammable gas or vapour occur (see **12.7.3**).

The protection of only part of a structure may accelerate the corrosion of nearby isolated sections of the structure as explained in **3.4.1** and **9.2**. For this reason it may be advisable to apply a coating with a particularly high insulation resistance to the protected section of the structure where it is near unprotected equipment or to take the other measures described in **9.3.4.3** to prevent possible damage.

With equipment containing electrolytes, corrosion could similarly occur on the inner surface of the unprotected section. With low resistivity fluids, for example brine, such corrosion could well be rapid. For this reason the inclusion of isolating joints in, for example, pipelines containing sea-water or strong brine is inadvisable (see also **9.3.6.3**). It may be possible to use an internally coated section of pipe with an isolating joint at the unprotected end of the section (see **4.3.1.3**).

3.4.4 Provision for testing

A cathodic protection installation is unlikely to remain effective unless it is adequately maintained. Details of tests that are necessary are given in sections 10 and 11. It is important that the necessary facilities be considered at the design stage so that testing can be carried out conveniently from the time of commissioning the installation. Recommendations relating to the provision of testing facilities for different types of structure or plant are given in sections 4 to 8.

3.5 Sacrificial anode installations

3.5.1 General

As indicated in **2.3**, cathodic protection can be achieved by burying or immersing, in the electrolyte that is in contact with the metallic structure to be protected, an electrode which is more electronegative than the metal to be protected and connecting it to the latter. Typical arrangements are illustrated in Figure 8 to Figure 11.

The current available from a single anode in a given electrolyte is limited by the relatively low driving potential obtainable (see Table 2) and its shape and size (see **3.5.2**). Use of the method is therefore generally limited to the protection of small areas of metal unless the structure is well coated, except for low resistivity electrolytes, for example sea-water, where bare structures are frequently protected by sacrificial anodes. It may be necessary to distribute a number of anodes along the length or over the surface of the structure to be protected.

The anodes may be buried or immersed at a distance from the surface of the metal to be protected and connected to it by means of an insulated conductor (see Figure 8 and Figure 9) or may be attached directly to the surface of the metal (see Figure 10 and Figure 11). If the anode is placed at a distance from the structure, the available current is more efficiently used because it is more uniformly distributed. It is more important to provide adequate spacing between the anode and the structure if the electrolyte resistivity is high and/or the structure is uncoated. Direct attachment to the metal is satisfactory if the electrolyte resistivity is low and may be more convenient in some cases.

3.5.2 Sacrificial anode design

The electrical resistance of an anode to the surrounding electrolyte depends upon electrolyte resistivity and on the size and shape of the anode [13], [14]. For a given volume of anode material, used, for example, in the form of a cylindrical rod, the resistance decreases if the length is increased; the effect of diameter being less important.

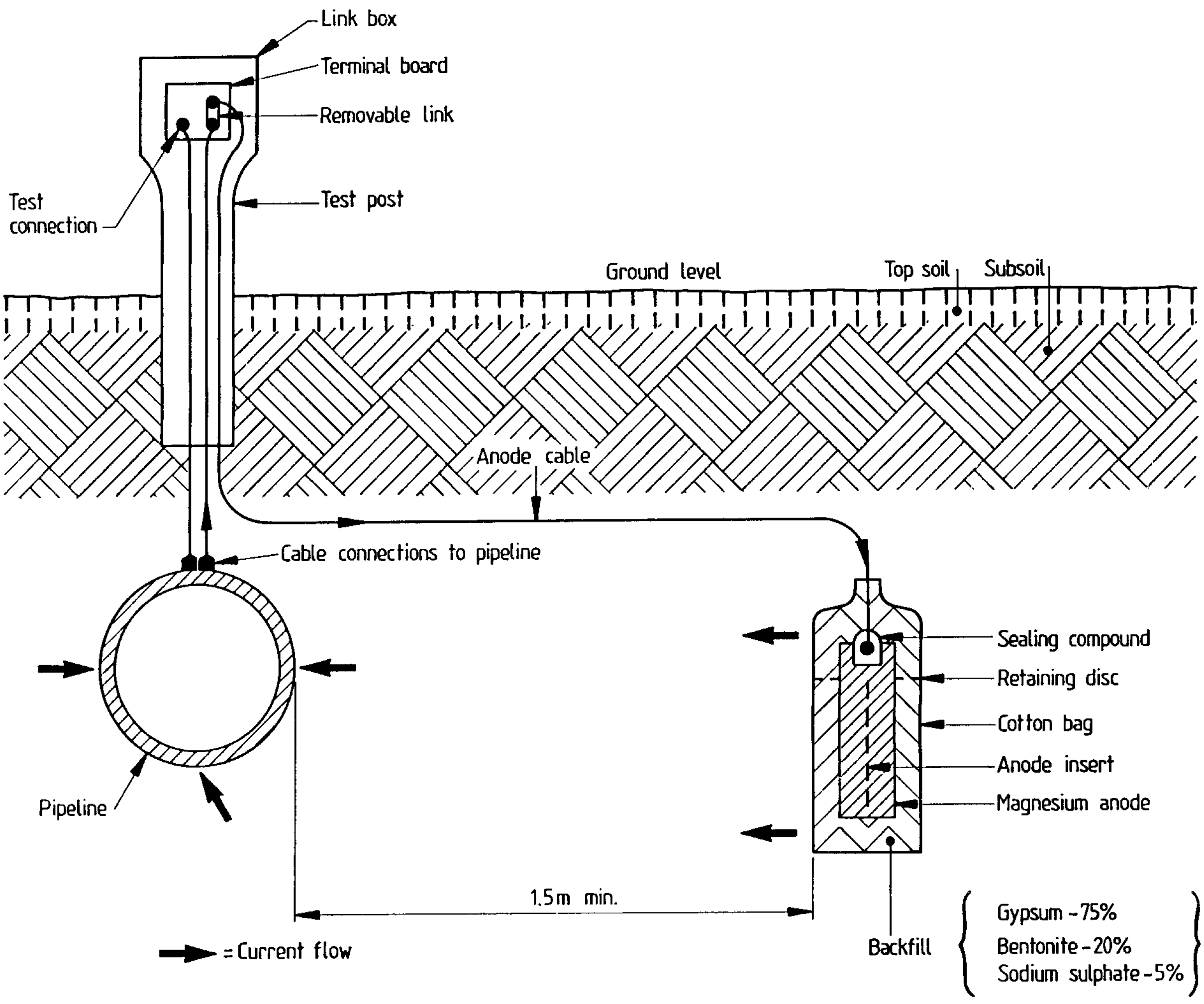
Thus, if the electrolyte resistivity is high (e.g. most soils) anodes are best made in the form of rods or relatively slender ingots or, for very high resistivity surroundings, as extruded strip or ribbon. With electrolyte of lower resistivity, provision of sufficient material to give an adequate life may require the use of thicker rods or ingots or even electrodes of approximately spherical form. Buried anodes can be surrounded with a backfill that has a lower resistivity than the soil to reduce the resistance (see Figure 8). The output also depends on the driving potential and thus upon the anode materials (see **3.5.3**).

Sacrificial anodes should contain inserts of a less electronegative material (e.g. steel) to maintain continuity and mechanical strength towards the end of the anode life. Inserts should be so shaped and treated that a mechanical key to the surrounding metal is provided.

Sacrificial anodes are normally produced by casting around a steel core or insert for direct or indirect attachment to the structure to be protected; some anodes may be produced by extrusion with or without a steel core. Cores are prepared prior to casting to ensure maximum electrical contact with the anodic alloy.

The inserts may project outside the body of the anode to provide means for attaching the anodes to the structure by welding or bolting (see Figure 10 and Figure 11). The former method gives the more reliable electrical connection but may render replacement more difficult. Alternatively, insulated cables may be connected to the steel insert. The connection should be sufficiently robust for the intended conditions of installation and service and should be designed so as to allow for almost complete consumption of the anode material before disconnection occurs. However, it is inevitable that not all of the anode material will be consumed, and it is common practice to include a utilization factor in the design.

A disconnection box, to enable the current to be interrupted or measured, is often useful. Such connections and the connection to the structure to be protected should be securely made and have low electrical resistance.



NOTE. In most cases anodes need to be distributed along the pipeline route.

Figure 8 — Typical cathodic protection of a buried pipeline with prepackaged sacrificial anodes

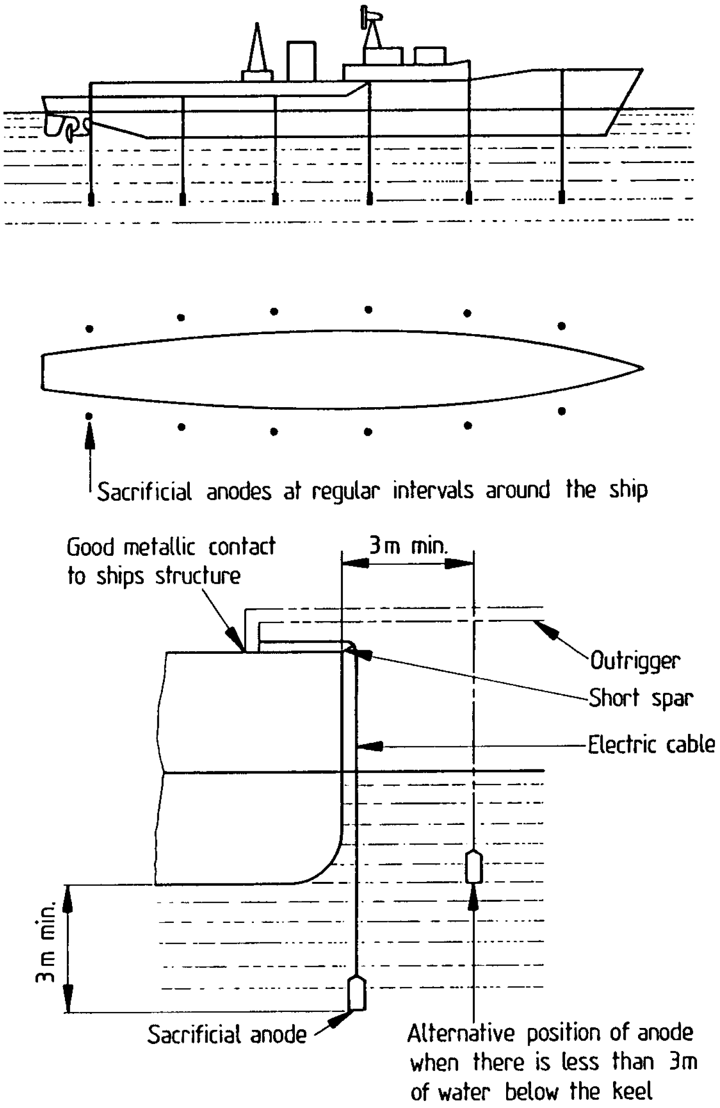


Figure 9 — Typical cathodic protection of a moored ship using sacrificial anodes

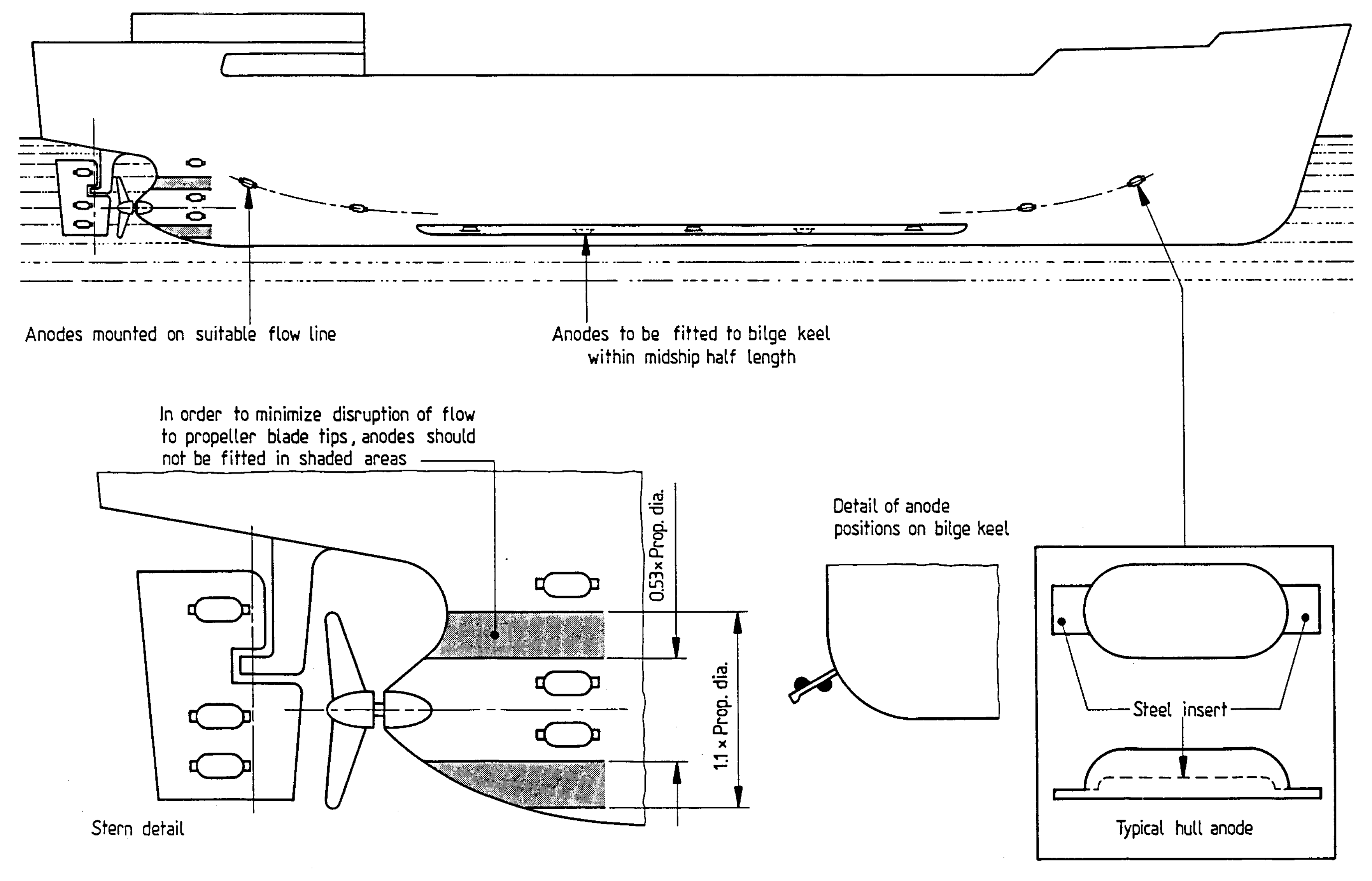
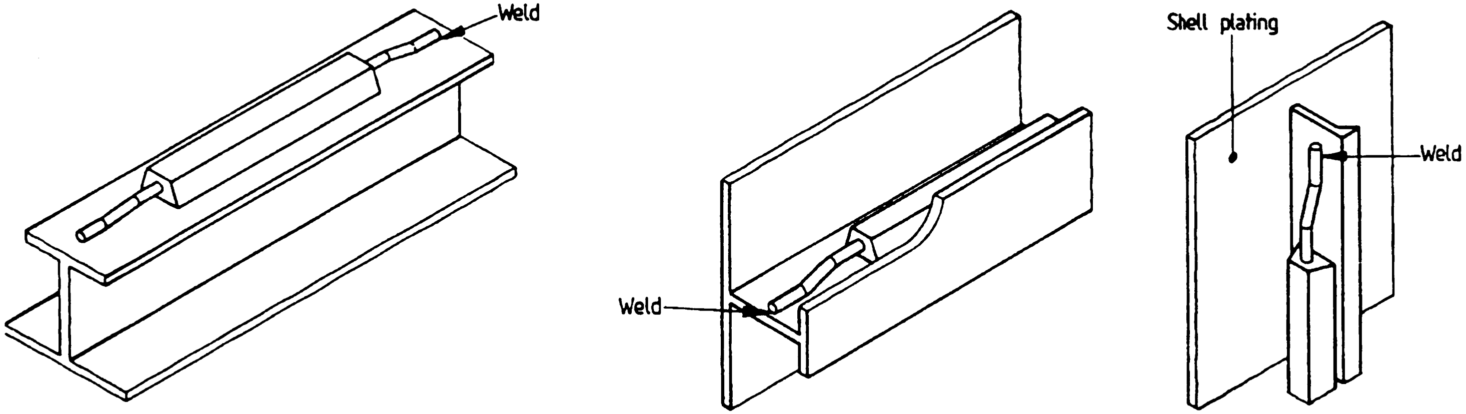


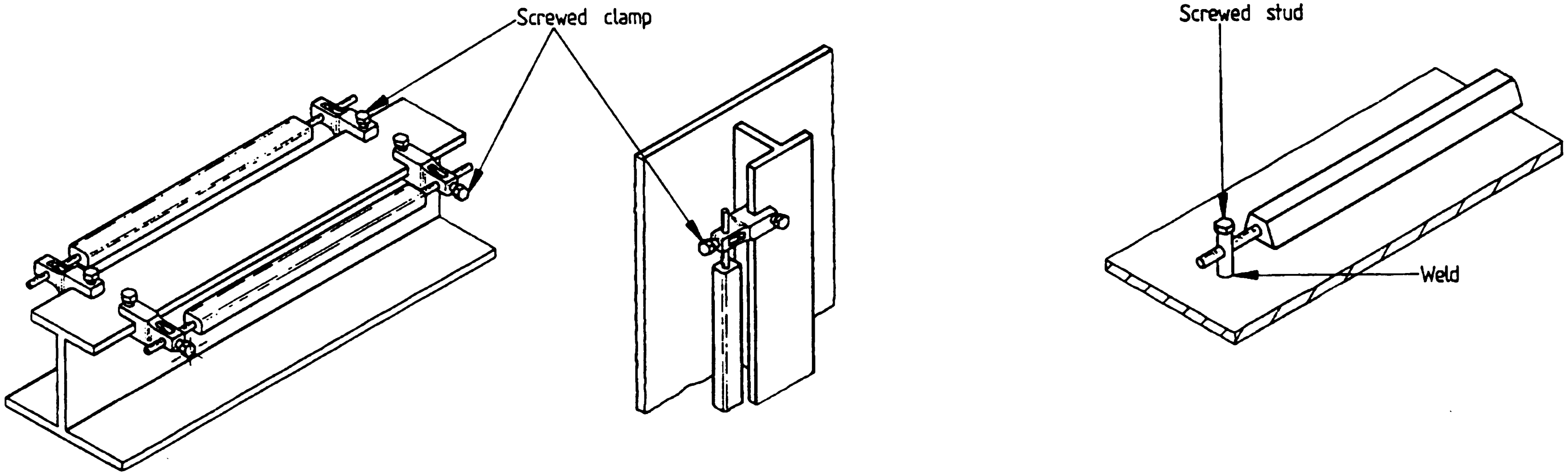
Figure 10 — Typical sacrificial anode scheme for cathodic protection of a ship's hull



(a) Bottom and side longitudinal

(b) Horizontal girders

(c) Vertical frame



(d) Bottom and side longitudinals

(e) Vertical frame

(f) Anode attachment

Figure 11 — Typical sacrificial anodes and installation arrangements for cathodic protection of storage tank interiors

3.5.3 Anode materials

3.5.3.1 *General*

Alloys used for sacrificial anodes are based on magnesium, zinc or aluminium. The performance, and hence the suitability of a particular alloy for a specific application, will depend on the composition of both the alloy and electrolyte, temperature of operation and anode current density. The compositions given in Table 2 are typical, but a wide variety of compositions exists within these groups of alloys.

NOTE Certain alloys may produce toxic products and it should be ascertained whether the particular alloy proposed is permitted under the intended conditions of use.

3.5.3.2 *Magnesium alloys*

There are two generic groups of magnesium alloys used in cathodic protection. Magnesium containing approximately 1.5 % manganese as a deliberate addition and magnesium containing approximately 6 % aluminium, 3 % zinc and 0.15 % manganese as additions. In both cases incidental impurities naturally occurring in the magnesium need to be controlled to limit polarization and self-corrosion. Manganese is added to sequester iron impurities and make the anode potential more negative. The high-manganese alloy has a higher driving potential and may be useful in higher resistivity electrolytes than the magnesium-aluminium-zinc alloys.

Magnesium alloys are used extensively where a high driving potential is desirable, e.g. in soils, and fresh and brackish waters. As their corrosion products are non-toxic they are suitable for use in potable water. Their low density and high driving potential make them particularly useful as suspended anodes and for temporary protection where the number of anodes should be limited for example, for ships that are laid up or being fitted out. Magnesium anodes can, however, produce sufficiently negative potentials to cause deterioration of paints and should therefore be used with care in some applications (see **3.8.1**). Furthermore, hydrogen is evolved from magnesium anodes and thermite sparking may occur when magnesium is impacted on rusty steel. The possibility of explosion hazards should therefore be borne in mind (see **12.6.1**). Special restrictions relating to the use of magnesium anodes in ships tanks are given in **6.4.4.1**.

3.5.3.3 *Zinc*

Commercial purity zinc is of limited use as an anode material because of excessive polarization due to iron present as an impurity. Anodes cast from high purity zinc, grade Zn 1of BS 3436, but selected to contain less than 0.0014 % iron, perform satisfactorily. Alloys based on less pure zinc have been formulated, in which the deleterious effect of iron is negated by addition of aluminium, which sequesters the iron as an inert intermetallic compound, or by addition of silicon which forms an iron rich dross which may be removed during the casting process. Cadmium may also be added to promote formation of soft, non-adherent corrosion products on the anode. Typical alloys may contain 0.5 % aluminium with up to 0.1 % silicon and/or cadmium. Alloys containing small additions of mercury, indium, calcium and lithium have been proposed for applications where higher driving potentials are desired, but none of these has found commercial application.

At temperatures exceeding 40 °C zinc may undergo a reduction of the driving potential, and has been shown to suffer intergranular corrosion with consequent loss of capacity. Alloys have been formulated to minimize intergranular attack. Zinc is particularly useful in sea-water applications, e.g. for the protection of ships' hulls, where its low driving potential against steel is insufficient to cause damage to most paints and enables the current output to vary with demand; thus, it is to some extent self-controlling (see **6.2.4.1**). Zinc anodes do not normally evolve hydrogen nor is there a risk of thermite sparking.

3.5.3.4 *Aluminium*

Aluminium corrodes to form an oxide film which is tightly adherent and causes rapid polarization when the pure metal is used as an anode. In chloride-containing electrolytes this breaks down to give very non-uniform attack by pitting.

The addition of an alloying element that leads to total breakdown of the oxide film ("activation") is necessary to make aluminium useful as an anode.

There are three generic groups of aluminium alloys used for cathodic protection anodes. All contain zinc in varying amounts together with tin, mercury or indium as the activator. In proprietary compositions additional alloying elements such as silicon, bismuth, manganese, magnesium or titanium may be included in the final formulation.

Table 2 — Typical information for sacrificial anode materials

Alloy	Common environment	Open-circuit potential (for reference electrode stated)	Capacity	Consumption rate
Magnesium		V	(A·h/kg)	kg/A year
1.5 % Mn	Soil/fresh water	– 1.7 (Cu/$CuSO_4$)	1 200	7.5
6 % Al, 3 % Zn	Soil/fresh water	– 1.5 (Cu/$CuSO_4$)	1 200	7.5
Zinc				
0.5 % Al, 0.1 % Cd	sea-water	– 1.05 (Ag/AgCl/sea-water)	780	11.25
Aluminium				
0.4 % Zn, 0.04 % Hg	Sea-water	– 1.05 (Ag/AgCl/sea-water)	> 2 800	3.15
5 % Zn, 0.04 % Hg	Sea-bed mud	– 1.05 (Ag/AgCl/sea-water)	1 800 to 2 000	4.38 to 4.86
3 % to 5 % Zn 0.01 % to 0.03 % In	Sea-water Sea-bed mud	– 1.1 (Ag/AgCl/sea-water)	1 800 to 2 000	4.38 to 4.86

Aluminium-zinc-tin alloys require heat treatment to achieve effective activation, and electrochemical testing is used in addition to chemical analysis to ensure adequate quality control. In general, these alloys have been superseded by the aluminium-zinc-mercury and aluminium-zinc-indium alloys which offer higher electrochemical capacity.

NOTE Some alloying elements, such as mercury or indium, are toxic and their release into the environment may be harmful. Their use in areas susceptible to pollution may therefore be discouraged.

Applications of aluminium-based alloy anodes are restricted to sea-water or sea-bed muds, and particular compositions are favoured in specific applications. In particular, not all alloys are suitable when operated at high temperatures especially when transferring heat. There are also indications that some formulations (notably aluminium-zinc-tin) suffer intergranular corrosion at lower temperatures (5 °C or less) and may be very slow to activate with reduced capacity.

Hydrogen evolution from aluminium alloys is generally slight. However, explosion hazards should always be borne in mind because of the risk of thermite sparking from impact of light alloys with rusting steel (see **12.7.1**).

3.6 Impressed current installations

3.6.1 General

Figure 12 shows a typical impressed current cathodic protection installation for a pipeline and the basis of the design is discussed in **3.3**. The selection of anode materials, and the design of the power source are discussed in **3.6.2** to **3.6.6**.

3.6.2 Anodes and groundbeds for impressed current installations

3.6.2.1 *Anode materials*

The most important characteristic of an anode material is normally the relationship between the rate of consumption and the current. Thus steel, if used as an anode, will provide about 0.11 A year/kg so that more than 9 kg of steel will need to be installed for each ampere year. Cast iron may remain effective longer than steel because the graphite that remains after the iron has been corroded away may leave the performance of the anode relatively unimpaired.

Other materials with lower consumption rates are available but these are generally more expensive. The relative importance of cost and consumption rate varies according to conditions. Thus, if the electrolyte resistivity is high, an extensive anode installation will be needed. Cheap material is therefore normally chosen and it will not be excessively costly to provide an additional amount to allow for its higher consumption. For anodes in a low resistivity environment, such as sea-water, a large mass of material is not generally required so that a compact anode of material capable of working at high current density may be more economical. Compactness may often be essential, for example to minimize interference with water flow. In such applications, the mechanical properties of the material and ability to withstand abrasion by suspended matter may also be important.

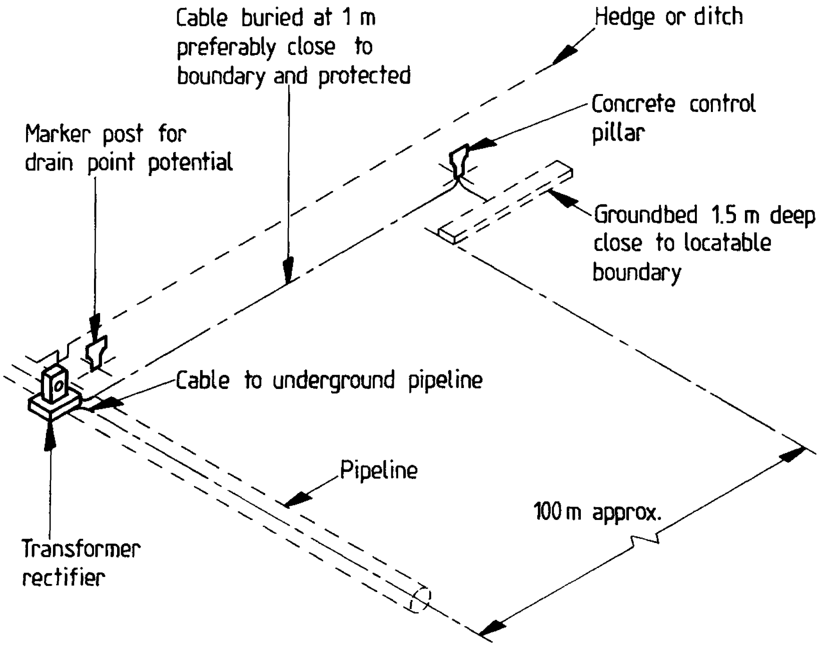


Figure 12 — Typical arrangement for the cathodic protection of a buried pipeline using impressed current

Graphite used as an anode material can be operated at a current density of 2.5 A/m^2 to 10 A/m^2. It is normally impregnated with wax or a synthetic resin to fill the pores and the consumption rate can then be appreciably lower than that of iron and steel. Chlorine which can be generated electrolytically in saline waters is particularly aggressive towards graphite anodes.

Other ferrous materials are also available which have a lower consumption rate than steel as long as the current density at the surface is not excessive. In these cases, a surface film of corrosion product is formed which is conducting. For example, high silicon cast iron will operate at current densities in the range 5 A/m^2 to 50 A/m^2 with consumption rates in the range 0.2 kg/A year to 1 kg/A year, according to anode shape and conditions. It is suitable for buried or immersed conditions. For use in sea-water 4.5 % chromium is usually included (see BS 1591) and an alloy containing 3 % molybdenum has been shown to be satisfactory.

Magnetite (Fe_30_4) is a natural mineral which can be made into a cathodic protection anode by proprietary methods. Such anodes are available in the form of cast hollow cylinders with an internal metallic lining to which a cable is connected and sealed. Magnetite has a low consumption rate of less than 5 g/A year and may be used in soils, fresh-water and sea-water. This material is brittle and requires careful handling.

The above materials are used with a carbonaceous backfill when buried, to lower the anode/earth resistance and to reduce primary anode consumption.

Carbonaceous backfills are prepared from cokes, bitumen (petroleum coke) and graphite granules and should contain at least 95 % carbon. They are used in a compacted form around anodes, where they lower anode/soil resistance, reduce primary anode consumption and facilitate the release of anodic gaseous products.

Lead alloys of various compositions are used in sea-water applications but are unsuitable for installations where deposits may form. These anodes rely on the formation of a lead dioxide ($Pb0_2$) surface film which constitutes a conducting medium that does not deteriorate rapidly and is self-repairing. For example, lead alloyed with antimony and silver can operate at current densities up to 300 A/m^2. In another type, the lead is alloyed with silver and tellurium. The performance may be affected adversely in deep water or waters of low oxygen content.

Thin platinum wire may be inserted into the lead alloy surface to form a bi-electrode which can be beneficial in the initial formation of a film of lead dioxide. This mechanism operates at a current density greater than 250 A/m^2. Such anodes can be operated at current densities up to 2 000 A/m^2. Other lead alloys are available and the operating conditions may be affected by the type of alloy.

Platinum and platinum alloys e.g. platinum/iridium are too expensive for use as anodes except in special applications. They are, however, frequently used in the form of a thin layer of platinum or platinum alloy about 0.0025 mm thick on a titanium, niobium or tantalum substrate.

These metals are used as the substrate because they are protected under anodic conditions by an adherent, inert, non-conducting surface oxide film, and therefore resist corrosion at any gap in the platinum. The application of platinum or platinum alloy (platinizing) can be confined to those areas where current transfer is required.

Anodes using these materials can operate satisfactorily at current densities up to 1 000 A/m^2 of platinized surface but operating voltages dictate that a lower figure is used as a basis for design. In electrolytes containing chlorides, the oxide film on titanium may break down if the voltage exceeds 8 V; with niobium and tantalum 40 V is permissible. Higher voltages may be permissible with fully platinized anodes or in non-saline environments. The life of the platinum film may be affected by the magnitude and frequency of the ripple present in the d.c. supply. Ripple frequencies less than 100 Hz should be avoided. Therefore, anode/electrolyte potential needs to be suitably limited and full-wave, rather than half-wave, rectification is preferable. The life of the platinum film may also be affected by the electrolyte resistivity, the consumption rate increasing with resistivity.

Recent developments have included the use of oxides of precious metals (e.g. ruthenium and iridium), mixed with other oxides, on a titanium substrate. These have operating conditions similar to the platinized anodes described above and are said to withstand current reversal. Another material available is a conducting polymer extruded onto a copper conductor.

Characteristics of the principal anode materials are summarized in Table 3. These are arranged in order of cost/consumption rate and are given only as examples.

3.6.2.2 *Design and installation of anodes and groundbeds*

Whether an anode is intended to be buried or immersed, its mass should be sufficient for it to last for a number of years and the design, including that of the connection, should be such as to allow almost complete consumption of the anode material before continuity is broken, i.e. a high utilization factor (see **3.5.2**).

It is often impossible to provide a suitably low resistance to the soil by the installation of a single anode of a size that can be conveniently handled. In such circumstances, a number of anodes can be installed in a group and connected in parallel. Such an assembly is referred to as a groundbed.

Immersed anodes should be sufficiently robust to withstand the stresses imposed by any liquid flow. Anodes located within pipework or similar plant should not offer excessive resistance to flow. Care should be taken in their design and positioning to minimize vibration and the resulting possibility of fatigue failure.

Complete integrity of the insulation of the connecting cables to anodes is essential. Any metal exposed to the electrolyte (soil or water) will be rapidly corroded.

The location of anodes or groundbeds in relation to the protected structure should be carefully considered in all cases. This is because too small a separation may result in local overprotection with resultant risk of damage to the coating and poor distribution of protective current. On the other hand, the adoption of an unnecessarily remote position will incur increased cabling and power costs.

The product of the reaction at the anode is normally oxygen but in chloride solutions the reaction at an anode that is consumed gives rise to the production of chlorine. Materials that are resistant to chlorine should, therefore, be used for mounting the anode or for any connecting cables installed nearby. Chlorine evolution may cause nuisance or, in confined spaces, create a hazard (see **12.6.3**) and provision should be made for natural venting.

3.6.3 Sources of power

The usual source of power for cathodic protection is derived from a mains operated transformer-rectifier. Where mains power is not available, other types of generator such as diesel, solar, wind, thermoelectric or turbine may be used.

3.6.4 Transformer-rectifier units

The transformer-rectifier unit should be oil or air cooled, continuously rated, self contained and suitable for the environment in which it will operate. The unit should be housed in a robust enclosure suitable for pole, wall or floor mounting as applicable. The enclosure should be provided with a lockable, front opening door, and should be suitably protected against the environment in accordance with BS 5420. If used in a hazardous area it should be suitably certified (see **12.7.6**).

The incoming a.c. supply should be terminated via an appropriately rated cut-out fuse, double pole neutral linked switch fuse or circuit breaker and residual current device to BS 4293 in accordance with the supplier's requirements.

The mains transformer should be double wound in accordance with BS 171, continuously rated and suitable for connection to the mains supply. The transformer should be fitted with an earth screen between the primary and secondary windings.

The rectifier should be bridge connected for full wave rectification, continuously rated at maximum current over the whole voltage range, and provided with suitable protection against surges.

For standard constant voltage units, on load regulation should be provided by switched tappings on the transformer, by an additional auto-transformer in the secondary side of the main transformer or by power electronic devices. The regulation should provide variable control from 5 % to 100 % of the rated d.c. voltage. The units may be provided with automatic control as indicated in **3.6.5**.

3.6.5 Control equipment

Arrangements are normally required to enable the protection current to be adjusted so that the appropriate protection potential is achieved and maintained. If the conditions are reasonably stable, as is normally the case with buried structures, it is sufficient to provide adjustment of the rectifier output with, possibly, variable resistors in individual anode circuits, or, alternatively, in the cathode leads if several are supplied from the same rectifier. Structure/electrolyte potentials are then measured periodically (see **11.4.2** and **11.5.2**) and any necessary adjustments made.

To provide a means of checking continued satisfactory operation between structure/electrolyte potential surveys, the normal requirements are the provision of a voltmeter to indicate the d.c. output voltage, and facilities to indicate the total output current and the current in each anode or cathode circuit if a number of anodes or cathodes is supplied from the same rectifier.

More frequent variations of conditions occur, for example, due to variable salinity in estuaries, change of flow rates in plant, or alteration of the speed of a ship. Manual control is feasible if the necessary supervision is available but automatic control, by one of the methods described below, may often be preferable. In some cases, a control system can be justified on economic grounds alone as it enables the protection current to be kept close to the minimum needed for protection. It may be deemed necessary in the case of coated structures, for example, where conditions vary considerably and frequent adjustments are essential, to maintain a structure/electrolyte potential between the minimum potential for protection and the potential at which coating damage is possible.

For permanent mounting in sea-water, the most suitable reference electrodes are types in which the sea-water is in direct contact with the metallic electrode i.e. the silver/silver chloride/sea-water electrode or the zinc/sea-water electrode. In estuaries, it may be necessary to take account of the effect upon the potential measured of the salinity of the water (see **10.2.1.3**).

A single reference electrode is often relied upon for controlling the output of a particular anode and its position is therefore important. For bare structures, reference electrodes are best placed at positions remote from anodes, where the effect of the cathodic protection is least, thus ensuring that the structure/electrolyte potential is at all points sufficiently negative. With coated or painted metal surfaces it is important to ensure that the metal/electrolyte potential does not become sufficiently negative to cause coating damage and an intermediate position may be preferable. Tests should normally be made, using temporarily-installed equipment, to confirm that acceptable conditions can be maintained over the full range of service conditions, and to determine the corresponding metal/electrolyte potential as measured by the reference electrode, that is to be used for control.

Table 3 — Characteristics of principal anode materials

Material	Density	Maximum operating current density	Consumption rate	Maximum operating voltage	Probable utilization factor	Remarks
	g/cm^3	A/m^2	mass/A year	V	%	
Steel	7.85	5	9 kg	50	30 to 50	Used with carbonaceous backfill
Impregnated graphite	1.1	10	0.5 kg	50	50	
High-silicon iron	7.0	50	0.2 to 1.0 kg	50	50 to 90	Higher consumption occurs in chloride containing environment unless chromium or molybdenum is added
Carbonaceous backfill	0.7 to 1.1	5	1 to 2 kg	50	50	Only used in conjunction with other anode materials
Magnetite	5.8	100	< 5 g	50	60	
Lead alloys	11.3	300	25 g	25	80	
Platinum on titanium, niobium or tantalum	21.5	1 000	10 mg[a]	8[a] 40[b]	90	Cannot withstand current reversal. Operating current density under oxygen evolution conditions should not exceed 200 A/m^2. Wear rates of platinized (and platinum/iridium) anodes increase with decreasing chloride levels

[a] Platinum on titanium.

