

Managing Cathodic Protection Life Extension for Offshore Pipelines

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ABSTRACT

The exploitation of offshore hydrocarbon reserves in the second half of the twentieth century required the installation of many thousands of kilometres of subsea pipelines. Typically, these pipelines were installed with operational lives of 20 to 30 years; and were provided with sacrificial anode cathodic protection (CP) systems designed for those lives.

Subsequently, developments in extending reservoir lives, together with the ability to tie-in marginal fields, means that many pipelines must operate beyond their original design lives. This prompts the re-evaluation of the remaining lives of the original anodes and, where appropriate, the retrofitting of supplemental CP.

This paper examines the process of evaluating the residual lives of existing anodes, and developing retrofit CP designs. In particular, it challenges the requirement of many CP design codes to polarize pipelines to a target potential of -900 mV (vs Ag|AgCl|seawater). It emerges that, relaxing the protection criterion from -900 mV to -800 mV would have a very considerable impact on the decision whether or not to retrofit CP; and on the cost of any subsequent retrofit system.

Keywords

Submarine pipelines, service life extension, protection potential, cathodic protection system evaluation, potential criteria, potential evaluation, retrofit design.

INTRODUCTION

The Problem

There is an ageing population of hydrocarbon transportation pipelines on the seabed around the world. Many of these pipelines are approaching, or have already exceeded, the ends of their original design lives. However, extended production lives means that they need to remain operational for many years. Furthermore, the majority of these pipelines have been designed without an external corrosion allowance. Their external corrosion control relies on the performance of the pipeline coating and the cathodic protection (CP) system.

To guarantee the integrity of its pipelines, an operator has to evaluate the status of the existing CP and, if necessary, install supplementary protection. Unfortunately, this process is complicated the fact that many of these pipelines are buried in the seabed; thus preventing direct assessment of the degree of anode consumption.

Reasons for Optimism

Historically, marine pipeline CP systems have employed zinc or aluminium alloy sacrificial bracelet anodes installed at regular spacings along the line. The mass, dimension and spacing of these anodes were determined by the information in the codes and standards current at the time.

Generally speaking, these codes evolved more by committee consensus than by evidence. This inevitably imparted conservatism. The end result is that the majority of pipeline CP

systems were “over-designed; and, therefore, more costly than needed. However, that has given the benefit that many pipeline CP systems, now nominally at the end of their design lives, still retain redundant anode capacity.

Pipeline operators can now benefit from that redundant capacity, but only if they can assess its magnitude.

ASSESSMENT

Survey Limitations

Assessing the condition of the bracelet anodes on a buried offshore pipeline requires overcoming several uncertainties.

1. The obvious one is that the anodes cannot be seen, so it is not possible to make a visual estimation of their consumption. Even if they were visible, experience suggests that evaluating anode depletion from images taken during dive surveys is far from precise.
2. There are no instrumental techniques available for assessing anode consumption. Various, remote survey methods are used to assess the level of polarization of the pipeline; and to detect electrochemical activity of the anodes. However, these survey methods tell us nothing about the remaining anode mass.
3. Visual assessment of unburied anodes near the pipeline terminations is also unreliable. The dissolution behaviour of anodes exposed to open seawater differs markedly from that of buried anodes. Moreover, most pipeline CP designs conservatively double-up the anode provision near the ends of the line.

Design Re-evaluation

A method of assessment that this author has used on behalf of a major operator involves re-evaluating the original design on the basis of current CP codes.

Thus, whereas the original design exercise determined the sacrificial anode provision needed to achieve (say) a thirty year life, we now back-calculate the life of that as-installed anode provision, assuming the present-day code predictions for coating breakdown and anode electrochemical parameters.

It emerges that the results of such back-calculation depend critically on the assigned protection potential.

PROTECTION POTENTIAL

Historical Background

Although cathodic protection originated with Davy’s pioneering work in the 1820’s [1], it languished in obscurity until the 1920’s when the application of forced current drainage was found to protect onshore welded petroleum pipelines in the USA. In 1933 Kuhn [2], having worked in the field for a decade, proposed -850 mV (measured against the Cu|CuSO₄ (satd.) half-cell) as the optimum potential for the protection of onshore steel pipelines. This corresponds to -800 mV measured against a Ag|AgCl|seawater reference. Henceforth, this paper uses only the latter reference scale.

