CORRECTIONS WITHIN DESIGN MANUAL FOR ROADS AND BRIDGES NOVEMBER 2002

SUMMARY OF CORRECTION - BA 83/01 Volume 3, Section 3, Part 3
CATHODIC PROTECTION FOR USE IN REINFORCED CONCRETE HIGHWAY STRUCTURES

BA 83/02 was originally produced in partnership with the Corrosion Prevention Association (CPA). Following its publication and as a result of some feedback, it was agreed with the CPA that the diagrams showing cathodic protection systems could be clarified. It was also agreed that Table 1 could be amended to reflect the latest information on the performance and application of different anode types.

Please remove pages 2/1 - 2/8 dated Febuary 2002 and insert new pages 2/1 - 2/8 attached, dated November 2002.

We apologise for the inconvenience caused.

Highways Agency
November 2002

London: The Stationery Office

VOLUME 3 HIGHWAY STRUCTURES: INSPECTION AND MAINTENANCE

SECTION 3 REPAIR

PART 3

BA 83/02

CATHODIC PROTECTION FOR USE IN REINFORCED CONCRETE HIGHWAY STRUCTURES

SUMMARY

This Advice Note gives guidance on the selection and installation of cathodic protection systems for the corrosion protection of reinforcement in highway structures. It has been produced in partnership with the Corrosion Prevention Association.

INSTRUCTIONS FOR USE

This is a new Advice Note to be incorporated in the Manual.

1. Remove existing contents page for Volume 3, and insert new contents page for Volume 3, dated February 2002.

2. Insert BA 83/02 into Volume 3, Section 3, Part 3.

3. Archive this sheet as appropriate.

Note: A quarterly index with a full set of Volume Contents Pages is available separately from The Stationery Office Ltd.

THE HIGHWAYS AGENCY

SCOTTISH EXECUTIVE DEVELOPMENT DEPARTMENT

THE NATIONAL ASSEMBLY FOR WALES
CYNULLIAD CENEDLAETHOL CYMRU

THE DEPARTMENT FOR REGIONAL DEVELOPMENT
NORTHERN IRELAND

Cathodic Protection for Use in Reinforced Concrete Highway Structures

Summary: This Advice Note gives guidance on the selection and installation of cathodic protection systems for the corrosion protection of reinforcement in highway structures. It has been produced in partnership with the Corrosion Prevention Association.

REGISTRATION OF AMENDMENTS

Amend No	Page No	Signature & Date of incorporation of amendments	Amend No	Page No	Signature & Date of incorporation of amendments

REGISTRATION OF AMENDMENTS

Amend No	Page No	Signature & Date of incorporation of amendments	Amend No	Page No	Signature & Date of incorporation of amendments

VOLUME 3 HIGHWAY STRUCTURES: INSPECTION AND MAINTENANCE
SECTION 3 REPAIR

PART 3

BA 83/02

CATHODIC PROTECTION FOR USE IN REINFORCED CONCRETE HIGHWAY STRUCTURES

Contents

1. INTRODUCTION

Scope

1.1 This Advice Note provides general information on the merits, selection and installation of various types of cathodic protection for the control of corrosion of reinforcement in reinforced concrete highway structures.

It relates principally to reinforced concrete highway structures at risk of reinforcement corrosion damage due to chloride contamination.

Cathodic protection is an electrochemical process involving the use of low voltage dc electricity which is caused to flow through the concrete and discharge on the reinforcement resulting in control of corrosion to insignificantly low rates.

This Advice Note also addresses the use of cathodic protection for new structures in chloride contaminated environments (also known as “cathodic prevention”).

It also gives guidance on particular cases where cathodic protection may not be appropriate.

This Advice Note should be used in conjunction with other DMRB Advice Notes and Standards in order to ensure that cathodic protection is only applied to those structures that have been properly and fully assessed in order to determine the causes of their deterioration, that cathodic protection along with associated repair and/or strengthening works is the most appropriate technique to extend the life of the structure and that repaired/protected structures will be fit for purpose following the works.

European Standard

1.2 This Advice Note is in accordance with the BS EN 12696:2000, “Cathodic Protection of Steel in Concrete.”

The BS EN 12696 Standard is a performance standard for cathodic protection of steel in concrete which is applicable to highway structures. It provides more detail of the technique, and specifications for cathodic protection of reinforced concrete highway structures should comply with BS EN 12696.

Corrosion Prevention Association

1.3 This Advice Note has been prepared with the assistance of the Technical Committee of the Corrosion Prevention Association (formerly the Society for Cathodic Protection of Reinforced Concrete). Members of the Association are a source of expertise in cathodic protection of reinforced concrete and include Consulting Engineers, Contractors and Material Suppliers.

History

1.4 Cathodic protection of steel in soils and waters has been practised for over 150 years. Cathodic protection of steel in concrete has been practised for some 50 years, starting with applications to steel reinforced concrete pipelines. Trial applications to atmospherically exposed reinforced concrete highway structure elements commenced in 1958. Extensive trials and full-scale demonstration projects followed by commercial applications in North America in the 1980s. UK highways bridge demonstration projects in 1986 and 1989 were followed by large scale commercial applications, notably to the Midland Links Motorways Viaducts support structures, starting in 1990.

Cathodic protection of atmospherically exposed reinforced concrete has, by the end of 2000, been applied to well in excess of 100,000m^2 of bridges, car parks, harbour facilities, tunnels and buildings within the UK and well in excess of 2,000,000m^2 overseas. Extensive research and trials have supported this extensive and rapidly growing track record to establish cathodic protection as a technique of proven efficacy and reliability.

There has been extensive use of cathodic prevention of new highway structures in Italy with some significant lengths of post tensioned reinforced concrete deck units for Autostrada receiving corrosion protection by cathodic protection.

1.5 Concurrently UK Consultants and Contractors have been responsible for large scale projects of cathodic protection applications to highway structures and harbour facilities internationally, notably in the Middle East and the Far East.

Cost Savings and Efficacy

1.6 Cathodic protection of reinforced concrete highway structures has been rigorously assessed, both in the UK and internationally, and demonstrated to be reliable and effective in controlling corrosion of reinforcing steel in chloride-contaminated concrete. Experience on such structures has demonstrated that the use of cathodic protection, as an alternative to extensive removal and repair of chloride-contaminated concrete, can significantly reduce contract costs, particularly when contract durations are reduced and the need for structural propping is avoided. The reduction of large scale concrete removal and reinstatement can result in contract cost reductions of between 20% and 80%.

System Selection and Life

1.7 In the highway structure environment, different types of cathodic protection system are available, with different operating characteristics. Satisfactory performance before maintenance can be expected to range from 10 to 40 years, depending upon system type, with embedded components of some systems having a theoretical design life of up to 120 years. However, electronic power supply and monitoring systems are likely to require replacement every 20 to 40 years.

System Monitoring and Long Term Costs

1.8 Cathodic protection requires that the impressed direct current (d.c.) flows either continuously or for the majority of the time. It is necessary to monitor this current flow and to intermittently monitor the effects of the cathodic protection on the steel/concrete electrochemical performance in order to demonstrate that corrosion control has been achieved. There is therefore an ongoing cost associated with electrical power (normally insignificant) and a cost of specialist monitoring, control and assessment to be incorporated into life cycle cost analysis.

2. DESCRIPTION OF CATHODIC PROTECTION SYSTEMS

General

2.1 There are two types of cathodic protection systems, impressed current and galvanic (also known as sacrificial). Both are discussed in this Advice Note, although galvanic anode systems have had limited use and are still considered experimental in UK applications to atmospherically exposed reinforced concrete structures.

2.2 The principles of cathodic protection are straightforward. Corrosion occurs by the formation of anodes and cathodes on the reinforcement surface, as shown in Figure 1. Corrosion occurs at the anode; a generally harmless reduction reaction occurs at the cathode. By introducing an external anode and an electric current, the reinforcement is forced to become cathodic and reduces corrosion to insignificant levels. The impressed current cathodic protection anode is a material that is consumed at a negligible or controlled rate by the anodic oxidation reaction.