[b] Platinum on niobium and platinum on tantalum.

Detailed descriptions of automatic control systems are beyond the scope of this code. The following two basic methods are available.

a) *Two-level control*. If major changes between two well-defined levels of current requirement occur, e.g. due to the change from stagnant to moving conditions, only two current settings are required. A switch can be incorporated to transfer from one to the other and this can be actuated automatically, for example by linking it to the valve controlling water flow. Provision for adjustment will be needed on each of the two settings so that the equipment can be set initially and reset periodically if need be.

b) *Full automatic control*. Various types of automatic power supply unit are available based, for example, on saturable reactors, thyristors or transistors. They vary the output current so as to maintain the measured metal/electrolyte potential close to a preset value. As indicated above, the preset value required will depend upon the position of the sensing electrode. Equipment is available for use on structures with complicated geometry, which will accept signals from a number of sensing electrodes, reject any that are outside the range that is probable with sensing electrodes in sound condition, and adjust the output so that the least negative is at the preset value.

A number of anodes can be supplied from a single control unit, even if they are mounted in different items of plant. This arrangement is satisfactory as long as the operating conditions are sufficiently similar. Alternatively, individual control units, each with a suitably positioned sensing electrode, can be connected in each anode circuit.

3.6.6 Power supplies to transformer-rectifier units

In rural situations, the transformer-rectifier unit will often be supplied from an overhead line. In planning the groundbed and any necessary extension to the overhead line system, care should be taken to ensure that there are no overhead line stay wires within the boundaries of the groundbed installation.

Where an underground service is installed to feed a transformer-rectifier unit, the use of a cable having a metallic sheath in contact with the soil may greatly increase the likelihood of interaction with the underground cable network. Use of cable with an anti-corrosion oversheath of an insulating material such as polyvinyl chloride will help to reduce interaction.

Although the earthing of an electrical installation is a consumer's responsibility, the electricity supply authority may, if requested and it is possible, provide an earth terminal at the supply position. However, if the metalwork of the transformer-rectifier unit is bonded to this earthing terminal, precautions should be taken to ensure that there is no possibility of metallic connection, even for a short period, between the earthing system and the groundbed of the cathodic protection installation.

Within the UK, electricity supplier may provide different types of supply with varying earthing requirements as described in appendix 3 of the IEE Wiring Regulations. It is important that the electricity supply authority be asked to state the type of supply and earthing requirements to ensure that the isolation and earth fault protection together with earth electrodes, if necessary, are provided by the consumer in accordance with the statutory regulations.

Provision should be made at the transformer-rectifier unit for isolation from the supply.

3.7 Comparison of the various systems

The advantages and disadvantages of the sacrificial anode and impressed current methods are set out in Table 4. A further method known as electric drainage is described in **4.6**. It is applicable only to structures affected by stray currents flowing in the soil, and may have advantages in suitable cases.

3.8 Particular considerations

3.8.1 Secondary effects of cathodic protection

The application of cathodic protection may give rise to secondary effects such as the development of alkalinity or the evolution of hydrogen at the protected surface (see **2.2.5**). The effects that may occur are as follows.

a) Alkalinity may cause the deterioration of some paints by saponification. This can be minimized by avoiding the use of very negative potentials and by using paints that are less susceptible to such damage (see, for example, **6.2.2.2**).

b) Alkalinity causes, in the case of sea-water or similar solutions, a white calcareous deposit (chalking). This is beneficial since the current density needed to maintain cathodic protection is reduced. If, however, formation of the deposit is excessive, water passages may be obstructed or moving parts impeded.

c) Aluminium is corroded in alkaline environments. Cathodic protection should therefore be applied to it only if the potential is maintained within certain limits (see **2.3.2.5**).

d) Exceptionally, lead can be corroded when protected cathodically in an alkaline environment (e.g. cables installed in asbestos-cement pipes).

e) Hydrogen evolved at strongly negative potentials may create an explosion hazard in enclosed spaces (see **12.6.1**).

f) Hydrogen embrittlement of high tensile or stainless steel is a possible danger.

g) Coatings may be disbonded by cathodic protection.

h) Rust and scale is sometimes detached from a surface during the initial period of operation of cathodic protection and may block water passages or cause other difficulties for a short period. If iron or steel has been seriously corroded, removal of rust that is plugging holes may cause a number of leaks to become apparent during this period.

i) Chlorine may be evolved at the anodes of an impressed current cathodic protection installation if the electrolyte contains chloride. This may cause nuisance or create a hazard (see **12.6.2**).

3.8.2 Effects of stray current from cathodic protection installations

Where a protected structure, or the anode(s) or groundbed(s), lie near to other buried or immersed metallic structures that are not fully insulated from earth, the latter (secondary) structures may, at certain points, pick up a proportion of the protective current due to potential gradients in the soil or water and return it to earth at other points. The secondary structures may corrode at these latter points (see section 9).

3.8.3 The avoidance of damage or hazard due to overvoltages

3.8.3.1 *General*

Overvoltages due to faults on power equipment or to lightning may cause serious damage to equipment installed to provide cathodic protection. If isolating joints have been inserted in a protected structure, there may be a risk of flashover and explosion if the structure contains low flash-point material. The following recommendations should be read in conjunction with any other relevant codes of practice or regulations (see also section 12).

3.8.3.2 *Damage to cathodic protection equipment by overvoltages*

The groundbed of a cathodic protection system, because of the essential parameters of its design, will usually be a lower resistance connection to earth than the associated protective earth system. The groundbed is also electrically separate from the protective earth system (see **3.6.6**). This may result in the associated equipment being subjected to overvoltages or excessive current [15] that originate either from faults on power equipment or from lightning as follows.

a) *Faults on power equipment via the protective earthing of equipment*. In high resistance areas, where it is difficult to obtain a good connection to earth, a system of protective earthing is often employed. This involves the bonding together of all the earth and/or neutral terminals of plant and equipment so that they are at the same potential, although this potential may be appreciably higher than true earth potential.

NOTE In such cases the use of a large mass of bare copper for earthing purposes should be discouraged because of the galvanic cell so created and also the increased cathodic protection current requirements (see CP 1013).

b) *Lightning*. Any currents due to strikes to the protected or associated structures are liable to flow to earth via the groundbed. This could damage the meters of the transformer-rectifier equipment and may also damage the rectifier stack.

In either case, overvoltages can arise across the terminals of the equipment, and a suitable surge diverter or protective spark gap should be installed across the output terminals of all transformer-rectifier equipment.

Further advice on protection against lightning is given in BS 6651. Recommendations relating to fault conditions on electricity power systems are given in **12.4**.

3.8.3.3 *Electrical isolation of buried structures that are associated with a lightning protection system*

Care is needed if isolating joints are to be installed in buried structures where lightning protection has been installed in accordance with BS 6651. In **18.3** of BS 6651:1985 it is recommended that metal cable sheaths, metal pipes and the like entering a building or similar installation should be bonded as directly as possible to the earth termination of the lightning protection system, at the point of entry to the building. This bonding is necessary in order to avoid a flashover with consequent risk of damage to the pipes, cables etc.

Table 4 — A comparison of sacrificial anode and impressed current systems

Sacrificial anodes		Impressed current	
1)	They are independent of any source of electric power.	1)	Requires a mains supply or other source of electric power.
2)	Their usefulness is generally restricted to the protection of well-coated structures or the provision of local protection, because of the limited current that is economically available.	2)	Can be applied to a wide range of structures including, if necessary, large, uncoated structures.
3)	Their use may be impracticable except with soils or waters with low resistivity.	3)	Use is less restricted by the resistivity of the soil or water.
4)	They are relatively simple to install; additions may be made until the desired effect is obtained.	4)	Needs careful design although the ease with which output may be adjusted allows unforeseen or changing conditions to be catered for.
5)	Inspection involves testing, with portable instruments, at each anode or between adjacent pairs of anodes.	5)	Needs regular inspection at relatively few positions; instrumentation at points of supply can generally be placed where it is easily reached.
6)	They may be required at a large number of positions. Their life varies with conditions so that replacements may be required at different intervals of time at different parts of a system.	6)	Generally requires a small total number of anodes.
7)	They are less likely to affect any neighbouring structures because the output at any point is low.	7)	Requires the effects on other structures that are near the groundbed of protected structures to be assessed; however, any interaction may be readily corrected.
8)	Their output cannot be controlled but there is a tendency for their current to be self-adjusting because, if conditions change such that the metal to be protected becomes less negative, driving e.m.f., and hence current, increases. It is possible, by selection of material, to ensure that the metal cannot reach a potential that is sufficiently negative to damage paint.	8)	Requires relatively simple controls and can be made automatic to maintain potentials within close limits despite wide variations of conditions. Since the e.m.f, used is generally higher than with sacrificial anodes, the possible effects of ineffective control or incorrect adjustment, for example damage to paintwork or coatings, are greater.
9)	Their bulkiness may restrict flow and/or cause turbulence and restrict access in circulating water systems. They introduce drag in the case of ship's hulls.	9)	Permits anodes to be more compact owing to the use of suitable materials; thus drag is negligible.
10)	They may be bolted or welded directly to the surface to be protected thus avoiding the need to perforate the metal of ships' hulls, plant to be protected internally, etc.	10)	Requires perforation in all cases on ships' hulls, plant etc., to enable an insulated connection to be provided.
11)	Their connections are protected cathodically.	11)	Requires high integrity of insulation on connections to the positive side of the rectifier which are in contact with soil or water, otherwise they will be severely corroded.
12)	They cannot be misconnected so that polarity is reversed.	12)	Requires the polarity to be checked during commissioning because misconnection, with reversed polarity, would accelerate corrosion.

The installation of isolating joints for cathodic protection purposes where buried structures approach terminal or other installations clearly runs counter to these recommendations since the deliberate electrical separation of the metallic services from other earthed components, including the earth termination of the lightning protection system, could, in the event of a lightning stroke, result in a breakdown through the soil or flashover of the isolating joint, with consequent risk of damage or explosion.

The isolating joints could therefore be bridged by discharge gaps to effect adequate connection between the two earthed systems during the discharge of lightning current. The impulse breakdown voltage of these gaps should lie below that of the isolating joints. The gaps should be capable of discharging lightning currents without sustaining damage and should be encapsulated to provide complete protection from moisture. Alternatively, polarization calls may be connected across the isolating joint and/or to an earth electrode.

3.8.3.4 *Buried structures near a lightning protection system*

Where a structure to be cathodically protected passes close to, but is not already incorporated in, a lightning protection system, it may be necessary to consider the need to bond the structure to the lightning protection system. This will depend on the distance between the structure and the earth electrodes of the lightning protection system and on the vulnerability of the structure to a lightning stroke through the soil.

A lightning stroke passing to earth through the protection system will cause breakdown of the soil around the electrodes. If a buried structure lies within the area of breakdown, damage to the coating or the metal of the structure and ignition of the contents, if flammable, could result. This danger is not confined to the vicinity of a lightning protection system; even in open country a lightning strike can occur sufficiently close to the structure for a similar effect to occur and a tree or other tall structure not provided with lightning protection can concentrate lightning strikes. However the lightning protection system may considerably increase the probability of damage to the structure. Such damage will be near the installation that has the lightning protection which may create additional hazards. The assessment of risks due to lightning is dealt with in BS 6651.

Bonding the structure to the lightning protection system enables lightning current to flow to the structure and thence to earth without soil breakdown occurring. However, the adverse effect on the operation of the cathodic protection system may be considerable. BS 6651 recommends that the resistance to earth of a lightning protection system should not exceed 10 Ω (see also [16]). Adverse effects on the cathodic protection could be avoided by connecting through a device that will allow lightning current to pass without being damaged and will limit the flow of cathodic protection current (see **12.5**).

The separation beyond which the structure is unlikely to be within the zone of soil breakdown can be calculated. Consider, for example, a lightning protection system with a single, small electrode. When lightning current flows to earth, the soil will break down throughout a hemisphere with radius S (in m) such that the stress at the surface is equal to the breakdown stress of the soil, E (in kV/m). Hence, by dividing the current, i (in kA), by surface area to get density and multiplying by the resistivity, ρ (in Ω·m), to get stress:

$$E = \frac{i\rho}{2\pi S^2} = \frac{i}{S} \times \frac{\rho}{2\pi S} = \frac{i}{S} \times R \qquad (5)$$

where R is the resistance from the breakdown region to remote earth.

Hence

$$S = iR/E \qquad (6)$$

or

$$S = \frac{i\rho}{2\pi E} \qquad (7)$$

The impulse breakdown strength of soil has been found to be between 200 kV/m and 500 kV/m while 200 kA can be taken as the current in an exceptionally severe lightning stroke. Putting the lower figure for impulse strength into equation (6) and taking 10 Ω as the resistance of the electrode to earth gives a spacing of 10 m. This is an upper limit because the recommendation in BS 6651 refers to the resistance of the electrode system to earth measured by conventional instrumentation i.e. under low voltage conditions. The resistance to earth during lightning discharge will be less. Equation (7) avoids this approximation and can be used if the soil resistivity is known with sufficient accuracy.

A lightning protection system for a large installation will have a number of electrodes, probably driven rods, connected together. The current can be assumed to be distributed roughly equally between these electrodes, so that the required spacing is reduced accordingly.

If the calculated spacing is less than the length of an earth rod, there is a further source of over-estimate because the original physical model becomes inaccurate when the calculated spacing is small compared with the length of the electrode. Calculation should take account of the current leaving the whole length of the rod and not be based on an assumption that it is concentrated through a hemisphere.

3.8.4 Effects of a.c. on cathodic protection systems

There is conflicting evidence as to the effect of a.c. on cathodic protection systems [17]. The consensus presently developing is that the presence of a.c. will in some circumstances interfere with the normal operation of cathodic protection installations. In general the effect is not significant and may result in slightly shorter lives for sacrificial anodes or slightly greater output from impressed power systems. Rarely the presence of a.c. can enhance the performance of a cathodic protection system[1]. It is however possible that in some circumstances the presence of a.c. could cause significant disruption to a cathodic protection scheme. Operators should therefore bear in mind the possible significance of a.c. present on their installations (see also **12.5**).

3.9 Testing

Tests which should be carried out during the design and commissioning periods and appropriate methods of test are discussed in sections 10 and 11. The sequence of tests should be commenced as soon as possible after commissioning.

It should be noted particularly that serious corrosion damage to the structure that is being protected could be caused by a period of operation with the d.c. supply incorrectly connected. Care should therefore be taken to confirm that the connections are correct as regards polarity, before or immediately upon commissioning (see item 12 of Table 4).

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[1] See references 1, 6 and 9 given in item [17] of the bibliography.

Section 4. Application to buried structures

4.1 Introduction

This section, which is intended to be used in conjunction with section 3, gives information on the application of cathodic protection to buried structures and deals specifically with pipelines, which is one of the most widespread applications, cables and storage tank bottoms. The cathodic protection of short lengths of immersed pipelines, for example river crossings, is dealt with in **4.3.3.5**.

4.2 General

4.2.1 Factors affecting design

The following factors affect the application of the principles outlined in section 3.

a) *Nature of the environment.* The chemical and physical characteristics of the environment and the rate at which they may change daily or seasonally need to be taken into account by the designer when calculating power requirement.

b) *Nature of the coating.* The use of potential alone as a criterion could be misleading due to the variation in IR drop through coatings of different thicknesses and resistivity. In order to avoid possible coating disbondment, the protective current applied should be controlled so as to achieve a structure/soil potential value no more negative than that recommended by the coating manufacturer. In any event, as a general guide, it should not exceed the level necessary to produce an instantaneous-off potential more negative than – 1.1 V.

For thick film coatings, such as reinforced coal tar enamel in high resistivity soil, this may correspond to a potential more negative than – 3.0 V, which could be acceptable, whereas thin film coatings, such as epoxy resin powder in low resistivity soil, could suffer disruption at values less negative than – 2.0 V. Other coatings may be more or less susceptible to overprotection, and the structure to soil potential may need to be limited to other values (see **3.8.1**).

c) *Polarization level.* For steel structures, the usual criterion of protection is – 0.85 V (copper/saturated copper sulphate reference electrode) with respect to the immediately adjacent soil. Where anaerobic conditions occur and sulphate-reducing bacteria may be present, a more negative value of – 0.95 V should be adopted (see **2.3.2.2** and Table 1).

d) *Linear electrical resistance.* Continuity of the structure and the value of linear electrical resistance will affect the attenuation rate of applied potential, especially on pipelines.

e) *Extent of neighbouring structures.* Proximity to neighbouring structures introduces the need to avoid interaction (see section 9).

f) *Availability of power.* The availability of a.c. power will influence the location of cathodic protection installations.

g) *Stray current.* Electric drainage (see **4.6**) may be used for structures near d.c. electric traction systems. Elsewhere, automatic control may be required if the stray current fluctuates.

h) *Loose polyethylene-sleeved pipes.* Where loose-fitting polyethylene sleeves are used as the primary method of protection, cathodic protection cannot be expected to be effective.

4.2.2 Sacrificial anode installations

Magnesium anodes (see **3.5.3.2**) are widely used but zinc anodes are sometimes employed in very low resistivity soils, i.e. below 10 Ω·m. Although magnesium anodes have a greater driving potential their use is normally limited to soils having a resistivity below 50 Ω·m. The range may be extended by the use of magnesium strip anodes.

Formulae are available from which the output from anodes of various shapes can be estimated (see, for example [7], [8], [13], [18] and [19]).

A special backfill is normally used to reduce the resistance between sacrificial anodes and the soil; it should be an electrolyte having a suitable resistivity and not aggressive with respect to the anode material. A typical formulation is powdered gypsum 70 %, granular bentonite 25 %, sodium sulphate 5 %.

NOTE Carbonaceous backfill should never be used in this application.

Magnesium anode installations are normally designed for an anode life in excess of 10 years. It is however, usual to check performance by potential and current measurements (see **11.4.1**) at regular intervals so that repairs and replacement may be effected. Appropriate measuring points should be provided (see **11.3.2.1**).

Only slight interaction effects are encountered with sacrificial anode systems (see **9.3.4.2**) while damage to coatings due to overprotection is unlikely.

4.2.3 Impressed current installations

Buried anodes can be surrounded by a carbonaceous backfill, such as coke, which reduces the resistance to the mass of the ground and may reduce the consumption of the anode material. It may be advisable to backfill above the anode with coarse aggregate to allow the escape of gas. This is normally oxygen but, in chloride containing solutions, the reaction at a non-consumable anode gives rise to the production of chlorine. This necessitates the use of proven chlorine-resistant insulating materials for any connecting cables adjacent to the anode.

Complete integrity of the insulation of the interconnecting cables is essential. Any metal exposed to the electrolyte (soil or water) will be rapidly corroded.

It is often impossible to provide a suitably low resistance to the soil by the installation of a single anode of a size that can be conveniently handled. In such circumstances, a groundbed, consisting of a group of anodes connected in parallel, can be installed.

Increasing the separation between the individual anodes reduces the resistance to the soil. However, the advantage thus gained decreases with increasing separation. An economic balance should, therefore, be struck between the number of individual anodes required, the cost of the interconnecting cables and greater site requirements and, alternatively, the risk and operational cost of using a higher source voltage.

Formulae are available from which the resistance to the soil of various anode configurations can be estimated (see, for example, [7], [8], [13] and [18]).

Anodes or groundbeds should be sited where the soil resistivity is as low as possible compatible with a suitable position in relation to the structure to be protected. If the site is not naturally damp, a trickle of water may sometimes be brought to it. The site should be chosen with due regard to the position of other buried structures (see section 9), accessibility for maintenance and operation and the availability of power.

If a suitable site cannot be found, consideration should be given to installing the anodes in holes bored through to an underlying layer of low resistivity soil or into the water table.

Groundbeds should normally be sited a minimum of 100 m from the structure to achieve spread of protection and even current distribution, but certain complex buried structures may require a distribution of small groundbeds individually placed much closer to the structure.

4.3 Pipelines

4.3.1 Structure preparation

4.3.1.1 *Electrical continuity*

The need for ensuring that any structure to which cathodic protection is to be applied is metallically continuous and has a low electrical resistance has already been referred to in **3.4.1**.

Steel pipelines having welded joints are intrinsically electrically continuous, whereas pipelines having mechanical joints may be discontinuous.

Continuity can be effected by brazing or welding a metal strip or cable of adequate cross-sectional area across each joint, taking care that all intermediate parts are connected. Bond resistance should be low e.g. not exceeding the equivalent of one pipe length.

The bond should be insulated to a level comparable to that of the structure to be protected. If the metals of the bond and of the structure differ, the vicinity of the junction should be coated to eliminate the possibility of electrolytic action in crevices between the bond and the structure. The mechanical strength of the bond should be adequate to withstand the effects of backfilling etc., and its current-carrying capacity sufficient for it not to be damaged by any possible surge currents from external sources (see **3.8.3**).

4.3.1.2 *Coatings*

Buried pipelines are coated as the primary method of corrosion prevention. Coatings also reduce the current density required to provide cathodic protection and increase the spread of protection, thus limiting the number of points at which cathodic protection needs to be applied on any particular installation (see **3.4.2**).

Suitable types of coating include:

a) plasticized coal tar or bitumen enamel, hot applied, usually with inorganic fibre reinforcement;

b) plastic tapes, either self-adhesive or for use with a primer/adhesive and usually based on polyvinyl chloride or polyethylene and sometimes laminated with rubber compounds;

c) urethane resins applied by brush or spray;

d) sintered or extruded high density polyethylene;

e) epoxy resins commonly applied in a partly cured powder form to a heated pipe surface.

The electrical resistance of a pipeline coating is important where cathodic protection is to be applied. Initial resistances in excess of 10 000 $\Omega \cdot m^2$ are attainable. The current density required will depend on the amount of coating damage sustained during lowering and backfilling operations but, if care is taken, cathodic protection can be achieved initially with current densities of 0.05 mA/m^2 or less.

A high quality coating is particularly important if the cathodic protection stations are to be widely spaced or if it is desirable to keep interaction effects to a minimum (see section 9).

The pipe should, wherever possible, be surrounded by a backfill with a minimum thickness of 150 mm. The backfill should be free from stones and other carbonaceous material such as coke. For ground conditions where the soil is unsuitable as backfill, consideration should be given to the importation of selected fill, such as clean sand, or to some form of mechanical protection which has a minimal shielding effect on the cathodic protection e.g. open mesh plastic netting. Where pipes cross streams or rivers, additional protection, in the form of concrete encasement over the pipe coating, may be required.

As the coating deteriorates, an appreciably higher current density is likely to be required to maintain protection and this should be allowed for in the design of the cathodic protection system. Factors contributing to coating deterioration include soil bacteria, soil stress, pipe movement, effects of pipeline product temperature, water absorption, third party damage, and over protection or cathodic disbondment.

Long-term experience of the particular coating under comparable conditions is the best guide to the performance likely to be obtained, but the choice of coating should take account of both construction and operating factors such as operating temperature, site bending and likely soil stresses.

More specific information on pipe coatings and their application, handling coated pipe, coating of welded joints etc., is given in reference [20].

4.3.1.3 ***Isolating joints***

In designing a cathodic protection system for a well coated pipeline, it may be found that it is connected to poorly coated or bare equipment such as pumping stations, storage tanks and electrical earths, which would constitute a large current drain on the cathodic protection system. In such conditions the benefits obtained by coating the pipeline (see **4.3.1.2**) will be largely lost unless the poorly coated or bare equipment is electrically isolated from the well coated pipeline, so confining the cathodic protection to the pipeline (see [21]). Electrical isolation may also be required between dissimilar metals, and between impressed current and sacrificial anode cathodic protection installations, to limit the effects of interaction or stray currents.

Where such isolation is provided the isolated structure should be regarded as a "secondary" structure and recommended testing and remedial action taken. Procedures described in section 9 enable the effects of interaction to be assessed and overcome.

Isolating joints for pipelines need to be suitable for the operating conditions encountered on the particular installation e.g. pressure and temperature, and the product. Breakdown of isolation has been one of the most common causes of failure of cathodic protection and due consideration should be given to the location and method of isolation and the ease of repair or replacement.

For locations where repair or replacement is extremely difficult, such as high pressure transmission pipelines, the use of monobloc pre-fabricated isolating joints is recommended [see Figure 13(a)]. These can be tested both hydrostatically and electrically prior to installation and, once installed, are unlikely to break down or be disturbed. Under dry conditions in free air and prior to installation, an insulation resistance in excess of 2 MΩ should be obtained using a 500 V insulation tester.

Where it is impractical or uneconomical to use monobloc isolating joints, standard flanges may be converted to isolating joints by fitting an insulating gasket, insulating sleeves over the studs or bolts and insulating washers under the nuts or bolt-heads, mild steel washers being inserted between the insulating washers and the nuts or bolt-heads to prevent damage to the insulating washers when being tightened [see Figure 13(b)]. It is essential that correct alignment of the flanges is achieved to prevent damage to the insulating sleeves. Special insulating gaskets are needed for ring type joints. Providing double insulation washers are used, a flange to bolt insulation in excess of 10 kΩ should be attainable on each bolt, measured using a low voltage insulation tester.

The internal bore and centralizing of the insulating gasket should ensure that no recess is formed internally between flanges in which material may accumulate that could bridge the insulating gap. The outer faces of the flange should be tape wrapped to prevent the ingress of dirt and moisture which could short-circuit the flange insulation.

If isolating joints are buried they should be coated overall to the same standard as the pipeline and test leads attached to both sides of the joint. Extra care should be taken as one side of the joint is not cathodically protected and any connected buried pipework could be affected by interaction.

For pipelines that contain an electrolyte there is a danger of corrosion being stimulated at the inner surface of the pipe on the "secondary" side of the joint. With electrolytes of low conductivity, e.g. potable water, it may suffice to coat the pipe internally for a distance equivalent to at least four diameters on the cathodic side of the isolating joint. Alternatively, a length of non-metallic piping may be installed to provide isolation.

For high conductivity electrolytes such as sea-water or brine, it will probably not be feasible to coat internally or replace with non-metallic pipe a sufficient length of pipe to eliminate entirely the danger of corrosion occurring internally near the isolating joint. Where the provision of an isolating joint is considered essential it may be prudent to install a heavier walled pipe on the unprotected side of the isolating joint with a corrosion allowance and accept the need for periodic inspection and replacement.

After installation final testing of the isolating joint will be necessary. This can usually be carried out on commissioning of the cathodic protection system by measuring the potential difference across the isolating joint.

4.3.1.4 *Test points*

Insulated conductors attached to the pipeline and brought to measuring posts or surface terminal boxes, should be provided at suitable intervals (usually not less than one per kilometre) along the route in order that the level of pipe/soil potential may be checked. Additional points may be required in certain critical areas such as pipe-sleeves, or where exceptionally aggressive soil conditions are present.

It may be worth providing additional points during construction, where the pipeline is near other structures, to assist in subsequent interaction testing (see section 9).

It is essential that the connection to the pipe should be insulated and well coated. The method of attachment to the pipeline will vary according to circumstances, but whatever method is selected, care should be taken to ensure that a sound electrical connection is made. Where conditions will allow, welded, brazed, soft soldered, conductive adhesive or thermit welded connections are preferable to bolted or clamp type connections.

Special considerations are involved in the attachment of conductors to high tensile steel pipelines. It is normal to make the attachment at a point not less than 150 mm from butt or longitudinal welds and to use a welding process. This should always be such as to preclude adverse metallurgical consequences. In cases where welding may not be advisable the use of conducting epoxy resins should be considered. Care should be taken in choosing the method for attaching cables to cast iron pipes because of the possibility of cracking and to lined pipes to avoid disbondment of the lining.

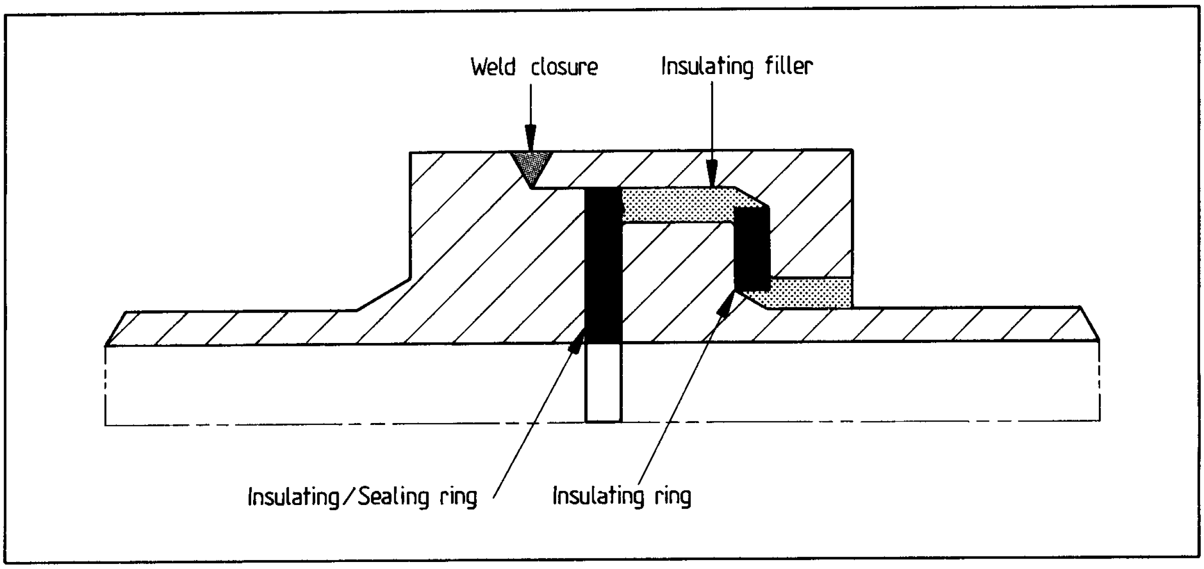
Test points on cross-country pipelines should be sited so as to be accessible but unlikely to be damaged, e.g. at field boundaries. Arrangements should be made, where necessary, for individual test leads to be readily identified. All surface terminal boxes should be weatherproof and designed to resist tampering and theft.

Test points to be used to estimate current in the pipeline (see **10.4.5**) may be provided by attaching two insulated conductors to the pipeline at a spacing sufficient to give a measurable voltage drop. The conductors should both be terminated in the same accessible protective housing.

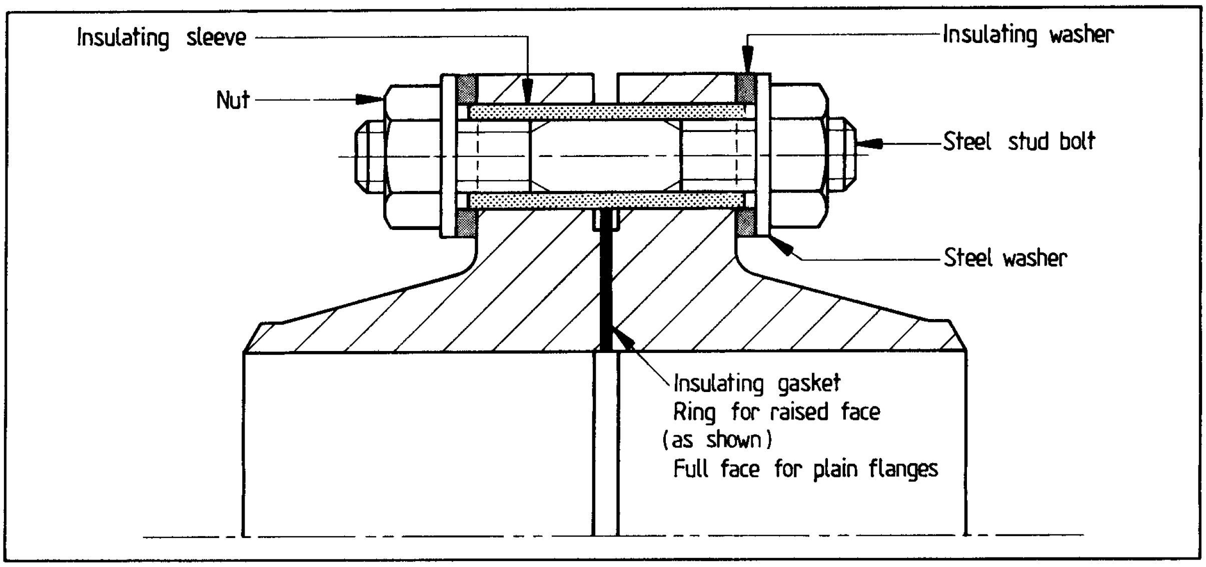
4.3.2 Application of cathodic protection

4.3.2.1 *General*

The use of sacrificial anodes is normally confined to pipelines that have good coatings and are laid in soils with low or moderate resistivity (see **4.2.2**).



(a) Typical monobloc type isolating joint (high pressure)



NOTE 1. This drawing does not show measures taken to prevent ingress of moisture.
NOTE 2. One piece insulating sleeves/washers may be adopted.
NOTE 3. Insulating washers may be adopted in one side only.
(b) Typical isolating flange

Figure 13 — Typical pipeline isolating joints

Impressed current may be used over a much wider range of soil resistivities and can be designed to operate in conjunction with all grades of coating. The choice between the two systems in any particular application will depend upon a detailed assessment of the technical and economic factors involved (see **3.7**).

4.3.2.2 *Sacrificial anodes*

Anodes should be spaced along the pipeline so that full protection is obtained at intermediate points. As far as conditions allow, anodes should be placed in areas with low soil resistivity at a minimum distance of 1.5 m from the pipe at a depth not less than pipe depth and sufficient to obtain permanently damp soil conditions. Interaction with secondary structures may be reduced if anodes are placed at least 2 m away from any secondary buried structure and so that the secondary structure does not lie between the anode and the primary structure (see **9.3.4.2**).

Under certain conditions, it may be preferable to group a number of anodes at a point remote from the pipeline. Design considerations, with respect to spacing etc., are similar to those for groundbeds (see **4.2.3**).

Sacrificial anodes may also be used to provide temporary protection of sections of a pipeline pending commissioning of an overall impressed current system. Similarly they may be installed to provide localized "hot spot" protection of an existing pipeline.

4.3.2.3 *Impressed current installations*

By employing an impressed current installation, considerable lengths of pipeline may be protected from a single source. Bare pipelines may require equipment every 2 km or 3 km. Use of a high grade coating enables the spacing to be increased by a factor of 10 or more depending on coating resistance, longitudinal resistance of the pipeline itself and the most negative permissible pipe/soil potential (see item b) of **4.2.1**).

The usual source of direct current is a mains-operated transformer-rectifier (see **3.6.4**). Where mains power is not available, another source, such as a diesel-driven or solar generator, or thermoelectric unit will be needed.

The groundbed (see **4.2.3**) should be located at an adequate distance (usually about 100 m or more) from the pipeline. If a buried pipeline is near a d.c. traction system it may be possible to employ "electric drainage" (see **4.6**). Where the effect of earth currents from a d.c. traction system cannot be offset or reduced by electric drainage, consideration can be given to the use of automatic control (see **3.6.5**) whereby the magnitude and polarity of the d.c. output are related to the pick-up, or discharge, of earth currents by means of a permanently-installed reference electrode.

Periodic checking of the system will be necessary (see section 11). In areas where seasonal factors cause considerable changes in groundbed resistance, use may be made of a d.c. supply having a constant current output or constant potential control (see **3.6.5**).

It is essential that interaction effects should be taken fully into account and suitable precautions adopted at the earliest possible stage (see section 9).

Cases may occur where it is possible to share, on some agreed basis, an existing cathodic protection system or to design a system to protect structures owned by different organizations. Such arrangements are known as "joint schemes".

4.3.3 Particular considerations

4.3.3.1 *Pipe sleeves*

Sleeves welded to the carrier pipe ensure that moisture cannot enter the annular space which can be filled with a dry inert gas under pressure, such as nitrogen, if the sleeve is coated externally to the same standard as the pipeline, the requirements of the cathodic protection system will be unaltered. This is the ideal arrangement.

Sleeve arrangements other than the above make the application of cathodic protection to the carrier pipe uncertain; their use should be avoided where possible in favour of the installation of thick wall pipe as required locally. If, however, the use of sleeves in the construction is mandatory, the following recommendations apply.

If moisture can penetrate between the pipeline and the sleeve, the pipeline within the sleeve should be coated to at least the same standard as the rest of the pipeline. The carrier pipe should be supported by non-metallic spacers which should be designed to prevent coating damage during installation. A steel sleeve will normally need to be properly isolated from the pipeline and this insulation should be verified at the time of construction.

Steel sleeves should also be coated externally. If the sleeve is installed by thrust boring, the coating should be selected, and appropriate precautions taken, to minimize the risk of coating damage during installation.

A beneficial effect may be obtained by installing sacrificial anodes of zinc or magnesium ribbon in the annular space and connected to the carrier pipe but it will not be possible to verify that cathodic protection is being obtained at all points; the effectiveness will depend on how moisture is distributed.

The following courses of action are possible in the case of metal sleeves.

a) *Bonding the sleeve to the carrier pipe*. The external surface of the sleeve will be protected. It should be coated to at least the same standard as the general run of the carrier pipe as, otherwise, the requirement for cathodic protection current will be increased.