Eighteen years later, Schwerdfeger and Dorman [3] endorsed Kuhn’s view. However, they pointed out that Kuhn’s “optimum” potential had, in the interim, become adopted as the least

negative potential. There has been no reason to challenge that value since that time; either onshore or in seawater¹.

The Codes

The first internationally recognized standard on CP was the NACE Recommended Practice RP0169 [5] published in 1969. Although its title includes “immersed” pipelines, its focus is onshore. That document originally gave five criteria for achieving full cathodic protection:

- two based on achieving potentials of -800 mV
- two based on potential swings of -100 mV and -300 mV
- one based on the inflection in an E-Log I polarization curve.

Over the various revisions of the code the -300 mV swing and the E-log I criteria were dropped, and the requirement to achieve -800 mV clarified to emphasise that the potential had to be a true polarised potential.

The early version of RP 0169 did not include any requirement for anaerobic environments such as, for example, seabed mud. However, the 2007 version of the document, now issued as a Standard Practice (SP0169), stated that the -800 mV criterion might be inadequate... “*in some situations, such as the presence of sulphides, bacteria, elevated temperatures...*”. It was not until the 2013 edition that a requirement for a further 100 mV of polarization was advised “*...where MIC has been identified or is probable.*”

The first internationally recognized code to require the additional 100 mV polarization for steel in anaerobic environments, where sulfate reducing bacteria (SRB) might be active, was British Standard Code of Practice CP1021 [6]. This was issued in 1973; albeit that the drafting committee started work on it prior to the issue of the 1969 NACE recommended practice.

Following the issue of CP1021, most other international marine CP standards offered the same guidelines for the minimum level of polarization that needs to be achieved to protect steel:

- -800 mV is required in open (aerated) seawater, and
- -900 mV for anaerobic environments where there is a perceived threat of microbiologically influenced corrosion (MIC) due to the activity of SRB.

Although the -800 mV figure can be traced back to Kuhn, the origin of the value of -900 mV for anaerobic environments such as seabed mud is less clear. It would appear that following its introduction by the BSI committee into CP1021, it was adopted unchallenged by subsequent international standards. A notable exception to this is the most recent version DNV RP B401 [8]. This advises a *design* potential -800 mV, even in anaerobic seabed mud.

¹ Up to the late 1960s, the British Royal Navy accepted a less conservative criterion of -750 mV [11].

THE -900 mV CRITERION

Need for Review

That there has been little challenge to the -900 mV criterion is understandable. In a code-driven industry, no career advantage accrues from advocating a less conservative approach to protection. Furthermore, relaxing the target protection potential gives rise to the philosophical conundrum of having to prove a negative. Offshore pipelines, especially in seabed mud, spend most of their lives at near the anode potential (typically more negative than -900 mV). Experience confirms that they do not suffer external corrosion. There is scant experience of their behaviour in mud at -800 mV; so there is no evidential basis for averring that -800 mV would confer adequate protection.

Previously, the only practical impact of the -900 mV criterion has been that it increased the number of, and reduced the spacing between, the anodes. However, since anodes were attached to the pipe in the yard or on the lay-barge, this would only have exerted a marginal effect on the overall pipeline project cost.

As we will see below, when it comes to offshore CP retrofits, the financial cost of adopting -900 mV instead of -800 mV is profound. For this reason, the present author has recently reviewed the -900 mV criterion in considerable detail. For details of that review the reader is referred to the original publication [4]. That review examines its experimental, thermodynamic and electrode kinetic basis. The following is a brief summary.

Laboratory Work

As noted, the requirement to provide an additional 100 mV polarization for environments such as seabed mud seems to have entered the English language codes in the 1973 BS CP1021. With few exceptions, it has remained in those codes since. Its inclusion appears to have relied on earlier work by Wormwell and Farrer [12] in 1952, Horváth & Novák [13] in 1964, and Booth & Tiller [14] in 1968. Subsequently, papers by Fischer [18] in 1981 and by Barlo and Berry [19] in 1984 have endorsed the -900 mV criterion.

