Cathodic Protection

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This is an update of a DTI publication first issued in 1981. The new version has been prepared by Eur Ing R. L. Kean of ARK Corrosion Services and Mr K. G. Davies, Corrosion Engineer, under contract from NPL for the Department of Trade and Industry.

1.0 Introduction

This Guide describes the basic principles of cathodic protection, the areas of use, and the general factors to be considered in the choice and design of a system. It gives a basic introduction and simple technical data on cathodic protection. Further assistance and information may be gained from organisations listed in Section 10, various independent or commercial consultants, and product suppliers.

2.0 History

The first reported practical use of cathodic protection is generally credited to Sir Humphrey Davy in the 1820s. Davy's advice was sought by the Royal Navy in investigating the corrosion of copper sheeting used for cladding the hulls of naval vessels. Davy found that he could preserve copper in seawater by the attachment of small quantities of iron, zinc or tin. The copper became, as Davy put it, "cathodically protected". It was quickly abandoned because by protecting the copper its anti-fouling properties became retarded, hence reducing the streamline of the ships, as they began to collect marine growths.

The most rapid development of cathodic-protection was made in the United States of America and by 1945, the method was well established to meet the requirements of the rapidly expanding oil and natural gas industry, which wanted to benefit from the advantages of using thin-walled steel pipes for underground transmission.

In the United Kingdom, where low-pressure, thicker-walled cast-iron pipes were used extensively, very little cathodic protection was applied until the early 1950s. The increasing use of cathodic protection in modern times has arisen, in part, from the initial success of the method as used from 1952 onwards to protect about 1000 miles of wartime fuel-line network. The method is now well established and is used on a wide variety of immersed and buried facilities and infrastructure, as well as reinforced concrete structures, to provide corrosion control.

3.0 The Principles of Cathodic Protection

Metal that has been extracted from its primary ore (metal oxides or other free radicals) has a natural tendency to revert to that state under the action of oxygen and water. This action is called corrosion and the most common example is the rusting of steel.

Corrosion is an electro-chemical process that involves the passage of electrical currents on a micro or macro scale. The change from the metallic to the combined form occurs by an "anodic" reaction:

$$\underset{\text{(metal)}}{M} \rightarrow \underset{\text{(soluble salt)}}{M^{+}} + \underset{\text{(electron)}}{e^{-}}$$

A common example is:

$$Fe \rightarrow Fe^{++} + 2e^{-}$$

This reaction produces free electrons, which pass within the metal to another site on the metal surface (the cathode), where it is consumed by the cathodic reaction. In acid solutions the cathodic reaction is:

$$\underset{\text{(hydrogen ions in solution)}}{2H^{+}} + 2e^{-} \rightarrow \underset{\text{(gas)}}{H_2}$$

In neutral solutions the cathodic reaction involves the consumption of oxygen dissolved in the solution:

$$O_2 + 2H_2O + 4e^{-} \rightarrow \underset{\text{(alkali)}}{4OH^{-}}$$

Corrosion thus occurs at the anode but not at the cathode (unless the metal of the cathode is attacked by alkali).

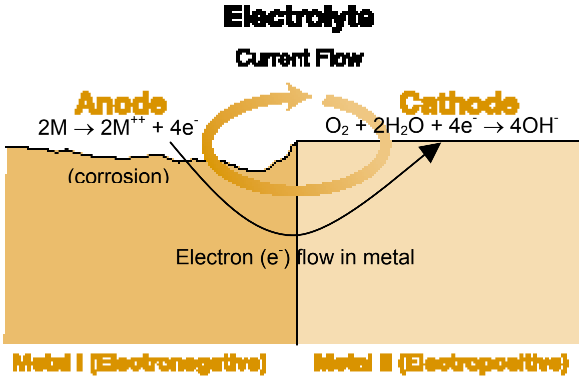

Figure 1. Corrosion cell / Bimetallic corrosion

The anode and cathode in a corrosion process may be on two different metals connected together forming a bimetallic couple, or, as with rusting of steel, they may be close together on the same metal surface.

This corrosion process is initially caused by:

Differerence in natural potential in galvanic (bimetallic) couples.

Metallurgical variations in the state of the metal at different points on the surface.

Local differences in the environment, such as variations in the supply of oxygen at the surface (oxygen rich areas become the cathode and oxygen depleted areas become the anode).

