

PETRONAS TECHNICAL STANDARDS

MANUAL

CATHODIC PROTECTION

PTS 30.10.73.10

JANUARY 2012



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PTS Title:	Cathodic Protection

This revision **PTS 30.10.73.10 – Cathodic Protection** (January 2012, Revision 0) has been updated to incorporate PETRONAS Lesson Learnt, Best Practice and new information issued by relevant industry code and standards. All updates in the documents are highlighted in *italic* font .

The previous version of this PTS (**November 2003**) will be removed from PTS binder/ e-repository from herein onwards.

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PREFACE

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They are based on the experience acquired during the involvement with the design, construction, operation and maintenance of processing units and facilities. Where appropriate they are based on, or reference is made to, national and international standards and codes of practice.

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Document Title: Cathodic Protection

This is a controlled document.

Acknowledgement

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1. INTRODUCTION

1.1 SCOPE

This PTS describes the basic principles for the control of corrosion of immersed, submerged or buried metal structures by cathodic protection, and gives guidance for the application, selection and design of cathodic protection installations.

This PTS should not be used as a cathodic protection design and/or construction specification. For such requirements, reference should be made to the various technical specifications or industry standards referred to in the relevant sections of this PTS.

This PTS is meant to provide sufficient background information to enable staff, responsible for the operation and maintenance of cathodic protection systems, to decide (in the absence of a specialist) if cathodic protection may be technically feasible and economically justifiable, and also to deal effectively with specialist consultants and contractors normally called in to carry out cathodic protection work.

Although the principle of cathodic protection is simple, its practical application calls for a certain skill and experience. In all but the most straightforward cases, experienced cathodic protection specialists should be consulted for the design of cathodic protection systems and for non-routine surveys and troubleshooting.

This PTS is a revision of the PTS of the same title and number dated November 2003. A summary of changes from the previous edition is listed in (1.7).

1.2 DISTRIBUTION, INTENDED USE AND REGULATORY CONSIDERATIONS

Unless otherwise authorised by PETRONAS, the distribution of this PTS is confined to companies forming part of or managed by the PETRONAS, and to Contractors nominated by them.

This PTS is primarily intended for use in oil and gas production facilities, but may also be used in oil refineries, chemical plants, gas plants and supply/marketing installations. When PTSs are applied, a Management of Change (MOC) process should be implemented. This is of particular importance when existing facilities are to be modified.

If national and/or local regulations exist in which some of the requirements may be more stringent than in this PTS, the Contractor shall determine by careful scrutiny which of the requirements are the more stringent and which combination of requirements will be acceptable with respect to health, safety, environmental, economic and legal aspects. In all cases the Contractor shall inform the Principal of any deviation from the requirements of this PTS which is considered to be necessary in order to comply with national and/or local regulations. The Principal may then negotiate with the Authorities concerned with the object of obtaining agreement to follow this PTS as closely as possible.

1.3 DEFINITIONS

1.3.1 General definitions

The **Contractor** is the party which carries out all or part of the design, engineering, procurement, installation, and commissioning or management of a project or operation of a facility. The Principal may sometimes undertake all or part of the duties of the Contractor.

The **Manufacturer/Supplier** is the party which manufactures or supplies equipment and services to perform the duties specified by the Contractor.

The **Principal** is the party which initiates the project and ultimately pays for its design and construction. The Principal will generally specify the technical requirements. The Principal may also include an agent or consultant, authorised to act for the Principal.

The word **shall** indicates a requirement.

The word **should** indicates a recommendation.

1.3.2 Specific definitions

cathodic protection - the process of reducing or preventing corrosion of metal structures in contact with an electrolyte by the flow of direct current from the electrolyte into the structure surface.

cathodic protection station - a combination of equipment installed to provide cathodic protection to the pipeline/steel structure.

corrosion potential - the theoretical potential of the surface, in the absence of net (external) electric current flowing to or from the steel surface (see also "natural potential").

current density - the amount of current per unit area of the steel surface, coated or uncoated, in contact with the electrolyte.

drain point - the point on pipeline where the negative terminal of the cathodic protection voltage source is connected to conduct (drain) the returning current from the pipeline to the voltage source.

electrolyte - a conductive liquid or material such as soil or water in which an electric current is transported by ions.

foreign structures/pipelines - metal structures or pipelines other than the one under consideration, in contact with the same electrolyte as the structure/pipeline under consideration, and which lie or may fall under the influence of that structure/pipeline's cathodic protection system.

Foreign structures/pipelines may be owned by the Principal or other companies, and may or may not be equipped with cathodic protection.

groundbed - the system of buried or submerged electrodes, to conduct the required current into and through the electrolyte to the steel surface to be protected.

midpoint - the point on a pipeline between two cathodic protection stations where the influence of the two cathodic protection stations is expected to be equal and the protection levels are usually lowest.

natural potential - the practical pipe-to-soil potential measured when no cathodic protection is applied and polarisation caused by cathodic protection is absent.

"INSTANT-OFF" potential - the pipe-to-soil potential measured immediately after the cathodic protection system is switched off and the applied electrical current stops flowing to the pipeline surface, but before polarisation of the pipeline has decreased.

"ON" potential - the pipe-to-soil potential measured while the cathodic protection system is continuously operating.

pipeline - the pipeline or pipelines with associated equipment as defined in the scope of the cathodic protection design contract.

steel-to-soil potential - the difference in electrochemical potential between a pipeline or foreign structure/pipeline and a specified reference electrode in contact with the electrolyte. Similar terms such as structure-to-soil potential, pipe-to-electrolyte potential, pipe-to-(sea)water potential are sometimes used as applicable in the particular context.

polarisation - the change of the pipe to soil potential caused by the flow of DC current between an electrolyte and a steel surface.

polarisation cell (Kirk cell) - a device inserted in the earth connection of a structure that isolates for DC in the cathodic protection range.

reference electrode - an electrode of which the electrochemical potential is accurately reproducible and which serves as a reference for pipe-to-soil potential measurements.

stray currents - electrical currents running through the electrolyte and originating from a foreign DC source, causing interaction with the corrosion and cathodic protection processes of the pipeline. Stray currents may also originate from the pipeline's cathodic protection system and act upon foreign structures/pipelines.

Amended per
Circular 24/08

Very toxic (substances) - substances that are very hazardous for the environment or human health, as specified in PTS 01.00.01.30. (which also identifies "toxic" substances by reference to chemical substances databases).

1.4 ABBREVIATIONS

AC	Alternating Current
Ag/AgCl	Silver/Silver Chloride as used for the Silver/Silver Chloride/Seawater type of reference electrode.
CIPS	Close interval potential survey
CP	Cathodic Protection
Cu/CuSO ₄	Copper/Copper Sulphate as used for the Copper/Copper Sulphate type of reference electrode.
DC	Direct Current
MMO	Mixed metal oxide (anodes)
ROV	Remotely operated vehicle

1.5 CROSS-REFERENCES

Where cross-references to other parts of this PTS are made, the referenced section is shown in brackets. Other documents referenced by this PTS are listed in (27).

1.6 PROPRIETARY NAMES

Names such as "Wenner", "Geonics", "Kirkcell" and "Swain" are used in this specification to indicate measuring techniques or equipment types, commonly understood by those names in cathodic protection engineering. It is not intended to indicate a requirement to apply equipment of that particular brand name.