However, after careful and critical examination, the review [4] was forced to conclude that these seminal publication do not actually demonstrate that -900 mV is required to protect against MIC.

Conversely, those publications could not be interpreted as confirming that -800 mV would be sufficient. The result is the classical philosophic conundrum of trying to prove a negative: an absence of corrosion in the absence of polarizing to -900 mV. The review of published field and laboratory CP test data does not permit us to summarily over-rule the codes.

Thermodynamics

The early theories of cathodic protection (see [15] for reviews) considered that it would provide protection if the potential was lowered to the equilibrium potential of the iron electrode. At that point, the anodic corrosion reaction:



could not proceed. Iron, and by inference steel, would be *immune* to corrosion.

In principle this view provides a straightforward way of determining the appropriate value for the protection potential. However, as demonstrated [4], strict application of thermodynamics leads us to an estimate of a protection potential for iron in water that is slightly more negative

than -1000 mV. This contravenes the practical experience that -800 mV suffices for steel in open seawater.

As an alternative to offering a thermodynamic explanation of CP in terms of immunity, there is a case to be made for CP leading of *passivity*. This was suggested by Ashworth [16] and followed by, amongst others, Leeds and Cottis [17] who also considered the importance of surface films formed under cathodic polarization. Generally speaking, depending on the composition of the test solution, and the cathodic potential, studies of this type show:

- films, including iron oxides, form on the metal surface, **and**
- a reduction in corrosion rate under applied cathodic polarization.

It is, therefore, tempting to interpret such experiments as indicating that the steel has, at least partially, passivated. However, it is also very important not to confuse correlation with causation. The fact that iron oxides are formed on steel does not necessarily mean that the steel is passive. After all: iron oxides are formed on freely corroding steel.

Our reading of the literature has not found any evidence that steel surfaces under CP exhibit the electrochemical characteristics of passivity.

In short: we cannot use straightforward thermodynamic considerations as a basis for setting the protection potential. Thermodynamics tells us what can and cannot happen. However, corrosion of steel can and does occur. The only interest of practical concern is how quickly, or how slowly, this occurs. Thermodynamics remains silent on this.

Electrode kinetics

The electrode kinetic interpretation of CP has, at its heart, the mixed potential theory of corrosion as developed by U.R Evans. Evans himself applied this theory to CP [15], and others have followed [20]-[23]. If this interpretation is accepted, then it follows that the nett rate of anodic dissolution (i.e. corrosion) of the steel at any given value of potential depends solely on the kinetics of the anodic reaction:



It is not contested that the rate of this reaction follows Tafel like behaviour. In other words there is a logarithmic relationship between the rate of the reaction and shift in potential away from the equilibrium potential (termed the “overpotential”). This is illustrated in Figure 1. Furthermore, the slope of the Tafel plot for this reaction is known to be very insensitive to the nature of the electrolyte. Baboian [25] has published a figure of 0.060 V/decade for steel in 0.1N Na₂SO₄. There is no reason to expect this figure to be notably different if the environment were seawater, or seabed sediments.

The current on the abscissa of Figure 1 is related directly to the rate of metal loss by Faradays Laws of Electrochemical Equivalence. This means the Tafel plot is telling us that: for every 60 mV negative (cathodic) shift in potential the corrosion rate of steel reduces by a factor of ten.

This does not mean that we can translate a potential measurement directly into a corrosion rate. Nevertheless, this is not a practical problem. As a matter of experience steel corroding in aerated seawater adopts a steady state potential in the region of -0.65 V. There is also a considerable body of marine test data [24] that tells us that, in this condition, the steel is corroding at a rate of approximately 0.1 mm/year.

On the basis that the iron dissolution reaction follows anodic Tafel behaviour, we can offer ball-park estimates of the corrosion rate as a function of the level of cathodic polarization. These are set out in Table 1.

