



CP 1021:1973

Code of Practice for

Cathodic protection

British Standards Institution



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CP 1021 : 1973

Contents

	Page		Page
Foreword	6	4. Application to buried structures	
1. General		4.1 Introduction	25
1.1 Scope	7	4.2 General	25
1.2 Definitions	7	4.2.1 Factors affecting design	25
1.3 Exchange of information	10	4.2.2 Galvanic anode installations	25
1.4 Related Codes of Practice	11	4.2.3 Impressed current installations	25
1.5 Related British Standards	11	4.2.4 Electric drainage	26
2. General Principles		4.3 Buried pipelines	27
2.1 Introduction	11	4.3.1 Structure preparation	27
2.2 Behaviour of buried or immersed metals in the absence of cathodic protection	11	4.3.2 Application to buried pipelines	29
2.2.1 The nature of metallic corrosion	11	4.3.3 Particular considerations	30
2.2.2 Polarization	12	4.4 Buried cables	31
2.2.3 Formation of cells	12	4.4.1 Structure preparation	31
2.2.4 Passivity	12	4.4.2 Application to buried cables	31
2.2.5 Reactions at cathodic areas	13	4.5 Oil storage tank bottoms	32
2.3 Cathodic protection	13	4.5.1 General	32
2.3.1 Basis of cathodic protection	13	4.5.2 Structure preparation	32
2.3.2 Cathodic protection criteria	13	4.5.3 Application to oil storage tank bottoms	32
3. Application: considerations applicable to most types of structure		4.5.4 Particular considerations	32
3.1 Introduction	14	5. Application to ships	
3.2 Range of application	14	5.1 Introduction	32
3.3 Basis of design	15	5.2 The cathodic protection of active ships' hulls	33
3.4 Design or modification of structures to be protected	16	5.2.1 Factors affecting design	33
3.4.1 Electrical continuity	16	5.2.2 Preparation for cathodic protection	34
3.4.2 Protective coatings	16	5.2.3 Current density required for protection	35
3.4.3 Isolation	17	5.2.4 Application: galvanic anode installations	36
3.4.4 Provision for testing	17	5.2.5 Application: impressed current installations for ships' hulls	37
3.5 Galvanic anode installations	17	5.3 The protection of ships during fitting out or when laid up	38
3.5.1 Method	17	5.3.1 Cathodic protection during fitting out	38
3.5.2 Galvanic anode design	17	5.3.2 Ships laid-up	38
3.5.3 Anode materials	18	5.4 The protection of ships' tanks	38
3.6 Impressed current installations	19	5.4.1 Factors affecting design	38
3.6.1 Methods	19	5.4.2 Protective coatings	39
3.6.2 Anodes and groundbeds for impressed current installations	19	5.4.3 Current density required for protection	39
3.6.3 Source of power	20	5.4.4 Design of galvanic anodes and galvanic anode system	40
3.7 Comparison of the various systems	22	5.4.5 Special considerations	41
3.8 Special considerations	22	6. Immersed structures (excluding ships)	
3.8.1 Secondary effects of cathodic protection	22	6.1 Introduction	41
3.8.2 Effects of stray currents from protection installations	22	6.2 Immersed structures: general	42
3.8.3 The avoidance of damage or hazard due to overvoltages	22	6.2.1 Structure preparation	42
3.9 Testing	24	6.2.2 Application of cathodic protection to immersed structures	42
		6.2.3 Particular considerations	43
		6.3 Submarine pipelines	44

	Page		Page
6.3.1 General	44	9.5.1 Soil resistivity	61
6.3.2 Structure preparation	44	9.5.2 Determination of bond resistance	61
6.3.3 Application of cathodic protection to submarine pipelines	44	9.5.3 Continuity of structure	61
7. The internal protection of plant		9.6 Tests required prior to installing cathodic protection: buried or immersed structures	62
7.1 Introduction	45	9.6.1 Soil or water samples	62
7.2 General considerations	45	9.6.2 Soil resistivity	62
7.2.1 Factors affecting design	45	9.6.3 Structure/electrolyte potential surveys	63
7.2.2 Galvanic anodes	45	9.6.4 Stray electric currents	63
7.2.3 Impressed current	45	9.6.5 Electrical continuity	63
7.2.4 Assessment of protection provided	45	9.7 Tests required during commissioning	63
7.3 Storage tanks	46	9.7.1 General	63
7.3.1 Tanks for storage of chemicals	46	9.7.2 Buried structures	64
7.4 Water circulating systems	46	9.7.3 Fixed immersed structures	64
7.4.1 General	46	9.7.4 Ships' hulls	64
7.4.2 Heat exchangers (tube and shell)	47	9.7.5 Internal protection of plant	64
7.4.3 Box coolers	48		
7.5 Industrial plant	48	10. Safety aspects	
8. Measures to safeguard neighbouring structures		10.1 Introduction	64
8.1 Introduction	49	10.2 Installation, operation and maintenance	65
8.2 General	49	10.3 Danger of electric shock	65
8.3 Buried structures	49	10.3.1 General	65
8.3.1 Notifying owners of other structures	49	10.3.2 Installations on buried structures	65
8.3.2 Interaction testing	50	10.3.3 Installations on immersed structures	65
8.3.3 Criteria for corrosion interaction	52	10.3.4 Installations for the internal protection of plant	65
8.3.4 Design of cathodic protection installations to minimize corrosion interaction	53	10.4 Fault conditions in electricity power systems in relation to remedial and/or unintentional bonds	66
8.3.5 Measures to reduce corrosion interaction	54	10.5 Hydrogen evolution	66
8.3.6 Special considerations	55	10.5.1 General	66
8.4 Jetties and ships: corrosion interaction at sea and river terminals	56	10.5.2 Special precautions for ships	66
9. Electrical measurements		10.6 Installation in hazardous atmospheres	66
9.1 Introduction	56	10.6.1 Explosion hazards	66
9.2 Voltage measurement: instruments	56	10.6.2 Measures to avoid the explosion hazard	67
9.2.1 Reference electrodes	56	10.6.3 Chlorine evolution	68
9.2.2 Potentials of reference electrodes	57		
9.2.3 Voltmeters	57	11. Operation and maintenance	
9.2.4 Potentiometers	58	11.1 Introduction	68
9.2.5 Recorders and data logging equipment	58	11.2 The period immediately following commissioning	68
9.2.6 Choice of instruments	59	11.3 Operation and maintenance: considerations relating to most types of structure or plant	69
9.3 Voltage measurement: methods	59	11.3.1 Potentials on protected structures	69
9.3.1 General	59	11.3.2 Galvanic anode installations: maintenance	69
9.3.2 Buried structures	59	11.3.3 Impressed current systems: maintenance	70
9.3.3 Immersed structures	59	11.4 Buried structures	71
9.3.4 Internal protection of plant	60		
9.4 Measurement of direct current	61		
9.5 Resistance measurement	61		