The principle of cathodic protection is in connecting an external anode to the metal to be protected and the passing of an electrical dc current so that all areas of the metal surface become cathodic and therefore do not corrode. The external anode may be a galvanic anode, where the current is a result of the potential difference between the two metals, or it may be an impressed current anode, where the current is impressed from an external dc power source. In electro-chemical terms, the electrical potential between the metal and the electrolyte solution with which it is in contact is made more negative, by the supply of negative charged electrons, to a value at which the corroding (anodic) reactions are stifled and only cathodic reactions can take place. In the discussion that follows it is assumed that the metal to be protected is carbon steel, which is the most common material used in construction. The cathodic protection of reinforcing carbon steel in reinforced concrete structures can be applied in a similar manner.

Cathodic protection can be achieved in two ways:

- by the use of galvanic (sacrificial) anodes, or
- by “impressed” current.

Galvanic anode systems employ reactive metals as auxiliary anodes that are directly electrically connected to the steel to be protected. The difference in natural potentials between the anode and the steel, as indicated by their relative positions in the electro-chemical series, causes a positive current to flow in the electrolyte, from the anode to the steel. Thus, the whole surface of the steel becomes more negatively charged and becomes the cathode. The metals commonly used, as sacrificial anodes are aluminium, zinc and magnesium. These metals are alloyed to improve the long-term performance and dissolution characteristics.

Impressed-current systems employ inert (zero or low dissolution) anodes and use an external source of dc power (rectified ac) to impress a current from an external anode onto the cathode surface.

The connections are similar for the application of cathodic protection to metallic storage tanks, jetties, offshore structures and reinforced concrete structures.

4.0 Advantages and Uses of Cathodic Protection

The main advantage of cathodic protection over other forms of anti-corrosion treatment is that it is applied simply by maintaining a dc circuit and its effectiveness may be monitored continuously. Cathodic protection is commonly applied to a coated structure to provide corrosion control to areas where the coating may be damaged. It may be applied to existing structures to prolong their life.

Specifying the use of cathodic protection initially will avoid the need to provide a “corrosion allowance” to thin sections of structures that may be costly to fabricate. It may be used to afford security where even a small leak cannot be tolerated for reasons of safety or environment. Cathodic protection can, in principle, be applied to any metallic structure in contact with a bulk electrolyte (including concrete). In practice, its main use is to protect steel structures buried in soil or immersed in water. It cannot be used to prevent atmospheric corrosion on metals. However, it can be used to protect atmospherically exposed and buried reinforced concrete from corrosion, as the concrete itself contains sufficient moisture to act as the electrolyte.

Structures that are commonly protected by cathodic protection are the exterior surfaces of:

Pipelines
Ships’ hulls
Storage tank bases
Jetties and harbour structures
Steel sheet, tubular and foundation pilings
Offshore platforms, floating and sub sea structures

Cathodic protection is also used to protect the internal surfaces of:

Large diameter pipelines
Ship’s tanks (product and ballast)
Storage tanks (oil and water)
Water-circulating systems.

However, since an internal anode will seldom spread the protection for a distance of more than two to five pipe-diameters, the method is not usually practical, or suitable, for the protection of small-bore pipework.

Cathodic protection is applied to control the corrosion of steel embedded in reinforced concrete structures (bridges, buildings, port and harbour structures, etc.) – See Guide in Corrosion Control, Corrosion and Protection of Steel in Concrete and it's Monitoring.
Cathodic protection can be applied to copper-based alloys in water systems, and, exceptionally, to lead-sheathed cables and to aluminium alloys, where cathodic potentials have to be very carefully controlled.

5.0 Basic Requirements for Cathodic Protection

The essential features of cathodic protection to metals that are surrounded by a conducting electrolyte, in each of the two types of system are as follows:

a) A galvanic system requires:
- i) Sacrificial anodes
- ii) Direct welding to the structure or a conductor connecting the anode to the structure
- iii) Secure and minimum resistance connections between conductor and structure, and between conductor and anode.

b) An impressed-current system requires:
- i) Inert anodes (clusters of which, connected together often in a backfill, are called the "groundbed").
- ii) A dc power source.
- iii) Electrically well insulated, minimum resistance and secure conductors between anodes and power source.
- iv) Secure and minimum resistance connections between power source and structure.

In both cases, fundamental design decisions must be made to select the type of system and the most suitable type of anode appropriate to that system. Also required, is the determination of the size and number of the power sources, or sacrificial anodes, and their distribution on the structure.