Impressed Current Cathodic Protection

2.3 Impressed current cathodic protection consists of an anode system, a d.c. power supply and monitoring probes, with associated wiring and control circuitry. One of the key decisions is the choice of anode. The alternatives are conductive coatings applied to the concrete surface, mixed metal oxide coated titanium mesh or grid in a concrete overlay, conductive mortar and overlays, coated titanium ribbon in slots, or various discrete anode materials in holes in the concrete. A schematic of an impressed current system is shown in Figure 2.

2.4 Figure 2 depicts an atmospherically exposed concrete structure where anodes are distributed across the concrete surface to pass current evenly to the reinforcing steel. For buried or submerged concrete remote anodes can pass current through low-resistance soil or water. In this application conventional cathodic protection as used for pipelines or submerged structures can be employed, as shown in Figure 3 (see also BS 7361: Part 1:1991).

Anode Systems

2.5 Available conductive coating anodes include a variety of formulations of carbon pigmented solvent or water dispersed coatings, and thermal sprayed zinc. Recently, thermal sprayed titanium has been used experimentally, with a catalysing agent spray applied onto the titanium coating.

2.6 Mixed metal oxide coated titanium mesh or grid anode systems are fixed to the surface of the concrete and overlaid with a cementitious overlay which can be poured or pumped into shutters or sprayed.

2.7 Discrete anodes are usually installed in purpose-cut holes or slots in the concrete. They are either:

- rods of coated titanium in a carbonaceous backfill;
- mixed metal oxide coated tubes;
- strips and ribbon;
- conductive ceramic tubes in cementitious grout.

Table 1 summarises the anode types and their relative performance. It is emphasised that the information in Table 1 is indicative only and based upon the experience in the UK to year 2000. Preliminaries, access, traffic management and concrete repair costs are not included.

For any particular application, the CP specialist must ensure that the chosen anode system and its design are suitable for the application.

Power Supplies

2.8 Cathodic protection generally operates with a current density to the steel surface in the range 5-20mA/m^2. The direct current is normally provided by an a.c. powered transformer-rectifier or equivalent power unit, taking single phase a.c., transforming it to lower voltage and rectifying it to d.c. and outputting it at typically 1-5 ampere, 2-24 volts to each independently operated anode zone. Thus it can be seen that the electrical consumption of an impressed current cathodic protection system is very modest. An anode zone is an electrically isolated area of anode. Each zone can receive different levels of current. Systems are divided into zones to account for different levels of reinforcement, different environments or different elements of the structure.

Cathodic prevention of new or not yet corroding reinforcement in concrete requires a current density to the steel in the range 0.5-2mA/m^2. The lower current density results in good current distribution and safe application to prestressed structures.

A permanent power supply will be required for impressed current cathodic protection systems, and where none is locally available arrangements must be made, and allowed for in the assessed system costs. In some situations street lighting supplies can be useful sources of power.

2.9 Transformer-rectifiers may be manually controlled or controlled either locally or remotely via modem to a computer.

Monitoring System

2.10 The monitoring system is usually closely integrated with the power supply. As shown in Figure 2 probes are embedded in the concrete to verify that all of the zones are working and that sufficient current is passing to protect the reinforcement. Monitoring of steel/concrete potential is with respect to embedded reference electrodes. These are usually silver/silver chloride/potassium chloride or manganese/manganese dioxide/potassium hydroxide. They are placed in the concrete in the most anodic (actively corroding) areas prior to energising the system.

Additional reference electrodes are placed in the concrete at locations of particular structural sensitivity, at locations of high reinforcement complexity or at locations of sensitivity to excessive protection.

Steel/concrete/reference electrode (so called "half cell") potentials are recorded and the decay in potential from "instant off" (a measure of the potential without IR errors, see Chapter 4) to a time of 4 to 24 hours or longer is used to determine the effectiveness of the system. A 100mV change in 24 hours or 150mV over a longer period is specified in BS EN 12696, along with certain other criteria.

Earlier UK and USA practice to require a 100mV potential decay in 4 hours will result in adequate protection but, particularly after long periods of operation, is likely to result in excessive protection.

2.11 It is usual to embed several reference electrodes in each zone of the cathodic protection system. The cathodic protection current can be interrupted and steel/concrete/reference electrode potentials and potential decays measured.

2.12 Computerised monitoring systems allow the collection of decay data to be automated. Remote monitoring systems allow this to be done without a site visit.

Galvanic Anode Cathodic Protection

2.13 The principles of galvanic cathodic protection are the same as for impressed current cathodic protection, except that the anode is a less noble (ie more active) metal than the steel to be protected and is consumed preferentially, generating the cathodic protection current. The potential difference between anode and cathode is a function of the environment and the relative electrode potentials of the anode and cathode materials. The current is a function of the potential difference and the electrical resistance. Figure 4 illustrates a galvanic system.

2.14 As the voltage and current cannot generally be controlled, the level of protection cannot be guaranteed and a low resistance environment is required. Galvanic anodes are well proven for applications to buried or submerged structures.

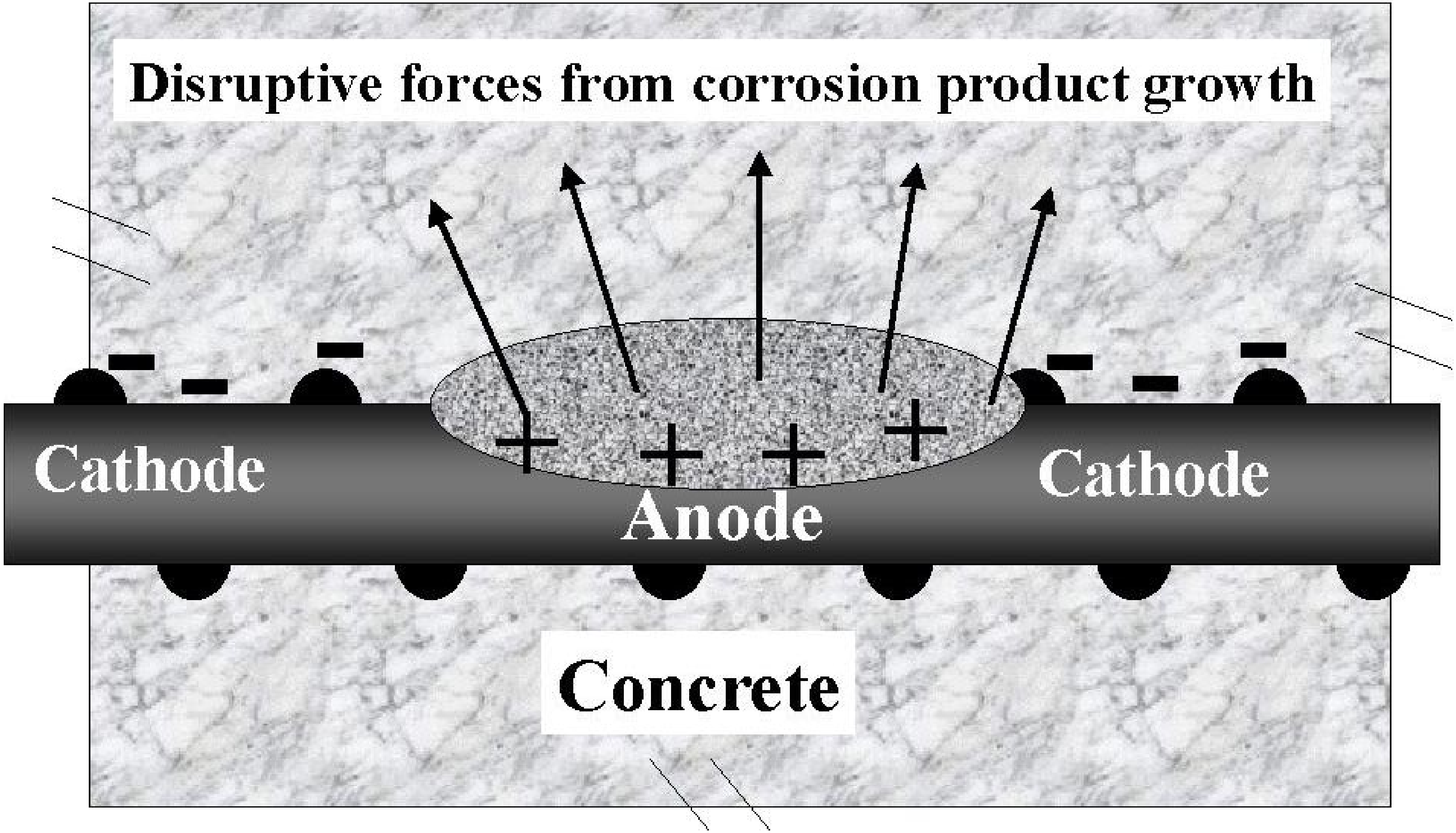

Figure 1. Schematic of embedded reinforcement corrosion cell

Note 1 – In cases of low oxygen activity at the anode, “black rust” may form, which will not lead to disruptive forces but can lead to rapid section loss and subsequent risk of structural failure.