CP 1021 : 1973

	Page		Page
11.4.1 Galvanic anode installations on buried structures	71	5. Cathodic protection system and distribution of structure/electrolyte potential	80
11.4.2 Impressed current systems on buried structures	71	a. Protection system	
11.4.3 Groundbeds for buried structures	72	b. Initial potentials	
11.5 Immersed structures (excluding ships)	72	c. After application of cathodic protection	
11.5.1 Galvanic anode installations on immersed structures	72	6. Cathodic protection with galvanic anodes	81
11.5.2 Impressed current systems on immersed structures	72	a. Cathodic protection of a buried pipeline	
11.6 The internal protection of plant	73	b. Cathodic protection of a submarine pipeline	
11.6.1 Galvanic anode installations for internal protection of plant	73	c. Cathodic protection of a moored ship	
11.6.2 Impressed current systems for internal protection of plant	73	d. Typical galvanic anode scheme for cathodic protection of a ship's hull	
11.7 Ships' hulls	74	7. Magnesium anode for burial prepacked with backfill	85
11.7.1 Galvanic anode installations on ships' hulls	74	8. Hemispherical galvanic anode for low resistivity waters	85
11.7.2 Impressed current systems: for hulls of active ships	74	9. Typical galvanic anodes for external mounting on a ship's hull (attachment by studs or welded straps)	86
11.8 Ships' tanks	76	a. Zinc anodes	
		b. Aluminium anodes	
		c. Magnesium anodes	
		10. Typical galvanic anodes for the internal protection of tanks	87
		a. Zinc anode (for welding)	
		b. Magnesium anode (for bolting and/or welding)	
		c. Aluminium or zinc anode (for attaching by clamp)	
		11. Typical impressed current schemes	88
		a. Typical impressed current system for laid-up ship	
		b. Typical impressed current system for buried pipeline	
		12. Hull anodes for impressed current	89
		a. Lead alloy hull anode with pre-fabricated shield	
		b. Example of hull penetration gland	
		c. Platinum alloy disk anode mounted on ship's hull	
		d. Platinized titanium disk anode recessed into ship's hull	
		13. Platinized titanium impressed current anode for protection of underwater structures	92
		14. Typical impressed current anodes for the internal protection of plant	93
		a. Continuous anode	
		b. Platinized titanium cantilever rod anode	
Appendix			
A. The significance of pH value and redox potential	77		
Tables			
1. Potentials for cathodic protection (volts)	14		
2. Typical information for galvanic anode materials in clean sea-water	18		
3. A comparison of galvanic anode and impressed current systems	23		
4. Potentials of reference electrodes with respect to the standard hydrogen electrode (at 25 °C)	58		
Figures			
NOTE. 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.			
1. Measurement of polarization	79		
a. Circuit			
b. Polarization curve			
2. Cell	79		
3. Cells due to differential aeration	79		
4. The basis of cathodic protection	80		
a. Corrosion cell			
b. Cathodic protection			

	Page		Page
15. Typical electric drainage systems	94	e. Porous plug reference point for measuring metal/electrolyte potential inside plant	
a. Polarized drainage without resistor (on an electrified line with single-rail track circuits)		17. Measurement of structure/soil potential to assess interaction	99
b. Polarized drainage with resistor and reactor (on electrified line with double-rail track circuits)		a. Typical arrangement of excavation and placing of reference electrode where structures are parallel	
c. Forced drainage on an electrified line without track circuits (drainage supplemented by rectified a.c.)		b. Typical arrangement of excavation and placing of reference electrode where structures cross	
16. Typical reference electrodes	95	18. Zero resistance ammeter	100
a. Typical copper/saturated copper sulphate reference electrodes		a. Zero resistance ammeter circuit used to measure bond current (bond disconnected)	
b. Typical silver/silver chloride reference electrodes		b. Zero resistance ammeter circuit used to measure current flowing in bond or structure (circuit not disconnected)	
c. Typical reference electrodes for mounting on ships' hulls		19. Approximate comparison of potentials using zinc, Cu/CuSO ₄ and Ag/AgCl reference electrodes	101
d. 'Screw-in' zinc electrode for measurement of metal/electrolyte potential inside plant		Bibliography	102

This Code of Practice represents a standard of good practice; compliance with it does not confer immunity from relevant legal requirements, including byelaws.

CP 1021 : 1973

Foreword

Cathodic protection is a means of preventing the corrosion of most metals wherever they are in contact with a mass of water or moist surroundings. 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 Code covers good current practice and contains both guidance on general principles and detailed information on the cathodic protection of particular types of structure or plant. For certain types of structure, for example, buried steel piling, insufficient evidence based on actual installations has been obtained to enable detailed information to be given. It should not, however, be assumed in such cases 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 Code notably on criteria relating to steel completely surrounded by concrete.

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 Code. The corrosion protection of iron and steel in this context is covered by CP 2008, 'Protection of iron and steel structures from corrosion'.

Throughout this Code, the essential features are indicated by the use of 'should' except where phrases such as 'it is essential that' or 'it is imperative that' have been used for emphasis.

British Standard Code of Practice for

Cathodic protection

1. General

1.1 Scope

This Code of Practice 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.

This Code indicates general circumstances in which cathodic protection is likely to be economical. Where cathodic protection is the intended method, the recommendations set out in the following clauses apply and sections are included which cover general principles, their application, the special problems arising in the protection of particular types of structure, the safeguarding of neighbouring structures, electrical measurements, safety, and the operation and maintenance of cathodic protection systems.

NOTE. The titles of the British Standard publications referred to in this Code of Practice are listed in 1.4 and 1.5.

1.2 Definitions

For the purposes of this Code, the following definitions apply. Other terms are as defined in BS 4727.

- (1) *Acidity*. The presence of an excess of hydrogen ions over hydroxyl ions (see also definition 49).
- (2) *Alkalinity*. The presence of an excess of hydroxyl ions over hydrogen ions (see also definition 49).
- (3) *Anaerobic*. Lacking free oxygen. In this Code, this refers to the state of the electrolyte adjacent to the metal structure.
- (4) *Anode*. The electrode through which direct current enters an electrolyte.
- (5) *Anode shield*. A protective covering of insulating material applied to a painted structure, usually a ship's hull, 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.
- (6) *Anodic area*. That part of a metal surface which acts as an anode.
- (7) *Backfill*. A low-resistance moisture-holding material immediately surrounding a buried anode for the purpose of increasing the effective area of contact with the soil.
- (8) *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.
- (9) *Bond*. A piece of metal, usually in the form of rectangular strip, circular solid wire or stranded conductor, 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 in respect of the other.
- (10) *Bond resistance*. The ohmic resistance of a bond including the contact resistance at the points of attachment of its extremities.
- (11) *Calomel reference electrode*. A reference electrode consisting of mercury in a standard solution of potassium chloride saturated with mercurous chloride (calomel).
- (12) *Cantilever anode*. An anode formed and supported as a cantilever.
- (13) *Cathode*. The electrode through which direct current leaves an electrolyte.
- (14) *Cathodic area*. That part of a metal surface which acts as a cathode.

CP 1021 : 1973

(15) *Cathodic protection*. A means of rendering a metal immune from corrosive attack by causing direct current to flow from its electrolytic environment into the metal.

(16) *Cell*. A complete electrolytic system comprising a minimum of a cathode, an anode and an intervening electrolyte.

(17) *Conductor*. A substance (mainly a metal or carbon) in which electric current flows by the movement of electrons.

(18) *Continuity bond*. A bond designed and installed specifically to ensure the electrical continuity of a structure. This may be permanent or temporary, in which latter case it is used to connect two sections of a structure which would otherwise be disconnected during the course of modification or repair (see also definition 9).

(19) *Continuous anode*. A long flexible anode.

(20) *Copper/copper sulphate reference electrode*. A reference electrode consisting of copper in a saturated copper sulphate solution.

(21) *Corrosion*. The chemical or electrochemical reaction of a metal with its environment, resulting in its progressive degradation or destruction.

NOTE. This Code is concerned with corrosion by electrochemical action.

(22) *Corrosion product*. The chemical compound or compounds produced by the reaction of a corroding metal with its environment.

(23) *Corrosion interaction*. 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.

(24) *Crossing point*. A point where two buried or immersed structures cross each other when viewed in plan.

(25) *Differential aeration*. The unequal access of air to different parts of a metallic surface, resulting often in the stimulation of corrosion at areas where access of air is restricted.

(26) *Drainage (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 (see also definition 36).

(27) *Drainage bond*. A bond to effect drainage (see also definitions 26 and 9).

(28) *Drainage tests*. Tests with current 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.

(29) *Driving e.m.f. (galvanic anode system)*. The difference between the structure/electrolyte potential and the anode/electrolyte potential.

(30) *Earth*.

- a. The conducting mass of earth or of any conductor in direct electrical connection therewith.
- b. A connection, whether intentional or unintentional, between a conductor and the earth.
- c. Verb: To connect any conductor with the general mass of earth.

NOTE. 'Ground' is sometimes used in place of 'earth'. Both terms include expanses of natural water.

(31) *Electrode*. A conductor of the metallic class (including carbon) by means of which current passes to or from an electrolyte.

(32) *Electrolyte*. A liquid, or the liquid component in a composite material such as soil, in which electric current flows by the movement of ions.

