

PETRONAS TECHNICAL STANDARDS

MANUAL

CATHODIC PROTECTION

PTS 30.10.73.10

JANUARY 2012



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PTS Circular 2012 - 1



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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 No: PTS 30.10.73.10

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'

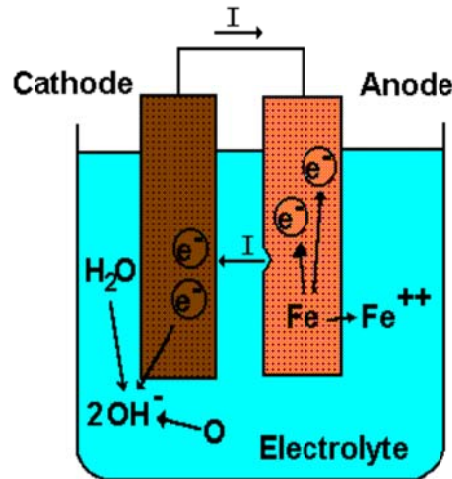
2. NATURE OF CORROSION AND PRINCIPLES OF CATHODIC PROTECTION

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.

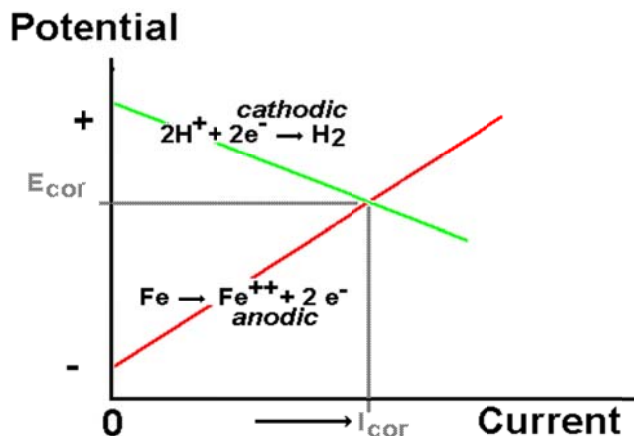
Because the reaction involves the flow of electrons, the reaction rate can be expressed as an electric current.

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.

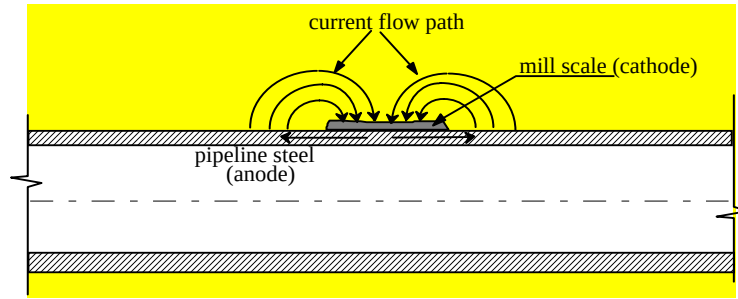
For additional information about reference cells and their application, see (2.3.3) and (10).

2.2 FACTORS AFFECTING CORROSION

2.2.1 Steel surface conditions

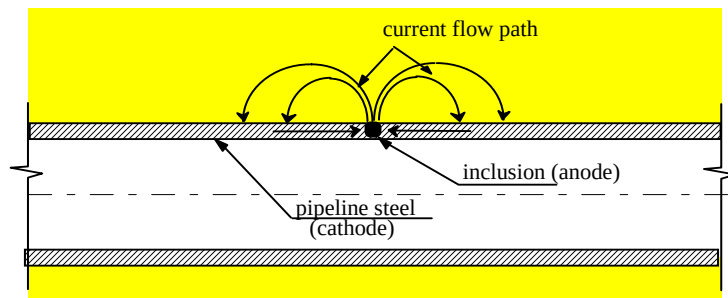
Parts of a steel surface that are partially covered with mill scale or certain corrosion products such as FeS are cathodic with respect to the surrounding areas of bare steel. Corrosion occurs, therefore, on the anodic bare metal as shown in Figure 3, and is particularly severe if the area of the mill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



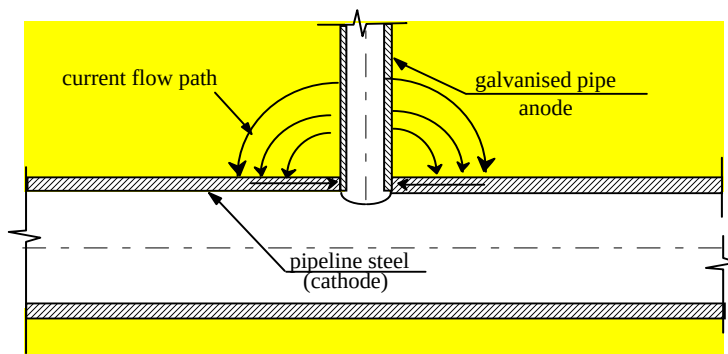
In some steels, impurities are occluded in the metal surface. If these are anodic with respect to steel, corrosion in the form of pitting may take place at these points; see Figure 4.

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:

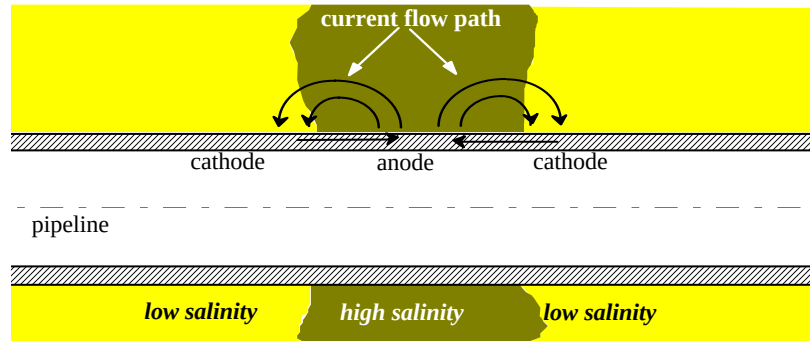
Soil

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.

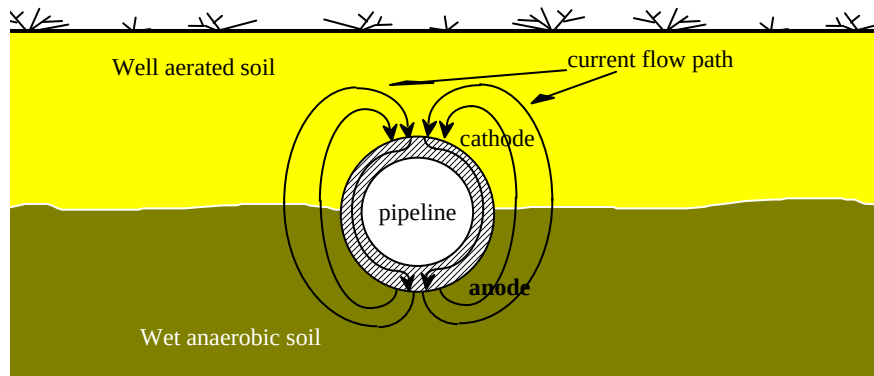
As pipelines often pass through soils which differ greatly in their physical and chemical make-up, differential effects are more pronounced in pipeline corrosion than in the corrosion of other more localised steel structures such as tanks and vessels.

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.

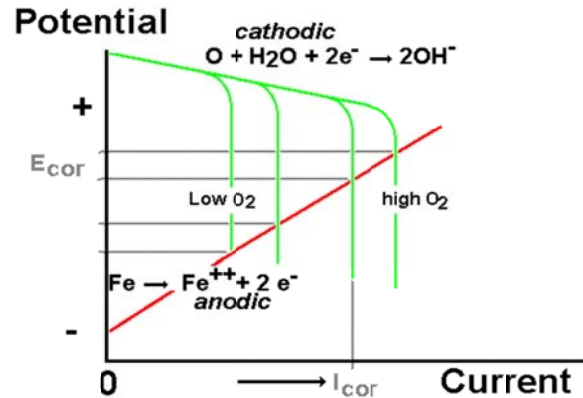
Figure 7 Corrosion at the underside of a pipe due to differential aeration



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).

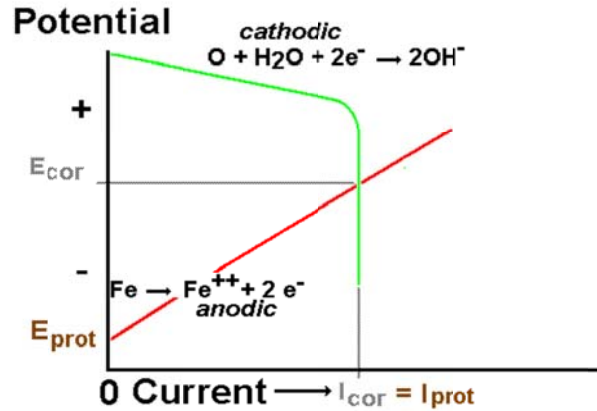
2.3 CATHODIC PROTECTION

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



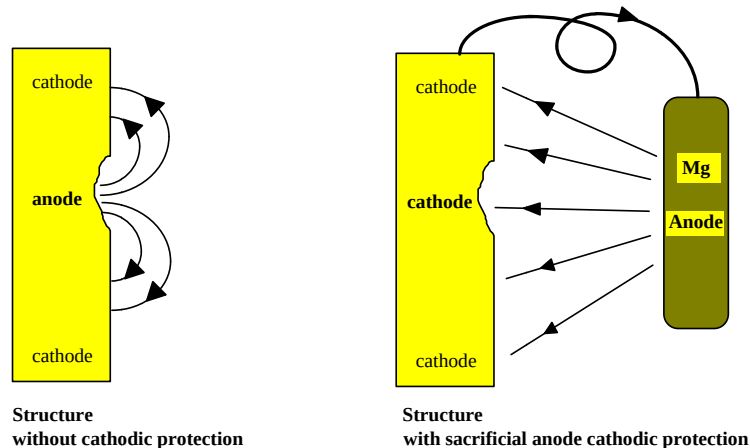
This is done by introducing an auxiliary anode into the electrolyte and forcing an electric current to flow from this anode through the electrolyte towards the surface of the metal to be protected, thereby eliminating the anodic areas. The current may be obtained by galvanic action between the structure 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



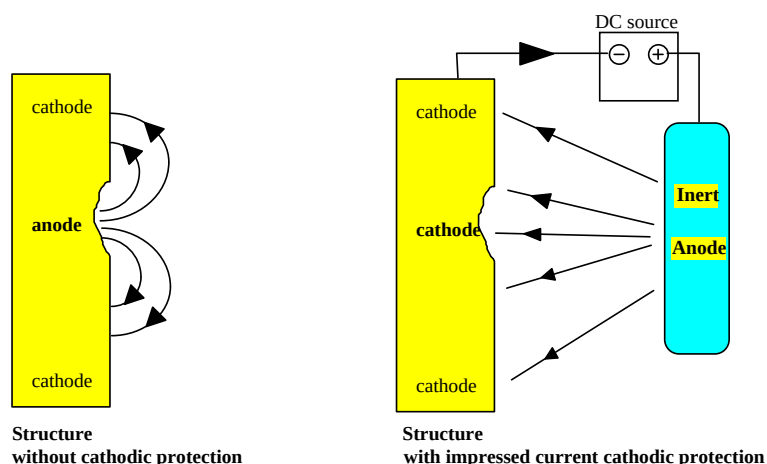
Sacrificial anodes are considered in greater detail in (4.5) and (5).

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.).

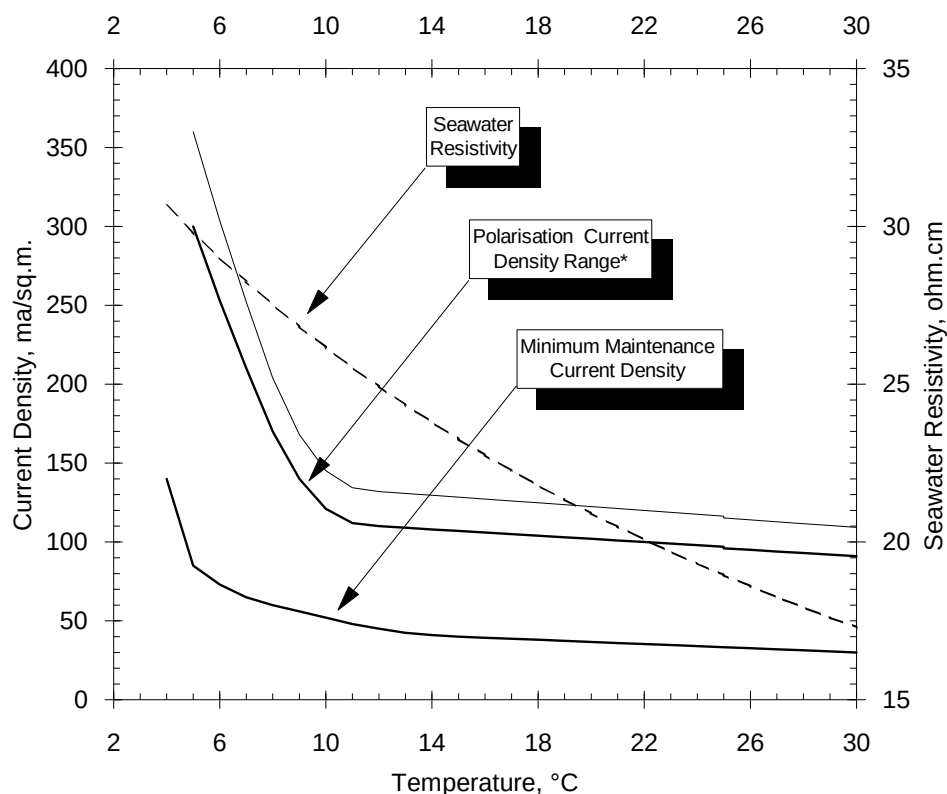
Table 5 Design current densities for non-buried offshore pipelines in different seawater conditions.

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
	Copper/Brass	- 380	-430
↓ MORE NOBLE	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

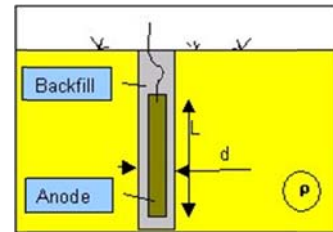
These anodes are usually cylindrical and provided with a cable tail for the electrical connection. They are installed in a bored hole surrounded by low resistivity backfill.

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

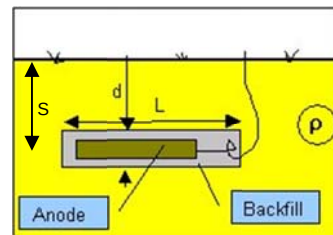
These anodes are usually cylindrical and provided with a cable tail for the electrical connection. They are buried horizontally in an excavated trench surrounded by low resistivity backfill.

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.



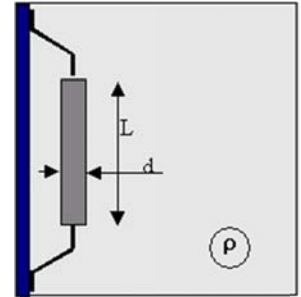
5.2.3.4 Stand-off anode in water

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.

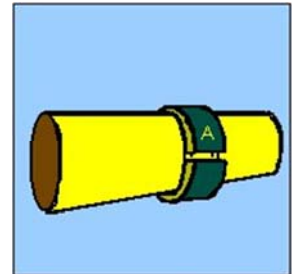
5.2.3.5 Bracelet anodes in water

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

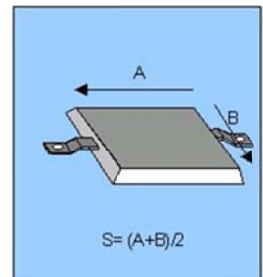
These anodes are used for ship hulls and other structures where space and drag must be minimised. They are mounted flat on a steel surface, rear side painted.

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.



5.2.3.7 Spacing factors

When anodes are placed in close proximity they mutually interfere. The resistance of a group of anodes is therefore higher than the single anode resistance divided by the number of anodes.

The spacing factor to be used for correcting the anode bed resistance is found from:

$$F_n = 1 + \frac{\rho}{\pi \cdot s \cdot R} \ln 0.66n$$

in which :

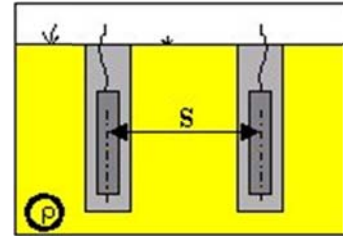
F_n = spacing factor (> 1);

ρ = soil resistivity in $\Omega \cdot \text{cm}$ at the depth of anode to be installed;

s = distance between anodes in cm;

R = single anode resistance;

n = number of anodes.



The anode bed resistance is obtained as follows:

$$R_n = F_n \frac{R}{n}$$

5.3 ANODE MATERIALS

5.3.1 Magnesium alloy

The advantage of magnesium as an anode material is the large potential difference between magnesium alloy and steel compared to zinc or aluminium. This enables magnesium to be used economically in media of higher resistivity (up to 3,000 $\Omega \cdot \text{cm}$) than when zinc or aluminium is used.

The disadvantage is the low efficiency, especially at low output.

The magnesium alloy generally used for cathodic protection is of "Low Impurity" grade.

For high resistivity applications (up to approximately 5,000 $\Omega \cdot \text{cm}$), a high output alloy is available with a 200 mV more negative open circuit potential and therefore a higher driving voltage.

The efficiency of both the "Low Impurity" alloy and the "High Output" alloys is about 50 %.

A less expensive commercial grade is available with higher impurity content. The efficiency is much lower, especially at low output rates (down to 20 %) and this type of alloy shall not be used.

Table 9 Composition of Magnesium anode alloys

Element	Low Impurity Alloy	High Output Alloy
Cu	0.02 % max.	0.02 % max.
Si	0.10 % max.	0.10 % max.
Fe	0.003 % max	0.003 % max
Ni	0.002 % max	0.002 % max
Mn	0.15 % min.	1.0 % min.
Al	5.3 % to 6.7 %	
Zn	2.5 % to 3.5 %	
Mg	Remainder	Remainder

Particularly when installed in chloride and sulphate free soils, magnesium anodes shall always be surrounded by a bentonite/gypsum backfill (5.4.1) to avoid polarisation of the magnesium and loss of the driving voltage.

5.3.2 Zinc

Zinc anodes of high-purity metal are required in order to provide a continuous protective current. Zinc of lower purity alloyed with aluminium, cadmium and/or silicon is also used. Zinc alloy complying with the requirements of USA Military Spec. MIL-A-18001K is suitable.

Table 10 Composition of Zinc anode alloys

Element	MIL-spec Alloy	High Purity Alloy
Cu	0.005 % max.	0.0001 % max.
Si	0.125 % max.	
Fe	0.005 % max	0.0005 % max
Pb	0.006 % max	
Cd	0.02 % to 0.15 % min.	
Al	0.10-0.50 %	
Zn	Remainder	Remainder

Zinc of too low **a** purity has often failed as an anode material, because corrosion products accumulate on the metal surface and greatly decrease current output.

The disadvantage of zinc is its relatively small current output, as its potential difference (driving force) with protected steel is approximately 250 mV compared to 600 mV for magnesium. Its advantage is the high efficiency, also at very low current outputs, and the fact that it is not easily passivated. This makes it ideal to provide protection in seawater when only a small current is required and a long service life is desirable. An example of this is the use of zinc anodes as bracelets on coated submarine pipelines.

Its use in soil and fresh water shall be limited to applications in media with a resistivity of not more than 1500 Ω .cm. When high output is required, such as for uncoated structures, a maximum resistivity of 500 Ω .cm is recommended.

Zinc anodes can be used at higher water temperatures where magnesium-alloy anodes or aluminium anodes will corrode too rapidly. The 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.

5.3.3 Aluminium

Aluminium alloys have found wide application for cathodic protection of offshore structures. The advantage of aluminium as anode material is its high current capacity and therefore its relatively low installation weight.

Aluminium may show a tendency to passivate with a resulting underprotection of the system. Therefore the anode composition is not always a guarantee for success and an additional test is recommended to show the tendency to passivation (5.5). However, with the proper alloy chemistry and after successful passivation testing, Al-Zn-In alloy is used in all applications, including pipelines and deep water systems.

The composition of anodes is often proprietary although typical (effective) compositions are shown in Table 11. The high performance indium activated alloy has a more stringent specification in chemistry and is the recommended alloy for pipelines in cold water and deep water applications. (The high performance specification is proposed as the recommended standard in ISO documents).

Table 11 Composition of Aluminium anode alloys

Element	Indium Activated Alloy	High performance Indium activated Alloy
Cu	0.01 % max	0.003 % max
Si	0.10 % max	0.12 % max
Fe	0.13 % max	0.09 % max
Zn	0.5 % to 5.0 %	2.5% to 5.75%
In	0.005 % to 0.05 %	0.016 % to 0.040 %
Cd		0.002 % max
Others		0.02 % max
Al	Remainder	Remainder

The indium-activated type is preferred. *Mercury- or cadmium-activated aluminium alloys may only be considered under the circumstances that the indium-activated aluminium ones are proven to be ineffective in providing protection. However, statutory regulations limiting the use of these alloys shall apply.*

Some anode compositions are claimed to be suitable in mud as well as in seawater.

Special alloys for high temperatures are offered. In practice, at elevated temperatures, the efficiency of aluminium anodes decreases strongly and the consumption pattern shows a localised attack like intergranular corrosion. For performance data on aluminium alloys in mud and at temperatures above 30 °C, see PTS 30.10.73.32.

Aluminium anodes are not recommended for other services than in seawater. In fresh water and in soil their performance is ineffective.

5.4 PRACTICAL APPLICATION

5.4.1 Installation of sacrificial anodes

5.4.1.1 In soil

Anodes are buried along the length or perimeter of the structure. They can be installed *vertically* or horizontally, if possible sufficiently deep to be in permanently moist soil. The distance of the anode to the structure will be relatively short, generally not more than 5 m.

The anode shall always be surrounded by a low-resistance backfill to prevent polarisation of the anode and to lower the anode resistance. *This backfill composition used for sacrificial anodes can be referred at Table 12.* Anodes can be purchased pre-packaged with backfill in a linen bag and provided with a cable tail ready for installation.

Table 12 Composition of Backfill for Magnesium and Zinc Anodes

Specific Soil Resistivity Ωcm	Backfill						
	For Mg Anodes				For Zn Anodes		
	Gypsum	Bentonite	Kieselguhr	Na_2SO_4	Gypsum	Bentonite	Na_2SO_4
Up to 20	65	15	15	5	75	25	-
	75	25	-	-	50	45	5
20-100	70	10	15	5	75	20	5
	75	20	-	5	-	-	-
	50	40	-	10	-	-	-
Above 100	65	10	10	15	-	-	-
	50	25	-	25	-	-	-

5.4.1.2 In water

Anodes will be ordered with cast-in steel core. This core shall be made of weldable steel and can have the form of flat strip, round bar or pipe. On offshore structures, the core is welded to the structure and serves as mechanical and electrical connection. On coated structures, such as pipelines or jetty piles, anodes are often clamped and a cable, which is thermite welded or (pin-)brazed to the anode core and the structure, makes the electrical connection.