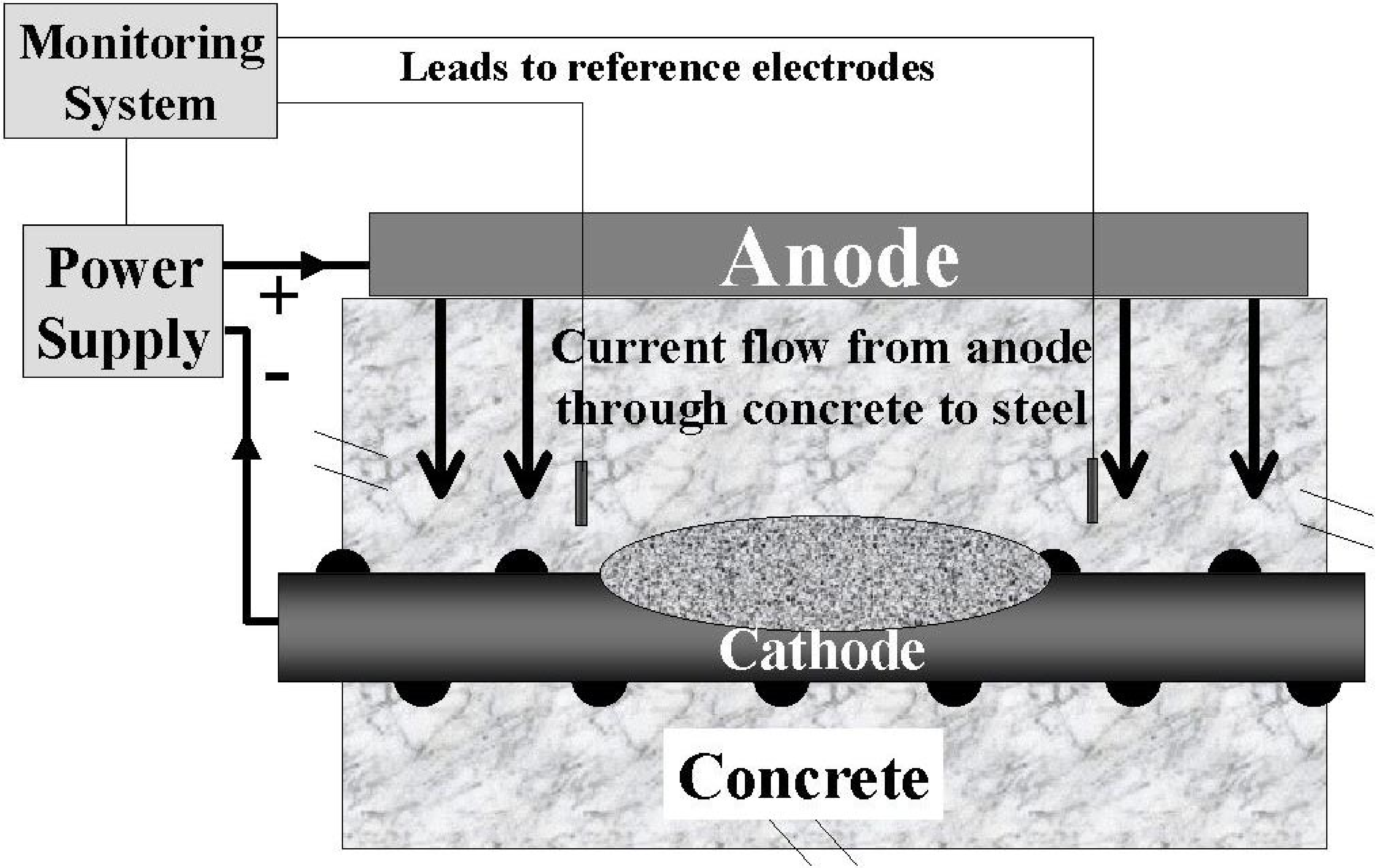

Figure 2. Schematic diagram of impressed current cathodic protection

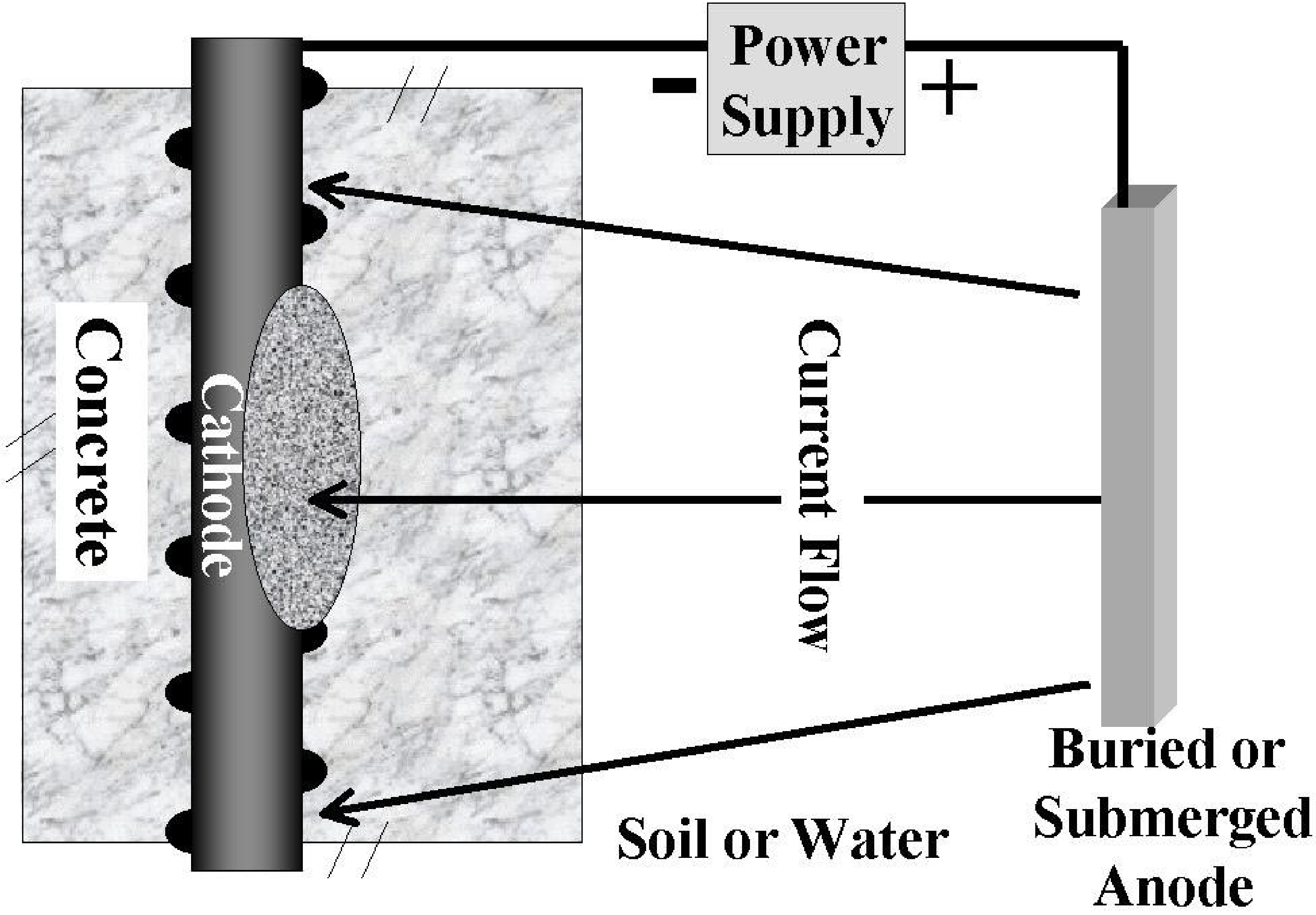

Figure 3. Impressed current cathodic protection schematic for buried or submerged steel in concrete