(33) *Electronegative*. A qualification applied to a metallic electrode to indicate that its potential is negative with respect to another metallic electrode in the system.

(34) *Electrosmosis*. The passage of a liquid through a porous medium under the influence of a potential difference.

- (35) *Electropositive*. A qualification applied to a metallic electrode to indicate that its potential is positive with respect to another metallic electrode in the system.
- (36) *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 (see also definition 26).
- (37) *Galvanic action*. A spontaneous electrolytic cell reaction in which the metallic anode corrodes.
- (38) *Galvanic anode*. An electrode used to protect a structure by galvanic action.
- (39) *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.
- (40) *Holiday*. A flaw, often in the form of a pinhole, in a protective coating.
- (41) *Impressed current*. The current supplied by a rectifier or other direct-current source (specifically excluding a galvanic anode) to a protected structure in order to attain the necessary protection potential.
- (42) *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 (see also definition 45).
- (43) *Interaction test*. A test to determine the severity of corrosion interaction between two buried or immersed structures (see also definition 23).
- (44) *Ion*. An atom, or group of atoms, carrying a charge of positive or negative electricity.
- (45) *Isolating joint*. A joint or coupling between two lengths of pipe, inserted in order to provide electrical discontinuity between them (see also definition 42).
- (46) *Joint cathodic protection scheme*. A scheme in which different structures, usually separately owned, are bonded together and protected by a common cathodic protection installation.
- (47) *Neutral*. Containing equal concentrations of hydrogen ions and hydroxyl ions (see also definition 49).
- (48) *Passivity*. The state of the surface of a corrodible metal or alloy where its electrochemical behaviour becomes that of a less reactive metal and its corrosion rate is reduced. This is generally the result of protective film formation.
- (49) *pH value*. A logarithmic scale used to indicate the relative concentrations of hydrogen ions and hydroxyl ions in an electrolyte (see Appendix A).
- (50) *Pitting*. A non-uniform corrosion of metal whereby a number of cavities, not in the form of cracks, are formed in the surface.
- (51) *Polarization*. Change in the potential of an electrode as the result of current flow.
- (52) *Polarization cell*. A device, inserted in the earth connection of the sheath and/or armouring of an electric power cable, that drains only a small current from the source used to provide cathodic protection for the cable but conveys to earth the full fault current of the cable.
- (53) *Primary structure*. A buried or immersed structure cathodically protected by a system that may constitute a source of corrosion interaction with another (secondary) structure.
- (54) *Protected structure*. A structure to which cathodic protection is applied.
- (55) *Protection current*. The current made to flow into a metallic structure from its electrolytic environment in order to effect cathodic protection of the structure.
- (56) *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.
- (57) *Reaction (anodic, cathodic)*. A process of chemical or electrochemical change, particularly taking place at or near an electrode in a cell.
- (58) *Reactive anode*. Synonym for 'galvanic anode' (see definition 38).
- (59) *Polarized drainage (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.

CP 1021 : 1973

(60) *Redox potential*. The potential taken up by a platinum electrode in a given aqueous environment in the absence of applied current (see A 2 of Appendix A).

(61) *Reference electrode*. An electrode the potential of which is accurately reproducible and which serves as a basis of reference in the measurement of other electrode potentials.

(62) *Remedial bond*. A bond established between a primary and a secondary structure in order to eliminate or reduce corrosion interaction (see also definitions 23 and 9).

(63) *Resistance bond*. A bond either incorporating resistors or of adequate resistance in itself to limit the flow of current (see also definition 9).

(64) *Sacrificial anode*. Synonym for 'galvanic anode' (see definition 38).

(65) *Safety bond*. A bond connecting the metallic carcase of a piece of electrical apparatus with earth, in order to limit the rise in potential of the carcase above earth caused by the passage of any fault current or excessive leakage current, and so reduce the risk of electric shock to anyone touching the carcase.

(66) *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.

(67) *Secondary structure*. A buried or immersed structure that may be subject to corrosion interaction arising from the cathodic protection of another (the primary) structure.

(68) *Sensing electrode*. A permanently-installed reference electrode used to measure the structure/electrolyte potential and to control the protection current.

(69) *Silver/silver chloride electrode*. A reference electrode consisting of silver, coated with silver chloride, in an electrolyte containing chloride ions.

(70) *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 one standard atmosphere.

(71) *Stray current*. Current flowing in the soil or water environment of a structure and arising mainly from electric power or traction installations. Such stray current can pass from the environment into the structure and vice versa.

NOTE. Stray alternating current is not considered in this Code.

(72) *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.

(73) *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. They reduce sulphates in their environment, with the production of sulphides.

(74) *Unprotected structure*. A structure to which cathodic protection is not applied.

1.3 Exchange of information

The application of cathodic protection 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. Except, therefore, in the case of installations the effects of which will be localized (particularly those for the internal protection of plant) the owners of any other structure or plant near the protection installation or protected structure should be consulted as further discussed in Section 8. There are also possibilities of electrical interference with telecommunication circuits and of causing false operation of railway signalling circuits.

Cathodic protection equipment may give rise to certain hazards, particularly in areas where there are flammable liquids or gases. In such cases, consultation is necessary. Where the equipment is required to be flameproof, the relevant provisions of CP 1003 apply (see 1.4 and 10.6.2).

1.4 Related Codes of Practice

Reference may be made to the following codes:

- CP 326 The protection of structures against lightning
- CP 1003 Electrical apparatus and associated equipment for use in explosive atmospheres of gas or vapour other than mining applications
- CP 1013 Earthing
- CP 2008 Protection of iron and steel structures from corrosion.

1.5 Related British Standards

The quality and standard of performance of apparatus and other parts of an installation should be not inferior to that specified in the appropriate current British Standard. The list set out below, which is not exhaustive, should be observed as applicable.

- BS 89 Direct acting electrical indicating instruments
- BS 148 Insulating oil for transformers and switchgear
- BS 171 Power transformers
- BS 1035-40, 1172-74, 1861, 1954 Raw copper
- BS 1036 Electrolytic tough pitch high conductivity copper
- BS 1037 Fire refined tough pitch high conductivity copper
- BS 1259* Intrinsically safe electrical apparatus and circuits for use in explosive atmospheres
- BS 2709 Electrical performance of semiconductor rectifiers (metal rectifiers)
- BS 2914 Surge diverters for alternating-current high-voltage power circuits
- BS 3535 Safety isolating transformers for industrial and domestic purposes
- BS 4147 Hot applied bitumen based coatings for ferrous products
- BS 4164 Coal tar based hot applied coating materials for protecting iron and steel, including suitable primers where required
- BS 4515 Field welding of carbon steel pipelines
- BS 4683 Electrical apparatus for explosive atmospheres
Part 2. The construction and testing of flameproof enclosures of electrical apparatus

2. General principles

2.1 Introduction

This Section is intended to give information on the electrochemical aspects of corrosion and cathodic protection as an aid to the understanding of the rest of this Code. There is, inevitably, some oversimplification; a number of reference books dealing with the subject are included in the Bibliography.

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

2.2.1 The nature of metallic corrosion. When a metal corrodes in contact with an electrolyte, neutral atoms pass into solution by forming positively charged ions. Excess negative electrons are left behind. For example, in the case of iron:



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 negatively charged electrons into the metal. Any area at which current flows in this direction is referred to as an anodic area. The metallic ions may react with negative ions in the solution to give insoluble corrosion products (e.g. rust in the case of steel). Such reactions do not materially affect the argument which follows except in cases when the corrosion product is such as to stifle further attack (see 2.2.4).

The electric circuit is completed by the passage of current from solution to metal at other areas known as cathodes. Various reactions occur at cathodes: these do not, in general, cause corrosion (see 2.2.5).

Because the same number of electrons are released for each atom of the metal going into solution, the current is proportional to the corrosion rate. For example, in the case of iron or steel, two electrons flow for

* In course of revision as a part of BS 4683.

CP 1021 : 1973

each atom going into solution, as shown in Equation 1, and a corrosion current of one ampere corresponds to loss of about 9 kg per year.