1.7 CHANGES FROM PREVIOUS EDITION

The previous version of this PTS was dated November 2003. Other than minor editorial changes, the following are the major changes from the previous edition:

Old section	New Section	Change
1.8		Deleted
1.3.2	1.3.2	OFF potential is standardized as INSTANT-OFF potential throughout the PTS
2.3.3	2.3.3	Update on potential value based on NACE Manual
4.2	4.2	- Addition of example - Update the scope of isolation to include polarisation cells
4.3	4.3	Inclusion of requirement for overprotection for aged coatings.
5.2.1	5.2.1	- Addition of a column specifying potential for normal soil wrt Cu/CuSO₄ electrode. - Adding table 8 based on NACE Manual - Adding comment to refer to manufacturer's data
5.2.2	5.2.2	Adding comments on zinc anode properties in high

Old section	New Section	Change
		temperature
5.2.3	5.2.3	Adding description of ρ
5.3.3	5.3.3	Change the restriction of using mercury and cadmium activated anodes
5.4.1.1	5.4.1.1	Updating the composition of backfill ingredients
5.4.3	5.4.3	Adding comment for cad weld requirements
5.5	5.5	• Change MIL spec to manufacturer's data sheet to standardize usage of term • Updating NACE RP to SP
10.2.2.2	10.2.2.2	Standardized CIP survey to CIPS
10.2.2.3	10.2.2.3	Incorporating Pipeline Current Mapper (PCM) device
10.2.2.4	10.2.2.4	Addition of practical troubleshooting adopted from BS7361-1 and rearrangement of previous section
10.2.4	10.2.4	Addition of practical troubleshooting adopted from BS7361-1 and rearrangement of previous section
10.4	10.4	Updating of monitoring technologies
11.1	11.1	To include temporary CP system as integral part of CP design
11.2.1	11.2.1	Add a few examples
11.2.3	11.2.3	Addition of SACP system issue for under protected area (hot spot area)
11.2.4	11.2.4	Requirement for CP Specialist involvement is reduced to 'should'

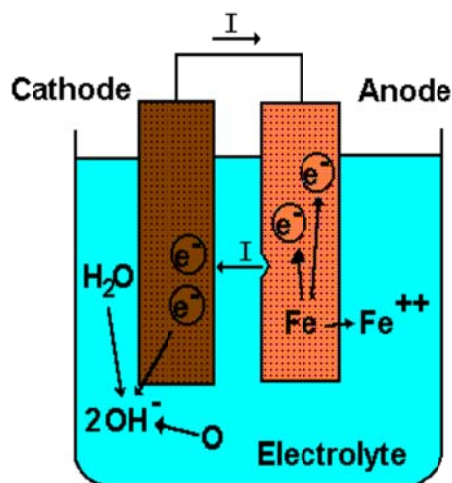
2. NATURE OF CORROSION AND PRINCIPLES OF CATHODIC PROTECTION

2.1 ELECTROCHEMICAL NATURE OF CORROSION

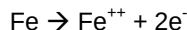
At ambient temperatures, the corrosion of metals is an electrochemical process in which the metal surface is in contact with an electrolyte. The electrolyte may be a film of moisture containing dissolved salts, e.g. as in the case of corrosion in the atmosphere, or may be the whole or part of the surrounding medium, e.g. when metal is immersed in fresh water or seawater or buried in the soil. In the last case, the electrolyte is the water in the soil, containing dissolved salts.

All metals in contact with an electrolyte have an electrochemical potential that is specific for the metal/electrolyte combination. Different metals have different potentials in a specific electrolyte. At the surface of one metal corroding in an electrolyte, there are anodic and cathodic areas, which have small differences in potential. They form active electrochemical cells in which current flows from the anodic areas into the electrolyte, and from the electrolyte into the cathodic areas (Figure 1).

Figure 1 The corrosion cell



At anodic areas, positively charged metal ions leave the metal surface, while at cathodic areas, electrons leave the metal surface. Thus, corrosion takes place at the anodic areas where metal ions react with the electrolyte to form the typical corrosion products. The basic electrochemical reaction is:



At the cathodic areas, dissolution of metal does not take place, but reduction reactions occur in the electrolyte. Depending on the pH and presence of oxygen, the basic electrochemical reaction can be:



At the anode the electrochemical current leaves the metal surface and at the cathodic areas the current enters the metal surface.

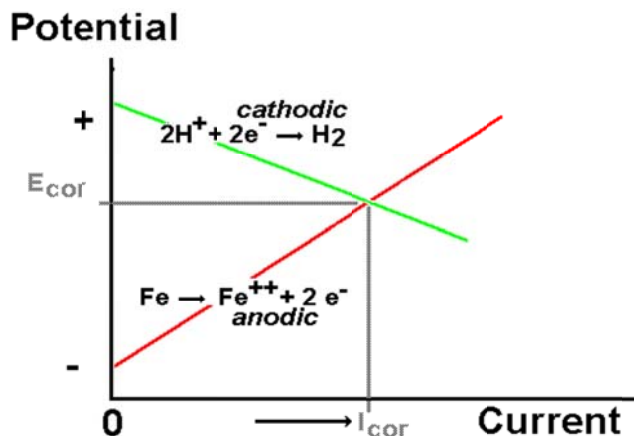
Because the reaction involves the flow of electrons, the reaction rate can be expressed as an electric current.

When a potential of a metal electrode is shifted negatively, the metal tends to attract the Fe^{++} ions and the anodic reaction is slowed down. When the potential is changed in a positive direction, the Fe^{++} ions are more easily released and the corrosion accelerates.

Similarly, the cathodic reaction rate is increased when the metal becomes more negative and the reaction slows down when the potential becomes more positive.

The shift of the potential of an electrode is called **polarisation**. The effect of changing reaction rates with polarisation can be illustrated in an "Evans diagram" shown in Figure 2.

Figure 2 The Evans diagram



The anodic current is equal to the cathodic current because at an isolated electrode, the number of electrons released by the anodic reaction is equal to the number of absorbed electrons in the cathodic reaction. Therefore, the natural potential or the "corrosion potential" (E_{cor}) will automatically be equal to that potential where the two lines in the Evans diagram cross.

The quantity of metal removed (the corrosion rate) is directly proportional to the current flowing at the corrosion potential, i.e. the corrosion current (I_{cor}).

For the purposes of corrosion studies and cathodic protection, electrochemical potentials of metals in an electrolyte are measured with respect to standard reference cells which have a well defined and constant potential with respect to a specific electrolyte. Examples are the copper/copper sulphate reference cell and the silver/silver chloride reference cell. The first is used mainly in soil, the second in seawater.

The natural surface potentials of iron and steel in contact with soil or water are always negative when referred to either of these half-cells; nevertheless, different areas of the same metal surface may have different potentials.

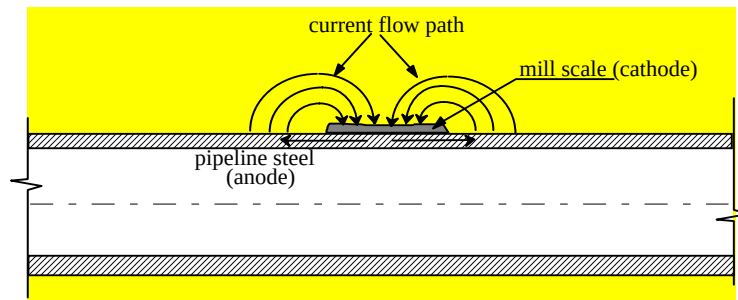
For additional information about reference cells and their application, see (2.3.3) and (10).

2.2 FACTORS AFFECTING CORROSION

2.2.1 Steel surface conditions

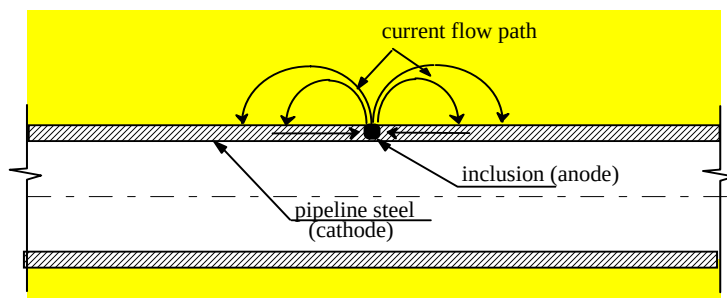
Parts of a steel surface that are partially covered with mill scale or certain corrosion products such as FeS are cathodic with respect to the surrounding areas of bare steel. Corrosion occurs, therefore, on the anodic bare metal as shown in Figure 3, and is particularly severe if the area of the mill scale is large in relation to the area of the bare metal. Corrosion will be in the form of pitting or cratering.