Other requirements that must be met to ensure that cathodic protection is applied in the most economic and reliable manner are:

a) Electrical continuity. The resistance of the conductor and structure should be such as to minimise the potential drop of the return protective currents through the structure.

b) Coatings. The provision of a protective/insulating coating to the structure will greatly reduce the current demanded for cathodic protection of the metallic surface. The use of a well-applied and suitable coating, increases the effective spread of cathodic protection current. A combination of applying both a coating and cathodic protection will normally result in the most practical and economic overall protection system. Ideal coatings are those that have a high electrical resistance, are continuous and will adhere strongly to the surface to be protected. Other desirable coating characteristics include; stability in the environment, abrasion resistance, and compatibility with the alkaline environment created or enhanced by cathodic protection.

c) Structure isolation. It is often desirable to limit the spread of cathodic protection. For pipelines and tanks, this may be achieved by the insertion of monolithic electrical isolation joints in the structure. Insulating flange kits are sometimes used though they often require regular maintenance. Polarisation cells that restrict low voltage cathodic protection dc currents, but allow passage of high voltage ac currents, may be used to isolate low-resistance earthing systems from a well-coated protected structure.

d) Test facilities. It is important to consider the location of test facilities, test stations, corrosion monitoring coupons, permanent half cells (reference electrodes), and the manner that data can be routinely collected or viewed.

6.0 Design Factors

6.1 Initial considerations

Modifications to the structure to incorporate requirements, such as those discussed in section 5, are best made at the early design and pre-construction phase of the structure. For underground structures it may be necessary to visit the proposed site, or for pipelines the proposed route, to obtain additional information on low-resistivity areas, availability of electric power, and the existence of stray dc current or other possible interaction.

It is common practice for a survey to be made before design. This survey is often combined with a study to establish economic justification for the recommended anti-corrosion proposal while the principal data necessary for design (chemical and physical) are also collected.

If the structure already exists, measurement of existing structure-to-soil potentials is essential to give valuable information as to which areas are anodic and which are cathodic. In addition, with the application to the structure of temporary cathodic-protection current, using any convenient dc source and a temporary anode system (groundbed), a more accurate assessment of current demand and the likely spread of protection to the structure may be assessed.

Design of a cathodic-protection system for a new structure should include the calculation of:
Current demand
Resistance to earth of the anodes
Quantity and location of anodes or anode systems
Electrical supply requirements
Test and monitoring facilities.

Project specifications and European or national guideline documents should be consulted.

In the case of onshore pipelines and other structures, negotiation with landowners, public authorities, or other interested parties, for easements and wayleaves for groundbeds, cable routes, transformer-rectifier sites, and electricity supplies should also be undertaken at the design stage.

6.2 Potential level and distribution

In practice, the structure-to-electrolyte potentials are measured using a standard half-cell (reference electrode). For example, a common protection criterion used for steel in an aerobic electrolyte of nearly neutral pH is a negative value of minus 850 mV. When exposed to sulphate-reducing bacteria, steel would require a more negative potential of minus 950 mV. Both values are with respect to a copper/copper sulphate half-cell. Ideally, to attain a high degree of accuracy and in order to minimise measurement errors, the half-cell should be very close to the surface at which the potential is being measured.

The potential values measured on a cathodically protected structure will be dependent on the anodic and cathodic reactions, structural geometry, and internal electrical resistance. However, the provision of a protective coating will have by far the greatest effect on the potential for a given applied current. The potentials will generally be most negative at a point nearest to the anode or groundbed and, for pipelines, will attenuate towards the natural corrosion potential as the distance from the anode or groundbed increases.

An example of potential attenuation is that, in the case of a power-impressed system, a single cathodic-protection installation may supply cathodic protection to as much as 150 km of extremely well coated pipeline, whereas for similar-sizes of bare (uncoated) pipelines it may be necessary to have installations at only 2 km intervals.

6.3 Economics of decisions

At the design stage of a cathodic-protection scheme, a decision must be made as to whether the scheme will be a galvanic or impressed-current system. In specific circumstances, the use of both types of systems may be appropriate, but care is required to avoid interaction between them.

Galvanic systems have the advantage of being –

- **a)** simple to install
- **b)** independent of a source of external electric power
- **c)** suitable for localised protection
- **d)** less liable to cause interaction on neighbouring structures.

