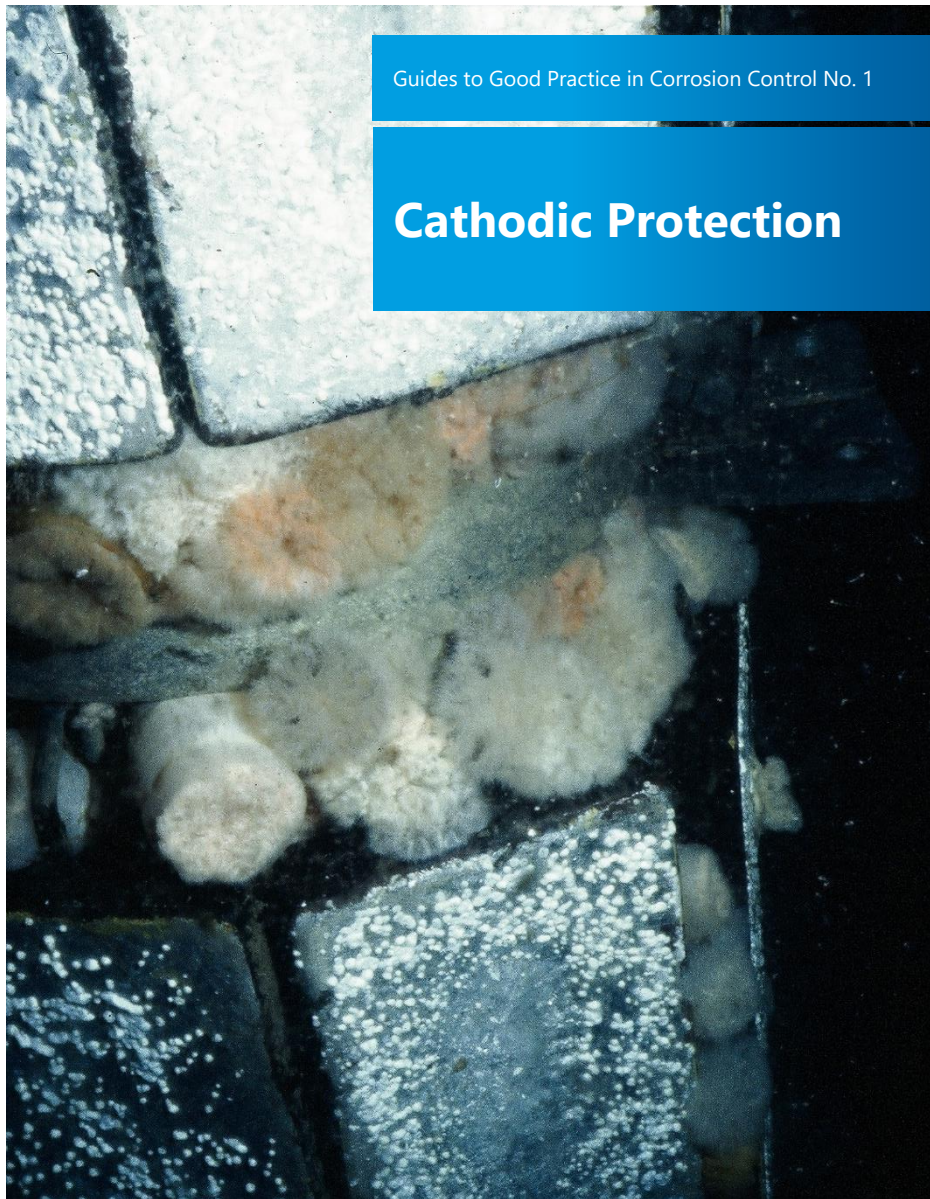


Guides to Good Practice in Corrosion Control No. 1

# Cathodic Protection





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**Front cover image:** Post installation photograph showing the expected and necessary corrosion of the anodes in order to deliver the cathodic protection current. The white artefacts are marine scaling. Photograph courtesy of Brian Wyatt, Corrosion Control.