Figure 3 Corrosion pattern on scaled surface



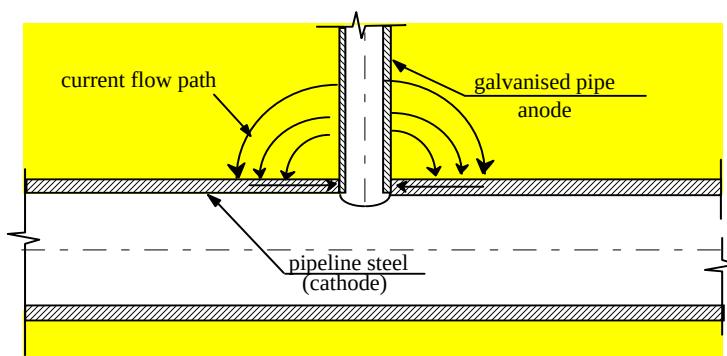
In some steels, impurities are occluded in the metal surface. If these are anodic with respect to steel, corrosion in the form of pitting may take place at these points; see Figure 4.

Figure 4 Corrosion pattern at metal inclusions



If dissimilar metals are in contact with each other and are surrounded by an electrolyte, the less noble metal tends to corrode more severely and the nobler one less severely than they would if there was no contact. A common example of this is the deterioration of the zinc coating on a galvanised pipe when connected to a bare steel pipe; see Figure 5.

Figure 5 Corrosion pattern between dissimilar metals



2.2.2 Electrolyte conditions

The rate of corrosion of the common metals in soil or water depends on different factors such as the concentration of electrolyte (i.e. resistivity), the concentration of dissolved oxygen and the temperature. In general, the severity of corrosion increases as one of these controlling factors increases. Because all the influences are operating at the same time, their relative importance shall be assessed as follows:

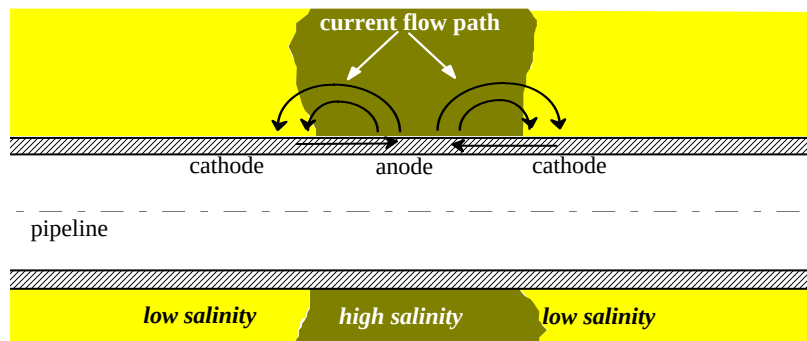
Soil

The steel-to-soil potential of buried steel is more negative (anodic) in soils with a high salt content than in soils with a low salt content. Higher salt concentration also causes lower soil

resistivity. Therefore, corrosion tends to be more severe on those parts of the steel surface in contact with the soils having the highest salt concentrations; see Figure 6.

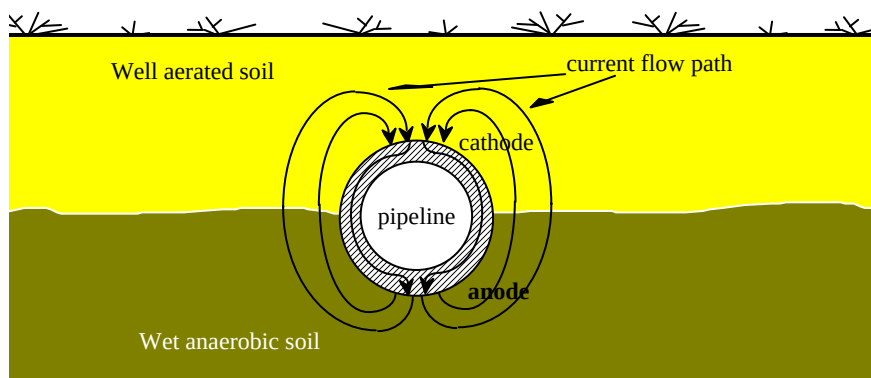
As pipelines often pass through soils which differ greatly in their physical and chemical make-up, differential effects are more pronounced in pipeline corrosion than in the corrosion of other more localised steel structures such as tanks and vessels.

Figure 6 Corrosion by different types of soil



Similarly, the steel-to-soil potential of buried steel is anodic in poorly aerated soils (low oxygen content) with respect to that in well-aerated soils (high oxygen content). In practice, good aeration and high electrical resistivity usually correspond to low moisture content, and vice versa. Thus, the soil in contact with the top of a large diameter pipeline may be relatively dry and well aerated while that in contact with the bottom of the pipe may be wet and poorly aerated. Consequently, corrosion occurs preferentially at the anodic areas along the bottom; see Figure 7.

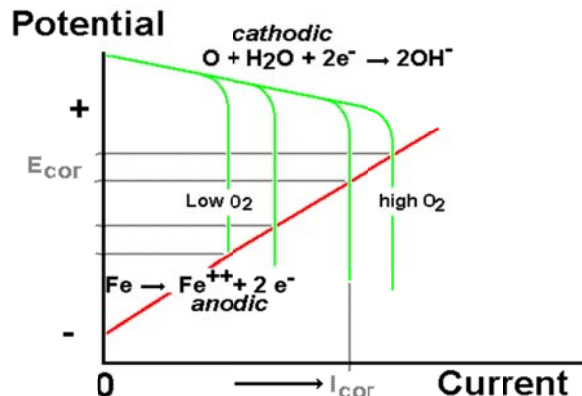
Figure 7 Corrosion at the underside of a pipe due to differential aeration



Water

In water, resistivity is one of the main factors influencing corrosion. However, because oxygen dissolves better in brackish water, steel will usually corrode more rapidly in brackish water than in normal seawater. Similarly, corrosion rates in well-oxygenated, cold (North Sea) water are normally higher than in warmer tropical waters. This can be illustrated in the Evans diagram (Figure 8) for neutral oxygenated water. Higher corrosion rates are also expected in turbulent waters where the diffusion of oxygen is faster.

Figure 8 Evans diagram for neutral oxygenated water



Electrochemical cells may form in water where different electrolyte conditions prevail. Depletion of oxygen due to deposits or different burial conditions of sub sea pipelines may cause accelerated corrosion. Different temperatures in the common electrolyte, for instance inside tanks, may cause localised corrosion.

2.2.3 Bacterial activity

In soils and water, bacterial activity is a common phenomenon. Bacteria produce substances that may influence corrosivity. The absence of oxygen, particularly in waterlogged soils, may provide a corrosive environment for iron and steel through the growth of sulphate reducing bacteria (SRB), which generate hydrogen sulphide. These microorganisms can exist in active form only in the absence of free oxygen and obtain their energy from the reduction of sulphates into sulphides. Bacterial corrosion of iron and steel under damp anaerobic conditions is usually rapid and severe. This type of attack can often be recognised by the bright (unoxidized) appearance of the corroded surfaces and the emission of hydrogen sulphide. The presence of sulphate reducing bacteria creates special requirements for cathodic protection systems (4.3).

2.2.4 Stray currents

Another cause of corrosion is the influence of stray currents in the surrounding soil. DC traction systems may cause appreciable electric currents to flow in the surrounding earth. Through a coating defect, a stray current may enter the pipeline, travel along the pipeline steel, and leave the line at another point to return to its source. Corrosion is concentrated at the anodic parts of the pipeline, where the current leaves the steel.