However, the current output available from the practical size and weight of galvanic anodes is relatively small and depends principally on the electrical resistivity of the electrolyte (local environment if buried / submerged / concrete). Thus, galvanic anodes of aluminium and zinc, which have similar driving emfs to steel of approximately 0.5V, are limited to use in electrolytes of less than 5 Ohm.m resistivity. The anodes are usually self-regulating because their current output is usually less than their maximum output capability and is controlled by the difference in potential between the two metals. The current from the anodes is not normally controllable; thus changes in the structure, such as the deterioration of a coating, that causes an increase in protection current demand, may necessitate the installation of further sacrificial anodes to maintain protection.

Impressed-current installations have the advantage of being –

- **a)** able to supply a relatively large current
- **b)** able to provide of high dc driving voltages (up to 50V). Enables it to be used in most types of electrolytes
- **c)** able to provide a flexible output that may accommodate changes in, and additions to, the structure being protected

Generally, however, care must be taken in the design to minimise interaction on other structures and, if no ac supply is available, an alternative power source (solar, diesel, etc.) is required. Impressed current systems require regular maintenance and monitoring.

Generally, galvanic systems have found favour for small well-coated, low current demand, structures or for localised protection. Impressed current schemes are utilised for large complex structures, which may be of bare metal or poorly coated. However, in North Sea offshore work, it has been found cost effective to provide galvanic protection to large uncoated platforms, and similar structures, where the initial cost of coating and the cost of maintenance are very high. In addition, the galvanic anodes offer easy to install robust systems, which being independent of a power source, provide protection immediately on “float-out” of the structure.

6.3 Problems to be avoided

There are certain limitations to the use of cathodic protection. Excessive negative potentials can cause accelerated corrosion of lead and aluminium structures because of the alkaline environments created at the cathode. These alkaline conditions may also be detrimental to certain coating systems, and may cause loss of adhesion of the coating. Hydrogen evolution at the cathode surface may, on high-strength steels, result in hydrogen embrittlement of the steel, with subsequent loss of strength. On some high strength steels, this may lead to catastrophic failures. It may also cause disbondment of coatings; the coating would then act as an insulating shield to the cathodic-protection currents.

Consideration must also be given to spark hazards created by the introduction of electric currents into a structure situated in a hazardous area. Generally sacrificial anode systems do not cause problems, as they are self-regulating and are often regarded as systems that can be ‘fit and forget’. They must, however, be inspected at periodic intervals to ensure they are capable of supplying continued protection.

Any secondary structure residing in the same electrolyte may receive and discharge the cathodic protection direct current by acting as an alternative low-resistance path (interaction). Corrosion will be accelerated on the secondary structure at any point where current is discharged to the electrolyte. This phenomenon is called "stray current corrosion".

Interaction may occur, for example, on a ship that is moored alongside a cathodically protected jetty, or on a pipeline or metal-sheathed cable that crosses a cathodically protected pipeline.

Interaction may be minimized by careful design of the cathodic protection system. In particular, by design of a scheme to operate at the lowest possible current density and by maintaining good separation between the protected structure and the secondary structure, and between the groundbeds or anodes and the secondary structure.

It is an advantage of sacrificial-anode schemes that they are not prone to creating severe interaction problems and therefore they are popular for protection in congested and complex locations.

Methods and procedures are available for overcoming interaction, and testing should be carried out in the presence of interested parties, so that the choice of remedial measures may be agreed, if and when the acceptable limit of interaction is exceeded.

6.4 Types of equipment

Various galvanic anode alloys of magnesium, aluminium or zinc are available in a variety of block, rod or wire forms. These alloys are cast around steel inserts to enable fixing of the anode and to maintain electrical continuity and mechanical strength towards the end of the anode life. The insert may be directly welded or bolted to the structure to be protected, or anodes may be connected to the structure by means of an insulated lead, usually of copper, as for onshore and offshore pipelines.

Impressed-current groundbeds in soils have traditionally consisted of high-silicon cast iron. However, mixed metal oxide (MMO) anodes are becoming increasingly popular for all environments because of their good mechanical and electrical characteristics and compact size. For seawater applications and areas where chlorides are present, MMO anodes work well as do high-silicon cast iron alloyed with chromium. Other anodes consist of lead alloy and platinum formed in a thin layer on a titanium or niobium base

There are many possible sources of dc power; the most popular is the selenium plate or silicon-diode rectifier with transformer unit in conjunction with an existing ac supply or diesel- or gas-engine-driven alternator. For most applications, a constant dc voltage or constant current systems are used.