2.2.2 Polarization. The potential difference between any metal and the surrounding electrolyte varies with the density and direction of any current crossing the interface. This variation is referred to as polarization. The relationship between potential and current may be determined by an arrangement as shown in Fig. 1a. It is not necessarily linear (see Fig. 1b). The section Z-A of the curve corresponds to corrosion and the more positive the potential the greater the corrosion rate. In practice it is difficult to draw firm conclusions as to the corrosion rate from measurement of the potential difference between metal and solution or soil because the shape of the curve and the potential corresponding to zero current flow both vary according to the properties of the surrounding electrolyte. However, it will be seen that any current flow which makes the potential more positive, normally increases the probability that corrosion will occur. Conversely, changing the potential in the negative direction reduces the corrosion rate and may prevent corrosion entirely.

The way in which the potential difference between a metal and the surrounding electrolyte is measured should be specified. If a metal electrode in direct contact with the electrolyte is used, the result will depend, to some extent, on the effect of the electrolyte on the particular metal chosen. For this reason a reference electrode, e.g. one of several types described in 9.2.1, should be used and the type of reference electrode should be stated when any results are quoted.

2.2.3 Formation of cells. Suppose that potentials of two different metals with respect to a solution are measured with the arrangement shown in Fig. 2, the switch S being open, and the metal marked A 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 C acts as cathode. Metals and conducting materials commonly used are listed below in such order that each normally acts as 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 the connection of magnesium to iron results in a cell in which the magnesium acts as anode and the iron as cathode.

Cells may also arise due to differing properties of the electrolyte in contact with different parts of the same metal surface. Thus, increased concentration of oxygen tends to make the potential of a metal more positive so that variation of soil density and porosity is a common cause of corrosion cells. Arrangements giving rise to such cells are shown in Fig. 3. The size of the cells may vary greatly. In Fig. 3c, for example, the anodic area may be small, the resultant pitting can, however, lead to rapid penetration.

For simplicity let anodic and cathodic areas be shown separately as in Fig. 2. It will be recalled that the anode was the electrode which, with the switch open, had the more negative potential with respect to the solution. If there is resistance in circuit this will still be true, even with the switch closed although the difference in potential will be smaller. This will also be true in cases such as in Fig. 3a in which anode and cathode are parts of the same metal surface in contact with different environments. If the total resistance in the circuit is low there will be little difference in the metal/electrolyte potential at the anodic and cathodic areas but corrosion will occur at the former, the potential at the anodic area being more positive than it otherwise would be due to the current flowing in the cell. This illustration has been included to emphasize the difficulty of determining whether corrosion is occurring by measuring the metal/soil potential without having other information.

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 films. The metals titanium and tantalum form highly resistant and adherent films and can therefore withstand strongly positive potentials without corroding.

2.2.5 Reactions at cathodic areas

The following are among the most common reactions that occur at cathodes:



The first of these reactions is favoured by acidity (excess of hydrogen ions) while the second is favoured by presence of dissolved oxygen. Both tend to make the solution near the cathode alkaline (excess of hydroxyl ions over hydrogen ions: see Appendix A). In contrast to the anodic reaction (e.g. Equation 1), cathodic reactions do not involve the passage of metal into solution; hence, in general, corrosion does not occur at cathodic areas.

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).

Although, as previously indicated, the reactions occurring at cathodes do not directly result in corrosion, it should be noted that the environment of the metal is altered, for example it becomes more alkaline. 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 implies the existence of anodic and cathodic areas (see Fig. 4a). In applying cathodic protection, a current (I' in Fig. 4b) is superimposed in such a direction that the structure to be protected acts as a cathode. If the current is sufficient, no part of the structure acts as anode. This entails the use of an auxiliary anode. If this anode is of a material such as magnesium, the protection current will flow due to the e.m.f. arising from the cell formed. Alternatively, the e.m.f. may be derived from a separate direct-current source, giving a wide choice of materials for the auxiliary anode including some which are not consumed.

In Fig. 4b, the anodic area (A) has been shown separated from the cathodic area (C) in order that the currents to the two areas can be seen. The criterion for cathodic protection is that the current flowing in the anode circuit is reduced to zero or reversed. However, anodes and cathodes are often parts of the same metallic surface (as shown in Fig. 3) and the individual anodic areas may be small. It is thus impossible, in most cases, to confirm that cathodic protection has been achieved by measuring the relevant current. For most of the metals commonly encountered, however, it is possible to state values of metal/electrolyte potential at which corrosion does not occur in environments such as soil or natural waters.

2.3.2 Cathodic protection criteria. Typical figures for the average current density required for cathodic protection are quoted in later parts of this Code. It is, however, stressed that average figures provide general guidance only. It is shown in 3.3 that the potential change, and hence the local current density, resulting from a practical cathodic protection installation, may vary considerably over the surface to be protected in a way that depends on the geometry of the installation, the resistivity of the water or soil, and the immediate environment of the structure.

Table 1 lists the protection potentials for full protection of various metals, measured against different standard reference electrodes.*

The differences in the potentials shown in the various columns arise from differences in the reference electrodes (see 9.2.2). Cathodic protection is achieved by ensuring that the metal/electrolyte potential is at, or more negative than, the value stated in Table 1 (see, however, Note 2 relating to aluminium).

* See Items 36, 37, 38 and 39 of the Bibliography.

CP 1021 : 1973

Table 1. Potentials for cathodic protection (volts)

Metal or alloy	Reference electrode			
	Copper/ copper sulphate	Silver/silver chloride/sea-water	Silver/silver chloride/saturated KCl	Zinc/(clean) sea-water
Iron and steel				
a. aerobic environment	—0.85	—0.8	—0.75	+0.25
b. anaerobic environment	—0.95	—0.9	—0.85	+0.15
Lead	—0.6	—0.55	—0.5	+0.5
Copper-based alloys	—0.5 to —0.65	—0.45 to —0.6	—0.4 to —0.55	+0.6 to +0.45
Aluminium				
a. positive limit	—0.95	—0.9	—0.85	+0.15
b. negative limit (see Note 2)	—1.2	—1.15	—1.1	—0.1

NOTE 1. All potentials have been rounded to the nearest multiple of 0.05 V. The figures for electrodes in which sea-water is the electrolyte are valid only if the sea-water is clean, undiluted and aerated.

NOTE 2. *Aluminium*. It is not at present possible to make firm recommendations for the protection of aluminium since this metal may corrode if made too strongly negative (see 2.2.5). There are indications that corrosion can be prevented if the potential is maintained between the limits shown in the Table. Alternatively, it has been recommended in the case of pipelines to make the metal/electrolyte potential more negative than its original value by 0.15 V*.

NOTE 3. *Lead*. In alkaline environments, lead may occasionally be corroded at strongly negative potentials.

NOTE 4. *Stainless steels*. In many environments, stainless steels will not require any form of protection. In some cases, anodic protection is used (see 7.3.1).

Stainless steels are, however, often susceptible to crevice corrosion. A crevice may be encountered between two metals, e.g. at a riveted or bolted seam, or between a metal and non-metal or at a gasketed joint. Crevice attack is a particular form of a 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 above is necessary. Difficulty can, however, arise if the crevice can seal itself off from the environment; the protective current cannot flow to the seat of the attack which may proceed unabated.

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

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

NOTE 5. *Steel in concrete* (see also 8.3.3.2). If steel, whether buried or immersed, is only partially enclosed in concrete, its protection potential is determined by the exposed metal and is as indicated in Table 1. Iron or steel fully enclosed in concrete free from chlorides would not normally require cathodic protection because of the alkaline environment. For circumstances where cathodic protection needs to be applied, for example because there is doubt as to adequacy of the concrete cover or to provide very high reliability, it has been suggested that potentials less negative than are normally required for the protection of steel may be suitable‡.

3. Application: considerations applicable to most types of structure

3.1 Introduction

This Section indicates the range of application 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. Sections 4 to 7 deal with particular classes of structure (including ships) or plant.

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.

* Report of N.A.C.E. Technical Unit Committee T-2M Materials Protection, October 1963, p. 106.

† See Item 30 of the Bibliography.

‡ See Item 31 of the Bibliography.