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## 1. 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 8, various independent or commercial consultants, cathodic protection contractors and product suppliers.

## 2. 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.

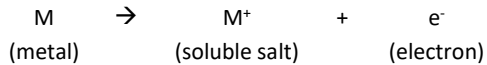
The most rapid development of cathodic-protection was made in the United States of America and by 1945, the method was well established to meet the requirements of the rapidly expanding oil and natural gas industry which wanted to benefit from the advantages of using thin-walled steel pipes for underground 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 such as buried pipelines, tank bases, ships' hulls, offshore structures, harbours and jetties, as well as reinforced concrete structures, to provide corrosion control. Cathodic protection is also used on the interior surfaces of water-storage tanks and water-circulating systems.

## 3. 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.

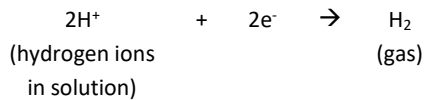
Corrosion is an electro-chemical process that involves the passage of electrical currents on a micro or macro scale. The change from the metallic to the combined form occurs by an "anodic" reaction involving the oxidation of the metal to its ions:



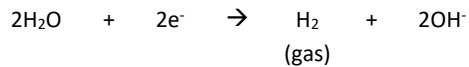
A common example is:



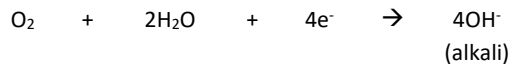
This reaction produces free electrons, which pass within the metal to another site on the metal surface (the cathode), where it is consumed by the cathodic reaction. In acid solutions the cathodic reaction is:



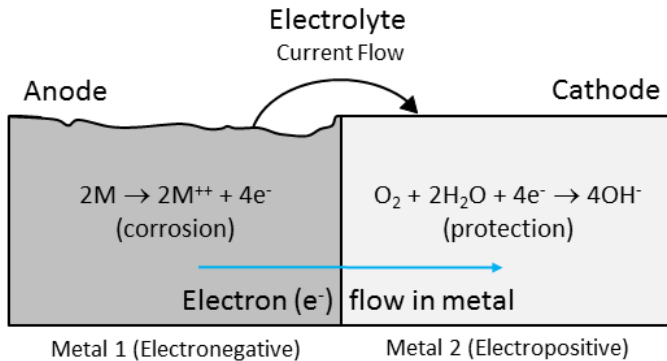
In alkaline solutions, where hydrogen ions are rare, the reduction of water will occur to yield alkali and hydrogen:



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



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:

- Difference 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)

Cathodic protection is an electrochemical corrosion prevention system based on the decrease of corrosion potential to a level at which the corrosion rate of the metal is significantly reduced (EN ISO 8044). For industrial structures, residual corrosion rates of less than 10  $\mu\text{m}/\text{yr}$  are typically achieved with a fully effective cathodic protection system.

The principle of cathodic protection is connecting an external anode to the metal to be protected and passing of an electrical dc current through the electrolyte onto the entire surface of the metal so that all areas become cathodic and therefore do not corrode.

The external anode may be a galvanic (sacrificial) anode, where the current is a result of the potential difference between the structure and the anode, 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.



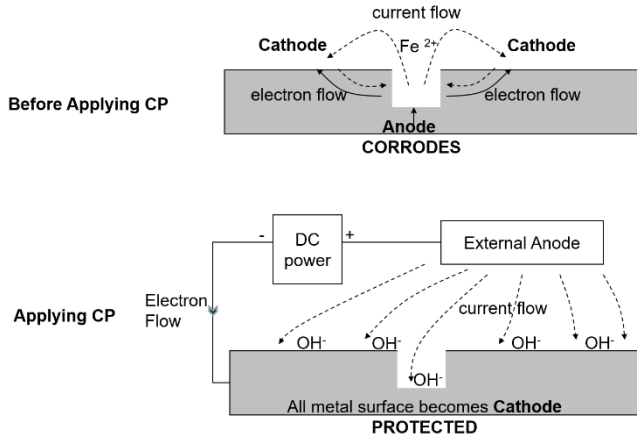
In the discussion that follows it is assumed that the metal to be protected is carbon steel, which is the most common material used in construction. Reinforcing carbon steel used in reinforced concrete structures can also be protected using cathodic protection.