Similarly, the impressed current from a cathodic protection system may also affect unprotected buried steel structures in the neighbourhood. This should be considered when planning a cathodic protection system, see (9).

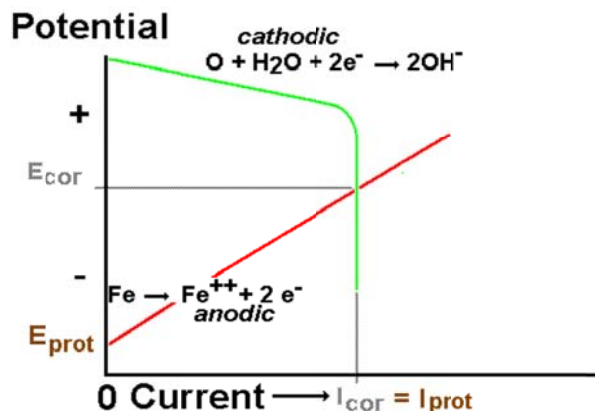
2.3 CATHODIC PROTECTION

2.3.1 Principle

In the Evans diagram, it can be seen that polarisation of the steel in the negative (cathodic) sense slows down the corrosion reaction until it is practically zero. It is this phenomenon that is used when cathodic protection is applied.

Polarisation of steel can be achieved by introducing an external current (I_{prot}) flowing into the steel to make up for the imbalance of the cathodic and anodic current at the polarised potential, i.e. the protection potential (E_{prot}). This is shown in the Evans diagram in Figure 9.

Figure 9 The principle of cathodic protection; definition of protection potential and current



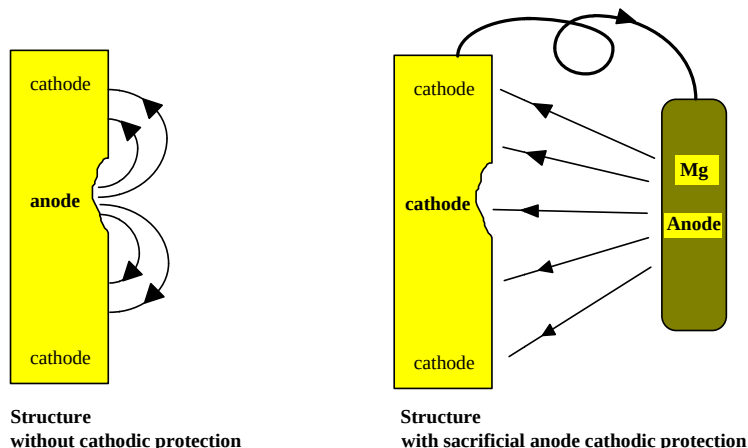
This is done by introducing an auxiliary anode into the electrolyte and forcing an electric current to flow from this anode through the electrolyte towards the surface of the metal to be protected, thereby eliminating the anodic areas. The current may be obtained by galvanic action between the structure and a "sacrificial anodes" or by "impressed current" from any convenient external source, such as a battery, a rectified AC supply, or a DC generator.

2.3.2 Cathodic protection systems

2.3.2.1 Sacrificial anodes

With the sacrificial anode method, use is made of galvanic action to provide the cathodic protection current. The surface of the structure is made cathodic by connecting it electrically to a sufficient mass of less noble metal buried or immersed in the common electrolyte; the less noble metal is then the anode. Magnesium, aluminium alloys or zinc are used for this purpose. The anodes are often referred to as sacrificial anodes because the structure is protected by the simultaneous consumption of the anodes by electrochemical dissolution.

Figure 10 The principle of sacrificial anode cathodic protection



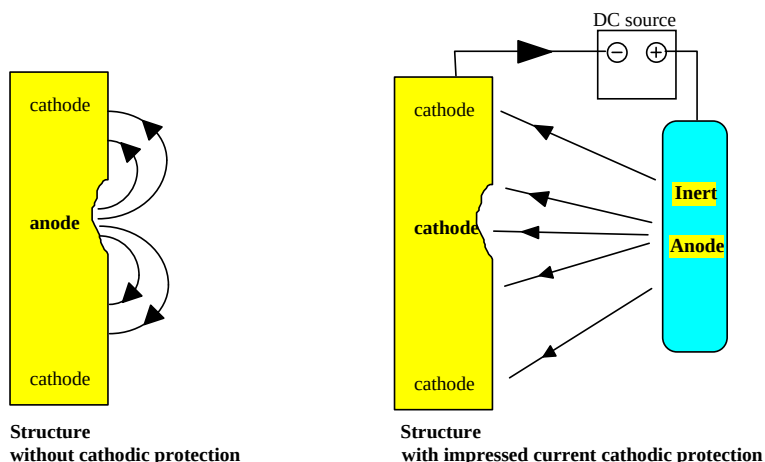
Sacrificial anodes are considered in greater detail in (4.5) and (5).

2.3.2.2 Impressed direct current

With the impressed direct-current method the structure is placed in an electric circuit with a direct-power supply and an earth system or groundbed. The groundbed may for instance

consist of graphite, high-silicon iron or platinised titanium anodes. The groundbed materials used should show a relatively low consumption rate if they are to be used for long periods.

Figure 11 The principle of impressed current cathodic protection



Impressed DC systems are considered in greater detail in (4.5) and (6).

2.3.3 Structure-to-electrolyte potentials

The effectiveness of cathodic protection applied to a structure can be assessed by measuring the electrochemical potential of the structure with respect to the electrolyte using a standard reference cell. Such a reference cell is a metal/electrolyte combination having a well defined and stable potential with respect to the electrolyte. There are different reference cells for different applications. Because the potentials of the different reference cells vary, the type of reference used shall always be stated in records and reports.

The most common reference cells for different applications are given in Table 1.

Table 1 The most commonly used reference cells

Type of reference cell	Main field of use	Potential vs. SHE	Potential vs. Cu/CuSO ₄	Potential vs. Ag/AgCl
Saturated Copper/Copper sulphate (Cu/CuSO ₄)	Soil and fresh water	+320mV	0 mV	+50 mV
Silver/Silver chloride/seawater (Ag/AgCl)	Sea water	+266 mV	-50 mV	0 mV
Saturated Calomel Electrode (SCE)	Laboratory	+242 mV	-70 mV	-20 mV
Standard Hydrogen Electrode (SHE)	Standard reference	0 mV	-320mV	-266 mV
Zinc (Zn)	Soil and seawater	-784 mV	-1100 mV	-1050 mV

Structure-to-electrolyte potentials in this manual are all given with respect to Cu/CuSO₄ or Ag/AgCl reference electrodes as appropriate for the application.

The potential of the structure with respect to the reference electrode is generally called the "structure-to-soil" potential when referring to land based systems (or "pipe-to-soil" as appropriate) and "structure (pipe)-to-seawater" potential when used for offshore systems.

The potential at minimum polarisation for full protection is called the "protection potential".

If the potential of the structure is made too negative, detrimental effects can occur such as damage to the structure's coating or hydrogen embrittlement. The most negative potential allowed under cathodic protection is called the "overprotection potential". The required values (criteria) for these potentials are given in (4.3).

2.3.4 Current (density) requirements

The amount of current required to achieve the protection criteria (4.3) depends on several factors. The protection current is proportional to the surface area to be protected. The required current is therefore expressed as current per unit surface area, "current density" and the common unit is mA/m².

The required current density also depends on the strength of the corrosion reaction. In principle, the corrosion current at the metal surface should be counteracted. Factors that influence the protection current density are water or soil composition, oxygen concentration, water velocity, temperature and metal surface condition. Details on current density requirements for design purposes are given in (4.4).