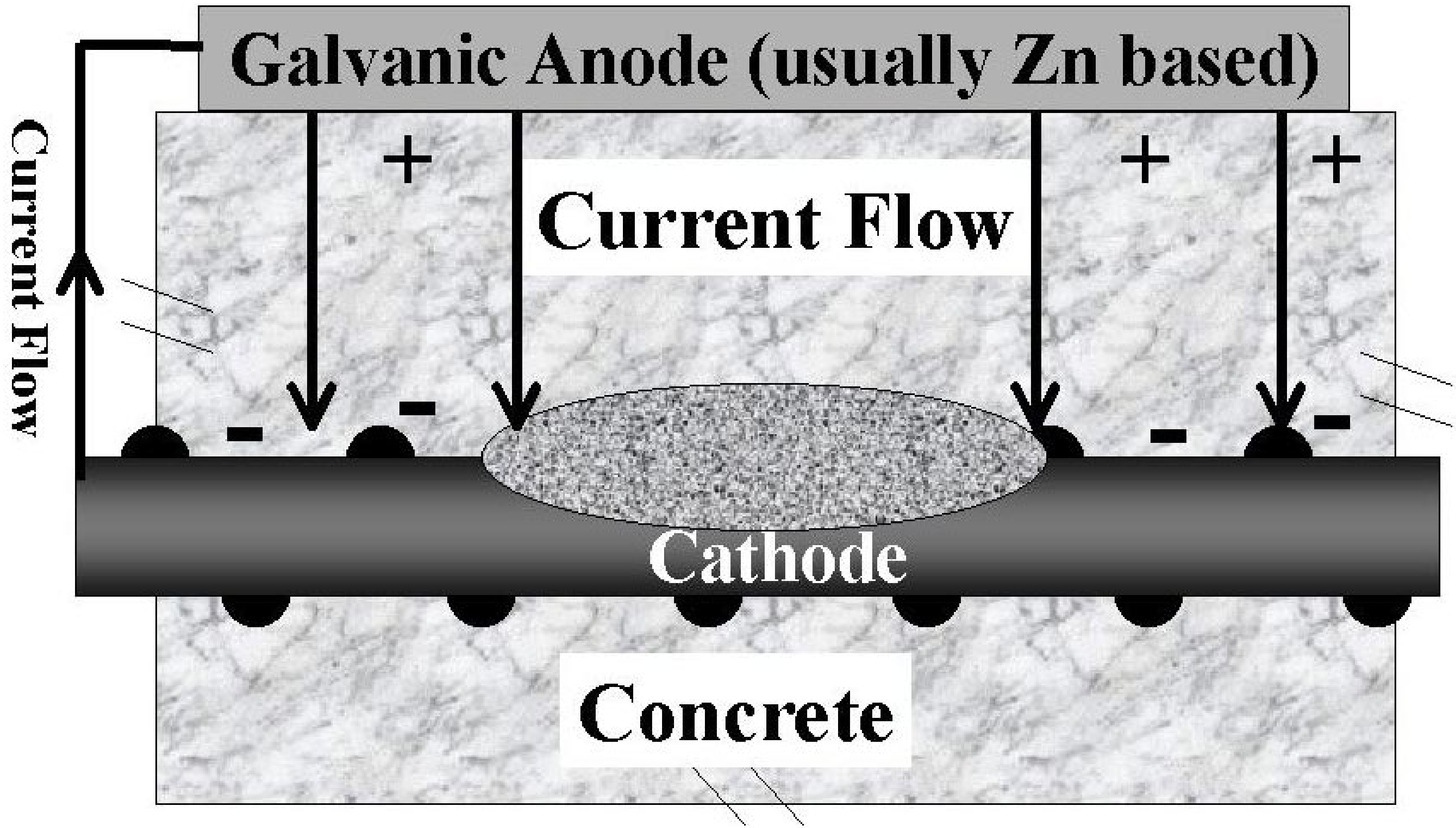

Figure 4. Schematic diagram of galvanic anode cathodic protection system

Table 1 – Anode Types and Characteristics

Anode Type See Note 1	Long Term Anode Current Density per m² of anode	Long Term Current Density per m² concrete	Supplier's Typical Anode Life Estimate See Note 2	Suitable for Wet Structures	Suitable for Running Surfaces	Dimensional & Weight Impact/ Installation	Other Performance Queries (Seek Specialist Advice)	Typical Installed Anode Cost Incl. Surface Preparation (2000 Costs) See Notes 3-8
Conductive Organic Coatings	$20mA/m^2$	$20\ mA/m^2$ Max	Up to 15 years	No	No	No Painted	Some unproven products	£20-£40/m²
Sprayed zinc	$20mA/m^2$	$20mA/m^2$ max	Up to 25 years	Possibly	No	No Thermal Spray	Limited UK experience Health & Safety during application	£60-£100/m²
Mixed metal oxide coated titanium (MMO Ti) mesh and grid in cementitious overlay	$110\text{-}220mA/m^2$	$15\text{-}110\ mA/m^2$ varying grades	Up to 120 years	Yes	Yes	Yes In circa 25mm overlay	Overlay Quality Control	£60-£100/m² including overlay
Discrete MMO Ti anodes, with carbonaceous surround	$800mA/m^2$ from carbonaceous surround	Circa 10-110 mA/m^2 subject to Distribution	Up to 50 years	Yes, not tidal	Yes	No Placed in pre-drilled holes		£40-£100/m²
Discrete anodes in cementitious surround. MMO Ti or Conductive ceramic	$800mA/m^2$	Circa 10-110 mA/m^2 subject to distribution	Up to 50 years	Yes	Yes	No Placed into holes or slots		£40-£100/m²
Cementitious overlay incorporating nickel plated carbon fibre strands	$20mA/m^2$	$20mA/m^2$ Max	Up to 25 years	Yes, not tidal	Yes, under wearing course	Yes Sprayed, circa 8mm thick	Limited experience	£30-£60/m²

Table 1 Notes

Note 1. Anode technology for reinforced concrete is rapidly evolving. The information reflects only those systems that have been relatively widely used before Year 2002.

Note 2. The performance of each element of the complete anode system is as important as the durability of the anode itself. The latest literature and experienced specialists should be consulted when determining the life of any particular anode system for any particular application.

Note 3. Transformer-rectifier/manual monitoring and cabling costs are additional. Year 2000 costs can be budgeted as £1,000 to £2,000 + £10 to £20/m^2.

Note 4. Remote monitoring and control capital costs are additional, Year 2000 costs are up to £6000.

Note 5. Future operation monitoring and control costs are extra.

Note 6. Preliminaries, access, traffic management and concrete repair costs are not included.

Note 7. For a typical 4 zone cathodic protection system, manual performance assessment and simple reporting regime costs (in 2000) are £1,500 - £2,500 per annum which can be reduced to £1,000 - £1,500 per annum by using remote monitoring and one visual inspection.

Note 8. All life and cost information is indicative. This information is for pre-budget assessments only. Full performance and cost details for individual systems and applications should be sought from specialists prior to selecting a particular system for a particular project.

3. ASSESSMENT PRIOR TO CATHODIC PROTECTION

General

3.1 Cathodic protection is generally selected for one of two reasons, either it is the only technically suitable treatment or it is the most cost effective treatment. Both arguments are structure specific and will require careful assessment of the structure and its condition.

Evaluation of Structure

3.2 In order to determine the most technically suitable and cost effective repair, the structural, physical and electrochemical condition must be determined by examining the documentary evidence in the form of inspection and testing reports and by specific site investigation. It is essential to determine the reasons for reinforced concrete deterioration. Cathodic protection may be considered as an option when dealing with reinforcement corrosion, but not other forms of deterioration.

