

# Subsea CP - Electrochemistry Meets Engineering

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## INTRODUCTION

In January 1824 Sir Humphrey Davy stood before members of The Royal Society to deliver the results of his investigations into preventing the corrosion of copper in seawater. He introduced his talk [1] by informing his audience that his findings ... “promise to illustrate some obscure parts of electro-chemical science”. He advanced the crucial proposition that, because ...”copper is a metal only weakly positive in the electrochemical scale....if it could be rendered slightly negative, the corroding action of seawater upon it would be null...”. This led him to the insightful view that ... “a very feeble chemical reaction would be destroyed by a very feeble electrical force”.

He then reported a series of experiments, carried out with the assistance of Michael Faraday, which demonstrated the effectiveness of small lumps of zinc in protecting both copper and iron in seawater. That evening can reasonably be regarded as witnessing the birth of cathodic protection (CP). Even so, at no point did Davy use the words “anode” or “cathode”; nor could he. The words themselves were not coined until 1831. In addition, the word “current”, which was in use to express the movement of electrical force, is also absent from his paper.

Davy, a natural philosopher, would have never referred to himself as an “electrochemist”. The coining of that word also lay in the future. Nevertheless, based on those and subsequent experiments, he was able to design a CP system which effectively controlled the corrosion of copper sheathing on the hull of HMS Samarang. Moreover, he did so even though the elucidation of most of the principles of electrochemistry, and the development of its jargon, lay in a future he was not destined to see.

The lesson is simple: although CP is an electrochemical technique, the CP system designer does not need to be familiar with electrochemistry. In many instances, it is simple enough to conjure up a fit-for-purpose design without any appreciation of the underpinning science. That this is so bears testament to the general robustness to the technique itself, and to the usability of industry guideline documents. The latter, albeit unintentionally, facilitate a “cook-book” approach to CP; frequently carried out by individuals whose flare is more for Excel® or MathCad® software than for electrochemistry.

Indeed, there is at least one major oil company which dispenses altogether with the nuisance of design for its CP systems. For pipelines, the contractor simply installs stock anodes and prescribed intervals along the line. Offshore platforms are protected by installing the appropriate number of standard design impressed current anode sleds.

Nevertheless, as this paper seeks to argue, the knowledge of some electrochemistry can come in quite useful from time to time.

## GUIDELINES

The references at the end of this paper include design codes [12 - 17] which are frequently cited in CP design reports and specifications. Of these, DNV RP B401 [12] is arguably the most widely used. For brevity, we shall simply refer to it as “DNV” in this paper. Very often, an offshore CP design specification does little more than call for the protection system to be designed in accordance with DNV. This is not unreasonable. A numerate individual can simply execute the steps set out in section 7 of DNV to produce a fit-for-purpose design. No comprehension of the electrochemical processes involved is actually required.

A typical code is a shorter document than any CP text book so, inevitably, the codes are obliged to omit material. Much of the subject matter left out relates to the electrochemical theory underpinning the subject. As noted, for most applications the omission of the theory is unimportant. Indeed, it can be argued that it is beneficial since it makes the documents more accessible to the non-specialist user. However, the purpose of this paper is to examine some elements of what the codes do not cover, and to consider the possible implications of these omissions.

## POTENTIAL

### What exactly do we mean by potential?

When working with the codes, we can regard “potential” simply as a voltage. However, an engineer with a good recollection of school-day physics will recall that when we measure voltages, we are actually measuring potential *differences*. In electrochemical systems, this begs the question: potential difference between what?

The simple, and not incorrect, answer is that the electrode potential (E) is difference between the electrical potential in the metal ( $\phi_m$ ) and the electrical potential in the solution adjacent to its surface ( $\phi_s$ ):

$$E = \phi_m - \phi_s$$

Apart from being a bit of a mouthful, this definition introduces the philosophical conundrum that we cannot actually measure  $\phi_m$ ,  $\phi_s$  or E. Nevertheless, we get around this by arbitrarily defining a primary standard, namely the standard hydrogen half-cell, against which all potentials can be referenced. Subsequently, electrochemists have conjured up secondary reference half-cells, which have a fixed offset from the primary, and which are convenient to use in either the field or the laboratory. The Ag|AgCl|seawater half-cell, to which all potentials in this paper are referred, is one of many examples of a secondary reference.

It turns out that the rate at which many, but not all, electrochemical reactions take place on a metal surface depends on the value of E. Crucially, as Davy discovered, making E more negative leads to protection. However, as noted, E depends  $\phi_m$  and  $\phi_s$ . Thus, making E more negative can be achieved by making  $\phi_m$  more negative; by making  $\phi_s$  more positive; or, in reality, by a combination of the two. For most offshore CP applications it is immaterial how the engineer actually envisages the manner in which the change in potential is brought about. Indeed, the point is moot, given that we can never actually know the individual values of  $\phi_m$  or  $\phi_s$ .

## Cathode Potential

Although the word “potential” is firmly established in the CP lexicon, the codes are less than rigorous in its treatment. For example, an engineer aware of the need for code compliance, has little difficulty seeing that if the code calls for a potential of -800 mV then a measurement of -795 mV constitutes a breach. This cannot be denied; but the more relevant question is: does it matter?

CP does not provide a simple, instantaneous “on-off” switch for corrosion. When CP is first applied the potential of the steel moves, over a period of time, to more negative values. In the parlance of the electrochemist: the steel polarizes cathodically. For example, if we measure the potential of steel which has been freely corroding in open seawater for a day or two, we usually find that it drifts about within the range -600 to -650 mV. In addition, there is a large body of evidence [2 - 8] which tells us that the steel is corroding in the region of 0.1 mm/year whilst it exhibits this potential.