The distance between anode and structure depends on the condition of the structure. For coated steel, the minimum distance is zero, while for a bare structure, the minimum is 25 cm. The maximum distance is not critical provided the electrical resistance of the interconnection is small compared with the anode resistance in the medium.

5.4.2 Anode distribution

Anodes used to provide protection in water should be evenly distributed over the surface of the structure.

The spacing between anodes used to protect pipelines varies between one anode every 150 m (bracelets offshore), to one anode (bed) every 5 km (well-coated landline).

Some benefit can be gained by modelling the CP requirement so that better (current) distribution is attained and (possibly) less anode material is required. For offshore pipelines anode spacing exceeding 300m shall always be justified by attenuation calculations or mathematical modelling.

5.4.3 Electrical connections

A low-resistance connection is essential to ensure maximum benefit from sacrificial anodes. Cables or anode cores should preferably be connected to the steel structure by welding. For offshore platforms and other offshore structures welding is always required and shall be done in accordance with approved welding procedures.

Cables are normally connected to sacrificial anodes by welding, brazing or crimping to the steel insert. The cable connection should be insulated using a suitable sheath or shrink sleeve.

Cables shall be connected to pipelines so as to ensure adequate mechanical strength and electrical continuity and to avoid damage to the pipeline. A method often used for cable to

steel connection is thermite welding (or cad welding). *To ensure the cad weld achieves satisfactory quality, the size of charge shall be appropriately chosen based on Manufacturer's instructions, clean surfaces and dry condition. The remaining thickness of the structure shall be verified to be above Minimum Allowable Thickness (MAT) as to ensure the cad welding process does not affect the integrity of the structure to be welded.*

Some authorities have objections against the use of thermite welding on high-strength steels because of possible copper penetration and resulting embrittlement. In such a case, use can be made of a steel doubler plate onto which the cable is attached (by cad weld or brazing). Provided the doubler plate is welded by using approved welding procedures the method circumvents the copper penetration problem.

At present more and more use is made of pin brazing or stud welding. Like thermite welding, the pin brazing process may cause copper penetration in the steel and the process shall be qualified for the type of steel and the application.

For the technical specification of the connection of cables to pipelines, refer to PTS 30.10.73.31.

Other methods for connecting anodes to structures are often used during retrofit exercises when welding is impossible or economically unattractive. The recommended methods are clamping, clamping plus hard-tipped bolting and friction all of which have had successful applications for over ten years. Wet welding is not permitted.

For further information on installation and commissioning of sacrificial anodes, see PTS 30.10.73.33.

5.4.4 Monitoring of sacrificial systems

Sacrificial anodes installed in soil should be provided with monitoring facilities to enable the measurement of the current output. This is to assess the useful life of the system and to check possible passivity. This is preferably done by the installation of a fixed shunt in an above ground test post.

For offshore installations, monitoring is normally done by divers or remotely operated vehicles (ROV) who measure closed circuit potentials and carry out visual inspections. The use of wireless transponders is sometimes used in remote places or deep waters.

For further reading on cathodic protection monitoring, see (10).

5.5 ANODE SPECIFICATION

A specification for sacrificial anodes is important to ensure that the anodes will have the required chemical composition and will be manufactured to a high standard to give the expected performance throughout their service life. This is particularly important for offshore applications (structures and pipelines) as replacement or retrofitting on such structures is impossible or extremely costly. For land based applications, retrofitting is often possible but may require shutdown of the equipment (tanks, heat exchangers). Moreover, any corrosion damage is irreversible and may be costly to correct.

Information shall be given about the application, environment and operating temperature of the anodes.

The specification should include the required dimensions of the anode, steel core, and brackets and the net and gross weight of anodes, or alternatively reference should be made to a Supplier's standard type and size of anode or anode assembly. Drawings of special anode construction can be included.

The required anode composition shall be included or reference shall be made to standard specifications such as *manufacturer's data sheet* for zinc anodes.

Metallurgical testing and physical inspection of cast anodes, anode identification and documentation shall be carried out in accordance with NACE SP0387. For bracelet anodes NACE RP0492 is applicable.

Sacrificial anodes for application in seawater shall be prequalified in accordance with Appendix 3 of PTS 30.10.73.32. (Appendix 3 of PTS 37.19.30.30. gives the same procedure.). For zinc and magnesium anodes, the passivity test in this procedure may be omitted.

6. PROTECTION BY IMPRESSED CURRENT

6.1 GENERAL

In addition to the structure to be protected and the electrolyte (soil, water, etc.), impressed current cathodic protection systems consist of the following essential components:

- the current source, such as transformer/rectifiers, solar generators, *thermal electric generators* etc.;
- the impressed current anodes, buried in soil or immersed in (sea) water;
- the interconnecting cables.

The system may also be provided with a current control circuit to regulate the protection level. Such regulation is particularly useful when different structures are protected by the same current source.

Each impressed current system shall be provided with an adequate monitoring system to check and regulate the protection levels. A monitoring system shall be an integral part of the design of any cathodic protection system (10).

6.2 CURRENT SOURCES

6.2.1 Transformer/rectifiers

Transformer/rectifiers are the most economical and usually most reliable current sources for impressed current cathodic protection. They shall be of a special design for cathodic protection service and able to operate under the prevailing service and weather conditions. They shall comply with IEC 60146 and fulfil the requirements of the hazardous area classification applicable to the site. When installed outdoors, they shall have a minimum degree of environmental protection of IP 54 in accordance with IEC 60529.

Transformer/rectifier units can be either oil- or air-cooled. For installation outdoors in hot climates, oil-cooled units are preferred. Units with a high current rating are often oil-cooled although modern semiconductor technology allows increased current capacities for air-cooled units. Air-cooled units are usually smaller and less expensive than oil cooled units with the same capabilities.

AC power for transformer/rectifier units can be either single-phase or three-phase. Especially for high power units, three-phase units are preferred because they normally provide a smoother DC output than single-phase units unless sophisticated smoothing circuits are installed.

The transformer/rectifier shall be provided with an isolator or Moulded Case Circuit Breaker (MCCB) on its incoming circuit and, where applicable, on its AC sub-circuits. Additionally, suitably sized fuses shall be installed on the transformer/rectifier's phase AC sub-circuits and negative DC output circuits.

The rectifying elements shall be constructed with high current density silicon diodes, so arranged as to provide full wave rectification. To prevent damage to overload or short spikes in the supply, the current rating of the diodes shall be more than 125 % of the maximum current rating of the rectifier and have a minimum peak inverse voltage of 1200 V.

The unit shall be able to withstand a short circuit at the output terminals of up to 15 s duration without damage to the circuits.

The output RMS ripple shall not exceed 5 % of the DC output current between 5 % and 100 % of the rated current output. This is particularly important for certain anode types such as platinised titanium.

The output voltage shall be adjustable from zero to the maximum rated output when on load. A stepless (continuous) adjustment is preferred. If tapping switches are used, these shall be front mounted switches with a step-size of maximum 3 % of maximum output. Transformer tapping should not be done by relocating jumpers unless changes in operating

conditions are expected to be infrequent (e.g. when subsequent potential or current control is used). Electronic voltage and/or current control may be used, e.g. in combination with automatic potential control (6.5).

For low current applications such as for well-coated pipelines, a ballast resistor may be required to provide a minimum load for good operation of the rectifier.

The transformer/rectifier shall be provided with approximately 70 mm diameter meters or similarly sized square pattern meters to read the output voltage and current. The measuring accuracy shall be better than 2 % of full scale.

The polarity of the DC terminals and AC supply terminals shall be clearly marked. AC and DC cables shall be physically separated e.g. by an insulating panel.

A built-in timer unit may be required. The timer unit may be mechanical or electronic and shall be capable of switching the full output current in a sequence of 50 s on and 10 s off. If more than one transformer/rectifier are protecting a single structure, all transformer/rectifier timer units should be provided with a facility for synchronous switching. During normal operation, the timer shall be bypassed.

If a transformer/rectifier is oil-cooled, the incoming cables shall terminate in separate non-oil filled cable boxes and penetration into the tank shall be via bushings above oil level. A sight glass and thermometer shall be provided.

6.2.2 Engine generator sets

Where AC power is not available to supply rectifiers and the required power is high, engine generator sets may be used to provide the electrical supply needed.

If a remote survey unit with alarms cannot be installed, a two-generator system shall be used (one running, one on standby) with an automatic changeover system.

Remote generator units are prone to failure and vandalism and require frequent maintenance. For critical systems, alternatives such as solar power may be a better option.

6.2.3 Batteries, solar and wind generators

If the AC mains suffers frequent power failures, the use of batteries, charged by mains powered battery chargers, may be used instead of transformer/rectifiers.

Batteries may also be charged by means of a wind-powered generator or by solar cells. The batteries should be charged on a regular basis to provide a continuous source of cathodic protection current.

Cathodic protection systems using batteries shall be provided with suitable output voltage and/or current control equipment and a load cut off system to avoid damage to the batteries due to a complete discharge.

Battery chargers and generators shall be provided with regulators to ensure that the recommended charging rates are applied and shall be equipped with a protection system to prevent overcharging of the batteries.

The design of wind and solar generators shall be based on extensive local weather reports, stating average and minimum sun and/or wind periods and intensity during all seasons, generally a one-year period, to determine the capacity of the system. The battery capacity shall be based on the required autonomy during the prevailing maximum time without sun or wind.

Wind and solar generators shall be rated to recharge the batteries in less than 48 hours from a partially discharged state due to an extended period of no wind/sun.

In tropical areas the generators and batteries shall be designed to operate in high ambient temperatures. Solar generators should be designed to maintain the design capacity at the highest ambient temperature.

6.2.4 Thermoelectric generators

Thermoelectric generators are based on the “thermocouple” principle. Heating one side of a stack of thermocouples, sized to provide the required DC power, generates power. Heating of the unit is normally accomplished by means of gas from the gas line that is protected by the unit.

Thermoelectric units are economical but their reliability depends largely on the quality of the supply gas. Dust and liquids transported with the gas may block the burner system and extinguish the flames. This can be avoided by using additional pressure control systems or filters but this makes these units less competitive.

Thermoelectric units tend to operate more efficiently in cold climates compared to hot (tropical) climates.

6.2.5 Closed cycle turbo generators

A closed cycle turbo generator consists basically of a combustion system, a vapour generator, a turbo alternator, an air-cooled condenser, a rectifier, alarms and controls housed in a shelter. It can supply 200 to 3,000 Watt of filtered DC power. The gas supply is normally provided from the gas pipeline or from a separate supply system. The units are manufactured by specialised companies. Like thermoelectric generators their reliability probably depends on the gas quality and cleanliness.

Within PETRONAS there is limited experience with this technique.

6.3 GROUNDBEDS

6.3.1 Anode Materials

6.3.1.1 General

Any current-conducting material could be used for the anodes or groundbeds, but for reasons of economy and required service life, the material should have a low consumption rate at an acceptable cost. Materials used for groundbed construction can be carbon steel scrap, cast iron scrap, graphite cylinders, special alloy rods or noble materials plated with “inert” materials such as platinum or mixed metal oxides. A description of the various materials is given below and approximate current densities and consumption rates are given in Table 12.

Table 13 Typical consumption rates of impressed-current anode materials

Impressed current anode Material	Maximum current density, A/m ²	Working current density, A/m ²	Consumption rate
Steel	-	0.5	10 kg/A.yr
Aluminium	10	4.8	2 kg/A.yr
Graphite	25	2.5 to 10	0.25 kg/A.yr
Silicon Iron	50	5 to 25	0.1 kg/A.yr
Magnetite	200	115	0.02 kg/A.yr
Lead Alloy	300	50 to 150	0.085 kg/A.yr
Platinised Titanium	2000	250 to 700	8 mg/A.yr
Platinised Tantalum or Platinised Niobium	2000	500 to 1000	8 mg/A.yr
MMO on Titanium	1000	500 to 100	1 mg/A.yr

6.3.1.2 Steel scrap

In some cases, steel scrap is used as an impressed-current anode. This may be for temporary protection or for economical reasons. Abandoned steel-lined oil or water wells can be quite suitable. The sections are thin, however, and early failure is likely. Another weakness is the anode cable connection, which should preferably not *in contact with* the soil. For long term protection of critical installations, the use of scrap metal is not recommended.

6.3.1.3 Cast iron scrap

Cast iron scrap generally has the advantage of being thick in section and of such form that any one piece will be in soil of more or less uniform resistivity. Moreover, a graphite surface is left exposed as the outer iron is consumed, so that the remaining iron with its graphite surface acts as a graphite anode, thus reducing the rate of iron consumption. Old engine blocks are examples. The anode cable connection remains the weak point.

6.3.1.4 Silicon iron

High silicon cast iron has been found to be a suitable anode material. It is relatively inexpensive and it is used on quite a large scale for groundbeds. It is suitable both in soil and water. In soil applications, it is normally surrounded by a carbonaceous backfill. Current densities can be high and consumption rates are low taking into account the high mass per anode. The anodes come in different sizes and different cable attachments. They are quite brittle and shall be handled carefully. For seawater applications the silicon iron is usually alloyed with about 5 % chromium to resist pitting.

6.3.1.5 Graphite

Graphite anodes have a low rate of consumption. The choice between graphite and silicon iron often depends on availability in a given area.

Graphite anodes are generally cylindrical in shape, though other forms are available. The graphite is impregnated with wax or resin, which reduces flaking, or disintegration of the anodes as the graphite is consumed. The anodes are supplied with terminal connections, and with cables if required.

When installed in soil, impregnated graphite anodes are generally used with a backfill of carbonaceous material such as coke breeze. In soil and seawater, current densities of up to 10 A/m² may be employed, but in fresh or brackish water, the current densities should not exceed 2.7 A/m² in fresh water or 5.4 A/m² in brackish water. At higher outputs, the surface of the graphite deteriorates excessively due to the formation of gas.

Graphite anodes are brittle and require careful handling during transport, storage, and installation. Long graphite cylinders may be broken by subsidence of surrounding soil.

6.3.1.6 Magnetite anodes

Magnetite (Fe₃O₄) anodes are made by means of a proprietary process. The magnetite is plated onto metal (copper alloy) cylinders, which provide the electrical connection. They are light in weight but brittle. Current output and consumption rate are favourable. Because of single-source supply, they are used less often than other alloys.

6.3.1.7 Lead alloy

An alloy of lead, silver, and antimony (1 % of silver, 6 % of antimony) has been used in salt water. At a current density of 108 A/m², the annual consumption is about 85 g/A. The alloy has good mechanical properties and can be cast or extruded to any desired shape.

Platinised titanium or MMO anodes have largely replaced this type of anode.

6.3.1.8 Platinised titanium, platinised tantalum or platinised niobium

This anode material has been applied on a large scale in both salt and brackish water. It is not satisfactory for use in soil or mud or close to the sea bottom. Niobium and titanium themselves rapidly develop on their surfaces an adherent oxide layer of high electrical resistance. This oxide layer prevents corrosion of the metal, so that the titanium/niobium

acts purely as an inert support for the platinum, which needs to be applied only to a relatively small area as it can withstand a very high current density. The titanium oxide is more sensitive to breakdown at an over voltage than niobium oxide.

Platinised anodes have good mechanical properties and their higher initial cost is offset by their long service life.

Although the current density limit is high, up to 540 A/m², the platinised anodes with titanium as a carrier shall be run at a low voltage, i.e., approximately 8 V to 10 V maximum when used in chloride containing environments.

A further limitation is that the passage of an alternating current will bring about the rapid disintegration of the platinum layer. The ripple from the alternating current transformer-rectifier supplying current to such anodes shall be kept below approximately 5 %. With a single-phase transformer-rectifier the ripple is frequently far in excess of this figure. This difficulty does not usually arise with three-phase transformer-rectifiers.

Provided the conditions regarding the current density, applied voltage, and ripple limitations are observed, the platinum layer, which is normally only about 2.5 µm in thickness, has a life expectancy of 10 years. If longer life is required, a thicker platinum layer shall be used.

6.3.1.9 Mixed metal oxide based anodes

These anodes are the latest technology in anode material and have largely replaced other anode types, both onshore and offshore. They consist of a proprietary mixture of (noble) metal oxides plated on a titanium or niobium substrate. This type of anode has the same advantages (and some limitations) as platinised anodes but is generally cheaper. They can be made in various shapes such as ribbons, rods, wires, mesh etc. Ribbon shapes are often used as distributed anodes for localised protection of pipes or under tank bottoms. Applicable current densities are high and consumption rate is low.

6.3.1.10 Distributed anode cables

Distributed anode cables consist of a copper core sheathed by a conductive polymer that allows passage of cathodic protection current to the soil. The current density of the anode is usually low, and such cables are mainly used for localised protection of pipelines. They have also been used successfully for the protection of coated buried tanks and vessels and for the protection of coated external tank bottoms. These anodes require a specialised design and should not be operated above their rated current density. Consumption rates or anode life can be obtained from the Supplier.

6.3.2 Impressed current anode design

6.3.2.1 General

Impressed current anode systems shall be designed so that their mass and quality are sufficient to last for the design life of the system. The resistance to earth shall allow the maximum predicted current demand to be met without exceeding the voltage capacity of the DC source during the design life of the system and the location is at such a distance from the structure as to provide a regular distribution of current. Finally the risk of causing harmful interference on other buried structures shall be minimized.

For seawater applications, the design of the anode system is relatively simple as no complex earthworks are required. Because of the low resistivity, anodes can be placed directly in the water. The main requirement is that the anodes are sufficient in number and size to limit the current density on the anode surface to the recommended value and that the anodes and cables are protected against mechanical damage from ships, anchors, mooring wires etc.

Onshore, selection of the location and the type of groundbed depends on local soil conditions and resistivity at various depths, including groundwater levels and resistivity. Strong seasonal changes in surface soil conditions may require deeper groundbeds. The available terrain may be limited for surface groundbeds and the risk of damage by excavation may also prohibit the use of surface groundbeds.

6.3.2.2 Deep groundbeds

Deep groundbeds should be used if the soil conditions at the required depth are suitable to meet the requirements. Deep groundbeds usually limit the risk of shielding and stray currents. They occupy a limited space, which is preferable in congested areas.

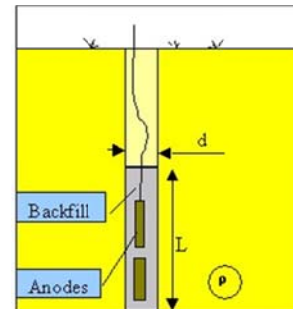
There are several methods of calculating groundbed resistance. Usually the calculations are based on Dwight formulae.

For a deep anode groundbed, the following relationship applies:

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

in which:

R_{deep} = groundbed resistance in Ω ;
 ρ = layer soil resistivity at depth in $\Omega.cm$ at the depth of anode to be installed;
 L = active length in cm;
 d = bore hole diameter in cm.



Deep groundbeds can be open hole or closed hole design.

The drilling and completion of the borehole and the installation of the anodes and backfill are specialized jobs that require an experienced contractor. The borehole design and construction shall be such that undesirable transfer between water bearing formations and pollution of underlying strata from the surface (e.g. tank farms) is prevented.

Metal or plastic casings are normally used at the surface for stabilizing the borehole. Steel casing or perforated plastic casing is used in the active section of the groundbed. The casing at depth shall be electrically isolated from metal surface casing and structures at the surface to avoid interference. For this isolation, plastic casing is normally used.

Deep groundbeds shall have venting pipes to prevent gas blocking of the well. These are normally made of chlorine-resistant plastic.

More information on the design, installation, operation and maintenance is available in NACE SP0572.

6.3.2.3 Surface groundbeds

Shallow surface groundbeds are often cheaper and can be used if the soil conditions at the surface (groundbed depth) are suitable to meet the requirements and if sufficient distance from the pipeline can be achieved and there is no risk of shielding.

In a shallow groundbed, the anodes may be installed horizontally or vertically. The choice depends on the soil resistivity distribution at various depths. The anodes at the highest point of the carbonaceous backfill shall be not less than 1 m below ground level.

The design shall include a calculation of the groundbed resistance. For a shallow anode groundbed, the same relationship applies as for sacrificial anodes. Formulae are given in (5.2.3.2) for vertical anodes and in (5.2.3.3) for horizontal anodes. Also, the same formulae for anode spacing factors apply (5.2.3.7).

The method of construction of the groundbed and the method of installation of the anodes and backfill may vary depending on the soil conditions, materials used and *Principal's* preference. The method of construction shall be included in the detailed design.

6.3.3 Impressed current backfill

A carbonaceous backfill or other low resistivity backfill material is normally used in impressed current groundbeds. The purpose of the backfill is to lower the groundbed resistance by increasing the contact surface area with the soil and to extend the anode life by moving the anodic reaction (formation of oxygen or chlorine) from the anode surface to the surface of the more inert coke column.

6.4 CABLES

For cathodic protection work, it is customary to use cross-linked polyethylene-insulated, PVC- or polyethylene-sheathed copper conductor cables, with cross sections depending on the current carried and the circuit resistance limits. If long runs of cable are required, larger cross-sectional areas may be needed to keep the voltage drop within acceptable limits. For mechanical reasons a minimum cable size (single core) of 6 mm² should be used.

For use in seawater, cables should be protected against marine organisms.

For use in deep groundbeds where oxygen and chlorine may be produced or where high acidity may occur, the cables shall be resistant to these conditions. PVDF (polyvinylidene fluoride, e.g. Kynar) is a suitable material.

The current-carrying capacity of cathodic protection cables (interconnection wire) is seldom used to its maximum. More consideration is given to the maximum acceptable circuit resistance. Sometimes cable resistance can have a considerable impact.

Buried and submerged cables should be installed in continuous lengths without breaks or joints. If joints or cable access are required, connections should be made above ground in appropriate distribution boxes.

Cables connected to the positive circuit of an impressed current cathodic protection system (anode cables) shall always be free from any damage to avoid rapid electrolytic corrosion of the copper conductor.

Table 14 gives an indication of the cable sizes required for various current loads in cathodic protection.

Table 14 Single core cable sizes used for cathodic protection

Nominal cross sectional area, mm ²	Number of strands	Single conductor resistance, Ω /km	Typical DC Current rating (A) (Temp. max. 70 °C)	Comparable AWG size
6	7	3.0	31	10
10	7	1.8	42	8
16	7	1.1	56	6
25	7	0.7	73	4
35	19	0.5	90	2
70	19	0.26	185	2/0

6.5 CURRENT CONTROL

6.5.1 Current control

When more than one structure is protected by the same impressed current source, each structure shall be provided with an individual negative connection. This is particularly valid for electrically isolated structures such as pipelines.

Variable resistors can be installed in the negative drain circuit, if required, to balance the current to each of the adjacent structures. Each negative circuit shall also be provided with a suitably sized shunt and diode at the DC source. The installation of the diode is required to minimize mutual influence of structures during "ON-INSTANT OFF" surveys.

All cables, diodes and current measurement facilities shall be installed in a distribution box.