2.3.5 Protective coatings

Coatings or linings are applied for corrosion protection of various structures that are buried or immersed. Ideally, the coating should be an impervious non-conducting, highly adherent coating which shields the structure completely from the electrolyte. However, this ideal condition is almost impossible to achieve at reasonable cost. Coatings are nearly always damaged to some extent during transporting, construction or operation. Some coatings are to a certain extent permeable to electrolyte and protective current and will always draw a small amount of current. Protective coatings are therefore often used together with cathodic protection as complementary systems. Cathodic protection provides a back up for coating damage and the coating limits the required current to acceptable levels (7).

2.3.6 Cathodic protection applications

In principle, cathodic protection can be applied to steel structures buried in soil or immersed in water or aqueous solutions. Typical applications are land based buried pipelines (11), submarine pipelines (12), offshore structures, wharves and jetties (13), oil and gas well casings (14), bottoms of vertical storage tanks (15), buried tanks and vessels (16), mounded storage tanks (17), underground piping and plant structures (18) and ships (20). Cathodic protection is also applied inside structures and equipment containing water such as heat exchangers (19) and storage tanks and vessels (20.3) and (21). These applications are further discussed in the indicated sections of this PTS.

Cathodic protection can also be applied to structures made of non-ferrous metals or ferrous alloys such as stainless steels. The main objective is often to prevent localised attack or corrosion by galvanic action when such materials are in contact with dissimilar metals. Such applications do have some limitations, which should be considered (23).

2.3.7 Cathodic protection limitations

In some cases, cathodic protection systems are not fully effective, even if ample current is available. This is when the steel structure is shielded from the electrical current. Shielding may be caused by the presence of metal objects between anodes and cathodes that may or may not be part of the structure to be protected. Examples of shielding structures are reinforced concrete or steel foundations, sheet piling, parallel pipelines, and casings.

Shielding may also be caused by non-conducting material. Disbonded coatings or loose wrappings (rock shields), but also pipeline lay debris are an important cause of shielding (7).

Another case of shielding occurs with thermally insulated lines. Cracks in the insulation layer may form a high resistance path where protective current may not reach the steel surface (11.2.3).

2.3.8 Cathodic protection design and design standards

For new construction projects, the design of the cathodic protection system shall be an integral part of the total design. For instance, pipeline isolation and the selection of pipeline coating systems depend on the cathodic protection system to be used while limitations affecting the application of cathodic protection may influence the mechanical design or material choice.

For the various cathodic protection applications, design standards exist, either as PETRONAS Group standards (PTS), local standards, national standards or international standards. In (27), a list of commonly used standards is given and applicable standards are also referred to in the Sections covering the different applications. PTS should take preference over other standards but local regulations may require that e.g. national standards be adhered to as well.

When a cathodic protection system is designed for retrofitting to an existing installation, certain repairs and modifications to the installation may be necessary to comply with the minimum specifications. Such requirements need to be determined by site investigations.

Cathodic protection systems shall be designed by a professional and experienced cathodic protection engineering Contractor. Local personnel may sometimes be allowed to design simple systems, depending on their knowledge and experience.

3. SURVEYS AND PRELIMINARY INVESTIGATIONS

3.1 ASSESSING THE NEED FOR CATHODIC PROTECTION

3.1.1 General

When new installations are designed, corrosion protection should be considered. For buried or submerged structures, cathodic protection can be considered as one of the corrosion protection methods depending on the type of structure, the environment and special conditions. In the design stage, it should be investigated whether or not cathodic protection is required, feasible, and economically justified. It shall be judged against alternatives (material selection, coating) or as a complementary system to alternatives (coatings). This Section gives some guidelines in order to make such a decision.

The most important criterion should always be whether there is a substantial increase in safety, environmental or economic risk due to corrosion if cathodic protection is not applied. The decision is often based on previous experience with similar installations in comparable soil or water conditions. In some cases, e.g. where a no-leak policy is in force, cathodic protection is normally applied without further investigation.

Based on such experience, it is PETRONAS Group practice to apply cathodic protection to (buried) land pipelines, sub-sea pipelines, offshore structures and jetties, seagoing vessels and mounded LPG storage vessels without exception. Cathodic protection of other hydrocarbon containing pressurised steel piping and storage tanks is highly recommended. (For special cases see (11.2.3))

For other structures, the corrosivity of the environment should be investigated to assess the need for cathodic protection. No known soil-survey technique will predict accurately and reliably where and to what extent corrosion of buried steelwork will occur. However, the following guidelines will provide a useful guide to the probable corrosion behaviour of a buried structure or pipeline and the need for cathodic protection.

Any additional information about the corrosion history of existing underground steelwork at or near the site should also be considered.

3.1.2 Soil / water resistivity

For any buried structure, the most important preliminary investigation is the measurement of soil resistivity at various points. Soil resistivity is usually a good first indicator for soil corrosivity as shown in Table 2.

Table 2 Approximate relationship between soil resistivity and soil corrosivity

Soil resistivity, $\Omega \cdot \text{cm}$	Soil Corrosivity
Under 1500	Very corrosive
1500 to 5000	Moderately corrosive
Above 5000	Slightly corrosive

In general, in very corrosive soils cathodic protection should be applied.

In moderately corrosive soils additional tests shall be done to determine the requirement for cathodic protection.

In slightly corrosive soils no cathodic protection is required unless there is a known corrosion history of similar installations under comparable soil conditions.

Some relatively high-resistivity soils may still be very corrosive, e.g. acidic peaty soils and anaerobic soils containing sulphate-reducing bacteria.

Over the life of a facility conditions can change, e.g. changing water tables and changing climates.

Deserts, although giving the impression of being dry and non-corrosive, can in most cases be considered as moderately corrosive.

Soil resistivity can be measured by different methods, depending on the location and the purpose.

The most common method is the "Wenner" or 4-terminal method. This is an in-situ method using 4 pins driven into the ground. A known alternating current is passed through the ground and the resulting voltage indicates the soil resistance. Changing the electrode spacing can vary the influence of depth. The resistivity is calculated by means of appropriate formulae. A description of the 4-pin Wenner Method and soil box method is given in ASTM G 57. Laboratory methods to determine soil resistivity are mostly based on soil box methods. A sample of soil is placed in a calibrated box and the resistance is measured. A 4-terminal-type measurement can also be made on (undisturbed) soil samples obtained from cores of test boreholes. The soil box can also be used for the measurement of water resistivity.

Some important hints for achieving accurate soil resistivity readings are:

- If possible, measurements shall be made in undisturbed soil. If this is not possible, e.g. when using the soil box method, the compacting should be the same as in the original soil or as is specified for construction. Less compaction will result in higher resistivity readings.
- In-situ resistivity measurements will be inaccurate when metal structures are buried in the vicinity of the measurement site.
- To eliminate the effect of any natural potential gradients in the soil, two measurements should be made at right angles. Large differences in results indicate inaccurate readings.
- Resistivity may change during different seasons. If possible, measurements should be made during different seasons. Distilled water may be added to dry soil samples to simulate wet season conditions. About 5 % wt of water is usually sufficient.
- When measuring soil resistivity to determine suitable groundbed locations, 4-point measurements should be made using different pin spacing to determine the resistivity at various depths.

Specialised soil resistivity survey methods are commercially available such as "Syscal" and "Geonics". The latter is based on an electromagnetic inductive technique and is specifically suitable for determining groundbed locations.

3.1.3 Soil composition

The investigation may include chemical analyses to determine the concentrations of various salts and the pH values of soil samples taken at various points at the site or along the pipeline route. Such analysis may indicate areas of high salt concentrations, bacterial activity and the presence of acidic waste. When low pH values are found (less than approximately 5.5), **cathodic protection should be considered**.