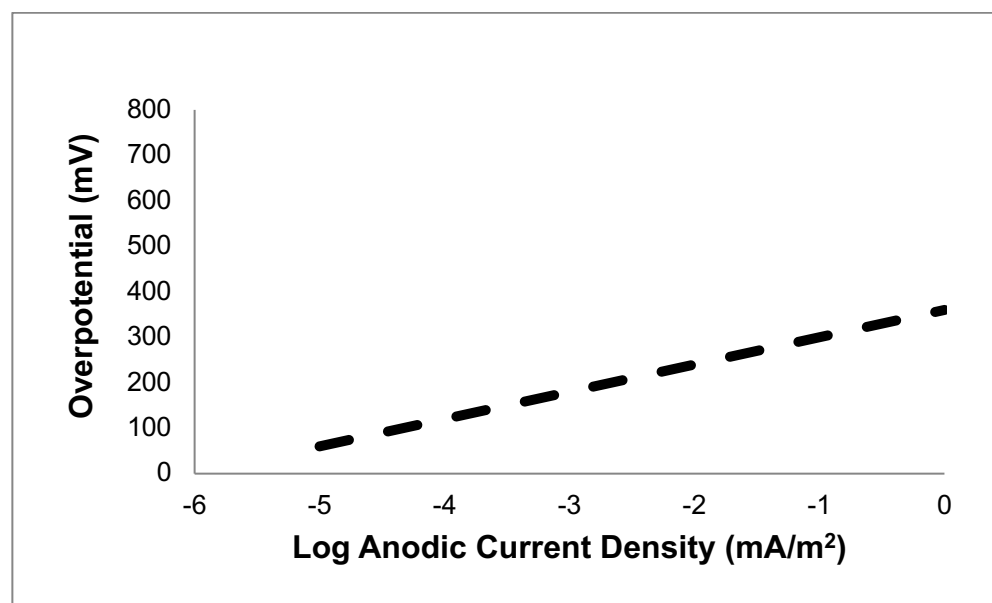


Figure 1 Schematic Tafel Behaviour for $\text{Fe} \rightarrow \text{Fe}^{2+} + 2\text{e}^-$

Potential Ag AgCl seawater (mV)	Reduction in Anodic Overpotential (mV)	'Ball-Park' Corrosion Rate		Remarks
		(A/m²)	(mm/year)	
-650	zero	0.090	0.1	Free corrosion
-710	60	0.009	0.01	'Acceptable' corrosion rate
-800	150	0.000 3	<0.001	Code compliance (aerated seawater)
-900	250	0.000 006	<0.000 01	Code compliance (seabed sediments)

Table 1 Ball-Park Corrosion Rate of Steel as a Function of Potential

The important message from electrode kinetics is that the nature of the environment, including the activity or otherwise of SRB, does not matter in the context of determining the protection potential.

IMPLICATIONS FOR CP ASSESSMENT

Bracelet anode designs for most pipeline CP systems have employed an excessive anode mass. This has been necessitated by the need to make a castable anode with sufficient surface area to deliver the required instantaneous current output at the end of the design life.

Thus, when re-evaluating original pipeline CP designs to assess whether retrofits are needed, the estimated remaining mass of anode turns out rarely to be a problem.

On the other hand, the increasing current demand placed on the anode, according to the coating breakdown predictions, does become life-limiting.

This is illustrated in Figure 2. It illustrates the outcome of a 1980 CP design re-assessed in accordance with the 2012 ISO standard [7]. The graph shows the progressive increase in current required from the anode from 1980 onwards. The kink in the (red) graph corresponds to the point at which the field joint coatings are assumed to have been effectively lost, but the factory-applied bitumen/concrete coating remains in place, and only degrading slowly.

The horizontal dotted line at 0.16 A shows the maximum current that could be delivered from an individual anode on the basis of a pipeline polarized to -900 mV (as required by the ISO standard). This implies that the anodes will have failed to fully protect the lines at some point at some point in the mid-1990s.

Conversely, the solid horizontal line at 0.47 A shows the maximum current that could be delivered from an individual anode on the basis of a pipeline polarized to -800 mV (as suggested in this paper). This shows that, providing the -800 mV criterion is adopted, the anodes will continue to protect the line for the foreseeable future.

