

Cathodic protection —

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

(formerly CP 1021)

Committees responsible for this British Standard

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- 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

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Publication(s) referred to	Inside back cover

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 It represents a revision of CP 1021:1973, which is withdrawn.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.

A British Standard does not purport to include all the necessary provisions of a contract. Users of British Standards are responsible for the correct application.

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

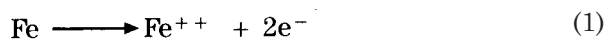
2.1 Introduction

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.

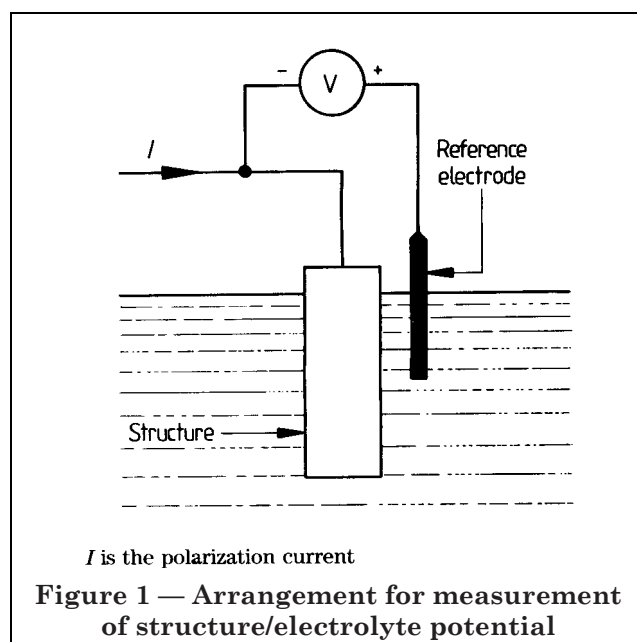


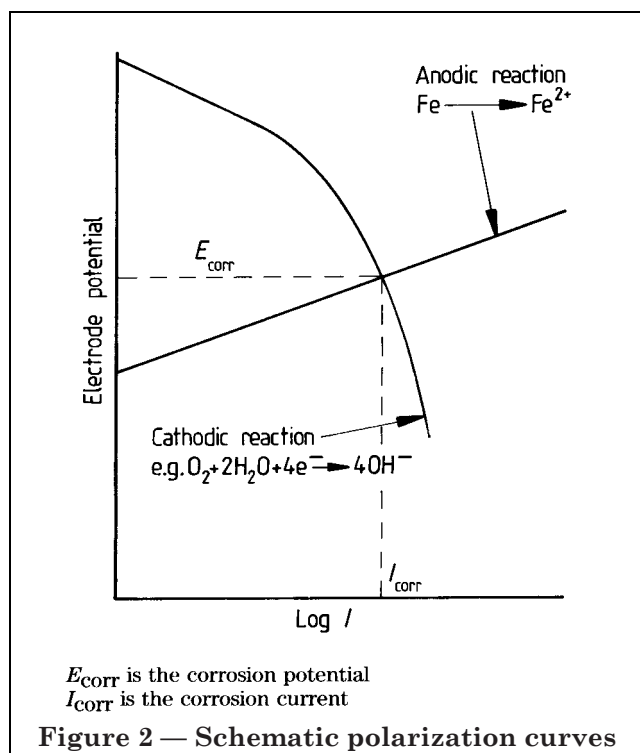
Thus corrosion is accompanied by the flow of an electric current from metal to electrolyte due to the movement of positive ions into the electrolyte and of electrons into the metal. Any area at which current flows in this direction is referred to as an anodic area, and the reaction is called an anodic 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 occurring 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.





2.2.3 Formation of cells

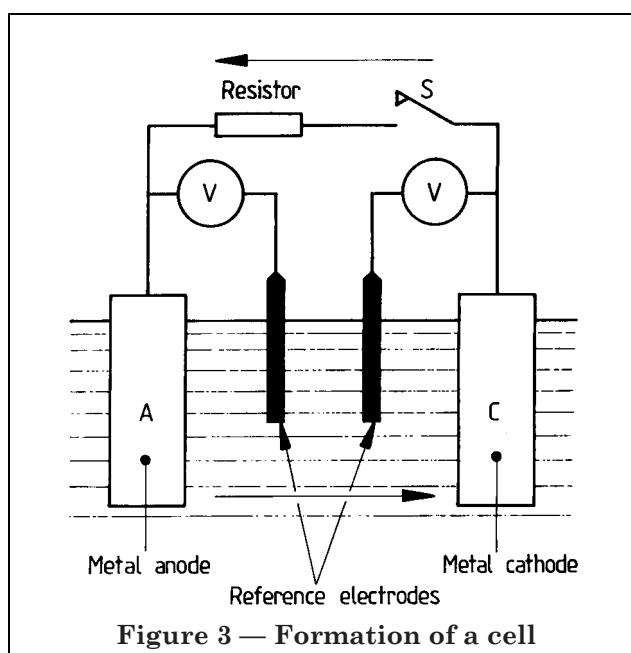
If the potentials of two different metals with respect to an electrolyte are measured with the arrangement shown in Figure 3, and the metal marked A is found to be more negative; when the switch is closed, current will flow in the direction shown by the arrows. Metal A will therefore be the anode and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