6.5.2 Automatic potential control

In some cases, the impressed current system can be provided with automatic potential control that automatically controls the protection level. This is always in combination with a suitable permanent reference electrode, buried close to the structure.

The potential measuring circuit shall have a high input impedance ($> 100 \text{ M}\Omega$) and the control system shall have an accuracy of $\pm 10 \text{ mV}$. Normally, adjustable voltage and current limiting circuits and/or alarms are provided to protect the system against overprotection in case of failure of a reference cell.

6.6 MONITORING

For the monitoring of impressed current systems, the installed voltmeter and ammeter are required as a minimum. For multiple circuits, permanent shunts shall be provided in the current source or distribution boxes. Where potential control has been installed, a permanent meter to read the structure to soil potential is needed.

Further monitoring devices are installed on the structure or pipeline and are further discussed in (10).

7. COATINGS AND CATHODIC PROTECTION

7.1 INFLUENCE OF COATINGS ON CATHODIC PROTECTION

Although it is technically possible to protect bare (buried or immersed) steel structures and pipelines by only applying cathodic protection, it is seldom desirable to do so because of the cost of providing the large current required and the difficulty of arranging anodes so as to give a uniform current distribution. A good coating of high insulating value greatly reduces the current required to maintain the steel at the required steel-to-soil potential and also provides a more uniform spread of current from the anodes. A protective coating should therefore always be applied to any buried structure or pipeline that is to be cathodically protected.

An exception to this guideline is the cathodic protection of some structures in seawater such as drilling and production platforms and of the internals of seawater tanks onshore and in oil tankers. Offshore platforms have been successfully protected by sacrificial anodes without a protective coating being applied. The low resistivity allows the passage of sufficient current, the compact structure allows a good current distribution and the formation of calcareous deposits can reduce the current demand of the structure over time.

The current required to protect a structure or pipeline is approximately proportional to the area of bare steel. Theoretically, cathodic protection should be unnecessary when the steelwork is perfectly coated. In practice, coatings are often damaged in transport or during laying, or may contain imperfections such as pinholes. Even in low-corrosivity soils, the slightest discontinuity in the protective coating may result in severe local corrosion, so that if corrosive conditions prevail, even coated structures or pipelines should be given cathodic protection.

Damage to protective coatings is often expressed as a percentage or fraction of the total surface and depends on the age of the structure. Initial coating damage is damage caused during construction. Sometimes porous coatings have an apparent initial coating damage e.g. fusion-bonded epoxy (FBE).

7.2 INFLUENCE OF CATHODIC PROTECTION ON COATINGS

Cathodic protection of painted or metal sprayed and painted structures should be considered carefully because oil-based paints may be saponified by the alkalinity developing at the cathodically protected surface; sprayed aluminium or zinc may be attacked in a similar way. The surface potential shall therefore be maintained as closely as possible to the value needed for protection, and over-protection avoided.

When cathodic protection is applied to metallic structures, the cathodic reaction may cause the evolution of hydrogen. Hydrogen can destroy the adhesion of coatings. The more negative the potential of the steel, the higher the risk of disbonding of the coating.

For this reason, and also to avoid hydrogen embrittlement (23), cathodic protection systems for coated structures and pipelines shall be designed so that the most negative *INSTANT-OFF* potential will not be more negative than -1150 mV vs. Cu/CuSO₄ reference.

Moreover pipeline coatings shall be tested for their resistance to cathodic disbonding by carrying out cathodic disbonding tests described in the pipeline coating specifications. Disbonding of coatings may lead to underprotection of the steel under such coatings and cause detrimental effects such as corrosion and carbonate stress corrosion cracking.

8. ELECTRICAL SEPARATION

8.1 GENERAL

To avoid cathodic protection current flowing to structures other than those intended, electrical separation may be necessary between different structures. This is in particular the case when unprotected structures are in the sphere of influence of large impressed current systems or when protected structures have different current demand due to different materials or coating types.

For instance, pipelines shall always be electrically isolated from other plant, foreign structures, pipelines, and electrical and instrument earthing systems. Isolation can also be used to separate underground piping and vessels from above ground structures and buildings (foundations).

In some cases, electrical isolation is not installed because the installation is so complex that maintenance of the isolation is practically impossible. If one isolating device fails, the whole isolation fails and can even cause dangerous currents to run between parts of equipment, possibly with the risk of sparking. An example of such a case is on vertical storage tanks where isolation of piping, drains, fire systems, earthing, instrumentation, etc. would otherwise be required.

In some cases where the cathodic protection systems are all sacrificial, pipeline isolation can sometimes be omitted. However, isolation should always be installed to separate installations of different owners.

Isolation of pipelines and piping is achieved by the installation of isolating joints or isolated flanges. If the pipe is transporting an electrolyte, isolating spools may have to be used; see (8.4). If piping carries an electrolyte in small quantities or intermittently, the electrolyte shall be prevented from bridging the isolating device by installing the isolation vertically or slanted or in a high point in the pipe(line).

Isolating joints or flanges are normally internally coated over a length of 0.5 m each side.

Isolating joints/flanges should not be buried. They shall be installed above ground or in inspection pits. In some cases however, such as in a shore approach, burial may be unavoidable.

The resistance across pipe isolation for cathodic protection is normally specified as 1 M Ω and shall be tested before installation of the joint or flange.

Isolating joints or flanges shall be protected against high voltages from power systems or lightning, by means of earthing or surge arrestors.

Isolating joints and flanges should be painted in a contrasting colour for easy identification. The colour should be consistent in one area. The paint shall be compatible with the pipe coating. Red yellow or black epoxy is commonly used. Paints containing metallic pigments (such as zinc or aluminium) shall not be used for isolating joints/flanges.

Isolating joints or flanges shall be provided with monitoring installations as detailed in (10) or in the design specification (e.g. PTS 30.10.73.31.).

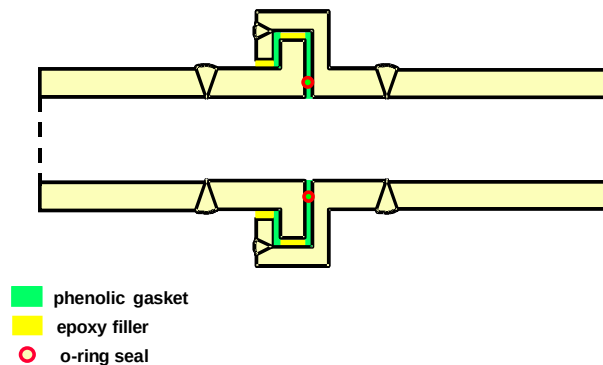
8.2 ISOLATING JOINTS

Electrical isolation in pipelines is mostly achieved by installing monolithic isolating joints. These are specially designed fittings including electrically isolating layers that conform to the pipeline design code. An example is shown in Figure 13.

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Circular 48/06**

The construction of these joints and the mechanical and electrical properties are specified in PTS 31.40.21.31.

Figure 13 Schematic diagram of a monolithic isolating joint

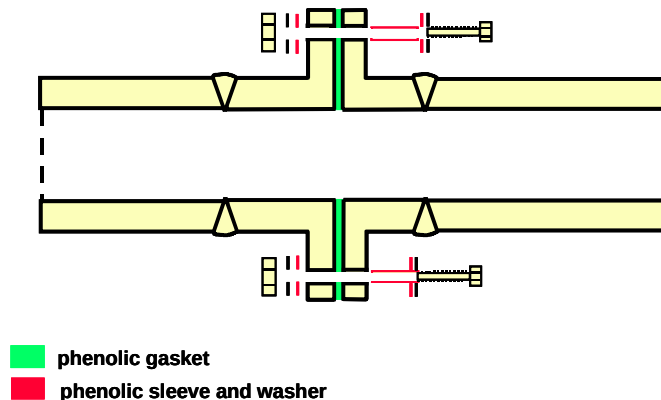


8.3 ISOLATED FLANGES

Where isolating joints are not possible, isolated flanges can be used. This may be necessary when retrofitting cathodic protection onto existing pipelines or piping.

Isolated flanges are standard ANSI type flanges provided with a special isolating gasket and isolating sleeves and washers for the isolation of the bolts. A schematic drawing is shown in Figure 14.

Figure 14 Schematic diagram of an isolated flange



Flanges and insulation kits shall meet the design requirements of the pipeline or piping. Insulating gaskets for raised face or full-face flanges are mostly of the neoprene coated phenolic resin type. Some types of isolating gaskets have a higher reliability due to special o-ring seals and sometimes coated metal gaskets (e.g. Pikotek).

Bolts are preferably isolated by means of full-length phenolic or composite sleeves and phenolic resin insulating washers. Steel washers are provided at both sides for mechanical protection of the isolating washers.

Isolated flanges shall be dedicated flanges, not in use for other purposes. For instance, valve flanges shall not be used for electrical isolation. Isolated flanges shall always be well supported to avoid damage due to mechanical loading.

Insulated flanges should be assembled and tested before being welded into the pipe. A voltage of 1500 VDC shall be applied across the flange assembly for one minute without causing breakdown of the insulation or flash over. Subsequently the resistance across the assembled flange shall be measured and shall be more than 1 MΩ.

To test existing flanges, the bolt-to-pipe resistance can be measured and the overall effectiveness of the isolated flange determined after cathodic protection has been applied. This can effectively be done by testing for the absence of current through the attached pipe using a "Swain-type" current clamp/meter.

Insulated flanges shall be protected against ingress of dirt and moisture by the application of flange protectors or protective tape, except when used in sour service conditions.

8.4 ISOLATING SPOOLS

If the product transported by the pipeline is an electrolyte, there is a possibility of cathodic protection current flowing across the isolation causing internal corrosion at the "unprotected" side of the isolation. To avoid this problem, the following guideline applies:

If the resistivity of the electrolyte is higher than 100 $\Omega\cdot\text{cm}$, or the volume occupied by the electrolyte is less than 5 % of the pipeline volume, the overall length of the isolating joint shall be four times the pipe diameter with a minimum of 1 m.

If the resistivity of the electrolyte is below 100 $\Omega\cdot\text{cm}$ and the volume of electrolyte is more than 5 % of the pipeline volume, isolating spools shall be used.

The length of an isolating spool shall be determined by the following formula:

$$L = (400 / \rho) \times D$$

where:

L = length of spool (cm);

ρ = electrolyte resistivity ($\Omega\cdot\text{cm}$);

D = nominal pipe diameter (cm).

Isolating spools may be manufactured out of non-conductive composite pipe material (GRE) or as an internally coated or lined steel spool with isolating joints or flanges at both ends, depending on pipeline service, pressure and temperature.

Where electrical isolation is installed to avoid galvanic corrosion in water systems having dissimilar metal connections, e.g. titanium heat exchangers, long spools are not required and a standard isolating joint of flange (internally coated over a length of 4xD) can be used.

8.5 ELECTRICAL EARTHING

Structures under cathodic protection should be electrically isolated from common or plant earthing systems to avoid a loss of current.

Electrical earthing of devices installed on the protected structure may be required for safety reasons or pipeline earthing may be required to mitigate the effect of induced electrical voltages (9).

Where electrical safety earthing is required, e.g. when instrumentation / electrical equipment is installed on or near the pipeline, PTS 33.64.10.33. shall be applied.

If pipeline earthing is to be installed to mitigate the effect of AC induced voltages on the pipeline (9), this should be done at the locations where the anticipated or measured voltages to ground are highest and where the pipeline is exposed and can be touched by personnel.

9. ELECTRICAL INTERFERENCE EFFECTS

9.1 STRAY CURRENTS

Stray currents are returning currents from large direct-current systems, employing an earth or with an uninsulated return path, that do not form part of the affected structure. Stray currents interfere with buried (or submerged) metal structures by flowing from the soil into the structure in one location and flowing from the structure into the soil in another location. The stray current uses the structure metal as a preferential (low resistance) return path. In the locations where the current flows from the metal into the soil, anodic currents may cause accelerated corrosion. Sources of stray currents can be own or foreign cathodic protection systems, DC railway or tramway traction, welding generators, and DC power systems.

The severity of stray currents is related to the difference in resistance between the soil or water and the metal structure (including coating). Therefore, most stray current problems occur in high resistivity soil. Stray current problems in seawater are uncommon.

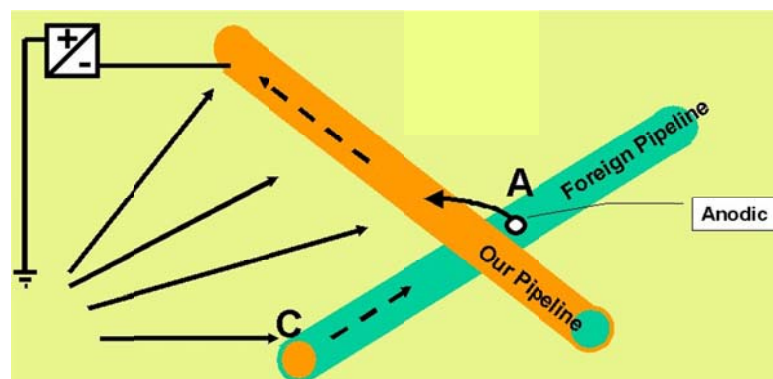
9.2 STRAY CURRENTS FROM CATHODIC PROTECTION SYSTEMS

Electrical interference in the form of stray currents can arise from cathodic protection systems themselves, mainly with impressed-current systems. Any buried metal in the sphere of influence of a cathodic protection system can be subject to this phenomenon.

The current applied to a protected structure or pipeline may be picked up by a neighbouring and unprotected line, for example where a protected pipeline crosses an unprotected one as shown in Figure 15. The unprotected pipeline becomes cathodic at the point where the current is picked up (C), and anodic at the point where the current eventually leaves the line (A), resulting in some protection at 'C' and corrosion at 'A'. Because point 'A' becomes anodic when the cathodic protection system is energized, the pipe-to-soil potential becomes more positive when the rectifier is switched on. This is commonly called "positive swing". A positive swing of maximum 20 mV is allowed; more than 20 mV positive swing indicates a possibly detrimental level of stray current and should be rectified.

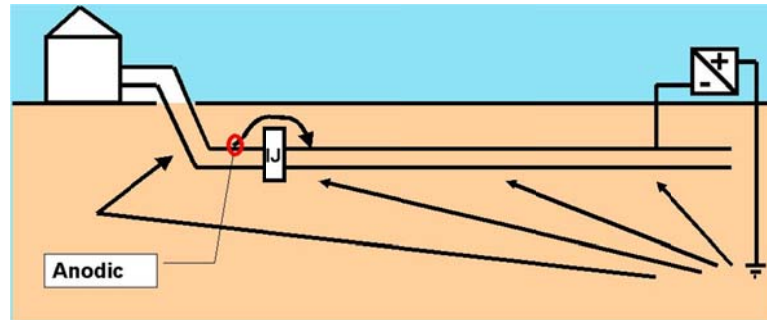
If both structures are cathodically protected and the positive swing on one structure is well within the protection criteria window, no corrective measures are required.

Figure 15 Stray current from impressed current cathodic protection system at a pipeline crossing



Another example of stray current from cathodic protection systems is when the current of a pipeline cathodic protection system is picked up by buried metal structures inside a plant and is discharged to the pipeline through the soil across the isolating joint (see Figure 16). This is one reason why isolating joints or flanges should not be buried.

Figure 16 Stray current from impressed current cathodic protection systems at an isolating joint



Electrical interference effects are negligible with sacrificial anode systems, as these anodes are placed much nearer to the protected structure than to any unprotected steelwork and because their driving voltage is usually much lower than that of impressed current system groundbeds.

The test method to determine the presence of detrimental stray currents from cathodic protection systems basically consists of measurements of ON-OFF potentials at the location where stray currents are likely to occur, such as crossings, isolation devices and parallel pipelines. The detailed method is described in (10).

9.3 REMEDIAL MEASURES

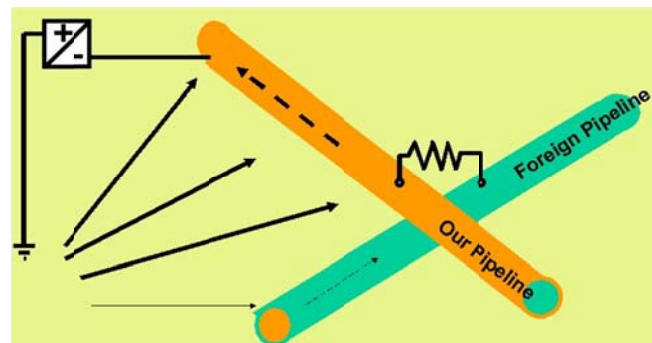
In the case of stray currents from cathodic protection systems themselves, it shall be ensured that neighbouring structures are not adversely affected.

Bonding the neighbouring structure or pipeline to the protected one can sometimes prevent interference, so that electrically the two become a single unit. Cathodic protection is then applied to the combined unit. This is the recommended method for use where structures are close together, as for example a pipeline lying in a common right of way with neighbouring pipelines.

When the affected structure cannot be directly connected to the cathodic protection system, there are two methods to prevent adverse stray currents: bonding or shielding.

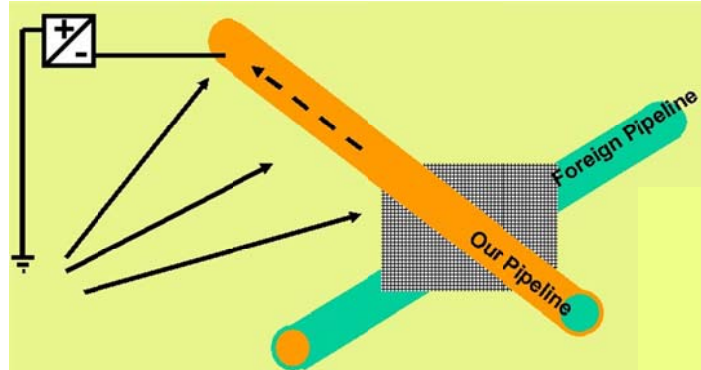
The application of resistance bonds to eliminate corrosion by interference is based upon the principle that the current collected by the unprotected pipeline should be conducted via a metallic conductor to the protected structure. The electrical resistance of this bond is made high enough to prevent too much current from flowing to the unprotected structure. The resistance bonds are installed where the structures are nearest to each other and controlled so that minimum current leaves the unprotected structure to earth. When the positive swing on the unprotected pipeline is less than 20 mV, the resistance bond is effective.

Figure 17 Resistance bond at a pipeline crossing



The pipelines at the crossing can also be provided with a dielectric shield and wrapping to prevent any current passing from the pipes to the soil and vice versa. A double adherent pipe wrapping in combination with plastic sheets buried in the soil between the two structures can minimize the amount of stray current.

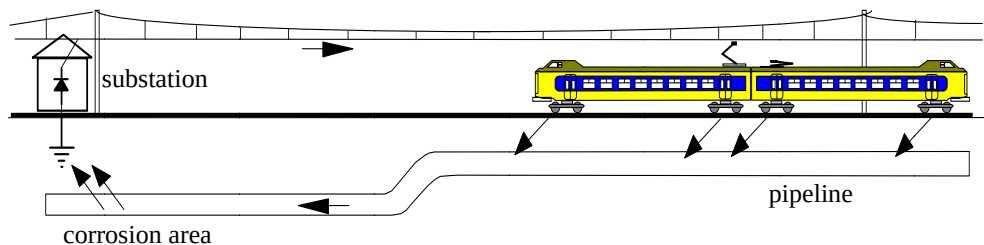
Figure 18 Shielding system at a pipeline crossing



9.4 STRAY CURRENT FROM TRACTION SYSTEMS

The returning currents from DC traction systems may be partly conducted by the soil back to the substation. This effect is larger when the resistance of the tracks is high and/or the isolation between tracks and soil is poor or absent. The current can cause stray currents on pipelines running more or less parallel to the railway. The current enters the pipeline at coating damages between the location of the train and the substation and the current leaves the pipeline usually close to the substation where it can cause severe corrosion.

Figure 19 Stray current caused by traction systems



As the stray currents are intermittent, depending on the rail traffic, they are difficult to detect. The established method is the registration of the pipeline potential in the suspect area for at least 24 hours. Sometimes buried steel coupons can indicate the strength of the stray current.

The most satisfactory method of dealing with this type of stray currents would be to eliminate them at the source by suitable insulation of the tracks or other means, but this is often impossible or extremely costly. It is then necessary to allow for the interference of stray currents when designing the cathodic protection system.

Light stray currents can sometimes be conducted back to the tracks by resistance and diode bonding. If the exit point of the current is known, zinc or other low resistance earthing blocks can be used to provide an exit point to earth. However, these need to be monitored over time to ensure complete depletion does not occur. Severe stray currents have to be

mitigated by potential controlled rectifiers of sufficient capacity and reaction time, placed in the vicinity of the points where the stray currents leave the steel to re-enter the soil. The main consideration is that the steel-to-soil potential should be as uniform as possible over the whole of the protected structure or pipeline. Where these points are near the railway, the rectifier can be connected directly to the railway. This will make cathodic protection possible, as it considerably reduces effects of peaks in the stray current exit to earth. Railroad operators are often reluctant to provide connections as the signalling system could become adversely affected.

9.5 ALTERNATING CURRENT INTERFERENCE

Alternating currents induced in pipeline systems running parallel with power lines or AC powered railways can generate voltages that may be harmful for personnel working on the pipeline and can also cause so-called AC corrosion. Such voltages require mitigation.

Pipelines and power transmission systems often share a right of way. Rules and regulations provide guidance on earthing of the power transmission system and the distances to be maintained between these and the pipeline(s) in question.

If routing the pipeline close and parallel to an overhead high-voltage system cannot be avoided, a study should be conducted by experts to determine which sections of the pipeline are influenced by a short circuit to earth and to what extent.

In several countries, safety recommendations have been published. Certain minimum distances should be maintained during construction and operation of a pipeline and certain maximum voltages are allowed (allowable touch voltages). NACE RP0177 describes the phenomenon. NPR 2760 is the Dutch guideline.

At valve stations, a steel net buried around the valve and electrically bonded to the pipelines may be required for the protection of personnel.

These recommendations deal with safe working voltages on pipelines caused by resistive, capacitive or inductive interaction. They mostly deal with fault conditions of the power systems that are of short duration.

During normal operation power lines can, however, induce AC voltages on a pipeline that may be less than the allowable touch voltage but can nevertheless cause corrosion on the pipeline. In the past this has been neglected but with the increasing extent of power networks there have been several cases of AC corrosion. Apart from AC high-voltage overhead lines, AC interference can also result from AC powered electric railways and tramlines.

There are a few brief guidelines that may indicate if AC corrosion is likely or not.

Detrimental AC interference is unlikely if the distance is more than 500 m or the length of the parallelism is less than 2 km.

If the induced AC voltage can be measured, an estimate can be made of the expected AC current density by:

$$I_{ac} = \frac{80 \times V_{ac}}{\rho \times \pi \times d}$$

where:

I_{ac} = the estimated AC current density in A/m²;
V = is the measured AC potential in mV;
 ρ = the soil resistivity in $\Omega \cdot \text{cm}$;
d = the diameter of the expected defect in cm.