Cathodic protection will not be effective inside the sleeve owing to shielding. Particular care should be taken to provide a good undamaged coating on the carrier pipe within the sleeve as this will be the primary corrosion protection. The inner surface of the sleeve could be coated, but anticipated corrosion can be allowed for in selecting the sleeve wall thickness.

b) *Leaving the sleeve unbonded*. With the sleeve unbonded, cathodic protection current will flow onto the outer surface of the sleeve and will then flow across the annular space to the carrier pipe if electrolyte is present. The direction of current flow is such as to reduce corrosion rate on the carrier pipe and at the outer surface of the sleeve but corrosion of the inner surface of the sleeve will be accelerated. The cathodic polarization produced by this current flow onto the sleeve and carrier pipe will depend on the quality of the coatings, the pipe diameters and the nature of the contacting electrolytes outside the sleeve and in contact with the carrier pipe.

Corrosion of the internal surface of the sleeve should be allowed for in selecting sleeve wall thickness. The use of a separate cathodic protection system for the external surface of the sleeve is possible but it needs to be implemented with care because there are risks of interaction occurring on the carrier pipe within the sleeve at positions inaccessible for measurement or inspection. These effects are dependent on the position of the anode, the nature of the annular electrolyte and the relative qualities of the sleeve and carrier pipe coatings.

c) *Resistive bonding*. A resistive bond between sleeve and carrier pipe, although allowing some current to reach the carrier pipe, may be insufficient for complete cathodic protection.

In general it is preferable to construct the sleeve, isolate it from the pipeline and operate using the method described in b). This is more likely to give acceptable results and this approach is also applicable to concrete sleeves.

In all cases, test points with attachments to both the carrier pipe and the metallic sleeve should be provided (see **4.3.1.4**) to facilitate commissioning and fault finding.

4.3.3.2 *Concrete encased pipe*

Pipe to be encased in concrete, as at river crossings, valve boxes etc., should first be coated to the same standard as the rest of the pipeline.

4.3.3.3 *Protecting existing pipelines*

Cathodic protection, usually by impressed current, may often be applied to old pipelines, even though they are bare or have badly deteriorated coatings, in order to prolong their life. High current densities will therefore be necessary. The current initially required can be determined by means of a drainage test carried out after isolating the pipeline as far as possible from other structures in contact with the soil. The final current requirement will usually be much less owing to long term polarization effects.

4.3.3.4 *Scale detachment*

After a cathodic protection system has been put into operation on an existing pipeline it may be found that there is a temporary increase in the number of leaks due to scale detachment at heavily corroded areas where the pipe wall has been previously seriously weakened or perforated. The majority of such leaks become manifest in the first one or two years operation of the cathodic protection system.

4.3.3.5 *River crossings*

Where a pipeline needs to be immersed in water for relatively short lengths such as at river or estuary crossings, it is usually included in the cathodic protection systems serving the associated buried pipelines. Either impressed current or sacrificial anode systems may be employed. Unless welded joints are used, it is particularly important to provide good bonding to ensure continuity of the structure and hence uniform distribution of potential. The provision of a good coating is essential, possibly supplemented by concrete encasement to provide both negative buoyancy and protection against mechanical damage. Alternatively, where higher current demand is anticipated at a crossing, isolating flanges could be installed at each end of the crossing and an independent cathodic protection system provided. Longer lengths of submarine pipelines need to be considered separately and information on the cathodic protection of pipelines of this type is given in Part 2 of BS 7361.

4.4 Cables

4.4.1 General

The basic principles for applying cathodic protection to the armouring or external sheathing of buried cables are similar to those for pipelines (see **4.3**). Recommendations specific to cables are given in **4.4.2** and **4.4.3**.

4.4.2 Structure preparation

4.4.2.1 *Electrical continuity*

If forms of joint involving mechanical contacts have been installed, it should be confirmed that adequate metallic contact exists.

In the case of armoured cables, it should be noted that unless the armouring is satisfactorily connected to the lead sheath at one or more points on each cable length between joints, corrosion of the inner surface of the armouring is likely to be accelerated as a result of applying cathodic protection.

4.4.2.2 *Coatings*

Cable coatings of bituminized paper and hessian layers are suitable for use with cathodic protection. Bare lead-covered cables in moist earthenware ducts can also be protected. It is possible in both these cases to protect, without using excessively negative potentials, lengths up to about 2 km from the point of application.

Cathodic protection is not normally considered to be necessary for cables having a sound extruded plastic sheath overall. If however, the other circumstances are favourable, cathodic protection could be applied very economically if it were suspected that such a sheath had been damaged locally.

4.4.2.3 *Isolation*

It may be found to be uneconomical to attempt to apply cathodic protection to the metallic sheath or armouring of power cables or to steel pipelines containing such cables, unless the metal to be protected is isolated from the main electrical earthing system. In this case, it is normally necessary to restore the path for fault currents by connecting the sheath to the earthing systems at the extremities through a polarization cell [22]. Such a cell allows only a small direct current to pass during the normal operation of the protection system which does not affect the operation of most systems. However, it is capable of carrying the full alternating current flowing under fault conditions with a suitably low impedance.

If isolation and separate earthing is required, it is feasible to design special joints to interrupt the continuity of the cable sheath.

4.4.2.4 *Test points*

Measuring points similar to those described for pipelines in **4.3.1.4** will normally be needed.

4.4.3 Application of cathodic protection

The procedures described in **4.3.2** are generally applicable to cables with lead sheaths and steel armouring; difficulty in applying cathodic protection to aluminium is referred to in **2.3.2.5**. In the case of telephone cables it should be noted that the ripple from the rectified d.c. may induce signal interference so that smoothing may be required. No trouble is normally experienced with protection currents up to 5 A.

4.5 Storage tank bottoms and similiar structures

4.5.1 General

Large storage tanks, such as those used in the petroleum industry, are often erected on earth foundation mounds. The top of the foundation mound may be provided with a bitumen-sand carpet or some form of coating may be applied to the underside of the tank bottom. During operation, the bottom of the tank is subject to flexure and settlement. The bitumen-sand carpet is therefore liable to be damaged, thus allowing parts of the tank bottom to come into contact with the soil of the foundation mound. Any coating applied to the tank bottom plates is also likely to be partially destroyed by the heat of welding of the lap joints, with the same result. If the tank is founded on a saline soil or in conditions where the water table can reach tank bottom level, or if the foundation has been contaminated with salt water or sea-water, then an aggressive environment is produced. If the environment is corrosive, cathodic protection may be applied to supplement the protection provided by carpeting or tank bottom coating.

4.5.2 Structure preparation

The tank foundation mound should as far as possible be constructed so that it will distribute protection current uniformly to the whole of the underside of the tank. This means that the use of rubble, rock fill etc., should be avoided and the mound should consist of fine-grained and well compacted material, to a minimum depth of 150 mm.

Storage tank bottoms are generally constructed by lap welding individual plates and are therefore electrically continuous. Where groups of tanks are to be cathodically protected, provision will need to be made for bonding between individual tanks.

If it is desired to confine the protection current to the tanks, isolating joints will be required in all pipelines and fittings connected to the tanks including electrical and instrumentation connections.

If flammable liquids are being stored, such joints should be located outside the tank bund (see **12.7**). Earthing electrodes connected to the tank should be of zinc, or stainless or galvanized steel.

4.5.3 Application of cathodic protection

Current density figures of the order of 10 mA/m^2 are normally required for uncoated tank bottoms resting on bitumen-sand carpets and, owing to the large areas involved, impressed current is usually preferred. Sacrificial anodes may, however, be worth consideration for small isolated tanks on soil with low resistivity (see **4.2.2**).

Where practical, groundbeds should be arranged symmetrically around a tank or group of tanks. Dependent upon the space available, the groundbeds should be located not less than one tank diameter from the tank periphery to provide optimum current distribution over the tank bottom. If this is not possible, consideration should be given to distributing a number of anodes or groundbeds evenly around the periphery of the tank or to installing borehole groundbeds (see **4.2.3**). The top anode of a borehole groundbed should be at a minimum depth of 10 m to facilitate current distribution.

If flammable liquids are being stored in the tanks, the preferred siting of the groundbeds is outside of the bund walls. Where this is not possible, the groundbeds and all connections should either be totally buried or, if above ground, comply with the requirements of the electrical classification of the hazardous area. This should also apply to any negative drain point connection to the tank (see **12.7**). If borehole groundbeds are used, any steel casing should be finished below ground level to ensure that any spark hazard due to inadvertent contact between the casing and protected steelwork cannot occur.

4.5.4 Particular considerations

Structure/soil potentials vary across the underside of a cathodically protected tank bottom so that rim potentials usually need to be more negative than – 0.85 V in order to ensure that this protection potential is attained at the centre.

On new constructions, reference electrodes can be installed at representative points across the foundation mound. These should be such that they will remain in good condition for a long time so that the potential at the rim corresponding to full cathodic protection at the tank centre can be determined.

If such reference electrodes have not been installed an arbitrary value of rim potential has to be adopted. Potentials in the range – 1.10 V to – 1.20 V (copper/copper sulphate reference electrode) have been found to be satisfactory.

Tanks that remain empty for long periods are unlikely to be fully protected because while the tank is empty the bottom moves out of contact with the foundation.

Tanks are often re-bottomed. When this is done the old bottom should be removed completely and the foundation made good as recommended in **4.5.2**.

4.6 Buried structures near d.c. electric traction systems

In many d.c. electric traction systems the negative pole of the d.c. supply is connected to the running rails which may be in contact with the earth. Thus the earth may provide an additional path, in parallel with the track, for current flowing from the traction unit back towards the point of supply. In the case of metallic pipelines or cables having metallic armouring or sheaths laid in the earth path, part of the current flowing in the earth may be picked up at one point on the pipeline or cable and discharged at another, leading to accelerated corrosion at the point of discharge.

Current leakage from a d.c. electric traction system can be minimized by providing:

a) track bedding with a reasonable value of electrical insulation between the rails and surrounding earth; and

b) good track conductivity by adequate bonding between rail lengths with frequent cross-bonding between tracks.

Significant current leakage does not normally occur with systems employing an insulated fourth rail as a return conductor.

Corrosion can be reduced by bonding the pipeline or cable sheath and armouring to a return rail at the more negative portions of the track, i.e. near substations or where negative feeders are connected to the rails. The bonding cable will drain some of the leakage current back into the rail and thence back to the point of supply thus ensuring that the structure receives partial, or sometimes complete, cathodic protection. This form of cathodic protection is known as direct electric drainage.

Direct electric drainage cannot be applied in all circumstances because of the likelihood of current reversal in the drainage bond. A rectifier (or other unidirectional device) is therefore usually provided for this purpose as illustrated in Figure 14(a) and Figure 14(b). This method is referred to as unidirectional electric drainage.

Under some fault conditions the track voltage may attain a relatively high value and it may be necessary to protect the rectifier and bond against excessive currents by means of an overload circuit-breaker or fuse. However, inclusion of a fuse necessitates frequent checking of the bond and the installation of a fuse failure alarm may be considered. A spark gap may also be included with the bond but this may not be required if spark gaps are provided elsewhere on the electric traction system.

It may also be necessary to provide a resistance and/or a choke in series with the rectifier to limit the drainage current. Whilst having regard to the threshold voltage at which the rectifier will conduct, the value of the resistance will be determined by site requirements to achieve optimum cathodic protection.

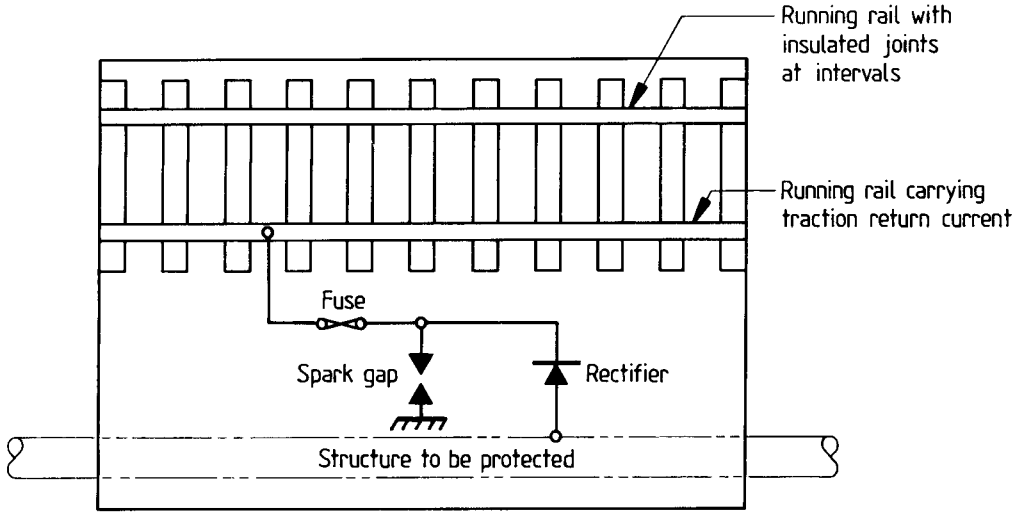
The degree of cathodic protection afforded to nearby buried structures by means of drainage bonds may be increased by the use of forced electric drainage which entails the insertion in the drainage connection of an independent mains-supplied cathodic protection rectifier as shown in Figure 14(c). It may be necessary to limit the output from the rectifier by means of a saturable reactor or transformer or similar device.

For railway signalling purposes, a relay and power supply are usually connected between the rails of a railway track so as to provide remote indication that a train is in the section. This arrangement is known as a track circuit and there are “single-rail” track circuits and “double-rail” track circuits. In the first type there are insulated joints in one rail at each end of the signalling section and the traction return current is confined to the other rail. In the second type there is an impedance bond connected at each end of the track circuit, which virtually prevents the passage of the track circuit signalling current between the rails and, in this case, the traction return current flows in both rails, as it does also when there are no track circuits.

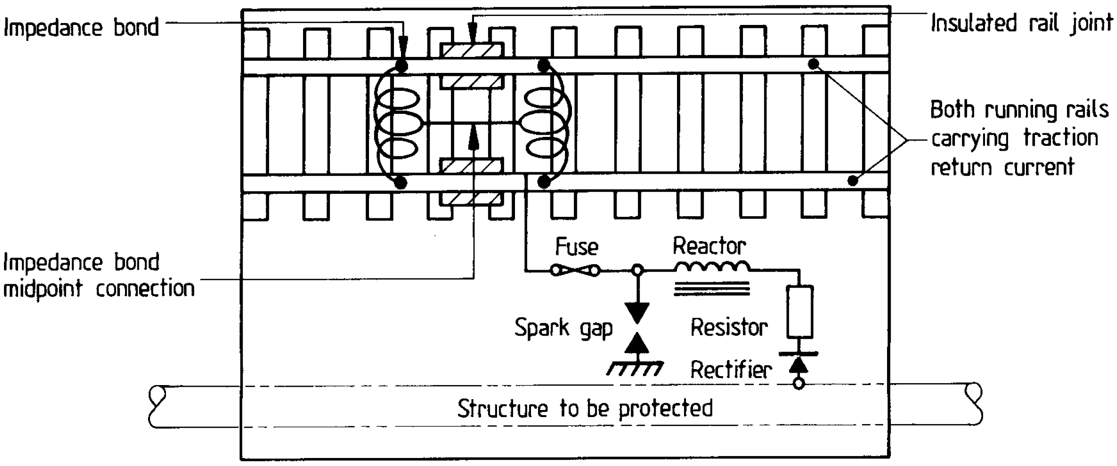
Irrespective of the type of drainage system used, the drainage bond connection to the track is made to one or both rails where there are no track circuits; only to the traction return rail where there are single-rail track circuits; and to the centre tapping of an impedance bond (or in certain cases direct to one rail) where there are double-rail track circuits. It is necessary for the precise arrangements for the connection to the track to be agreed with the railway authority. Figure 14(a) shows the case with single-rail track circuits, Figure 14(b) the case with double-rail track circuits and Figure 14(c) the case with no track circuits.

Under no circumstances should any connection or bonding be made to railway running rails or structures without consultation with, and subsequent written permission from, the railway authority.

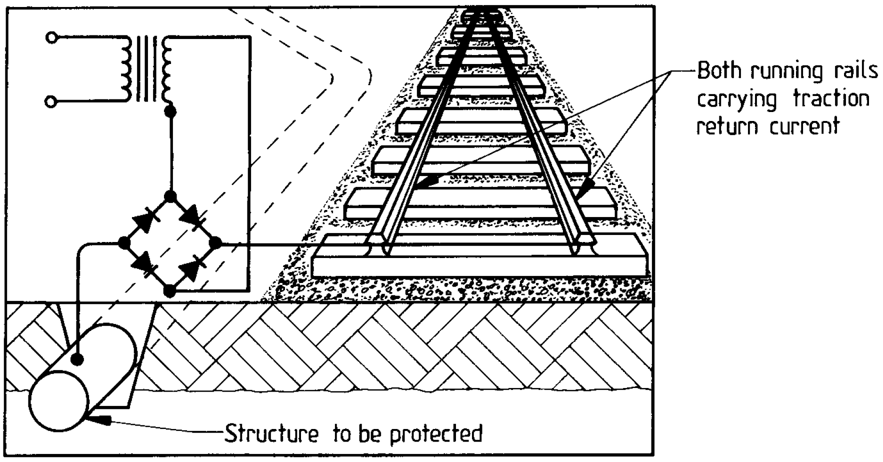
For further information regarding interference problems involving d.c. traction systems see reference [23].



(a) Unidirectional drainage with resistor on a d.c. electric traction system with single-rail track circuits



(b) Unidirectional drainage with resistor and reactor on a d.c. electric traction system with double-rail track circuits



(c) Forced drainage on a d.c. electric traction system without track circuits (drainage supplemented by rectified a.c.)

NOTE. A spark gap may not be required if spark gaps are fitted at strategic locations in the traction system.

Figure 14 — Typical electric drainage system for d.c. electric traction

Section 5. Reinforcing steel in concrete

5.1 General

5.1.1 Introduction

Steel embedded in Portland cement based concrete, mortar or other similar material is normally prevented from corrosion by the high level of alkalinity produced by the hydration of the cement. However this preventative action breaks down in the presence of chlorides. The use of well compacted, carefully mixed, low water/cement ratio, well size-graded and properly cured concrete with adequate cover to the steel, will delay chloride intrusion and thus corrosion, for many years.

Once the breakdown has occurred, atmospheric oxygen and water which may already be present will produce corrosion of steel in reinforced concrete.

Chlorides occur naturally in sea-water. Steel in reinforced concrete structures exposed to marine atmospheres with high chloride contents has long been known to be liable to corrosion. Chlorides are also now commonly used as road de-icing agents in winter and have penetrated road bridges with consequent corrosion. At one time, chlorides were also used, in the form of calcium chloride, to accelerate the initial set of concrete. Where sea-water was used in mixing, or unwashed sea sand, desert sweepings or unwashed sea dredged aggregate incorporated, chlorides would be introduced into the concrete.

The delay before the onset of corrosion depends on the permeability and thickness of the section of concrete to be penetrated. Thin sections such as bridge balustrading suffer corrosion very rapidly when the concrete is permeable. Steel corrosion produces expansive forces which generate cracks in the concrete. Once cracked, concrete will readily admit further water, oxygen and salt to the steel and the corrosion rate will increase.

Fully immersed or buried structures suffer corrosion damage only when there is unusually high oxygen availability. More usually, chloride intrusion corrosion does not occur in fully immersed structures.

Some corrosion of reinforcing steel has also been encountered where there has been no significant intrusion of chlorides, but where the integrity of the concrete has become damaged by progressive carbonation of the alkaline cement-gel, expansive reaction between certain alkali susceptible aggregates and the cement-gel or by cracks induced by frost damage or loading.

5.1.2 Cathodic protection of steel in concrete

In most cathodic protection situations, the electrolyte is sea-water, soil water or other similar material which is usually near neutral (pH 6 to 8). The steel is the structure, and coatings apart, is in contact with the bulk electrolyte.

Steel in concrete, however, is in contact only with the relatively inert aggregates and hydrated Portland cement-gel forming the concrete, into which some chlorides may have become introduced.

Those structures fully immersed in an electrolyte (i.e. totally buried or immersed) can be provided with a "conventional" cathodic protection anode and power source. When the structure is not immersed or buried, but in the atmosphere, the anode needs to be applied to the structure itself, in order that current can be passed through an electrolyte, in this case the concrete, to the cathode.

The text of **5.5** on design considerations provides guidance on the different requirements for immersed and non-immersed structures. However in both cases, the criteria for protection differ substantially from conventional cathodic protection in near-neutral soil or water electrolytes and are dealt with in **5.4**.

5.1.3 Application of cathodic protection

Cathodic protection is applicable to any structure or any part of any structure where the steel reinforcement is in continuous contact with the concrete electrolyte and where the concrete itself is continuous; it is not applicable to reinforcement in cracked or delaminated sections nor to steel wires in ducting. Cracks small enough to be bridged by water or in ducting cement paste are acceptable. Waterproofing membranes, asphaltic road or wearing courses can present discontinuities or barriers in the electrolyte and this possibility needs to be evaluated in each case.

In practice, cathodic protection has been utilized to prevent further corrosion of steel in concrete into which chlorides have already penetrated or been introduced. However, to date the extent of this usage is limited and experience is still being gained.

It is uncommon to find the use of cathodic protection justified for a new structure at the design stage if alternative economical means are available to prevent chloride intrusion, given always the particular circumstances of exposure expected, maintenance available, life required, cost and convenience of total replacement. However, if a decision is taken at the design stage to apply cathodic protection to a new structure, then considerable provision can be made during construction to facilitate the later application of cathodic protection and this will significantly reduce costs and improve and simplify effective current distribution, monitoring and control.

It is often necessary to carry out repairs, to the extent of replacing delaminated material, before installing cathodic protection.

Sacrificial anode protection is unlikely to be effective on structures other than those immersed in sea-water owing to the low driving voltage available.

Structural elements appropriate for cathodic protection are those already affected by, or likely to be affected by, corrosion from chloride intrusion such as bridge decks, support beams, columns, piles, pipes and culverts, tank walls and building frames, occurring as parts of bridges, viaducts, buildings, etc.

Even after cathodic protection has been applied, there may be areas of reinforcing which were corroding actively and near to causing cracking of the cover. It may be anticipated that in the very early life of the protection system, such deterioration could continue for a time.

5.2 Preliminary survey

5.2.1 General

Surveys preliminary to the application of cathodic protection will be likely to be concerned primarily with establishing the cause and extent of deterioration in the structure and not all the data will be necessary for the design of a cathodic protection system, beyond defining the extent of any scheme required. It is essential however, that all delaminated concrete between the reinforcement to be protected and the proposed anode sites, should be repaired. The survey data can also be used to determine those areas where corrosion is most likely to occur and, therefore, where cathodic protection is most necessary. Surveys of the location and depth of reinforcement will assist decisions on anode location.

Survey techniques available are detailed in **5.2.2** to **5.2.7**.

5.2.2 Visual examination

Most gross faults, cracks and areas requiring attention can be located by careful visual inspection which will frequently reveal the cause of the defect.

5.2.3 Equipotential mapping

By arranging for a single negative connection to the reinforcement, with a high resistance millivoltmeter and a movable reference electrode, measurements taken on a grid over the surface of the structure can be represented as equipotential contours. In this way, with the structure not under cathodic protection, areas on the first layer of reinforcement below the surface can be represented as anodic or cathodic, i.e. corroding or protected. Table 5, incorporating data from reference [24], can be used for guidance.

Table 5 — Equipotential mapping of reinforcing steel in concrete

Surface potential relative to copper/copper sulphate reference electrode	Chance of underlying steel corroding actively
mV	%
less negative than – 200	5
– 200 to – 350	50
more negative than – 350	95

5.2.4 Chloride content analysis

Samples of finely ground concrete obtained from the structure either by drilling or by slicing removed cores may be analysed for chloride and cement content.

This technique can be usefully employed to define both the area of a structure where chloride has penetrated and the depth of penetration.

No satisfactory threshold value for chloride content has been established. The presence of any chloride should always be assumed to place the structure at risk. Some authorities set a maximum chloride level of 0.3 % (*m*/*m*) as allowable before remedial action is necessary (see [25] and BS 8110). Lower values are also used [26].

5.2.5 Carbonation depth measurement

Carbonated cement gel has a pH of about 8.5, compared with pH 12.5 for uncarbonated gel. Indicators can be used as a spray on removed cores to determine the depth of carbonation by the development of a change of colour at the boundary. Phenolphthalein which changes from colourless below about pH 9 to pH 10 to a red/pink colour at highly alkaline pH is an appropriate indicator.

5.2.6 Location of reinforcement

The location of and depth of cover over the reinforcing steel can be determined using electromagnetic fluxmeters (covermeters).

5.2.7 Delamination

Areas of concrete which are detached may be identified by their characteristically resonant sound when tapped with a light hammer.

Instruments utilizing ultrasonic pulses, infra-red thermography or radar frequency waves are available to identify delaminated or cracked concrete.

5.3 Structure preparation

It is necessary to remove detached concrete and repair the structure to the point where continuity of electrolyte between anode and cathode is ensured. The use of repair materials with conductivity much lower than the remaining sound concrete will render these repaired areas difficult to protect. Thus the use of very high resistivity highly modified repair mortars is undesirable. It is accepted that the effect of differences between repaired and unrepaired concrete is to create further corrosion cells; thus the corrosion will not be prevented by making isolated repairs. Where the surfaces to be protected include fittings, such as bearing plates, services, drains or road signs, care must be taken to ensure that the metallic fixings are made continuous with the cathode and do not provide low resistance circuits directly to the anode (short-circuits).

Many anode systems require the concrete surface to be sandblasted before anode application. This has the effect of cleaning out or exposing cut ends of binding wires, fixing nails, spacers etc, which may have been left in the shutters before the concrete was poured. Such items should be ground out, since they will otherwise produce unsightly staining and could short-circuit the applied anodes. As far as possible, the reinforcing steel in the member to be protected should be electrically continuous. It is unlikely to be possible to demonstrate satisfactorily that this is, or is not, so throughout. It is advisable however, to ensure that the principal bars are continuous especially if the member is precast or suspected of having discontinuous reinforcement. Tightened binding wire used in assembling cages before pouring will generally provide sufficient connection.

Continuity checks are best carried out before anode placement by direct reading of resistance by voltage drop measurement. Depending on the size and length of the bars, typically resistances of less than 0.1 Ω may be considered satisfactory. Where unstable resistances of greater than 10 Ω are measured, direct bonding will be necessary.

5.4 Protection criteria

The action of the cathodic protection current flow is to produce an increase in alkalinity at the cathode. This effect is known as cathodic polarization. Diffusion of oxygen towards the cathode surface will reduce the polarization effect (depolarization).

Generally, cathodic protection of steel in concrete requires that current passes through a relatively small cross section of relatively high resistance material. It is not usually possible with the current flowing, to avoid introducing a significant IR drop potential error into the conventional measurement of steel/electrolyte potential using an electrode on the concrete surface.

Measurement of the instantaneous-off potential would provide a significant indicator of protection, but it would not assist in determining the level of “reserves” of polarization achieved, nor the rate at which depolarization proceeds.

For these reasons the “polarization decay” criterion is favoured [27]. In this, the instantaneous-off potential is measured. The applied current remains interrupted and the off potential measurement is repeated. The difference between these two readings over a 4 h period should be at least 100 mV.

This polarization decay criterion has the virtue of being independent of the nature of the reference electrode used for its measurement, or, in relation to the IR drop error, its position.

The effectiveness of the spread of cathodic protection to all areas of steel can only be assessed by multiple measurements of decay at representative positions throughout the structure.

5.5 Design considerations

5.5.1 General

Concrete structures which are fully immersed in water, or buried in soil, may be treated generally in accordance with the recommendations on marine and buried structures in relation to the location and type of any anode system used. The monitoring and protection criteria for reinforced concrete should be employed however.

5.5.2 Current density

Precise values for required current density in relation to concrete permeability, chloride level and polarization level have yet to be established. Systems appear to operate successfully within the range 5 mA to 20 mA per square metre of steel surface to be protected.

5.5.3 Distribution of anodes

Precise factors influencing required anode spacing have not been satisfactorily established. However, structures in the atmosphere have been satisfactorily protected with a maximum spacing of 200 mm between discrete anodes passing current.

5.5.4 Anode systems

Surface anode systems need to operate in intimate contact with the concrete structure being protected. Since anodic products are acidic in nature, there is a tendency for a reaction with the alkaline concrete surface and subsequent anode detachment unless the production of acidic ions is minimized or they are somehow neutralized or washed out before this reaction.

The life of anode systems in general appears to be governed not by the primary anode material itself, but by the efficiency with which it can preserve the adhesion at the anode material/concrete interface. This is not the case with bridge decks where the anode system can be retained in position by gravity.

In general, anodes mounted on concrete would be expected to operate below a current density of 10 mA per square metre of concrete in order to limit the possibility of premature anode failure.

The additional dead load imposed on a structure by the anodes should be given careful consideration by the structure owner before approval is given. Appearance and maintenance requirements will also be factors to consider.

Anode systems should be located so as to avoid the risk of low resistance circuits being formed with other surface metallic fixings which are in contact with reinforcements. The anode systems which have been applied to reinforced concrete structures can be divided into two categories.

a) *Horizontal (bridge deck) installations*

1) Conductive overlay. These generally use primary high silicon cast iron anodes in a conductive petroleum coke overlay.

2) Slotted. Slots are cut in the deck, primary anode wires inserted and the slots then filled with a conductive polymer grout.

3) Conductive mesh. These systems initially used conducting polymer grout with primary anode wires laid on the deck. Recently the use of conducting polymer mesh and expanded titanium with metal oxide coating has become widespread. These are covered with concrete or mortar.

b) *Substructure installations*

1) Sprayed metal. Zinc has been sprayed on concrete and used as continuous anodes.

2) Conductive paint. Paints, that are normally acrylic based and loaded with carbon, are applied direct to the concrete surface.

3) Conductive mesh. Expanded titanium mesh with a mixed metal oxide surface (see **3.6.2.1**) is fixed to the structure by spraying an unmodified or highly modified mortar.

4) Discrete anode. Conductive metal oxide tiles have been used which are connected by titanium strips.

5.5.5 Cathode connections

Cathode connections for current carrying or measurements cables are effectively made either by drilling the reinforcing bar and fixing the lugged cable mechanically or using compression straps. Soldering, welding and brazing of reinforcing bars involving high heat input is to be avoided but pin brazing or thermit welding could be considered.

5.5.6 Current control

The moisture content of the surface layer of a concrete structure varies considerably with atmospheric conditions. This in turn affects both electrical resistivity and, possibly, oxygen diffusion rate in the concrete (depolarization rate). The overall effect is for the cathodic protection circuit resistance to fluctuate widely with changes in atmospheric conditions.

Both “constant current” and “constant voltage” control systems for the power source should be provided. During commissioning, the engineer can select the most satisfactory mode of operation. Owing to doubts about the long term stability of embedded reference electrodes, automatically controlled systems are not favoured at present.

5.5.7 Post-tensioned prestressing tendons

Where prestressing wires are contained in a metallic or other grout filled conduit, there is no possibility of ensuring a satisfactory level of protection to the wires. Cathodic protection is not an appropriate technique for these installations. The possibility of overprotection and its detrimental effect on prestressed components is currently unknown and it would be inappropriate to apply cathodic protection to such systems (see also **5.5.8**).

5.5.8 Limits of potential

When cathodic polarization is provided at high current density and ON, IR-free potentials (see **10.7.4**) more negative than – 1.1 V (copper/copper sulphate reference electrode) are produced, there is the possibility that hydrogen can be one of the products produced at the cathode.

High strength steels and steels subjected to high stress levels may be adversely affected by hydrogen and may either become embrittled or crack. Care is therefore needed in both material selection and design in order to minimize such possible harmful effects. As a guide, acceptable protective potentials and strength levels for steels immersed in sea-water are given in items [28] and [29] of the bibliography.

Cathodic protection is inappropriate for highly stressed high tensile steel.

In practice the achievement of protection of deeply embedded steel can be restricted by the need to ensure that any steel closer to the surface also remains within this potential limit.

5.5.9 Bond strength

The load bearing capacity of reinforced concrete relies on a high level of static adhesion between the concrete and the steel. Formation of gaseous cathodic products which are unable to diffuse away from the interface, could lead to disruption of this interfacial adhesion.

If the fine or coarse aggregate used in the concrete is susceptible to attack by alkali (alkali/silica reaction) then it may be anticipated that loss of interfacial adhesion will occur when cathodic protection is applied. This is because the pH at the cathode will be increased.

5.5.10 Factors affecting the choice of cathodic protection

While cathodic protection is a means, possibly the only means, of indefinitely extending the life of reinforced concrete structures which are suffering reinforcing steel corrosion arising from chloride intrusion, the option to use cathodic protection should be taken up only after satisfactorily resolving the following considerations.

a) It has to be possible, and practicable, to carry out superficial repairs to ensure continuity of the electrolyte.

b) The cost of structural and cosmetic repair, cathodic protection installation and maintenance should be appreciably less than repair or replacement of the affected member.

c) Provision has to be made for maintenance of the cathodic protection system so that continuous operation and achievement of protection potentials are ensured.

d) The appearance of the protected structure should be acceptable.

e) It has to be demonstrated that the reinforcing steel is, in the main, electrically continuous.

f) The structure should not contain aggregate susceptible to reaction with high levels of alkali.

5.6 Monitoring

5.6.1 Potential

In order to apply the "polarization decay" criterion described in **5.4**, a reference electrode is required. Reference electrodes placed on the surface of the concrete will reflect the average potential measurement of the steel surfaces in proximity to the electrode. Any measurement taken with the applied current ON (see **10.7.4**), is likely to contain a significant IR potential drop error.

Considerably greater precision is obtainable from electrodes embedded into the structure close to the steel. However, the repair material used to backfill the hole required to install the electrode and cable will not have the same properties as the surrounding concrete. Thus the current distribution will be disturbed and the measured potential may not reflect potentials occurring generally in the undisturbed areas of the structure.

By monitoring the readings from a surface electrode and an embedded electrode, any differential can be calibrated for any particular part of the structure.

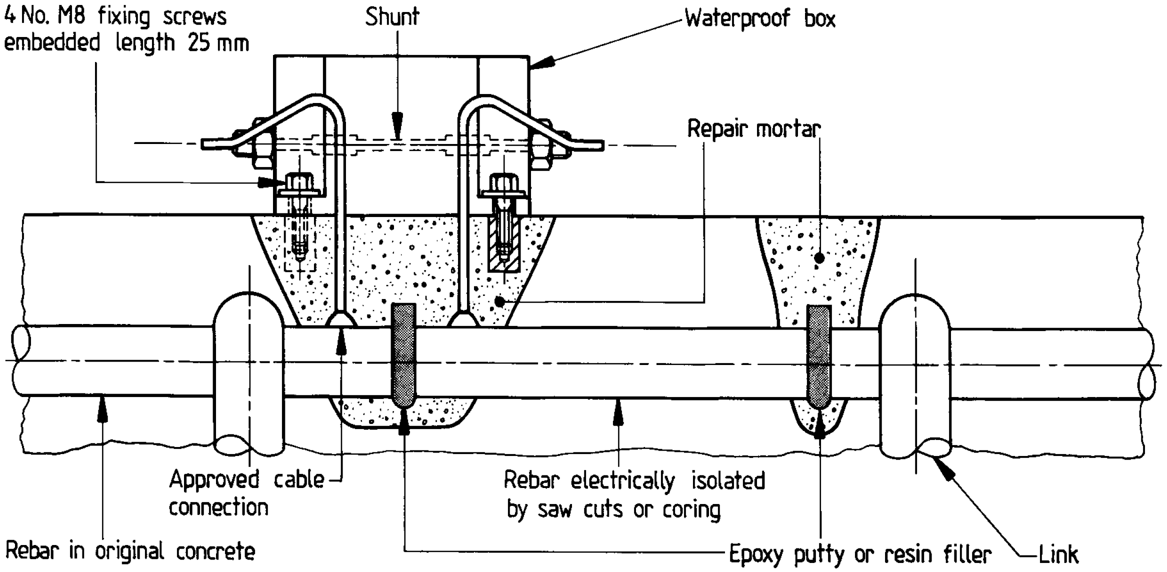
Reference electrodes of copper/copper sulphate or silver/silver chloride (see **10.2.1.2** and **10.2.1.3**) are used on the surface of concrete structures. The constituents of hydrated cement may react with the reference electrode solutions. Reference electrodes used in this way should be clean, and maintained and calibrated regularly.

Silver/silver chloride/potassium chloride reference electrodes are available for embedment. Alternatively, electrodes such as graphite, whose electrochemical action is of an irreversible or non-reproducable nature, may be employed provided that they are regularly calibrated from a surface reference electrode.

5.6.2 Isolated bars

In consultation with the structural engineer, bars located at representative situations throughout the member under protection are selected. Cores are taken at selected points, for example 500 mm apart, and the bars cut through to produce isolated lengths. Leads are attached, the cut ends epoxy coated and the core holes repaired.

By utilizing the arrangement shown in Figure 15 these isolated bars may be used to determine the current and polarization level achieved at representative locations through the structure.



NOTE. The section of rebar chosen for isolation must not include tiebars, links or other metallic contacts.

Figure 15 — Arrangement for monitoring cathodic protection of reinforcing steel in original concrete by means of isolated bars

Section 6. Application to ships

6.1 Introduction

This section deals with the cathodic protection of ships' hulls (see **6.2**); the protection of the hulls of ships that are being fitted out or are laid up (see **6.3**); and with the cathodic protection of ships' tanks (see **6.4**). It is intended to be read in conjunction with section 3.

6.2 The cathodic protection of ships' hulls

6.2.1 Factors affecting design

6.2.1.1 ***General***

In applying the techniques that have been outlined in section 3, the following considerations, applying specifically to ships, should be taken into account.

a) Work can conveniently be done on the outside of the hull only when the ship is in dry dock.

Sacrificial anodes should therefore be designed for a life which is a multiple of the expected interval between dockings, unless divers are available to renew the anodes if these are of the bolted-on type.

b) Increased drag resulting when anodes are mounted on the hull may need to be taken into account.

