Design and operational guidance on cathodic protection of offshore structures, subsea installations and pipelines
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Design and operational guidance on cathodic protection of offshore structures, subsea installations and pipelines
Foreword

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<th>Definition</th>
</tr>
</thead>
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<tr>
<td>$A$</td>
<td>fatigue damage summation failure limit</td>
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<tr>
<td>$A$</td>
<td>area</td>
</tr>
<tr>
<td>$a$</td>
<td>linear dimension, distance</td>
</tr>
<tr>
<td>$b$</td>
<td>linear dimension</td>
</tr>
<tr>
<td>$b_f$</td>
<td>final coating breakdown factor</td>
</tr>
<tr>
<td>$b_m$</td>
<td>mean coating breakdown factor</td>
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<tr>
<td>$C_d$</td>
<td>drag coefficient</td>
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<td>final current density for protection of bare steel</td>
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<tr>
<td>$C_i$</td>
<td>inertia coefficient</td>
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<tr>
<td>$C_{m}$</td>
<td>mean current density ($A/m^2$) for protection of bare steel</td>
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<tr>
<td>$D$</td>
<td>outside diameter of pipeline</td>
</tr>
<tr>
<td>$d$</td>
<td>density of anode material</td>
</tr>
<tr>
<td>$E$</td>
<td>electrochemical potential</td>
</tr>
<tr>
<td>$E_a$</td>
<td>equilibrium anodic potential</td>
</tr>
<tr>
<td>$E_c$</td>
<td>equilibrium cathodic potential</td>
</tr>
<tr>
<td>$E_{corr}$</td>
<td>corrosion potential</td>
</tr>
<tr>
<td>$E_p$</td>
<td>polarised electrochemical potential</td>
</tr>
<tr>
<td>$G$</td>
<td>Electrical conductance of pipeline coating</td>
</tr>
<tr>
<td>$I$</td>
<td>electric current</td>
</tr>
<tr>
<td>$I_{corr}$</td>
<td>corrosion current</td>
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<tr>
<td>$I_f$</td>
<td>final current to be delivered by the cathodic protection system</td>
</tr>
<tr>
<td>$I_{lim}$</td>
<td>limiting current</td>
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<tr>
<td>$I_m$</td>
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<tr>
<td>$I_p$</td>
<td>polarised corrosion current</td>
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<tr>
<td>$J_c$</td>
<td>current density at steel surface</td>
</tr>
<tr>
<td>$K$</td>
<td>stress intensity</td>
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<td>$K_{fc}$</td>
<td>fracture toughness</td>
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</tr>
<tr>
<td>$L$</td>
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<td>$l_a$</td>
<td>anode length</td>
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<td>$l_p$</td>
<td>distance from drain point to which pipe is protected</td>
</tr>
<tr>
<td>$M$</td>
<td>consumption rate of anode material</td>
</tr>
<tr>
<td>$N$</td>
<td>number of fatigue cycles to failure</td>
</tr>
<tr>
<td>$N_1$</td>
<td>number of cycles to failure under constant amplitude cyclic loading</td>
</tr>
<tr>
<td>$P$</td>
<td>periphery of anode</td>
</tr>
<tr>
<td>$R$</td>
<td>ratio of maximum and minimum steel thicknesses</td>
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<td>anode surface potential</td>
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<tr>
<td>$S_c$</td>
<td>cathode surface potential</td>
</tr>
<tr>
<td>$S_i$</td>
<td>anode spacing to meet maximum current requirements</td>
</tr>
<tr>
<td>$S_{th}$</td>
<td>stress range</td>
</tr>
<tr>
<td>$S_M$</td>
<td>anode spacing to meet mean current requirements</td>
</tr>
<tr>
<td>$T$</td>
<td>design life (h)</td>
</tr>
<tr>
<td>$t$</td>
<td>Unconsumed anode thickness</td>
</tr>
</tbody>
</table>

Cathodic protection of offshore structures
u  utilisation factor
\( \bar{u} \)  water particle velocity
\( \dot{\bar{u}} \)  water particle acceleration
V  volume of element
\( V_p \)  potential
\( V_p' \)  potential at point P
\( V_a \)  anode material closed circuit potential
\( V_d \)  pipe potential at drain point
\( V_o \)  open circuit potential of unprotected steel
\( V_p^+ \)  positive limit for adequate pipeline protection
\( V_{th} \)  tension hill potential
W  required net mass of anode material
w  mass per anode
\( x \)  gap between half shells of bracelet anode
\( \bar{Z} \)  arithmetic mean of anode length and width
\( \Delta K_{th} \)  cyclic stress intensity threshold
\( \eta \)  overpotential
\( \rho \)  resistivity
\( \delta \)  density of sea water
Preface