However, economic considerations 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. Thus, a certain amount of attack in the form of pitting may be tolerable on some structural members while the same severity of attack would cause failure of a pipe. If the consequences of penetration by corrosion are important, for example hazards due to leakage of a 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 cathodic protection would be regarded as economical even under otherwise unfavourable circumstances.

The large variety of structures to which cathodic protection has already been applied can be seen from the Introductions of Sections 4 to 7.

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 being that the structure/electrolyte potential is, at all positions, more negative than the appropriate protective potential given in 2.3.2. Fig. 5a represents, in outline, the system required, 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 the lower parts of the figure. The following factors tend to increase the non-uniformity of the cathodic protection:

- (1) small separation between the anode and the structure (particularly if the electrolyte resistivity is high),
- (2) high resistivity of soil or water (particularly if anodes are close to the structure),
- (3) high current density required to protect the structure (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 anaerobic bacteria (see 2.2.5)),
- (4) high electrical resistance between different parts of the structure.

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; only a small proportion of the surface may require protection.

Normally, however, the whole of the metal surface is to be protected and non-uniformity, as shown in Fig. 5, 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, i.e. galvanic anodes and impressed current, are described in 3.5 and 3.6 and their characteristics are compared in 3.7. It is sometimes possible (see 4.2.4) to make use of current flowing in the soil due to the operation of traction systems.

Economical design of 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

CP 1021 : 1973

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 7). 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 the 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 8). There are also some secondary effects of cathodic protection (see 3.8.1) which need to be taken into account.

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 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 (see 3.3). 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 structure and return to the electrolyte (see Section 8). 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 area 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. As indicated in 3.3, the fact that the current is spread more uniformly may reduce the number of points at which cathodic protection need be applied.

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, or materials such as bitumen and coal tar which are often reinforced with glass fibre or other fibrous material. Plastics sheet or tapes may also be used for certain structures. The most suitable form of coating depends on the type of structure and its environment; more particular information is given in Sections 4 to 7. 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 potential gradients in the surrounding soil thereby decreasing interaction with neighbouring buried structures (see Section 8).

The protection current, particularly if strongly negative potentials are used, may produce sufficient alkali (see 2.2.5) to affect the coating adversely. 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 7. It is, however, possible to give only general information in respect of coatings. If, in a particular case, the coating performance was critical, it would be desirable to determine the properties by test beforehand.

Useful information on coatings will be found in CP 2008.

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

Metal spraying is not treated as a coating for the purposes of this Code; its use in conjunction with cathodic protection is unlikely.

3.4.3 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 such a case, 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 Section 8). 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 10.6.2 (5)). They should not be installed in above-ground situations where concentrations of flammable gas or vapour occur (see 10.6.2 (4)).

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 8.2. 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 8.3.4.3 to prevent possible damage.

With equipment containing electrolytes, corrosion could similarly occur on the inner surface of the unprotected section. With highly conducting 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 8.3.6.3).

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 9 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 7.

3.5 Galvanic anode installations

3.5.1 Method. As indicated in Section 2, cathodic protection can be achieved by burying or immersing, in the electrolyte that is in contact with the metal to be protected, an electrode that is more electronegative than the metal to be protected and connecting it to the latter. Typical arrangements are illustrated in Figs. 6 to 10.

The current available from a single anode in a given electrolyte is limited by the relatively low driving e.m.f. obtainable (see 3.5.2) and the size that can be handled conveniently. Use of the method is therefore generally limited to the protection of small areas of metal unless the structure is well coated. 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 Fig. 6a and c) or may be attached directly to the surface of the metal (see Figs. 9 and 10). 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. Direct attachment to the metal is satisfactory if the electrolyte resistivity is low and may be more convenient in some cases.

3.5.2 Galvanic anode design. The resistance associated with an anode depends upon electrolyte resistivity and on the size and shape of the anode*. 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 (see Fig. 8). Buried anodes can be surrounded with

* See Item 34 of the Bibliography.

CP 1021 : 1973

a backfill that has a lower resistivity than the soil to reduce the resistance (see Figs. 6a and 7). The output also depends on the driving e.m.f. and thus upon the anode material (see 3.5.3).

Galvanic 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 shaped so that a mechanical key to the surrounding metal is provided and, in the case of zinc anodes, should be hot-dipped zinc-coated.

The inserts may project to provide lugs for attaching the anodes by welding or bolting. The former method gives the better 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 so designed as to allow for almost complete consumption of the anode material before disconnection occurs.

Some form of disconnection box, to enable the current to be interrupted or measured, is essential in certain applications. Such connections and the connection to the structure to be protected should be securely made and have low electrical resistance.

3.5.3 Anode materials. Alloys used for galvanic anodes are based on magnesium, zinc or aluminium.

The performance of any alloy varies with composition and operating conditions such as temperature, salinity and current density but the values given in Table 2 are typical for sea-water.

Table 2. Typical information for galvanic anode materials in clean sea-water

Alloy	Potential with respect to Ag/AgCl electrode under typical working conditions	Approx. practical consumption rate
	V	kg/ampere-year
Magnesium (Mg-Al-Zn)	-1.5 to -1.7	8
Zinc (Zn-Al-Cd)	-1.05	12
(Zn-Hg)	-1.05	12
Aluminium alloys:		
Al-Zn	-0.97	4 to 8
Al-Zn-Sn	-1.1 to -1.15	4 to 9
Al-Zn-Hg	-1.05	3.5 (approx.)

NOTE. Performance in soils is variable and is generally less favourable than indicated by the figures above. In fact, zinc and aluminium are not usually employed in soils for this reason. Performance in sea-water may also be affected by pollution.

3.5.3.1 Magnesium alloys. These usually contain about 6 % aluminium and 3 % zinc; 0.15 % manganese may be added to combat the effects of heavy-metal impurities. Magnesium alloys are used extensively where a high driving e.m.f. 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 waters. Their low density and high driving e.m.f. make them particularly useful for 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 10.6.1). Special requirements relating to the use of magnesium anodes in ships' tanks are given in 5.4.4.1.

3.5.3.2 Zinc. Commercial quality zinc is of little use as an anode material because of excessive polarization due to iron present as an impurity but anodes cast from high-purity zinc containing less than 0.0015 % iron perform satisfactorily. Alloys based on less pure zinc have been developed in which the iron impurity is inactivated by addition of aluminium. Typical alloys contain 0.5 % aluminium with up to 0.1 % silicon and/or cadmium; other alloys containing small additions of certain other activating agents such as mercury have been developed for applications where anode polarization may be a problem. Zinc is particularly useful in sea-water applications, e.g. for the protection of ships' hulls where its low driving e.m.f. 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 5.2.4.1). Zinc anodes do not normally evolve hydrogen nor is there a risk of thermite sparking.

3.5.3.3 Aluminium. Several alloys based on aluminium have been developed and increasing use is being made of these materials particularly in sea-water applications. Binary alloys with zinc contain 3 % to 7 % zinc. Their performance depends on the purity of the aluminium used, iron being a particularly harmful impurity. A low yield and polarization, due to the development of a corrosion product with high electrical resistance, may result if aluminium of less than 99.8 % purity is used in such alloys. Alloys based on superpure aluminium give high yields and exhibit less polarization but are more expensive. The low driving e.m.f. of these binary alloys limits their use to sea-water but the current will tend to be even more self-controlling than is the case with zinc.

Ternary alloys containing zinc and tin and based on selected commercial purity aluminium have also been developed. A typical composition is 5 % zinc and 0.08 % tin in 99.8 % pure aluminium. These alloys can give a slightly higher driving e.m.f. than zinc alloys and high yield per unit weight of metal depending upon the detailed composition and the effectiveness of heat treatment. Applications of these alloys have been largely confined to sea-water.

There are also aluminium alloys that contain mercury and zinc and have acceptable outputs. Similar alloys containing mercury, zinc and magnesium may give more negative potentials but somewhat lower yields. Aluminium-zinc-indium alloys are also available.

There are indications that the efficiency of some aluminium anodes, for example one type of anode containing zinc and tin, drops off considerably at low temperatures (5 °C or less) due to intergranular corrosion. Full information is not available but it was found that a type of anode based on zinc and mercury operated satisfactorily at similar temperatures.