- magnesium (most electronegative of the materials listed);
- zinc;
- aluminium (certain aluminium alloys may be more electronegative);
- iron and steel;
- lead;
- brass;
- copper;
- 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.

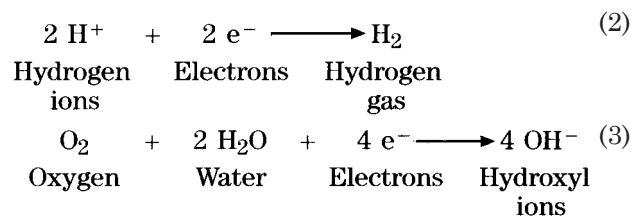


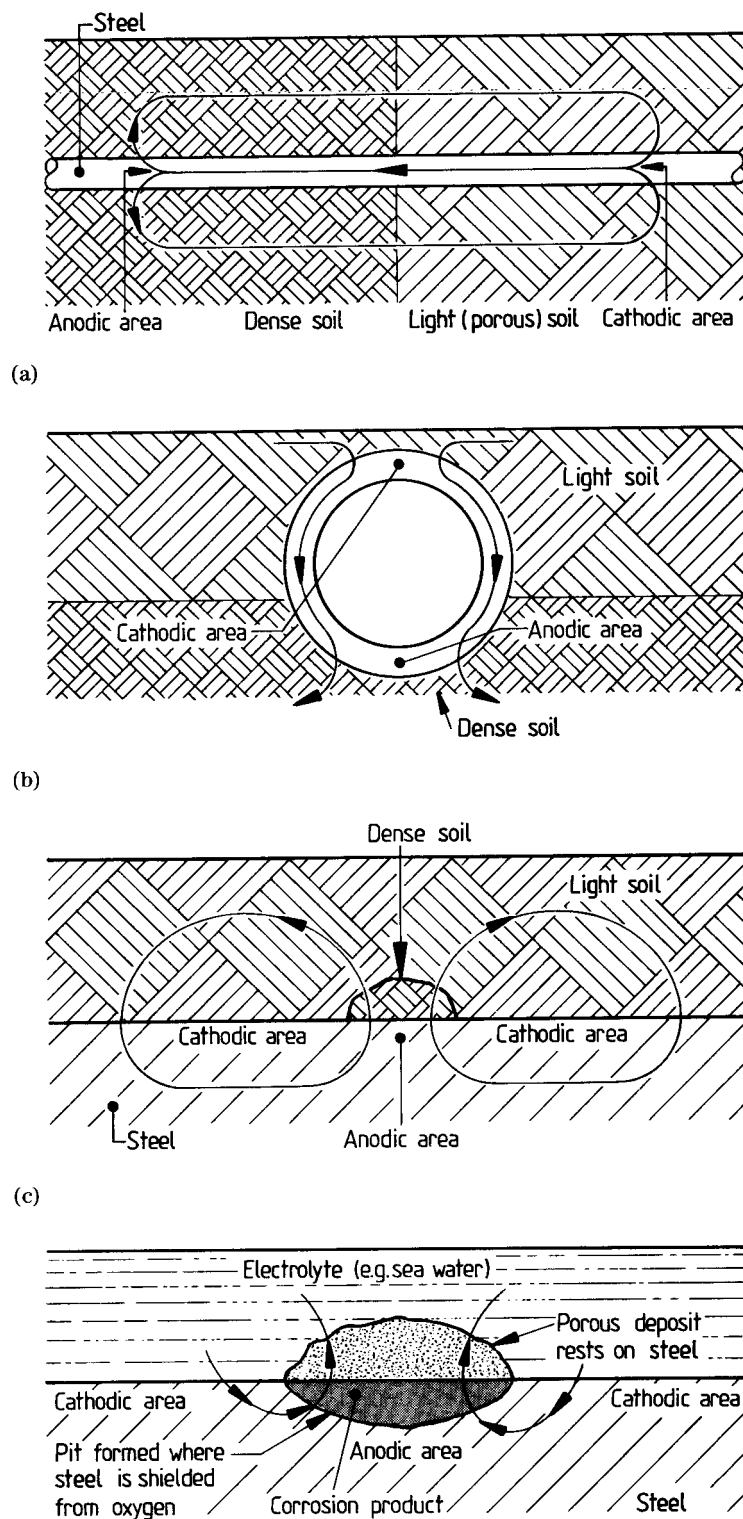
2.2.4 Passivity

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.



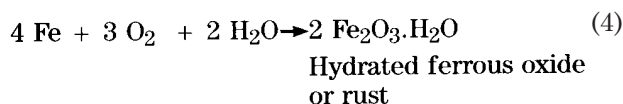


(d)
NOTE. Arrows indicate the direction of current flow.

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.