In areas of concern the AC current density can be estimated by means of AC coupons buried at pipeline depth and connected to the pipeline through a measuring device.

When the estimated AC current density is less than 20 A/m², the probability of AC corrosion is negligible; when the AC current density is more than 100 A/m² the probability of AC

corrosion is high. When the AC current density is between 20 A/m^2 and 100 A/m^2 , the effect is uncertain and more tests may be needed.

AC corrosion can be more severe in anaerobic and chloride containing soil, at damaged areas measuring about 1 cm^2 to 3 cm^2 and at low frequencies ($< 100 \text{ Hz}$). Mild AC corrosion can be mitigated by cathodic protection; severe AC corrosion requires special measures such as earthing or the installation of mitigation wires.

To predict the extent of the influence a detailed study by a specialized firm will be required.

Special attention should be paid to the cathodic protection of pipelines and the over voltage protection for rectifiers.

9.6 TELLURIC CURRENT

Geomagnetic field variations associated with the ionospheric currents establish large-scale systems of electric currents within the earth by a process of electromagnetic induction. The global pattern of these currents flowing near the surface of the earth is known to be extremely complex due to factors such as the wide range of electrical conductivities of different strata.

The frequency of the fluctuations has been recorded to be in the order of one fluctuation per several hours.

If suitably positioned, a pipeline of considerable length could pick up and discharge telluric currents. If the current picked-up is considerable in comparison with the total current applied for corrosion prevention (which could be the case with a very well-coated pipeline in high-resistivity soil) the effect of telluric current on such a system would become noticeable and may have to be corrected. In general, telluric currents do not cause corrosion but can hamper the measurements of cathodic protection levels.

A number of countermeasures can be taken to combat ill effects from telluric currents. Sectioning the line by insertion of insulation flanges or joints will reduce long line current flow. Installation of discharge points by providing zinc or magnesium anodes at strategic locations will reduce the risks of corrosion at discharge of current at coating imperfections.

Expert advice should be obtained if telluric effects are suspected.

10. MONITORING CATHODIC PROTECTION SYSTEMS

10.1 GENERAL

After a cathodic protection system has been installed, it should be checked periodically to ensure that the equipment is functioning correctly and that the protected structure is being maintained at the required potential.

Changes may occur due to causes such as deterioration of coatings, changes of soil resistivity with seasonal rainfall, changes in the resistance of groundbeds, anode wastage, etc.

During design and construction, monitoring facilities shall be installed or test locations shall be assigned that represent the various parts of the structure and cover the worst-case situation. Monitoring facilities may vary with structure type and are further described for each cathodic protection application. Typical monitoring stations are described in PTS 30.10.73.33. for general facilities and in PTS 30.10.73.31. for pipelines. It is advised to give each test location a unique tag number.

During installation and commissioning, the necessary information shall be gathered as described in PTS 30.10.73.33. This information serves as a baseline for later measurements. Polarisation of some types of structures can take several weeks or months to complete.

For each cathodic protection system, a set of monitoring procedures should be available that contains as a minimum:

- the scope of the structure, what is to be protected or not;
- a list and description of key and other monitoring points (11.3);
- the protection criteria and related test methods;
- a monitoring time schedule;
- a set of maintenance procedures such as adjustment and repair procedures etc.

The data shall be analysed after each survey and corrective action taken as soon as possible but in any case within one month. Whenever a cathodic protection system is installed, the necessary instruments should be purchased to enable the engineer in charge to make the required measurements.

10.2 IMPRESSED CURRENT SYSTEMS

10.2.1 Routine monitoring

10.2.1.1 Availability survey

The availability of the impressed current system shall be monitored at regular intervals. For new systems this may be more frequent than for stable existing systems. Such monitoring should include as a minimum for each current source: measurement of output voltage, output current and drain point potential. When multiple circuits are connected to the same current source, the current and potential of each circuit may be measured separately. The frequency of this monitoring depends on the reliability of the power source and the stability of the cathodic protection system; it may range from monthly to twice yearly.

10.2.1.2 Protection level survey

The protection levels should be monitored at key monitoring points at regular intervals and compared with the protection criteria. These measurements can be made as "ON" potentials or as "ON/INSTANT-OFF" potentials depending on the system. Requirements are described separately for each type of structure. If anomalies are found, the current output of the system may have to be adjusted or a more extensive survey or a specialised survey (10.4) may be required. The frequency of the measurements of protection levels also depends on the stability of the system but should be at least once per year. If strong

seasonal influences are expected, measurements shall be made taken at least twice a year.

10.2.1.3 Functional inspection

The functional inspection of cathodic protection equipment should be done on a regular basis and is normally done in conjunction with the above monitoring schedules. Functional inspection procedures shall be included in the monitoring procedures and may include mechanical damage, vandalism, corrosion damage, wear of components, secure electrical connections (hot terminals), checking of charge controllers and batteries of solar systems, calibration of meters and reference electrodes, cleaning of dust and growth (plants, insects).

10.2.1.4 Monitoring of special features

Monitoring of special features such as isolating joints, flanges, pipeline casings, crossings, foreign structures, resistance bonds, stray current mitigation systems etc., shall be done at a regular basis and may coincide with another monitoring schedule. The frequency and procedure shall be included in the monitoring procedure.

10.2.2 Specialized surveys

10.2.2.1 ON/INSTANT-OFF potential measurements

When potentials are measured in high resistivity soil with the cathodic protection system switched on ("ON" potential), the voltage drop in the soil due to the cathodic protection current can cause a significant difference between the measured potential at soil grade and the true potential at structure (pipeline) depth. This error is called the IR drop. In order to reduce this error to a minimum and measure a more true potential, the cathodic protection current is switched off momentarily and the potential ("*INSTANT-OFF*" potential) is measured immediately after interruption (within seconds). This potential is not affected by IR drop. Transformer-rectifiers should be provided with automatic and synchronisable interrupters for this purpose. Both "ON" and "*INSTANT-OFF*" potentials should be recorded for future reference. Although often ranked here as a specialized survey, *ON/INSTANT-OFF* potential measurements are in practice used for routine monitoring to enable direct comparison with protection criteria (4.3).

10.2.2.2 Close Interval Potential Survey (CIPS)

Potential measurements at key points (11.3) or pipeline test posts are a good indication of the general protection levels of a pipeline. It is, however, possible that in an area between test posts there are locations where coating damages exist that are not fully protected. To detect such locations, a close interval potential survey (CIPS) can be carried out which basically consists of ON/INSTANT-OFF potential measurements every one or two metres. Contact with the pipeline is made in the nearest test post or other accessible location via a trailing wire. During the survey, the transformer/rectifier(s) are interrupted in synchronization. Many systems are computer controlled and take the readings synchronized with the rectifier interrupters. Some modern interrupters use either radio timing signals or GPS.

It is sometimes necessary to measure the pipe-to-soil potential at a fixed point as well to detect time dependent variations (such as stray currents) that might be mistaken for localised defects. The measurements are usually presented in graphical form together with pipeline features (crossings, fittings) that can serve as a reference point to relocate the defects. By means of this technique, those defects that are under protected can be listed for repair or adjustment.

10.2.2.3 Coating Surveys

There are several coating survey techniques to detect coating defects in pipeline (or other) coatings: three AC techniques and one DC technique are described here.

Pearson survey employs an AC transmitter connected between the pipeline at a test post and an earthing electrode, and a receiver with metal ground pins carried by two persons walking at a fixed distance over the pipeline. At the location of coating damage, the electric

field generated in the soil is detected by the two sets of pins and the receiver. The location can be determined relatively accurately and the signal strength is indicative of the relative size of the defect. This technique is particularly suitable for detecting single defects and is often used as a commissioning tool for pipeline coating projects. Where pipelines run in close proximity or where there are multiple defects, the results may be unclear. The signals can be fed into a recording device, and this technique is sometimes combined with CIPS.

AC attenuation is a technique that is contactless and basically measures the electromagnetic field around the pipeline generated by an AC transmitter. The frequencies used are higher than with the Pearson survey. This is done by taking measurements at defined points along the line, often at readily accessible locations. The normal attenuation of the signal is measured, but in the presence of significant defects or coating deterioration the attenuation will be higher. Such suspect sections can then be surveyed at smaller intervals and the deteriorated section is identified for further investigation. This technique is particularly useful for long pipelines that have no cathodic protection history or survey record.

CP Current Mapper is a similar technique to AC attenuation but uses a very low frequency (2 Hz to 10 Hz), comparable with a quickly interrupted DC signal. It often uses existing cathodic protection stations. A special detector is placed over the line and can measure the direction and the magnitude of the current.

*New survey equipment eg **Pipeline Current Mapper (PCM)** is able to perform both function ie AC attenuation and CP Current Mapper.*

Direct Current Voltage Gradient (DCVG) is a technique that detects the potential gradients in the soil generated by the cathodic protection system. By means of two reference electrodes, the direction of the (interrupted) cathodic protection current can be detected and leads the surveyor to the coating defects. The exact location is determined and pegged. The relative signal strength is indicative of the relative size of the defect (i.e. as %IR). This technique works also on parallel pipelines.

These four techniques each have their own advantages and disadvantages in operability, accuracy, speed and cost. They do not give an accurate record of the pipeline protection level like the CIPS. If more information is required, expert advice should be sought.

10.2.2.4 Trouble shooting

i) Pipe to soil findings and TRU condition

Table 15 Fault Detection

<i>Problems/Symptoms</i>	<i>Factors/Reason</i>
<i>i) Structure/electrolyte potential becomes more positive as protection system is switched on</i>	<i>Indicates reversed connections which is the most serious fault and which could result in severe damage to the structure in a relatively short period.</i>
<i>ii) Applied voltage zero or very low, current zero</i>	<i>1) failure of AC fuse or tripping of other protective device; 2) failure of AC supply; 3) failure of transformer-rectifier</i>
<i>iii) Applied voltage normal, current low but not zero</i>	<i>1) deterioration of anodes or groundbeds; 2) drying out of soil around groundbeds, or some anodes no longer immersed; 3) accumulation of electrolytically produced gas around anodes; 4) disconnection of some of the connections to individual anodes of a groundbed or anode system; 5) disconnection of part of the protected structure.</i>
<i>iv) Applied voltage normal, current zero</i>	<i>1) severance of anode or cathode cables; 2) failure of d.c. fuse or ammeter of transformer-</i>

	rectifier unit; 3) complete failure of groundbed or anode system.
v) Applied voltage and current both low	1) control on transformer-rectifier unit set too low; 2) transformer or rectifier failing; 3) electricity supply faulty.
vi) Applied voltage and current both high	Control on transformer-rectifier set too high
vii) Applied voltage and current normal but structure/electrolyte potential insufficiently negative:	1) break in continuity bond or increased resistance between point of connection and point of test; 2) greatly increased aeration of soil at or near point of test due to drought or increased local drainage; 3) alteration of environment causing rapid depolarization or increase in oxygen content of water due, for example, to reduced level of pollution or increased flow; 4) faulty isolation equipment e.g. short circuiting of an isolation joint in a pipeline; 5) protected structure shielded or otherwise affected by new structures; 6) failure of cathodic protection system on another part of the same structure or on a secondary structure bonded to it; 7) deterioration of, or damage to, protective coatings; 8) addition or extension to buried structure, including fortuitous contact with other metallic structures; 9) interaction from another cathodic protection system; 10) effects of stray a.c. on the structure
viii) Applied voltage and current normal, but structure/electrolyte potential abnormally negative:	1) break in continuity bonding at position further from the point of application than the point of test; 2) decreased aeration of soil or electrolyte at point of test; 3) reduction in rate of flow of electrolyte; 4) secondary structures have been removed or have been cathodically protected or bonds to them broken; 5) effects of stray AC on the structure.
ix) Applied voltage and current normal but structure/electrolyte potential fluctuates	The presence of stray earth currents e.g. interference from DC traction systems or telluric/geomagnetic effects

ii) Identify location of high current densities (coating defect location)

To obtain data for calculating coating resistivity or the current flow and distribution in a complex pipeline network, **line currents** can be measured. These are return currents flowing through pipelines or piping back to the drain point of the system. Measurement of these currents allows the mapping of current consumption of different parts of the structure or pipeline and identifies locations of high current densities (deteriorated coating) or current sinks (short circuits).

Line currents can be measured by **DC current clamps** on small lines (as used for cables) and DC current coils (e.g. **Swain coils**) for larger diameter pipes in above ground or excavated sections. The **CP current mapper** (10.2.2.3) can be used to estimate the current in buried sections.

The differences in pipe-to-soil potentials between two fixed points on the pipeline, together with the known resistance of the pipe, can be used to calculate the **line current** flowing in the pipeline by applying Ohm's law. The steel pipe resistance can be

calculated or calibrated. If these currents are low, the measured voltage drop is very small and the result may not be very accurate.

iii) Isolating Joint Assessment

*The measurement of **ON/INSTANT-OFF potentials** at both sides of an isolating joint or flange or at two crossing pipelines may indicate if the **isolation** is working or passing and if there is a case of **stray current** corrosion (9). The cathodic protection current is switched on and off in a regular cycle and the potential swing of the unprotected side is observed when the cathodic protection current is activated.*

If the potential at the unprotected side shows a negative swing when the current is activated, there is an electrical path between the protected and unprotected side (the isolation is passing or by-passed). If there is no significant swing or a positive swing not more than 20 mV, the isolation is holding and there is no detrimental stray current. If the positive swing is more than 20 mV, the isolation is holding but there is some detrimental stray current that should be investigated and rectified. The status of isolation devices can also be checked by means of a Swain type DC current coil. If current is flowing through the pipes connected by the isolating fitting, this fitting is passing.

10.3 SACRIFICIAL ANODES

10.3.1 Routine monitoring

10.3.1.1 Protection level survey

The main routine monitoring for sacrificial anode systems is the measurement of the structure-to-soil potential. For land-based systems, a Cu/CuSO₄ reference electrode is used for measurements of key points in the systems. These key points should also be located in places remote from buried sacrificial anodes. Utilizing the same test posts as for the anodes may not cover underprotection.

For offshore and coastal structures (platforms and jetties), potentials are measured by means of an Ag/AgCl reference electrode. Potential measurements can often be taken from the deck using a weighted reference electrode with a long cable. Measurements can also be taken from a launch or small boat. Measurements should be taken at the allocated key points at different depths (e.g. surface, bottom and mid-depth). During the measurements, the tide and any occupancy of a jetty by a (possibly cathodically protected) ship should also be recorded.

For offshore pipelines, routine monitoring can be carried out from accessible places such as the extremities of the pipeline. The potential may be influenced by the host structure, if the pipeline is in electrical contact with it. It should be checked whether or not the riser is "shorted" to the host structure before this or any other type of CP survey is conducted. The potential of the riser may not be a good indicator of the potential profile along the whole pipeline. Where possible, potential measurements in more remote locations from the platform or plant should be taken, for instance from a boat by means of a trailing wire to the pipeline end. Potential measurements in deeper water are usually regarded as specialised surveys (10.3.2).

On stable onshore sacrificial anode systems, routine potential measurements at key points shall be taken on a yearly basis. If anomalies are detected, a more detailed survey may be initiated such as a global potential survey or an anode performance survey.

During the polarization period, potentials shall be checked more frequently to obtain an early warning if the system is inadequate.

On offshore sacrificial anode systems, the degree of monitoring employed (techniques and frequency) should be commensurate with the criticality and condition of the pipeline/structure. If previous survey data is not available, or no analysis of the previous data has been carried out, the survey should be carried out annually. When anodes are within 2 years of the end of their original design life, the protection level survey should be carried out annually. Where the original CP design was conservative, the actual remaining

anode life may be well in excess of 2 years. This actual remaining anode life can be used in scheduling future CP surveys.

If routine visual inspection of an offshore structure reveals additional steelwork on the structure not included in the current structure CP drawings (for example debris in electrical contact with the structure, new conductors, new caissons, new risers etc.), a CP survey should be carried out immediately, structure potentials measured, structure CP drawings updated, the impact on the structure anode design life assessed and the need for any remedial work assessed (e.g. removal of debris, installation of additional anodes, etc.).

The potential of the protected structure can never become more negative than the anode potential itself except for magnesium anodes, the latter is usually well within the protection window.

10.3.1.2 Anode performance survey

Current output from the anodes is self-regulating because as the potentials of the structure, are progressively depressed, the driving force between anode and cathode becomes smaller. This automatically results in a lower current drain. Calculation will show that zinc and aluminium anodes can provide approximately twice the design current at the very start of the polarization period, and with the advancement of polarization the current gradually reaches the equilibrium state (which could be lower than the design current drain).

If the anodes used are suspended under water and accessible, an indication of the probable remaining life can be obtained by periodically lifting and weighing them. A comparison of the rate of wastage will also show the extent to which individual anodes are contributing to the protective system. Where anodes are fixed to the structure the anode wastage shall be estimated by dimensional measurements by divers or ROV surveys. Key anodes, installed at representative locations that are regularly inspected, should be defined. Cleaning of anodes is required to measure anode wastage and this may increase the usage slightly.

From the anode usage the approximate average current output can be calculated and the remaining life of the anodes can be estimated.

Where anode cable tails are accessible, they can be clamped with a current clamp meter to measure and trend their current output.

Anode surveys on offshore structures should generally be done in conjunction with other routinely scheduled underwater inspection activities. Where the anodes are within 2 years of the end of their original design life, an additional survey of the anodes is required, aligned with the protection level survey (10.3.1.1).

For offshore pipelines, anode surveys are carried out as part of the specialized surveys (10.3.2). The condition of the anodes is determined from visual observation and field gradient measurements, and by assessing the potentials on the pipeline.

For land based sacrificial anodes the anode current can be measured at the test post used to connect the anode with the structure. Such current measurements should be done together with potential measurements and can be regarded as routine surveys. From the anode current records the anode wastage can be estimated and the remaining anode life assessed. A decreasing trend in anode output (after full polarisation) can also be an indication of anode depletion.

Requirements for the monitoring of sacrificial systems in specific equipment are described in the equipment related section of this PTS.

10.3.2 Specialized surveys

For submerged systems, specialist companies normally carry out the detailed measurement of protection levels and assessment of anode condition. Depending on depth, distance, current strength, pipeline coating condition and pipeline burial condition, the surveys can be performed by means of direct contact measurements obtained by divers or ROV surveys, or by means of field gradient techniques in ROV surveys.

The trailing wire technique should not be used for long offshore pipelines. With this technique, the accuracy of the potential measurements depends on the position of the towed reference electrode with respect to the pipe. As this is very difficult to control, these surveys have limited accuracy. The trailing wire technique can be used in special cases where the other techniques also give lower accuracy data (e.g. surveying a totally buried line where electrical contact cannot be made with the pipeline over long distances of the line).

When such a survey is contracted out, it should be clearly specified what kind and quantity of measurements should be done, at what locations and how they should be reported.

The survey technique may consist of direct potential measurements hand-held (by divers) or surface instruments, relative potential measurements (if no electrical contact with the pipeline can be made, e.g. when buried, current density measurements using special ROV probes or a combination of these.

Offshore cathodic protection surveys are mostly done in conjunction with underwater video.

For land based sacrificial systems, a *CIPS* can also be carried out but the measurement of *ON/INSTANT-OFF* potentials is mostly impossible. If adequate test facilities have been provided and the connection between pipeline and anode is available, *ON/INSTANT-OFF* surveys can be performed for short pipelines using synchronisable portable interrupters. On the other hand, the low current output of the sacrificial anodes normally produces only small IR drop errors. Allowing for 25 mV extra apparent polarisation will normally compensate for possible errors.

For high integrity requirements where coating condition and cathodic protection performance are critical, *CIPS* are valuable inspection/monitoring tool and sacrificial anodes should not be used in these situations.

10.3.3 Trouble shooting

The main reasons for poor performance by sacrificial anode systems are short circuits to unprotected structures, depletion of anodes and passivity of anodes.

i) *Short circuits manifest themselves mainly as localised underprotection (10.3.1.1) in the vicinity of other structures and by high anode outputs (10.3.1.2) in the same location. Short circuits can be localised by measuring potentials at the adjacent "unprotected" structure and/or measuring current flow in possible metallic connections such as isolating devices, earthing cables etc. For onshore sacrificial anode systems, detection is more difficult (than with impressed current systems) as sacrificial anodes cannot easily be interrupted because of the high number of connections.*

ii) *Depletion or passivation of single anodes in a system is not always apparent as neighbouring anodes may take over the duty of the depleted or passive anode. Systematic depletion or passivation is revealed as general or localised underprotection. Anode depletion normally occurs in systems approaching the end of their design life, whereas passivation often occurs in relatively new systems.*

Anode outputs of land-based anodes can be measured through the connection cables in the test post. For offshore anodes specialised surveys (10.3.2) are needed to measure the output of fixed or welded anodes. Divers can inspect immersed anodes; depleted anodes exhibit loss of anode material, while passive anodes normally show little or no consumption and are often covered in marine growth. For buried anodes, excavation is normally required to judge the state of the anode surface.

iii) *If the potential has become insufficiently negative, an indication of the cause can be obtained from a current measurement.*

a) Current zero or lower than expected:

- 1) Wastage of anodes and possible need for replacement;*
- 2) Deterioration of anode/cathode connection, breakage of anode or cables;*
- 3) Drying out of soil around anode;*

4) *Effects of pollution on anodes.*

b) *Current level maintained or increased:*

- 1) *Inadvertent metallic contact with newly installed structures;*
- 2) *Faulty isolation equipment;*
- 3) *Alteration of environment causing rapid depolarization, or increase in oxygen content of water due, for example, to a reduced level of pollution;*
- 4) *Extension of the structure;*
- 5) *Deterioration of, or damage to, protective coatings*

10.4 AUTOMATIC AND REMOTE MONITORING

For onshore systems, conventional monitoring is carried out by operators or inspectors travelling to the cathodic protection station or test station to take readings. It is also possible to install automatic monitoring equipment that transmits the data or alarm to the office or control room.

The available equipment can measure the required parameters and transmit these through SCADA systems, GSM communications, satellite communications, or Radio Frequency (RF) communication to the operator. Signals can also be processed and stored in the test station and only deviations are transmitted as an alarm; the operator or inspector visits the station to investigate the alarm and/or to download the data.

There are a large variety of automatic and remote monitoring systems available, sometimes tailor made for a project. Before deciding on the installation of remote monitoring the following points should be considered.

- the cost of remote monitoring should offset the conventional monitoring cost; cost of the maintenance of the remote system itself should be included;
- remote potential monitoring is as accurate as the permanent reference electrodes; these require regular calibration;
- remote monitoring does not replace visual inspections for damage, defects and vandalism and does not replace regular maintenance of systems.

Common parameters that are usually considered in remote monitoring system;

- *Transformer/rectifier DC output voltage*
- *Transformer/rectifier DC output current*
- *Incoming AC power supply*
- *Pipe-to-soil drain point potential*

For offshore impressed current systems, similar automatic monitoring may be applicable. Automatic monitoring is rarely used on offshore sacrificial anode systems, as these are zero maintenance systems.