Hydrogen evolution from aluminium alloys is usually slight but explosion hazards should always be borne in mind because of the risk of thermite sparking from impact of light alloys with rusty steel (see 10.6.1).

3.6 Impressed current installations

3.6.1 Methods. Fig. 11 shows typical impressed current cathodic protection installations and will be understood from the discussion in 3.3. The selection of anode materials, and the design of the power source are discussed in the following sections.

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 ampere-year per kilogram 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.

More resistant materials are available but these are generally more expensive. The relative importance of cost and resistance to corrosion 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 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.

Graphite can be used as an anode material and operates at a current density of 2.5 A/m² to 10 A/m². It is normally impregnated with wax or a synthetic resin to fill the pores and if this treatment is satisfactory the consumption rate can be appreciably lower than that of iron or steel. Chlorine is particularly aggressive towards graphite anodes.

Alloys are also available that resist attack, as long as the current density at the surface is not excessive, because of the formation of a film of corrosion product which is sufficiently conducting for satisfactory operation to continue. For example, high-silicon cast iron will operate at current densities in the range

CP 1021 : 1973

5 A/m² to 50 A/m² with consumption rates in the range 0.2 kilogram per ampere-year to 1 kilogram per ampere-year, according to anode shape and conditions. It is suitable for buried or immersed conditions.

Lead alloys of various compositions are used in sea-water applications. These anodes rely on the formation of lead peroxide film which constitutes a conducting medium that does not deteriorate rapidly and is self-repairing. For example, lead alloyed with 2 % silver can operate at current densities up to 300 A/m². In another type, the lead is alloyed with 0.1 % silver and 0.01 % tellurium. Micro-anodes of thin platinum wire are inserted into the lead surface and in the commissioning periods secondary currents flow from the micro-anode to the lead surface which then produce a film of lead peroxide. This mechanism operates at a current density greater than 250 A/m². Such anodes can be operated at current densities up to 2000 A/m². Other lead alloys are available and the operating conditions may be affected by the type of alloy. Lead alloy anodes are unsuitable for installation in mud.

Platinum and platinum alloys are too expensive for use as anodes except in special applications. They are, however, frequently used in the form of a thin layer (about 0.0025 mm thick) on a titanium or tantalum base. These latter metals are used as the base 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 platinizing can be confined to those areas where current transfer is required.

Anodes using these materials can operate satisfactorily at current densities up to 1000 A/m² of platinized surface but current densities of 500 A/m² to 700 A/m² are preferable as a basis for design. In electrolytes containing chlorides, the oxide film may break down if the voltage exceeds 8 V. Higher voltages may be permissible 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. Anode to electrolyte voltages need, therefore, to be suitably limited and full-wave, rather than half-wave, rectification is preferable.

3.6.2.2 Design and installation of anodes and groundbeds. Whether the 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.

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 close 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 not 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 10.6.3).

3.6.3 Source of power

3.6.3.1 Transformer and rectifier unit. Where a suitable a.c. supply is available, a transformer and rectifier unit is normally used as the source of power, although other sources can be used.

The d.c. output voltage should be adjustable (see 3.6.3.2). In the case of an a.c. mains supply, this may be effected by providing a range of tapings on the transformer. In certain applications transformer/rectifiers having an adjustable constant current characteristic can be used with advantage. Rectifiers are usually of the selenium, silicon or germanium types. Since the loading is continuous, efficiency is important and especially the maintenance of efficiency throughout the lifetime of the plant. The equipment should conform with BS 148, BS 171 and BS 2709 as applicable*.

The whole assembly, which may be floor-mounted, wall-mounted or pole-mounted, is often required to be weatherproof and sometimes flameproof (see 10.6.2).

* Terminal markings are given in these standards for the relevant piece of apparatus.

3.6.3.2 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 11.6.2) 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, an ammeter to measure total output current, and an ammeter in each anode circuit if a number of anodes are 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 later, 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, if the variations in conditions are considerable, and frequent adjustments are essential to maintain structure/electrolyte potentials within the range set by the protection requirements and the potential at which coating damage is possible.

For immersed conditions, the silver/silver chloride electrode or, if applicable, the zinc/sea-water electrode (see 9.2.1), are most suitable for permanent mounting and can be used for manual control or as sensing electrodes in an automatic system. A single electrode is often relied on for controlling the output of a particular anode and its position is 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 also required 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 sensing electrode, i.e. the reference electrode that is to be used for control.

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

(1) *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.

(2) *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. Each control unit can be mounted in any convenient position near the anode that it controls or the control units can be grouped together. Integral screw-in units (referred to as 'automatic anodes') are also available*. These comprise a cathodic protection anode, a sensing electrode and a solid state control circuit.

3.6.3.3 Supplies to transformers and rectifier unit. In rural situations, the transformer and rectifier unit will normally be supplied from an overhead line. In planning the groundbed and any necessary extension to the

* See Items 23 and 24 of the Bibliography.

CP 1021 : 1973

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 polyvinylchloride 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 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.

3.7 Comparison of the various systems

The advantages and disadvantages of the galvanic anode and impressed current methods are set out in Table 3. A further method known as electric drainage is described in 4.2.4. It is applicable only to structures affected by stray currents flowing in the soil, and may have advantages in suitable cases.

3.8 Special considerations

3.8.1 Secondary effects of cathodic protection. It will have been noted from 2.2.5 that 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. The effects that may occur are described in the following paragraphs.

(1) Alkalinity may cause the deterioration of paints. The effect 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, 5.2.2.2).

(2) 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.

(3) Aluminium is corroded in alkaline environments and can therefore be cathodically protected only if the potential is maintained within certain limits (see 2.3.2).

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

(5) Hydrogen evolved at strongly negative potentials may create an explosion hazard in enclosed spaces (see 10.5 and 10.6).

(6) Hydrogen embrittlement of high tensile steel is a possible danger.

(7) Hydrogen produced at flaws in a coating may progressively detach the coating from the surface of the metal.

(8) 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 during 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.

(9) 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 10.6.3).

3.8.2 Effects of stray currents from protection installations. Where a protected structure, or the anode(s) or groundbed(s), lies 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 others. The secondary structures may corrode at these latter points (see Section 8).

3.8.3 The avoidance of damage or hazard due to overvoltages. 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 is 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.

Table 3. A comparison of galvanic anode and impressed current systems

Galvanic anodes	Impressed current
(1) They are independent of any source of electrical 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 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) Requires generally a small total number of anodes.
(7) They are less likely to affect any nearby neighbouring structures because the output at any one point is low.	(7) Requires the effects on other structures that are near the groundbed of protected structures to be assessed but interaction is often easily corrected, if necessary.
(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 galvanic 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 ships' hulls.	(9) Allows of more compact anodes by the use of suitable materials: 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, so that polarity is reversed, can accelerate corrosion.

CP 1021 : 1973

3.8.3.1 Damage to cathodic protection equipment by overvoltages. The groundbed of a cathodic protection system will often be the best available connection to earth in a particular locality and this may result in the associated equipment being subjected to overvoltages or excessive current* that originate either from faults on power equipment or lightning as follows:

(1) *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†.

(2) *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 lightning considerations is given in CP 326. Requirements in relation to fault conditions on electricity power systems are given in 8.3.5.1(2) and 10.4.

3.8.3.2 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 CP 326. That Code requires, in 209b.(iv), 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 breakdown through the soil as a result of a lightning discharge with consequent risk of damage to the pipes, cables etc.

The installation of isolating joints for cathodic protection purposes where buried structures approach terminal or other installations clearly runs counter to these requirements 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 flash-over of the isolating joint, with consequent risk of damage or explosion.

To satisfy the opposing requirements, the isolating joints should 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.

3.8.3.3 Buried structures in the vicinity of a lightning protection system. Where the structures to be cathodically protected pass close to, but are not already incorporated in, a lightning protection system installed to protect some other structure or installation, the question may arise as to the minimum distance between a lightning protection earth and other buried metalwork, for example the groundbed of a cathodic protection system, beyond which the need for bonding as mentioned in 3.8.3.2 can be discounted.