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

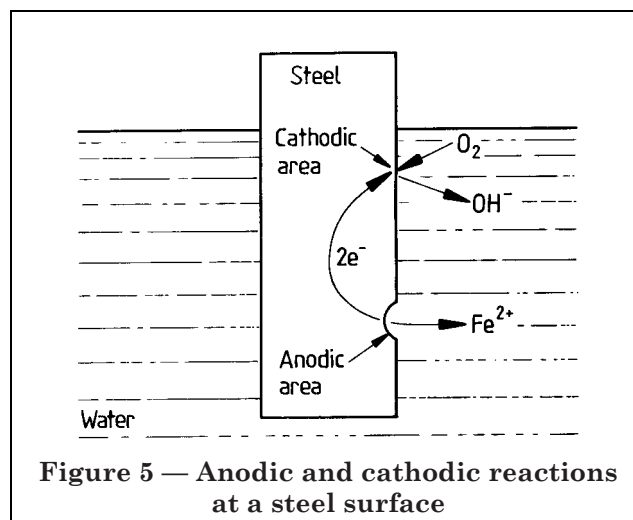
2.3.1 Basis of cathodic protection

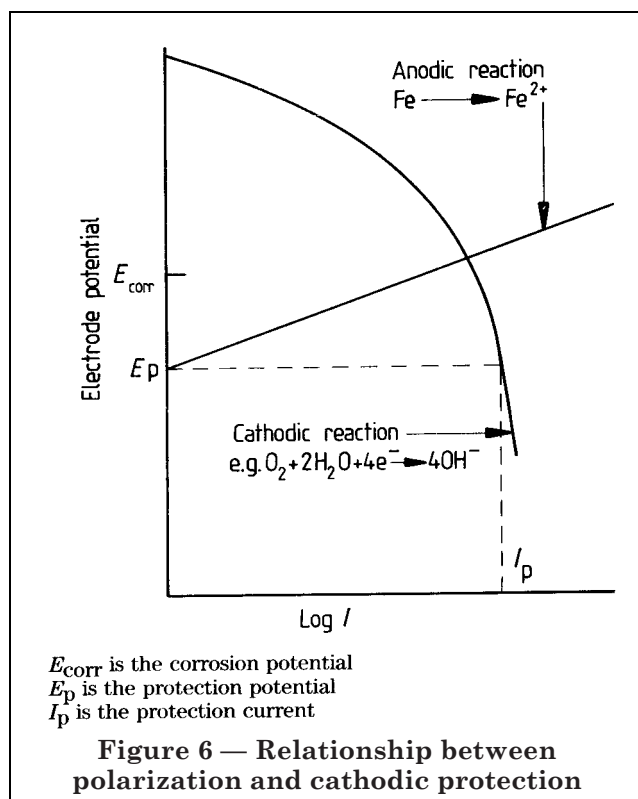
Corrosion requires the existence of anodic and cathodic areas. The corrosion process in aerated water is shown in Figure 5. If electrons are caused to flow into the structure from an external source, then the positive ions leave the metal surface less readily, but the cathodic process is enhanced.

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.





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.