This is discussed in **6.2.1.2**.

c) Corrosion rates are normally higher at the stern.

This is principally due to increased turbulence near the propeller(s) and the formation of a cell between a bronze propeller and the steel hull. Because of these effects, cathodic protection is sometimes provided only at the stern.

d) Electrical contact between the propeller and the hull is at best intermittent.

Unless positive action is taken to establish a low resistance electrical contact between the propeller shaft and the hull (see **6.2.2.1**), the propeller should not be regarded as being covered by the protection system.

If the propeller is to be brought within the protection scheme (as is normal with impressed current systems and sometimes with full hull schemes) an allowance should be made in the system design for the additional current that will flow to the propeller blades.

e) Strongly negative potentials can damage paint.

Ships' hulls are invariably painted and economical use of cathodic protection requires the application of paints that will resist the chemical and physical effects that occur (see item a) of **3.8.1** and item g) of **3.8.1**). Care is, therefore, necessary to ensure that the paints used are compatible with the protection potentials proposed (see **6.2.2.2**).

f) Current requirements for cathodic protection of a ship's hull vary.

This is because of factors such as the speed of the ship relative to the water, and paint deterioration. These factors are particularly relevant to the design of control for impressed current systems (see **6.2.5.1**).

6.2.1.2 ***Effect of drag***

A factor in the choice of method is the drag imposed by a large number of sacrificial anodes. The drag imposed by suitably designed impressed current anodes should be negligible.

The possible increase in hull resistance should be considered at the design stage. If this is important, the anodes should be shaped and positioned to minimize turbulence in the stream lines around the hull.

The importance of drag increases with the service speed of the vessel. An increase in hull resistance will result in a measurable increase in the shaft horse-power required to maintain a given speed, and increased fuel consumption.

The designer will need to assess the disadvantage of the increased drag resulting from the use of external anodes against advantages such as the reduced roughness to be expected with a hull that is cathodically protected and the probable reduction in the need for maintenance painting.

6.2.1.3 ***Choice of method***

No general rule can be stated in respect of choice between the sacrificial anode or impressed current methods. This should be based on careful consideration of the relevant circumstances and overall economics. Entries in Table 4 which are of special importance with respect to ships are 6), 8), 9), 10), 11) and 12). The decision should take into account factors that determine the bulk of sacrificial anode material which would be required, and the importance attached to increased drag.

6.2.2 Preparation for cathodic protection

6.2.2.1 *Bonding of propellers, rudders and stabilizing fins*

If the appendages of a ship such as the propeller(s), rudder(s) and stabilizing fins (if fitted) are to be included in the protection system provided for the hull, low electrical resistance bonding is required.

If these items are not specifically to be part of the hull protection system then it is advisable to ensure, either that adequate electrical insulation is maintained, or that they are bonded such that potential differences occurring from the application of protection to the hull are restricted within limits that will prevent arcing and/or corrosion interaction damage.

In the case of propellers it is normal to fit a slip-ring to the propeller shaft inside the ship and provide brush gear with electrical connections to the main hull structure to eliminate the possibility of damage that can be caused to bearings and gearing by electrical arcing. Experience has shown that, if such arrangements are designed to maintain the potential difference between the shaft and propeller and the hull to less than 100 mV (with the shaft rotating) damage is prevented. With propellers made of bronze (or alloys that give a large natural potential difference between the propeller and the hull), bonding creates a galvanic cell which will accelerate the corrosion process if the cathodic protection system is inoperative.

In order to determine the maximum resistance that may be tolerated in the slip-ring circuit, the current flow may be estimated from the propeller area and the current density allowance recommended in **6.2.3**. A measurement of slip-ring/brushgear resistance with the shaft stationary will not indicate the efficiency of the arrangement with the ship in service. For this reason it is desirable to fit a voltmeter (with a high internal resistance) to a second brush insulated from the hull to measure potential difference. An arrangement of shaft bonding and in-service monitoring is shown in Figure 16.

In the case of rudders and stabilizer fins made from steel, it is normal to bond to ensure that protection is provided. The shafts of such devices oscillate and it is therefore appropriate to use a flexible bonding strap or a cable. The resistance of the bond and its connections both to the hull structure and to the shaft should be such as to ensure that minimal (less than 20 mV) potential differences occur. A cable or conductor with a cross-sectional area of 35 mm^2 and a length not exceeding 3 m terminated in lugged and bolted connections will normally prove adequate.

A basis for estimating current flow in the bond is to consider the surface area of the appendage and the application of current at the maximum density that the hull system is designed to provide. In service the use of a voltmeter will confirm bond efficacy, and methods of measurement of bond resistance are described in **10.5.4**.

6.2.2.2 *Protective coatings for ships' hulls*

Cathodic protection does not eliminate the need for outer-bottom paint. A bottom paint system is necessary for economy and good distribution of current when cathodic protection is applied and is required to protect the outer-bottom during periods when the cathodic protection may be inoperative. It is also essential to cover the area above the light load line to protect it when it is not submerged, while below that, anti-fouling paint is commonly required and a coating between this and the steel is necessary.

The coating system to be used for a cathodically-protected hull should be chosen with care and applied in accordance with the coating manufacturer's instructions for this application.

With correctly applied cathodic protection, most of the hull will not be more negative than – 0.8 V to – 0.9 V (silver/silver chloride/sea-water electrode). However, with impressed current systems, and with sacrificial anodes of materials with high driving potential such as magnesium alloys, more negative potentials occur near the anodes.

Many marine anti-corrosion paints, including the widely used coal-tar pitch and bituminous types, can withstand the alkali produced in the general hull area, although conventional coatings of oil-based and oleoresinous paints that are softened and blistered by alkali are unsuitable. In areas with potentials more negative than – 0.9 V (silver/silver chloride/sea-water electrode), high quality coatings resistant to alkalis need to be used. Economic considerations will determine whether these should be applied overall or only to areas near anodes.

Success depends on an adequately prepared surface which ideally should be freshly blast cleaned and free from weathered or unsuitable shop primer.

Where the potentials foreseen are more negative than can be withstood by a paint coating, an insulating shield as described in **6.2.2.3** needs to be applied near the anode.

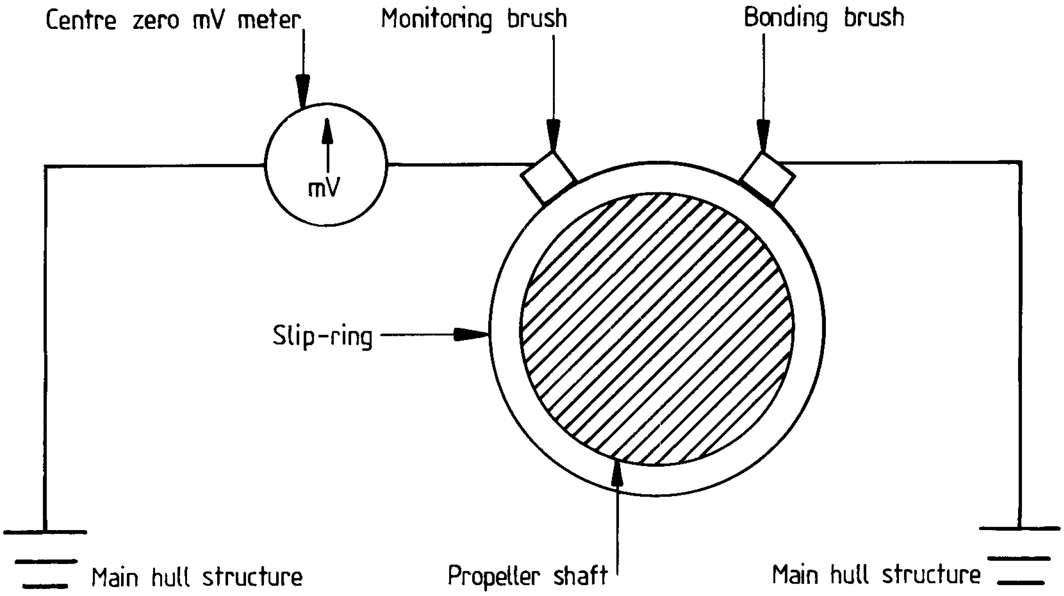


Figure 16 — Bonding and arrangement for monitoring of cathodic protection of a ship's propeller

6.2.2.3 ***Insulating shields for impressed current systems***

The current at which the anodes are required to operate will result in unduly negative potentials immediately adjacent to the anode. These potentials may result in disruption to conventional coatings and can be detrimental to high strength steels causing hydrogen embrittlement and a reduction in fatigue life. It is therefore important to provide an insulating layer on the hull around an anode capable of withstanding these conditions. Such areas are called dielectric shields and should extend from the anode to a distance at which the potential will not disrupt the normal coating.

The shape and size of the dielectric shield will be determined by the shape of the anode, the maximum current output and the resistivity of the water.

The radius (in m) of a shield for a disc-shaped electrode is given approximately by the formula:

$$r = \frac{\rho I}{2\pi(E_o - E)} \qquad (8)$$

where:

E_o is the general potential of the hull when protected (in V)

E is the most negative potential that can be withstood by the hull paint near the edge of the shield (in V)

ρ is the water resistivity (in Ω·m)

I is the current (in A)

The equipotential lines around a strip anode are approximately elliptical and this is the theoretical shape of an anode shield. Normally, however, an anode shield is made as a rectangle. It will need to extend to a distance b on either side of the strip and to a similar distance beyond the ends of the strip, where b is equal to the minor semi-axis of the relevant ellipse.

b can be calculated from:

$$b = \frac{L\alpha^{1/2}}{\alpha - 1} \qquad (9)$$

where:

L is the length of the strip

α is exp $\{2\pi L\,(E_o - E)/\rho I\}$

The major axis of the ellipse, L_o, is given by the equation:

$$L_o = \frac{L(\alpha + 1)}{\alpha - 1} \qquad (10)$$

These formulae have been obtained by modifying equations 3.05 and 3.11 from reference [19].

There are possible errors due to the simplified physical model used. For example the anode is represented as a line source of current, of which the density is uniform along its length, and is regarded as being placed at the surface of a semi-infinite conducting medium representing the water.

The material used to form the dielectric shield should possess good electrical insulation properties, be non-hygroscopic (or be unaffected by water absorbtion) and be capable of withstanding alkaline conditions (produced as a result of the anode dissipating current) and cathodic disbonding.

Dielectric shield materials in common use are either of the high performance coating type or of the prefabricated type.

High performance coatings are often applied directly to the hull surface after abrasive blast cleaning and may be of the epoxy putty type or high build polyurethane. Cleanliness, adequate coating thickness and optimum surface profile are essential if the best possible performance of these materials is to be achieved. Manufacturers' recommendations vary, but cleaning to Sa 2½ of ISO 8501-1 and coating thickness of 5 mm adjacent to the anode are not uncommon. It should be possible to reduce thickness as distance from the anode increases and potential decreases.

Prefabricated shields are formed from glass (or fibre) reinforced polyester/epoxy resin or thermoset plastics, either as thin sheet materials pre-bonded to a steel doubler plate or supplied for direct attachment to the hull. This latter type is less common in merchant shipping as the installation costs are higher. Where large flat areas are available are integral anodes and dielectric shields engineered from resin or plastics, and avoid more durable and mechanically resistant solutions and avoid the need for periodic maintenance of coatings.

Combination dielectric shields are often used where a primary shield is formed immediately adjacent to the anode using a very high performance material tolerant to large electrical potentials and alkalinity. As the distance from the anode increases and potential decreases, materials such as high build coatings provide a cost effective secondary shield area.

The overcoating of dielectric shield areas with anti-fouling paint does not normally reduce the performance of the shield. However, care should be taken to ensure that the active surfaces of the anode are not coated.

6.2.2.4 *Provision for measurement in impressed current systems*

It is important to be able to control an impressed current system so that protection is maintained and so that the potential does not, at any part of the surface, become sufficiently negative to cause damage to the paint or other coating.

As always, the criterion of correct cathodic protection is the potential of the protected metal (see Table 1). To measure this at sea, one or more reference electrodes are fitted externally on the hull, the types commonly used being silver/silver chloride/sea-water and zinc/sea-water. Typical arrangements are shown in Figure 17. Leads are brought inboard to a high-resistance voltmeter the other terminal of which is connected to the hull.

The positioning of reference electrodes is important since the metal/electrolyte potential varies over the hull. It is desirable to mount reference electrodes at representative positions; the choice depends on the number and siting of anodes and is a matter for the specialist designer (see **10.3.3.2**).

It is very important to guard against the application of paint to reference electrodes.

6.2.3 Current density required for protection

The current density required to protect a painted ship's hull will depend on the nature and condition of the paint coating. Practical experience has shown that protection of ships with recently applied high quality coatings may be maintained at current densities of less than 1 mA/m^2. As the coating breaks down during normal service, this figure will increase significantly. Should the coating be subject to heavy damage resulting from arduous service the proportion of bare steel will rise and the average current density needed for protection will fuse accordingly. If, for example, 50 % of the area to be protected is bare steel, a current density in excess of 100 mA/m^2 for the bare areas should be allowed for, that is an average current density in excess of 50 mA/m^2.

The use of high capacity impressed current anodes will result in an uneven current density across the hull, which should be borne in mind when calculating system capacity. The current density used to calculate system capacity should be applied to the wetted surface area of the hull calculated at the vessel's maximum draft.

A higher current density will be required around the stern, due to the propeller(s) and to water turbulence, and this should be taken into account by disposing anodes accordingly. It is particularly relevant in the case of sacrificial anodes (see **6.2.4.4**).

If the propeller(s) are to be bonded to the hull (see **6.2.2.1**), an additional current allowance should be made. For example, in the case of a bare bronze propeller, a typical figure is 500 mA/m^2 of the propeller surface for normal merchant service conditions.

The above applies generally both to sacrificial and to impressed current installations, but it should be borne in mind that, as equipment and installation costs of impressed current systems favour large units and higher currents, it is normal practice to have available a greater current capacity than is usual with sacrificial anode systems. The cathodic protection system should have sufficient capacity to take account of the deterioration of the protective coating during the docking cycle.

6.2.4 Application of sacrificial anode installations

6.2.4.1 ***Choice of material***

In the case of ships' hulls the principles discussed in **3.5.3** are applicable. However since the anodes will be mounted on the hull and operate in sea-water with low resistivity the use of a high driving potential material such as magnesium is not required. The use of low driving potential anode material such as zinc and some aluminium alloys is advantageous because it allows the system to be self-adjusting. For instance when zinc is used, if the hull potential changes from the protection level by 0.1 V the driving potential will be 0.35 V instead of 0.25 V, and the current will rise approximately 40 %.

6.2.4.2 ***Sacrificial anode design and attachment***

Anodes may be attached by welding or by studs. If the latter method is employed, the studs should be securely welded to the steel plate and the nuts locked to prevent the anodes becoming detached. It is important that the nuts be tightened on to the anode insert and not on to the consumable metal. This is essential to ensure continued electrical connection. Where it is intended to weld anodes to the hull plating itself, it should be confirmed that the plating is unlikely to be adversely affected by welding and rewelding. Anodes which are to be placed in the midships section of a ship should preferably not be attached to the shell plating but to the bilge keel; this is recommended by the majority of ship classification societies. With welded-on anodes it is better practice for the inserts to be welded to small doubling plates which have been previously carefully welded to the hull.

Precautions should be taken when welding on ships in service, the tanks of which may contain oil. The use of stud fixing eliminates the necessity for freeing tanks of gas before the installation of replacement anodes.

6.2.4.3 ***Mass of anode material***

The total current requirement will be the product of the wetted areas involved and the current density selected (see **6.2.3**), taking into account any additional allowance for the propeller(s).

The current capacity of the system in ampere years will then be determined by the life required from the anodes, which should be related to the usual periods between dry-dockings. It should be further borne in mind in this connection that as anodes are consumed, their output falls. A more uniform level of protection may be obtained, therefore, by arranging to replace half the anodes at alternate dockings.

The total mass of anode material may be calculated from the ampere-year capacity required and the rate of consumption of the selected alloy (in mass per ampere year) as given in Table 2.

6.2.4.4 ***Number and distribution of anodes***

The number of anodes to provide the necessary ampere-year capacity may be calculated from the total mass of anode material required and the anode mass selected (see also **3.5.2**).

The mass and dimensions of individual anodes will depend chiefly on the alloy proposed (see **3.5.3**) but will also be influenced by consideration of drag and by ease of handling. Adjustment of the number of anodes calculated as above may be called for, however, if the number involved is likely to prove difficult to distribute satisfactorily around the hull and stern. Normally, for example, in the case of zinc or other low-potential anodes, the distance between hull anodes or anode groups is limited to about 6 m to 7.5 m. Space limitations and greater current demand at the stern and rudder (see **6.2.3**) usually require anodes to be closer together in these areas.

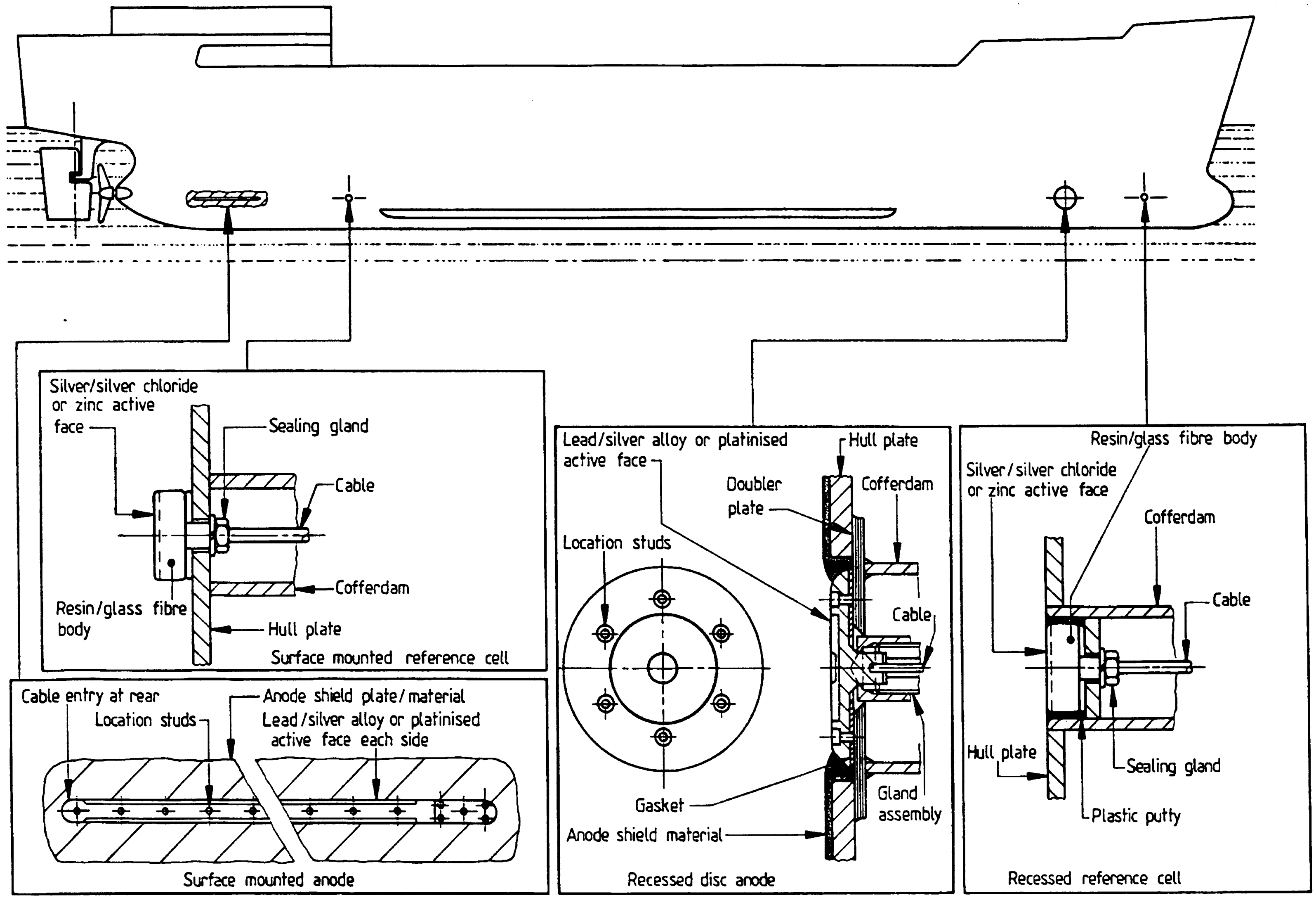


Figure 17 — Typical impressed current scheme for cathodic protection of a ship's hull

It should be noted that if anodes are butted in line to reduce drag, or placed very close together, the output may be reduced to little more than half that which would result if the same size and number of anodes were widely spaced. Consideration should be given to this fact when designing the system to allow for both the output and the anode life required. It is common practice, when a ship is to be given complete protection, to locate approximately 15 % of the total quantity of anode material around the stern, including the rudder, the remainder being distributed along the sides of the hull. Often, however, it may be considered that adequate protection of a particular ship may be achieved by providing the anodes around the stern area only. In this case, the quantity of anode material fitted around the stern and rudder should be approximately 25 % of the total quantity that would have been needed had the complete hull been protected.

A typical protection scheme is shown in Figure 10, and areas are indicated in which it is imperative that anodes are not located, to avoid turbulence resulting in erosion.

6.2.4.5 *Protecting anodes during painting*

Paint will restrict the action of zinc or aluminium alloy anodes significantly and, if an appreciable area is covered, it may make the anodes ineffective. To prevent this, it is recommended that anodes be suitably masked during painting or that all paint be removed with solvent before it dries. The fiercer reaction of magnesium anodes will dislodge small amounts of paint.

6.2.5 Application of impressed current installations

6.2.5.1 *Current supply and control*

Direct current is normally provided by an automatically controlled transformer-rectifier unit.

It is sometimes desirable to provide two, or more, current sources each supplying a separate group of anodes. Current is taken from the negative pole of the supply to any convenient earth position on the hull, and from the positive pole, by insulated cable, to each anode (see **6.2.5.3**). Normally the ship classification societies will require the arrangement for glands where cables pass through the hull plating to include a small coffer-dam.

Current control is required if correct cathodic protection is to be maintained because the current required is not constant. Apart from the general increase due to gradual deterioration of, or damage to, the hull paintwork in service, there are a number of recurring changes that have to be borne in mind, as follows.

a) *A change in the underwater area of the hull.* In the case of oil tankers and cargo ships for example, there is usually a considerable difference between the wetted area of a ship when lightly ballasted and that of the same ship when fully loaded. This may result in as much as a 50 % increase in current demand.

b) *A change in the speed of the ship.* The increase in current required for a ship at service speed compared with that for the same ship when stationary will largely depend on the paint condition; it may be only a small percentage if the paint is in excellent condition but if the paint is poor it may increase by a factor of two or three.

c) *A change in water conditions.* Increase in temperature will result in greater current requirement; for example the demand in tropical waters may exceed that in temperate waters by 20 % to 25 %. If the salinity decreases, an increased voltage will be required to maintain protection at positions remote from anodes.

d) *A disturbance of the outer skin of the hull.* An example is the underwater “scrubbing” sometimes practised for de-fouling purposes; this may double the current demand for a few days until polarization is re-established.

6.2.5.2 *Anode materials*

It is usual to use anode materials which may be worked at high current densities (see **3.6.2.1**); the most common are the lead/silver alloy and platinized titanium.

6.2.5.3 *Hull-mounted anodes*

Anodes may be in the form of long strips or discs secured to, but insulated from, the hull (see Figure 17).

On small ships, anodes are often sited near the stern so as to provide a higher current density in the stern area. On large ships, a number of anodes may be spaced around the hull. For safety reasons in tankers, it is not permissible for anode cables to be led through cargo tanks, although they may be led through cofferdams and ballast-only tanks provided they are installed in heavy steel conduit and correctly terminated.

It is difficult to attach cables to the outside of the ship in order to locate anodes abreast of the cargo tanks. For these reasons, present practice is to locate anodes forward and aft of the cargo tank space or, in some instances, aft of the cargo tank space only. If anodes are confined to aft locations, adequate protection of the forward parts of the hull may be achieved provided the hull paint does not suffer much damage or deterioration in service. The greater the paint damage, the less effective will be this anode arrangement in protecting the forward parts. The direction of motion of the ship does not affect the way in which the current is distributed.

6.3 The protection of ships' hulls during fitting out or when laid up

6.3.1 Cathodic protection during fitting out

6.3.1.1 *General*

If cathodic protection is to be applied to a ship, it is desirable that it is applied from the time of launching. Conditions in fitting-out berths are often severely corrosive (see note) and it becomes especially important to prevent the onset of corrosion and damage to paintwork during this period which could influence the effectiveness of the permanent scheme. This does not necessarily apply in fresh-water fitting-out berths.

NOTE During fitting out, it is not unusual for temporary d.c. cables to be brought on board from a shore supply, and d.c. welding to be in progress on the ship or neighbouring ships. The possibility of leakage of current causing intense local corrosion of the outer-bottom or disbonding of coatings has frequently been suspected. Such current leakage is likely to be intermittent, but much greater than the current normally needed for cathodic protection which will, therefore, not prevent damage or cathodic disbonding of the coating arising in this way. Leakage currents will be evident by abnormal and probably irregular voltage readings, if their occurrence happens to coincide with a hull potential survey. They can be detected by installing a recording voltmeter between a suitable reference electrode and the hull.

6.3.1.2 *Sacrificial anode systems*

When it is intended that a ship shall carry sacrificial anodes in service, they should be fitted before launching, and they will protect the hull during fitting out and until the first docking.

If cathodic protection in service is to be by impressed current, then temporary sacrificial anodes may be suspended over the ship's side and bonded electrically to the hull. These can be hauled on board if the vessel has to change berths, and lowered again on arrival at the new position. Magnesium anodes are generally preferred for their high output, but should be hung at some distance (3 m or more) from the nearest point on the hull to avoid possible damage to paint (see **6.2.2.2** and Figure 9). Anodes of zinc or aluminium may be used close to the hull without detriment, and may be preferable in shallow water.

6.3.1.3 *Impressed current systems*

A shore based impressed current system may be used with anodes laid on the bottom of the basin. Where mobility is important, shore powered temporary impressed current anodes may be suspended over the ship's side. These are usually platinized titanium rods supplied from a manually controlled transformer-rectifier unit in a weatherproof housing on the upper deck. Regular monitoring of potential is essential (see **6.3.1.4**).

6.3.1.4 *Operation*

The current required may be estimated with a knowledge of the area to be protected and the condition of any coating that has been applied (see **6.2.3**). The anodes should be chosen so as to ensure that even current distribution is obtained.

After installation and when stable conditions have been reached a potential survey should be undertaken (see **10.3.3.2**) with a portable reference electrode. This survey should be repeated at regular intervals of typically one month unless conditions are expected to vary in which case the interval should be shorter. The number of anodes should be varied (in the case of a sacrifical anode system) or the anode output altered (in the case of an impressed current system) to maintain the correct level of protection.

6.3.2 Cathodic protection while a ship is laid up

If the duration of inactivity is not predictable, permanent hull-mounted sacrificial anodes may not be suitable, since their replacement requires docking. The choice between suspended sacrificial anodes (see Figure 9) and an impressed current system powered from a shore supply will be determined by accessibility of supply and whether occupation of a berth is anticipated. At permanent moorings, sacrificial or impressed current anodes may be laid on the sea-bed provided the clearance between the anodes and the keel at low water is sufficient to avoid paint damage.

The initial setting of the correct current requires two or three potential surveys at intervals of a few days. Thereafter, surveys may be at intervals of several months, provided the water conditions remain stable.

6.4 The protection of ships' tanks

6.4.1 Factors affecting design

6.4.1.1 *General*

The cathodic protection of ships' tanks that are regularly used either solely for water ballast, or for cargo and water ballast on alternate voyages, is limited to sacrificial anode systems. Impressed current systems are excluded for safety reasons from spaces that might contain flammable gases on some occasions and also because, in the case of tanks containing only water ballast, there is a risk of chlorine evolution. Zinc, aluminium or magnesium anodes may be used, as described in **3.5.3**, but for installations where service conditions are likely to involve the presence of explosive gas mixtures, anode material selection will be governed by the safety regulations applicable (see **6.4.4.1** and **12.6.1**).

Selection of the alloy to be used will also depend on the overall economics and the compatibility of the alloy with any cargo which might be carried in the tank. The latter should always be checked. On the one hand there is the possibility of contamination of cargoes and on the other the attack of the anodes themselves.

It should be noted that when protection systems approved by the ship classification societies are to be used in tankers and dry cargo ships, these societies permit a reduction in the thickness of certain members of a ship's structure. Reference should be made to the rules and regulations of the relevant society, e.g. Lloyd's Register of Shipping, Bureau Veritas or det Norske Veritas).

6.4.1.2 *Electrolyte*

The first requirement of a sacrificial anode system is the presence of an electrolyte which, in the case of ship's tanks, will usually be sea-water (resistivity approximately 0.25 Ω·m) but will sometimes be brackish and occasionally fresh water. As the electrical resistivity varies appreciably between such waters, so will the current output from any given anode, and a protection scheme should, therefore, be designed for the water most usually carried in the tank and, if it is practicable to do so, water of appreciably different salinities should be excluded.

6.4.2 Protective coatings

A combination of cathodic protection and a paint coating may provide the most satisfactory method of protection for tank interiors, provided that the paint is compatible with the cargo and any inert gas likely to be used and is sufficiently alkali resistant. In particular, consideration should be given to such a combination where parts of tanks may be difficult to protect cathodically or may suffer unduly during non-ballast periods, i.e. when the tanks are empty or contain cargo. During such periods shallow layers or pools of water may, for example, lie on tank bottoms and other horizontal structural members and possibly cause local attack.

Wastage of steelwork may take place at the top of a tank particularly if the crown of the tank forms the exposed upper deck of a ship, where stress and temperature variations are greater than elsewhere. This wastage may be both serious and difficult to prevent by cathodic protection. Protection of such deck heads by cathodic protection alone is adequate only if:

a) the ballast water is maintained at deck level; and

b) during non-ballast periods the deck temperature is kept fairly low and fluctuation is kept to the minimum by means of insulation or, less effectively, light coloured heat-reflecting deck paint.

As these conditions are usually difficult to attain in practice, a more satisfactory solution is to paint the under deck structure and provide cathodic protection to the remainder of the surfaces. Some protection may be afforded by inert gas in cargo tanks and to a lesser extent in cargo/ballast tanks.

6.4.3 Current density

Under conditions of constant immersion in sea-water, the metal/electrolyte potential in a tank may be maintained at protection level by an average current density of the order of 30 mA/m^2 to 40 mA/m^2. The conditions most commonly found in practice, however, involve intermittent immersion for periods varying from as little as 30 h to 40 h in some trades, to many days in others. Under these conditions, rapid repolarization upon each ballasting should be aimed at, and some degree of overprotection is useful in, producing calcareous deposits on the steelwork. It is customary, therefore, to provide current appreciably in excess of that which would be required under conditions of constant immersion. It may also be necessary, in certain cases, to allow for the effects of oil or other deposits. For example, it may be anticipated that enough masking of the surface to be protected will occur to cause an appreciable reduction in the current needed to achieve protection.

In tanks used for normal sea-water, either alone or alternating with clean cargoes, it can be assumed that the surfaces of the steelwork are unlikely to be masked by deposits and the design current density is usually taken as 130 mA/m^2 for peak and upper wing tanks of bulk carriers and 110 mA/m^2 for other water ballast tanks and cargo/ballast tanks in product tankers. On the other hand, if a tank is to be used for sea-water alternating with cargoes that are known to leave barrier deposits, a lower current density may reasonably be assumed, generally on the basis of previous experience. Allowance may also be made for the effect on anode output of contamination of the anodes themselves, but it is recommended that anode materials that are particularly liable to be affected by contamination should be avoided, as the rate of polarization or repolarization during short-duration ballast voyages would be adversely affected to a marked degree. Probably the most frequently encountered examples of this are tankers engaged in the regular carriage of crude oil. The design current density normally assumed in such applications is approximately 90 mA/m^2 averaged over the whole of the surface being considered.

The design current densities given above apply to ships for which the normal ballast voyage is longer than about 5 days. It is recommended that the figures be increased by approximately 10 % for ships that are expected to be engaged on shorter ballast voyages.

In those cases where a ship's tank is partly or wholly painted, cathodic protection may be recommended to suppress corrosion on any unpainted areas and/or localized pitting at defects in the paint coating. In these circumstances, a current density of 5 mA/m^2 for those surfaces that are painted is normally adequate. Where parts only of a tank are painted, the total current can be estimated as the sum of that for the uncoated and that for the coated areas.

The current delivered by an anode during its active service in a ship's tank will vary, under any given conditions, with the degree of polarization of the steelwork, but due allowance for this variable has been made in calculating the current densities.

6.4.4 Design of sacrificial anodes and sacrificial anode systems

6.4.4.1 *Anode design and attachment*

For normal application, anodes are of simple basic design, usually in the form of castings but sometimes as extruded bar or section. They have, except for those designed for special applications, a steel core for direct attachment by welding or bolting to the steelwork of the tanks or to appropriate steel brackets. Typical anode shapes and sizes are shown in Figure 11. If there is doubt as to whether reliable electrical continuity between anode core and tank structure can be maintained with bolted connections, these should be bridged by small, suitably placed, weld deposits.

Anode and bracket design should be such that there is no likelihood of detachment in service through structural failure, or of portions of an anode breaking away from the core. All welds used for attachment of anodes and brackets should be in accordance with the full structural standard applicable elsewhere in the tank concerned. Anodes should not be sited where they are likely to be damaged during operations within the tanks.

Each cathodic protection scheme is required to be submitted to, and receive the prior approval of, the appropriate ship classification society or societies and/or the registry authority for the vessel.

In the case of tanks which may at any time contain explosive gases there is danger from incendive sparks [30] which can be produced by an anode or portion of an anode becoming detached and falling on to a steel member beneath. In this connection, the International Association of Classification Societies forbids the use of magnesium anodes in the cargo tanks of tankers.

Aluminium anodes present risks in this context but are accepted at present for use in cargo/ballast tanks in tankers provided that they are not located at a height (in m) greater than 27/W where W is the total mass (in kg) of anode and insert. Exceptions to the height rule have been made where the anodes are located on wide horizontal surfaces from which they cannot fall, such as webs, and girders with upstanding face flats or flanges. Zinc presents no sparking hazard and the use of zinc anodes is permissible although, should a zinc anode fall from a sufficient height, the steel insert may produce an incendive spark by contact with rusty steel.

6.4.4.2 *Capacity of anode systems*

In determining the ampere-year capacity of the anode system to be provided in a tank, the following factors should be taken into account:

a) the total current for the ship's hull, calculated from the current density figures indicated in **6.4.3**;

b) the life required.

NOTE This is generally 5 years to coincide with special surveys which are normally convenient occasions for replacement.

c) the percentage of the time that the tank will contain electrolyte.

The capacity (in ampere years) will be given by:

[Total current (in A)] × (life in years) × (fraction of time that electrolyte is present).

6.4.4.3 *Mass and number of anodes*

The total mass of anode material required can be calculated from the ampere-year capacity as determined in **6.4.4.2**, and the consumption rate of the selected alloy as given in Table 2.

The mass and form of individual anodes that can be used will depend on a number of factors, such as ease of handling and the geometry of the tank structure.

Once the type of anode has been selected, the number of anodes required to provide the calculated ampere-year capacity can be calculated by dividing the total mass of anode material by the mass of the individual anodes.

6.4.4.4 *Distribution of anodes*

Practical experience will generally provide information on the limiting distances which are advisable between anodes of any particular type if cathodic protection is to be achieved. For example, in a bare (i.e. uncoated) tank, the limiting distance between typical zinc anodes 1.2 m long is commonly accepted to be around 3.5 m in a lateral direction but only about 1 m in a longitudinal direction. In the case of tanks of complicated structure it may be necessary to adjust these spacings.

If the number of anodes calculated on this basis is appreciably different from that calculated from the ampere-year capacity, it is recommended that an alternative anode size be selected and the calculation repeated. The eventual design may need to be a compromise between the two calculated values.

The output from an anode of a given mass depends on its shape (see **3.5.2**).

It is particularly important to ensure that the required output is obtained from a group of anodes towards the end of the design life period. To minimize the effects due to the change of anode dimensions it may be worthwhile to arrange a staggered replacement schedule. To facilitate such an arrangement, an initial installation could consist of approximately equal numbers of two different masses, one being twice the other.

Precautionary and other measures that are applicable under operational conditions are dealt with in section 11.

6.4.5 Particular considerations

6.4.5.1 *Hydrogen evolution*

The safety regulations referred to in **6.4.4.1** prohibit the use of magnesium for the protection of cargo tanks in tankers. In other types of ship it is important to take account of the fact that there may be a hazard due to the evolution of hydrogen gas whenever a magnesium-protected tank is ballasted (see **12.6.1**).

When anodes of materials such as zinc that have a relatively low driving e.m.f. are used in normal ballast water, the amount of hydrogen is usually negligible. This may not, however, be the case when electrolytes other than normal ballast water are carried and precautions similar to those applying in the case of magnesium anodes are necessary. This would arise, for example, in the case of tankers which are required to load refinery waste such as spent caustic soda. The preferred practice is to carry such liquids in tanks not fitted with anodes but where this is not possible, it is essential that any gas evolved has free access to the atmosphere and that it cannot find its way into accommodation or other enclosed spaces (see **12.6.1**).

6.4.5.2 ***De-scaling***

A result of the cathodic protection of bare steel tanks is the gradual detachment of the corrosion scale that is usually present on the steelwork prior to the installation of anodes. This normally presents little trouble in new ships but in a ship which has been allowed to scale up badly in service, there will probably be a considerable quantity of fallen scale that will need to be removed from the tanks during the first few months after the fitting of anodes to obviate trouble with cargo or ballast discharge.