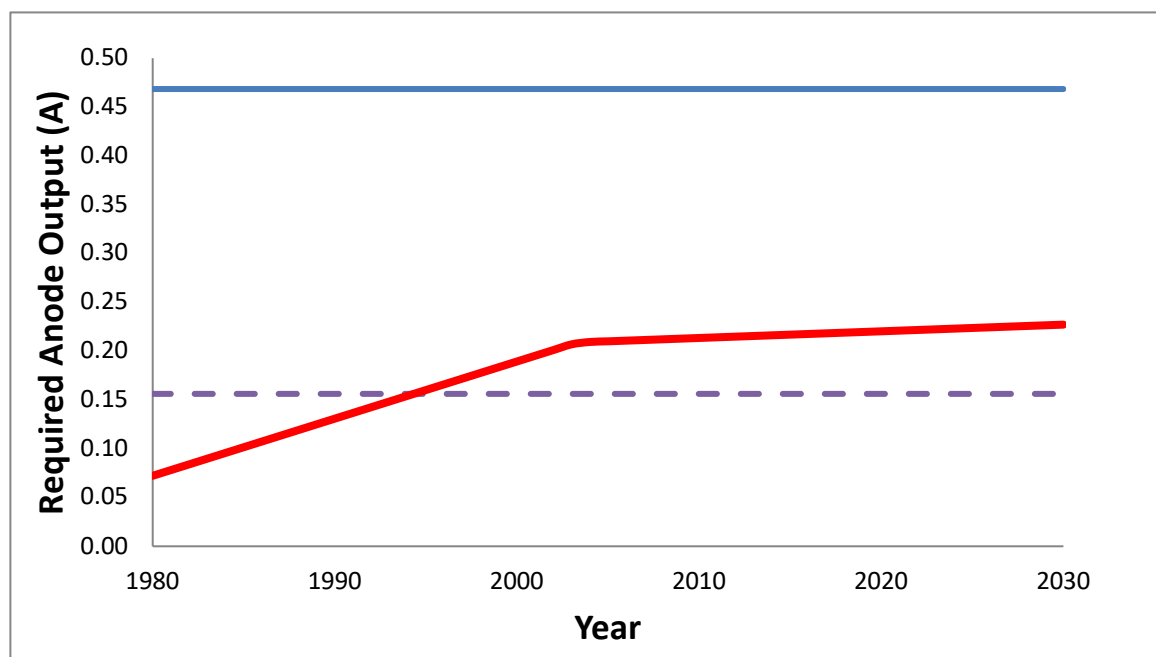


Figure 2 Notional Output of 0.905 m long Al-Zn-In bracelet anode on 30" pipeline

IMPLICATIONS FOR CP RETROFIT DESIGN

Retrofit CP for offshore pipelines is usually achieved by installing anode sleds on the seabed; and making sub-sea cable connections to the pipeline. Offshore installation work is expensive, so there is an incentive to minimize the number of retrofit sleds needed to protect a pipeline. In other words, the design intention is to maximize the spacing between sleds.

There is usually little difficulty in providing ample anode mass on a sled; nor it too difficult to design for an adequate instantaneous current output.

The limiting factor in the designs is the attenuation of potential along the line. There are a number of ways of estimating the attenuation of potential along a pipeline. In the case of offshore lines methodologies are given in [7] and [9]. However, for our purposes it is convenient to use a re-arrangement of the formula published by Uhlig [10].

$$\Delta E_{dp} = \Delta E_{min} \cosh \left\{ \sqrt{\frac{R_L}{R_C}} \frac{L}{2} \right\}$$

where:

- L/2 = protected length of line**
- ΔE_{dp} = potential shift at drain point**
- ΔE_{min} = potential shift at section end**
- R_L = pipe wall resistance/unit length**
- R_C = coating resistance . unit length**

ΔE_{dp} is fixed by the operating potential of the anodes on the sled. We may assume that, in the absence of CP, the steel pipeline would normally be corroding at about -0.65 V. Sled-mounted retrofit anodes installed on a pipeline are often buried to avoid being snagged by trawlers. In the buried condition, they will typically operate at -0.95 V [8]; so ΔE_{dp} is about -0.3 V.