10.5 RECORDS AND REPORTS

10.5.1 Records and databases

Cathodic protection monitoring records shall be kept accurately for the life of the cathodic protection system. The reason for this is that this protection history is vital to judge the condition of the pipeline or structure during its life. Pipeline risk-based inspection (RBI) systems require full cathodic protection record history e.g. to so that intelligent pigging operations can be safely postponed if necessary. Keeping records may also be required by local regulations.

Records are often kept in computerised systems. For small operations, records can be kept in simple systems like spreadsheets, for large systems custom made databases can be installed.

The database should always be based on a full inventory of the cathodic protection equipment including cathodic protection stations, test stations, bonds, foreign structures'

test stations, etc. Systematic unique codes should be used for each item including equipment details such as shunt values and cable colours, to minimise errors.

Records should be kept in a central place, accessible for interpretation and auditing.

Cathodic protection data is not always suitable for storage in inventory databases such as SAP or Pacer. The wealth of data masks the important data. Separate databases should be kept for data and for reported anomalies (and solutions) in the appropriate maintenance systems.

10.5.2 Interpretation and trending

Cathodic protection monitoring data should be analysed in relation to the monitoring procedures and the protection criteria (4.3). Where required, *ON/INSTANT-OFF* measurements should be taken or ON measurement results compared with previous *ON/INSTANT-OFF* data. All data falling outside the protection window should be flagged and further investigated. Advice should be given for adjustment or repairs.

Cathodic protection data should be compared with previous data and possible trends identified. This can normally be done by means of graphs in the data systems. Examples of trends are:

- sudden voltage and current loss indicates power or rectifier failure;
- sudden current loss while maintaining voltage indicates cable breaks or open fuses;
- sudden decrease of protection level (at same current output) indicates short circuits;
- slow decrease of protection levels at the same current indicated coating failure;
- increase of current to maintain protection levels also means coating deterioration or short circuits;
- increase of transformer/rectifier voltage to maintain current indicates anode deterioration.

By means of data trending, certain adjustments or maintenance activities can be predicted and planned, e.g. replacement of groundbeds.

10.5.3 Performance reports

The functioning of cathodic protection systems should be reported on a regular basis, the frequency depending on the local regulations, quality system or other company requirements.

Monitoring reports should contain only those details that are required for the level of reporting.

Performance reports should contain the following data as a minimum:

- summary of monitoring activity (location, installation);
- number of points monitored and not monitored (including reason why);
- number of points under or overprotected including (possible) reasons;
- action list to solve problems and improve protection;
- summary of special activities and specific problem areas.

Additional details may be reported as required.

11. PROTECTION OF BURIED ONSHORE PIPELINES

11.1 GENERAL

When buried pipelines are to be laid, cathodic protection should be considered as an anti-corrosion measure supplementary to the protective pipeline coatings. It is *PETRONAS* practice to apply cathodic protection on all buried pipelines irrespective of soil conditions.

For new construction projects, the design of the cathodic protection system shall be an integral part of the total pipeline design *which consists of temporary cathodic protection system for pipeline during construction and permanent cathodic protection system during in service pipeline.*

Retrofitting is always a more expensive option. Pipeline isolation and a suitable pipeline coating system shall be provided in the pipeline design. Adequate monitoring facilities shall be provided in the pipeline design and be installed during the construction of the pipeline.

To achieve an effective cathodic protection design for a pipeline system, a site survey is necessary to collect essential information on soil resistivity, geographical factors, the likelihood or the existence of stray currents and any other important features along the pipeline route.

When designing a cathodic protection system for retrofitting to an existing pipeline, certain repairs and modifications to the pipeline may be necessary to achieve effective cathodic protection. A current-drainage test is often the best and quickest method to assess the required protection current.

The presence of sulphate-reducing bacteria shall always be considered and in regions where there is evidence of their presence or the character of the soil favours their growth, the pipe-to-soil potential should be maintained at the appropriate value (4.3).

Cathodic protection systems for onshore, buried pipelines shall be designed in accordance with PTS 30.10.73.31.

11.2 APPLICATION

11.2.1 Electrical isolation of pipelines

Pipelines shall be electrically isolated from other pipelines and structures to prevent interaction and loss of cathodic protection current. Isolation should be installed at both extremities of a pipeline and at branch lines. Pipeline sections with different coating systems or running in different types of soil/water (e.g. river crossings) may also be isolated if needed. Pipelines are sometimes sectioned by isolating devices, e.g. *major road and river crossings*, and in areas of high telluric activity (9.6). More information on pipeline isolation is described in (8) and in PTS 30.10.73.31.

11.2.2 Choice of system

For the cathodic protection of land based buried pipelines, an impressed current system is preferred.

Sacrificial anodes may be selected for technical and economic reasons, e.g. when power supply is not available, where localised protection is needed, where accessibility is difficult or where vandalism is a problem. To apply sacrificial anode cathodic protection, the soil resistivity shall always be low enough to expect effective galvanic action. Magnesium anodes can be used in soil with a resistivity up to 3,000 $\Omega\cdot\text{cm}$ (5.3.1), Zinc anodes can be used in soil with a resistivity of up to 1,500 $\Omega\cdot\text{cm}$ (5.3.2). Aluminium anodes are normally not used in land applications.

11.2.3 Specific Design issues

Newly installed onshore cathodic protection systems take some time to polarise a bare structure while supplying much current, whereas pipeline cathodic protection normally only requires little current to polarise the well coated pipeline, especially as modern pipeline coatings act as highly dielectric isolators. Often a few milliamperes is sufficient for a pipeline of several kilometres. Many cathodic protection systems on new pipelines are

designed and rated to provide the required cathodic protection current at the end of the design life and are therefore often oversized for the start of the pipeline's life. This may result in control problems and overprotection. To provide a minimum load to the current sources, a ballast resistor may be installed. Sometimes, some of the cathodic protection stations are not used for many years until the current demand reaches a higher level. This may be detrimental to certain components of the cathodic protection system such as batteries connected to solar systems that require a regular charge cycle. In such cases, the cathodic protection system may be designed for a shorter life or a lower output rating and be upgraded later in the service life when needed; refer to PTS 30.10.73.31.

When an installed system shows the control problem described here, it may be possible to install an "artificial load" in the form of uncoated steel plates at regular distances along the pipeline. These plates may then act as coupons for potential monitoring, and it may be assumed that, if these plates are well protected, smaller defects in the pipeline coating will be protected too. The installation of such panels on well coated pipelines (PE, PP) is always a good tool to improve monitoring of the cathodic protection system performance.

Most pipelines are made of various grades of carbon steel. Some pipelines are made of alloyed steel such as austenitic, duplex or martensitic stainless steel. The protection criteria for these materials may be different from those for carbon steel (23), however, these lines are sometimes laid in the same servitude as carbon steel lines and may be connected into the same cathodic protection system. The protection criteria for carbon steel can be applied to austenitic stainless steels to avoid using different potential levels and possible interference. Expert assistance shall be sought when applying cathodic protection on duplex or martensitic stainless steel pipelines.

Thermally insulated lines are provided with thick layers of insulating coatings that provide a barrier to cathodic protection current. In the case of large defects, cathodic protection will be effective. Long, thin cracks in the insulation will allow moisture to penetrate to the pipe surface but the high electrical resistance inside the crack blocks cathodic protection current. For this reason insulated lines are often not fitted with cathodic protection and rely on the coating integrity. Isolating joints should nevertheless be installed at the extremities of the insulated pipeline and also test stations installed to allow trouble shooting, e.g. by specialised coating surveys. Special monitoring systems may be required to determine coating and insulation integrity on these lines.

For underprotected area where the impressed current is insufficient, sacrificial anodes can be used as a supplementary protection. For soil resistivity below 10,000 Ω -cm, the usage of high potential magnesium alloy anodes could be used. For soil resistivity above 10,000 Ω -cm, the usage of similar alloy anodes in the form of ribbon or metal strip that is installed in close proximity to the pipelines could be used. However, the efficiency of the anodes could be reduced due to high soil resistivity.

11.2.4 Installation

Installation *should* be done by or under supervision of a professional cathodic protection specialist or *subject matter experts (SME)*. This is particularly important for components that are to be buried and will not be accessible at a later stage. Therefore, the guidelines and check lists for installation and commissioning of pipeline cathodic protection systems given in PTS 30.10.73.33. shall be used and any specific instructions from the cathodic protection designers and suppliers shall be followed.

Monitoring stations should be installed at the same time as the pipeline construction. This is usually more cost effective and it also allows monitoring of the line (and any temporary cathodic protection systems) during the construction phase.

11.3 MONITORING

Monitoring facilities shall be included in the design and installed *during construction*. Monitoring stations on pipelines shall at least be located at every pipeline feature such as pipeline crossings, isolating joints or flanges, cathodic protection drain points, pipeline casing, selected road and water crossings and further every 200 m to 1000 m in between other stations.

Some of these stations may be selected as "Key monitoring points". These comprise 10 % to 25 % of the monitoring stations that are representative for specific sections or lie within the influence of other structures e.g. at crossings. These key points may be monitored more frequently than other stations.

Protection criteria can be set for all test stations together or separately for each test station. The latter is often done when high IR drops are expected or when interference has been identified.

Pipeline cathodic protection should be monitored by means of consolidated procedures to ensure correct and comparable data. Monitoring frequencies shall be established for availability surveys (10.2.1.1) and protection level surveys (10.2.1.2).

12. PROTECTION OF SUBMARINE PIPELINES

12.1 GENERAL

Submarine pipelines are pipelines that run under (sea)water. They can be divided into different groups.

- offshore pipelines are pipelines that run between offshore platforms or other production structures or from such structures to shore over considerable length;
- coastal submarine pipelines such as loading lines running from shore installations to structures or manifolds over relative short distances;
- deepwater pipelines, installed in depths greater than 500 m that require special attention because of the circumstances at depth;
- inland water and lake crossings that may require special design parameters because of different water composition etc.

In general, the low and uniform resistivity of seawater simplifies the operation of cathodic protection systems for submarine pipelines. The preferred system consists of sacrificial anodes placed in the form of bracelets around the pipe.

The current demand in various seawaters can vary considerably depending on salinity, temperature and current. For most situations the current demand is only dependent on temperature. (4.4) gives the design values for current densities to be used for submarine pipelines.

Impressed-current systems should not be used. However, some coastal submarine lines (and also a few offshore lines) are equipped with impressed current cathodic protection systems, operated from shore (or from platforms). In these cases, the coastal pipelines can be treated as on-shore lines, with the difference that monitoring (access) is more difficult.

Submarine lines are seldom close enough to other structures to interfere with them, although old steel wire rope, anchor chains, wrecks, etc., on the sea bed and in contact with the lines will cause difficulties by draining the protective current if in metallic contact. One other area of concern is the possible interference between pipelines at pipeline crossings; methods of avoiding interference shall be included in the design. A check for interference at pipeline crossings shall be included in potential surveys of the pipeline (10.3.1)

Cathodic protection systems for offshore pipelines shall be designed in accordance with the technical specification in PTS 30.10.73.32., which is based on DNV RP-B401, a well established recommended practice for offshore cathodic protection but has been amended/supplemented so as to be applicable to offshore pipelines only and uses variables extracted from Group experience that are less conservative.

For the application of cathodic protection in deep water systems some specialist guidelines have been developed and are available through the Group cathodic protection specialists.

12.2 APPLICATION

12.2.1 Electrical Isolation

Electrical isolation is an important consideration for offshore cathodic protection system control. Isolation in a pipeline may be accomplished by the use of either an insulated flange assembly or of an isolation joint in the line. There are a number of situations where the use of such devices should be considered:

- Changes of Ownership – This could be at a riser attached to a host structure of different ownership, or at a subsea pipeline tie-in. In either case isolation between structures is normal practice. At subsea tie-ins the insulator is normally incorporated into the subsea “hot-tap” assembly, in which case subsea intervention is required to verify isolation.

- Landfalls – When an offshore pipeline makes landfall it is often accompanied by a change in the cathodic protection system; there may be a switch between sacrificial and impressed current systems, or a shore based impressed current system designed to protect all or part of the offshore system may be involved. In either case it is prudent to separate the systems at this point to facilitate more accurate monitoring and control between the systems, and prevent potentially detrimental system interactions.
- Change of system type – galvanic anode systems shall be electrically isolated from impressed current systems where offshore pipelines connect with structures or other pipelines.
- Bare structures tied to coated pipelines – Except as covered above, electrical pipeline isolation between galvanic anode CP systems installed on platforms and pipelines can be omitted. With good CP design both platform and pipeline can be adequately protected without impairing the lives of their individual CP systems. However, offshore pipelines shall be isolated from other unprotected or less protected structures, which could drain current from the pipeline's CP system.
- Flexible sections – Flexible sections may be installed in offshore pipelines as jumpers, or to handle excessive seabed movements. These may cause electrical discontinuity in the pipeline which may be undesirable. If so continuity bonding provisions shall be made on both sides of the flexible section shall be protected independently.

Wherever possible the insulator shall be installed at a point with easy access; this will improve system maintainability. At a platform, the insulator is normally installed in the riser above water. If the flange is installed at an inaccessible location this can make CP monitoring difficult unless test leads are installed. The insulator should not be installed subsea at the riser base reliable monitoring of the system is very difficult when this method is employed.

The most common bypasses on offshore systems are un-insulated riser clamps, damaged insulation flange assemblies, stainless steel control tubing bypasses, topside pipe supports and piping bypasses. It shall be ensured that none of these are present. Where risers are electrically isolated from the structure, both halves of insulated riser clamps shall be protected.

Bolting does not always guarantee electrical continuity; where electrical continuity is required the design shall be checked at all flanges.

The potential sparking hazard of insulating devices should be recognized and considered in the design and location of such devices.

12.2.2 Current requirements

Current density requirements are given in (4.4).

The total current required depends on the area of bare steel on the pipeline to be cathodically protected, and for this reason submarine pipelines should be well coated before laying. The coating damage is expressed as a "coating breakdown factor" and is different for new and old pipelines.

If the seawater temperature profile along the pipeline route is not known, the required current density shall be based upon the minimum seabed temperature measured, which will usually be the temperature at the deepest location along the pipeline route.

If the seawater temperature profile along the pipeline route is known, the curves in Figure 12 should be used with the averaged pipeline section temperatures to obtain current densities for each section. It may be necessary to subdivide the pipeline, based on the local annual average seawater conditions.

For risers in the splash zone, current densities selected shall be 10 mA/m² higher than for the equivalent riser or pipeline beneath the splash zone (at the same temperature).

For pipelines fully buried in sediments or artificially covered (e.g. rock dumping), a design current density (mean and final) of 20 mA/m² shall be used, irrespective of temperature or depth.

Pipelines operating with elevated temperatures (in excess of 50 °C) on the outside surface of the pipe may require an adjustment of the design current density. Increasing water temperature decreases oxygen solubility. Increasing temperatures also accelerate the corrosion rate. The design current densities shall be increased by 1 mA/m² for each °C that the metal/environment exceeds 50 °C. Elevated temperatures can also reduce both anode and coating performance. For temperatures above 80 °C a special assessment of current densities should be carried out.

The design current densities discussed above are also applicable to the CP of all types of bare stainless steel (austenitic, martensitic and duplex).

If subsea facilities are included in the design of the pipeline CP system, the current drain to subsea structure, wellheads, manifolds and well casing shall be included. An allowance should be included in the total design current density requirements to compensate for the current load imposed by the well casings below the mudline. Values typically range from 1.5 to 5 A per well.

12.2.3 Sacrificial anodes

Sacrificial anodes on submarine pipelines are normally applied as 'bracelets' at intervals along a new line. Aluminium-indium is the standard bracelet anode material, although zinc anodes are sometimes used.

Aluminium anodes at high temperatures suffer from intergranular attack and may show excessive consumption. Zinc anodes at high temperature suffer from undue consumption or potential reversal of the zinc. Aluminium-indium anodes shall not be used above 80 °C and zinc anodes shall not be used above 50 °C, unless satisfactory performance has been demonstrated in tests and has been documented. In addition the anode electrochemical capacity reduces as temperatures increase above 30 °C, and this has to be taken into account in the design.

Where the pipeline is operating at elevated temperatures, the anodes are typically installed as sled type anodes, placed alongside the line with a cable connection to the line. Specialist advice shall be sought for further details. Other applications e.g. roll-layed pipelines may also require sled type anodes.

12.2.3 Impressed current

A (shore-based) impressed current system comprises a transformer-rectifier, with anodes placed in the sea below the low-water mark or in a deep anode bed at the shore end of the pipeline at a distance of 90 m to 150 m from the line. With impressed current, the current output can be adjusted, first to obtain the high initial output needed to polarize the line and build up the calcareous coating, and subsequently to give the steady lower output required for normal operations. The distance over which such a system can work effectively is at best 20 km from the drain point.

Although rarely used, in some circumstances impressed current systems may be the preferred choice for protecting offshore pipelines. In these situations specialist advice should be sought.

12.3 MONITORING

On submarine pipelines, key monitoring points should be identified for regular monitoring. These are often only the beginning and the end of the pipeline that are accessible from shore or platforms. These surveys are of limited use because of the possible interactions between the platform and pipeline cathodic protection systems and the limited length of the pipeline covered by such a survey. If the pipeline is equipped with isolating joints, the effectiveness of these joints can also be monitored. It is technically feasible to install automatic monitoring devices at locations along the pipeline, though this is rarely justifiable

in terms of cost, maintenance and the limited need for measurements. The remainder of the line should be monitored using specially organised underwater surveys.

Away from the pipeline ends, potential measurements are costly to carry out. Nevertheless, the pipe potentials are the only indicators for judging the adequacy of the protection. Potential measurements taken close to the pipe are the most accurate and informative. Contact with the pipe can be made at anode bracelets.

A number of techniques are available that measure the potential gradients around a submarine pipeline. From these measurements, the presence of coating defects and their severity is deduced. In addition, some information on potential is obtained. Various methods are described in (10.3).

13. PROTECTION OF MARINE STRUCTURES

13.1 GENERAL

The term marine structures covers a large variety of objects such as offshore drilling and production platforms, piers, jetties, and mooring dolphins.

Corrosion is at maximum at a small distance below the water line and gradually decreases with depth. In mud, corrosion is usually much less severe. The submerged steel surface and the steel in the mud can be cathodically protected.

Corrosion in the tidal zone or the “splash” zone above low water level may be severe and cannot be fully protected by cathodic protection. Protection shall be given by the use of heavy-duty coatings and adequate corrosion allowance.

The submerged sections of offshore drilling and production platforms are normally uncoated and rely completely on cathodic protection. Cathodic protection systems for offshore structures shall be designed in accordance with PTS 30.10.73.32., which is based on DNV RP-B401, a well established recommended practice for offshore cathodic protection, but has been amended/supplemented so as to be applicable to structures only and uses variables extracted from Group experience that are less conservative.

The steel piles of shore facilities such as jetties, dolphins and piers are normally coated and cathodic protection is installed to protect the steel where the coating is damaged. Cathodic protection is usually applied by means of sacrificial anodes, attached to the individual piles. PTS 30.10.73.32. is generally applicable, although conditions are often less severe than for offshore structures.

Steel sheet piling in harbour installations can be coated or uncoated and may be protected by means of cathodic protection.

13.2 APPLICATION

13.2.1 General

Either sacrificial anodes or impressed current systems or a combination of both may be used to protect marine structures. Impressed current systems should be used with utmost care as the risks of inadequate protection are considerable.

13.2.2 Current requirements

The current required for cathodic protection varies with the salinity, temperature (oxygen content) and flow conditions of the water. For the design of cathodic protection for offshore structures, the requirements in the technical specification PTS 30.10.73.32. should be followed. For general purposes e.g. for shore installations, the current densities in (4.4) can be used. In the case of doubt, expert advice should be sought.

On offshore platforms, marine conductors (protective pipes through which wells are drilled) are often closely packed in the conductor bay area. Adequate current densities shall be made available for the protection of the marine conductors. Full electrical continuity may not always be provided and special measures may be required to ensure this. Adequate current capacity shall also be available for the current drain from well casings; 2 A to 5 A for each well should be allowed for.

13.2.3 Sacrificial anodes

For offshore structures, sacrificial anodes are the standard type of cathodic protection system. It is more attractive to use aluminium-indium alloy or zinc anodes for cathodic protection, for reasons of high dependability, immediate availability and no subsequent maintenance during the design life. The anodes on platforms are welded onto the structure prior to installation of the platform. The welded connection serves as the mechanical and electrical connection. On jetty piles the anodes are normally fitted shortly after piling using mechanical clamps to avoid coating damage. Electrical contact can be made by heavy-duty contact bolts or by welding contact strips to an above-water location. The system can be designed to last for any length of time.

For offshore structures, aluminium-indium alloy is mainly used as this material provides the highest long-term output per unit weight. The design of sacrificial anodes on uncoated structures shall take into account the high current required to polarise the steel and occasional high currents required to repolarise after heavy storms.

13.2.4 Impressed current

An impressed current system is often appropriate for use on harbour installations such as uncoated sheet piling. It may be provided by means of silicon iron anodes, suspended in the water or installed on the sea bed, or suspended platinised titanium or mixed metal oxide anodes; the anodes are located in such a way as to obtain a uniform current distribution. Both water and soil sides shall receive current from anodes located facing the respective sides and appropriate current distribution boxes should be installed to supply enough current to each surface.

Impressed current system's are not normally used on steel offshore platforms because of the mechanical weakness of cables and anode systems and the frequent monitoring and maintenance requirements.

When marine structures are cathodically protected, adequate precautions shall be taken to avoid interference effects when impressed current is used and also to ensure that danger does not arise through the production of sparks when ships, barges, etc., make or break electrical contact with the protected structure.

13.3 MONITORING

On offshore structures, key monitoring points should be identified for regular monitoring. These are often locations where a reference electrode can be suspended close to sub-sea parts of the structure. On platforms, the location of these points may vary according to the design of the structure. On jetties, approximately 10 % of all piles should be designated as key points.

Potential measurements should be taken at several depths under the water surface to monitor the effect of anode proximity. Normally 1 m under surface, mid-depth and close to the seabed are adequate. Care shall be taken to ensure that the reference electrode does not get entangled with the structure. For water depths >30 m the maximum measured depth shall be 30 m.

More detailed monitoring can be undertaken by divers or ROVs. The key points should all be covered so that the measurements can be "Calibrated" with suspended reference electrodes.

If the protection levels deteriorate over time, the consumption rate of the anodes should be checked. Whenever diver or ROV (underwater video) surveys are undertaken for reasons other than cathodic protection monitoring, the opportunity should be used to survey protection potentials and/or anode consumption as well.

When local underprotection is found at key piles, all piles in the affected area may be monitored to identify the source of the low protection.

14. PROTECTION OF OIL WELL CASING

14.1 GENERAL

Casing corrosion may be caused by the presence of sulphate-reducing bacteria, acidic water, or corrosion cells set up between formations containing water of different salt content or between casing and flow lines. Corrosion sensitive sections are those in (oxygen-rich) water bearing formations. During construction of a well, the outside of the casing is cemented with a layer of concrete that also acts as a sealant between layers. These cementing jobs are not always carried out with sufficient care or they are unsuccessful due to the permeability of the layers. These insufficiently cemented sections are the parts of a casing that require additional protection.