Section 7. Immersed structures (excluding off-shore applications)

7.1 Introduction

This section, which is intended to be read in conjunction with section 3, deals with the cathodic protection of immersed structures such as steel pile jetties, mooring and berthing dolphins, sheet steel piling and buoys. Because of the special considerations which apply, offshore oil and gas related structures and submarine pipelines are discussed separately in Part 2 of this code (see foreword).

7.2 General

7.2.1 Structure preparation

7.2.1.1 ***Electrical continuity***

It is essential that structures to be protected should be electrically continuous, for reasons given in **3.4.1**. Bonding of steel-piled structures should, where possible, be designed as an integral part of the structure. The bond system may comprise mild steel reinforcing bar of a suitable size, cast into the concrete deck slabbing, or an external system. Where relative movement between two parts of the structure is expected, e.g. at expansion joints and fenders, bonds need to be flexible. Outlying structures, such as mooring dolphins, can be connected to the main system by submarine cables of adequate size.

7.2.1.2 ***Protective coatings***

Coatings and their functions are described in **3.4.2**. The cost of any coating applied to piles or similar structures will be offset by the reduction in the cost of a cathodic protection system which is at its maximum when designed to protect the bare structure. It is, therefore, worth making an economic comparison between the possible alternatives.

Cathodic protection is usually considered to be fully effective up to about half-tide mark. Above this level, other measures are needed to alleviate corrosion in the tidal and splash zone. These might include specially resistant coatings, or cladding in a corrosion-resistant metal.

7.2.1.3 ***Isolation***

Isolation of the structures to be protected, from other structures in the vicinity, may be required. Isolating joints may, for example, be placed in all pipelines at the shore end of a jetty to prevent current flowing to shore installations. As indicated in **3.4.3**, measures may be necessary to prevent the accelerated corrosion of structures that are not to be included in the cathodic protection scheme.

Isolating joints may also be needed, for safety reasons, to break the continuity of solid loading arms or the steel armouring of flexible hoses on jetties (see **12.7**).

7.2.2 Application of cathodic protection

7.2.2.1 ***Current density***

Structures such as bare steel piles in the open sea, typically having a resistivity of 0.25 Ω·m, require initial average current densities of the order of 100 mA per square metre (of maximum wetted area of bare steel). This requirement is likely to fall over a long period of continuous operation to a value between 70 mA/m^2 and 30 mA/m^2, due to formation of calcareous deposits (see item b) of **3.8.1**). The embedded part of a pile will usually require from 10 mA/m^2 to 30 mA/m^2, depending on its environment. The principal factors affecting current density requirements are velocity of water movement, salinity and temperature. In estuarine conditions, higher current densities may be needed because of water movement. Dilution by fresh water may cause wide fluctuations in the power required and the use of automatic control may need to be considered (see **3.6.5**). Such fluctuations lead to the uneconomical use of protective current and, where impressed current systems are used, may lead to overloading of the rectifiers unless these are suitably protected. The problem is aggravated by the stratification of waters with different levels of salinity, which may alter the distribution of current.

If piles are coated below mean water level, current requirements are much reduced, depending on the type of coating employed and the damage suffered during driving. For example, with 0.2 mm of coal-tar epoxy coating applied to cylindrical steel piles, full protection of wetted and embedded parts can be obtained at an overall current density of about 5 mA/m^2. In practice, thicker coatings are normally used but it should be borne in mind that a coating will deteriorate with time. This process is usually accelerated by the action of marine organisms. The cathodic protection should be designed with a suitable margin of capacity to cover this condition.

Higher mean current densities than are indicated above would be necessary if immersed components of non-ferrous materials such as copper or bronze are connected to the steel. In such a case a potential survey is needed to ensure that adequate protection potential is reached at all parts of the steel.

7.2.2.2 *Types of cathodic protection system employed*

The choice of system is primarily governed by the total current required. Other considerations may apply to particular installations, but small currents are usually best provided by sacrificial anodes whilst large currents call for the provision of impressed current systems. If an a.c. power supply is available, the latter type of system is generally more economical for all but the smallest installations.

7.2.2.3 *Sacrificial anode systems*

Sacrificial anodes are normally used in conjunction with some form of structure coating. Information on materials for sacrificial anodes is given in **3.5.3**.

Zinc and aluminium anodes can be attached directly to the structure, because their low driving potentials are unlikely to cause coating deterioration (see **3.8.1**). The projecting lugs of each anode may be attached to the structure by bolting or welding, or a combination of both, before the structure is immersed. Welding is more reliable than bolting but if the latter method is used, care should be taken to ensure adequate electrical contact. Duplicate lugs can be provided to which replacement anodes may be bolted. This enables all the active material of the original anodes to be fully utilized.

Magnesium anodes are normally placed at a distance from the surface to be protected because, if directly attached, they may produce potentials that are sufficiently negative to cause coating deterioration (see **3.8.1**). A link box, as shown in Figure 8, may be provided in the connecting cable. If the structure/electrolyte potential is found to be too negative, resistance can be inserted; the life of the anode is thereby prolonged. Magnesium anodes give appreciably higher current outputs than other types of sacrificial anode but their life, in practicable sizes, is usually limited.

To avoid the need for underwater work on existing structures, anodes can be welded to steel bars which are then attached to the structure at a point above water level. This also facilitates renewal when required.

Where no link is provided for current measurement, the need for replacement is generally assessed on the basis of measurement of structure/electrolyte potentials, supplemented if necessary by inspection of the anodes by a diver.

7.2.2.4 *Impressed current systems*

Transformer-rectifier units, as described in **3.6.4**, are usually used as the source of direct current if an a.c. power supply is available. Automatic control is sometimes required (see **3.6.5**). The properties of anode materials are given in **3.6.2.1**. Anodes capable of operating at high current densities can generally be used when immersed structures are to be protected because in most cases the electrolyte resistivity is low. Land-based groundbeds may sometimes be required and these should be as described in **3.6.2** and **4.2.3**.

Impressed current anodes are usually supported clear of the sea bed and it may be advisable to make provision for easy lifting to facilitate inspection and maintenance. It is essential to guard against corrosion of the connections between the cables and the anodes, which could render the protection system inoperative. The point of connection of the cathode lead to the protected structure may often be in the splash zone and will also need to be coated.

In the case of jetties, it is often better to use a number of anodes distributed among the piles rather than one or two large groundbeds remote from the structure. A distributed anode system results in more uniform pile potentials and less interaction with other structures.

The protection of sheet steel piling will usually require separate groundbeds or anode systems for the landward and seaward sides of the piling. The total surface area of the sheet piling, together with that of the tie rods and anchors, should be used in estimating the total current required for protection.

Anodes should be so distributed as to ensure a substantially uniform level of protection although, if necessary, adjustment can also be achieved by preset resistors at suitable points or by using different sizes of anode or cathode cable.

7.2.3 Interaction with adjacent vessels

In certain cases, it may be advantageous to provide a flexible bond connection to vessels which lie alongside a cathodically protected structure for long periods in order to protect their hulls and to prevent interaction effects (see **9.4**). Account should be taken of the additional current required when designing the cathodic protection installation. It should be borne in mind that alterations in berthing will affect the current requirement and care should be taken that removal of a vessel does not lead to overprotection and consequent damage to paint protection of the piling [see **3.8.1** a)]. For vessels carrying cargoes that bear a risk of fire or explosion, ship to shore bonding is not recommended (see **12.7**).

Section 8. The internal protection of plant

8.1 Introduction

This section deals with some of the considerations that are generally applicable to the internal protection of plant and makes recommendations that are specific to storage tanks (see **8.3**), water circulating systems (see **8.4**) and other industrial plant. It is intended to be read in conjunction with section 3.

NOTE Further information can be found in references [31] to [34].

8.2 General

8.2.1 Factors affecting design

In providing cathodic protection within confined spaces, it is often impossible to provide sufficient spacing between the anode and the surfaces to be protected to obtain reasonably uniform current distribution. As a result, the effect of each anode is generally more local than in other applications. This is particularly true when, as frequently occurs, the use of a protective coating is found to be uneconomical. Careful placing of anodes is therefore essential; they should be placed near the points where corrosion is, or is expected to be, most severe. Factors that affect both the initial pattern of corrosion and the current density needed for protection are the nature and condition of the electrolyte (oxygen content, temperature, resistivity and velocity) and the use of non-ferrous metals in construction of the plant (see **8.4**). Where conditions vary, automatic control, as described in **3.6.5**, may be needed.

It should be noted that many of the criteria given in other parts of this code relate to relatively pure or saline waters at normal temperatures and may not necessarily be applicable to conditions in some types of industrial plant.

In some applications, the possibility of electrolytically-produced hydrogen or chlorine accumulating may call for special measures (see **12.6**).

8.2.2 Sacrificial anodes

The characteristics of sacrificial anode materials are given in **3.5**, together with indications of design principles. Zinc, in the absence of chloride, becomes more noble than steel at temperatures greater than 60 °C, and may suffer from intergranular attack above 40 °C, so that its use at elevated temperatures may be restricted.

Anodes may need to be designed to suit the geometry of the plant to be protected. Those shown in Figure 11 may be suitable for some plant applications. Arrangements for fixing are described elsewhere in this code (see, for example, **6.4.4.1**).

8.2.3 Impressed current systems

Anode materials for impressed current systems are referred to in **3.6.2.1**. Anode design and configuration is also a factor in planning installations. For applications in fully enclosed plant (i.e. other than open-topped tanks), the main type in general use is the cantilever anode of platinized titanium.

The advantage of the cantilever anode is ease of replacement. If the titanium is platinized only for a length near the tip, separation can be provided between the surface to be protected and the effective part of the anode.

Equipment for power supply is described in **3.6.4**. Arrangements for controlling the current in each anode circuit and, in some cases, automatic control, may be required (see **3.6.5**).

Where cathodic protection is applied internally to plant, corrosion interaction affecting neighbouring structures is unlikely since appreciable current flows only through and inside the protected plant.

8.2.4 Assessment of protection provided

Sacrificial anodes are usually attached by welding or bolting and it is normally impossible to measure the output current. While potential measurements can be made using the techniques described below, it is more usual in the case of small items of plant to assess the effectiveness of the protection by routine inspection of the internal surfaces and of anode wastage. Inspection should also be made to check that there is no build-up of anode corrosion products which may obstruct water flow or encourage corrosion. This may arise on units which are not continuously flushed with water and is more likely with the use of magnesium anodes.

In the case of impressed current installations, the provision of reference electrodes, as described in **10.3.4**, is essential for maintaining correct operating conditions. Permanently-installed reference electrodes are also required for automatic control (see **3.6.5** and **10.3.4**).

8.3 Storage tanks

8.3.1 Water storage tanks

Impressed current cathodic protection is the method normally used for large tanks such as overhead water towers, oil refinery sea-water storage tanks, boiler feed-water tanks and river water tanks in power stations. In the case of open-topped tanks, anodes of silicon iron or platinized titanium, or lead anodes, if possible toxicity is not a consideration, may be suspended from adequate supports. Alternatively, it may be preferable to drill the tank and insert anodes and reference electrodes through the wall. Anodes should be so distributed that they are in the best positions to ensure even current distribution, i.e. at points roughly equidistant from the bottom and the sides of the tank, and so placed as to ensure adequate penetration of current into the corners.

When the water resistivity is exceptionally high, as for example in boiler feed-water tanks, copper-cored platinized titanium continuous anodes may be used; the high resistivity of the water necessitates considerable anode lengths being used to achieve adequate current distribution.

Where sacrificial anodes are used, they are normally attached directly to the metal surface to be protected. Corrosion is most probable near the waterline where differential aeration effects are greatest; anodes will normally need to be distributed up to about 600 mm below the minimum water level.

For domestic water tanks, sufficient current may be obtained from a single magnesium anode.

8.3.2 Tanks for storage of chemicals

Among the types of plant that have been protected are brine storage tanks, acid storage facilities, and electrolytic resistance tanks.

The methods of applying cathodic protection to tanks containing chemicals are similar to those for water storage tanks. Care needs to be taken in selecting anode material to ensure that it does not react with the chemicals involved. Sacrificial anodes are seldom suitable and it is normal to use impressed current with platinized titanium anodes. The criteria for protection potentials given in **2.3.2** are not necessarily applicable.

NOTE An alternative system, used to protect certain types of chemical plant, is that of anodic protection. A stable oxide film is established on the surface of the metal to be protected by making the metal/electrolyte potential more positive. Its use is mainly confined to the protection of titanium and stainless steel.

8.4 Water circulating systems

8.4.1 General

Circulating water systems are often constructed from cast iron (see note) or mild steel, and where the metal is not subject to harsh conditions such as mechanical erosion, high temperature or chemically aggressive coolants, a moderate increase of thickness will generally ensure a reasonable life. With cast iron, mechanical considerations in casting often result in an adequate wall thickness. There is, therefore, generally little economic incentive to protect, for example, runs of iron or steel pipework, particularly as this requires anodes to be mounted about every four pipe diameters along the length of the run.

The corrosion rate may be locally high due to galvanic action between the various combinations of metal and alloys in the system. Generally, the ferrous component acts as an anode and so corrodes. This process is more important if the oxygen content of the water and the water velocity are high. In such circumstances, the protection of large heat exchangers or coolers becomes economical and details are given in **8.4.2** and **8.4.3**.

Difficulties of application have prevented the benefits of cathodic protection being extended to the inside of other items of plant, even where the combination of materials can give rise to corrosion at appreciable rates; the basic principles of sound design practice have not, therefore, emerged. Thus, in the case of pumps, even with the impressed current system, it is difficult to position sufficient anode material to provide the relatively large protection current densities that are needed, particularly at points where galvanic action may occur, without interfering with water flow. Similarly with valves, care must be taken to position the anodes according to the proportions of the service life during which the valve will be in the open and in the closed positions, in such a way as to ensure that the current reaches those parts of the exposed surface which are subject to severe corrosion. If the water is stagnant for long periods it may be necessary to take measures to prevent the accumulation in parts of the system of chlorine developed at the anodes.

NOTE With cast iron, graphitic corrosion occurs in which metal is removed, leaving the graphite. This does not materially alter the application of cathodic protection except that, the graphite being electropositive, the current density required may be increased.

8.4.2 Heat exchangers (tube and shell)

8.4.2.1 *General*

Typical plant has cast iron water boxes with tube plate and tubes of copper-based alloys. Where this is the case, the cast iron corrodes, the effect falling off with increasing distance from the components in copper-based alloy. Severe local attack with deep penetration may thus occur on cast iron adjacent to tube plates.

Non-ferrous tube plates and tube ends may also be attacked, principally due to water turbulence and corrosion erosion, and cathodic protection may help to reduce the rate of attack. It has been observed that the coating of a ferrous water box, or its replacement by a non-metallic type, has been accompanied by accelerated tube end attack due to the removal of the cathodic protection previously afforded by the corroding water box. In such a case, provision should be made for alternative means of protecting the tube plate and tube ends, for example, by installing sacrificial anodes (see **8.4.2.3**).

In circulating water systems, the flow velocity is usually much higher than is encountered with immersed structures and this, together with the presence of metals that are more electropositive than iron, increases the current density required for protection. A rough guide to the amount of current required for cathodic protection of condensers and coolers has been found by experience to be about 2 A/m^2 based on overall tubeplate area.

The protective current may be provided by either sacrificial anodes or an impressed current system, the factors determining the system to be used being largely those previously outlined (see **3.7**) including current requirements, power availability, possible hazards and the accessibility of the components for maintenance. Impressed current has advantages in that the current may be manually or automatically varied to maintain full protection at all times irrespective of changes of flow rate or composition of the cooling water.

Sacrificial anodes cannot normally be so adjusted and also require comparatively frequent renewal. On large power station condensers, sacrificial anode renewals may not only be costly but also involve considerable effort. Sacrificial anodes are generally more suitable for smaller units, particularly if periodic shut-downs provide regular opportunities for inspection and anode renewal. They may also be of advantage in plant where hazardous atmospheres exist (see **6.4.4.1**, **12.6** and **12.7**) since the use of flameproof electrical equipment, which would be necessary with an impressed current system, can be avoided.

In certain modern heat exchangers, titanium condenser tubes are installed. The potentials corresponding to full cathodic protection are such that hydrogen evolution is possible and a possible hazard of the formation of titanium hydride exists. Care should be taken to avoid overprotection in these circumstances as titanium hydride may induce an embrittlement effect at the inlet ends of the tubes.

8.4.2.2 *Water box coatings*

The use of coatings in conjunction with cathodic protection may not lead to economy because, even with a well-coated box, the current that will flow to the heat exchanger surface, which cannot be coated, will still be considerable. Any coatings that are adversely affected by the alkaline environment produced near anodes should not be used; coatings which may come off as sheets, causing tube blockage e.g. rubber and neoprene coatings should be avoided. Coatings should be evaluated for their resistance to cathodic disbonding as described in BS 3900-F11.

8.4.2.3 *Sacrificial anode systems*

The anodes are usually of either zinc alloy or magnesium. Zinc anodes are generally more suitable where the cooling water has a low resistivity, e.g. sea or estuarine water, due to their longer life. With high resistivity cooling water, magnesium anodes are generally more suitable because their higher driving potential enables them to provide a greater current output than would be the case with zinc anodes. In certain cases, e.g. where the water box is very well coated or of non-ferrous material, soft iron anodes may be fitted to provide cathodic protection of the tube plate and tube ends.

NOTE Iron corrosion products are beneficial in assisting film formation on non-ferrous metals; ferrous sulphate is sometimes injected to produce inhibiting films.

In any particular installation, anode wastage rates will be mainly determined by the mean temperature, flow velocity and resistivity of the cooling water. In view of these variable factors, it is often advisable to determine anode wastage rates by trial. If cathodic protection is being applied to an existing design of water box, the maximum amount of anode material which can be installed will be limited by the physical dimensions of the water box; anodes should not cause excessive water velocity or turbulence.

In many industrial plants, regular opportunities for opening up condensers for anode inspection and renewal occur during plant shut-downs. In the case of oil refinery units, this may be every 2 years to 3 years and it may be possible to install sufficient anode material to provide continuous protection over this interval. In some cases, this will entail modification to the water box, for example, dished floating head covers can be made deeper to allow space for the anodes and to maintain sufficient crossover area to avoid undue turbulence.

For zinc alloy anodes in sea-water-cooled condensers, the minimum anode mass to be installed on the cover of a coated water box for a 5 year life in a temperate region can be estimated from the formula:

$$W = 80D^2 \qquad (11)$$

where

W = mass of zinc anodes (in kg)

D = nominal diameter of the wetted part of the tube plate (in m)

In tropical regions the anode life will be about half that stated above.

8.4.2.4 ***Impressed current systems***

High quality coatings are not normally used in conjunction with impressed current. Cantilever platinized titanium anodes are generally used and need to be distributed about the water box to ensure adequate distribution of current.

Reference electrodes will be required so that the effectiveness of the cathodic protection can be measured and these should be mounted near the point of maximum galvanic influence and remote from anodes. If adequate levels of protection are reached at such points, it can be assumed that all parts of the box are adequately protected. It is not general practice to protect coolers of less than 500 mm diameter. If, however, this needs to be done for special reasons, the factors relating to large condensers also apply, except for the location of anodes, which can be of the cantilever type mounted centrally on the end covers.

8.4.3 Box coolers

"Coil in box" coolers comprise a series of pipe coils, of from 75 mm to 150 mm diameter in a steel box through which a flow of cooling water is maintained. The coils, which usually carry hot oil, are generally arranged in vertical banks and the necessary anodes can be installed only in the restricted space between these banks of tubes.

In order to obtain an adequate spread of protection current both along the tubes and also vertically down the bank of tubes, either a series of vertical or horizontal anodes is required, or a combination of both.

Depending on conditions, impressed current with either lead alloy or platinized titanium anodes can be used. It is usually impossible to accommodate sufficient sacrificial anode material to maintain protection over a useful life.

It should be noted that a significant temperature gradient may exist from the top to the bottom of the box which will cause an appreciably higher output current density from anodes located near the water surface. Under certain circumstances, this can lead to overprotection near the water surface at the expense of underprotection in the bottom corners of the box. This tendency should be taken into account in determining the configuration of the anode system.

Because of the higher output of anodes near the water surface, vertical anodes that are suspended from above the water level are subject to wastage in the form of necking. This problem may be overcome by a suitable anode shape, e.g. a tapered anode, or by sleeving the anode at the water line.

8.5 Other industrial plant

There are often secondary factors which make the application of alternative means of avoiding corrosion, such as the utilization of coatings, impracticable. One typical application, now fairly widespread, is the utilization of impressed current cathodic protection in bottle-washing machines, as broken bottles tend to damage any applied coatings. For similar reasons, cathodic protection has been applied to pasteurizers. Steep liquid tanks can also be protected.

Section 9. Measures to safeguard neighbouring structures

9.1 Introduction

This section describes how the cathodic protection of a buried or immersed structure or stray current from other sources may cause accelerated corrosion of neighbouring structures, and the measures necessary to alleviate such interaction.

9.2 General

The application of cathodic protection to a buried or immersed structure (referred to as the primary structure) causes direct current to flow in the earth or water in its vicinity. Part of the protection current traverses nearby buried or immersed pipes, cables, jetties or similar structures, or ships alongside (termed secondary structures), which may be unprotected and the corrosion rate on these structures may, therefore, increase at points where the current leaves them to return to the primary structure. This effect is described as corrosion interaction.

Corrosion interaction can be minimized by exercising care during the design stage, as discussed in **9.3.4**, can be assessed by tests and criteria described in **9.3.2** and **9.3.3**, and can be corrected, if necessary, by measures described in **9.3.5**.

Corrosion interaction affecting neighbouring structures is unlikely to occur as a result of applying cathodic protection to plant internally because appreciable currents flow only through and inside the protected plant.

The recommendations in **9.3** apply particularly to structures such as pipelines, although the basic principles are applicable generally. Special considerations applying to jetties and ships are discussed in **9.4**.

Besides possibly causing corrosion, currents from cathodic protection systems could cause false operation of railway signalling equipment and could interfere with telecommunication circuits (see **9.3.6**).

9.3 Buried structures

9.3.1 Notifying owners of other structures

9.3.1.1 *General*

It is essential, throughout the planning, installation, testing, commissioning and operation of a cathodic protection scheme, that notice of actions proposed be given to all organizations and owners having buried metallic pipes, cables or other structures in the near vicinity of the installation. These notices are intended to ensure that information becomes available to enable a system to be installed in such a manner that corrosion interaction is kept to a minimum and that enough information is given to other organizations to enable them to determine whether corrosion interaction is likely.

The following recommendations indicate the stages at which other organizations should be notified and the information that should be provided at each stage. The notification of corrosion interaction testing referred to in **9.3.1.4** may be combined with the further notification (see **9.3.1.3**) if convenient, and these notifications need only be sent to organizations who have indicated, in reply to a preliminary notification, that they have structures likely to be affected by the operation of the scheme.

9.3.1.2 *Preliminary notification*

At an early stage during the planning of a cathodic protection scheme, a preliminary notification should be sent to each organization having buried metallic structures near the proposed installation (but see **9.3.6**). The notice should include, as far as possible, the following information, (including any drawings):

a) whether sacrificial anodes or an impressed current system will be employed;

b) information as to the route or site of the structure to be cathodically protected;

c) position of groundbeds or anodes if known at this stage;

d) approximate dates by which the system is likely to be ready for commissioning.

NOTE The preliminary notice should not be delayed unduly if all the information is not readily available.

The notice should also include a request for any particulars needed relating to the buried structures belonging to the other organizations in the area, for use in designing the scheme to give the minimum corrosion interaction. Such a request should preferably be accompanied by additional copies of any drawings with a request that they be marked up and returned.

9.3.1.3 ***Further notification***

If any of the information listed in **9.3.1.2** is not available at the time of preliminary notification, this should be supplied subsequently at least one month before the date proposed for corrosion interaction testing. In particular, the sites of proposed impressed current groundbeds should be notified well before construction commences. In the case of sacrificial anode installations, the information provided should show the relative positions of the anodes and the primary and secondary structures. It may often be possible for the parties to agree that interaction testing is unnecessary in the case of sacrificial anode installations (see **9.3.4.2**).

9.3.1.4 ***Notification of corrosion interaction testing***

After commissioning tests of the system have been completed (but see **9.3.6.2**), notification should be sent to all organizations who have indicated that they have structures likely to be affected by the operation of the scheme. The following information should be supplied at least one month before the date proposed for interaction tests:

a) the anticipated current at which each rectifier or sacrificial anode will be operated during interaction tests;

b) an indication of structure/soil potentials along the primary structure before and after the application of protection;

c) dates for the tests.

At the time of the tests, there should be available to all participants, suitably scaled plans showing the layout of the primary and secondary structures at the test locations together with the locations of the cathodic protection installations, drawn up from information supplied by both the operator and the other interested parties.

9.3.1.5 ***Interim and subsequent notification***

If, after preliminary notification, or at any time after the cathodic protection scheme has been brought into regular service, it is found necessary to alter the scheme substantially, details of the proposed amendments should be sent to all organizations having buried metallic structures near the revised cathodic protection scheme.

9.3.2 Interaction testing

9.3.2.1 ***Stage at which interaction tests should be made***

At least one month should be allowed, if required, for the owners of nearby structures to examine details of the proposed scheme and to respond so that the operator may arrange for interaction tests. Tests should be made within three months of switching on the cathodic protection.

9.3.2.2 ***Tests to assess corrosion interaction***

The changes in structure/electrolyte potential due to interaction will vary along the length of the secondary structure and a negative potential change at any point will often indicate the presence of positive changes at other parts of the structure. For most metals, only positive potential changes are liable to accelerate corrosion (see **2.2.2**). The usual object of interaction testing is, therefore, to find the areas where the potential change is positive, to locate, by testing a number of positions, points at which the potential change locally reaches a maximum and to assess each maximum value with sufficient accuracy.

In the case of discontinuous structures (such as mechanically jointed pipelines) it is essential that each discontinuous section should be treated as a separate structure for testing.

In certain cases, negative changes of potential in excess of the level that would be needed for cathodic protection may adversely affect the structure or its coating (see **9.3.3.4**).

The current used for the test should be the maximum required during normal operating conditions to give the level of protection required on the protected structure. A test current below the anticipated current required during normal operation may not bring about the maximum changes in potential on secondary structures.

Details of suitable apparatus and the method of connection for carrying out tests at each position are given in section 10. The criterion is the magnitude of the change of potential of the secondary structure (see note) with respect to its electrolytic environment that occurs when the cathodic protection is switched on or when the sacrificial anodes are connected. This change is usually equal in magnitude to, but has the opposite sign from, the change occurring when the protection is switched off.

NOTE When, as is normally the case, the positive terminal of the meter is connected to the reference electrode, the potentials measured are usually negative and a change in the positive direction will be indicated by a *reduction* in the meter reading.

The change recorded should be that change clearly seen to be due to the switching on of the cathodic protection unit, not more than 15 s being allowed for the instrument to indicate the resulting change of structure/electrolyte potential before the reading is taken. If there are also fluctuations of potential due to the effects of stray currents from other sources, then only those changes caused by the switching on of the cathodic protection unit should be recorded. Several observations should be made at each point and compared. In marginal cases, the number of observations should be increased and examined for consistency. This is of particular importance at positions where tests indicate that the changes in the positive direction on the secondary structure are locally at a maximum. The position of the reference electrode is often important (see **10.3.2.2**).

It is important to synchronize the measurement of structure/electrolyte potential with the switching. This can be done by providing radio, or other, communication between the individual who is making the actual measurement and the one who is controlling the cathodic protection unit, the cathodic protection being switched on and off alternately by hand. Alternatively, the cathodic protection unit can be switched on and off at agreed regular intervals by means of a suitable time-switch.

The change in structure/electrolyte potential resulting from the cathodic protection should be measured at a sufficient number of points, generally working outward from the anode of the protection system, and with the spacing being sufficiently close, to give an overall picture of the distribution of structure/electrolyte potential change. Detailed attention should be given to crossing points or points of close proximity between the primary and secondary structures and to regions where the change produced has been found to be in the positive direction.

Where more than one cathodic protection unit is installed on a particular structure, the combined effect should be ascertained. Arrangements should be made for all units which cause an appreciable effect at the position of tests, to be switched on and off or connected and disconnected simultaneously.

9.3.2.3 *Information required during and at the completion of interaction tests*

The protection current measured at each rectifier during interaction tests, and the finally agreed currents to be employed as a result of any remedial measures, should be notified to all organizations attending the tests and all authorities who have indicated that they have structures likely to be affected by the operation of the scheme.

9.3.2.4 *Tests after remedial measures have been applied*

Further testing may be required after agreed remedial measures (see **9.3.5**) have been applied.

If, after providing bonds between two structures or fitting sacrificial anodes in order to reduce interaction, the structure/electrolyte potential of the secondary structure is found to be appreciably more negative than that measured with the cathodic protection switched off during the initial interaction testing, this will normally be sufficient indication that the mitigation procedure is achieving its purpose. The criterion should be the change of the structure/electrolyte potential between the original condition with the cathodic protection switched off and the final remedied condition with the cathodic protection operating, switching and bonding or anode connection being carried out quickly to minimize any effects of variations from other sources.

It may happen that the initial structure/electrolyte potential of the secondary structure is more negative than the potential of the primary structure. For example, a galvanized steel structure without applied cathodic protection, even when its structure/electrolyte potential is changed in the positive direction due to the effect of a nearby cathodic protection scheme, may be more negative than a cathodically-protected lead or ungalvanized steel structure. Under these circumstances, an adverse effect cannot easily be offset by bonding since, owing to galvanic action between the primary and secondary structures, the structure/electrolyte potential of the latter would be made more positive, the effect being larger than any beneficial effect due to the cathodic protection. Bonding could be made effective only by making the primary structure more negative, for example, by increasing the total protection current or moving one of the groundbeds closer to the point where it is proposed to bond. Alternatively, the secondary structure could be protected by a separate cathodic protection scheme, possibly by installing sacrificial anodes connected to the secondary structure. In exceptional cases it may be found possible, by special agreement between the parties, to accept structure/electrolyte potential changes on the secondary structure greater than the accepted normal limit (see **9.3.3**) and thereby avoid the need for remedial action.

9.3.2.5 *Repeat tests*

When the cathodic protection system is put into service, arrangements should be made for repeat tests to be made on neighbouring structures at 2 year intervals or at intervals agreed between the parties concerned depending on the magnitude of the structure/electrolyte potential changes observed. The necessity for re-testing should also be considered when changes are to be made to either the primary or the secondary structures or their cathodic protection systems (see also **9.3.6**).

9.3.3 Criteria for limiting corrosion interaction

9.3.3.1 *General*

As explained in section 2, any current flow that makes the potential of a metal surface more positive with respect of its surroundings is liable to accelerate corrosion. The structure/electrolyte potential is therefore used as the basis of assessment. Positive structure/electrolyte potential changes are the more important. Steel surrounded by concrete needs special consideration for reasons explained in **9.3.3.3**. Occasionally, negative changes have to be limited (see **9.3.3.4**).

9.3.3.2 *Limit of positive structure/electrolyte potential changes for all structures except steel in concrete*

The maximum positive potential change at any part of a secondary structure, resulting from interaction, should not exceed 20 mV. This figure was adopted on the basis of information provided by the Joint Committee for the Co-ordination of the Cathodic Protection of Buried Structures when the previous code, CP 1021:1973, was being drafted. Subsequent experience has provided no indication that corrosion damage occurs when this limit is respected. However, in many circumstances, particularly if the existing conditions provide a measure of cathodic protection at the relevant part of the structure, higher potential changes could be tolerated.

Some structures are inherently more resistant to stray currents. For example, for cables having a good extruded-plastics coating, the danger of damage to the coating in making test connections for interaction testing is probably a greater risk than that due to interaction. Any interaction associated with cable systems is likely to be manifested at the nearest earthing facility.

Should the secondary structure be provided with independent cathodic protection, then the owners of the secondary structure may agree to accept a greater positive potential change on this structure, provided that its potential remains more negative than the value given in Table 1.

In the case of potential changes resulting from current leakage from a d.c. electric traction system, which may be continuously varying due to movement of the trains, larger maximum positive changes may be acceptable.

9.3.3.3 *Limit of positive structure/electrolyte potential changes for steel in concrete*

The maximum positive potential change recommended in **9.3.3.2** is inapplicable to steel that is completely covered by concrete. Under such conditions, steel becomes passive so that corrosion is prevented. The governing consideration may, therefore, be the disruptive effect of the evolution of oxygen which occurs when the steel is more positive than about + 0.5 V (copper/copper sulphate reference electrode). However, the behaviour of the steel may be affected by the presence of chlorides (whether introduced initially or due to a saline environment) which may prevent passivation, so that it is impossible to make general recommendations.

Another complication is that it is not a simple matter to evaluate the structure/electrolyte potential or to measure changes in it across the steel/concrete interface. Changes in the steel/soil potential measured simply by placing the reference electrode in the soil close to the concrete (as distinct from close to the steel) may need to be compared with a limit other than the 20 mV given in **9.3.3.2**. However, until another limit more appropriate to these circumstances is approved, it may be convenient to use the 20 mV limit as a basis for decision as to whether or not corrective measures should be undertaken.

These considerations apply only to steel fully enclosed in sound concrete. If the steel is only partially encased, the provisions of **9.3.3.2** apply to any area of the surface in direct contact with the soil. It should be noted that in these conditions a cell may be formed in which the steel in contact with soil acts as an anode. The structure/soil potential of this steel is likely, therefore, to be more positive at positions near the concrete and there may be corrosion quite apart from any effect of interaction.

9.3.3.4 *Negative changes of structure/electrolyte potential*

If the recommendations given in **9.3.4** are followed, excessive negative changes of structure/electrolyte potential on the secondary structure will normally be avoided. Large negative changes may, however, occur if the groundbed of an impressed current cathodic protection scheme is unduly close to a secondary structure. Except in the case of aluminium (and, exceptionally, lead in an alkaline environment), corrosion is unlikely to result from making the structure/electrolyte potential more negative. The considerations are, therefore, the secondary effects described in **3.8.1** particularly the disruption of coatings; and those dealt with in **9.3.6**. In the absence of any special considerations, structure/electrolyte potentials more negative than – 2.5 V should be avoided on buried structures.

9.3.4 Design of cathodic protection installations to minimize corrosion interaction

9.3.4.1 *General*

It is impossible to estimate precisely the amount of corrosion interaction likely to be caused by a cathodic protection scheme. The magnitude of any positive changes of structure/electrolyte potential on neighbouring secondary structures will depend mainly on the following.

a) *The quality of the coating on the primary structure*. The better the coating the smaller will be the current required for protection and the interaction effects will be reduced accordingly.

b) *The quality of the coating on the secondary structure*. A coating on the secondary structure tends to increase the measured positive changes of structure/electrolyte potential. However, high positive changes of structure/soil potential across a resistive coating indicate a possibility of enhanced corrosion should local coating defects exist or develop later.

c) *The magnitude of the structure/electrolyte potential change on the primary structure in the vicinity of the secondary structure*. Because interaction effects are roughly proportional to this structure/electrolyte potential change, it should be kept to the minimum required to provide protection at positions remote from the point of application. A larger structure/electrolyte potential change is necessary at the points of application if the length of structure protected from any one point is increased. Thus, interaction can be reduced by applying the protection at a larger number of points so that the structure/electrolyte potential change on the primary structure is more uniform and by ensuring, as far as other considerations allow, that the points of application and associated larger structure/electrolyte potential changes are remote from other structures.

d) *The spacing between the primary and secondary structures*. Interaction will be greatest at a crossing point or other proximity. The greater the separation of the structures, the less the effect will be.

e) *The distance between the groundbeds or anodes and the secondary structure*. Structures close to the anode system may be affected by the potential gradient around the anode producing changes in potential both near to and remote from, the anode. Anodes or groundbeds should not, therefore, be placed close to other structures.

f) *Soil or water resistivity*. The potential gradient at any point in the soil is the product of current density and resistivity. Thus, in general, interaction is minimized by siting groundbeds in low resistivity areas.

9.3.4.2 *Sacrificial anodes*

The current available from a single sacrificial anode of typical size in most soils is generally of the order of tens of milliamperes compared with impressed current installations where tens of amperes may be produced. If the total current is less than 100 mA, interaction testing may be omitted. Even if the current exceeds 100 mA, corrosion interaction is unlikely, particularly if anodes are placed at least 2 m away from any secondary buried structure and so that the secondary structure does not lie between the anode and the primary structure.

If anode outputs in excess of 100 mA are used, or groups of anodes installed together are used, or if anodes are sited so that another underground metallic structure lies between the anode and the primary structure, interaction testing should be offered.

It may be important to reach agreement at an early stage as to whether testing is necessary for a particular anode system, as connecting links to facilitate disconnection for testing purposes may be necessary. Links may, of course, be required for testing the output of anodes, whether interaction testing is considered necessary or not.

9.3.4.3 *Impressed current installations*

The following precautions should be taken.

a) Structure/electrolyte potentials on the primary structure should be kept to the minimum consistent with the required level of protection being obtained.

b) High quality coatings should be provided to minimize protection current on a new buried or immersed structure that is to be protected cathodically with particular attention to coating integrity at crossings with secondary structures.

c) The new structure should be sited as far from neighbouring structures as is practicable and the spacing at all crossing points ascertained as being the maximum which conditions permit.

d) The longitudinal resistance of the structure to be cathodically protected should be made as low as is practicable by means of continuity bonds, welded joints, or other means.

e) The groundbed should be sited as far from neighbouring structures as is practicable.

f) Consideration should be given to installing anodes at a considerable depth, e.g. 15 m to 30 m.

g) The total current to be applied should be distributed from a sufficient number of units to ensure a reasonably uniform distribution of structure/electrolyte potential on the primary structure.

h) The total current should be confined to the primary structure by suitable isolation when feasible.