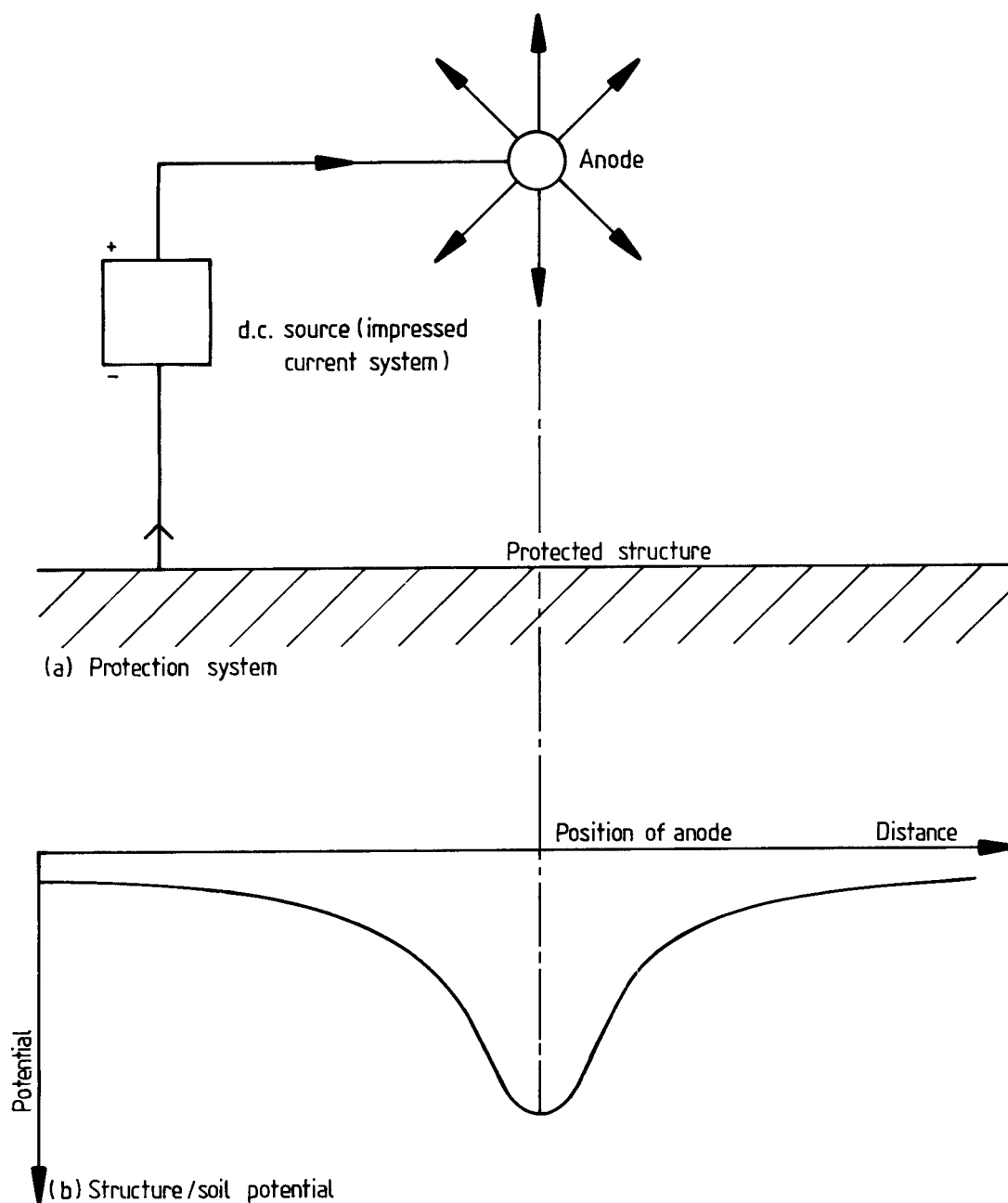


Figure 7 — A cathodic protection system and the distribution of structure/electrolyte potential

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.