Leaks that develop in the casing of a well constitute a serious problem and are expensive to repair. Damage may also be inflicted to the annulus by water entering through casing leaks. The cost of installation of a cathodic protection system of a well casing is only a fraction of the cost of work-over of a well, apart from deferment of production.

Cathodic protection prevents corrosion only on the outside surface of the casing; therefore, protection against internal corrosion problems should be dealt with in a different way (e.g. inhibition).

The decision to install cathodic protection on well casings may be influenced by different factors such as:

- a history of corrosion problems of wells in the same area of the same construction and materials;
- evidence of corrosion or anodic sections on the external casing as measured by well logs;
- general safety (high pressure, sour wells, populated areas); or
- economics (high volume producers, long design life).

Additional information on well casing cathodic protection can be found in NACE RP0186.

14.2 APPLICATION

14.2.1 Current

The current density required for protection varies from 5 mA/m² to 30 mA/m² of casing surface area, dependent on environment and quality of cementing. As a first guideline, protection currents for wells of different depths are as follows:

Approximate depth, m	Current, A
900	2
1500	5
2400	30

A method for determining the current required for cathodic protection of an individual well casing is the measurement of the steel-to-electrolyte potential with stepped increase of impressed current (E-log I test).

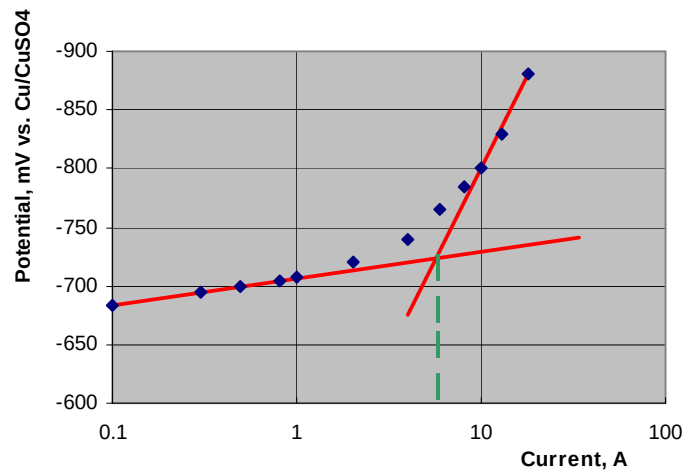
The location of the half-cell in such a test shall be remote from the wellhead. The OFF potential after each current step increase shall be measured whilst interrupting the current for approximately one second. The time over which each current step increase is applied shall be a constant (e.g. one or two minutes).

A graph is drawn of the steel-to-electrolyte potential against the logarithm of the impressed-current. The relationship is a straight line with a slight inclination at low currents; after a break point, the curve continues as a straight line with a sharper rise at higher currents.

The break point indicates the current required to provide cathodic protection, see Figure 20.

As the measurements are taken over a short period, full polarization does not occur and the steel-to-water or steel-to-soil potential at the break point is not a measure of the potential required to provide protection.

Figure 20 E-log I relationship for oil well casings



A more accurate method features the use of a potential profile tool. Electric currents in the casing can be measured by means of a tool equipped with spring-loaded contacts spaced at about 7.5 m intervals, which is run inside the casing. From the potential difference between these contacts, the direction and magnitude of electric currents flowing in the casing can be derived by means of Ohm's law, or by comparison with a calibrating current. In this way it can be checked whether the cathodic protection prevents electric current from leaving the casing (absence of cathodic areas). Running the tool before applying cathodic protection shows whether cathodic protection on the casing is necessary; after cathodic protection has been applied it shows the effectiveness of the cathodic protection.

The disadvantage of this method is that in order to carry out a full series of tests, the well should be available for a long period of time, which may be expensive.

14.2.2 Impressed current

The current source is a transformer-rectifier or solar generator depending on the availability (or the cost of providing) mains power.

The groundbed can be a deep or shallow groundbed, depending on the soil resistivity at depth. The groundbed is placed at a distance of 30 m to 60 m from the well, or in a central position when more wells are protected by one groundbed. No unprotected buried structures shall be placed between the groundbed and the well(s) to prevent stray current corrosion.

The wellhead of the protected well should be insulated from the flow lines, by means of insulating flanges or joints, to control the loss of current to other structures and to prevent stray currents.

When several wells are protected in one system, each should be connected via a variable resistor or an active current regulator to the negative pole of the current source. The latter limits the current returning from the well to a preset value independent of currents drained from other parts to the rectifier.

Buried flow lines can be protected by the same system by means of separate drain cables and current control, or by bleeding some current across the isolating device by means of a resistive bond. If wellhead isolation is not possible, the flow lines are automatically protected, however care shall be taken to avoid overprotection, which would damage the

coating on flow lines. The design should allow for the additional current drain from the flow lines.

In some designs surface flow lines are used as return current path and the well side is provided with a current regulator. This eliminates the need for long cabling. Insulation is then also required at the gathering station side of the flow line.

14.2.3 Sacrificial anodes

Magnesium-alloy anodes can be used when a low current is required. In general, they are suitable for protecting only the upper 60 m to 90 m of a well. In other instances, the current required necessitates the use of an impressed current system.

14.3 SPECIAL CONSIDERATIONS

14.3.1 Surface shoe effect

The difference in potential caused by cathodic protection, between the production string and the surface string, can give rise to bridging of the current at the shoe of the surface string. This is known as the 'surface shoe effect' and could cause corrosion of the production string opposite the shoe of the surface string, due to electric current leaving the production string at this depth and flowing through the electrolyte to the shoe of the surface string.

Observations in the field as well as theoretical calculations have shown, however, that any corrosion due to 'surface shoe effect' is negligible. The contention that this effect will cause serious corrosion unless a metallic connection is made between the two strings at the shoe is incorrect.

14.3.2 Currents set up by cathodic protection

Cathodic protection current picked up by casings of other wells may cause corrosion at places where the current leaves them. Unprotected wells situated within about 450 m of a protected well or its groundbed should therefore be protected against stray currents. To accomplish this, a current of about 1 A should be drained continually from the wells, either by connecting them via a resistor to the cathodic protection system or by installing magnesium alloy anodes.

Flow lines should be checked for stray currents and resistance bonds installed where necessary.

Under the effect of steam injection for secondary oil recovery, corrosion can be aggravated considerably as a result of the increased temperature. In areas where casing leaks were a hitherto rare, the leak rate can become unacceptably high. To prevent this from occurring the timely application of cathodic protection is required.

Usually, no special requirements are needed for wells on steel structures, as these will receive protection from the total system. On concrete structures however, special measures may be required.

14.4 MONITORING

The casing to soil potential at the surface is often measured but the result is not an indication of full protection at depth. Trends in the potential value, however, are used to identify changes in the general protection level.

The current to each well should be measured at regular intervals e.g. yearly or whenever significant changes in the cathodic protection systems occur (additional wells or cathodic protection systems).

The best way to ensure full protection of the well casing is to run a potential profile tool inside the well casing. This method requires the well to be shut in and the tubing to be removed. Although this can become expensive, it should be done from time to time on representative wells in a field whenever the opportunity arises (during well work-overs) or if severe doubts arise regarding the protection levels. The current to other wells can then be

adjusted. When in doubt, a slight overprotection can be applied because there is normally no risk of coating damage or hydrogen embrittlement.

15. PROTECTION OF VERTICAL STORAGE TANKS

15.1 GENERAL

Cathodic protection of vertical storage tanks is usually applied to protect the underside of the tank bottom in contact with the soil. Cathodic protection of the internal (bottom) of vertical storage tanks containing water is described in (21).

The decision whether or not to apply cathodic protection is often controversial. It is argued that the tank foundations can be constructed so that tank bottom corrosion can be avoided. There are, however cases where tank bottom corrosion has occurred or may occur. In such cases, cathodic protection is a suitable method to minimise external bottom corrosion.

The following parameters *shall be applied* when new tanks are installed or the bottoms of existing tanks are replaced.

- General parent soil corrosivity. *For soil resistivity under 5,000 Ω .cm requires cathodic protection.*
- Corrosion history of the same area. If other tanks have suffered bottom corrosion in the past, cathodic protection shall be applied.
- Tank design/construction. Some tank designs make retrofitting of cathodic protection systems difficult, expensive or impossible. For example, tanks with secondary containment are extremely difficult to retrofit.

In general, the cost of installation of cathodic protection during new construction is a fraction of the cost of tank repair or cathodic protection retrofitting.

For the design and installation of cathodic protection installations for vertical storage tanks reference is made to API RP 651 or NACE RP0193.

15.2 APPLICATION

15.2.1 Electrical isolation of tanks

In general, the electrical isolation of vertical storage tanks from plant or other structures need not be considered. The tank structure is often connected to many plant service systems such as fire mains, drains, safety devices, lightning conductors and instrument earthing. Maintaining full isolation is difficult and costly, if not impossible. Because of the sometimes high currents involved, one insulation failure can have severe safety consequences. Electrical isolation should therefore only be considered at the perimeter of e.g. a tank farm and a cathodic protection system should be designed so that interference with other structures is minimised and detrimental stray currents are avoided. This means that localised cathodic protection systems are preferred over flood systems where tanks are in the proximity of other plant structures.

15.2.2 New construction

The selection of the cathodic protection system depends largely on the tank design and on the location and function of the tank in a plant. It also depends on the tank bottom condition, e.g. coating. Application of a surface coating on the underside of the bottom plates before they are welded in (leaving a clean edge for welding) can reduce the area to be protected by 90 %, thereby reducing the required cathodic protection current demand and system size considerably. Heavy-duty epoxy coatings shall be used for this purpose.

Standard tank foundations often use bitumen sand as the top layer in direct contact with the tank bottom. If cathodic protection is applied bitumen sand should not be used to ensure regular current distribution. Clean sand (with low chloride and sulphate content) should be used.

When secondary containment or so called leak detection systems are installed under a storage tanks, in the form of plastic sheets, the anodes shall be installed between this sheet and the tank bottom. In this case remote anode systems cannot be used.

15.2.3 Sacrificial systems

Sacrificial anode systems can sometimes be used. Such use is limited to small tanks (< 15 m diameter), preferably having coated bottom plates and in a parent soil having a resistivity lower than 500 Ω .cm. Anode material is usually magnesium or zinc ribbon anodes or closely spaced distinct anodes. The anode to tank connections should be made accessible (e.g. in a distribution box) to allow current measurements and control. The usual design methods for current capacity and lifetime calculations apply.

15.2.4 Impressed current systems

Impressed current cathodic protection has been successfully applied to external tank bottoms with a variety of anode designs and anode materials. The anode system is the most vulnerable part of this type of cathodic protection application as repair is usually not possible and replacement is difficult and costly. It should therefore be given full attention.

Conventional (deep) groundbeds may be installed in tank farms where the risk of interference with other plant is low. In this case, electrical isolation should be provided at the perimeter of the tank farm.

The preferred anode construction is placement of anodes under the tank floor in a pattern that ensures good current distribution to the underside of the floor. Anode materials used for this system may be:

- Closely spaced distinct anodes installed horizontally or vertically, e.g. silicon iron anodes.
- A grid of ribbon or wire anodes such as mixed metal oxide coated titanium, of adequate length and spacing to provide the required current distribution. The ribbons or wires should be closely interlinked to ensure continuity in case of local breakage during construction or service.
- A number of anode wire loops can be considered. Loops can be individually connected to the current distribution system to control locally high current demands.
- A grid of cable type anodes such as "Anodeflex".

The anodes or anode grids are normally placed about 0.5 m below the tank bottom inside the tank foundation.

A multiple of positive cable connections should be provided above ground to ensure continued operation in case one connection fails.

Reference electrodes are installed simultaneously; see (15.3).

Transformer/rectifiers should be installed outside the bund wall. Anode distribution boxes should be provided with shunts and a provision to install resistors to allow current measurement and control. Negative distribution boxes should be provided when more than one tank is protected by one transformer/rectifier.

15.2.5 Retrofitting

When cathodic protection is required on existing tanks, the design of the retrofit system depends on factors such as the tank bottom condition, accessibility, foundation construction and safety factors.

When a tank bottom is heavily corroded and needs to be taken out of service, the grid type anode system may be installed at the same time that the tank bottom is replaced. In many cases such an anode system may be the same design as for a new tank.

If the tank is not accessible, discrete anodes are installed in bored holes drilled close to the tank. These boreholes can be drilled vertically around the tank perimeter (small diameter tanks), slanted or horizontally under the tank depending on accessibility or on the presence of secondary containment systems. The anodes are usually pre-packaged in carbonaceous backfill and several anodes per borehole are possible to provide the required current

output. Reference is made to the standards API RP 651 and NACE RP0193 for installation options and design.

15.3 MONITORING

To enable monitoring of cathodic protection levels of tank bottoms, permanent reference electrodes shall be installed under the tank bottoms. For tanks with a diameter of less than 10 m, one reference point under the tank centre is sufficient. For larger tanks one or more reference electrodes at mid-radius are required. Copper/copper sulphate electrodes are adequate; an additional zinc reference cell should be installed alongside the copper/copper sulphate electrode for back-up or calibration purposes. The location of each reference electrode and its external connection should be clearly documented.

Protection levels of the tank perimeter can be measured by means of portable reference cells placed at the tank edge. Adequate earth contact can be provided by installing PVC tubes protruding through the bituminous foundation surfacing down to the tank bottom level. Potentials measured at the tank perimeter may be more negative than those under the centre of the tank. When only rim potentials are measured, the protection criteria should be set more negative to account for this difference.

Other monitoring equipment is sometimes installed such as micro-slotted inspection tubes at about 1 metre below the bottom that allow potential measurements across the tank bottom by means of portable reference electrodes. These tubes can sometimes be retrofitted by directional drilling techniques.

16. PROTECTION OF UNDERGROUND TANKS

16.1 GENERAL

There are many types of underground tanks that require corrosion protection. Examples are tanks at filling stations, domestic fuel or gas tanks, mounded LPG storage tanks, and buried drain tanks. These tanks have a variety of dimensions and shapes.

**Amended per
Circular 10/04**

All buried tanks shall be coated by an adequate coating system that is compatible with cathodic protection; see PTS 30.48.00.31. Before installation of the tank, the coating should be checked for holidays.

The requirement for cathodic protection depends mainly on the soil corrosivity. As a guideline, when the soil resistivity is less than 10,000 $\Omega\cdot\text{cm}$ cathodic protection is recommended, when the soil resistivity is below 5,000 $\Omega\cdot\text{cm}$, cathodic protection is mandatory. The national regulations should be checked for local requirements.

**Amended per
Circular 24/08**

Local circumstances or safety considerations may require the use of cathodic protection, for instance where other cathodic protection systems are installed (stray currents) or when very toxic or pressurised substances are stored (LPG tanks).

For the protection of small tanks (a few tanks only), the use of sacrificial anodes is usually adequate. For the protection of larger tanks, an impressed current system may be a more economic choice. The calculation of current requirements, siting of the anodes, interconnection of tanks by bonds, and correct placing of insulating flanges in a complicated system of pipe work will generally be a task for a cathodic protection specialist.

Additional information on cathodic protection for underground storage tanks can be found in NACE RP0285.

Mounded pressurised LPG storage tanks require special attention and such cathodic protection systems are described in section (17).

16.2 APPLICATION

16.2.1 Electrical Isolation

Insulating flanges or joints should be installed in the lines to and from the tanks if no requirement is foreseen for cathodic protection of those lines. The insulation shall be placed above ground, close to the tank.

Short, well coated buried steel lines connected to a single tank and having a good coating can be incorporated in the cathodic protection system. Buried lines made of other metals such as copper shall always be isolated from the tank.

When electric equipment and/or instrumentation is installed on buried tanks (e.g. electric pumps), the earthing system shall be isolated from the tank by means of polarisation cells or diode bridges. Earthing for lightning protection shall be separated in a similar way unless a separate earthing using zinc-earthing rods is installed.

If several tanks are installed in the same area, the tanks shall be electrically isolated from each other to avoid interaction between tanks and to facilitate separate measurement of current consumption for each tank.

16.2.2 Sacrificial anodes

Anodes should preferably be sited on a line normal to the long axis of the tanks at a distance of about 5 m from the outside surface of the tank; if two anodes are used one should be positioned on each side of the tank. For a well-coated tank, the siting of the anodes is not critical, and they may be sited to suit conditions, at a distance of approximately 3 m to 6 m from the tank.

The anodes should be buried at a depth which places them in permanently moist soil. The use of chemical backfill around sacrificial anodes is preferred.

The lifting lugs situated at either end of the tank provide convenient points of attachment for anode cables. The lugs should be scraped carefully to expose the bare metal, and the cable end attached by bulldog camp or by thermit welding; the coating should then be made good.

The cables from the tanks should preferably be connected to the cables from the anodes via a measuring box, including a measuring wire from the tank to enable periodic checks of the steel-to-soil potential to be performed, as well as current measurements of the anodes.

16.2.3 Impressed current

For large tanks or a large group of tanks, an impressed current system of protection is often the most suitable and a more economic solution. The tanks can be protected by a remote shallow or deep groundbed, however if the tank is installed in a congested area such as a refinery, a localised or distributed anode system is preferred. The location of anodes depends on the tank configuration and needs to be designed from case to case.

Mounded LPG storage tanks require well-designed cathodic protection systems and the specification of such systems is given in section (17).

16.3 MONITORING

The monitoring system for each tank differs depending on size and complexity.

For small tanks a single test point may suffice, for large (mounded) storage tanks more test points are required. For domestic tanks and filling station tanks, potential measurements from the earth grade are normally sufficient. For industrial storage tanks or deep tanks, permanent reference electrodes shall be installed during tank construction and the test cables terminated in test posts or boxes. For impressed current systems, interrupters shall be provided to enable ON-OFF potential measurements. Requirements for monitoring installations for mounded LPG storage tanks are given in section (17).

Low resistance shunts shall be installed in the negative drain cables of impressed current systems and in the anode cables of sacrificial systems to enable current measurements. This should or shall be done to measure the current density required for protection, which is a tool for determining the coating quality.

Monitoring should be carried out at least once every two years for domestic sacrificial systems and once a year for small industrial installations and impressed current installations. For cathodic protection systems on tanks inside an industrial plant, the test frequency is normally related to the cathodic protection test schedule of the plant.

Some countries require more frequent testing and the local regulations should be consulted.

17. PROTECTION OF MOUNDED STORAGE TANKS

17.1 GENERAL

Mounded storage tanks for LPG storage require special attention because of their specific geometry and soil conditions that can restrict current distribution and adequate protection. Detailed specifications are in PTS 34.51.11.30.

This document gives the minimum requirements for the design of cathodic protection systems for mounded storage vessels. It is based on a mounded vessel design featuring a sand-bed foundation without additional supporting structures such as saddles, piles, rafts etc. Foundations of the last type, as well as access tunnels as used for bottom outlets, will influence the regular current distribution so that special requirements may apply.

For guidance, the most important features are given below.

17.2 APPLICATION

17.2.1 Electrical Isolation

Each vessel shall be electrically isolated from all other vessels, pipelines, plant, buried metal structures and electrical and instrument earthing systems. Monoblock isolating joints shall be installed above ground in all piping attached to each individual vessel. These joints shall be suitable for the expected temperature range as given in the design data.

The resistance across isolating joints shall be measured immediately before they are welded into the pipeline. The minimum resistance shall be 1 MΩ. Isolating joints shall be painted in a contrasting colour for easy identification, and their integrity should be checked periodically.

Safety and instrument earthing installed on the vessels shall be provided with polarisation cells to avoid loss of cathodic protection current while maintaining a low resistance to earth for hazardous voltages.

If more than one vessel is installed, polarisation cells shall be installed in the earthing of each individual vessel to ensure electrical insulation between the vessels. The polarisation cells shall be suitably rated for the expected voltages and currents.

17.2.2 Sacrificial anodes

Sacrificial anodes shall not be used for these tanks unless there are special technical reasons for doing so.

17.2.3 Impressed current

Impressed current via transformer/rectifiers is normally used. Several tanks can be protected by one single transformer/rectifier. The current distribution to the tanks is ensured by the installation of distribution systems in the negative drain circuits and by adequate placement of the anodes. Rectifiers should be potentially controlled.

The deep groundbed is the preferred type for mounded storage tanks on sand foundations. There may be cases where other anode configurations are necessary, e.g. when a raft foundation is used, when the subsoil has a high resistivity (rock) or when so-called ventilation layers are installed under the tanks (to vent vapours from contaminated sub-soil). Distributed anodes are mostly made as wire loops around the tanks with current distribution boxes in each loop.

17.3 MONITORING

The protection criteria are the same as for pipelines. The window is from -850 mV (full protection) to -1150 mV (overprotection) vs. Cu/CuSO₄ reference.

Monitoring facilities for mounded storage vessels shall be designed to ensure an effective survey of the level of the cathodic protection at different locations of the vessel. The minimum requirements for monitoring facilities are as follows:

Permanent Cu/CuSO_4 reference cells shall be installed under each vessel and at both sides of each vessel in three locations, at the centre of the vessel and at three metres from each end of the vessel. Pre-packaged zinc reference cells shall be installed at three locations under the vessel adjacent to the Cu/CuSO_4 reference cells. The zinc reference electrodes shall be used for back up and for calibration of the Cu/CuSO_4 electrodes. The permanent reference cells shall be buried at a distance of 0.10 m to 0.15 m from the vessel wall.

Two negative test cables are connected to each vessel, one at each end. *All* monitoring cables terminate in a junction box installed in an accessible place at the foot of the vessel mound. From this box the required cables for the potential control equipment are run to the transformer-rectifier.

The installation of the reference cells shall be closely co-ordinated with the installation of the vessel and the mound to allow timely installation and prevent damage of test cables and the sand-bed foundation.

On the top of the mound, there shall also be access to the soil cover to allow monitoring by means of hand-held reference cells.

The transformer/rectifier should be monitored once per 3 months to ensure continued operation. ON-OFF potential measurements shall be carried out at least yearly. If the protection levels between tanks or parts of one tank show a large difference and tend to fall outside the protection window, the cathodic protection system shall be re-balanced.

18. PROTECTION OF UNDERGROUND PIPING AND PLANT STRUCTURES

18.1 GENERAL

The application of cathodic protection to underground plant structures has historically been problematic because of the complexity of the structures and the limited understanding of cathodic protection requirements during design.

Different types of structures can be identified for the purposes of cathodic protection inside a plant.

- Underground process piping, normally pressurised and transporting various products that can be a health, safety or environmental hazard if released through a leak. Although most process piping is installed above ground, some lines may be buried such as road crossings or for safety (impact) reasons.
- Underground drain systems varying from storm water drains to hot product drains. They are usually not pressurised.
- Cooling water lines that are vital for the operation of a plant and would cause major process disruption if unserviceable.
- Fire water lines and distribution systems.
- Underground structural steel, piles and foundations, including rebar in concrete.
- Underground electrical earthing systems.