It is also important to understand the reinforcement details in order to choose the most suitable anode and to design the system correctly. It is assumed that the structural integrity is fully assessed and the structure will be maintained in a safe condition before, during and after treatment.

All available drawings and relevant records are reviewed to assess the location, quantities, nature (eg smooth, ribbed, galvanised, epoxy coated, prestressed) and electrical continuity of reinforcement. The available information is confirmed and supplemented as necessary by site and laboratory tests as described below.

Life cycle cost analysis

3.3 Cathodic protection usually leads to significant whole life cost savings compared with the alternate long term repair option of removal and replacement of all chloride contaminated concrete, when the entire repair and maintenance cycle for the structure is calculated.

Cathodic protection is likely to be an effective method of corrosion control for those structures that require a long residual life after repair. Further cycles of patching will be avoided and only maintenance of the anode system, cabling and electronics will be required.

Comparison of cathodic protection with other techniques

3.4 When selecting a treatment for corrosion damaged reinforced concrete, the advantages and limitations of the different treatment methods must be evaluated. Irrespective of the selected treatment to control or repair corrosion related damage it will normally be advantageous to minimise future chloride contamination by dealing with the source of the problem, and the counteraction of leakages. Improvements to the provision or maintenance of drainage, replacement expansion joints and waterproofing must be considered and the use of pore lining impregnants such as silane (DMRB Vol.2.4.2 BD 43 and MCHW Vol.1 and 2). The main treatments available for highway structures can be summarised as follows:

i) Do Nothing - acceptable if either a short life is required or to await full or partial replacement. May be supplemented by other measures such as enclosure or some form of containment if there is a risk of concrete delamination. May be supplemented with corrosion monitoring (see below).

ii) Patch Repairs - Usually required prior to any other treatment. Patches may exacerbate corrosion in adjacent areas due to the "incipient anode" effect, where a corroding anodic area is protecting the adjacent reinforcement, but once patch repaired the adjacent reinforcement starts corroding in chloride contaminated concrete. Discrete galvanic anodes may sometimes be incorporated into patch repairs in order to help control this phenomenon.

iii) Coatings – pore lining impregnants such as silane are usually applied to elements exposed to chlorides before opening the structure to traffic. However, once sufficient chlorides are present at reinforcement depth then application will not stop corrosion but may reduce the corrosion rate.

iv) Concrete Replacement - it may be feasible to remove all corrosion damaged and chloride contaminated concrete, eg where salt water run down occurs in a well-defined area of a bridge substructure.

v) Cathodic Protection - will control corrosion across the whole area treated. Reduction in extent of concrete repair, with associated reductions in programme period, noise, dust, propping and traffic management. Cathodic protection usually requires a permanent electricity supply to run the system and regular monitoring and adjustment by qualified personnel. If remote monitoring is installed then a permanent communication link is usually required.

vi) Electrochemical Chloride Extraction (also known as desalination or chloride removal). This involves temporary power supplies, anodes and typically liquid electrolyte in temporary shutters. The system operates on the same principle as cathodic protection but the current density is 1000 – 2000mA/m^2 (c.f. 10-20mA/m^2 for cathodic protection) and the treatment for 3 to15 weeks changes the concrete chemistry. Chlorides are extracted into the liquid electrolyte for eventual disposal and very high levels of hydroxyl ions are generated at the steel.

Life and effectiveness of treatment are still being assessed, and are likely to be structure specific in terms of concrete quality, cover, reinforcement details, chloride content and exposure. Initial costs are similar to cathodic protection but contract periods may be longer.

Chloride extraction does not need permanent power supplies. In principle, monitoring is also not required although in practice checks on the corrosion condition are recommended to determine the life of the treatment. Chloride extraction may not provide adequate corrosion control if chloride contamination continues.

vii) Realkalisation – the equivalent of chloride extraction but used where the structural concrete is carbonated. Its description is similar to that provided for chloride extraction in (vi) above but the treatment time is typically 5-15 days. The electrolyte is selected to assist in re-establishing the original highly alkaline conditions within the concrete cover, thereby controlling the corrosion. It is not suitable for chloride contaminated or for both chloride contaminated and carbonated structures.

viii) Replacement - A properly designed replacement element or structure has advantages but also has financial and logistical disadvantages.

ix) Corrosion Inhibitors – for information on the life and effectiveness of corrosion inhibitors reference should be made to BA 57 (DMRB Vol.1.3.8).

x) Corrosion/Durability Monitoring - may be installed to monitor the ingress of chlorides and the initiation of corrosion of structures in harsh environments or to monitor the performance after many of the above treatments, including do nothing, and around the edges of repairs or concrete replacement. Corrosion monitoring has also been installed to monitor new structures.

Site Survey

3.5 All areas of the structure requiring cathodic protection are checked for delamination of the concrete cover. Defects such as cracks, honeycombing, or poor construction joints that permit significant water penetration and could impair the effectiveness of the cathodic protection, are recorded.

Chloride content, in increments of depth through the cover zone and past the reinforcement may be measured at representative locations. Carbonation depth measurements may also be conducted at representative locations.

Representative concrete cover and reinforcement dimensions are measured, for correlation with chloride and carbonation measurements and to confirm the documentation of reinforcement quantities and location. The risk of electrical short circuits between anodes and reinforcement and with other steel such as tie wires is also assessed.

3.6 The documentary information is assessed and supplemented with tests to confirm the extent of electrical continuity within and between elements. This is usually carried out as part of the potential (half-cell) survey but should also be performed on a representative basis as follows:

a) electrical continuity between elements of the structure within each zone of the cathodic protection system;

b) electrical continuity of reinforcement within elements of the structure;

c) electrical continuity of metallic items, other than reinforcement, to the reinforcement itself.

3.7 Potential surveys of representative areas, both damaged and apparently undamaged, are carried out using portable equipment. Measurements are taken, preferably on an orthogonal grid, at a maximum spacing of 500 mm.

It may not be necessary to carry out a steel/concrete/reference electrode potential survey of the entire structure. It may be appropriate to survey in more detail those areas where reference electrodes are planned to be permanently installed in order to place them in the most anodic areas and other suitable locations.

Electrical continuity of the reinforcement within any survey area is essential and should be verified before the steel/concrete potential survey.

Measurements in areas identified as delaminated should be treated with caution. Delaminations can produce readings inconsistent with the level of corrosion of the reinforcement.

Existing repairs are checked to ensure they are in good condition and are compatible with cathodic protection, ie capable of passing current to the reinforcement.

Merits of cathodic protection

3.8 There are a number of merits of cathodic protection:

- undamaged chloride contaminated or carbonated concrete does not require replacement; concrete repair costs are consequently minimised;
- since concrete breakout is minimised, then it is likely that temporary works such as structural propping during repair will also be minimised;
- concrete repair work and structural propping frequently requires lane closures and traffic control. These costs are consequently minimised;
- minimising concrete breakout reduces uncertainties over structural behaviour due to redistribution of stress;
- there is no need to cut behind the rebar to remove chlorides. In practice this may be required, in part or whole, to ensure adequate bonding of the patch repair material;
- cathodic protection controls corrosion for all the steel regardless of present or future chloride level or carbonation;
- cathodic protection can be applied to specific elements, eg cross heads, or to entire structures;
- the cathodic protection current controls corrosion in areas adjacent to concrete repairs that would normally require removal if only patch repairing were carried out;
- the requirement for regular monitoring of a cathodic protection system is usually regarded as an argument against cathodic protection. However, it means that a continuous assessment of the corrosion condition is available;
- the integration of continuous corrosion condition monitoring can be an important benefit for critical structures and for structures in severe exposure conditions. Costs of continuous monitoring, inspection and control are low (typically less than 5 man-days per year).

Cathodic protection of Critical/Sensitive Elements

3.9 Particular caution and attention to detail is required when considering the application of cathodic protection to critical or sensitive elements such as concrete hinges or half joints.

The existing condition and structural performance of these elements must be fully assessed in order to determine that controlling corrosion by the application of cathodic protection will result in continued safe operation. Further, as these elements tend to have very complex reinforcement details the cathodic protection design, in particular in respect of distribution of current and the adequate provision of performance monitoring devices, requires careful attention.

It is recommended that such systems should be the subject of a fully independent cathodic protection and structural design check and certification. (See Clause 5.2).