The principles of cathodic protection were clearly understood and concisely expressed by Sir Humphrey Davy as long ago as 1824. At that time, Sir Humphrey was President of the Royal Society, and his attention had been drawn by the Navy Board to the rapid decay of the copper sheathing used as a cladding for the hulls of ships which were constructed of wood and consequently highly susceptible to penetration by "tersedos" (wood borers). In this connection, Volta had discovered, in 1800, a method of generating an electric current by means of a Voltaic Pile, and in 1832-1833 Faraday had put forward the 1st and 2nd laws of electrolysis. Both Volta's and Faraday's discoveries formed the basis for modern electrochemistry.

In his Bakerian lecture of 1806 Davy had advanced the hypothesis that "chemical attractions may be exalted, modified or destroyed by changes in the electrical state of bodies; that substances will only combine when they are in different electrical states; and that by bringing a body naturally positive artificially into a negative state its usual powers of combination are altogether destroyed". This statement summarises concisely the basic principles of cathodic protection.

In this paper to the Royal Society, which was read on 22 January 1824 Davy stated:

"Copper is a metal only weakly positive in the electro-chemical scale; and according to my ideas it would only act upon sea water when in the positive state; and, consequently if it could be rendered slightly negative the corroding action of sea water upon it would be nil".

Davy then points out that this statement would apply irrespective of the purity of the copper, and goes on to consider how it could be effected in practice. "I at first thought of using a Voltaic cell (Volta's original Voltaic pile consisted of alternate discs of copper and zinc separated by pieces of cloth and immersed in diluted sulphuric acid) but considered it hardly applicable in practice". He then tried various combinations of copper coupled to different metals and found that a piece of zinc as large as a pea or the point of a small iron nail was adequate to preserve to 40 or 50 square inches (260 or 320 cm²) of copper, irrespective of its geometrical form.

In this paper to the Royal Society, Davy stated that the Lord Commissioners of the Admiralty had given him permission to use ships of war to ascertain the practical value of his results, and the first ship to be cathodically protected was the HMS Samarang in which iron blocks were used successfully as anodes to protect the copper.

Thus Davy was responsible for establishing the principles of cathodic protection, and he was the first to use sacrificial anodes to protect another metal. He also foresaw the use of electrical power for protection, but his ideas at that time were in advance of technology.
Sacrificial anodes for protecting copper sheathing were used for only a relatively short time, and although the precise reason is not known it has to be remembered that it was about the time when the wooden hulls of warships were being replaced by wrought iron. Another view is that in preventing the corrosion of copper it also weakened its anti-fouling properties! Cathodic protection then became dormant for about 100 years until the early 1930s, when the oil companies in Texas used an impressed current system and scrap iron anodes to protect underground pipelines. Today, it is quite usual for the time interval between a discovery and its practical application to be only 10 to 20 years.

Control of the corrosion of North Sea offshore platforms by cathodic protection has resulted in the rejection of many well established principles based on experience gained in the protection of other structures. Thus it has been accepted that the most economical method of using it was in conjunction with a protective coating, and that it was more economical to use sacrificial anodes for small structures and impressed current for large.

To assess the position, the Cathodic Protection Study Group carried out by means of questionnaire a survey of the experience gained by the operators using sacrificial anodes (zinc or aluminium), impressed current or hybrid systems. All of them gave reasonable protection with the sacrificial anode system, which was the most popular, proving to be the most satisfactory. In the case of the impressed current system, the major problems were mechanical and electrical rather than inadequate current distribution, in particular, failure or operation resulting from disbonding of the cables. Only one operator used a paint coating, and it appeared that protection of the bare structure did not result in excessive consumption of anode material.

Over the years, and since the more widespread use of cathodic protection in the early 1930s for protecting underground pipes, there have been many developments in anode design and construction. In the case of impressed current systems, the use of graphite as a conducting anode material has declined with the development of composite anodes in which platinum is used economically in the form of a thin coating on either titanium or niobium.