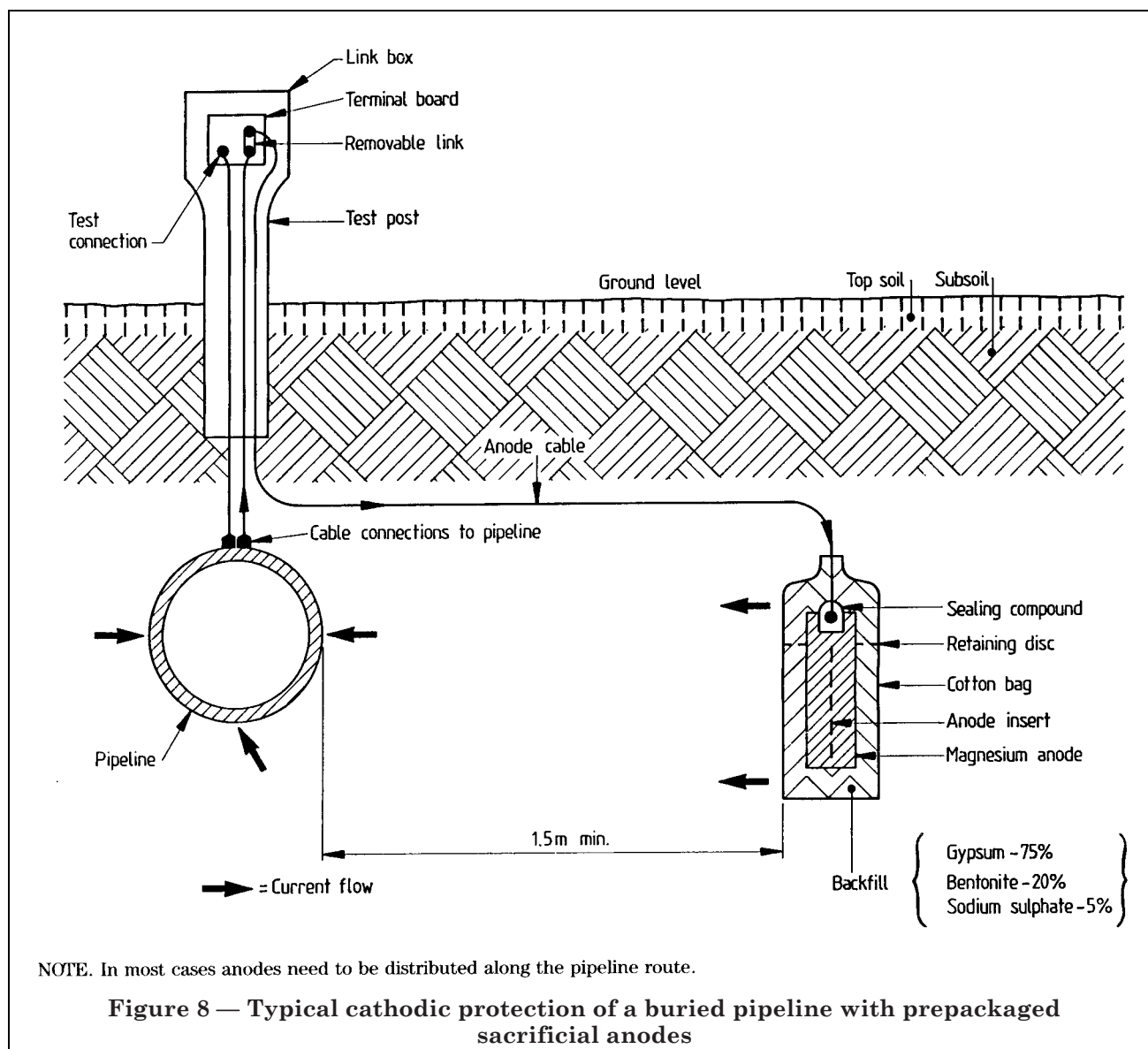
Thus, if the electrolyte resistivity is high (e.g. most soils) anodes are best made in the form of rods or relatively slender ingots or, for very high resistivity surroundings, as extruded strip or ribbon. With electrolyte of lower resistivity, provision of sufficient material to give an adequate life 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.