Other structures, already referred to in previous Sections are:

- Transmission pipelines that may traverse the plant area and which may be protected by dedicated cathodic protection systems (11).
- Vertical storage tanks (external bottoms) (15).
- Underground vessels or tanks (16).

The most suitable method of corrosion protection shall be determined for the various plant structures, by a combination of material selection, painting and coating and cathodic protection.

For buried or submerged steel structures the use of cathodic protection shall be considered in combination with coatings to achieve the required distribution of protective current.

**Amended per
Circular 24/08**

For buried structures, the requirement for cathodic protection shall be based on the criticality of the structure, the corrosiveness of the soil and possible interference with other structures. Critical structures may include piping and vessels, cooling water lines, piping carrying very toxic substances, storage tanks and marine facilities. *Cathodic protection is required for underground piping and structures in soil having resistivity below 1,500 Ω .cm.*

When dissimilar metals are buried and electrically continuous, interaction may occur, which may include galvanic corrosion. This interaction can be prevented by cathodic protection.

For all buried piping and other equipment, the criticality shall be determined to establish the requirement for corrosion protection. Buried piping that is to be cathodically protected shall be coated by a coating system compatible with cathodic protection.

18.2 APPLICATION

18.2.1 Electrical separation

The structures that are to be cathodically protected shall, in principle, be isolated from other structures that are not in the scope of the cathodic protection system, i.e. earthing, instrument lines, pipe supports, reinforcement steel, above ground steel structures etc. The location of the earthing shall be carefully selected to avoid bridging of the isolation devices.

The safety or instrument earthing of electrical equipment connected to buried structures requiring cathodic protection shall be separated by polarisation cells.

Where electrical isolation is not possible, a localised cathodic protection system, using line anodes or anodes installed close to the structure to avoid interaction with other structures, may be considered.

18.2.2 Selection of cathodic protection system

Because of the complexity of a plant, or when cathodic protection is retrofitted after construction, "flood" cathodic protection systems have been installed, designed to protect all underground metallic structures in a plant. When, for instance, a steel fire water line is surrounding and traversing a plant, the separation of specific units is difficult. Electrical safety earthing systems and earthing requirements for lightning protection may also provide electrical bonding of all equipment in a plant. This normally requires a high cathodic protection current output from a number of transformer/rectifier systems using a grid of distributed deep groundbeds. The use of surface groundbeds for plant cathodic protection has been unsuccessful because of shielding effects and interference with earthing systems.

Such flood systems are normally expensive, difficult to balance and adjust and have an inherent risk because of currents flowing through all parts of the plant piping and equipment. If the plant design allows, isolated systems or local distributed anode systems should be installed.

The selection of sacrificial systems vs. impressed current systems is described in (4.5). For buried plant structures, such selection depends on soil resistivity and coating quality (current demand) of the underground structure.

Some examples of localised or distributed systems are:

- vertical storage tanks having impressed current anodes under the tank floor (15);
- buried tanks and vessels having sacrificial or impressed current anodes (16);
- steel cooling water lines having a network of impressed current anodes along the pipeline route;
- road crossings having sacrificial anodes installed close to the crossing;
- isolated plant drain systems (such as sulfinol drains) protected by a small distributed impressed current system.

18.3 MONITORING

Inside plant areas, the complicated underground structure and regular modifications and maintenance activities require frequent monitoring to be carried out.

The cathodic protection monitoring points shall be selected and documented and shall include:

- all isolating joints and flanges;
- all other isolating devices such as polarisation cells and diode bridges;
- all transformer/rectifiers and sacrificial anode connections;
- key points on all protected structures;
- key points on non-protected structures adjacent to protected structures to check for interference or current loss;
- all permanent reference electrodes installed at storage tanks and vessels.

The minimum frequencies for monitoring should be once every 3 months for transformer/rectifiers and once per year for all other key points and isolating devices.

19. PROTECTION OF HEAT EXCHANGERS

19.1 GENERAL

Cathodic protection of heat exchangers and coolers is mainly applicable to water coolers. Closed cooling water systems do not require cathodic protection as the corrosivity is normally reduced by the addition of corrosion inhibitors and oxygen scavengers.

Internal corrosion of heat exchangers in open cooling water systems depends on the corrosivity of the cooling water (seawater vs. fresh water) and on the galvanic effects of dissimilar materials, often used in such equipment. Combinations of carbon steel and copper alloys are specified in PTS 31.21.01.31. and in some designs, other combinations of metals (stainless steel, titanium) may be used. Even when a single type of alloy is specified, there may still be the possibility of galvanic activity between slightly different compositions (e.g. plate and weld material). Cathodic protection can reduce these galvanic effects.

The type of cathodic protection system depends on the material or combination of materials to be protected and the water properties (resistivity and temperature).

19.2 APPLICATION

19.2.1 Shell and Tube Heat Exchangers

Standard shell and tube heat exchangers are made of carbon steel (non corrosive cooling water) or copper alloys (corrosive cooling water). In PTS 31.21.01.31., some combinations are allowed such as carbon steel shells and copper alloy tube sheets and tubes. Such combinations are deprecated because of the difficulty of applying cathodic protection. To reach the protection potential criterion for carbon steel, the copper alloy should be polarised first, which is normally not possible with sacrificial anodes.

Carbon steel parts in shell and tube heat exchangers should be protected from galvanic attack by fitting zinc or magnesium anodes, the choice depending on the water resistivity. The size of the anode chosen will depend on the expected current requirements (size of the heat exchanger) and the interval between shutdowns when the anodes are replaced. With seawater as the cooling medium and water temperatures of up to 45 °C, the current density required for the cathodic protection of steel is 110 mA/m² to 220 mA/m². The actual anode usage can best be judged from the anode consumption at the time of replacement.

Copper alloy only needs mild polarisation to counteract possible galvanic cells between different alloys. For this reason iron anodes are normally used that can provide sufficient polarisation and will not be wasted too quickly (which would happen if zinc or magnesium were used). There is also an inhibiting effect from the dissolved iron on the (pitting) corrosion of the copper alloy tubes due to the formation of a thin oxide layer on the inner tube surface. The anodes should be made from soft iron ("Armco iron"); carbon steel is sometimes used but can cause fouling by scale formation.

The anodes should not have be sized so that they interfere with the water flow. Methods of fixing the anodes are shown in Standard Drawings S 21.072 and S 21.073.

If the sacrificial anodes cannot be made large enough to last for the full period between shutdowns, the use of impressed current can be considered. This requires the installation of anodes (through hull penetrations) of sufficient strength to withstand the turbulent water flow. When impressed current is used, permanent reference cells should always be installed.

If stainless steel coolers are used, the internals can be protected from pitting corrosion by the installation of resistance-controlled cathodic protection (RCP). For details see (23).

If a heat exchanger has titanium parts, cathodic protection should be used with care as the potential range for full protection of steel can cause embrittlement of some titanium alloys.

19.2.2 Other Coolers

Because of the high water temperature and the heavy current requirement, an impressed current system should be used for the cathodic protection of box coolers, although the space available for the anodes is small and their dimensions and numbers will need to be limited.

The high water temperatures prevailing in box coolers, often over 40 °C, make the self-corrosion rate of magnesium too high to allow sacrificial magnesium alloy anodes to be used satisfactorily. Zinc anodes are unsatisfactory because they supply too low a current and at higher temperatures their polarity with respect to steel may be reversed, see (5.3.2).

With seawater as the cooling medium and water temperatures of up to 45 °C, the current density required for the cathodic protection of steel is 110 mA/m² to 220 mA/m².

The tube-to-water potentials should be maintained at -0.85 V with reference to the standard copper/copper sulphate electrode.

19.2.3 Internal coating of heat exchangers

If sacrificial anodes are unable to provide protection and impressed current is not an option, internal coating or a combination of coating and cathodic protection can solve some problems of internal corrosion in heat exchangers. If dissimilar materials of construction are used, the anodic parts (i.e. the copper alloys) should be coated. This will give the highest reduction in current demand and provides the best surface area ratio between cathodic and anodic construction materials. Coating of the cathodic metal (steel) alone may increase the corrosion rate in possible holidays in the coating due to unfavourable surface area ratios.

The coating should have a near perfect adhesion to the substrate as flakes of coating material may block the tubes when they flake off. Aluminium spray on copper alloy tube sheets has been applied and seems to be a promising solution.

19.3 MONITORING

Monitoring of the protection levels inside coolers and heat exchangers is only possible when a permanent reference electrode has been installed. When sacrificial anodes are used, monitoring should be done on a yearly basis. When impressed current is installed, the normal monitoring of the transformer/rectifier is needed and potential measurements should be done more frequently or when changes in current occur.

When no reference cells are installed, the operation of the anodes can be judged during inspections of the exchangers during shutdown. Absence of signs of corrosion means that the cathodic protection system is operating adequately. Fully wasted anodes should be replaced by larger ones, if possible, to last until the next inspection.

The adequacy of the number and distribution of anodes in a box cooler should be ascertained by measuring tube-to-water potentials. An additional check can be obtained by means of test coupons installed in the box and connected to the cooler by a cable.

20. PROTECTION OF SHIPS

20.1 GENERAL

The application of cathodic protection on external ships' hulls depends greatly on the trade and routes of the ship and on the construction of the ship. The current requirement of a ship's hull varies with the water type, temperature and the ship's speed. The state of the painting system also influences the current demand.

The types of ships requiring cathodic protection are ocean going crude and product carriers and general cargo vessels, ships for inland and coastal trade, and small boats and barges.

Ships converted to floating production, storage and offloading units (FPSOs) are special units that are described in (21).

Specific problems encountered are the limitations in placement of (impressed current) anodes on tankers, large coating damage, galvanic effects from bronze propellers, and effects from mooring, anchors and other uncoated attachments.

20.2 EXTERNAL PROTECTION OF THE HULL

20.2.1 General

**Amended per
Circular 10/04**

The external protection of hulls is usually provided by means of paint coatings. Recommendations for hull coatings are given in PTS 30.48.00.31.

The protective paint coating, however, is easily damaged in localized areas by mechanical action such as anchors and by erosion at parts of the stern frame and the leading edge of the rudder; preferential corrosion also occurs at rivet heads and welds. Cathodic protection can be of value in preventing or greatly reducing corrosion at these areas.

The cathodic protection of hulls can be achieved by the use of sacrificial anodes or by impressed current systems. On bare steel, a current density of 45 mA/m² to 55 mA/m² is sufficient in static seawater but at speeds of 13 knots and more, up to 160 mA/m² may be required. Therefore, the design of a cathodic protection system can be difficult if the future trade is unknown.

Because of the possible high current demand, impressed current is often preferred for ships in normal trade but because of the restrictions for placement of impressed current anodes, sacrificial systems are also employed. In some cases, a combination of impressed current and sacrificial anodes (hybrid systems) uses the advantages of each of these systems.

20.2.2 Sacrificial anodes

Magnesium or aluminium-alloy or high-purity zinc anodes can be used either for protection of the whole hull, when they should be fitted at intervals around the hull, or for local protection, e.g. protection of the stern frame or the rudder itself where most paint damage occurs.

Because of their greater driving voltage, magnesium alloy anodes should be used for craft operated partially or wholly in brackish or substantially fresh water. The steelwork under and for 0.9 m around the anode should be painted with an alkali-resistant paint to prevent cathodic disbondment.

Zinc is the recommended anode material for craft operating in seawater because of its longer life and low risk of causing cathodic disbondment.

For the design of sacrificial anode systems, the normal design rules apply, however the final and average paint damage is difficult to predict and the design life should be well beyond the time of the next expected dry-docking.

Sacrificial anodes are normally shaped so as to give the least drag in flowing seawater and are usually in the shape of flat plates or droplets. The anodes are welded to the hull by means of the projecting steel strips that are an integral part of the anode construction.

Sacrificial anodes shall be used on ships and barges that do not have on-board power to drive impressed current cathodic protection systems.

20.2.3 Impressed current

When mains power is available, the required impressed current can be generated by standard transformer/rectifiers and supplied to anodes fixed on the ship's hull through the hull plates. Impressed current anodes for ships are normally made of platinised titanium in the shape of long wires or flat plates, embedded in resin.

These anodes shall be constructed so as to minimise the drag during voyages and are often made very slim or flush with the ship's hull. The disadvantage of the close proximity of the anodes to the hull is that the current distribution is difficult and that the coating close to the anodes may suffer from overprotection and cathodic disbondment. Therefore, plastic dielectric shields shall be installed around the hull anodes. Sometimes polyester coating is used in the area directly around the anode.

The cathodic protection systems (anodes) are normally placed where the largest current demand is expected, i.e. at the bows (anchor damage) and at the stern (propeller, high flow, erosion). On very large ships a separate system may be installed amidships if the construction of the vessel allows.

Because of the varying current demand with the ship's speed or trade, an automatic potential control system that regulates the current to maintain a constant potential should be used. For this system, reference electrodes shall be installed on the ship's hull, remote from the anodes. More than one reference electrode per system may be installed as a back up, e.g. at starboard and portside. The preferred type of reference electrode is silver/silver chloride, though some systems use zinc reference cells.

20.2.4 Hybrid systems

On very large crude carriers the installation of cathodic protection systems at the bow and stern may not be sufficient to protect the full length of the hull and bottom. Especially when large coating damages are present near the anodes, the current distribution is disturbed and protection is restricted to the vicinity of the anodes. The installation of additional anodes amidships is often impossible on single hull ships because of the presence of cargo tanks where cables cannot be installed. In those cases, additional sacrificial anodes have proved they can provide the required protection. The two systems do not adversely interfere. When the impressed current distribution is good, the sacrificial anodes provide less current.

20.2.5 Propeller protection

In cathodic protection systems, provision shall be made to include the propeller. A slip ring is fitted to the propeller shaft at a convenient point and an electric connection is made to the hull by means of metal brushes riding on the slip ring. To ensure adequate continuous low-resistance contact, the contact surfaces of the slip rings should be silver-plated or should incorporate solid silver inlays, and the brushes should be of a self-lubricating type. Wear rates cannot be predicted, but provision should be made for replacement between periodic dockings until experience is gained.

20.2.6 Protection of stationary vessels

Oil and gas production operations are increasingly using floating production units, often made from converted ships or purpose built vessels. Although some of these vessels can be moved under their own power or towed, they are mostly stationary for prolonged periods. These vessels are normally anchored by multiple anchor chains (uncoated). In the cathodic protection design adequate allowance should be made for the protective current required for these attachments. Further details on the protection of FPSOs is given in (21).

20.3 PROTECTION OF CARGO AND BALLAST TANKS

Cathodic protection for cargo and salt-water ballast tanks is normally provided by sacrificial anodes. In permanent ballast tanks, e.g. trim tanks and segregated ballast systems,

corrosion protection is usually provided by means of a high performance tank coating and sacrificial (zinc) anodes.

In crude oil cargo tanks, some water may collect on the tank bottom and cause bottom corrosion, especially in the aft part of tanks where the water collects during normal stern trim of the ship. This corrosion process may be accelerated by the presence of acidic components leaching out of some crude oils or due to the formation of sulphide scales in sour crude oils that can form strong corrosion cells. In most cases, the installation of anodes directly on or above the tank bottom can prevent corrosion, similar to the system recommended for crude oil tanks onshore (22).

Mixed cargo/ballast tanks that carry alternately crude oil cargo and ballast water require internal cathodic protection by sacrificial anodes.

These tanks are normally not fully coated; in some cases only the bottom area is coated to provide more protection against water layers under crude oil and to improve the effectiveness of bottom anodes.

Magnesium and aluminium anodes have not been allowed in the past because of the possible sparking (thermit reaction) should they fall on rusted steel. Local regulations should be checked for any restrictions of anode materials.

A cathodic protection system is particularly important because of the formation of electrochemical cells between well-cleaned steel and sludge-covered steel. Large corrosion cells have been shown to exist between oily bulkheads and cleaner bottoms. Cathodic protection designs are often made separately for bottom and bulkheads because of their different current demand. For tank bottoms a current density of about 120 mA/m² is required, for bulkheads 30 mA/m² to 60 mA/m² is sufficient. Anodes should be regularly distributed over the tank surface. At elevated locations (> 10 m), the maximum anode weight is 20 kg; this is related to the maximum allowable impact energy that might cause incendiary sparking. The anode life depends greatly on the ship's trade as repolarisation of the steel is required after each fill of the tank. Short trips "consume" more anode material in time than long voyages. In most cases cargo/ballast tanks are not coated or only the bottom is coated.

Most product tankers have segregated ballast tanks to avoid product contamination. Cargo tanks do not normally require cathodic protection unless there is evidence of water entrainment. Flat bottom anodes may be sufficient for accidental water presence.

Tank anodes are normally constructed as 20 to 50 kg standoff anodes with steel cores welded to special supports with a standoff of 30 to 50 cm. The size of the anodes depends on the design life, which is, as a minimum, twice the interval between dry dockings.

20.4 MONITORING

External cathodic protection systems on ships shall be regularly monitored. Output current and voltage are often recorded daily, but at least a weekly record should be kept. The monitoring data should preferably include output current and voltage of each transformer/rectifier system, potential measurements by permanent reference cells, ship's speed and location. The latter may help during some trouble shooting operations. From time to time individual anode currents may be measured to confirm the good operation of the anodes.

External cathodic protection systems on stationary vessels may be monitored less frequently when a stable protection pattern has been reached. Similar to offshore structures, potential monitoring by means of suspended reference cells can be done and key monitoring points should be assigned.

Cathodic protection systems inside tanks may be monitored by means of permanent reference cells or by lowering a reference cell down the hatch opening. This is not normally done because of safety restrictions. If in doubt, (cargo)/ballast tank cathodic protection systems can be checked by means of specialised instruments such as instrumented anodes or corrosion probes.

In some deep and narrow ballast tanks such as double bottoms and some types of ballast tanks on LNG carriers, there might be a situation where oxygen depletion can occur and where sulphate-reducing bacteria can develop. In those cases a potential criterion of -900 mV vs. Ag/AgCl reference is required.

21. PROTECTION OF FLOATING PRODUCTION, STORAGE AND OFFLOADING SYSTEMS (FPSO'S)

21.1 GENERAL

Oil and gas production operations are increasingly using floating production units, often made from converted ships or purpose built vessels. Although some of these vessels can be moved under their own power or towed, they are mostly stationary for prolonged periods. These vessels are normally anchored by multiple anchor chains (uncoated) and production vessels are connected to wells and other sub-sea equipment. In the cathodic protection design adequate allowance should be made for the protective current required for these attachments.

FPSOs are a special case for protection, as the CP systems are required for the field life (for example 30 years); FPSOs are not dry docked every 5 years as is common with ships. The common approach is to use aluminium-indium alloy anodes. With an FPSO it is feasible to employ "temporary" suspended anode systems if the fixed anodes become exhausted.

Moreover, the service of the tanks of a FPSO is different from that of tanks on normal trading vessels. Tanks are used for the processing of produced crude and may contain large amounts of production water, stationary ballast or mixtures of (sour) hydrocarbons and water. This may require a different cathodic protection approach.

For FPSOs the intervals between dry-docking are much longer than for ships. Therefore the design life of sacrificial anode systems shall be adequate to cover the full operational period of the vessel.

21.2 EXTERNAL CATHODIC PROTECTION

21.2.1 General

Paint coating provides the external corrosion protection of the primary structure of an FPSO. As the vessel is stationary the external damage of this coating by anchors and mooring is less likely. Some damage can be expected by support vessels and degradation of the coating system by ageing. For a 20-year design life a coating breakdown 10% (final 20%) can be expected.

Current densities required for protection are similar to those required for fixed offshore structures. Refer to figure 12 for design current density values. The seawater temperature at the permanent mooring location is required to determine the required current density (PTS 37.19.30.30). The effect of the sea voyages from construction / fit out yard to location should be considered in the design.

Allowance should be made for other uncoated and coated attachments of the vessel such as anchor chains, risers and umbilicals. Anchor chains may not always receive the full benefit of the vessel's cathodic protection system as their length (especially with deep water applications) may cause an appreciable attenuation of protection levels and full electrical continuity between chain links is not guaranteed due to the possible accretion of marine life forms. In these cases the installation of separate anodes on the anchor chains should be considered.

21.2.2 Impressed current

If continuous power is available, impressed current systems can be employed.

The anode construction can in principle be the same as for ships, although there is more freedom for construction and distribution of anodes on the hull.

It is common practice for FPSOs to have wing and bottom ballast tanks that allow placement of anodes in those areas of high current demand, e.g. near mooring systems and riser attachments.

Because the vessels are stationary, there is less need to use recessed anodes for drag reduction. The use of protruding or suspended impressed current anodes is possible. In all cases, dielectric shields shall be used in the vicinity of the anodes to improve the current distribution and avoid cathodic disbonding or deterioration of the standard paint coating system close to the anodes.

For the protection of FPSOs mixed metal oxide anodes are commonly used.

21.2.3 Sacrificial anodes

Sacrificial anode systems can also be used because of the low current requirements compared to ocean going vessels and the likely absence of major anchor damage. As for fixed offshore structures, aluminium-zinc-indium anode material should be used.

There is no requirement to use flat hull-type anodes for drag reduction. Standoff anodes can be used, which allow larger anodes to be fitted and also improve the current distribution.

21.3 PROTECTION OF TANKS

21.3.1 General

Cathodic protection of FPSO tanks is normally accomplished by means of sacrificial anodes. The types of tanks requiring cathodic protection are ballast tanks, crude storage tanks and production tanks (receiving tanks and slops tanks).

For the design of storage/reception tanks and slops tanks on FPSOs the rules governing such tanks on board normal tankers are not applicable, FPSO tanks are not operated in anywhere near the same regime as those on a tankers used for regular transport and can have much higher current demands. In addition, there is a very high chance of bacterial corrosion, because tanks on FPSO's, unlike on tankers, are not regularly cleaned. Increased corrosion can also be caused by the formation of an iron sulphide scale, which is cathodic with respect to bare steel, leading to strong galvanic corrosion of the bare steel. For these reasons, a heavy-duty tank lining and a cathodic protection system help to avoid costly repair bills.

Design life of tank cathodic protection systems is the same as for the whole structure as retrofitting is not possible or very costly because it may interrupt production.

In tanks with venting there is a risk of condensation type corrosion in the top of the tank. The tops of these tanks can be protected by thermal sprayed aluminium coatings (conventional coating is not suitable because recoating of the tank during its lifetime is extremely difficult).

With sacrificial anodes inside tanks there is a risk of hydrogen build up. Tanks should be properly ventilated to minimise the risk of explosive atmospheres building up in the top of the tanks. Because of this risk, great care should be taken when entering the tanks.

21.3.2 Ballast tanks

Ballast tanks only contain seawater ballast. They are normally internally coated by heavy-duty coating systems. The cathodic protection system is required to provide protection against coating damage and uncoated attachments such as piping.

Ballast tanks are often complicated structures with internal web frames and many edges that are prone to coating damage. The coating is exposed to atmosphere at certain times and therefore coating damage is more likely than in continuously immersed structures. Coating damage of up to 20% is possible. In seawater current densities of 50 mA/m² on bare steel are normal; repolarisation of the steel during every re-ballasting operation should be allowed for.