As early as 1920, G Baum patented an anode (US Patent 1,477,009) consisting of tantalum partly coated with a thin layer of platinum for the anodic oxidation of sulphate to persulphate. In fact, many of the anodes used for impressed current cathodic protection originate from those used in previously in electrolytic oxidation processes (e.g. lead dioxide, magnetite, oxides of the platinum metals, etc).

In the case of sacrificial anodes, emphasis has been on the formulation of zinc, aluminium and magnesium alloys which give the most negative potential and maximum anode efficiency.
Although there have been a number of improvements in the technology of using cathodic protection, it needs to be emphasised that this also applies to other methods of corrosion control. An example is the Thames Flood Barrier, in which it had been envisaged that the conventional methods of coatings and cathodic protection would be used for all interior and exterior surfaces of steel in contact with Thames water. However, in the case of the rising sector gate, the use of anodes was precluded because of the very small distance of separation between the steel gate and the concrete sill which is about 225 mm where the gate is supported by the gate arm, decreasing to about only 100 mm at the centre.

For this reason, cathodic protection could not be used, and protection had to be confined to a thick coal-tar epoxy coating which was formulated to resist the highly abrasive conditions which occur by Thames water containing silt rushing through the gap when the gate is raised into the defence position. The barrier has been in service for about 5 years, and it is understood that has been very little deterioration in the steelwork.

It is made clear from the title that this guide is intended primarily for offshore structures, subsea installations and pipelines, and it is probably the most comprehensive single publication dealing with these topics. However, it is apparent to me after reading the page proofs that its scope is very wide indeed, and that it should be of value to all those who are concerned with the protection of steel structures in marine environments.

L.L. Shreir

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1. Introduction

1.1 BACKGROUND

The project was undertaken in response to an initiative by the Department of Energy to build on the work of their Cathodic Protection Study Group (CPSG). That Group was set up by the Department to review the practice of cathodic protection on offshore oil and gas installations in UK waters, to consider the adequacy of existing standards and rules, to identify requirements for further information, and to advise on action required.

The CPSG sat from November 1979 until April 1982. It circulated an extensive questionnaire to all major offshore operators. Its conclusions reflected both the practices adopted and the degree of corrosion actually being experienced at that time.

A recommendation of the CPSG called for the production of a "comprehensive design and operation manual for cathodic protection systems for the North Sea". These guidelines are aimed at meeting that recommendation.

The guidelines were produced by a collaboration between specialist authors and members of the Project Steering Group. They included several who had participated in the original CPSG, others in possession of recent operational experience of CP in the North Sea, and potential users.

The objective is to provide, in a single, widely available document, practical guidance to designers and operational staff on the design, installation and operation of effective cathodic protection systems offshore. The guidelines are intended to be of use to engineers who are not CP specialists but who need familiarisation, also to be available as a source book for specialists.

1.2 SCOPE OF THE GUIDELINES AND SUGGESTIONS FOR THEIR USE

Three needs are answered by these guidelines.

First, they provide necessary background material for any engineer who encounters cathodic protection of offshore structures either directly or indirectly. Section 2 provides the link between the principles of corrosion and with the practical aspects. Section 9 provides guidance on the commissioning, operation, monitoring and surveying of CP systems.

Second, guidance is given to members of design teams through every step of the design process. All Sections refer to relevant documents, but Section 11 lists and comments on the principal documents containing current legislation, standards and guidance. Section 6 restates the fundamental design objective and discusses factors affecting the choice of design criteria. Section 7 describes the properties of concrete, leading to a discussion on the special features which characterise the electrochemical corrosion of steel embedded in concrete. The experience of nine operators of
concrete structures is presented, particularly on how CP system performance has compared with the original design. Section 8 reviews design requirements for the cathodic protection of subsea installation and pipelines. Section 10 discusses the effect of CP on the design of steel structures. Section 12 presents a review of existing CP design, operation and monitoring practice on North Sea and other UK waters oil and gas fixed steel platforms, utilising the results of a questionnaire updating the data collected originally by the CPSG.

Third, various aspects are addressed in detail. Section 3 covers the effects of CP on mechanical properties such as corrosion fatigue and hydrogen embrittlement. Section 4 covers organic coatings. Section 5 covers the calculation and modelling for the design of CP systems.