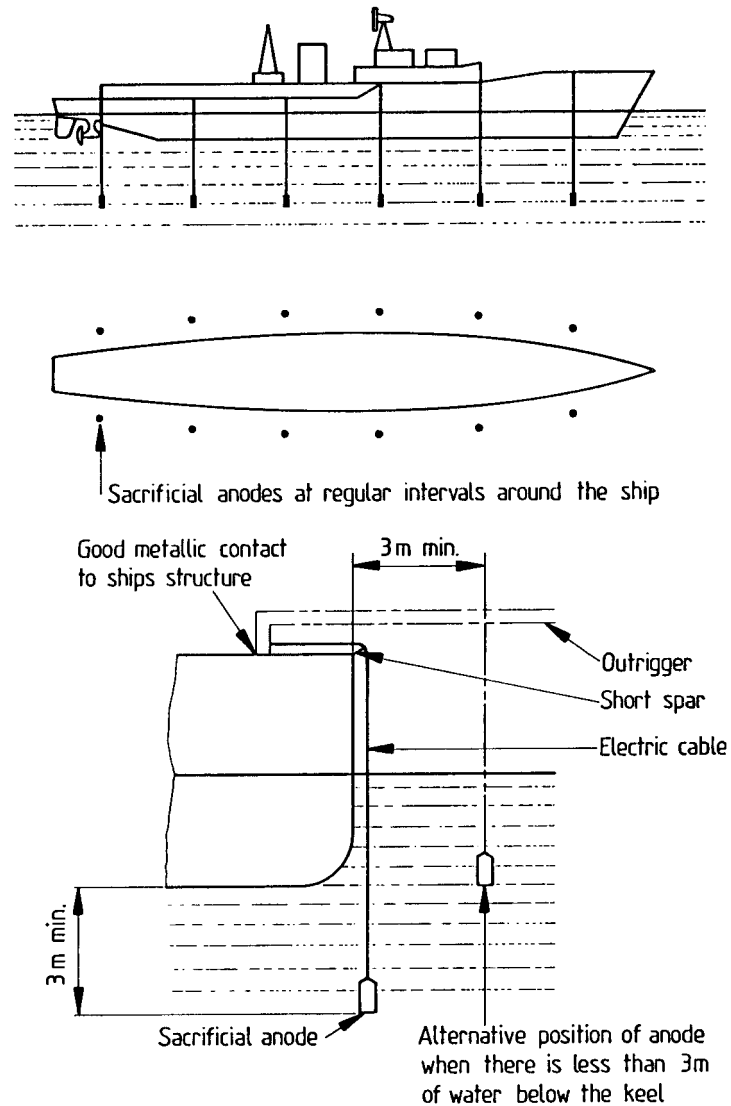
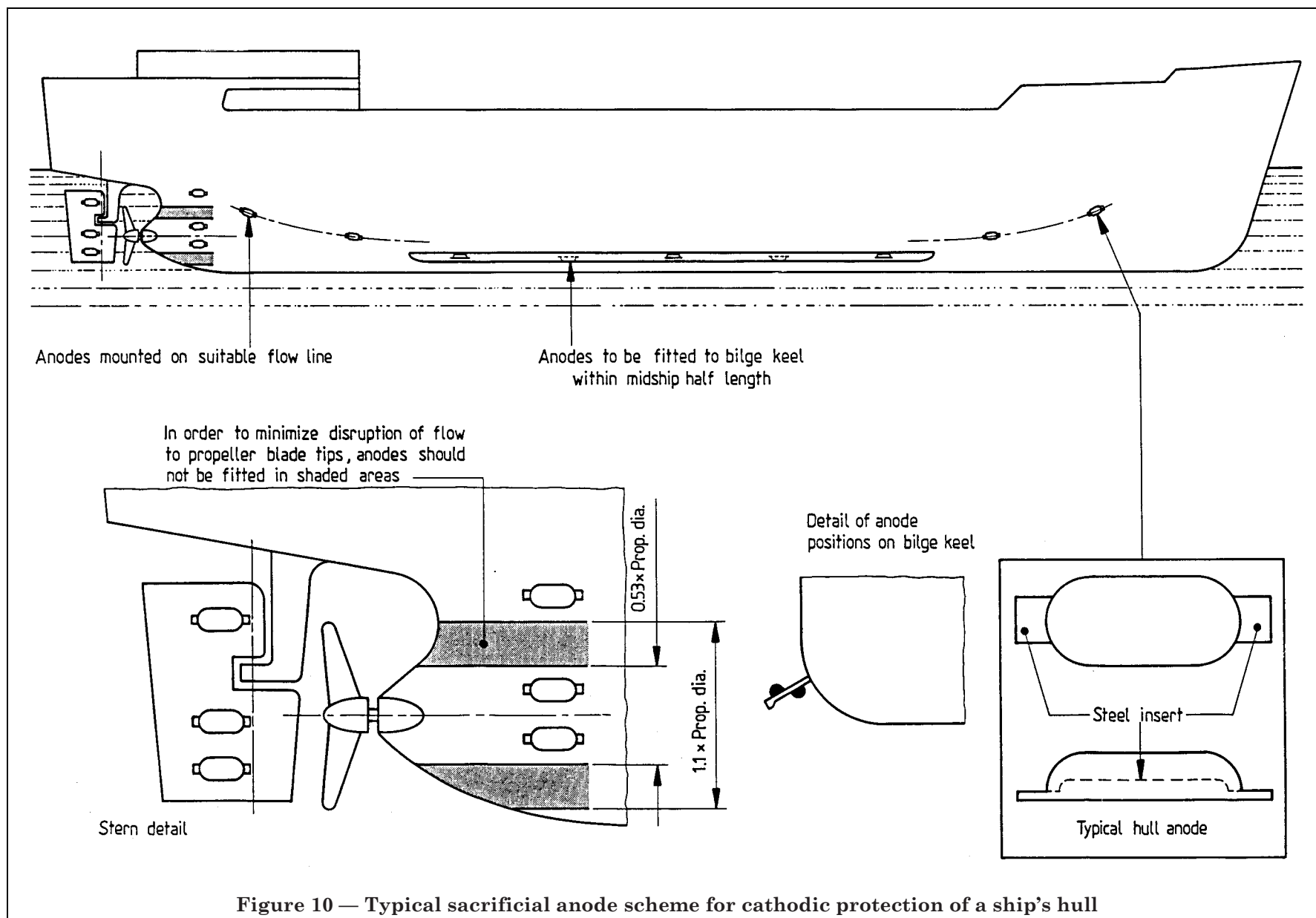