High salt concentrations in original soil are usually indicated by the soil resistivity measurements. If imported sand or soil is used for backfilling, construction of foundations and/or mounds for LPG storage vessels, this sand should be analysed to confirm that its salt content does not exceed maximum allowable concentrations and that minimum pH values are adhered to.

When bacterial activity is expected, measuring redox potentials may give an indication of bacterial activity. When sulphate reducing bacterial activity is detected, **cathodic protection should also be considered**.

Other information, available from other sources, may also be of value such as the general nature of the soil, presence or absence of vegetation, the depth of water tables, etc.

3.1.4 Soil variations

Corrosion can occur in fairly high-resistivity soils if there is a considerable variation in composition and/or resistivity at different points at the construction site or along the route of a pipeline, causing concentration-cell effects. Differences in soil composition such as in the

case of partial land fill or reclamation may also cause concentration cell effects, which may require the installation of cathodic protection. For existing pipelines, soil variations can be detected by measuring the natural potential of the pipeline at regular intervals.

3.1.5 Interference and stray currents

When an installation is planned or built in the vicinity of other installations or near railways using DC traction, a survey shall be carried out to assess the risk of interference or stray currents. To determine the most vulnerable locations, the type and locations of DC current sources (cathodic protection stations, railway sub-stations) shall be determined and the possible effects on the proposed installation shall be estimated. There are several methods to avoid or mitigate stray currents (9).

3.2 EXISTING INSTALLATIONS

When cathodic protection systems are retrofitted on existing installations, some investigations are required. In principle the same requirements as for new construction apply but in many cases older constructions may not comply with new standards. Checks should be made regarding electrical isolation, coating quality and interference.

Electrical isolation should be installed or repaired, or when this is not possible, the cathodic protection system should be designed to minimise current loss to foreign structures (hot-spot systems or localised systems).

The coating quality can be checked by performing a current drainage test. Current is applied to the structure by means of a temporary current source and grounding to achieve protective potentials and the required current is determined. If excessive currents are required the cause shall be removed, e.g. by coating repair.

The same current drainage test can be used to investigate interference by foreign systems. Also the influence of existing cathodic protection installations on the installation to be protected shall be checked. It is sometimes possible to use existing impressed current systems by installing additional drain cables.

4. DESIGN OF CATHODIC PROTECTION SYSTEMS

4.1 GENERAL REQUIREMENTS

When a cathodic protection system is designed for a certain structure or installation, there are some minimum requirements that the system shall fulfil. The cathodic protection system shall be capable to fully control corrosion on the structures while avoiding adverse effects on the structure itself and on foreign structures/pipelines. This means that:

- The protection shall be limited to the structure(s) defined in the scope (4.2);
- The whole structure or pipeline shall be polarised to comply with the protection criteria (4.3);
- The system shall be able to supply sufficient current for protection during the design life of the system (4.4);
- The system shall be reliable (4.5);
- The installation shall be as cost effective as possible through its design life (26);
- It shall be possible to monitor and maintain the system (4.6) and (10).

4.2 DETERMINING THE SCOPE OF CATHODIC PROTECTION SYSTEMS

Before the design of a cathodic protection system is started, the scope of the system shall be determined. When a pipeline is to be protected, the protective current should not leak away to the adjacent installations connected by the pipeline. When a buried vessel is to be protected inside a depot or complex, the protective current should only (or mainly) flow to that vessel.

The scope may be determined by the physical boundaries of installations or by the function, type of construction or owner/custodianship. Sometimes the installation may be sub-divided into smaller units, for instance, when different coating systems are used or when protection criteria are different (different construction materials).

The scope boundaries shall be provided with electrical isolation to prevent interaction between different systems. This includes:

- the installation of isolating joints or flanges in pipelines and piping (8),
- *installation of polarisation cells for cathodic protection isolation from the earthing grid and prevent stray cathodic protection current flowing to hazardous areas via the earthing grid (8.5)*
- installation of separate cathodic protection current control when a combined current source is used (6.5). (*eg resistive bonding*)

Where electrical isolation is not possible or not practicable, a localised cathodic protection system may be used (6.3). Typical situations, problems and solutions are given in the Sections covering the different applications.

By determining the scope of a system, the type of structure, surface condition and total surface area are defined and the boundaries for the design and monitoring are laid down.

4.3 CATHODIC PROTECTION CRITERIA

As explained in (2.3.3), the structure to be protected should be polarised to a minimum level for full protection, and in some cases there is also a maximum level to prevent detrimental effects. These requirements shall be determined for each installation under cathodic protection.

Corrosion of carbon steel in normally aerated soils and waters can be reduced to a generally acceptable level if the steel is maintained at a potential more negative than the protection potential given in Table 3.

The protection potential for anaerobic environments is applicable when soil investigations have confirmed the presence of active sulphate reducing bacteria in anaerobic soil (3.1.3).

When the potential of the structure is made too negative, detrimental effects can occur such as damage to the structure's coating or hydrogen embrittlement of susceptible steels. The most negative potential allowed under cathodic protection, the overprotection potential, should not be exceeded (Table 3).

In some cases the overprotection criterion in existing installations is more negative than the figure in Table 3. *For some aged coatings (more than 10 years) this may be allowed if experience has shown that coating deterioration or disbondment is acceptable provided satisfactory performance has been demonstrated in tests and has been documented and approved by Technical Authority.* For the design of new installations the overprotection criterion shall be adhered to.

When cathodic protection is applied to metals or alloys other than carbon steel, different protection criteria apply. These are further discussed in (24).

The given (over-) protection potentials are free of IR drop (10.2.2.1). In soil the potential shall be measured as "INSTANT-OFF" potential (10). In low resistivity waters "INSTANT-OFF" potentials are mostly not required if IR drop is not significant.

Table 3 Potential criteria for the design of cathodic protection of carbon steel

	"INSTANT-OFF" POTENTIALS, mV		
	REFERENCE ELECTRODE		
	Cu/CuSO ₄	Ag/AgCl/ seawater	Zinc
Protection potential for steel in aerobic environment	-850	-800	+250
Protection potential for steel in anaerobic environment	-950	-900	+150
Overprotection limit for carbon steel	-1150	-1100	-50

NOTE: Cu/CuSO₄ reference is used for pipelines in soil, Ag/AgCl/seawater reference is used in seawater. Zinc reference is used in both soil and seawater for special monitoring purposes only.

4.4 CATHODIC PROTECTION CURRENT REQUIREMENTS

The amount of current required for full cathodic protection of the structure varies for the different types of electrolyte, temperature, salinity (resistivity) and (sea) water flow or turbulence.

Table 4 gives the recommended design current densities for cathodic protection of buried and immersed structures.

Table 4 Design current densities for cathodic protection of bare steel at ambient temperatures

Environment	Current density, mA/m ²
Soil, 50 to 500 Ω.cm	20 to 40
Soil, 500 to 1500 Ω.cm	10 to 20
Soil, 1500 to 5000 Ω.cm	5 to 10
Soil, over 5000 Ω.cm	5
Fresh water	10 to 30
Moving fresh water	30 to 65
Brackish water	50 to 100
Sea water	see Table 5
Sea-mud zone	20 to 30

In seawater, the required current density depends upon the water temperature, oxygen content, seawater velocity and the ability to build up protective calcareous films on bare metal surfaces. For most applications in less than 500 m water depth, the design current density is mainly dependent on seawater temperature. Table 5 gives design values for pipelines under different seawater conditions (ref. PTS 30.10.73.33.).