Cautionary Notes for Cathodic Protection

3.10 Cathodic protection requires good electrical continuity of the reinforcement. Fusion bonded epoxy-coated reinforcement is difficult to cathodically protect unless the reinforcement cage has been made electrically continuous prior to coating. Any other organic coatings would have similar problems. Metallic coatings on the reinforcement (eg galvanising) will change the requirements for cathodic protection control and would need proper evaluation.

3.11 There is a theoretical risk that the alkali generated at the reinforcement by the cathodic reaction could exacerbate any tendency for alkali silica reaction in the aggregates. BS EN 12696 states "Cathodic protection applied in accordance with this standard has been demonstrated to have no influence on alkali silica reaction/alkali aggregate reaction (ASR/AAR)." However, if ASR/AAR is a principal cause of deterioration and not reinforcement corrosion, cathodic protection alone will not be an appropriate solution.

3.12 Cathodic protection works by changing the steel/concrete potential which is measured between an embedded reference electrode and the steel. If the potential becomes too negative, the cathodic reaction generates excessive hydrogen. Prestressing steel may be sensitive to hydrogen embrittlement and, due to the high tensile loading of prestressing members, failure can be catastrophic. The risk of hydrogen embrittlement is even more acute if there is any corrosion of the prestressed steel as pits or notches form initiation sites for failure and are more susceptible to hydrogen evolution and as initiation sites for failure.

It is not currently recommended to apply cathodic protection to any prestressed or post-tensioned concrete elements. If there are no other viable remediation options, and provided the tendons are in good condition with no corrosion, then cathodic protection may be considered. Such applications should be provided with the necessary sub-division of anodes into small zones with detailed performance monitoring devices, in particular reference electrodes, in order that excessive cathodic protection is avoided. It is recommended that such systems should be the subject of a fully independent cathodic protection and structural design check and certification (See Clause 5.2).

3.13 Cathodic protection applied in accordance with the procedures described in BS EN 12696 to reinforced concrete has been demonstrated to have no adverse effects on the bond between reinforcement and concrete.

4. CATHODIC PROTECTION SYSTEM OPTIONS

General

4.1 Alternative cathodic protection systems are summarised in Chapter 2.

Impressed Current Systems versus Galvanic Anode Systems

4.2 The majority of cathodic protection systems applied to reinforced concrete internationally and, particularly in the UK, are impressed current systems where the electrical d.c. power supply is a mains powered transformer-rectifier or similar power supply. These systems can be controlled to accommodate variations in exposure conditions and future chloride contamination.

4.3 Galvanic anode systems have been used in relatively minor trials in the UK and are reported to be quite successful in trials in the USA, particularly in hot humid, marine, conditions where the electrical resistivity of the concrete will be low. It is considered that more extensive performance data are required for galvanic anode systems applied to atmospherically exposed reinforced concrete in UK conditions before their use is recommended for highway structures in the UK.

Power Supplies

4.4 Typically the power supplies for cathodic protection systems are rated at 0-12 volts for conductive coating or mesh anode systems and 0-24 volts for discrete anode systems or for special applications where a high resistance between anode and reinforcement is anticipated.

4.5 The most common power supply for the low voltage d.c. requirement is a transformer-rectifier, itself supplied from the single-phase mains distribution system. Switched mode power supplies are also widely used. The d.c. power supply will normally also be used as a point at which the performance monitoring system is terminated for either local or remote monitoring.

The d.c. power supply may be controlled:

- manually;
- remotely via a modem;
- a combination of both.

4.6 Where a.c. power is not available solar panels and wind generators can provide the necessary power.

Anode Systems

4.7 There are a variety of anode systems that are summarised in Chapter 2. In addition to those anode systems described in this Advice Note there are emerging systems. Where such systems are proposed, evidence should be provided to demonstrate adequate performance and a high probability of achieving the desired design life. This evidence should include properly researched and monitored accelerated laboratory testing and field trials. Field trials should incorporate a minimum of two UK winters and should be applied to a civil engineering structure exposed to conditions that are representative of the environment of the highway structure being considered as a recipient of the new anode system.

4.8 Where the foundations are either buried or immersed in sea or brackish water, it may be appropriate to apply cathodic protection using buried or immersed anodes remote from the foundations. These anodes are of a significantly lower cost for material supply and installation than the anodes in Table 1, which are specifically designed for installation into and onto concrete.

Galvanic anodes of magnesium (normally for soil applications), zinc or aluminium alloys (normally for sea water applications) or impressed current anodes (high silicon cast iron, mixed metal oxide coated titanium or magnetite), have a long and proven record in the applications of cathodic protection to steel exposed to soils and waters.

4.9 Typically these anode systems in soils or waters can be designed with an anticipated life in the range 20-40 years, but they are easier to replace than anodes installed in or on concrete. Expressed as a cost per square metre of concrete being protected their cost would be typically in the range £5-£15 per m^2 at 2000 costs.

Other Life Determining Factors

4.10 By appropriate anode selection and design it is possible to provide cathodic protection systems with design lives in the range 10 to 120 years.

4.11 Many cathodic protection systems, particularly those using mixed metal oxide coated titanium mesh or grid anodes encased in cementitious overlays, will encase all cabling within the concrete and thereby protect the equipment from environmental damage and, in particular, vandalism.

The environment for cables will be particularly extreme with the concrete being highly alkaline. Also the anodic reaction products generate acidic conditions adjacent to the anodes, requiring careful selection of sheath materials, particularly if the cable is in close proximity to the anode.

4.12 Cabling systems installed on the external surfaces of highway structures in cable trays or similar cable management systems have been vulnerable to vandalism and present maintenance problems. Wherever possible, cables should be buried in chases within the concrete for protection.

4.13 Transformer-rectifiers, monitoring systems and their enclosures are vulnerable to damage and to atmospheric corrosion. Their specification and location should aim to minimise the risks of vandalism and mechanical damage and the enclosure should provide environmental protection against the worst case environment in accordance with IEC 529.

The enclosure materials and/or corrosion protection treatment should provide a minimum of 10 years to first maintenance in respect of atmospheric corrosion. It is probably reasonable to anticipate a 25 year life before replacement of the electrical and electronic systems that comprise the transformer-rectifiers and monitoring systems.

Performance Monitoring Systems

4.14 As outlined in Chapter 2, the performance of cathodic protection systems is monitored by measuring the effects of the cathodic protection current flow on:

a) steel/concrete potential measured with respect to reference electrodes installed in the concrete adjacent to the steel;

b) steel/concrete potential measured with respect to reference electrodes or (less accurate) probes installed in the concrete and the magnitude of potential decay with time after the cathodic protection system is switched off.

4.15 Reference electrodes or probes should all be selected on the basis of sufficient documentary data from the manufacturers or system suppliers to demonstrate their accuracy, their functional ability and their longevity as required within the cathodic protection system.

Suitable Reference Electrodes are:

- silver/silver chloride/0.5M potassium chloride gel electrode
  (Ag/AgCl/0.5M KCl)

- manganese/manganese dioxide/0.5M potassium hydroxide electrode
  (Mn/MnO_2/0.5M KOH).

4.16 Generally, accurate reference electrodes may have a life in the range 10-20 years. Potential measuring probes (sometimes called pseudo electrodes) may be less accurate but have a life expectancy well in excess of 20 years.

4.17 Steel/concrete/reference electrode potential measurements taken with the cathodic protection current switched ON will contain errors due to the voltage established by the current (I) flowing through the resistive (R) concrete and films on the reinforcement. These are termed IR drop errors. To avoid these errors the steel/concrete potential is measured “instant off” typically between 0.1 seconds, and 0.5 seconds after switching OFF the cathodic protection current.

The absolute value of the steel/concrete potential is one of the criteria in BS EN 12696, as well as the decay from that value over a period of 24 hours or longer with the cathodic protection current switched OFF, as in 2.10.

4.18 The voltage or current signals from the performance monitoring reference electrodes or probes and their associated connections to the steel reinforcement can be monitored manually, locally at the structure or can be data logged either locally or via a modem interface for remote interrogation and data collection.