9.3.5 Measures to reduce corrosion interaction

9.3.5.1 *Choice of method*

In addition to reconsidering the precautions taken during the installation of the cathodic protection scheme, and to ensuring that the current is the minimum necessary to provide an acceptable level of protection, one or more of the following methods should be considered by the parties concerned as a means of reducing corrosion interaction at the points on the secondary structure where positive changes in excess of the recommended maximum have been measured.

The method adopted should aim at restoring the structure/soil potential of the secondary structure to the original value, or preferably making it more negative than the original value.

The following techniques are available.

a) A joint cathodic protection scheme could be installed so that full protection is given to both structures.

b) The two structures could be connected together by means of one or more remedial bonds, which may include suitable resistors to limit the current to the minimum necessary to correct the interaction. This is one of the most effective methods of reducing possible corrosion interaction. The remedial bond should preferably be connected to the secondary structure at or near the point where the maximum positive structure/electrolyte potential change was measured, but if the structures are some distance apart at this point, and it is more convenient, the installation of a remedial bond at a point not too far distant, where the structures are closer together, may be satisfactory. For reasons referred to in **3.4.1**, it is essential that any structure to be so bonded should be electrically continuous. If it is suspected that the secondary structure may be discontinuous, each discontinuous section should be tested separately and remedial action taken as necessary.

The bond, the connections to the two structures, and any resistors, should be constructed to specifications satisfactory to the owners of both structures. The bond should be an insulated copper conductor and be of adequate size to carry any fault current that may flow (see **12.4**), but should be of not less than 16 mm^2 cross-sectional area. Where possible, the bond termination should be installed inside a suitable housing or building where it can be regularly inspected. When a buried bond is required, mechanical protection against digging operations may be necessary; it is desirable that suitable identification markings be provided.

In circumstances where it is clear that corrosion interaction will occur, much testing time will be saved if provisions for bonds are installed at suitable positions before interaction tests are made. It is not always necessary to measure the current flowing in the bond, but if a regular check of the current is required, for example, where resistance bonds have been provided to control the current, a suitable enclosure and a removable link or other bolted connection may be installed at a point accessible to both parties.

Bonding between structures may be precluded by safety considerations (see **12.4**). For example, the bonding together of electric transmission towers and pipelines containing flammable liquids or gases is generally to be avoided. In such cases, the other measures for eliminating the effects of interaction suggested in **9.3.4.3** and in items c) and e) below, are to be preferred.

c) One or more sacrificial anodes could be connected to the secondary structure where the positive potential changes occur, usually where the two structures are close to each other.

d) The resistance between the two structures could be increased, at a point where a positive change is measured, by applying locally an additional good quality coating or wrapping to the primary and/or secondary structure or by inserting insulating material between the structures.

e) In the case of a pipeline, a section of pipe adjacent to secondary structures could be electrically isolated by means of isolating joints. The isolated section can then be bridged by means of an insulated cable of appropriate size to maintain continuity along the main section of the pipeline. The isolated section can be generally protected by means of sacrificial anodes. Alternatively, one of the isolating joints can be shunted by a resistor of such a value that the pipe between the isolating joints is protected without causing excessive interaction. This method is particularly applicable at parts of the route near groundbeds where the primary structure/electrolyte potentials are strongly negative, creating possible severe interaction on secondary structures. The method can be applied at road crossings where there may be a number of secondary structures, or at railway crossings to limit interaction with signalling and other equipment. A section of pipe can also be isolated at crossings with electrified railways to reduce the effects of stray traction currents on the pipeline.

The unprotected sides of isolation joints should be treated as structures likely to suffer interaction and tests carried out accordingly.

It is very important to ensure that methods that entail extending the cathodic protection to further structures are not used in such a way that consequent negative potential changes on such structures, in turn, cause corrosion interaction on a third structure.

9.3.5.2 *Temporary operation of an installation*

If it is urgently required to operate a cathodic protection installation which is completed except for arrangements necessary to reduce structure/electrolyte potential changes on neighbouring plant, it is recommended that, wherever it seems unlikely that material damage will be caused to the secondary structure, agreement should be sought for a limited period of operation without remedial measures. This is to enable the protection to be maintained while the necessary additional work, which should be put in hand as soon as possible, is carried out.

The period during which such temporary operation may be permitted depends on the amount by which the measured structure/electrolyte potential changes exceed the limit given in **9.3.3.2**, on any available evidence as to the existing state of the two structures, and on the period, if any, during which the protection has already been operated prior to testing. If there is no history of corrosion on the secondary structure it is suggested that, where it is expected that the remedial measures will eventually eliminate the adverse changes entirely, temporary operation may be acceptable for a period not exceeding three months with structure/electrolyte potential changes of up to + 50 mV.

9.3.6 Particular considerations

9.3.6.1 *Cathodic protection systems installed adjacent to telecommunication services: electrical interference*

If a telecommunication cable is bonded to, or close to, a cathodic protection system energized from a source of alternating current through rectifiers, or if the groundbed of the cathodic protection system is sited close to the earth electrodes of a telecommunication system, there may be interference with telecommunication circuits. This is due to harmonic currents of the fundamental frequency of the alternating current supply feeding the rectifier unit inducing unwanted noise voltages into the telecommunication circuit.

With rectifier output currents of the order of 5 A or less, interference is unlikely. With greater currents, or if interference occurs, consideration should be given to the provision of smoothing for the rectifier.

9.3.6.2 *Cathodic protection systems adjacent to railway signal and protection circuits*

In addition to the provisions for prevention of corrosion interaction on buried structures it is imperative that the use of cathodic protection on, or adjacent to, railway property be so planned and operated as to ensure that it cannot cause false operation of railway signalling systems.

Commissioning or other tests proposed in the vicinity of railway lines should not be commenced until the railway authority has given permission for them to proceed. Possible causes of false operation of signalling systems include the following.

a) Current from the cathodic protection system can interfere with the operation of the track relays of railway track circuits of the direct current type.

b) Alternating current components in the rectified current of the cathodic protection system can interfere with the operation of the track relays of railway track circuits of the alternating current type.

c) Induction in cable or line wires from the harmonics in the rectified current of the cathodic protection system can interfere with remote control transmission associated with signalling installations.

Railway authorities should be given at least one month's notice of tests. When carrying out interaction testing in collaboration with the railway authorities, they will normally require additional tests [35] to agreed procedures to confirm the absence of risk to their signalling and other circuits. If the railway authorities agree to the bonding of the protected structure to the running rails, or to structures which are themselves connected to the running rails, special precautions may be required to safeguard the railway signalling equipment (see also **4.6**).

9.3.6.3 ***Internal interaction at discontinuities in cathodically protected structures***

As already indicated in **3.4.1**, **3.4.3** and **4.3.1.3**, if cathodic protection is applied to a pipeline containing a conducting electrolyte, interaction across any discontinuities can cause corrosion of the internal surfaces. Testing to ensure that the pipeline is electrically continuous (see **10.5.5**), and bonding between sections, if necessary, is, therefore, particularly important.

Testing to assess interaction, as described in **9.3.2.2**, is impracticable in most cases as it would be necessary to install special test points, as described in **10.3.4**, to enable the potential between the inner metallic surface and the electrolyte to be measured.

9.4 Jetties and ships: corrosion interaction at sea and river terminals

Corrosion interaction may arise due to cathodic protection of a ship if it is moored alongside an unprotected vessel or jetty, or due to cathodic protection on jetties which may cause interaction while unprotected ships are alongside.

In either case, the interaction may be reduced where safe (see below) by bonding the unprotected ship to the protected ship or jetty. This will be effective only if the resistance of the bond is low compared with that of the current path through the water. Bonding is sometimes dispensed with in the case of small vessels, notably tugs, that are alongside a protected jetty for short periods. Fortuitous contact may provide some alleviation.

For vessels carrying cargoes that bear a risk of fire or explosion, ship to shore bonding is not recommended (see **12.7.9**).

Interaction can be minimized in designing cathodic protection for jetties, by locating anodes on the landward side or within the peripheral boundary of the outer piling. The bonding of ships moored alongside a cathodically-protected jetty will increase the current required for protection and the installation should be designed accordingly.

Section 10. Electrical measurements

10.1 Introduction

This section indicates the apparatus needed and the techniques for measuring voltage, current and resistance, and testing for continuity of structures to ensure the successful commissioning of a cathodic protection installation. Some survey techniques are described.

The stages at which these tests are carried out on particular installations are indicated in the appropriate clauses. Tests for corrosion interaction are dealt with in section 9, and the tests needed during commissioning and as an aid to operation and maintenance are dealt with in section 11.

10.2 Potential measurement: instruments

10.2.1 Reference electrodes

10.2.1.1 *General*

Reference electrodes [36] as described in **10.2.1.2** to **10.2.1.4** are normally used for measuring structure/electrolyte potentials, or as sensing electrodes for control systems (see **3.6.5**).

A copper/copper sulphate reference electrode is most suitable for making contact with soil and fresh water while a silver/silver chloride reference electrode is preferable for immersion in saline waters. Zinc electrodes can be used in clean sea-water. Electrodes to be used as sensing electrodes need to be so designed as to be stable over a long period.

In reference electrodes having a metal electrode in contact with a concentrated salt solution (e.g. copper sulphate or potassium chloride), the concentration is maintained by excess solid salt being present. Contact with the electrolyte (i.e. soil or water) is made via a porous plug acting as a salt bridge between the electrolyte and the concentrated salt solution, thus preventing contamination of the salt solution. The porous plug may be of wood or ceramic construction. These electrodes will remain suitable for use until the salt is exhausted by diffusion through the porous plug. When not in use they should be stored in a saturated solution of the relevant salt.

These electrodes need to be checked periodically against a freshly-made electrode and they should be made up with fresh materials if the difference in potential is more than 20 mV.

For immersion in uncontaminated sea-water, the silver/silver chloride electrode can be made more suitable for long-term use by omitting the porous plug so that the metal and silver chloride are in contact with sea-water. The same arrangement can be used in brackish waters but it should be noted that measurements are affected by variation of salinity (see **10.2.1.3**).

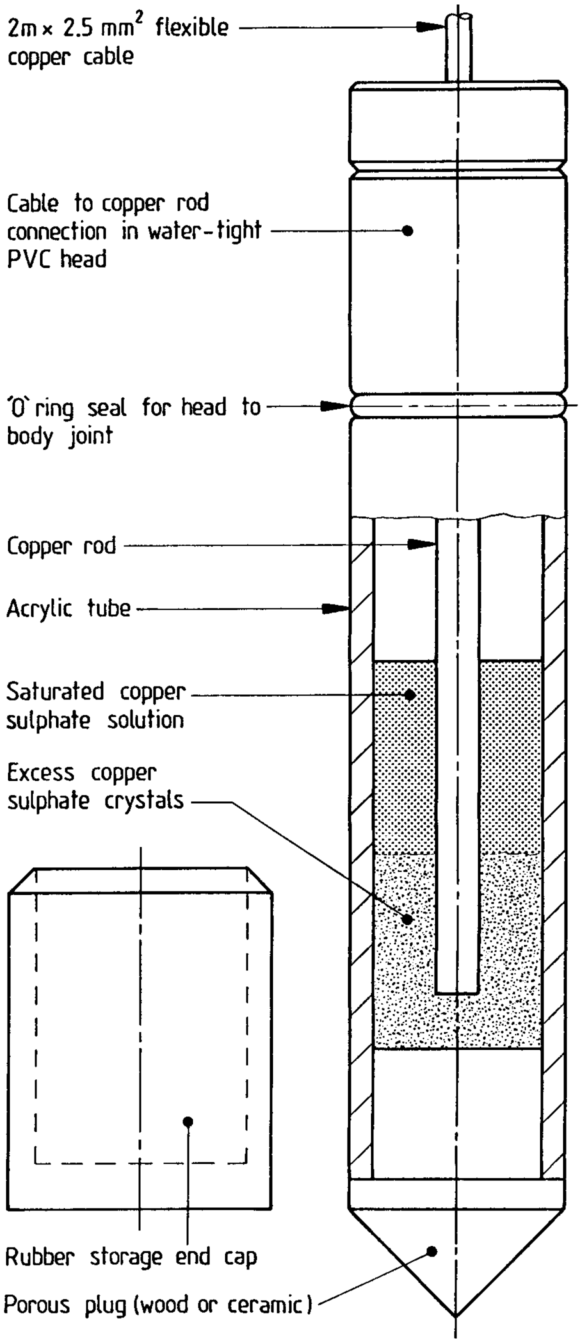


Figure 18 — Typical copper/copper sulphate reference electrode

10.2.1.2 *Copper/copper sulphate reference electrode*

A form of copper/copper sulphate reference electrode that is suitable for measurements under most conditions, including probing, is shown in Figure 18. The dimensions may be made to suit the method of use, but the surface area of copper electrode in contact with the copper sulphate solution should be large enough to prevent polarization during tests. The metallic electrode should be of high conductivity copper of at least the purity specified for grade C 101 in BS 2874.

The copper should be cleaned to remove all traces of oxide and grease and immersed in saturated copper sulphate solution. It is essential that saturation be maintained by providing excess solid copper sulphate. The copper sulphate solution should be made with fine crystals of copper sulphate to at least analytical reagent (AR) grade or British Pharmacopoeia (BP) quality and with distilled or de-ionized water which should preferably be boiled in a clean glass or enamelled container before use. Electrical contact with the soil is made only through the porous element, which is kept moist by seepage of copper sulphate solution. If an electrode of this type is to be stored for a long period, it should be immersed in saturated copper sulphate solution.

With the copper/copper sulphate electrode, it should be noted that, if the solution reaches an iron or steel surface the latter can become plated with copper locally, possibly setting up a local galvanic corrosion cell.

10.2.1.3 *Silver/silver chloride reference electrodes*

A silver/silver chloride electrode is formed from silver, the surface of which has been coated with silver chloride by thermal or electrolytic methods. The electrode has a high degree of stability. The silver/silver chloride element may be used directly in sea-water or saline estuarine waters. In other applications [e.g. steel in concrete (see **5.6.1**)] a silver/ silver chloride/potassium chloride electrode may be used. Methods of making silver/silver chloride electrodes are given in reference [36].

Electrodes for use in sea-water are encased in perforated containers for mechanical protection and to allow free access of sea-water to the electrode; they should be immersed in fresh sea-water for several hours before use. The cable end should be insulated to prevent the electrode becoming short-circuited.

Variation of the salinity of the water will affect the potential of such an electrode. Dilution of the sea-water, as may occur in estuaries, makes the electrode more positive so that, in principle, a more negative minimum potential than the value quoted in Table 1 for the silver/silver chloride/sea-water electrode should be used. However the change will not be greater than 60 mV for each 10-fold change in concentration so that, in many locations, the effect can be allowed for by adopting a slightly more negative protection potential. If, however the effects on the measurements of variation of salinity are unacceptable, the element should be immersed in a saturated solution of potassium chloride in a non-perforated container, the electrode being separated from the environment by a porous plug. When not in use, this type of electrode should be stored in a saturated solution of potassium chloride.

10.2.1.4 *Zinc reference electrodes*

Although it is normally inadvisable to use a metallic electrode in direct contact with the electrolyte around the structure for measurement purposes, zinc in clean sea-water is sufficiently consistent for many applications. Its use in electrolytes other than sea-water is not recommended. It is essential that the zinc should be sufficiently pure, i.e. 99.9 % zinc, with an iron content not exceeding 0.0014 % (see **3.5.3.3**). Some of the zinc alloys used for sacrificial anodes may also be suitable. The metallic electrode can be made in any convenient form.

Zinc electrodes are cheaper and more robust than silver/silver chloride electrodes and can be used, unless a high degree of stability is required. Experience with zinc in clean sea-water has shown variations between electrodes of ± 30 mV, and with a silver/silver chloride/sea-water electrode, variations of ± 5 mV.

10.2.2 Potentials of reference electrodes

The potentials of various reference electrodes with respect to the standard hydrogen electrode are given in Table 6. The calomel electrode is included as it is often used in the laboratory for checking the condition of reference electrodes used in the field. It is insufficiently robust for field use.

Table 6 — Potentials of reference electrodes with respect to the standard hydrogen electrode (at 25 °C)

Electrode	Potential
	V
Copper/copper sulphate	+ 0.32
Silver/silver chloride/saturated potassium chloride	+ 0.20
Silver/silver chloride/sea-water	+ 0.25 (approx.)
Calomel (saturated potassium chloride)	+ 0.25
Zinc/sea-water	– 0.78 (approx.)

NOTE 1 The effect of temperature does not normally need to be taken into account during field testing.

NOTE 2 The potentials of reference electrodes are generally quoted with respect to the standard hydrogen electrode although the latter is seldom used in practice. The purpose of the table is to enable structure/electrolyte potentials measured with one reference electrode to be expressed in terms of another. For example, it will be seen that the zinc/sea-water electrode is 1.10 V more negative than the copper/copper sulphate electrode. A potential of – 0.85 V measured on the copper/copper sulphate electrode would thus be 1.1 V more positive (i.e. + 0.25 V) with respect to a zinc/sea-water electrode. Figure 19 gives scales for conversion of structure/electrolyte potentials measured with the most commonly used reference electrodes.

10.2.3 Voltmeters

It is essential that voltmeters, used for measuring the differences of potential between the structure and the electrolyte, have a high resistance since error is otherwise caused by potential drop in the external circuit (principally arising from the resistance of the reference electrode and contact between the reference electrode and the electrolyte). To ensure that this error is minimized the internal resistance of the voltmeter needs to be greatly in excess of the external circuit resistance.

A voltmeter, with an input resistance in excess of 10 MΩ, is normally used for measuring structure/electrolyte potentials. Specialized voltmeters are available having a variable input impedance from 1 MΩ to 100 MΩ. With such meters, measurements can be verified to ensure that high external resistance effects are eliminated by increasing the input resistance until there is no appreciable change between consecutive readings.

Voltmeters with high input resistance (i.e. greater than about 10 MΩ) should be used with care; if, for example, the reference electrode becomes disconnected or develops a high resistance an apparently valid reading can be obtained via unsuspected leakage paths.

Voltmeters used for potential measurements should be insensitive to any alternating voltage superimposed on the potential being measured and to alternating magnetic fields, to avoid errors from these causes.

Where the change of structure/electrolyte potential is being measured for interaction testing on a neighbouring structure, it is essential that the meter will indicate potential changes to within 2 mV.

Voltmeters for other purposes, for example, measuring the output of rectifier units, should comply with the appropriate requirements of BS 89.

10.2.4 Potentiometers

Portable potentiometers with sensitive null point detectors increase the resistance which can be tolerated in the measuring circuit since, at balance, no detectable current flows externally. In the process of balancing, the maximum current should not be great enough to polarize the reference electrode, and the null point detector should be sufficiently sensitive to give the accuracy required with the highest external resistance that is likely to be encountered. In addition to potentiometers of the type in which voltage is indicated by the setting of calibrated resistors, a potentiometric voltmeter is frequently a useful combination instrument. The voltmeter may be used either directly, or as the detector in a potentiometer circuit. The potentiometer resistors are uncalibrated and, after balance, operation of a switch transfers the voltmeter directly across the potentiometer circuit for evaluation of the difference of potential. Since the introduction of high resistance digital voltmeters, the use of potentiometers has declined.

10.2.5 Recorders and data logging equipment

If a continuous record of structure/electrolyte potential is required, a voltage recorder of suitable range and input resistance may be used. This type of equipment enables the variation of potential to be appreciated and shows any deviation due to change in environment or operational condition. The facility is especially advantageous where these changes are expected to be frequent, as when monitoring the effect of leakage currents from d.c. traction systems.

Some electronic recorders read after they have balanced to the null point; the design of the reference electrode is thus not critical. Other recorders have a low impedance. In this case, it should be confirmed by experiment that the metallic electrode is satisfactory; if necessary the surface of the metallic electrode and/or area of contact with the soil or water should be increased.

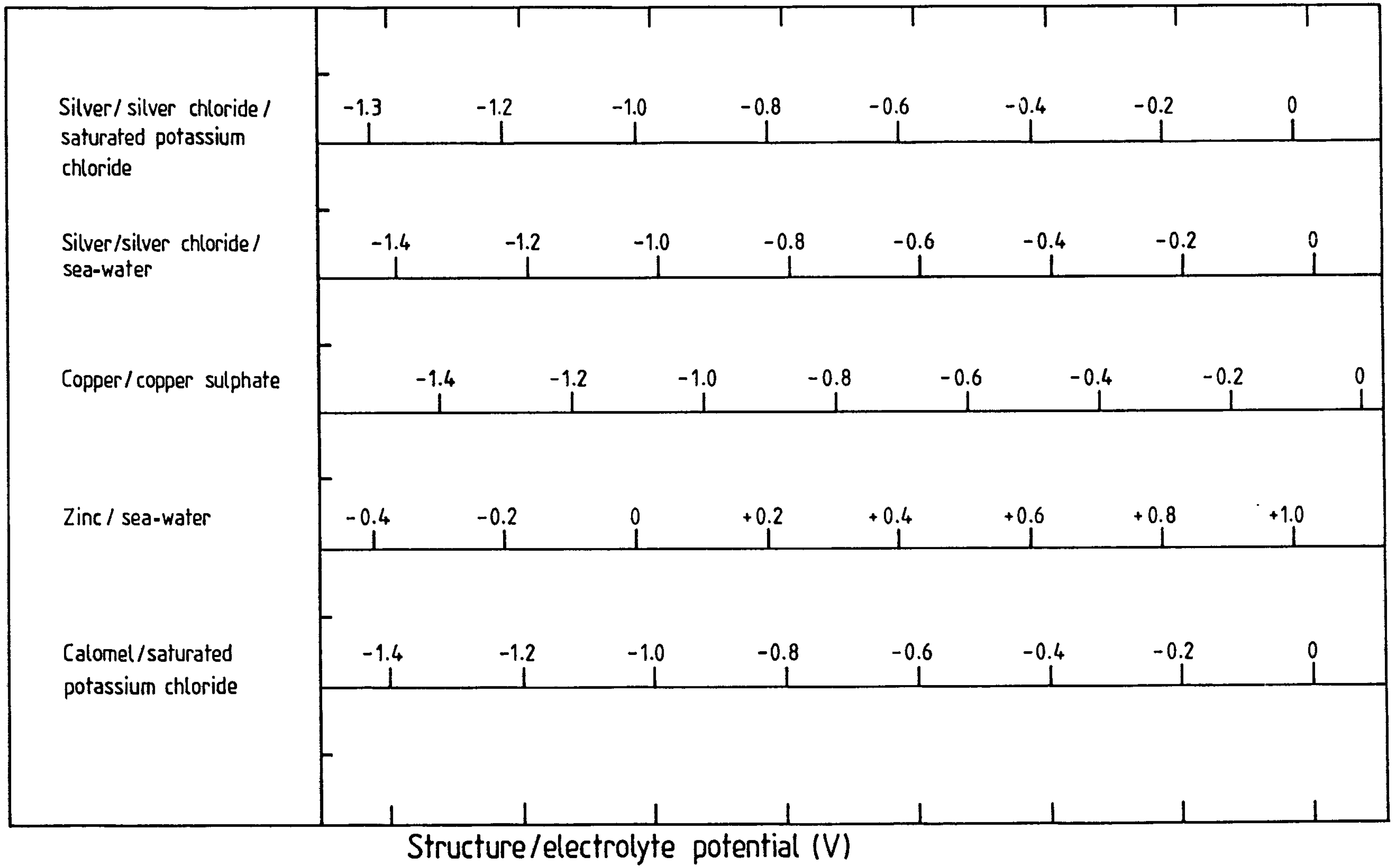


Figure 19 — Comparison of structure/electrolyte potentials measured with various reference electrodes

Digital multi-channel data recorders are used to monitor large cathodic protection installations [37] and [38]. Such voltmeters have, typically, an accuracy of 0.1 % and an input impedance of 1 MΩ to 1 000 MΩ depending on the operating range. In addition to the digital display, facilities for typed print-outs and data storage on disc or tape are available. The latter can be processed so that only anomalous readings need be examined.

Portable microcomputers are now being used for the collection, storage and processing of field measurements particularly where large volumes of data are being recorded.

10.3 Potential measurement: methods

10.3.1 General

The connection to the structure may be made at any accessible part of the structure-close to the intended position of the reference electrode, and good metal to metal contact is essential. It is also essential that there is a continuous low-resistance metallic circuit between the point of connection and the part of the structure nearest the reference electrodes; connection should not be made beyond mechanical joints, at points such as hand wheels of valves, to service pipes of doubtful metallic continuity, or to cables loaded with a cathodic protection current.

10.3.2 Buried structures

10.3.2.1 ***Making contact with the structures***

Where further tests are likely to be required, and in the case of new installations, it is preferable to provide test points at which an insulated conductor, securely connected to the structure, is brought to an accessible position (see **4.3.1.4**). If this is not possible, then soil and protective coating should be carefully removed from around the structure so that metallic contact can be made.

10.3.2.2 ***Placing of reference electrode***

The reference electrode should be placed directly above the structure to be measured. When the reference electrode is placed near the surface of the structure, removal of soil could alter the potential gradient and excavation should be kept to a minimum. Adequate contact with the soil is necessary when placing the reference electrode, account being taken of the measuring circuit to be used. No special methods are available for use during interaction testing and it is normally considered uneconomical to excavate for the sole purpose of burying a reference electrode. It should be noted, however, that errors due to soil potential gradients can be appreciable and can lead to either over or under-estimation of positive potential changes, depending upon the relative positions of these structures (see [39]).

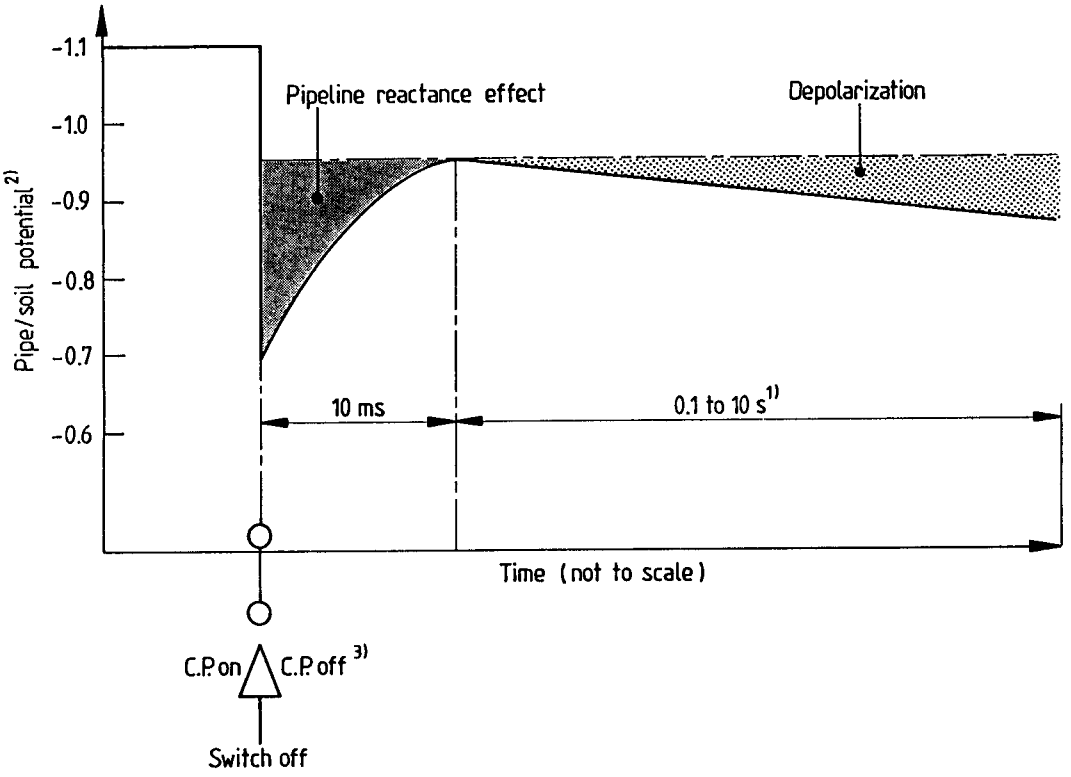
The resistance to earth of the reference electrode can be reduced by wetting the contact area. In the case of paving, it may be satisfactory to bury the reference electrode in a pile of moist soil or sand placed over the cracks between paving stones. Effective contact should be confirmed by altering the resistance of the test instrument e.g. by altering the ranges. In the case of potentiometric instruments, it is sufficient to confirm that there is adequate sensitivity to out-of-balance.

If potential drop through the soil (IR drop) is included in the measurement the error is in such a direction that under-protection could result. The measured potential would be a more negative potential than that existing at the structure/electrolyte interface (see **2.3.2.1**). The reference electrode should be placed as close as possible to the structure under test without actually touching it. Even when this is done there will be the possibility of error due to IR drop through any protective coating. Testing methods have been developed for use when IR drop is considered to be a problem (see **10.3.2.3** and **10.3.2.4**).

10.3.2.3 ***Instantaneous-off potential method***

When the current flowing across a polarized interface is switched off, the potential difference across the interface changes more slowly than a resistive potential drop (i.e. the IR drop) which collapses immediately. If, therefore, the structure/soil potential is measured immediately after the protection current is interrupted, a reading indicating the polarized interface potential can be obtained; this is the indicator of whether protection has been achieved, under this method.

The rate at which the potential difference across the interface decays depends on factors such as the nature of the soil and the period of time for which the structure has been polarized (i.e. the period for which the cathodic protection has been operating [40]). These factors therefore determine the time available, after switching off, for measuring the potential. Excessive delay results in the existing protection level being underestimated due to depolarization. Periods during which the measurement can be made ranging from 0.1 s to 3 s have been suggested [40] [41]. (See Figure 20.) The measurements are carried out with the cathodic protection switched off and on at intervals; in most cases a ratio of 1 off: 4 on, will not introduce significant depolarization. Synchronizing is necessary if there is more than one current source.



[1)] This period significantly shortened in the presence of sulphate-reducing bacteria.

[2)] With respect to copper/copper sulphate reference electrode.

[3)] C.P. = Cathodic protection.

Figure 20 — Instantaneous-off or polarized potential measurement on pipelines

If the structure has a number of holidays of different sizes distributed over the surface, the exposed metal may be polarized to different potentials. In the period immediately after switching off the protection, current would be exchanged between the areas of exposed metal thereby re-introducing some additional IR drop error. If this current is significant the potential indicated will be between the extremes of metal/soil potential for holidays near the point of test. Use of this method can therefore lead to under-protection. Generally this additional error is negligible in comparison with the IR drop error caused by the flow of cathodic protection current. However stray d.c. currents are much more likely to cause this effect, the error increasing with the magnitude of the current. Coupon methods can be used to avoid this problem (see **10.3.2.4**).

Despite these possible sources of error the potentials measured by this technique are considered by many authorities to be a more useful guide to the degree of protection achieved than those measured by the simpler techniques that ignore IR drops.

10.3.2.4 *The use of coupons*

Coupons should be of metal similar to the structure under test and should have a coating similar to that on the structure except for a defined area that is left bare. They should be buried as near as possible to the structure and at a level such that the soil is similar in composition and moisture content to that surrounding the structure. They are connected to the structure through an accessible test link.

It is assumed that the coupon metal will take up a potential, with respect to the adjacent soil, that is similar to the structure/soil potential at a holiday. For this reason the area of the coupon metal exposed to the soil should be chosen so that it represents one of the largest holidays considered likely to occur on the structure.

The coupon/soil potential can be measured using the instantaneous-off potential method. The use of a coupon enables all the current to be interrupted at the test link and thus removes the effect of the protective current, interaction between different areas of exposed metal, and stray currents. Moreover, the current flowing into the known exposed area of the coupon can be measured to give the current density. Where the protected structure local to the coupon has a high current demand, it is possible that measurement of the coupon potential may be misleading.

10.3.3 Immersed structures

10.3.3.1 *Immersed structures other than ships*

Where access to the bonded steelwork of a jetty is difficult to achieve from the deck, it is usual to provide a number of suitable points at deck level where a connection can be made. Fixed reference electrodes are not generally used (unless as sensing electrodes for automatic control) owing to the difficulty of maintenance. Portable reference electrodes suffer the disadvantage of being extremely difficult to position against the structure with any consistency. In order to overcome this, perforated plastic locating tubes can be fixed on the structure at positions where readings will be required; the reference electrode is dropped down the tube to predetermined depths thus permitting consistent positioning of the reference electrode relative to the protected structure.

Test positions for protected structures should be determined by the anode layout (e.g. distant groundbeds or a number of underwater anodes) but care should be taken to include readings at positions remote from anodes (e.g. on the side of a pile shielded from an anode) and close to anodes to monitor for overprotection.

10.3.3.2 *Ships' hulls*

The potential of a ship's hull will be influenced by its speed through the water and the resistivity of the water. To determine that adequate protection is provided at times of highest demand on the protection system, potential measurements should be taken with the vessel at its maximum draft and at full speed. Measurement with the vessel underway is possible only if permanent reference electrodes (such as those shown in Figure 17) have been fitted to the external hull. Electrodes of this type are common with impressed current systems where they are used to monitor potentials and control the system output.

It is normal practice to measure the potential of a ship's hull while it is at rest with the use of a silver/silver chloride/sea-water reference electrode, suspended from the deck of the ship, and a voltmeter. Care should be taken to ensure that the vessel is in clean sea-water, that the electrode is located within 50 mm of the hull and at a minimum of 500 mm below the surface, and that a good connection is obtained to the main hull structure for the voltmeter. Measurements should be taken at sufficient horizontal and vertical intervals to ensure that readings are obtained at positions midway between successive anodes or remote from any anode. A minimum of six positions should be measured, i.e. one at the bow, one at the stern and two along each side.

In many instances the use of suspended electrodes does not permit accurate electrode positioning. The use of a diver or remote controlled underwater vehicle could overcome these limitations particularly for measurements on the bottom of the ship.

If a diver is used to obtain measurements from a vessel fitted with an impressed current system, safety precautions should be taken to prevent electric shock (see **12.3.3**). When a suspended electrode is used from the deck of a vessel intended for the carriage of flammable cargo, safety precautions should include, checking that all instruments are safe for the area of operation (see **12.7.7**) or that the area is declared gas-free.

10.3.3.3 *Ships' tanks*

Suspended reference electrodes (normally silver/silver chloride/sea-water) in conjunction with a high impedance voltmeter may be used to measure the potential of the internal structure of a tank containing ballast water. If the tank is used for the carriage of flammable cargoes, or the location from which the measurements are to be made is a hazardous environment, then all the measuring instruments should be safe for use in the area (see **12.7.7**) or the area should be declared gas-free.

The positioning of the electrode within the tank will be restricted by the number and size of the openings. Readings should be taken at various vertical locations to ensure that the electrode is midway between successive anodes or remote from any anodes and care should be taken to ensure that an adequate connection to the tank structure is obtained for the voltmeter. If the tank has been ballasted recently, sufficient time should be allowed for the steel to polarize, or the readings repeated at 12 h intervals until stability is obtained. If the tank has been ballasted with anything other than clean sea-water the anodes may be prevented from protecting the tank.

10.3.4 Internal protection of plant

10.3.4.1 *General*

With fully enclosed plant, it is normally necessary to install permanent measuring points or reference electrodes. Where the positions at which measurement should be made can be predicted, these facilities are preferably installed before commissioning.

Alternatively, potential surveys can be carried out (see **11.2.6**) initially with temporary equipment to determine the positions where the potentials are most positive and whether the most negative potentials are acceptable.

10.3.4.2 *Permanently-installed reference electrodes*

The most convenient method of mounting reference electrodes inside plant is by means of a "screw-in" assembly such that the electrode can easily be withdrawn for inspection and replacement of either the entire unit or the electrode material. The electrodes can be wired to central monitoring and control equipment. A disadvantage lies in the difficulty of checking the accuracy of the electrodes, once installed.

For detailed potential surveys, or if it is impossible to use "screw-in" mountings, reference electrodes can be attached by suitable non-metallic fixings to the protected surface and the insulated connecting leads brought out through the plant wall through a suitable gland.

Generally, it is advisable to install at least one reference electrode for each cathodically-protected compartment. The reference electrode should be installed at the position where corrosion is most likely, e.g. at junctions of ferrous and non-ferrous materials and/or remote from anodes.

10.4 Direct current measurement

10.4.1 General

In order to measure direct current an ammeter is normally inserted in series into the circuit. For direct current measurement a moving coil instrument or d.c. digital meter is needed.

The insertion of an ammeter will increase the total resistance of the circuit and thereby reduce the current, giving an error in the value measured. It is therefore essential that the resistance of the meter is kept to a small proportion of the total circuit resistance. Manufacturers' data normally states the value of this resistance in terms of millivolts at full scale deflection. Using this value the actual voltage drop across the meter caused by the measured current can be determined and compared with the driving voltage (e.m.f.) of the circuit. The value of the voltage drop across the meter as a percentage of the e.m.f, gives the approximate percentage error of the meter reading.

10.4.2 Impressed current systems

For current measurements in impressed current systems, e.g. transformer-rectifier output, and anode currents, the driving voltage is usually several volts or more. The value of the voltage drop across the meter is therefore usually a small percentage of the driving e.m.f, and introduces only a minor error in the value of the measured current. Most multirange instruments provide ranges up to 10 A. For higher currents, a calibrated shunt is used in conjunction with the millivolt range of a multimeter. The millivolt drop across a shunt of known resistance can be used to calculate the current. For example a 50 A/75 mV shunt has a resistance of 0.0015 Ω or each 1.5 mV measured equates to 1 A. For a permanently connected meter, the scale would be calibrated to read amperes directly.