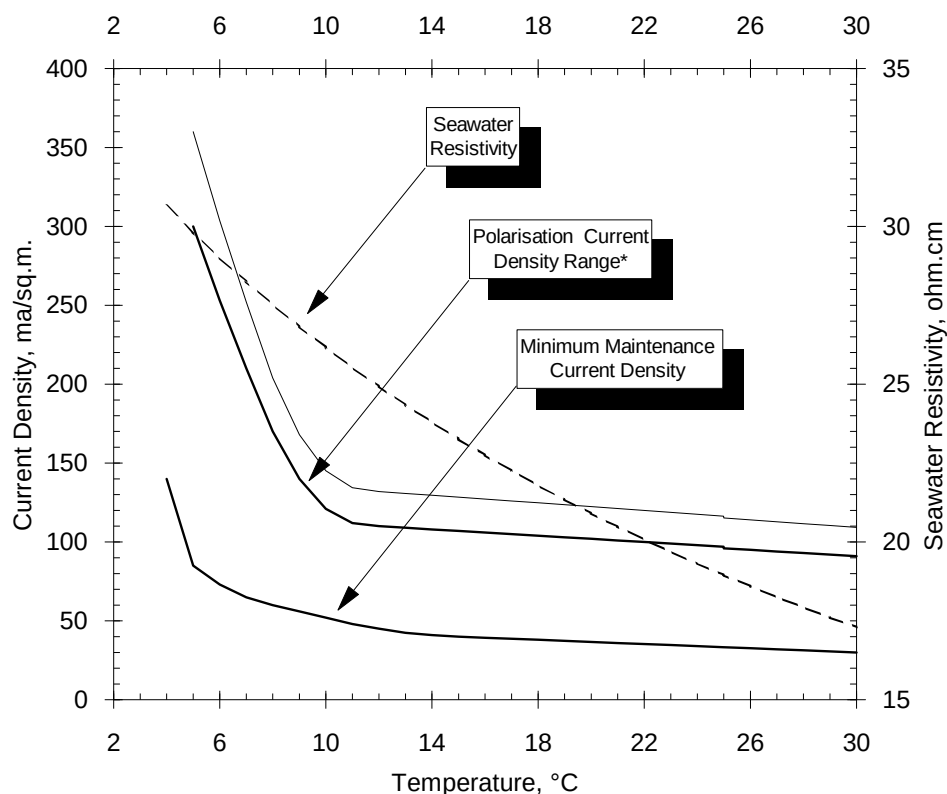
Table 5 Design current densities for non-buried offshore pipelines in different seawater conditions.

Sea water temperature, °C	Design current density, mA/m ²		
	Low lateral water flow /turbulence	Moderate lateral water flow /turbulence	High lateral water flow/turbulence depth < 20 m
> 20 (Tropical waters)	50	60	70
12 to 20 (Sub tropical waters)	60	70	80
7 to 12 (Temperate waters)	70	80	100
< 7 (Arctic waters)	90	100	120

Design current densities for offshore platforms are determined by means of empirical data, which is summarised in Figure 12 (ref. PTS 37.19.30.30.)

FIGURE 12 DESIGN PARAMETERS AS A FUNCTION OF SEAWATER TEMPERATURES

Polarisation (Initial) and Maintenance (Average) Current Density and Seawater Resistivity



* NOTE: The lower Polarisation Current Density curve is the minimum requirement. The upper curve is meant for sensitivity analysis. For Driving Voltages other than 0.25 Volts, multiply the polarisation current density values by 0.25/Driving Volts, where Driving Volts = -0.80 - (Anode Operating Potential)

Although Table 5 and Figure 12 cover the majority of worldwide locations, there are specific locations where higher and lower current densities have been reported, where there are significant changes in oxygen content with depth and/or significant seabed currents, and/or the depth is greater than 500 m:

Table 6 — Maintenance current densities for extreme conditions

Location	Water Depth m	Temperature °C	Current Density mA/m ²	Comment
US West Coast	up to 500m	10 to 12	90	moderate current flow
Cook Inlet	all depth	2	380	high seabed currents
Australia	up to 500m	12 to 18	90	large seasonal temperature variation
Norwegian sea	up to 1500 m	-1 to 4	300	cold deep conditions

4.5 SELECTION OF THE TYPE OF CATHODIC PROTECTION SYSTEM

The type of cathodic protection system (sacrificial or impressed current) to protect a structure shall be selected to fulfil all protection requirements and also to provide the most cost effective option. Important factors to be considered are:

- **electrolyte resistivity:** a high resistivity often requires the use of impressed current. For limitations of the use of sacrificial anodes, see (5);
- **total current demand:** except in very low resistivity electrolytes, e.g. for uncoated offshore platforms, high current applications mostly require impressed current systems;
- presence of **stray currents:** when stray currents are encountered impressed current shall always be used;
- availability of **power supply:** impressed current requires an external power source. In remote locations sacrificial anodes may be a solution, while solar or wind power for impressed current may be an alternative;
- **existing systems:** the use (spare capacity of) existing self-owned impressed current cathodic protection systems, or their spare capacity, may be considered;
- presence of **other conductors:** impressed current may cause interference with other conductors and localised sacrificial anodes may be a solution e.g. for small objects inside an industrial area;
- **maintenance:** sacrificial systems usually require less maintenance than impressed current systems. Also, the availability of skilled maintenance staff may influence the choice;
- **design life:** There are sometimes limitations in the amount of sacrificial anode material that can be installed. For instance, magnesium anodes for onshore are often only good for about 10 years and regular change-out may be required;
- **safety** considerations: in classified areas the use of impressed current may be restricted;
- **economic considerations:** when all technical requirements are fulfilled, economic evaluation (including operating and maintenance cost) may indicate preference for one of the two protection methods.

For some applications, experience has shown that one system is always preferred. Thus, for the cathodic protection of land based buried pipelines, an impressed current system is preferred, while for offshore pipelines and structures sacrificial anodes are preferred. For recommendations on systems to be used, refer to the relevant Sections in this PTS.

4.6 MONITORING FACILITIES

The protection potential is the most important criterion for full protection. Therefore protection can only be ensured if the result can be measured in terms of potential values. For this reason facilities shall be installed to allow electrical contact with the pipeline or structure and to measure other parameters that may be useful to monitor the system performance.

The monitoring facilities shall always be included in the design of a cathodic protection system and shall be installed during new construction. In cases where cathodic protection is not installed but may be required in the future, it is usually more economical to install the monitoring facilities during the project.

Monitoring procedures shall be prepared during the design and shall be related to the type of monitoring facilities. They are part of the operating procedures of a cathodic protection system.

5. PROTECTION BY SACRIFICIAL ANODES

5.1 GENERAL

When two dissimilar metals are placed in an electrolyte and joined by a conductor, an electric current tends to flow from one metal to the other depending on their relative position in the electrochemical series (see Table 7).

Table 7 Electrochemical series of metals

	Material	Approximate potential in seawater (mV vs. Ag/AgCl reference)	Approximate potential in normal soil (mV vs. Cu/CuSO₄ reference)
LESS NOBLE ↑	Magnesium	- 1650	-1700
	Aluminium	- 1100	NA
	Zinc	- 1050	-1100
	Steel	- 630	-680
	Cast Iron	- 630	-680
	Stainless steel (active)	- 600 to - 550	-650 to -600
↓ MORE NOBLE	Copper/Brass	- 380	-430
	Cupro-Nickel	- 300	-350
	Stainless steel (passive)	- 200 to - 70	-250 to -120

Any such current flow will increase the corrosion of the less noble (anodic) metal and reduce that of the more noble (cathodic) one. This is the basis of cathodic protection with sacrificial anodes.

Steel structures are protected by connecting them to anodes (magnesium, aluminium alloy, or zinc). These metals are less noble than steel, and are available at an economic price.

In the same way, iron or steel sacrificial plates and plugs can be used to prevent corrosion and de-zincification of brass, or reduce crevice attack on austenitic stainless steels and titanium. These metals are more noble than steel.

This Section will primarily discuss the use of sacrificial anode materials (Al, Zn, Mg) for the protection of steel.