Aluminium/zinc/indium anodes of the standoff type are commonly used in ballast tanks.

21.3.3 Crude storage tanks

On FPSOs segregated storage tanks are used for crude oil storage. Most oil cargo will contain some water, typically 1%. The protection of the bottom section of the cargo tanks, where the water collects, should be protected by a combination of coatings and cathodic protection. The expected water level in the tanks determines the shape and height of the anodes. Flat bottom anodes or low standoff anodes can be used.

In the water layers of crude storage tanks bacterial activity can occur. Therefore the design of the cathodic protection system shall be based on the criterion for anaerobic environments (i.e. -900 mV vs. Ag/AgCl reference).

21.3.4 Production tanks

In the tanks used for crude oil production, different mixtures of crude oil and water (sea water or production water) are mostly present. Highly corrosive conditions can occur caused by the high corrosivity of highly saline production water, the presence of high concentrations of CO_2 or H_2S , bacterial activity and galvanic activity between sludge covered steel and bare steel. The water content of these tanks can also vary from shallow bottom layers up to half the tank height, under crude oil in receiving/settling tanks.

The coating and cathodic protection systems should be designed to cope with these situations. Full coating of these tanks is usually recommended. Cathodic protection systems shall be designed to cope with the intended production regime. High current densities can be expected, up to 120 mA/m². Bacterial activity in these tanks is possible and the protection criterion shall therefore be set for anaerobic conditions as for crude oil storage tanks.

Because anodes are frequently wetted by product, they shall be able to regain activity after immersion in crude oil.

21.4 MONITORING

The external cathodic protection system shall be monitored regularly. When impressed current is used, the voltage and current should be recorded to monitor sudden changes in the current demand. Monitoring of sea and weather conditions may help the interpretation of the results.

As for other structures, key monitoring points should be assigned for regular monitoring. Permanent reference electrodes can be mounted in positions such as the turret/moonpool and riser areas. Other areas of the external structure can be surveyed by divers using hand-held reference cells or by suspended reference cells.

The performance of cathodic protection systems inside hydrocarbon containing tanks is difficult to monitor. Permanent reference electrodes are the easiest way to monitor protection levels. In crude-containing tanks zinc reference electrodes have been successfully used on ships. Intrinsically safe test equipment is required for measurements inside these tanks.

In the past, corrosion probes (electrical resistance probes), electrically connected to the structure, have been successfully used to monitor the effectiveness of cathodic protection systems. Instrumented anodes have also been used to monitor anode output and analyse anode usage.

Finally, whenever such tanks are internally examined, e.g. for structural inspection, the opportunity should be taken to visually inspect the cathodic protection system for anode usage, anode passivity, coating breakdown and possible bacterial activity.

22 INTERNAL PROTECTION OF TANKS, PRESSURE VESSELS AND WATER LINES

22.1 GENERAL

Internal corrosion protection of tanks, pressure vessels and piping is mainly effected by the application of high performance coatings. Depending on the corrosion risk and the selected corrosion control system, the internal surface of pressure vessels may be bare carbon steel, coated carbon steel or a corrosion resistant alloy. In some cases where equipment contains water or water-contaminated products, this equipment may additionally be protected by cathodic protection. This choice depends on corrosivity, geometry and expected effectiveness of the cathodic protection system. Large diameter steel cooling water lines may also be provided with a coating in combination with cathodic protection.

22.2 PROTECTION OF WATER TANKS

Typical water tanks are storage tanks for firewater, process water or potable water onshore and (sea)water ballast tanks offshore or on ships. Demineralised water may be very corrosive because of the absence of iron ions in the water and so demineralised water tanks may require corrosion protection.

When water tanks are internally coated a cathodic protection system may be considered as a backup system; if regular coating inspection and maintenance is possible this may not be needed. The cost of installing a cathodic protection system may be offset against the cost of more frequent coating maintenance. In coated tanks sacrificial systems are mostly used but impressed current systems may alternatively be used, especially for anode retrofits. When using magnesium anodes or impressed current are used, the overprotection limit should be observed to avoid cathodic disbondment of the coating.

Uncoated water tanks often require impressed current cathodic protection, especially if they are emptied and filled frequently. Impressed current installations mostly consist of anodes, suspended from the tank roof about half the tank radius from the tank shell. A permanent reference anode should also be included and positioned close to the wall or bottom.

Further information on the design of impressed current systems for tank cathodic protection can be found in NACE RP0388.

22.3 PROTECTION OF PRODUCT TANKS

Internal cathodic protection in tanks and vessels shall be considered if a tank contains water or products in which water may settle out to form a water layer on the tank bottom. The requirements for such installations shall be considered from case to case. In some cases, the tank bottom is coated to provide protection; in other cases, coatings are not used.

Amended per Circular 10/04

PTS 30.48.00.31. gives requirements for tank linings.

Additional cathodic protection is provided in the form of sacrificial anodes mounted close to the tank bottom to provide protection in expected thin water layers. However, the current distribution in thin water layers is not very good and for that reason long thin anodes may be more effective than small thick blocks. Anodes should be installed in the lowest part of tanks and vessels without obstructing the process flow.

Tanks operating with a permanent water bottom such as settling tanks may have the conventional anode blocks installed on the bottom and on the shell.

The anodes should preferably be welded to the bottom or to supports on the bottom. All coating (if present) should be repaired after welding. The anodes should remain uncoated.

Further information on the design of sacrificial anode systems for tank cathodic protection can be found in NACE RP0196.

22.4 INTERNAL PROTECTION OF PROCESS VESSELS

Like storage tanks, production and process vessels containing water may be equipped with cathodic protection systems. The type of installation required depends on the type of water, the operating temperature and the presence and status of internal coating.

Further information on the design of these systems can be found in NACE RP0575.

22.5 INTERNAL PROTECTION OF LARGE DIAMETER WATER LINES

Carbon steel cooling water lines are sometimes used for seawater if non-metallic (GRP) materials are not feasible. The internal surface is normally coated. As the coating will always suffer from some deterioration, additional cathodic protection may be installed. Sacrificial anodes are normally used. Such systems have typical restrictions: the internal pipe surface shall be fully coated to ensure a proper current distribution; the field joint areas shall therefore also be coated and this requirement tends to restrict the use of such lines to large diameters. The anodes may not form an obstruction to the water flow or cause severe turbulence; this requirement also prohibits the use of sacrificial anodes in small diameter lines.

The anode design shall be based on high lateral water flow, ambient seawater temperatures, 1 to 2% coating damage and the full design life of the pipeline. A current density of 2 mA/m² (calculated on the coated surface area) is normally adequate. Anode distribution will typically be one anode in 3 to 5 pipe joints.

Anodes should be of a long slender type to cause as little drag as possible for the water flow. Zinc is the recommended material because of its high efficiency at low current output. To prevent possible coating damage in the vicinity of the anodes due to overprotection, a dielectric shield should be provided around the anode (about 0.5 m from the anode footprint) in the form of a double thickness coating layer with good cathodic disbonding properties.

22.6 MONITORING

Monitoring criteria in tanks follow the general protection criteria. The type of monitoring installation depends on local conditions, safety aspects and the tank construction. Water tanks can be provided with permanent reference electrodes and can sometimes be monitored by means of suspended reference cells through roof openings. Inside product tanks, the installation of permanent reference cells is difficult as the products or crude oil cause contamination of the reference electrode or its membrane. Sometimes zinc reference electrodes can be used. The use of manually suspended reference electrodes is limited due to restricted entry of tanks.

In pressure vessels monitoring is not usually done by measuring protection potentials. The design and the self-regulation of the sacrificial anodes is relied upon. During internal vessel inspections the anode consumption should be checked against the design, actual usage and water content and exposure time.

Water pipelines may be monitored by means of permanent reference electrodes through the pipe wall. This is more difficult in below ground and subsea sections. As anodes are distributed regularly in the line, one or two easily accessible (above ground) locations can be selected for monitoring the typical performance of the cathodic protection system. During internal inspections of the lines, the anode consumption should be checked against the design.

23. PROTECTION OF REINFORCING STEEL IN CONCRETE STRUCTURES

23.1 GENERAL

When concrete is exposed to water or moisture, this can act as an electrolyte. Reinforcing steel in the concrete can be exposed to this electrolyte; however, the alkaline nature of the concrete should provide corrosion protection of the embedded steel by the formation of a passive layer. Normally steel in concrete should not require further protection.

If the passivity of the reinforcement steel is destroyed, for instance by the presence of chlorides or other aggressive salts or chemicals, corrosion of the steel can occur and the expansion of the corrosion product can damage the concrete. The source of such contamination can be the use of contaminated sand (e.g. sea sand) for making the concrete. Exposure to sea or salt laden atmospheres in combination with insufficient concrete cover can be the cause of reinforcement bar corrosion.

If corrosion of reinforcing steel occurs, this can in principle be mitigated by cathodic protection. Typical applications are concrete bridges that are contaminated by road salt and concrete seawater cooling systems.

23.2 APPLICATION

The application of cathodic protection to concrete structures is highly specialised work, requiring detailed investigations. Discontinuities in the cathodic protection circuit, such as non-continuous reinforcement steel and gaps between steel and concrete, may prevent effective cathodic protection. As a minimum the electrical continuity of the reinforcement bar especially in sub sea and marine structures, should be ensured and checked.

Reinforcement bar cathodic protection is often retrofitted after concrete damage has taken place. It should be investigated where cathodic protection is required and where future damage is likely. If possible, any damage to the concrete should be repaired before cathodic protection can be effectively applied.

The investigation consists of a detailed potential measurement where differences in potential between parts of the structure indicate the presence of corrosion activity. Unlike steel in seawater, corrosion potentials of steel in concrete are in the range of -250 mV to -400 mV vs. Cu/CuSO_4 reference. Further investigation includes testing for electrical continuity of the reinforcement bars to ensure protection for all parts inside the concrete.

The required current density is difficult to predict. It can sometimes be estimated by conducting an E-log I test similar to the test described for well casings (14.2). The criterion for full protection is a minimum negative polarisation of the reinforcement steel by 100 mV.

Impressed current is normally applied for cathodic protection of reinforcement bars in concrete. It consists of a current controlled transformer/rectifier and special anodes that can be glued or sprayed onto the concrete surface or embedded inside the concrete. Because of the difficult current distribution, large anodes or many small anodes are normally required.

For new construction projects reinforcement bar corrosion can be avoided by the use of high quality concrete made with low chloride sand and by providing sufficient cover over the reinforcement bar. The reinforcement steel shall be electrically continuous in case cathodic protection is required in future. In some critical structures, spaces for future anodes and reference cells are already provided during actual construction.

Additional guidance on the application of cathodic protection of steel in concrete is given in NACE RP0290.

For sub sea concrete structures, the protection of the reinforcement bar can be achieved together with the protection of any attached steel structures such as drill pipes and conductors. When sacrificial anodes are used, the current required for protection of the reinforcement bar is normally self-regulating.

23.3 MONITORING

Monitoring of cathodic protection of concrete reinforcement bars consists of recording the output parameters of the impressed current systems and of potential measurements of the reinforcement steel by means of a reference cell in contact with the concrete surface. Special precautions are needed to avoid errors due to the high resistance of the concrete. Details and procedures of potential measurements are given in ASTM C 876. This document also gives guidance on the interpretation of monitoring results.

Proprietary monitoring probes may be installed within the concrete on critical structures such as seawater intakes and LPG tank foundations.

Impressed current cathodic protection systems protecting concrete reinforcement bars shall be monitored regularly. Availability surveys shall be carried out monthly and potential measurements once or twice per year or whenever significant changes in output current or voltage are observed.

24. PROTECTION OF STAINLESS STEEL STRUCTURES

24.1 GENERAL

In most cases stainless steels are corrosion resistant and do not require additional corrosion protection. Cathodic protection may be required if stainless steels are used in an environment where pitting or crevice corrosion can occur, e.g. in (sea-)waters at temperatures above ambient, or are used in combination with carbon steel components that require cathodic protection. Cathodic protection shall always be applied to stainless steels with caution to avoid detrimental effects on the various types of stainless steel. The advice of a cathodic protection specialist shall be obtained.

Two different applications of cathodic protection shall be considered:

- Internal protection of stainless steels, e.g. stainless steel components in seawater systems at elevated temperatures,
- External protection of stainless steel, e.g. stainless steel pipelines.

For carbon steel pipelines or buried vessels internally clad with stainless steel, the external cathodic protection is the same as for carbon steel pipelines (11,12) or vessels (16).

24.2 APPLICATIONS

24.2.1 Austenitic stainless steel

Internal protection

Austenitic stainless steels will suffer pitting or crevice type corrosion when exposed to certain electrolytes such as seawater or chloride containing waters. Susceptibility to pitting depends on the pitting potential of a material. When the potential of the austenitic stainless steel can be kept more negative than its pitting potential, this type of corrosion can be avoided. A negative potential shift of 100 mV is often sufficient. Passive stainless steel can easily be polarised and only small currents are required. Internals of stainless steel water systems can be cathodically protected by sacrificial anodes provided with a serial resistor to control the current to a low level, enough to provide this polarization. This system is called resistance cathodic protection (RCP) and is provided by a specialist company (Corrocean). It requires accurate calculations. Reference electrodes should be installed to monitor the potential changes is recommended. Similar systems have also been installed in stainless steel heat exchangers in seawater service.

External protection

Buried or submerged stainless steel pipelines or components normally have heavy duty coatings applied and do not need cathodic protection. However, if installed in the sphere of influence of other cathodic protection systems, the stainless steel should be connected into the existing cathodic protection system to avoid stray currents. The protection criteria for other steels can be applied but overprotection shall be avoided.

24.2.2 Duplex stainless steels

Internal protection

Although duplex stainless steels are less sensitive to pitting and crevice corrosion, they can be treated in a similar way as austenitic stainless steels. RCP systems can be applied to duplex stainless steels.

External protection

Duplex stainless steels can suffer from hydrogen embrittlement if overprotected. The protection criteria for single duplex stainless steel components are set less negatively than for carbon steel. Polarisation to -600 mV is regarded as sufficient for full protection. However, duplex stainless steel pipelines are often used in oil and gas production and may be installed in the same area or route as carbon steel pipelines or in combination with carbon steel structures sub sea. In those cases the same protection criteria should be applied as for the carbon steel pipelines but overprotection shall be avoided. In practice, no

overprotection has been observed on duplex stainless steel components such as tie in spools in carbon steel lines, which have sacrificial anode systems.

24.2.3 Martensitic stainless steels

Internal protection

Martensitic stainless steels are normally not used in seawater processes and cathodic protection of internals is not applied. If internal cathodic protection is considered, specialist advice shall be sought.

External protection

Martensitic stainless steels or martensitic/ferritic stainless steels such as 13 Cr steels can be susceptible to hydrogen embrittlement when overprotection occurs, similar to high strength steels. In particular, weldments of such steels have proved to be susceptible to hydrogen attack. This risk seems to be particularly high during construction and commissioning phases before the equipment is used up to its (elevated) operating temperature. Damage has e.g. been found close to sacrificial anode attachments (anode doubler plates). The sensitivity of such steels and weld material should be investigated and overprotection should always be avoided.

24.3 MONITORING

The cathodic protection criteria for corrosion resistant steels and some high strength steels depend on the susceptibility of the material to hydrogen induced stress cracking. The protection criteria for buried and subsea pipelines made of such materials shall be determined on a case by case basis. This is also applicable when designing a cathodic protection system for a pipeline crossing or approaching another pipeline made of such a material. Protection criteria shall be documented and included in a monitoring plan.

The monitoring methods and frequencies are normally the same as for other pipelines. Cathodic protection systems installed inside stainless steel equipment should be monitored on at least a yearly basis or more frequently whenever large fluctuations are detected.

25. SAFETY PRECAUTIONS

As cathodic protection necessitates the use of electrical equipment, certain safety precautions shall be taken in hazardous areas.

The potential difference between cathodically protected steel structures and the surroundings means that contact with another steel structure may produce a spark. In particular, the breaking of contact may produce a spark. The energy released by sparking, and therefore the risk of ignition of flammable mixtures, is strongly influenced by circuit parameters such as inductance, resistance, applied potential, physical nature of the contacting surfaces, rate of breaking of the contact, etc. It is not always possible to predict whether an incendiary spark will be produced in a given instance. Every cathodic protection installation in a hazardous area shall be regarded as potentially dangerous and precautions should be taken to avoid sparking.

Area classification shall be in accordance with PTS 80.00.10.10.

Electrical equipment shall be in accordance with PTS 33.64.10.10.

Safety precautions for rectifiers, switches and cables are the same as for any other electrical equipment.

Transformer/rectifiers should be installed outside hazardous areas where possible.

Current-carrying cables in classified areas shall always be terminated so that they cannot be dismantled without special precautions. Cable connections to equipment should be made by welding or direct brazing.

Before separating two parts of a cathodically protected system, e.g. at a flange, it shall be ensured that a sufficiently solid parallel current path exists to conduct the cathodic protection current. If this cannot be ensured, the breakpoint shall be bridged by a cable to avoid sparks. The bridge shall be maintained until the parts are rejoined.

Whenever work is carried out on impressed current cathodic protection installations, gas tests shall be conducted to ensure the absence of flammable mixtures. Negative gas test results do not permit the non-observance of other safety precautions described here or in other procedures.

For more details on safety aspects related to cathodic protection, reference is made to BS 7361-1. This contains useful guidance on aspects such as general requirements for transformer rectifiers, voltage gradients over buried groundbeds, danger of electric shock to divers, earth-fault currents on buried structures, hydrogen evolution in closed systems, explosion hazards, and chlorine evolution.

26. ECONOMIC CONSIDERATIONS

26.1 APPLICATION AND ECONOMIC JUSTIFICATION

The decision to install cathodic protection shall be based on the combination of criticality of the structure or pipeline, the design life, environmental issues as well as the corrosivity of the soils and waters. The requirements for cathodic protection are assessed in (3.1)

Wherever possible, cathodic protection should be considered at the design state, as retrofitting cathodic protection is almost invariably more expensive.

From a technical perspective cathodic protection may be optional. In these cases a life cycle cost comparison should be carried out, comparing the capital and operating costs for such protection with the estimated long-term maintenance costs that would be expected if cathodic protection were not applied. This assessment may prove the economic justification of cathodic protection. Maintenance costs will, however, often be difficult to quantify.

26.2 COST OF CATHODIC PROTECTION

The cost of a well-designed cathodic protection system is often only a few percent of the total investment for the installation to be protected. The cost does vary with the complexity of the structure or the facility. For guidance, for long pipelines or tank bottoms it can be around 2 %, for offshore pipelines a little more and for e.g. buried piping or tanks, a figure of 5 % is considered realistic.

27. REFERENCES

In this PTS reference is made to the following publications:

- NOTES: 1. Unless specifically designated by date, the latest issue of each publication shall be used (together with any amendments/supplements/revisions thereof).

**Amended per
Circular 10/04**

PETRONAS STANDARDS

Index to standard drawings PTS 00.00.06.06.

**Amended per
Circular 24/08**

Definition of temperature, pressure and toxicity levels PTS 01.00.01.30.

Design of cathodic protection systems for onshore buried pipelines PTS 30.10.73.31.

Design of cathodic protection systems for offshore pipelines (amendments/supplements to DNV RP B401) PTS 30.10.73.32.

Installation and commissioning of cathodic protection systems. PTS 30.10.73.33.

**Amended per
Circular 48/06**

Pipeline isolating joints (amendments/supplements to MSS SP-75) PTS 31.40.21.31.

Painting and coating of new equipment PTS 30.48.00.31.

Selected construction materials for shell-and-tube heat exchangers PTS 31.21.01.31.

Electrical engineering guidelines PTS 33.64.10.10.

Electromagnetic compatibility (EMC) requirements PTS 33.64.10.33.

Mounded horizontal cylindrical vessels for pressurised storage of LPG at ambient temperature (endorsement of EEMUA publication no 190) PTS 34.51.11.30.

Design of cathodic protection systems for new fixed offshore steel structures (amendments/supplements to DNV RP B401) PTS 37.19.30.30.

Area classification (amendments/supplements to IP 15) PTS 80.00.10.10.

STANDARD DRAWINGS

NOTE: The latest edition of Standard Drawings can be found in PTS 00.00.06.06.

Magnesium and zinc sacrificial anodes for tubulars S 21.072

Steel sacrificial plates in bronze floating heads and channels for tubulars of 350 mm nom. dia. and larger. S 21.073

AMERICAN STANDARDS

Cathodic protection of aboveground petroleum storage tanks API RP 651

Issued by:

*American Petroleum Institute
1220 L Street, Northwest
Washington, D.C. 20005 USA*

Standard specification for cast and wrought galvanic zinc anodes ASTM B 418

Standard test method for half-cell potentials of ASTM C 876

uncoated reinforcing steel in concrete

Standard test method for field measurement of soil resistivity using the Wenner four-electrode method

ASTM G 57

Issued by:

*American Society for Testing and Materials International
100 Barr Harbor Drive
West Conshohocken, PA 19428-2959 USA*

Anodes, sacrificial zinc alloy

MIL-A-18001K

Issued by:

*Superintendent of Documents,
Government Printing Office.
Washington DC 20402 USA*

Mitigation of alternating current and lightning effects on metallic structures and corrosion control systems

NACE RP0177

Application of cathodic protection for external surfaces of steel well casings

NACE RP0186

External cathodic protection of on-grade carbon steel storage tank bottoms

NACE RP0193

Galvanic anode cathodic protection of internal submerged surfaces of steel water storage tanks

NACE RP0196

Corrosion control of underground storage tank systems by cathodic protection

NACE RP0285

Impressed current cathodic protection of reinforcing steel in atmospherically exposed concrete structures

NACE RP0290

Metallurgical and inspection requirements for cast galvanic anodes for offshore applications.

NACE RP0387

Impressed current cathodic protection of internal submerged surfaces of carbon steel water storage tanks

NACE RP0388

Metallurgical and Inspection Requirements for Offshore Pipeline Bracelet Anodes

NACE RP0492

Design, installation, operation and maintenance of impressed current deep groundbeds

NACE RP0572

Internal cathodic protection systems in oil-treating vessels

NACE RP0575

Issued by:

*NACE International
1440 South Creek Drive
Houston TX 77084 USA*

BRITISH STANDARDS

Cathodic protection

BS 7361-1

Issued by:

*British Standards Institute
389 Chiswick High Road
London W4 4AL UK*

DUTCH STANDARDS

Mutual influence of pipelines and high-voltage circuits

NPR 2760

INTERNATIONAL STANDARDS

Semiconductor converters - general requirements and line commutated converters

IEC 60146

Classification of degrees of protection provided by enclosures

IEC 60529

Issued by:

Central Office of the IEC,

3, Rue de Varembe,
CH 1211 Geneva 20 Switzerland

*Copies can also be obtained from national standards
organizations.*

NORWEGIAN STANDARDS

Cathodic Protection Design

DNV RP-B401

*Issued by:
Det Norske Veritas Industri Norge AS
PO Box 300,
N-1322 Høvik, Norway*