10.4.3 Very low voltage circuits

With sacrificial anodes, the driving voltage is of the order of a few hundred millivolts and in bond circuits between two structures the driving voltage may be lower still. The insertion of an ammeter into these circuits can alter the current, giving rise to a significant error in the value of the measured current.

It is essential to select a meter or range of a multimeter that will not significantly alter the circuit resistance. Special purpose meters and shunts are available having less than a 50 mV drop at full scale deflection thus minimizing the measurement errors.

If it is not possible to select a suitably rated meter or shunt, by taking some additional voltage measurements with a separate high resistance voltmeter the corrected value of current can be calculated (see Figure 21).

10.4.4 Zero resistance ammeter circuit

To overcome the problems detailed in **10.4.3** a zero resistance ammeter can be used as shown in Figure 22 (a). This comprises an ammeter in series with a variable d.c. voltage source which is adjusted to give zero voltage across a galvanometer connected between the measuring terminals, the ammeter indicating the true value of current.

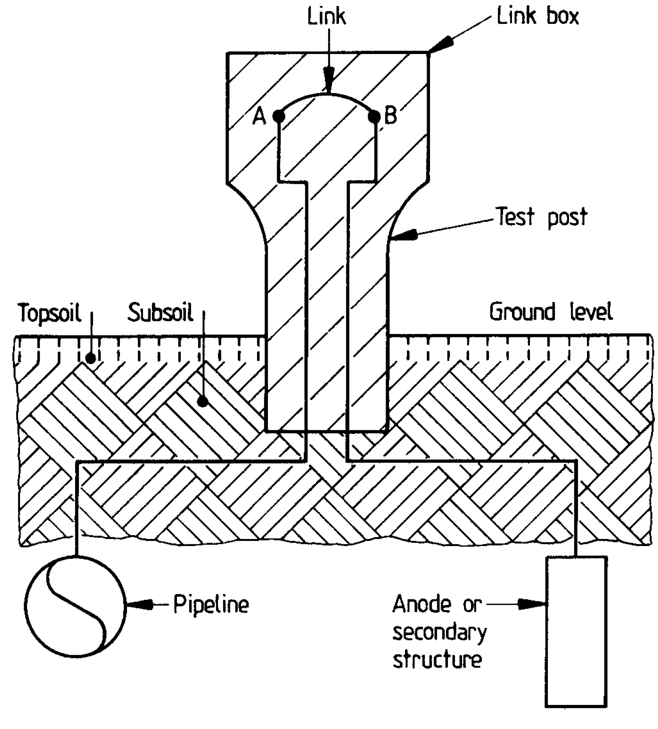
Provided that the galvanometer has a sufficiently high sensitivity, the apparatus can also be connected in parallel with the conductor carrying the current, as shown in Figure 22 (b). The instrument can be used as previously since, when the galvanometer has been brought to a null reading, the current has been diverted through the ammeter. Alternatively, the change in the galvanometer reading due to reversing a measured current, can be noted so that the galvanometer may be calibrated for use as an ammeter in which the section of bond or structure between the two galvanometer terminals acts as a shunt. The latter method is useful if the currents are fluctuating.

10.4.5 Pipeline current

A span of pipe may also be used in the same way as a calibrated shunt to calculate the current flowing in the pipeline as shown in Figure 22 (b). The voltage drop along the span is measured using a micro- or millivoltmeter. The resistance of the pipe span may be calculated from the pipe dimensions or by passing a known current through the pipe span and measuring the voltage drop.

The line current may then be calculated by Ohm's law.

If regular measurements of the current flowing along a pipeline are required, it may be preferable to insert an isolating joint into the pipeline. The isolating joint can be bridged with a removable link or a shunt to enable current to be measured.



Procedure

(a) Remove link between terminals A and B.

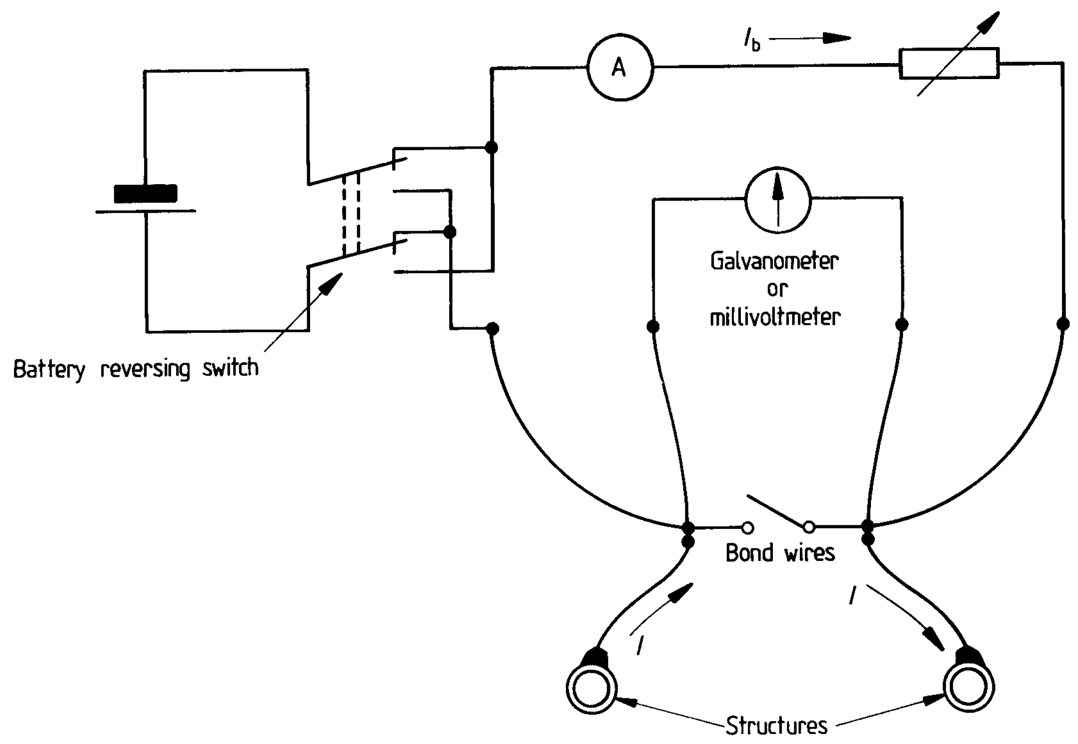
(b) Measure potential across AB with high impedence millivoltmeter (V_1).

(c) Connect ammeter across AB and measure current (I).

(d) Measure potential across AB with ammeter still connected (V_2).

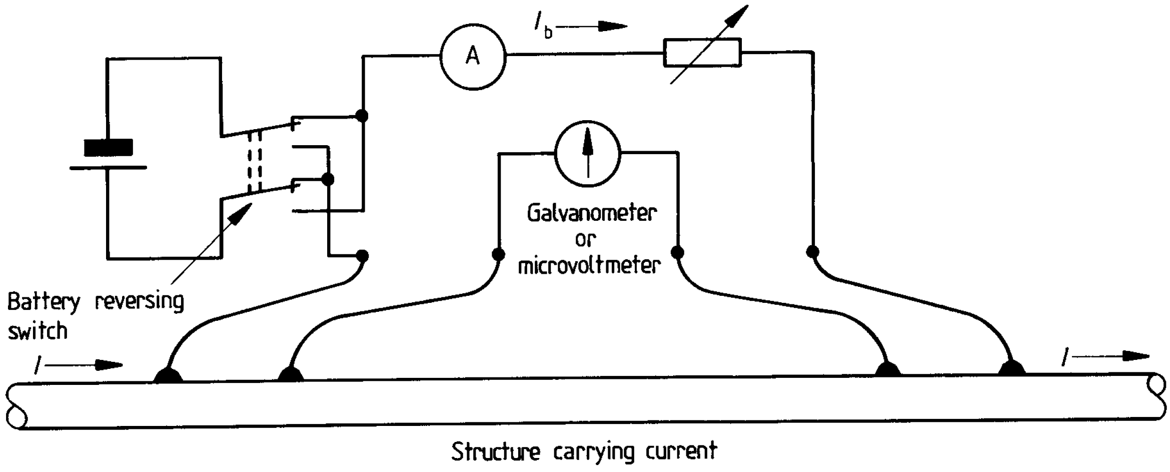
$$\text{True current} = \frac{IV_1}{V_1 - V_2}$$

Figure 21 — Method for determining true current flow in very low voltage circuits



NOTE 1. With current I_b adjusted to give no deflection on the galvanometer, I_b is equal to the bond current.

(a) Zero resistance ammeter circuit used to measure current flowing in a bond (bond disconnected)



NOTE 2. If current I_b is adjusted to give no deflection on the galvanometer, then $I_b = I$.
If reversing I_b gives deflections D_1 and D_2, a deflection D corresponds to a current whose value is $2ID/(D_1 + D_2)$.
If the meter indicates voltage the resistance R between the inner pair of connection points is given by:
$R = (V_1 + V_2)/2I$
where reversal of current I_b gives deflections V_1 and V_2. Reversing the current eliminates the effect of any fluctuation of the steady current flowing in the conductor under test. It is assumed that the resistance between the inner pair of connection points is much lower than that of the meter.

(b) Zero resistance ammeter connected across length of conductor

Figure 22 — Zero resistance ammeters

10.4.6 "Clip-on" ammeters

For currents greater than 10 A a "clip-on" or "clamp" ammeter may be used. These operate using Hall-effect sensors and clip around a current carrying conductor without the need to break the circuit. These should however be used with caution for measuring currents of less than 10 A as the sensitivity is poor at the low end of the scale (minimum range usually not less than 100 A) but may be useful for providing an indication that a circuit is carrying current.

10.5 Resistance measurement

10.5.1 Earth electrode resistance and soil resistivity

The necessary methods of testing are described in **401** and **402** of CP 1013:1965[2]. Separate electrodes are used to pass the test current into the ground and to measure the potential drop caused by the test current. Steel spikes are normally used; polarization at the potential measuring electrode is avoided by using alternating current at other than mains frequency to avoid interference.

The instruments normally indicate resistance directly. In the case of earth electrode resistance measurement, the resistance given is that between the electrode and the soil at a distance equal to the spacing between the potential spike and the electrode. Since it is normally required to know the resistance of the electrode to remote earth, it is important that the spike/electrode spacing be sufficient. In the case of a test on a groundbed, this spacing should also be large compared with the greatest dimension of the electrode system under test.

Soil resistivity is usually measured by the Wenner four-electrode method. This requires four electrodes in line with uniform spacing. Current is passed between the two outer electrodes and the inner two are used for potential drop measurement. The steel spikes used as electrodes need to make adequate contact with the soil but should not be driven to a depth greater than one-tenth of the electrode spacing although one-twentieth is preferable. Watering in moderation around the electrodes is permissible to ensure adequate contact with the soil.

The resistance indicated will be the ratio of the change of potential difference between the inner pair of electrodes to the test current. The soil resistivity (in $\Omega \cdot m$) will be $2\pi aR$ where R is the resistance (in Ω) and a is the electrode spacing (in m). The test gives an approximate average value of the resistivity to a depth equal to the electrode spacing.

In very dry or highly resistive soils or where measurements to considerable depths may be required for deep well groundbed design, resistivities may be determined using electromagnetic induction techniques [42].

10.5.2 Determination of bond resistance

Where it is necessary to determine the value of the resistance which should be connected in series with a bond, to adjust the structure/electrolyte potential of a structure to a desired value, it can be done either by inserting a series of fixed calibrated resistors until a suitable value is found, or adjustment can be made by using a variable resistor, the resistance of which is subsequently measured. Alternatively, if the galvanometer shown in Figure 22 (a) is calibrated to indicate voltage, the desired potential conditions on the structure can be obtained by adjustment of the resistor. The necessary resistance value is determined as the ratio of the voltage to the current. This arrangement has the advantage of obviating the need for low resistance leads. This method may be used to measure the bond resistance between hull and rudder etc, on ships. Special milliohm meters are also available for measuring the very low resistance of bonds.

10.5.3 Bonding of ships propellers

Methods of determining the resistance of bonds described in **10.5.4** are applicable to ships' propellers. Since the contact-resistance of the brushes running on the shaft will increase as the shaft rotates, resistance measurements made with the shaft stationary may lead to a false appraisal of bond resistance. The use of a high resistance voltmeter connected between an additional brush running on the slipring and the hull will indicate the shaft/hull potential difference. The voltage drop across the monitoring brush/slip-ring will be insignificant due to the high resistance of the measurement circuit. Figure 16 illustrates the arrangement.

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[2] CP 1013:1965 is being revised as BS 7430. The relevant methods of test will be described in clause **16** of BS 7430.

10.5.4 Bonding of ships rudders and stabilizers

The resistance values of bonds required for rudders and stabilizers is of the order of 0.001 Ω. This is outside the limits of detection of commercial resistance meters and requires the use of special low resistance meters. The value may be calculated by measuring the potential drop that occurs when a current of known fixed value is passed through the bond.

The arrangement shown in Figure 22 (b) may be used. A current of the order of 10 A or 20 A should be injected by pointed probes to the rudder stock and the hull. Probes connected to a millivoltmeter are then used at alternative points to measure potential difference. The current should be reversed to ensure that the potential difference is caused solely by the applied current.

With the ship in service, measuring the potential difference between the rudder stock or stabilizer fin shaft and the hull will enable bond effectiveness to be monitored.

10.5.5 Continuity of structure

Any disconnections or high resistance joints may become apparent by a large change in potential when structure/electrolyte potential measurements are made at various points along the length of the structure after cathodic protection has been applied.

Where this method is being used to locate high resistance joints, sufficient current should be used to give a large structure/electrolyte potential at the point of negative cable connection, for example – 1.0 V to – 1.5 V. Where there is an abrupt decrease of the structure/electrolyte potential, there is either a resistive joint or a connection to a buried metallic structure between the point of test and the negative cable connection point. Each change of reference electrode location should be accompanied by a corresponding change in the location of the structure connection.

It may also be necessary to determine whether the armour of a buried cable is satisfactorily in contact with the sheath. Appreciable potential differences between the sheath and the armour of a cable, when cathodic protection is applied by means of connection to the sheath, indicates a poor connection.

Another method of locating discontinuities, which can be applied to buried cables and pipelines, uses an audio-frequency current impressed on the structure from which a signal is picked up by means of a search coil and headphones. Points of electrical discontinuity are indicated by a sudden decrease in signal strength. This method has proved satisfactory in open country but needs care in urban areas where the presence of other services in the ground will often cause misleading results.

In the case of structures such as buried pipelines, when such discontinuities are suspected, a constant voltage (up to 12 V) can be applied between two points on the pipeline some distance apart. Discontinuites will be indicated by a change in the potential gradient, i.e. a sudden voltage drop. It is possible to locate these points accurately by using two wander probes, each making contact with the pipe, a sensitive voltmeter being connected between them.

The comparative longitudinal resistance of pipe joints may be assessed by measuring the potential drop across a joint caused by the passage of a known impressed current of the order of 10 A to 20 A. The equipment can be as shown in Figure 22 (b), the galvanometer being calibrated as a millivoltmeter. The four connections to the pipe can be made using probes with hardened points; the probes connected to the millivoltmeter should be insulated. The impressed current should be reversed and the test repeated to confirm that the potential drop measured is due solely to the applied test current.

WARNING. Probing should not be carried out without prior consultation with other authorities concerned, to ensure that there is no possibility of causing damage to their buried services. Probing will cause damage to pipeline coatings.

10.6 Tests prior to installing cathodic protection on buried or immersed structures

10.6.1 Soil and water samples

Samples of the various types of soil from positions along the route may be required. Such samples should be of not less than 250 g in mass and should be placed in sealed, sterile, air-tight containers. Besides bacteriological analysis, information may be needed as to sulphate, chloride, carbonate and sulphide content. The pH value and the redox potential (see Appendix A) may also need to be determined.

Although resistivity and bacteriological data may in many cases provide sufficient guidance, chemical information may be useful in diagnosing the nature of the corrosion liable to occur and in determining the most suitable type of anode material.

In the case of immersed structures, any analysis of water samples should include measurement of the oxygen content and conductivity. It should be noted that, particularly in the case of estuarine waters, considerable variation can occur according to the state of the tide and also according to the season. Moreover, stratification is often present and the use of a suitable sampling technique is recommended.

10.6.2 Soil resistivity

Soil resistivity measurements (in Ω·m) taken over the area occupied by the structure may be required. The main objects of the measurements are:

a) to form an assessment of how corrosive the soil is on the basis of the following approximate relationships:

resistivity	
up to 10 Ω·m	severely corrosive
10 Ω·m to 50 Ω·m	corrosive
50 Ω·m to 100 Ω·m	moderately corrosive
100 Ω·m and above	slightly corrosive

b) to enable a decision to be reached on the type of cathodic protection to be installed, i.e. whether by sacrificial anodes or by impressed current.

The number and positions of the points at which soil resistivity readings are carried out for any particular buried structure need to be judged on the size of the structure in relation to the probable variation in soil conditions over the site. Practical and economic factors will normally limit the number of readings taken and the possibility of small areas of low resistivity escaping detection may, therefore, need to be taken into consideration.

It is usual to carry out initial readings along a pipeline route at spacings between 1 km and 3 km according to the expected variability of soil resistivity, additional readings being taken as considered necessary to define the extent of particularly corrosive areas.

Readings may also be carried out in positions where electric power is conveniently available, to provide data for the design of impressed current groundbeds.

When the Wenner method, as described in **10.5.1**, is used, the test indicates average resistivity at a depth equal to the separation between the test electrodes. If a pipeline route is being surveyed, tests can usefully be made with spacings equal to the pipe depth, half the pipe depth and twice the pipe depth. This gives a result relating to the environment of the pipe and also indicates how resistivity varies with depth. If the pipeline is already installed, particularly if it is poorly coated, the tests should be made with the line of electrodes perpendicular to and remote from the pipeline.

Soil resistivity surveys to determine corrosiveness should, where possible, be carried out during periods when the lowest resistivity values are likely to be encountered, namely at a time when damp soil conditions and high water tables exist. Surveys should not be carried out under severe frost conditions owing to the difficulty of obtaining sufficiently low electrode/soil resistance.

Tests made to provide information for the design of groundbeds should preferably be made following a dry spell to obtain the "worst" case.

Readings are taken with electrodes spaced at intervals up to about one-quarter of the expected length of the groundbed, dependent on the variation of soil resistivity with depth at the site chosen.

10.6.3 Structure/electrolyte "natural" potential surveys

It may be useful to carry out a survey to determine the structure/electrolyte potential variation along, or over the surface of, the structure as described in **10.3**, employing a suitable reference electrode and voltmeter. Such a set of potential measurements may indicate those points on the structure where the worst corrosion is likely to be taking place.

With no applied cathodic protection, and in the absence of stray currents, the most negative structure/electrolyte potentials indicate the corroding areas. On the other hand, if corrosion is due predominantly to stray current in the soil, the more intense corrosion will be associated with the more positive structure/electrolyte potentials. (See **2.2.3**).

10.6.4 Stray electric currents

Where the presence of stray electric currents is suspected, e.g. in proximity to d.c. electric traction systems or where varying structure/electrolyte potentials indicate the possibility of such currents, it is sometimes necessary to determine more accurately the extent of stray current effect on the structure. This can be done by plotting the potential field in the area, using a stationary reference electrode, or a structure, as a reference point. The effect due to the operation of an electric traction system can be found by making a potential survey during the time the system is working and repeating the tests after the system has been shut down [43].

10.6.5 Tests for electrical continuity

Tests should be carried out whenever the continuity of the structure is in doubt, to locate any discontinuities (see **10.5.5**).

10.7 Specialized surveys

10.7.1 General

There are a number of specialized survey techniques being utilized to provide additional detailed data concerning corrosion prevention systems (see reference [44]).

These techniques would normally be carried out by specially trained personnel using purpose-built equipment and instrumentation, often only available from specialist contractors. These surveys are generally time-consuming but the information gained may not be available from other methods. Examples of these techniques are given in **10.7.2** to **10.7.4**.

10.7.2 Pearson survey

This is used to locate defects in buried pipeline coatings by injecting an a.c. signal between the pipeline and remote earth and measuring the potential difference between two contacts with the soil approximately 6 m apart (see [45]). Two operators walk along the route, making the necessary contacts with the soil, either in-line directly over the pipeline or side-by-side with one operator over the pipeline. Any local increase in the potential difference might indicate a coating defect or perhaps a metallic object in close proximity to the pipe. The in-line method is helpful in the initial location of possible coating defects, since any increase in potential difference (usually received as an increase in audio signal) is obtained as each operator passes over it. However, when there is a series of defects close together or where information on a particular defect is required, the side-by-side method is usually adopted. It is necessary to traverse the entire length of the pipeline and the interpretation of the results obtained is entirely dependent on the operator unless recording techniques are used.

10.7.3 Current attenuation survey

This is used to locate defects in buried pipeline coatings. The method is similar to the Pearson survey technique but a search coil is used to monitor the actual current flowing in the line from the injected a.c. signal. Any significant attenuation of the current may indicate a coating defect or contact with another metallic structure.

10.7.4 Close interval potential survey

This is used to determine the level of cathodic protection throughout the entire length of a pipeline. It may also indicate areas affected by interaction and coating defects. The pipe/soil potential is measured at close intervals (less than 1.5 times the depth of pipeline) using a high-resistance voltmeter, half cell and a trailing cable connected to the pipeline at a test point.

A plot of potential against distance is produced allowing features to be identified by changes in potential values caused by local variations of cathodic protection current density.

The survey may be carried out with the cathodic protection system energized continuously (an "ON" potential survey) or with all the cathodic protection supplies switched simultaneously by synchronized timers using the instantaneous-off potential method (see **10.3.2.3**).

Because of the large amount of data to be handled, a field computer or data logger is normally used which may be programmed to produce the plots of potential against distance.

Section 11. Commissioning, operation and maintenance

11.1 Introduction

This section indicates the stages at which tests should be made and describes routines to ensure the continued effective operation of cathodic protection systems, both in general and in particular applications such as for buried and immersed structures, reinforced concrete structures, ships' hulls and tanks, and internally-protected plant.

The relevant test instruments and the techniques for their use are described in section 10.

The effectiveness of a cathodic protection installation depends on applying and maintaining the correct potential difference between the metal and the adjacent environment at all parts of the structure. This is the objective of the procedures described in this section.

11.2 Tests during the commissioning period

11.2.1 General

The structure/electrolyte potentials at various points on a structure will continue to change for some time after protection has been applied. Tests should, therefore, be made at intervals and currents adjusted as necessary until conditions become stable with potentials at all points not less negative than the values given in Table 1. A comprehensive survey should then be made and the results analysed to provide a list of conveniently carried out tests by which the continued satisfactory operation of the protection system can be confirmed.

Immediate action should be taken if abnormally positive changes in potential occur, particularly at the point(s) of application of current indicating that one or more transformer-rectifiers have been reversed.

More frequent inspections (for example at monthly intervals) are recommended where:

a) the non-operation of one transformer-rectifier would result in a total or partial loss of protection;

b) the non-operation of the transformer-rectifiers is likely, due to factors outside the operators control, e.g. known unreliable power supplies, joint operation with a third party, susceptibility to electrical storms; or

c) protection is provided by a single bond from another protected structure.

It is important that commissioning and routine test readings should be permanently recorded. In many instances, comparison with these provides the only information that is available as to the condition and performance of the system. To this end, a routine should be established for the periodic review of the measurements to ensure that the conditions are satisfactory. Consideration should be given to the computerization and graphical presentation of records, with the inclusion of exception reporting for test measurements that fall outside set limits.

11.2.2 Buried structures

Structure/electrolyte potentials should be measured at a series of points including, particularly, points remote from the groundbed or anode positions. Outputs should be adjusted to the minimum that gives the desired level of protection (see Table 1).

The period required for the potentials to become stable may vary from a few days for a well-coated structure, to a few months for a bare or poorly coated structure.

Where possible, currents from individual sacrificial anodes or transformer-rectifier units should be measured. In the case of a complicated pipe system, it is also useful to measure the current flowing from individual branches or sections. These should be recorded and a routine for subsequent retesting established as indicated in **11.2.1**.

Once the operating conditions have been established, organizations that might be installing underground equipment in the area in the future should be given sufficient information for them to be aware of possible interaction problems. This would include, for example, groundbed positions and expected currents, and, if not already provided, an indication of the routes of the protected structure and of any structures that have been bonded to it to reduce interaction.

11.2.3 Fixed immersed structures

Structure/electrolyte potentials should be measured, at the points provided, soon after the protection is switched on. Individual (or group) anode currents should be measured and adjusted to the minimum that gives protection (see **2.3.2**).

The subsequent variation of structure/electrolyte potential depends on whether the structure is immersed in sea-water or estuarine water, and would be affected by variables such as the total range of conductivity, oxygen content, water flow rate and degree of pollution. In clean sea-water, the potential of the continuously immersed portion of a bare structure would be expected to become stable within several months; a coated structure would stabilize more quickly. The potential of the metal in the tidal range should be checked at high tide to determine whether the cathodic protection system is adequate to restore full polarization to that portion without detriment to the continuously immersed portion.

11.2.4 Ships' hulls

If cathodic protection is by sacrifical anodes and no permanent reference electrodes are fitted, tests are usually restricted to a visual examination of the anodes (whilst the ship is in dry dock), to confirm that the correct number of anodes have been fitted in the locations recommended by the supplier, that they have been adequately attached and that they have not been covered with any coating. If the rudder, stabilizers (if fitted) and propeller are to receive protection from anodes mounted on the hull the quality of bonds should be confirmed, see **10.5.3** and **10.5.4**. With the ship in the water, tests are restricted to a hull/electrolyte potential survey, as described in **10.3.3.2**, to indicate the level of protection with the vessel at rest.

If cathodic protection is by impressed current, tests usually include the following.

a) A visual examination is made of the installation both internally and externally (whilst the ship is in drydock) to confirm that the equipment has been installed in accordance with the suppliers recommendations, that all anodes and electrodes have not been painted and have been correctly connected, that the rudder, stabilizers (if fitted) and propeller have been bonded and that a negative connection capable of handling the full current output of the power unit (transformer-rectifier) has been fitted.

b) Electrical checks are made on the power unit to verify the correct output polarity, the ability of each anode to dissipate power, the operation of the automatic control system, the setting of the control point and any current and voltage limits.

c) With the ship in the water, a hull/electrolyte potential survey is made as described in **10.3.3.2** to indicate the level of protection with the vessel at rest. With the ship under way, readings are taken from permanent control electrodes as well as of the current and output voltage of the power unit. Potential differences between propeller shaft and hull, rudder and hull and stabilizers (if fitted) and hull are also measured with the ship under way to confirm adequate bonding (see **10.5.3** and **10.5.4**).

The hull reference potential will normally be set within the range – 0.80 V to – 0.85 V (silver/silver chloride/sea-water reference electrode).

11.2.5 Reinforced concrete structures

The considerations in **11.2.1** to **11.2.3** generally apply. Interaction on adjacent structures is unlikely to occur and the notification to other authorities may thus be omitted. However, interaction may be experienced on adjacent elements of the structure under protection and this should be investigated (see section 9).

11.2.6 Internal protection of plant

Structure/electrolyte potentials should be measured at the test points before and soon after the installation is switched on. The currents at individual anodes (or groups of anodes) should be monitored and adjusted as necessary after a further period, e.g. one week, then, if no serious departure is observed, again after one month. At each adjustment, the individual and total anode currents should be noted for reference.

Each sensing electrode used for automatic control should be checked against a suitable reference electrode installed close to it. Unless there is experience with similar plant, reference electrodes should also be installed at a sufficient number of positions in the protected equipment to enable a representative potential distribution curve to be plotted. This will show whether the position of the sensing electrode was chosen judiciously and whether the correct control setting has been selected. If more than one sensing electrode provides the feedback signal to the controller, the readings on each should be compared for incompatibilities before and after switching on the protection. Readings may show differences due to the presence of electropositive materials, and the gradients around anodes. Ideally, all the sensing signals should be within 50 mV when the protection is switched on. Slightly wider tolerances (e.g. 100 mV) may still form an acceptable basis for control.

11.3 Operation and maintenance: considerations relating to most types of structure or plant

11.3.1 General

The effectiveness of the cathodic protection system is assessed by measuring the currents and potentials at the points selected during the commissioning period (see **11.2.1**), and action can then be taken if the results differ from the expected values.

11.3.2 Sacrificial anode installations: maintenance

11.3.2.1 *General*

It is difficult to lay down detailed procedures because of the variety of structures involved and because of the possible absence of accessible equipment. Maintenance can, however, be just as critical for these systems as for impressed current systems, and those components which are accessible should be regularly inspected if protection is to be maintained.

The frequency and extent of inspection and potential measurement will depend upon such considerations as the likelihood of disturbance by other agencies (excavations and roadworks in the case of pipelines in urban areas), and the possibility of additions or alterations to the structure (a network of buried pipes may be the subject of much extension or alterations, whereas a jetty may remain structurally unaltered for many years).

Where link boxes or similar devices are provided, current should be measured in addition to potential to confirm that the anodes are still operating. A record of the current output will also enable an estimate to be made of the anode consumption.

This is, however, impossible where anodes are bolted or welded directly to the surface of the metal.

If anodes are available for inspection, their appearance will indicate whether they have been supplying current, but this will not establish that a satisfactory level of protection is being provided.

11.3.2.2 *Fault location*

If the potential has become insufficiently negative, an indication of the cause can be obtained from a current measurement.

a) *Current zero or lower than expected*:

  1) wastage of anodes and possible need for replacement;

  2) deterioration of anode/cathode connection, breakage of anode or cables;

  3) drying out of soil around anode;

  4) effects of pollution on anodes.

b) *Current level maintained or increased*:

  1) inadvertent metallic contact with newly installed structures;

  2) faulty isolation equipment;

  3) alteration of environment causing rapid depolarization, or increase in oxygen content of water due, for example, to a reduced level of pollution;

  4) extension of the structure;

  5) deterioration of, or damage to, protective coatings.

11.3.3 Impressed current installations: maintenance

11.3.3.1 *General*

The maintenance of equipment such as rectifiers, transformers, transformer oil, switchgear, and a.c. supply cabling is not covered in detail in this code; procedures are similar to those followed when such equipment is used for other applications. Particular attention should be given to safety and earthing measures, equipment in hazardous areas, which should be maintained in accordance with BS 5345, and the maintenance of metallic enclosures to BS 5493.

Regular checks should be made on all accessible cables connecting transformer-rectifier units to protected structures or plant and to anodes or groundbeds, to ensure that the insulation is in a good condition, and that end connections are clean and tight. Insulation of the anode leads is particularly important. Cables installed to provide connections to other structures and/or permanent test points should also be tested at regular intervals.

11.3.3.2 *Fault detection*

If abnormal values of potential and current are noted, comparison with expected or earlier values will indicate the nature of the fault as follows.

a) *Structure/electrolyte potential becomes more positive as protection system is switched on*:

This indicates reversed connections which is the most serious fault and which could result in severe damage to the structure in a relatively short period.

b) *Applied voltage zero or very low, current zero:*

  1) failure of a.c. fuse or tripping of other protective device;

  2) failure of a.c. supply;

  3) failure of transformer-rectifier

  NOTE Approximately 2 V may still be indicated on the voltmeter due to the back e.m.f. between the steel structure and carbonaceous backfill in the groundbed.

c) *Applied voltage normal, current low but not zero:*

1) deterioration of anodes or groundbeds;

2) drying out of soil around groundbeds, or some anodes no longer immersed;

3) accumulation of electrolytically produced gas around anodes;

4) disconnection of some of the connections to individual anodes of a groundbed or anode system;

5) disconnection of part of the protected structure.

d) *Applied voltage normal, current zero:*

1) severance of anode or cathode cables;

2) failure of d.c. fuse or ammeter of transformer-rectifier unit;

3) complete failure of groundbed or anode system.

e) *Applied voltage and current both low:*

1) control on transformer-rectifier unit set too low;

2) transformer or rectifier failing;

3) electricity supply faulty.

f) *Applied voltage and current both high:*

Control on transformer-rectifier set too high.

g) *Applied voltage and current normal but structure/electrolyte potential insufficiently negative:*

1) break in continuity bond or increased resistance between point of connection and point of test;

2) greatly increased aeration of soil at or near point of test due to drought or increased local drainage;

3) alteration of environment causing rapid depolarization or increase in oxygen content of water due, for example, to reduced level of pollution or increased flow;

4) faulty isolation equipment e.g. short circuiting of an isolation joint in a pipeline;

5) protected structure shielded or otherwise affected by new structures;

6) failure of cathodic protection system on another part of the same structure or on a secondary structure bonded to it;

7) deterioration of, or damage to, protective coatings;

8) addition or extension to buried structure, including fortuitous contact with other metallic structures;

9) interaction from another cathodic protection system;

10) effects of stray a.c. on the structure.

h) *Applied voltage and current normal, but structure/electrolyte potential abnormally negative:*

1) break in continuity bonding at position further from the point of application than the point of test;

2) decreased aeration of soil or electrolyte at point of test;

3) reduction in rate of flow of electrolyte;

4) secondary structures have been removed or have been cathodically protected or bonds to them broken;

5) effects of stray a.c. on the structure.

i) *Applied voltage and current normal but structure/electrolyte potential fluctuates:*

The presence of stray earth currents e.g. interference from d.c. traction systems or telluric/geomagnetic effects.

11.4 Buried structures: operation and maintenance

11.4.1 Sacrificial anode installations

While specific procedures may be defined in an operation and maintenance manual, or laid down by a regulatory body, the following routines are typical for well-coated structures.

a) At 3-monthly intervals, measure and record structure/soil potentials at representative measuring points, in particular where potentials are known to be least negative.

b) At 12-monthly intervals, check and record structure/soil potentials at all measuring points and the current flow in each link. Points where secondary structures have been bonded to the primary structure or on which sacrificial anodes have been used to overcome corrosion interaction should also be included. As a general rule, the structure/soil values obtained for the latter should be at least as negative as those recorded at the time of installing the bond or anode.

Visually check all test facilitates for servicability and damage and carry out maintenance and repairs as necessary.

11.4.2 Impressed current installations

11.4.2.1 *General*

Typical procedures for impressed current installations, assuming the use of transformer-rectifier units, which are the most common power source, are as follows.

a) At maximum intervals of 3 months check for satisfactory operation of transformer-rectifier units, record output voltages and currents and measure structure/soil potentials at the point(s) of application of current, midway between the points of application of the current, and at the extremities of the structure being protected by the cathodic protection system, noting any departures, from normal.

b) At maximum intervals of 12 months, measure structure/soil potentials at all measuring points or, where appropriate, at representative points that have previously been shown from a close interval potential survey (see **10.7.4**) to indicate that the required levels of protection are generally being obtained throughout.

Points where secondary structures have been bonded to the primary structure or on which sacrificial anodes have been used to overcome corrosion interaction should also be included. As a general rule, the structure/soil potential values obtained should be at least as negative as those recorded at the time of installing the bond or anode.

Visually check all test facilities and transformer-rectifier installations for serviceability and damage and carry out maintenance and repairs as necessary.

c) At intervals of 5 years to 10 years for appropriate structures, give consideration to the carrying out of a close interval potential survey (see **10.7.4**).

11.4.2.2 *Groundbeds*

Groundbeds may not continue to give the desired output current for a variety of reasons, the higher current installations being the more susceptible to change.

Horizontally installed groundbeds may suffer from soil drying at certain times of the year which will increase the groundbed electrical resistance. Thus, for the same applied voltage the current output will be reduced. This can be counteracted by either increasing the transformer-rectifier output voltage or by watering the groundbed. For typical installations on well-coated buried pipelines in the UK neither of these actions is likely to be necessary.

Where soil drying is a known problem, vertically bored or deepwell groundbed configurations are commonly used, so that despite the season constant wetting of the groundbed can be relied upon. Such groundbeds require a ventilation system the size and complexity of which will depend on current output. A decrease in current for a given voltage may also result from blockage of the groundbed gas vents (see **4.2.3**) and it may be necessary to remove the top layers of the groundbed and replace them with more porous material (see also **12.3.2**).

NOTE A sudden change in the effectiveness of a groundbed could be the result of the installation of new structures by another organization. In such a case the action to be taken will need to be discussed with the owner of the new structures it being pointed out that these are liable to suffer damage by interaction.

11.5 Immersed structures: operation and maintenance

11.5.1 Sacrificial anode installations

Routine readings of structure/electrolyte potential at a limited number of representative points and, in cases where facilities are provided, of the current output of each anode, should be made at suitable intervals, usually every 3 months.

Where anodes are connected to fixed immersed structures by cables, the latter should be regularly examined for possible damage due to wave action, mooring of small craft, flotsam, etc. The need for anode renewal will be indicated when structure/electrolyte potential levels are no longer sufficiently negative. In some cases, it may be possible to raise representative anodes for inspection to assess the wastage rate.

With anodes attached directly to the submerged parts of the structure, e.g. anodes welded to steel piles prior to driving, current outputs cannot be measured and the need for renewal has to be based on measurement of structure/electrolyte potential supplemented by information on anode wastage. In some cases this can be obtained when the anodes are exposed for short periods at low tides; otherwise inspection by divers will be necessary. Although directly-attached anodes are usually designed for long life, they will eventually be consumed and, to avoid the underwater work involved in anode renewal, it may be practicable to use cable-attached anodes, or anodes welded to steel bars which can then be attached to the structure above water level (see **7.2.2.3**). Alternatively, the use of impressed current may be considered.

It should be noted that if sea-water is heavily polluted, this may affect the performance of the anodes.