5.2 ANODE CHARACTERISTICS

5.2.1 General

Each anode material has its typical electrochemical potential. This potential determines the driving voltage of the anode, i.e., the voltage difference between the anode and the (protected) steel (Table 7). The more negative the open anode potential, the greater the driving voltage and the more powerful the anode system. This is particularly important when sacrificial anodes are used in high resistivity soils.

Table 8 Properties of sacrificial anode materials

Anode Alloy	Open potential, mV vs. Ag/AgCl	Theoretical capacity Ah/kg	Practical capacity, Ah/kg	Current Efficiency %	Practical consumption kg/A.y
Zinc (Mil-Spec)	- 1050	820	780	95%	11
Aluminium-Indium	- 1100	3000	2500	83%	3.3
Magnesium (commercial)	- 1450	2200	450-900	20-41%	10 -19
High Output Mg	- 1650	2200	1100	50%	8

The current output of an anode depends on the driving voltage and on the circuit resistance. Assuming that the resistance of metallic connections is low, this resistance is mainly determined by the soil or water resistivity, and the shape of the anode (5.2.3).

Current output determines the rate of consumption, i.e. the service life of an anode. This can be expressed as anode consumption rate (kilograms of anode material consumed per Ampere.year, kg/A.y) or as the anode Capacity (the number of Ampere-hours (Ah) that can be supplied by one kg of anode material, Ah/kg), see Table 8. *It is highly recommended to refer to manufacturer's data sheet for detailed properties of sacrificial anodes,*

All these parameters are considered in the sacrificial anode system design.

5.2.2 Anode efficiency

In practice, the theoretical capacity of sacrificial anodes is not fully available for cathodic protection. Part of the anode material is consumed in protecting the structure, and, part is also consumed by the normal self-corrosion of the anode.

The percentage of the theoretical anode capacity actually being used for cathodic protection (practical capacity) is the "anode efficiency".

The efficiency of low impurity magnesium-alloy anodes is usually about 50 %. Commercial magnesium alloys may have a lower efficiency. The efficiency is also influenced by the current output of the anodes. When anodes are used at a current density ranging from less than 1 A/m² to 2 A/m², the efficiency can decrease, even for the low impurity and high voltage anodes.

Zinc anodes normally operate at an efficiency of about 90 % and aluminium anodes at about 94 %. *The zinc anode potential gradually deteriorates with higher temperatures and at temperatures over 50 °C there is a risk of the potential becoming more positive than that of steel ("inversed polarity"), thereby promoting corrosion rather than preventing it. Zinc anodes shall therefore not be used above 50 °C unless satisfactory performance has been demonstrated in tests and has been documented.* Above 50 °C, the efficiency of aluminium anodes decreases and can drop to 25 % or less at 80 °C.

At increased temperatures, e.g. in box coolers, the self-corrosion of the anodes is greater and therefore their efficiency decreases. For this reason, magnesium alloy anodes should generally not be used when the temperature is higher than approximately 30 °C in brackish or salt water or higher than approximately 45 °C in fresh water.

Also, depending on the construction of the anode, some material may become detached from the steel core at the end of the anode life. The part of the anode that is effectively used is the utilisation factor (or percentage). The utilisation factor normally depends on the design of the anode.

5.2.3 Current output of anodes

5.2.3.1 General

The current output of sacrificial anodes depends on the driving force available and the circuit resistance. The driving force is the difference in potential between anode and protected steel. The former depends on the type of anode used and is given in Table 8. The potential of the protected steel is the minimum requirement as given in Table 3.

The circuit resistance can be calculated and is the sum of cable resistance (which should be negligible) and anode-in-medium resistance. For the calculation of the latter a number of formulae are available each covering a type of medium or position of anode. The effect of mutual interference of adjacent anodes is detailed (5.2.3.7). In different manuals one may find slightly different formulae derived from different models. In practice the differences between results are negligible compared with the accuracy of resistivity measurements.

5.2.3.2 Vertical anode in soil

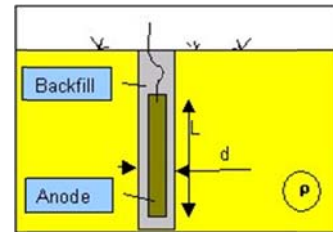
These anodes are usually cylindrical and provided with a cable tail for the electrical connection. They are installed in a bored hole surrounded by low resistivity backfill.

For a single anode placed in soil vertically, the following relationship applies:

$$R_{\text{vert}} = \frac{\rho}{2\pi \cdot L} \cdot \left(\ln \frac{8L}{d} - 1 \right)$$

in which:

- R_{vert} = anode resistance in Ω ;
- ρ = soil resistivity in $\Omega \cdot \text{cm}$ at the depth of anode to be installed;
- L = anode length in cm;
- d = anode diameter in cm.



5.2.3.3 Horizontal anode in soil

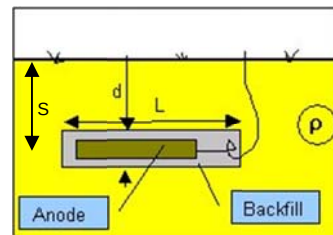
These anodes are usually cylindrical and provided with a cable tail for the electrical connection. They are buried horizontally in an excavated trench surrounded by low resistivity backfill.

For an anode single or in multiple series in a single horizontal line (trench) the following relationship applies:

$$R_{\text{hor}} = \frac{\rho}{2\pi \cdot L} \cdot \left(\ln \frac{4L}{d} + \ln \frac{L}{S} - 2 + \frac{S}{\frac{1}{2}L} \right)$$

in which:

- R_{vert} = anode resistance in Ω ;
- ρ = soil resistivity in $\Omega \cdot \text{cm}$ at the depth of anode to be installed (S);
- L = anode length in cm;
- d = anode diameter in cm;
- S = anode depth in cm.



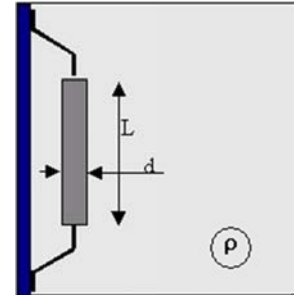
5.2.3.4 Stand-off anode in water

These anodes are normally trapezoidal anodes, or sometimes cylindrical, D or Δ shaped, mounted on steel cores or supports by welding at a distance of 25 to 50 cm from the structure surface. For a stand-off anode the following relationship applies:

$$R = \frac{\rho}{2\pi \cdot L} \cdot \left(\ln \frac{4L}{d} - 1 \right)$$

in which:

- R = anode resistance in Ω ;
- ρ = water resistivity in $\Omega \cdot \text{cm}$ (for seawater see figure 12);
- L = anode length in cm;
- r = mean effective radius in cm.



For non-cylindrical anodes the mean effective radius is approximated as the radius of cylinder with the same cross-sectional area.

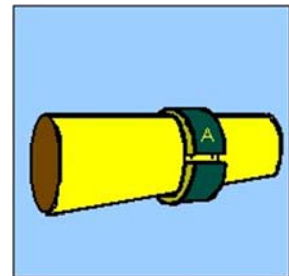
5.2.3.5 Bracelet anodes in water

For a bracelet-type anode as (e.g. used on pipelines) the following relationship applies:

$$R_{\text{bracelet}} = \frac{0.315\rho}{\sqrt{A}}$$

in which:

- R = anode resistance in ohm
- ρ = medium resistivity in ohm cm (for seawater see figure 12);
- A = the exposed surface area in cm^2 .



5.2.3.6 Flat plate anodes

These anodes are used for ship hulls and other structures where space and drag must be minimised. They are mounted flat on a steel surface, rear side painted.

For a flat plate anode the following relationship applies:

$$R_{\text{plate}} = \frac{\rho}{2S}$$

in which:

- R = anode resistance in Ω ;
- ρ = medium resistivity in $\Omega \cdot \text{cm}$ (for seawater see figure 12);
- S = mean length of the 2 sides (thickness ignored) in cm.