Figure 9 — Typical cathodic protection of a moored ship using sacrificial anodes



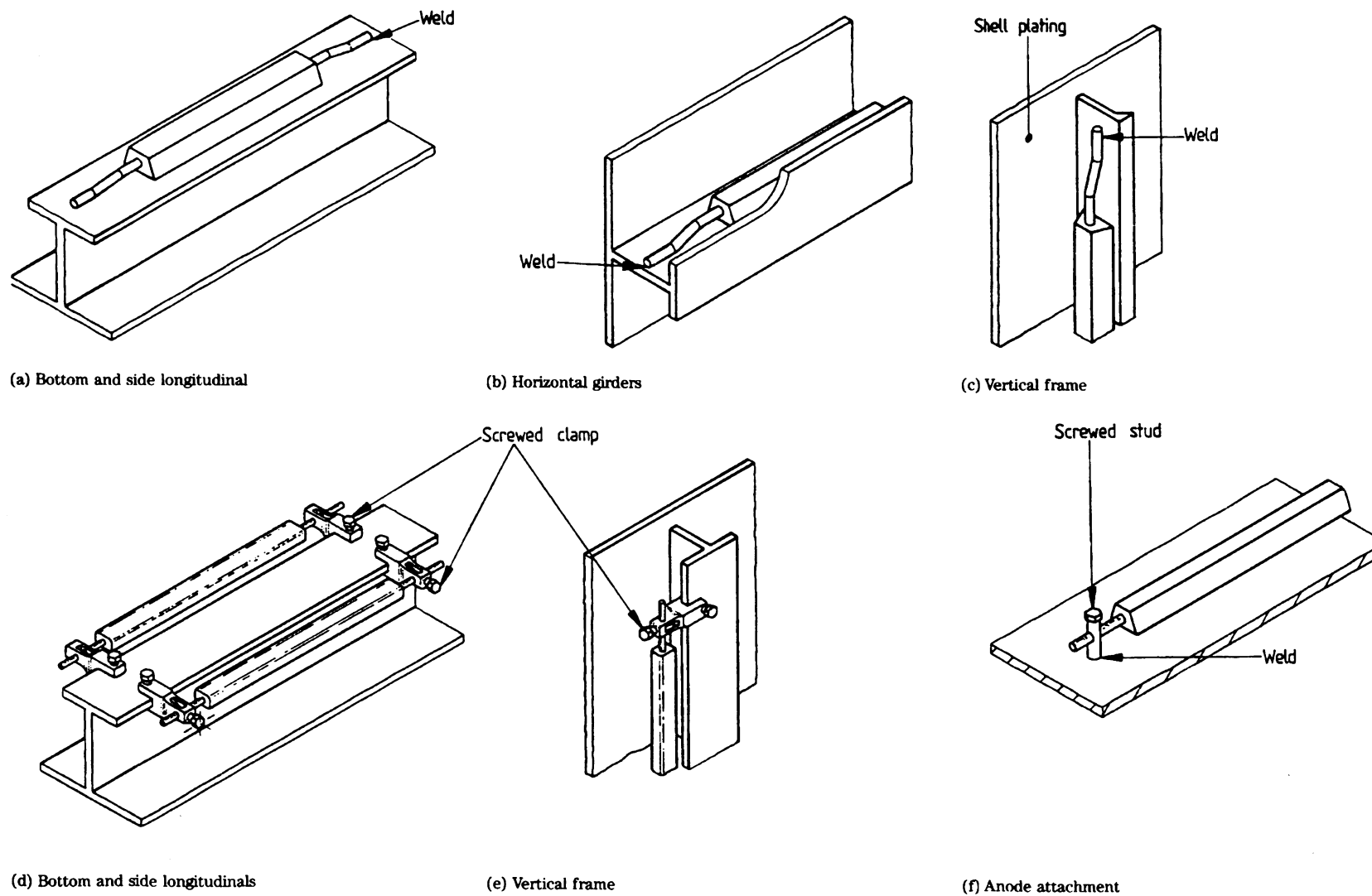


Figure 11 — Typical sacrificial anodes and installation arrangements for cathodic protection of storage tank interiors