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 anodes that are connected directly or through a test facility 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 electrochemical series, causes a 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 (very low or low dissolution) anodes and use an external source of dc power, usually a transformer rectifier, to impress a current from an external anode onto the cathode surface. The metals commonly used, as impressed current anodes are high silicon iron, graphite, mixed metal oxide coated titanium and magnetite.



**Figure 2.** Current flow with and without cathodic protection

These methods are used for the application of cathodic protection to buried pipelines, metallic storage tanks, jetties, offshore structures and reinforced concrete structures.

## 4. Advantages and Uses of Cathodic Protection

The main advantage of cathodic protection over other forms of anti-corrosion treatment is that it is easily applied and its effectiveness may be monitored continuously. It can usually be upgraded economically to extend its life.

Cathodic protection can, in principle, be applied for 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.

Cathodic protection is commonly applied to a coated structure to provide corrosion control to areas where the coating may be damaged. It can also be applied retrospectively to existing structures to prolong their life.

Specifying the use of cathodic protection at the commencement of a project will avoid the need to provide a “corrosion allowance”. This will enable more economical, thinner wall and lighter structures to be used. Cathodic protection may be used to provide structure integrity to prevent leakage of products that may cause fire/explosion and environment pollution.

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

- Pipelines
- Storage tank bases
- Ships’ hulls
- Jetties and harbour structures
- Steel sheet, tubular and foundation pilings
- Offshore platforms, floating and subsea 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 may be 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.

## 5. Basic Requirements for Cathodic Protection

The essential features of cathodic protection for 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 with a tubular/rod steel core or fitted with a length of cable
- ii. Direct welding of the steel core to the structure for marine applications, or using the anode cable to connect to the structure via a test post and test cable attached to the structure. This allows for monitoring potentials and anode current measurement on buried structures
- iii. Secure and minimum resistance connections between the core and structure, and between conductor and anode

b) An impressed-current system requires:

- i. Inert anodes. These may be clusters of anodes, connected together often in a carbonaceous backfill called a “groundbed”, installed remotely at some 100m from the structure for buried structures. Alternatively, for marine applications, they may be distributed around the structure but electrically isolated from it
- ii. A dc power source
- iii. Electrically well insulated, minimum resistance and undamaged conductors between anodes and power source positive terminal
- iv. Secure and minimum resistance connections between structure and power source negative terminal

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 current and voltage output and number of the power sources or sacrificial anodes and their distribution around the structure.

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

- Electrical continuity. The resistance of the conductor and structure should be such as to minimise the voltage drop in the cables and the return protective currents through the structure
- Coatings. The provision of a protective/insulating coating to the structure will greatly reduce the current demand for cathodic protection as the exposed area of the

metallic surface is very small. 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; low deterioration factor, 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 allow passage of any induced ac currents and dc lightning currents but restrict the flow of cathodic protection dc currents, may be used to connect protected structures to safety copper earthing systems without a large drain of current on the cathodic protection system.

d) Test facilities for monitoring. 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. 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 buried structures such as pipelines, 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. For buried structures, the additional information should include soil resistivities at various depths, availability of electric power, locations for groundbeds, proximity of other metallic structures, the existence of stray dc current, proximity of HVAC overhead power lines or other sources of possible interference.