4.19 Remotely controlled distributed d.c. power supplies typically incorporate remote monitoring and control as an integrated part of their package. The larger multi-channelled systems in centralised enclosures can typically be provided with or without remote monitoring.

4.20 Remotely controlled and/or remotely monitored cathodic protection equipment can transmit their data and be commanded with control instructions via the full range of communication networks including hardwired telephone, wireless (mobile) telephone, e-mail, radio, etc. Consideration should be given to possible extensions of the cathodic protection system and associated communication network and the relative merits of simple stand-alone systems or extensive networked systems. Competitive procurement issues may be complex in this sector.

4.21 Typical costs of a remote monitoring and control system are presented in Table 1.

Cathodic Protection of New or Undamaged Structures

4.22 Cathodic protection can be applied to reinforcing steel in concrete that is not presently corroding to prevent depassivation and corrosion when chloride levels at the steel concrete interface eventually become sufficiently high. This is sometimes referred to as ‘cathodic prevention’.

4.23 The use of cathodic prevention can be considered at construction for any structure where the exposure conditions to chlorides will mean that significant corrosion will occur during the design life of the structure. This might include the tidal zones of marine highway support structures or tunnels where the external ground water or estuarine conditions are saline. As yet it has not been extensively used in the UK but it is increasingly used in regions with severe durability problems.

4.24 Cathodic prevention, particularly if installed at the time of construction, is likely to be significantly lower in cost than cathodic protection installed during the service life of a structure.

4.25 Where chloride contamination due to exposure is considered to be sufficient to result in corrosion damage during the design life of the structure, but does not presently justify the installation of a cathodic prevention system at construction, consideration may be given to the installation of a corrosion/durability monitoring system. This would give early warning of the ingress of chlorides, and the ability to plan a cathodic prevention system installation or other preventative maintenance.

5. DESIGN PROCESS AND PROCUREMENT

Procurement and Design Routes

5.1 A number of established routes are available for the design and procurement of cathodic protection systems for reinforced concrete. The main alternatives can be outlined as follows:

i) Full and detailed design and specification by the Client's Consultant, with no design responsibility upon the Contractor. Such an approach may be appropriate for stages of a phased repair programme where consistency and continuity of design is considered essential.

Novel and innovative installations, where the risk of technical and practical problems is higher, may also benefit from this approach.

A disadvantage of this approach is that the experience of the Contractor is excluded until the installation phase of the project.

ii) Detailed performance specification and outline cathodic protection design by the Client's Consultant, with the Contractor responsible for the detailed system design. This is a widely used approach and has many advantages both technically and practically.

An advantage of this approach is that the experience and ingenuity of the Contractor can influence the final design, typically subject to checking and approval by the Client.

iii) Detailed performance specification and outline design by the Client's Consultant with restricted design scope for the Contractor, for example, through the exclusion of certain anode options. This approach can allow the experience of the Contractor to contribute to the design while controlling particular aspects of the installation and as such may be seen to have many of the advantages of both i) and ii).

iv) Full and detailed specification and design by the Contractor as part of a design and build package. In principle, this approach should allow procurement procedures to be simplified.

As with all procurement and design routes, the experience and capabilities of the personnel involved should be carefully controlled and monitored. See 5.3.

Design Review/Certification

5.2 On completion of the detailed cathodic protection design, irrespective of the procurement route, the principal aspects of the design should be subject to review by appropriately experienced personnel. See 5.3.

As a minimum, a design review should include the following:

i) Review of existing data as employed by the designer during the selection and design of the cathodic protection system.

ii) Review of design methodology and comparison with specification and any outline system design.

iii) Numerical checks of critical and other selected design calculations, including evaluation of any assumptions made.

iv) Preparation of concise report, detailing the findings from i) - iii) above and stating clearly how the design conforms to the specification. The report should also highlight any technical or practical concerns that have been identified.

In certain cases, the contract will demand the completion of a formal certificated independent design check, clearly stating that the design is consistent with the specification and highlighting any aspects of the design that are not in accordance with the specification.

Personnel

5.3 Due to the specialised nature of cathodic protection, and its design, specification and installation for reinforced concrete structures, it is essential that the experience and capabilities of key personnel are established prior to any works proceeding.

All works resulting in the production of a specification, system design (outline or detailed), the installation, commissioning and operation should be overseen by experienced personnel with at least one of the following:

i) An appropriate degree plus a minimum of three year's responsible experience in the design and specification or installation and operation (as appropriate) of cathodic protection systems for reinforced concrete.

ii) Professional Membership in the Institute of Corrosion or Certificated as a Cathodic Protection Specialist or Corrosion Specialist of NACE International plus a minimum of three years' responsible experience in the design and specification or installation and operation (as appropriate) of cathodic protection systems for reinforced concrete.

In all cases, evidence of qualifications, experience and details of previously installed and operational cathodic protection systems should be sought prior to the approval of specialist personnel.

Where an organisation cannot provide such personnel from their own permanent staff, it is acceptable for an appropriate external specialist or company to be brought in as a specialist consultant or contractor.

It is common practice for the Consultant and Contractor for cathodic protection contracts to be members of the Corrosion Prevention Association (CPA).

Quality Management Systems

5.4 The various, well-defined stages associated with the specification, design, installation and operation of cathodic protection systems for reinforced concrete structures can be readily integrated into an appropriate Quality Management System. Such systems are widely operated by the majority of Consultants and Contractors (eg under BS EN ISO 9000).

Quality Management System requirements should be defined in the contract. Appropriate documents may include:

i) Quality Plans;

ii) Design/Calculation Sheet;

iii) Design Review/Certification;

iv) Method Statements and Material Data Sheets;

v) Installation Test Records;

vi) Commissioning and Performance Documentation;

vii) As-Built Drawings of concrete repairs and the cathodic protection systems.

6. INSTALLATION

Removal of Damaged Concrete/Old Repairs

General

6.1 The installation should be overseen by personnel with the experience and expertise detailed in 5.3. The installation will incorporate specialist trade skills which may include concrete repair, surface preparation, coating application, sprayed concrete application and specialist cathodic protection component installation skills. These skills should be demonstrated and documented to appropriate levels for both trade operatives and site supervisors. In the planning and execution of the work all the normal construction industry requirements regarding safety, risk assessments, safety plans and environmental assessments should be properly addressed.

6.2 The original concrete and previous repairs are required to conduct the electrical current from the anode to the steel reinforcement. In order to achieve a uniform current distribution the concrete needs to be sound and the electrical resistivity of the repairs should be within the range 50% - 200% of that of the parent concrete.

6.3 All areas of unsuitable or defective concrete identified during the survey are removed and any exposed reinforcement prepared by removing all loose corrosion scale, and if necessary replaced.

It is not necessary to remove sound but chloride contaminated or carbonated concrete.

Electrical Continuity of Steel Reinforcement

6.4 Electrical continuity checks are carried out by either measurements of electrical resistance or potential difference, at representative locations and for all reinforcement in concrete repair areas, within the vicinity of the cathodic protection system.

These checks are to ensure electrical continuity within the reinforcement. If discontinuity is found appropriate electrical bonding should be carried out.

6.5 If the structure incorporates other metallic components within the area of the cathodic protection system or adjacent to the cathodic protection system (eg drainage pipes, brackets, dowel bars, bearings), it is necessary to either bond the metallic components to the cathodic protection system negative (reinforcement), or to electrically isolate the metal from the system negative.

Installation of Negative Connection and Performance Monitoring Equipment

6.6 Negative connections are required between the reinforcement and the transformer-rectifier. A minimum number of two negative connections should be made in each zone.

6.7 Reference electrodes are installed to enable the measurement of the potential of the steel/concrete interface. Reference electrodes should be installed at anodic locations in each zone.

6.8 All electrodes and probes should be installed within a concrete breakout or drilled hole that does not disturb or affect the surrounding concrete around the element of reinforcement to be measured, ie reinforcement should NOT be exposed within 0.5m of the electrode, probe or coupon.

Concrete Repairs

6.9 Concrete repairs are required to reinstate the concrete to its original profile where cracking or spalling has occurred or where the previous repairs are unsuitable.

It is not necessary to remove sound but chloride contaminated or carbonated concrete.