11.5.2 Impressed current installations

The current output of the transformer-rectifier unit may need to be adjusted from time to time to maintain a satisfactory level of protection on the structure. During the initial period of operation (i.e. for a period of 6 months to 12 months) it is usually possible to decrease the current as polarization increases. If the rectifier output is not reduced, structure/electrolyte potentials may become excessively negative and structure coatings may be damaged (see **3.8.1**). However, it may later be necessary to increase the current in order to maintain protection, to counteract the effects of unavoidable damage to, or deterioration of, coatings.

In cases where appreciable changes in water resistivity occur and automatically-controlled or constant-current equipment is not provided, the transformer-rectifier output should be set at a level which provides the best compromise for both high and low water resistivity conditions. It is essential to test during periods of low water resistivity to confirm that there is no risk of overloading the equipment.

The transformer-rectifier voltage and current output should be measured at least once a month. In estuarine conditions, the effect of tidal variation should be studied and subsequent tests made at selected tidal levels. Structure/electrolyte potential readings at a limited number of representative points should also be made monthly for the first year of operation. Thereafter, if stable conditions have been established, the interval between structure/electrolyte potential readings may be increased to 2 months or 3 months, depending on local conditions. Pipeline isolation joints, where installed, should be checked every 12 months.

Piled structures comprising steel piles and concrete decking should have the bonding system checked by measuring the structure/electrolyte potential of each individual pile. This check is usually carried out after about 12 months operation of the cathodic protection system and is not normally repeated without specific reason, e.g. damage to the structure. Where the form of construction is such that the piles are automatically integrally bonded, e.g. steel deck members welded to the piles, a bonding check is not usually necessary.

Power supply equipment will require normal electrical maintenance (see **11.3.3.1**). Groundbeds will periodically require complete renewal depending on design and loading (see **3.6.2.1**). Anodes such as platinized titanium will, however, normally have a life in excess of 5 years; the need for renewal will be indicated by a gradual decrease in current output.

Most types of marine groundbed and connecting cables are subject to various forms of mechanical damage which may result in a decrease in current output.

11.6 Reinforced concrete structures: operation and maintenance

The following schedule of operations is recommended.

a) At monthly intervals, check and record instrument readings and note any departure from normal. Readjust as required.

b) Every 6 months, record all monitoring probe readings and structure/electrolyte potentials at test points provided. Visually check all components for damage.

c) Every 12 months, check power source enclosure and mountings and repair as required. Open all junction boxes and inspect visually.

11.7 The internal protection of plant: operation and maintenance

11.7.1 Sacrificial anode installations

Frequent and regular inspection of sacrificial anodes is essential to ensure continuing satisfactory operation, but their use in many types of enclosed equipment poses difficulties in respect of access since a minimum of down time is often demanded in industrial plants.

Performance should be assessed both by measurement of the metal/electrolyte potentials and by visual inspection of the protected plant. In general, sacrificial anodes are directly attached to the surface to be protected so the current cannot be measured. However a guide to their rate of consumption and the anticipated life can be assessed by periodically measuring their dimensions after removing any surface debris and corrosion product.

11.7.2 Impressed current installations

11.7.2.1 *Manual control*

At regular intervals (dictated by experience, but initially of the order of 1 month), all the anode currents and structure/electrolyte potentials should be monitored so that an overall picture of the trend and fluctuation is built up. With sea-water as the electrolyte, several months may be needed before potentials become stable; appreciable potential changes may not occur at positions remote from anodes until a calcareous deposit has been built up on metal near the anodes [see **3.8.1** b)]. As indicated in **3.6.5**, reference electrodes used for control need to be carefully located. Unless experience enables suitable positions to be chosen initially, it may be necessary to install a number of reference electrodes for use during the initial period to determine the best location for permanently-installed control electrodes.

The current output of the anodes may be adjusted either individually or collectively until suitable structure/electrolyte potentials are obtained.

11.7.2.2 *Automatic control*

The control equipment should ensure that the metal/electrolyte potential at the sensing electrode remains constant which, if the initial commissioning has been carried out correctly, will ensure that potentials are maintained within a suitable range at all positions (see **3.6.5**). Structure/electrolyte potential check readings are necessary to confirm the continued performance of the control system and other essential equipment.

It is necessary to check the sensing electrodes at regular intervals. This should be carried out using a standard electrode and an independent high resistance voltmeter. Although automatic monitoring units are available, it is essential that the electrodes and control units are checked periodically to ensure proper functioning.

11.8 Ships' hulls: operation and maintenance

11.8.1 Sacrificial anode installations

Where anodes are connected to ships' hulls by leads, e.g. during fitting out or when laid up, the same maintenance of leads and their insulation, junctions and connections, is required as for buried structures.

Potential measurements of the hull should be carried out periodically using a portable reference electrode.

When potential measurements are taken on tankers used for the carriage of low flash point cargoes it is essential for safety reasons that an intrinsically safe voltmeter be used.

In general, potential readings more negative than – 0.80 V (silver/silver chloride/sea-water reference electrode) indicate a satisfactory level of protection.

Anodes attached to the hull should be inspected during dry docking to determine the amount of metal or alloy remaining. If necessary anodes should be mechanically cleaned to remove loose corrosion products to enable an accurate assessment to be made.

Anodes which have insufficient metal or alloy remaining to enable their continued oepration until the next scheduled dry docking should be replaced or augmented by the addition of further anodes. Hull anodes are cast with various thicknesses which largely determine anode life. Typically, an anode with a thickness of 5 cm may be expected to last 18 months to 24 months.

Anodes which show little or no sign of wastage when inspected are likely to be passive. The electrical contact of the metal or alloy to the steel insert and the electrical contact of the steel insert to the hull (in the event of anodes attached by bolts) should be verified. Anode surfaces should be confirmed as being free from coating. If neither electrical contact or coating is identified as the cause of the anode being passive it should be removed and replaced.

If the vessel operates for a significant proportion of its time in fresh or brackish water, the performance of the anode will be affected by a reduction in current (causing a reduction in protection ability) and as a consequence a reduction in the rate of consumption.

11.8.2 Impressed current installations

11.8.2.1 *Operation of cathodic protection on ships*

Automatically controlled systems are normally fitted on ships and the reference electrodes not only measure the hull potential but also control the anode output.

Full details of the operation and maintenance of such a system should be provided in the manufacturer's handbook which should be retained on board the vessel.

Readings of the hull potential, current output and voltage together with general operational factors such as draught and water temperature, should be logged daily.

Minor adjustments may be necessary to the setting of the control potentials if the readings indicate:

a) low levels of protection where the potential is more positive than – 0.8 V (silver/silver chloride/sea-water reference electrode);

b) excessive negative potentials, e.g. more negative than – 0.95 V.

NOTE Such potentials should be avoided in order to reduce the risk of coating damage.

Factors that will affect the current required for protection and therefore necessitate re-adjustment, are listed in **6.2.5.1**.

Where spurious readings are suspected, checks may be carried out using a portable reference electrode suspended over the ship's side together with an intrinsically safe voltmeter on vessels used for the carriage of low flash point fuels.

There may be some interaction effects, particularly when the ship is berthed alongside a steel jetty, and some authorities may require the ship's protection system to be switched off prior to berthing. Any electrical connection between the ship and a steel jetty should only be made after prior agreement with the relevant authority, especially if the jetty is also cathodically protected.

The successful operation of manually-controlled systems requires the active co-operation of ships' staff. It is usual to operate at two current settings, one in harbour and one at sea. As a first approximation, the current at sea may be set at double that found to give a hull/electrolyte potential of – 0.8 V (silver/silver chloride sea-water reference electrode) in harbour. Measurement by the hull-mounted reference electrodes will indicate the further adjustments which should be made at sea to attain the correct potential. Several hours should be allowed to elapse for the current distribution to settle after each adjustment.

The preferred current values thus determined should be recorded and the anode currents should be set to the appropriate level whenever the ship proceeds to sea or returns to harbour. Current and hull/electrolyte potential readings should be noted daily or as frequently as possible and further adjustments of the preferred current will usually be found necessary to allow for deterioration of hull paint.

At intervals of, about 3 months, a hull/electrolyte potential survey should be carried out in harbour using a portable electrode at appropriate test positions around the hull (see **10.3.3.2**), the reference electrode being immersed at various depths not less than 500 mm and including some tests with the electrode at approximately the depth of the anodes. It is important that this test be carried out in clean sea-water of average salinity. If this is not possible in harbour, the survey should be carried out while at sea and while the speed of the ship relative to the water is not more than 2 knots. The test positions should include the positions of the fixed reference electrodes and thus provide a check on the accuracy of the latter. When discrepancies arise between the hull/electrolyte potentials measured by any of the fixed electrodes and the portable electrode, both electrodes should be checked as soon as possible against a reliable reference electrode.

11.8.2.2 *Maintenance of cathodic protection on ships*

Routine maintenance of electrical equipment inside the ship should be carried out on a periodic basis with the supplier's instructions strictly observed. Typically the performance of the transformer-rectifier, anodes and electrodes should be verified every 3 months.

Transformer-rectifier units should be inspected for integrity, insulation, security of connections and cleanliness. Switches should be lubricated, anode output fuses confirmed as intact and the ability of the unit to perform within the manufacturer's specification should be verified.

Cable penetration glands in the hull and coffer dams should be checked for leakage of water, and junction boxes for security of electrical connections and any signs of overheating in anode cable connections.

Rudder stock bonding cables and propeller shaft slip-rings with their brush gear should be inspected at least once a week to confirm that the potential difference with respect to the hull is maintained at less than 20 mV for rudders and less than 100 mV for propeller shafts. Security of connections, cleanliness and, in the latter case, wear of slip-ring contact surfaces and brushes should be checked.

Maintenance of external hull components will be carried out during dry docking of the ship when the protection system should be switched off prior to the dock being pumped out.

Anodes and their mountings or holders should be inspected for signs of damage and/or degradation. The active surfaces of platinized titanium anodes should be of uniform grey appearance; a non uniform appearance may signify loss of platinum coating. Mixed metal oxide anodes should exhibit active surfaces with a uniform matt black appearance. Lead/silver anodes will show some signs of roughening and wastage, the surfaces should be chocolate brown in appearance and free from extensive white deposits which could signify the production of lead chloride associated with rapid consumption of the lead.

Dielectric shields formed by the application of coatings to the hull should be free from blisters and breakdown which will be characterised by white calcareous deposits. Any signs of breakdown of this type of shield or of the hull coating adjacent to the shield, should be removed by abrasive blast cleaning followed by the application of high duty alkali-resistant coating of minimum thickness corresponding to the original application. Precautions should be taken to prevent coating being applied to the anode surfaces; any coating on the anodes should be removed by solvent and not by mechanical means.

Breakdown of prefabricated dielectric shields of reinforced polyester/epoxy resin or thermoset plastics will be apparent through blistering and possible loss of shield material. Repairs to this type of shield may be possible by the use of epoxy putties or similar materials. Alternatively the shield should be replaced by fitting a new prefabricated unit or by the application of high performance coating or epoxy putty to the blast-cleaned steel.

Reference electrodes and their mountings or holders should be inspected for signs of damage or degradation. The faces of zinc electrodes should be free from coatings and of uniform grey colour with a slightly rough appearance.

11.8.2.3 *Detection of faults at sea*

Aids to diagnosis of faults are given in **11.3.3.2**. The following list indicates the types of fault and abnormality most likely to occur with installations on ships' hulls and the actions which need to be taken.

a) *Reversed connection*. This is the most serious fault and could cause rapid penetration of hull plating. Evidence of such an error is given by the hull/electrolyte potential which, on a properly connected system, should become more negative with respect to a silver/silver chloride/sea-water reference electrode placed remote from the anode, when the system is switched on.

b) *Defective insulation of anode or anode cables*. If such a fault is suspected, the system should be switched off and the back e.m.f, between the anode cable and the hull measured. With lead anodes, the back e.m.f. immediately after switching off should be in the range of 1.5 V to 2.0 V; with platinium or platinized titanium anodes it may exceed 2.0 V. A low or zero reading indicates defective insulation of the anode or connecting cable and the anode should be switched out of circuit until a more thorough investigation can be carried out.

c) *Faulty reference electrodes*. Defects due to faulty insulation, exhaustion of electrode material, or high impedance, may be indicated by the hull/electrolyte potential survey. Usually more than one electrode is fitted, e.g. to port and starboard, and they may be compared. If the automatic controller can operate from either, it is good practice to use them alternately except when alongside other ships or a jetty when the more remote electrode should be used.

d) *Entry into fresh water*. The high resistivity of water of low salinity restricts the spread of current from the anodes. Thus higher anode voltages than normal are required to achieve the required spread of current and protective hull/electrolyte potential remote from the anode. If the equipment cannot supply this current at the higher output voltage required to overcome the increased resistance, the protection potential will not be attained. The underprotection, being temporary, may be acceptable but as current will be concentrated at areas near the anodes, it may be advisable to switch off the equipment, to prevent damage to the hull paint. Performance of the system should be rechecked on returning to more saline water.

11.9 Ships' tanks: operation and maintenance

Cathodic protection of ships' cargo tanks is by sacrificial anodes (see **6.4.1.1**). It can be applied only if the tanks are also used for water after cargo discharge. For various reasons, some tanks may be left empty for part of a ballast voyage, or used only on alternate voyages. It is necessary, therefore, if a useful degree of protection is to be achieved, to set a lower limit to the proportion of the total service time that any individual tank should be water-ballasted. Practical experience indicates that such ballast periods should add up to not less than those given in Table 7.

Table 7 — Recommended periods of water ballasting for ships' tanks protected by sacrificial anodes

Tank contents	Period of water ballasting as a proportion of total voyage time
	%
Water ballast alternating with dry cargo	40
Water ballast alternating with void spaces	40
Water ballast alternating with cargo oil	25
Water ballast alternating with fuel oil	25

In general, ballast voyages should be arranged for a minimum period of at least 5 days. On the other hand, it is not possible to set any limit to the time intervals between successive ballastings, but these should be as short as it is practicable to arrange. Where it is normal practice to use an alternating arrangement of ballast tanks on successive voyages, it is advisable to provide the ship with set ballast plans coveting all normal conditions of trim and stability so that each protected tank is assured of regular ballasting. As it is usually impracticable regularly to ballast and therefore to protect every tank in a ship, the nomination of tanks for this purpose should involve careful selection.

Where sea-water is the normally carried ballast, it is recommended that when water of resistivity higher than 25 Ω cm is taken on in a river or estuary, such water be discharged at sea as soon as convenient and the tank or tanks refilled with sea-water.

As service conditions in a ship's tank can seldom be accurately predicted, the performance of an anode installation should preferably be checked periodically by visual inspection and, when it is practicable to do so, by means of suitably positioned reference electrodes attached to, but insulated from, the steelwork of the tank. Potential measurements will then indicate when the need for any anode renewal arises. Typically, systems are designed for a nominal 5 years and inspected every 2 years.

When fall-off in protection cannot be determined by such means, it is normal practice to decide, in conjunction with the anode manufacturers, the limiting size at which anodes should be replaced. As it is seldom practicable to weigh anodes, suitable dimensions should be selected (e.g. length or circumference) and inspectors advised of the limit set.

Safety precautions which need to be adopted for the avoidance of explosion hazard from low flashpoint cargoes, or residual gas/air mixtures are given in **12.6** and **12.7**.

Section 12. Safety

12.1 Introduction

This section indicates some of the safety precautions, generally applicable to electrical equipment that should be taken into account in the context of cathodic protection systems. It deals specifically with possible hazards from electric shock due to fault conditions in electric power systems, with incendive hazards due to hydrogen evolution and sparking in dangerous atmospheres [30], and with toxicity hazards due to chlorine evolution. Measures that may be required to eliminate hazards are described.

12.2 Applicable standards and regulations

Cathodic protection systems should comply with the regulations listed in the foreword, the British Standards referred to in the text of this code and those listed in Appendix B, and with any other statutory regulations, bye-laws or standards that may apply.

12.3 Danger of electric shock

12.3.1 General

The current normally used for impressed current cathodic protection is rectified a.c., taken from a step-down transformer and a rectifier.

The transformer should be double wound and should comply with BS 171, or those requirements of BS 3535 which are applicable to transformers used for industrial and similar purposes. The core of the transformer, unless double-insulated, and all the exposed metalwork should be effectively earthed (see also **3.8.3**).

It is unnecessary to earth the output circuit of the equipment as it is earthed by means of the combined effect of the groundbed or immersed anode and the natural earthing of the structure to be protected. Therefore, unless the transformer is a double-insulated isolating type complying with BS 3535, it should be a type having an earthed metallic screen between the windings, or windings on separate limbs of the core. If this is not possible then steps should be taken to ensure that the combined resistance to earth of the groundbed and the protected structures is low enough to permit operation of the protective fuses or switchgear in the event of a fault between the input or high voltage windings of the transformer (i.e. mains voltage) and the d.c. output of the associated rectifier. The electricity supplier should be asked to state the type of supply, as categorized by the IEE Wiring Regulations, it is intended to provide, and whether an earth terminal will be made available or an earth electrode will need to be provided at the intake position. Also advice should be sought on whether additional protection in the form of a residual current operated device should be provided. Means to isolate the a.c. supply should be provided at the transformer-rectifier unit.

It is also necessary for all live terminals to be suitably protected to ensure that accidental contact cannot be made.

Automatic transformer-rectifiers with constant current or current limiting control may not operate overcurrent protection devices when d.c. faults occur. Special provision should therefore be made to provide suitable protection.

12.3.2 Installations on buried structures

In the case of buried groundbeds, attention should be paid to the danger of possible harm to persons and animals due to the voltage gradient at the surface of the soil. This will depend on the depth and geometry of the groundbed, the soil resistivity, the output voltage of the transformer-rectifier and the current flowing into the soil, and should at no point be such that the voltage occurring between the feet of persons or animals having access to the site could be dangerous.

To keep voltage gradients at safe levels, the following precautions should be taken.

a) The d.c. output voltage of the cathodic protection supply should be kept below 50 V d.c.

b) The anodes and the upper surface of the carbonaceous backfill surrounding the anodes should be buried at least 900 mm below ground level, so that only a proportion of the output voltage appears across the surface of the ground.

c) The leads should be fully insulated and protected against mechanical damage between the anode connections and a point well above the surface of the ground.

The danger might be increased if, for example, a wire fence on wooden supports passes close to the groundbed. If the wire were earthed at some distance from the groundbed, the voltage between the wire and the soil near the groundbed would be a substantial proportion of the total voltage drop through the soil. These matters should be considered at the design stage, any necessary confirmatory tests being carried out during commissioning.

A similar danger would occur if a wire fence on wooden supports were altered in order to install a groundbed, and a wooden support replaced by a metal support buried close to the groundbed.

12.3.3 Installations on immersed structures

When groundbeds are placed in open water, possible dangers to bathers or fish should be considered. The risk is greater in fresh water than in sea-water.

There is a possibility of danger from electric shock to divers if they approach to within 1 m to 2 m of impressed current anodes which are in operation; this is particularly important when the underwater scrubbing of a ship's hull is in operation. Ships' impressed current systems should be switched off before divers commence submerged work of any kind unless the requirements of Diving Safety Memorandum No 2/1985 [46] are met.

12.3.4 Installations for the internal protection of plant

Safety procedures should be adopted that make it impossible for personnel to enter tanks or pipes that normally contain water, whilst the electrical supply to the anodes is switched on.

12.4 Fault conditions in electricity power systems in relation to remedial and/or unintentional bonds

There is possible risk in bonding a cathodic protection system to any metalwork associated with the earthing system of an electricity supply network, whether by intention or not. This is particularly important in the vicinity of high-voltage sub-stations.

Bonds between metalwork associated with an electrical power system (e.g. cable sheaths) and cathodically protected structures, can cause danger when abnormal conditions occur on the power network. The principal danger arises from the possibility of current flow, through the bonds, to the protected structure, due to either earth-fault conditions or out-of-balance load currents from the power system neutral (see also **9.3.5.1**).

The current, together with the associated voltage rise, may result in electric shock, explosion, fire or overheating and also the risk of electrical breakdown of coatings on buried structures. Such hazards depend on the local system conditions and should be considered if bonds between electricity supply equipment and other plant are being contemplated. Adequate precautions should be taken to remove any danger (see **3.8.3** and also BS 6651).

The insertion of current limiting resistors in bonds through which heavy fault current might flow should be avoided as far as possible. If they are used, it is essential that they should be carefully designed for the expected conditions.

Bonds and any associated connections should be adequately protected from damage or deterioration.

Because of the uncertainties, bonds between power system equipment and other structures are generally best avoided, use being made of other methods of avoiding interaction problems, for example, the attachment of a sacrificial anode to the affected structure.

12.5 Induced alternating voltages and currents

Alternating current flowing in overhead conductors produces an alternating magnetic field. Where the field cuts another conductor, an a.c. voltage is induced in the latter conductor. Thus, where a pipeline runs parallel to a high voltage overhead power line or to the overhead line equipment of an a.c. electrified railway, an a.c. voltage will be induced in the pipeline where it is cut by the magnetic field and current may flow in the pipeline.

The magnitude of the voltage appearing on the pipe depends on many factors including:

a) the overall geometric configuration of both structures;

b) the magnitudes of the currents flowing in the conductors (which may be unbalanced due to abnormal load or fault conditions on the power line);

c) pipeline and coating characteristics; and

d) soil resistivity.

In cases where the overhead line has an earthed neutral, unbalanced or fault conditions can result in substantial currents flowing in the ground. These currents, which can arise both from induction or conduction, can find their way into the pipeline.

The study of induced currents and voltages and the provision of mitigation measures can be very complex and should therefore only be undertaken by technically competent personnel [47], [48] and [49].

For an electrically well balanced overhead 3 phase power line, a parallelism of less than 3 km is unlikely to induce voltages of a hazardous magnitude during normal load flow conditions. However for an unbalanced single phase supply e.g. an a.c. electrified railway, or earth faults on the power line, hazardous voltages may be induced even over short lengths.

When induced voltages are calculated to be present at an unacceptable level, then it is essential that steps to reduce these voltages to safe values are taken. One of the most effective techniques for mitigating induced voltages is to earth the pipeline at strategic locations i.e. at peak voltage locations. This may be done by connecting earthing mats, earthing rods, sacrificial anodes, or continuous strip or wire anodes to the pipeline. The choice of earthing system depends on the soil resistivity and the level of voltage to be dissipated. The impedance of the earthing system should be low enough to reduce the induced voltage to safe levels.

If non-sacrificial materials are used for mitigation, a d.c. decoupling device e.g. a polarization cell, should be used to connect the earthing system to the pipeline so that excessive current drain or shielding does not affect the cathodic protection.

Where sacrificial anodes are used, provision should be made to facilitate testing the earthing system at maximum intervals of 12 months.

Where there is a possibility that induced voltages would be developed that could cause arcing across isolating joints, electrolytic ground cells, polarization cells or other suitable devices should be used. Cables connecting these devices and the connections themselves should be properly sized and designed for maximum fault current and anticipated duration.

If polarisation cells are used, special precautions are required in handling the strong caustic solution (usually potassium hydroxide 30 %) used to fill the cells.

12.6 Evolution of dangerous gases

12.6.1 Hydrogen evolution

12.6.1.1 *General*

In impressed current systems, and sometimes with magnesium anodes, excessive polarization can cause evolution of hydrogen on the protected structure. Thus, in situations such as closed tanks where hydrogen can collect, an explosion hazard can arise. To avoid this hazard, it is necessary for all designs to include adequate venting to prevent the build up of hydrogen.

Where hydrogen evolution could produce an explosion hazard, the structure/electrolyte potential should be carefully monitored. Hydrogen evolution is not significant at structure/electrolyte potentials less negative than – 1.0 V with reference to a silver/silver chloride/sea-water electrode, for steel in sea-water.

12.6.1.2 *Special precautions for ships*

Hydrogen gas forms an explosive mixture with air and for this reason all protected tanks that contain ballast water or have just been de-ballasted cannot be regarded as gas-free space until tested and found safe. It should be borne in mind that the highest concentrations of hydrogen in a tank will be in the upper part of the tank, i.e. immediately below the deckhead or within the hatch coaming. It is essential, therefore, that an escape route to the atmosphere for this gas be ensured at all times.

No dangerous accumulation of gas is likely if the tank hatch lids are in the raised position but if, for any reason, they have to be lowered and fastened, it is essential that there is a suitable venting pipe to allow the gas to escape. In the event of such a pipe being fitted with a pressure/vacuum valve, this should be set in the “open” position, giving completely free access to the atmosphere.

During dry-docking it may be necessary, for trim or other reasons, to ballast or partly ballast one or more tanks that are cathodically protected by magnesium. To ensure that hydrogen gas is readily dispersed, the tank lids should be secured in the open position throughout the period the vessel is in dry dock.

12.6.2 Chlorine evolution

For an impressed current cathodic protection installation in a marine environment, the anode reactions result in the electrolytic formation of chlorine. Sea-water is normally slightly alkaline and the chlorine will form sodium hypochlorite. Under stagnant conditions, the chlorine may be evolved as a gas and could present a hazard to inspection and maintenance personnel.

It is sometimes impossible with internal protection of enclosed vessels or plant to drain a vessel completely before entering for maintenance. If it happens that anodes remain energized and immersed, the chlorine level in the remaining water may increase. Disturbing the water, e.g. by walking through it, will release enough chlorine in the restricted air space to cause acute discomfort; the cathodic protection should, therefore, always be switched off before a vessel is entered.

The formation of hypochlorite and gaseous chlorine will be minimized by the incorporation of a system of two-level or automatic control into the cathodic protection installation to maintain the structure/electrolyte potentials within set limits.

12.7 Installations in hazardous atmospheres

12.7.1 General

Flammable mixtures of gas, vapour or dust may develop wherever hydrocarbons or finely divided materials are handled, stored or processed (see BS 5345 and reference [50]). Such hazardous atmospheres may be ignited by an electric arc or spark. Unless proper precautions are taken all electrical installations, including cathodic protection systems, will introduce the danger of sparks and ignition.

Typical examples of where this hazard can occur are tanks, pipelines [50], manifolds, loading jetties, cargo vessels and tankers [51].

Cathodic protection systems that are to operate where flammable concentrations of gas or vapour may occur should conform to the statutory and other safety regulations applicable to the particular structure and industry concerned, for example, the ship classification societies have laid down requirements governing the use and inspection of anodes within the tanks of ships classified by them (see **6.4.4.1**) and approval should be obtained in each individual case as appropriate. Some of the explosion hazards cathodic protection may cause and the measures needed to avoid them are described in **12.7.2** to **12.7.11**.

12.7.2 Bonds

Intentional or unintentional disconnection of bonds across pipeline joints or any other associated equipment under protection or fortuitously bonded to protected equipment constitutes a hazard.

To avoid the hazard, bonds should be installed outside the hazardous area or in a protected position to avoid an unintentional break. The cathodic protection supply should be switched off or disconnected by means of a flameproof switch (see BS 4683-2, BS 5501 and BS 5345).

12.7.3 Isolating joints

Intentional or unintentional short-circuit of isolating joints e.g. by tools, or breakdown due to voltage surges on the protected structure induced by lightning or electrical power faults constitute a hazard.

To avoid the hazard, isolating joints should, if possible, be located outside the hazardous area. Where this is not practicable, measures should be adopted to avoid arcing or sparking. These would include the use of resistance bonds fitted in a flameproof enclosure or located outside the hazardous area, an encapsulated spark gap or surge diverter, zinc earth electrodes connected to each side of the isolating joint or a polarization cell connected across the isolating joint, or to earth. The surfaces of the isolating joint should be insulated to prevent fortuitous short circuiting by tools.

12.7.4 Short-circuits between points of different potentials

Unintentional short-circuits by fortuitous bridging of points of different potential, e.g. by metal scraps, odd lengths of wire, mobile plant constitute a hazard.

This hazard is difficult to foresee but may be limited by bonding all metalwork together to minimize the potential difference between different parts of the structure.

12.7.5 Disconnection, separation or breaking of protected pipework

Cathodically protected pipework will have a portion of the protection current flowing through it. Any intentional disconnection, separation or breaking of the pipework would interrupt the current flow and may produce arcing depending on the magnitude of the current.

During any modification, maintenance or repair of cathodically protected pipework, transformer-rectifiers that affect that section of pipework should be switched off and a temporary continuity bond attached across any intended break. It is essential that the bond is securely clamped to each side of the intended break and remains connected until the work is completed and electrical continuity restored or until the area is certified as gas-free or non-hazardous.

12.7.6 Electrical equipment

All electrical equipment installed in a hazardous area should be flameproof and certified for use in that area (see BS 4683-2, BS 5501 and BS 5345). To avoid the need for flameproof equipment, the equipment should be located outside the hazardous area. Double pole switches should be provided in each circuit entering a hazardous area to ensure that both poles are isolated during maintenance etc. (see also **12.7.5**).

It is essential that any cables carrying cathodic protection current should be installed in such a manner that disconnection cannot take place within the hazardous area without de-energizing the cathodic protection system. The cables should also be adequately protected mechanically to prevent accidental breakage.

12.7.7 Test instruments

The connection and disconnection of instruments used for measuring and testing cathodic protection systems may produce arcing or sparking.

Where measurements are taken within the hazardous areas, the meter used should be intrinsically safe in accordance with BS 5501. The test leads should be connected to the structure before being connected to the meter. Alternatively, the area should be tested and declared gas-free, allowing conventional instruments to be used.

Consideration may also be given to the use of permanently installed reference electrodes and test leads with the cables taken outside the hazardous area where conventional instruments can be used.

12.7.8 Internal anodes

Unintentional short-circuiting of impressed current anodes when the liquid level is lowered in plant under internal cathodic protection can constitute a hazard.

Arrangements should be made to ensure that the circuit is automatically or manually isolated when the anode is not submerged, i.e. when the anode circuit becomes an open circuit.

12.7.9 Loading lines

The connection or disconnection of loading lines to tankers, barges, rail or road gantries and associated pipelines can be hazardous.

Rail and road gantry supply pipelines that are cathodically protected should be fitted with isolating joints prior to coming onto the gantry.

For loading and discharge between a jetty and a tanker, where both the jetty and tanker are usually under cathodic protection, the following precautions are necessary [51], [52]. Because of the large currents present in both jetty and tanker cathodic protection systems and the difficulty of achieving a sufficiently low resistance bond between tanker and jetty, currents may still flow between the two. The use of a bond is therefore ineffective and possibly a safety hazard. Ship to shore bonding cables should no longer be used.

Effective isolation between the two is maintained by the use of isolating joints in the loading lines unless local regulations still have a mandatory requirement for ship to shore bonding.

NOTE If a loading cable is insisted upon, the connection point for the bonding cable should be well clear of the manifold area. There should be a flameproof switch in the bond circuit located on the jetty which has to be in the "off" position before connecting or disconnecting the cable. The switch should only be closed when the cable is properly fixed and prior to cargo hoses being connected and should remain closed until after the hoses have been disconnected.

In order to provide protection against arcing during connection and disconnection of cargo hoses, it is necessary to fit an isolating joint or flange or a single length of non-conducting hose in each of the metal arms or cargo hose strings to ensure electrical isolation between the ship and shore. All metal on the seaward side of the isolation should be electrically continuous with the ship and all metal on the landside continuous with the jetty earthing system.

Isolating joints or flanges should be designed to avoid accidental short-circuits. Where the loading line is wholly flexible, the isolation should be fitted at the jetty manifold. Where the line is partly flexible and partly a metal loading arm, the isolation should be inserted between the flexible hose and the metal arm. For an all metal arm, care should be taken to ensure that the isolation cannot be fortuitously short-circuited by guy wires, tools etc.

Similar conditions apply to ship to ship transfers of hazardous cargoes. An isolating joint or flange should be fitted to the manifold of one vessel and the line securely earthed to the manifold of the other vessel or, alternatively, a length of non-conducting hose may be fitted in the hose string. Care has to be taken to ensure that isolation is not included at both ends leaving an insulated section of pipe on which an electrostatic charge could build up, thereby causing a spark hazard.

For tankers at submarine line berths at least two sections of non-conducting hose should be inserted into the string of flexible hoses at the end of the rigid line. These should preferably be the second and third hoses from the tanker manifold.

Where single buoy moorings are provided with electrical isolation, these precautions are not considered necessary.

Switching off the cathodic protection systems on jetties and ships is not considered advisable since on busy jetties this would mean an almost total loss of protection on the jetties. Also, the considerable difference in depolarization times for the jetty and ship would probably create a larger potential difference between the two than leaving both systems operating. Providing both cathodic protection systems are properly adjusted then the amount of cathodic interaction will be minimized.

12.7.10 Sacrificial anodes

Whilst the normal operation of a sacrificial anode is not considered hazardous, there is a danger of incendive sparking if a suspended or supported sacrificial magnesium or aluminium anode or portion of anode becomes detached and falls onto steel (see also **6.4.4.1**). This risk is not present with zinc anodes.

12.7.11 Instruction of personnel

In locations where any of the above hazards may occur, it is essential that operating personnel be suitably instructed, and durable warning notices should be authoritatively displayed as appropriate. Suitable written procedures and work authorization permits should be included in the operations manual.

Appendix A The significance of pH value and redox potential

A.1 The pH value

The acidity (or alkalinity) of aqueous electrolytes often determines the behaviour of buried or immersed metals, depending on the tendency of the metals to displace hydrogen, and on the stability of any oxide films on their surfaces.

The pH value is the measure of acidity commonly employed. The following expression has adequate practical validity:

$$\text{pH} = -\log_{10}(\text{H}^+) \qquad (12)$$

where (H^+) is the concentration of hydrogen ions in gram-ions per litre of electrolyte.

The numerical scale is fixed by the nature and extent of the ionic dissociation of pure water itself according to the following relation:

$$\text{pH} + \text{pOH} = \text{Constant} \quad \text{(at stated temperature)} \qquad (13)$$

where pOH is analogous to pH but refers to the hydroxyl ion concentration. The constant has the value 14.0 at 25 °C and, since pure water dissociates into equal numbers of hydrogen and hydroxyl ions, the neutral point of the pH scale at 25 °C corresponds to the pH value 7.0.

For practical purposes, pH values usually lie in the range 0 to 14. Acid electrolytes have pH values numerically below that of the neutral point whereas alkaline electrolytes have pH values numerically above. The logarithmic progression of these figures should be emphasized.

A.2 Redox potential

The redox potential of a soil is considered to provide a means of assessing whether that particular soil is conducive to activity of *Desulphovibrio desulphuricans* (sulphate-reducing bacteria). The bacteria flourish under reducing conditions (low redox potential) but become dormant under oxidizing conditions (high redox potential).

The redox potential of the soil is determined by measuring the potential of a platinum electrode with respect to a saturated calomel or other reference electrode, both being in contact with the soil under test. The pH value of the soil also needs to be determined (see **A.1**).

The redox potential can then be calculated from the equation:

$$E_\text{H} = E_\text{p} + E_\text{r} + 60\,(\text{pH} - 7) \qquad (14)$$

where:

E_H is the redox potential on the hydrogen scale (in mV),

E_p is the redox potential (in mV), measured with respect to a reference electrode having a potential E_r with respect to the standard hydrogen electrode (E_r is + 250 mV for a saturated calomel electrode [see Table 6)]

pH is the measured acidity of the soil.

In near-neutral electrolytes, E_H indicates how corrosive they are with respect to iron and steel, as indicated in Table 8:

Table 8 — Corrosiveness of electrolytes with respect to iron and steel

E_H	Degree of corrosion
mV	
< 100	Severe
> 100 ≤ 200	Moderate
> 200 ≤ 400	Slight
> 400	None

If the pH value is outside the range 5.5 to 8.5 the redox potential has no significance because sulphate-reducing bacteria are active only in the near-neutral pH range.

The determination and assessment of redox potential in the field and laboratory are described in Parts 3 and 9 of BS 1377. The type and nature of the probes required are also described.

Appendix B Related British Standard specifications and codes of practice

BS 148, *Specification for unused mineral insulating oils for transformers and switchgear.*

BS 970, *Specification for wrought steels for mechanical and allied engineering purposes.*

BS 970-1, *General inspection and testing procedures and specific requirements for carbon, carbon manganese, alloy and stainless steels.*

BS 2709, *Specification for the electrical performance of semiconductor rectifiers (metal rectifiers).*

BS 2914, *Specification for surge divertors for alternating current power circuits.*

BS 4147, *Specification for bitumen-based hot-applied coating materials for protecting iron and steel, including suitable primers where required.*

BS 4164, *Specification for coal-tar-based hot-applied coating materials for protecting iron and steel, including a suitable primer.*

BS 4417, *Specification for semiconductor rectifier equipments.*

BS 4515, *Specification for welding of steel pipelines on land and offshore.*

BS 5467, *Specification for cables with thermosetting insulation for electricity supply for rated voltages of up to and including 600/1 000 V and up to and including 1 900/3 300 V.*

BS 6004, *Specification for PVC-insulated cables (non-armoured) for electric power and lighting.*

BS 6346, *Specification for PVC-insulated cables for electricity supply.*

BS 6926, *Specification for copper for electrical purposes: high conductivity copper wire rod.*

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NACE RP 01-69-83[4]

Control of external corrosion on underground or submerged metallic piping systems.

Table 1 — *Index of coating references.*

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Standard for coal-tar protective coatings and linings for steel water pipelines — enamel and tape — hot applied[5].

AWWA C 213-79

Standard for fusion-bonded epoxy coatings for the interior and exterior steel water pipelines.

BGC/PS/CW 1

Specification for external wrap operations for steel linepipe using coal tar[6].

BGC/PS/CW 3

Specification for external wrap operations for steel linepipe using hot applied bitumen.

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[3] CP 2010 is under revision. The revised Parts of CP 2010 will be issued as Parts of BS 8010.

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[5] Published by the American Waterworks Association Standards Committee on steel pipe.

[6] This publication is a partial replacement only of the Department of Transport Specification for Road and Bridge Works, 5th edition, 1976.

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BSI — British Standards Institution

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