If the structure already exists, measurements of existing structure-to-soil potentials are essential to give valuable information as to which areas are anodic and which are cathodic. In addition, by the application of a temporary cathodic-protection system (current drain test) to the structure, using any convenient dc source and a temporary anode system (groundbed), a

more accurate assessment of current demand and the likely spread of protection along the structure may be assessed.

For marine structures, water resistivities, temperatures, flow rates and tidal levels need to be obtained for design purposes.

Design of a cathodic-protection system for a new structure should include the calculation of:

- Surface areas
- Coating efficiency
- Current demand
- Resistance to earth of the anodes
- Quantity and location of anodes or groundbeds
- Electrical supply requirements
- Test and monitoring facilities

Project specifications and International 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) – saturated copper /copper sulphate for soils and freshwater and silver/silver chloride /seawater for marine and brackish waters. The common protection criterion used for steel in an aerobic electrolyte of near neutral pH is a negative value of -850 mV with respect to a copper/copper sulphate half-cell. When exposed to sulphate-reducing bacteria, steel would require a more negative potential of -950 mV with respect to a copper/copper sulphate half-cell. In seawater, a silver/silver chloride/seawater reference electrode should be used with criteria of -800mV and -900mV respectively.

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 or techniques to minimise the measurement errors should be used.

The potential values measured on a cathodically protected structure will be dependent on the anodic and cathodic reactions, structural geometry, and structure and electrolyte electrical resistance. However, the provision of a protective coating will have by far the greatest beneficial by greatly reducing the applied current allowing it to spread much further from the anode. 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 a similar-size bare (uncoated) pipeline, it may be necessary to have installations at less than 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 interference between them. In some cases, if the impressed current scheme has a long delay before energisation, a temporary galvanic anode system may be installed to provide protection during this delay period.

Galvanic systems have the advantage of being:

- Simple to install
- Independent of a source of external electric power
- Suitable for localised protection
- Less liable to cause interference on neighbouring structures.

However, due to the low driving voltage (difference in potential between the steel structure and the galvanic anode), the current output available from a practical size and weight galvanic anode 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 voltages to steel of approximately 0.5V, reducing to 0.25V when structure is polarised, are usually limited to marine applications; magnesium with a driving voltage up to 1V, reducing to 0.65V when structure is polarise, is used for buried applications.

The current from the anode 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. Also, build-up of calcareous scale deposits on the structure will reduce the current demand from initial level to maintenance level for marine structures.

Impressed-current installations have the advantage of being:

- Able to supply a relatively large current
- Able to provide high dc driving voltages (up to 50V). which enables it to be used in most types of electrolytes
- Able to provide an adjustable output that may accommodate changes in, and additions to, the structure being protected
- Able to provide protection over long distances using remote groundbeds

Generally, however, care must be taken in the design to minimise interference on other structures and, if no ac supply is available, an alternative power source (solar, wind turbine, 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, and long pipelines. However, in offshore work, it has been found cost effective to provide galvanic protection to large uncoated platforms, and similar structures, where the initial costs of coating and the costs 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.

## **6.4 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 can lead to catastrophic failures. It may also cause disbondment of coatings where the coating would then act as an insulating shield to the cathodic-protection currents. When used inside enclosed tanks, gases may be given off providing a hazardous atmosphere which should be vented off.

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 but 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 current by acting as an alternative low-resistance path. Corrosion will be

accelerated on the secondary structure at any point where current is discharged into the electrolyte. This phenomenon is called "stray current corrosion" or "interference".

Interference 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.

Interference 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.

An advantage of sacrificial-anode schemes is that they are not prone to creating severe interference problems and therefore they are often used for protection in congested and complex locations.

Methods and procedures are available for overcoming interference 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 interference is exceeded.

## **6.5 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 to the structure, attaching a connecting cable and maintaining 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 cable, via a test facility for onshore pipelines or directly for offshore applications.

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/weight. The anodes are normally installed within a column of carbonaceous backfill to reduce the resistance to earth of the groundbed. For seawater applications and areas where chlorides are present, MMO anodes are utilised, also high-silicon cast iron alloyed with chromium.