This distance, S , can be estimated from the relationship $S = \frac{iR}{E}$ where i is the crest value of the lightning current discharged through an earth termination of resistance, R , and E is the impulse breakdown strength of the soil.

Although no systematic tests have been carried out, tests on a variety of soil specimens have indicated values of E to be from 0.2 kV/mm to 0.5 kV/mm. Assuming the lower of these, together with a current of 200 kA (an exceptionally severe lightning current), separation, S , (in metres) is given by $S = R$ where R is the resistance of the earth electrodes before any bonding to other structures has been carried out. CP 326, which should be consulted, requires that the resistance to earth of the whole lightning protection system should be not more than 10 Ω ‡.

3.9. Testing

Tests and testing methods to be carried out during the design and commissioning periods are discussed in Sections 9 and 11. The sequence of tests should be commenced as soon as possible after commissioning.

* See Item 14 of the Bibliography.

† 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).

‡ See also Item 35 of the Bibliography.

It should be particularly noted 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 (12) of Table 3).

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 oil-storage tank bottoms. The general information will be of use should exceptionally aggressive conditions lead to a requirement for the cathodic protection of structures such as buried storage tanks or foundation piling but insufficient information on actual installations is available to enable specific advice to be given.

4.2 General

4.2.1 Factors affecting design. The following factors affect the application of the principles outlined in Section 3:

(1) Variations of conditions affecting the cathodic protection of buried structures are generally slow. Manually adjusted control equipment is therefore usually sufficient (see 3.6.3.2). Automatic control may, however, be required if the structure to be protected is affected by stray currents from electric traction systems; the control system has to be quick acting. Suitable equipment is available (see (1) and (2) of 3.6.3.2). The position of the sensing electrode should be carefully chosen.

(2) The nature of the coating and the method of application will determine the most negative potential that can be applied without likelihood of coating damage. Conventional limits of structure/soil potential for coal tar and asphaltic pipeline enamels are -2.0 V with an absolute minimum of -2.5 V (copper/copper sulphate reference electrode). Other coatings may be more susceptible to overprotection and the structure/soil potential may need to be limited to less negative values (see also 3.8.1).

(3) For steel structures, the usual criterion of protection is -0.85 V relative to a copper/copper sulphate reference electrode (see 2.3.2). Where anaerobic conditions occur and sulphate-reducing bacteria may be present, a more negative value of -0.95 V should be adopted.

(4) Special backfills can be used to assist in obtaining a low resistance between anodes and the soil.

(5) Special care is needed to avoid accelerating the corrosion of other buried structures by interaction (see Section 8).

(6) For buried structures near electric traction systems, electric drainage can be used (see 4.2.4).

4.2.2 Galvanic anode installations. Magnesium anodes (see 3.5.3) are widely used but zinc anodes are sometimes employed in very low resistivity soils, i.e. below $3 \Omega \text{ m}$. Although magnesium anodes have a greater driving e.m.f., their use is normally limited to soils having a resistivity below $50 \Omega \text{ m}$ with a possible upward extension, in favourable circumstances, to about $80 \Omega \text{ m}$. 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*.

If a special backfill is used to reduce the resistance between galvanic anodes and the soil it should be an electrolyte having a suitable resistivity and not aggressive with respect to the anode material. A typical specification is powdered gypsum 70 %, granular bentonite 25 %, sodium sulphate 5 %. The use of a special backfill is not normally considered unless the soil resistivity exceeds about $5 \Omega \text{ m}$.

Magnesium anode installations are normally designed for an anode life in excess of 5 years. It is, however, usual to check performance by potential and current measurements (see 11.4) at regular intervals so that repairs and replacements may be effected. Appropriate measuring points should be provided (see 11.3.2.1).

Only slight interaction effects are encountered with galvanic anode systems (see 8.3.4.2) 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

* See, for example, Items 7, 9, 21, 22, 25 and 34 of the Bibliography.

CP 1021 : 1973

material. This is because conduction from the anode to the coke is largely by movement of electrons rather than by electrolytic processes. 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 solutions, the reaction at a non-consumable anode gives rise to the production of chlorine, which 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 number of anodes can be installed in a group and connected in parallel. Such an assembly is referred to as a groundbed (see definition 39).

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 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*.

It may be worthwhile to connect the individual anode cables together at a junction box installed in an accessible position so that the anodes can be tested individually.

Anodes or groundbeds should be sited where the soil resistivity is as low as is 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 8).

If the above requirements cannot otherwise be met, consideration should be given to installing the anodes in holes bored to a considerable depth, i.e. 15 m to 30 m.

4.2.4 Electric drainage. In d.c. traction systems, the negative of the d.c. supply is usually connected to the running rails which are in electrical contact with the soil. Thus the soil will provide an additional path, in parallel with the track, for current flowing from the traction unit towards the point of supply. Particularly in the case of extensive structures such as pipelines or cables, part of the current flowing in the soil may be picked up in one area and discharged in another, leading to accelerated corrosion.

This can be prevented by bonding the pipeline or cable sheath and armouring to a return rail at the most negative portions of the track, i.e. near sub-stations or where negative feeders are connected to the rails. The bonding cable will then carry most of the return traction current 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 'electric drainage' or 'drainage'.

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 authorities.

The electric drainage method can be applied in all circumstances because of the likelihood of current reversals in the drainage bond; a rectifier (or other unidirectional device) is therefore usually provided as illustrated in Fig. 15a. This is referred to as 'polarized electric drainage'.

The track voltage may attain relatively high values and it may be necessary to protect the rectifier and bond against excessive currents by means of suitable series resistors and/or inductors and overload circuit-breakers or fuses and by providing more than one drainage connection (see Fig. 15b).

For railway signalling purposes, a relay and power supply are usually connected between the two 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 each signalling section and the traction return current is confined to the other rail. In the second type there is an impedance bond at each end of each track circuit and 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 connection to the rail is made to both rails where there are no track circuits, to the traction return rail only where there are single-rail track circuits, and to the mid-point of an impedance bond where there are double-rail track circuits.

Fig. 15a shows the case with single-rail track circuits, Fig. 15b the case with double-rail track circuits and Fig. 15c the case with no track circuits.

* See, for example, Items 7, 9, 21, 22 and 34 of the Bibliography.

The amount of cathodic protection applied 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-operated cathodic protection rectifier as shown in Fig. 15c. It may be necessary to limit the output from the rectifier by means of saturable reactors or transformers or similar devices.

4.3 Buried 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 metallicity 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 certain types of rubber-sealed joints are discontinuous.

Continuity can be effected by brazing or welding a metal strip or cable of adequate cross-sectional area across each break, taking care that all intermediate parts are connected. Bond resistance should be kept as low as possible.

The bond should be insulated to a level comparable to that of the structure protected. If the metals of the bond and of the structure differ, the vicinity of the junction should, in any case, be coated to eliminate the possibility of electrolytic action in crevices between the bond and the structure; this would not necessarily be prevented by the cathodic protection. 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 heavy currents from external sources (see 3.8.3).

It is often advisable to insert, in selected bonds, a removable link to allow for the temporary insertion of an ammeter for test purposes (see Section 9).

4.3.1.2 Coatings. Buried pipelines are coated to reduce the current density required and to increase the spread of protection and thus to limit the number of points at which cathodic protection must be applied on any particular installation (see 3.4.2).

Suitable types of coating include:

- (1) coal tar or asphaltic enamel, hot applied, usually with glass-fibre reinforcement, and with or without an asbestos felt outer-wrap,
- (2) plastics 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,
- (3) petroleum wax impregnated fabric with a plastics outer sheath,
- (4) extruded high density polyethylene,
- (5) epoxy resins based.

The electrical resistance of a pipeline coating is important where cathodic protection is to be applied: initial resistances in excess of $10\,000\ \Omega\ m^2$ 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 even 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 (see Section 8) to a minimum. This will require close supervision of the application of the coating and of all operations which may cause coating damage and of final 'holiday' detection.