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 1 of 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
<i>Magnesium</i>		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
<i>Zinc</i>				
0.5 % Al, 0.1 % Cd	sea-water	– 1.05 (Ag/AgCl/sea-water)	780	11.25
<i>Aluminium</i>				
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	Sea-water	– 1.1	1 800 to 2 000	4.38 to 4.86
0.01 % to 0.03 % In	Sea-bed mud	(Ag/AgCl/sea-water)		

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.

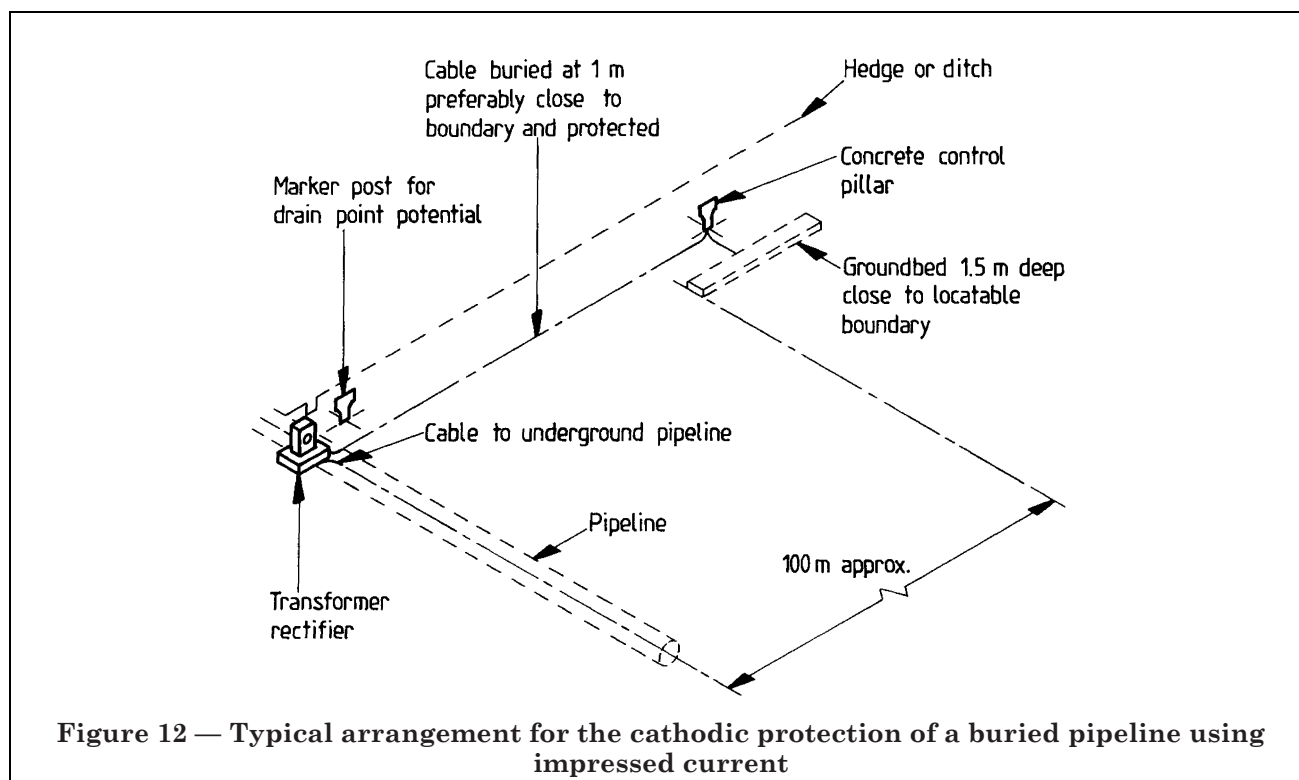


Figure 12 — Typical arrangement for the cathodic protection of a buried pipeline using impressed current

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_3O_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 (PbO_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 $2\,000 \text{ A/m}^2$. 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 $1\,000 \text{ A/m}^2$ 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 tapplings 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.						