The end of the protected section is reached at a distance (L/2) from the anode sled where the pipeline potential is at the least negative permitted target potential. If the target potential is -0.9 V then ΔE_{min} is -0.25 V. This means that the maximum permitted potential attenuation along the line would be -0.25 V – (-0.3 V) = 0.05 V. However, if the target potential is relaxed to -0.8 V then the maximum permitted attenuation increases to 0.15 V.

The impact of this is seen in the Figure 3. This is an example of a retrofit CP design exercise for a pipeline buried in seabed sediments; with ΔE_{min} set at -0.25 V (blue line) and 0.15 V (red line). R_L is calculated from the known cross-sectional area of the pipe wall and the specific resistivity of steel. R_C assumes that the polarization resistance at any bare steel exposed by coating breakdown is 1 Ωm^2 [26]. As can be seen, relaxing the required protection potential in seabed mud from -900 mV to -800 mV effectively doubles the permitted spacing between the retrofit anode sleds.

CONCLUSIONS

The requirement in most cathodic protection design codes to set a protection potential 100 mV more negative in anaerobic environments emerged in 1973 with the publication of BS Code of Practice 1021. It seems that the requirement first arose because of a plausible, but incorrect, perception that a more negative potential was required for a more aggressive corrosion threat. Once this requirement had entered one code, it was reproduced in others; and has remained largely unchallenged since.

However, a critical examination of the literature underpinning the original adoption of this more negative protection potential has failed to find a convincing case. Attempts to justify the

-900 mV criterion for anaerobic environments on the basis of thermodynamic principles fails; as does the corresponding attempt to justify -800 mV for aerobic environments.

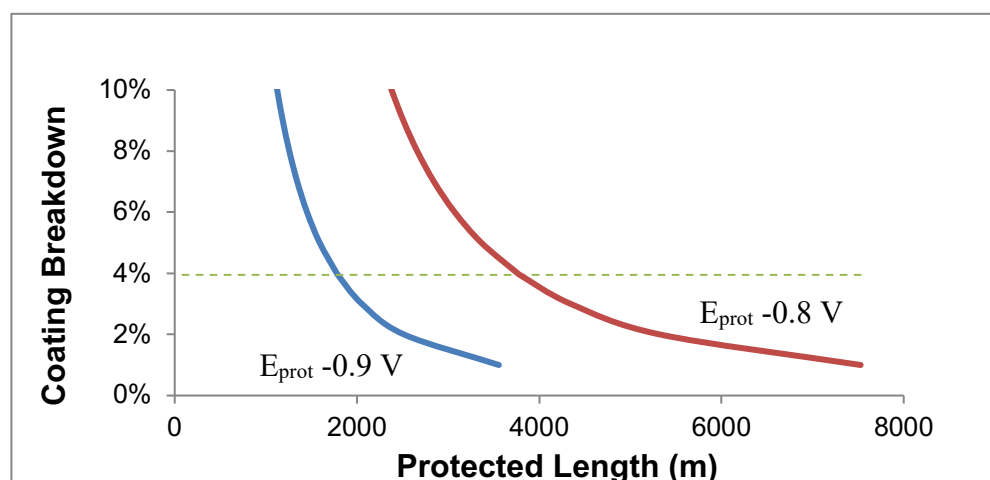


Figure 3 Protected lengths for 30" 16.7 mm WT line protected by Al-alloy anode sled.

It is only when CP is viewed on the basis of electrode kinetics, does it emerge that -800 mV is appropriate. Furthermore, because the anodic Tafel slope for the iron dissolution reaction is essentially independent of the cathodic corrosion processes, this means that -800 mV is also appropriate for anaerobic conditions. This holds even if there is a threat of MIC.

The benefit in relaxing the -900 mV protection criterion for steel in anaerobic environments to -800 mV would be a considerable saving in the future costs of retrofit CP systems for buried offshore pipelines.

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