There are many possible sources of dc power; the most popular is the bridge rectifier or thyristor with transformer unit in conjunction with an existing ac supply or diesel- or gas-engine-driven alternator. For low power requirements, switched mode power supplies are also used benefitting from good efficiency and smaller size. For most applications, a constant dc voltage or constant current systems are used. However, if the environment is variable (such as



tidal estuaries), automatic potential controlled system using feedback from a permanent reference electrode may be used.

In remote areas, power sources include solar, wind or thermo- electric generators, or, on gas pipelines, closed-cycle vapour turbines. The solar and wind generators require substantial storage batteries to operate in no sun/wind conditions. The choice is dependent on power requirements, maintenance capabilities, and environmental conditions.

## 7. 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 saturated copper/copper sulphate, silver/silver chloride/seawater, silver/silver chloride/ potassium chloride and zinc. The choice usually depends on the electrolyte in which it is used.

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 and as given in 6.2.

Transformer rectifier outputs may be displayed by telemetry at central control stations or on a remote data base website. Many cathodic protection systems are increasingly being controlled and monitored by remote computers and modem links.

Galvanic-anode outputs may also be monitored, as can currents in electrical bonds between structures. Tests to measure interference 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 and test facilities.

It is good practice to inform all owners of cathodic protection systems and metallic 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. Sources of Advice

Institute of Corrosion (ICorr) - [www.icorr.org](http://www.icorr.org)

NACE International, USA - <https://nace.org>

Institute of Materials, Minerals and Mining (IOM3) - [www.iom3.org](http://www.iom3.org)

The Institution of Civil Engineers - [ice.org.uk](http://ice.org.uk)

Corrosion Protection Association (Reinforced Concrete) - [www.corrosionprevention.org.uk](http://www.corrosionprevention.org.uk)

Pipeline Industries Guild - [www.pipeguild.com](http://www.pipeguild.com)

Corrosion/Cathodic Protection Consultants – Various listings.

## 9. Further Information

The following references provide further information on cathodic protection. Potential users are recommended to employ qualified and experienced specialists (Level 4 Senior Cathodic Protection Design Engineer certificated to ISO 15257) to design and undertake the work.

### 9.1 Other useful publications

Cathodic Protection. J.H. Morgan 1987 2nd Edition, NACE International

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

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' 1989, NACE International.

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

Corrosion control for buried pipelines. D W Harvey, NPL, Measurement Good Practice Guide No. 121, September 2011

### 9.2 Standards

BS EN ISO 15589-1:2017	Petroleum, petrochemical and natural gas industries. Cathodic protection of pipeline systems. On-land pipelines
BS EN ISO 15257:2017	Cathodic protection. Competence levels of cathodic protection persons Basis for certification scheme
BS EN ISO 13174:2012	Cathodic protection of harbour installations

BS EN ISO 12696:2016	Cathodic protection of steel in concrete
BS EN 16299:2013	Cathodic protection of external surfaces of above ground storage tankbases in contact with soil or foundations
BS EN 16222:2012	Cathodic protection of ship hulls
BS EN 15112:2006	External cathodic protection of well casing
BS EN 14505:2005	Cathodic protection of complex structures
BS EN 13636:2004	Cathodic protection of buried metallic tanks and related piping
BS EN 13509:2003	Cathodic protection measurement techniques
BS EN 13173:2001	Cathodic protection for steel offshore floating structures
BS EN 12954:2001	Cathodic protection of buried or immersed metallic structures. General principles and application for pipelines
BS EN 12499:2003	Internal cathodic protection of metallic structures
BS EN 12495:2000	Cathodic protection for fixed steel offshore structures
BS EN 12474:2001	Cathodic protection for submarine pipelines
BS EN 12473:2014	General principles of cathodic protection in seawater

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