The pipe should, whenever possible, be surrounded with a backfill that is free from stones and carbonaceous material such as coke. If this is impracticable, an additional wrapping of heavy bituminized felt or other suitable material should be provided. Where pipes cross streams or rivers, additional protection, in the form of concrete encasement over the pipe coating, may be required (see 6.3).

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 etc.

CP 1021 : 1973

Long-term experience of the particular coating under comparable conditions is the best guide to the performance likely to be obtained. Pipeline enamels based on coal tar usually exhibit lower long-term water absorption rates than those based on asphalt. Other factors will, however, need to be taken into account in choosing between coal tar and asphaltic enamel for any particular application.

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

(1) CP 2008.

*(2) The Institute of Petroleum Code of Practice for Petroleum Pipelines (Pt. VI of the Model Code of Safe Practice in the Petroleum Industry).

†(3) Institution of Gas Engineers. Communication 690. Transportation and handling of wrapped steel pipes.

‡(4) American Waterworks Association Code No. C.203.

(5) BS 4164.

(6) BS 4147.

(7) BS 4515.

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 equipment such as pumping stations, storage tank bottoms etc., which would constitute a large extra cathodic protection load. 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 pipeline, so confining the cathodic protection to the pipeline (see also (2) of 11.3.3.2).

Consideration should be given to the possibility, already referred to in 3.4.3, that part of the current flowing towards the protected pipeline may flow through equipment that has been isolated and accelerate corrosion. This risk can be reduced by paying special attention to the coating of the pipeline near such equipment and by locating the grounded as distant as possible from such equipment. It is essential that the decision is based on an assessment of the relative costs of providing complete or partial protection and an assessment of the likelihood and consequences of corrosion of the various parts of the isolated equipment. Once the cathodic protection is commissioned, procedures described in Section 8 enable any effects of interaction to be assessed and overcome.

If the pipe contains an electrolyte, there is danger of corrosion being stimulated at the inner surface of the pipe. With weak electrolytes, for example potable waters, it may suffice to coat the pipe internally for at least two diameters either side of the isolating joint. Replacement of a length of pipe by a length of non-metallic piping, if practicable, may be a more economical method.

In the case of highly conducting electrolytes such as sea-water, or brine, it will probably not be feasible to coat or replace a sufficient length of pipe to eliminate the danger of corrosion occurring internally near the flange. The tests to determine the length of pipe that should be treated would be complicated (see 8.3.6.3). Where the provision of an isolating joint is considered to be essential and conditions allow, it may be considered best to install extra-heavy-walled pipe on either side of the joint and to accept the need for periodic inspection and replacement.

Isolating joints for pipelines need to be adequate for the maximum pressure and temperature conditions encountered on the particular installation. The usual method of insulating flanged joints is to employ insulating sleeves on the studs or bolts and insulating washers under the nuts and/or the heads of the bolts, bright mild steel washers being provided to prevent damage to the insulating washers when being tightened. The insulating sleeves and washers are usually of synthetic resin bonded fabric; the insulating gaskets may be of compressed non-graphited asbestos or other suitable material. Wire reinforced gaskets or electrically conducting gaskets are unsuitable.

The internal bore and centralizing of the insulating gasket should ensure that no recess is formed internally, between flanges, in which material that would bridge the insulating gap might accumulate.

* See Item 20 of the Bibliography.

† See Item 28 of the Bibliography.

‡ See Item 29 of the Bibliography.

Under dry conditions, and before connection to other structures on either side, an electrical resistance greater than 1 M Ω should be attainable for pipes of 500 mm diameter or less. Care should be taken to ensure that the testing voltage is appropriate to the intended service conditions.

If isolating joints are installed below ground they should be coated overall with pipeline enamel or other suitable material and have test leads brought to the surface from the pipe on either side. If they are installed above ground, the gap between the flanges should be filled with compound and the outer faces of the flange taped to minimize the possibility of accidental short circuit. Isolating joints should be painted a distinctive colour for identification.

It is preferable to assemble isolating joints and test them both hydrostatically and electrically before they are installed in the pipeline, the isolating joint being supplied with short lengths of pipe so that the joint can be welded into the pipeline without being dismantled. If insulation is being introduced at a pair of flanges already provided in the pipeline, care should be taken to ensure that it is not damaged. In either case, final testing of the isolating joint after assembly will be required. This can usually most conveniently be carried out on commissioning the cathodic protection system by measuring the change of potential across the flange.

The majority of the foregoing also applies to various types of non-flanged, prefabricated isolating joints or couplings which are now becoming available.

Special considerations will apply in cases where it is required to insulate flanges employing ring type joints.

4.3.1.4 Measuring 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 general 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 link boxes during construction at points where the pipeline is near other structures, to assist in subsequent interaction testing (see Section 8).

It is essential that the connection to the pipe be 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, 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 pipe because of the possibility of cracking.

Measuring points on cross-country pipelines should be sited so as to be accessible but unlikely to be damaged, e.g. at field boundaries. If painted identity plates are used where cattle have access, the paints should be non-toxic. 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.

4.3.2 Application to buried pipelines

4.3.2.1 General. The use of galvanic anodes is normally confined to pipelines which have good coatings and are laid in soils with low or moderate resistivity (see 4.2.2).

Impressed current may be used over a much wider range of soil resistivity 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 Galvanic 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 and at such a depth as to obtain permanently damp soil conditions. Interaction with secondary structures may be reduced if anodes are placed 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 8.3.4.2).

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).

CP 1021 : 1973

Galvanic anodes may also be used to provide temporary protection of sections of a pipeline where particularly corrosive conditions exist, e.g. at river estuary crossings, pending commissioning of an overall impressed current system. Similarly they may be installed to provide 'hot spot' protection of an existing line.

4.3.2.3 Impressed current. By employing impressed current, considerable lengths of pipeline may be protected from a single source. Bare pipelines may require equipment every two or three kilometres. 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 (2) of 4.2.1).

The usual source of direct current is a mains-operated transformer/rectifier (see 3.6.3). Where mains power is not available, other sources such as diesel-driven generators, wind-driven generators, generators driven by turbines operated by the fluid in the pipeline, fuel cells, thermo-electric units etc., 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 4.2.4). 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 3.6.3.2) 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 (see 3.6.3.1).

It is essential that interaction effects be taken fully into account and suitable precautions adopted (see Section 8).

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. Pipe sleeves may act as a shield preventing the flow of cathodic protection current to the carrier pipes inside them; their use should, therefore, be avoided where possible*. If, however, their use is mandatory, measures as indicated below should be taken:

(1) *Protection of carrier pipe.* Any section of pipe installed inside concrete or steel pipe sleeves should be coated to at least the same standard as the remainder of the pipeline. If it is feasible to keep the pipe inside the sleeve dry by means of suitable end seals, this will ensure freedom from corrosion. If, however, it is impossible to exclude water, consideration may be given to installing galvanic anodes in the form of magnesium or zinc strip attached to the carrier pipe. The carrier pipe should be supported by insulating centralizers in order to prevent coating damage during installation and, where steel sleeves are used, to prevent electrical contact between pipe and sleeve. Such contact is to be avoided since, unless protection has been provided by galvanic anodes inside the sleeve, the carrier pipe will be left without protection because of the shielding effect of the sleeve. If the sleeve is poorly coated it will also cause a marked increase in the current required for cathodic protection. If insulation is provided, it should be checked before backfilling.

(2) *Protection of sleeve.* If a steel sleeve is used and is insulated from the carrier pipe, corrosion will be accelerated, particularly at the inner surface if moisture has not been excluded from the space between the sleeve and the pipe. If the sleeve is to be cathodically protected, it should if possible be coated to the same standard as the pipeline. The sleeve can be cathodically protected by connecting it to the pipeline through a surface connection box or by means of galvanic anodes. If the sleeve is cathodically protected, it is particularly desirable to safeguard the carrier pipe inside the sleeve either by complete exclusion of moisture or by use of galvanic anodes.

It may be possible to seal the pipe sleeve to the pipe by welding at each end and to fill the annular space with an inert gas, e.g. nitrogen. The sleeve should then be coated externally to reduce the cathodic protection current demand but it would be unnecessary to coat the pipe inside the sleeve.

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.

* See Item 28 of the Bibliography.