In remote areas, power sources include thermo- electric generators, closed-cycle vapour turbines, and solar or wind generators. The latter two are used in conjunction with lead-acid or similar storage batteries. The choice is dependent on power requirements, maintenance capabilities, and environmental conditions.

There are also automatic control units available that will adjust current output in accordance with potential changes at a half cell.

7.0 Monitoring and Maintenance

Cathodic-protection systems may be monitored effectively by the measurement of structure-to-electrolyte potentials, using a high input impedance voltmeter and suitable half-cell. The standard practical half-cells are copper/copper sulphate, silver/silver chloride/seawater, silver/silver chloride/ potassium chloride and zinc.

Adjustments are made to the cathodic-protection current output to ensure that protective potentials are maintained at a sufficiently negative level as defined by the project specification. The level of protection in soils and water is accepted at steel potentials of minus 850 mV (wrt $Cu/CuSO_4$) or minus 800 mV (wrt Ag/AgCl/seawater).

Transformer rectifier outputs may be displayed by telemetry at central control stations. Many cathodic protection systems are increasingly being controlled and monitored by remote computers and modem links. Other communication systems that enable, for example, pipe-to- soil potentials to be monitored from a helicopter or light aeroplane, are available.

Galvanic-anode outputs may also be monitored, as can currents in electrical bonds between structures. Tests to measure interaction are usually conducted annually where areas are at risk or after adjustments to cathodic-protection current output.

Maintenance includes the mechanical maintenance of power-supply equipment and the maintenance of painted surfaces of equipment.

It is good practice to inform all owners of cathodic protection systems and infrastructure in the area of influence of any new cathodic protection systems, or of significant changes to existing systems, so that the effect on these facilities may be assessed.

8.0 Sources of Advice

Corrosion/Cathodic Protection Consultants – Various listings.

Institute of Corrosion
Corrosion House, Vimy Court, Leighton Buzzard
Bedfordshire. LU7 1FG

National Association of Corrosion Engineers (NACE)
International
Houston, Texas, USA

Institute of Materials, Minerals and Mining
1 Carlton House Terrace, London. SW1Y 5DB

The Institution of Civil Engineers
One Great George Street, Westminster, London SW1P 3AA

Corrosion Protection Association (Reinforced Concrete)
Association House, 99 West Street, Farnham, Surrey GU9 7EN

The Society of Operations Engineers
22 Greencoat Place, London. SW1P 1PR

Galvanisers Association
6 Wren’s Court, 56 Victoria Road, Sutton Coldfield
West Midlands B72 1SY

Paint Research Association
8 Waldegrave Road, Teddington, Middlesex, TW11 8LD

Pipeline Industries Guild
14/15 Belgrave Square, London SW1X 8PS

9.0 Further Information

The following references provide further information on cathodic protection. Potential users are recommended to employ qualified and experienced specialists to design and undertake the work. The following handbook provides listings of various manufacturers, suppliers, consultants, and contractors.

The Corrosion Handbook, 1999, (incorporating Corrosion Prevention Directory), MPI Group, (Inst. of Materials, Inst. of Corrosion)

Other useful Publications:

J.H. Morgan 'Cathodic Protection' National Association of Corrosion Engineers (NACE) 1987 2nd Edition.

Peabody's Control of Pipeline Corrosion. (2nd edition, Ed by R Bianchetti), NACE, Houston, 2000.

Corrosion and corrosion control. H H Uhlig, Wiley, New York, 1985 (3rd edition).

Corrosion. L L Shreir (2 vols), Newnes-Butterworth, 19 (3rd edition).

Cathodic Protection Criteria - A Literature Survey' National Association of Corrosion Engineers (NACE) 1989.

W.V. Baeckmann 'Handbook of Cathodic Corrosion Protection', (3rd edition) Gulf Pub., 1997.

Standards

BS 7361 Part 1 1991 'Cathodic Protection Part 1 - Code of Practice for Land and Marine Applications' British Standards Institution, U.K.

BS EN 12473 General principles of cathodic protection in sea water.

BS EN 12474 Cathodic protection for submarine pipelines.

BS EN 12696 Cathodic protection of steel in concrete
Part 1 : Atmospherically exposed concrete

BS EN 12954 Cathodic protection of buried or immersed metallic structures – General principles and application for pipelines.

BS EN 13173 Cathodic protection for steel offshore floating structures.

BS EN 13174 Cathodic protection for harbour installations.