6.10 Standard concrete repair techniques based on best practice guidance and the manufacturer's recommendations should be used to reinstate the concrete. The concrete repair materials should be selected for their compatibility with cathodic protection systems as in 6.2 above.

The steel reinforcement should not be primed and no bonding agents should be used.

6.11 Where an anode system is being applied to the surface of the concrete, repairs should be cured without the use of a curing membrane.

Anode Installation

6.12 The concrete should be prepared prior to the installation of the anode. For surface mounted anodes the concrete should be adequately prepared to ensure a good physical bond between the concrete and the anode or its overlay. Surface preparation should present a clean, sound, dust free surface of suitable roughness and exposure of aggregate for the various anode or overlay types.

6.13 Internal anodes should be inserted into chases or holes cut into the concrete. Chases may need to be grit blasted to provide a physical key for the cementitious backfill. Holes do not normally require any further preparation.

6.14 During the installation of anodes it is important to check for any possible electrical short circuits between the anode and the steel reinforcement and that anode/steel spacing is adequate.

6.15 The concrete should be inspected to identify any tie wire or steel which may short-circuit to the anode. Particular attention should also be given to any soffit areas where there may be loose tie wire etc. on the surface.

6.16 Conductive coating anodes may be spray applied or hand applied (roller or brush). The anodes have a primary anode which distributes the current evenly to the anode surface. The primary anode is usually a metal wire or ribbon which is either fixed to the concrete surface prior to the anode application or is incorporated into the coating film.

6.17 Titanium mesh or grid anodes should be fixed to the concrete surface using plastic fasteners. Anode sections are interconnected with spot welded titanium strip which may also be used as current distributors. The anode should be encapsulated in a cementitious overlay that can be either spray applied or cast.

6.18 Internal anodes should be embedded in concrete chases or holes using cementitious material or graphite backfill.

6.19 A minimum number of two anode/cable connections should be provided in each anode zone.

6.20 The correct installation of the anode is essential for the success of the cathodic protection system. It should only be undertaken by appropriately trained personnel.

Electrical Installation

6.21 All power supplies, monitoring systems and cables should be installed to provide adequate protection from vandalism and the environment. Where the risk of vandalism is high, cabling should be embedded within the concrete surface.

6.22 Prior to energising, the system should be tested to prove the function and polarity of all circuits. These tests should be documented.

Commissioning

6.23 Before energising, the “as found” condition should be established by measurement of steel/concrete potentials at permanently embedded reference electrodes.

6.24 Initial energising should be at low current and should be immediately followed by testing to demonstrate that all zones are operating correctly.

6.25 The system should then be adjusted to a suitable level of current and allowed to operate for a period before Performance Monitoring (typically 28 days).

Records

6.26 During the installation the cathodic protection contractor must maintain adequate and accurate records. The documentation shall comprise the following:

i) Installation Record Drawings

ii) Test Reports and Data

iii) Certification of materials

iv) COSHH information

The Installation Record Drawings shall show all cathode (including reinforcement bonding positions), anode and connections, reference electrode, corrosion rate probes, cabling layouts and junction box positions.

The records will form part of the Maintenance Manual for the structure.

Training

6.27 Before the completion of the Contract, arrangements should be made to provide training for staff of the Maintenance Organisations for ongoing management of the cathodic protection system. In some cases it may be possible or desirable to retain specialist advisers to manage the system. Consideration must be given to the procurement of such services.

7. PERFORMANCE ASSESSMENT, INSPECTION AND MAINTENANCE

7.1 The intervals and procedures for routine inspection and testing vary from one cathodic protection system to another dependant upon the structure, the cathodic protection system type, the reliability of power supplies, the environment and the vulnerability to damage.

7.2 Those systems provided with electronically data logged or electronically data transmitted performance monitoring systems may require less frequent physical inspection as the routine testing can be undertaken automatically.

7.3 Consideration can be given to extending the intervals between routine inspection and testing if no faults, damage or significant variation in system performance are indicated by successive inspections/tests.

7.4 Routine inspection procedures are typically as follows:

a) Function Check comprising:

- confirmation that all systems are functioning
- measurement of output voltage and current to each zone of the cathodic protection system
- assessment of data.

Typically, the Function Check should be undertaken monthly in the first year of operation and, subject to satisfactory performance, thereafter at 3 monthly intervals.

b) Performance Monitoring comprising:

- measurement of “instant OFF” IR error free polarised potentials
- measurement of potential decay over a period of 24 hours or longer
- measurement of parameters from any other sensors installed as part of the performance monitoring system
- limited visual inspection
- assessment of data
- adjustment of current output.

Typically the Performance Monitoring should be undertaken at 3 monthly intervals in the first year of operation and, subject to satisfactory performance and review at 6 monthly to 12 monthly intervals thereafter.

c) System Review comprising:

- a review of all test data and inspection records since the previous System Review
- full visual inspection
- preparation of a System Review report incorporating recommendations for any changes to the operation and maintenance or system review intervals and procedures. Cathodic protection systems that are operating in a reliable and stable manner can benefit from the reduced costs of extending the intervals between both Function Checks and Performance Monitoring.

Typically, the System Review should be undertaken annually.

7.5 Maintenance of the cathodic protection system is generally restricted to fault finding, replacement of electrical components within the d.c. power supply units, if required, repairs to cabling, trunking, conduit, junction boxes, repairs to conductive coating anodes and general maintenance to the power supply enclosure. See Table 1 for typical anode system life.

7.6 The requirement of cathodic protection systems to receive the routine inspection procedures described in Clause 7.4 must be addressed in the continuing management requirements of structures provided with cathodic protection. Both Function Check and Performance Monitoring work can be undertaken by properly trained technician grade personnel. Local staff can be trained for this work and this is often a requirement incorporated into a cathodic protection installation and commissioning contract.

Remotely monitored systems do not need to be visited for function checks. The maintenance procedures should be fully documented in maintenance and operation manuals.

The System Review activity should be undertaken by personnel who are appropriately expert and experienced as in Clause 5.3.

In the event of a cathodic protection system being adopted by different Maintenance Organisations or operators, the records and manuals should enable the continued satisfactory operation of the system.

8. BIBLIOGRAPHY

1. BS EN 12696: 2000 Cathodic Protection of Steel in Concrete. British Standards Institution, 2000.

2. CPA Corporate Members Directory.
ISBN: 0 9525190 5 4.
Web-Site: www.corrosionprevention.org.uk

3. BS 7361: Cathodic Protection. Part 1: Code of Practice for Land and Marine Applications, British Standards Institution, 1991.

4. "Cathodic Protection of Reinforced Concrete – Status Report", Corrosion Prevention Association (formerly SCPRC), Report No. 001.95, 1995.

5. Boam, K.J., Unwin, J. "The Midland Links – A Maintenance Strategy" Institution of Highways & Transportation, National Workshop - New Concepts for Management of Highway Structures, Leamington Spa, pp 59 to 73, 1990.

6. Unwin, J., Hall, R.J. "Development of Maintenance Strategies for Elevated Motorway Structures" Proc. 5th Intl. Conf. On Structural Faults and Repair, Ed. Prof. M.C. Forde. Vol. 1 pp 23 to 32., 1993.

7. CPA Monographs as listed in Reference 2 above.

8. DMRB Standard BD43 'Impregnation of concrete highway structures'.

9. DMRB Advice Note BA57 'Design for durability'.

10. MCHW Volume 1 'Specification for Highway Works'.

11. MCHW Volume 2 'Notes for Guidance on the Specification for Highway Works'.

9. ENQUIRIES

All technical enquiries or comments on this Advice Note should be sent in writing as appropriate to:

Head of Civil Engineering The Highways Agency St Christopher House Southwark Street London SE1 0TE	G BOWSKILL Head of Civil Engineering

Chief Road Engineer Scottish Executive Development Department Victoria Quay Edinburgh EH6 6QQ	J HOWISON Chief Road Engineer

Chief Highway Engineer The National Assembly for Wales Cynulliad Cenedlaethol Cymru Crown Buildings Cathays Park Cardiff CF10 3NQ	J R REES Chief Highway Engineer

Assistant Director of Engineering Department for Regional Development Roads Service Clarence Court 10-18 Adelaide Street Belfast BT2 8GB	D O’HAGAN Assistant Director of Engineering