In corrosion control, our prime objective is to reduce the rate of the corrosion half-reaction:



This half-reaction is electrochemical in nature. Since two electrons are released into the metal for each iron atom corroded away from the surface, we can consider the corrosion as a rate of flow of electrons or, in other words, a current. If we now apply CP to the steel we make its potential more negative, and this has the effect of reducing the corrosion current; and hence the corrosion rate. It follows that there must be a relationship between the amount the potential changes (or, in electrochemical parlance, the “polarization”) and the corrosion current. Importantly, however, electrochemical systems do not obey Ohm’s law. In the case of the anodic half-reaction for the dissolution of iron, the current changes logarithmically with changes in the potential; at least in the potential ranges of interest to CP. This is a general feature for electrochemical reactions described as being under activation control. Such behaviour is often described as following a Tafel relationship.

The implications of this are illustrated in Table 1. We see that even applying only a modest potential shift (about 60 mV) to a corroding steel structure reduces the corrosion rate by an order of magnitude. For most offshore engineering endeavours this is probably all the protection we need. If we polarize by a further ~60 mV then we reduce the corrosion rate by another order of magnitude. The rate is now only ~1% of the unpolarized value. The time needed to corrode a 1 mm corrosion allowance would be of the order of a century.

Cathodic Polarization	Corrosion Rate (typical) mm/year	Life of a 1 mm Corrosion Allowance (years)
None (Freely Corroding)	0.05 to 0.15	7 – 20
-60 mV	0.005 to 0.015	70 – 200
-120 mV	0.000 5 to 0.001 5	700 – 2000
-180 mV	0.000 05 to 0.000 15	7000 – 20000

**Table 1 Effect of Polarization on the Corrosion Rate of Steel in Seawater**

What this means is that a failure to achieve a target potential of -800 mV need not prompt precipitous remedial action. Judgement has to be exercised over the interpretation of the result. It may be indicative of a CP system that is beginning to come to the end of its life, in which case retrofitting additional anode capacity might need to be considered to extend the life of the structure. On the other hand, a few isolated “out-of-compliance” readings might simply reflect the impracticality of achieving uniform potentials on structures of complex geometry; but do not necessarily impact on the integrity of the structure.

Consideration of the Tafel type behaviour of the iron dissolution reaction leads to another intriguing conclusion in respect of applying the CP design guidelines. The case in point is the relevant design protection potential for steel in seabed mud. Prior to the early 1990s the situation was quite straightforward for the CP designer. Contemporary codes [9 - 11] called for a design potential of -900 mV. The reason for this is that sulphate reducing bacteria (SRB), which are known to accelerate the corrosion of carbon steel, can metabolize in anaerobic environments such as seabed mud. This corrosion threat prompted more negative design protection potentials. For example, Morgan [18] tells us that ... *in anaerobic soils or waters that contain sulphate reducing bacteria steel is found to be protected when its potential is depressed a further 100 mV...*(i.e. to -900 mV).

Presently, however, the situation is less clear cut. For example, the current version of DNV states that it *has been argued that a design protective potential of -900 mV should apply in anaerobic environments*, including typical seawater sediments. Despite this, it advises a design potential of -800 mV. Conversely, the current ISO standard for the CP of offshore pipelines [16] firmly recommends -900 mV, as does the current EN standard [17].

This apparent discrepancy between recognised codes presents the CP design engineer with a problem when it comes to designing a system. The key to resolving this lies with the application of a little electrochemistry. SRB can be associated with some very high corrosion rates (possibly several mm per year). Nevertheless, the mechanism of the corrosion remains electrochemical. It is not biological. The changes that the micro-organisms make to the chemical environment at the metal surface stimulate the cathodic corrosion half-reaction, and hence the corrosion rate. This is important, because it means that the Tafel relationship governing the anodic iron dissolution reaction still holds. Electrochemistry tells us that, if -800 mV assures protection in aerated seawater, then it will also do so in seabed mud. Thus, Morgan correctly says that steel is protected at -900 mV in the presence of SRB; but what he does not actually tell us is whether or not it would also be protected at -800 mV. Electrochemistry tells us that it would.

### **Anode Potential**

The codes discuss the potentials, or more usually the range of potentials, to which we should polarise the metal we wish to protect. They are somewhat less forthcoming about the potentials of sacrificial anodes. Typically we are given a value for the operating potential of the anode, and we then use this to calculate its current output when it is coupled to the cathode.

It is implicit in the guidelines that we can regard the electrochemistry of the anode as having essentially zero output resistance. In other words, we can draw as much current as we wish from its surface without materially affecting its potential. Within the limits of most CP designs, this is a reasonable approximation because the dissolution kinetics of a well formulated

anode alloy in seawater are very rapid. For most offshore CP applications, it then becomes a reasonable design approach to estimate the anode output on the basis of its resistance to remote earth.

This approach is valid providing the potential in the solution ( $\phi_s$ ) adjacent to the anode does not become noticeably more negative. However, this is just the situation which can arise when one anode is placed near another. In effect, the current output from an adjacent anode creates an electrical field which influences the value of  $\phi_s$ . This in turn effectively reduces the electrode potential difference between the anode and the seawater; and so suppresses its output. The effect is, of course, mutual. Each of the two adjacent anodes influence each other in the same way. The situation is exacerbated if more anodes are placed in close proximity to each other.

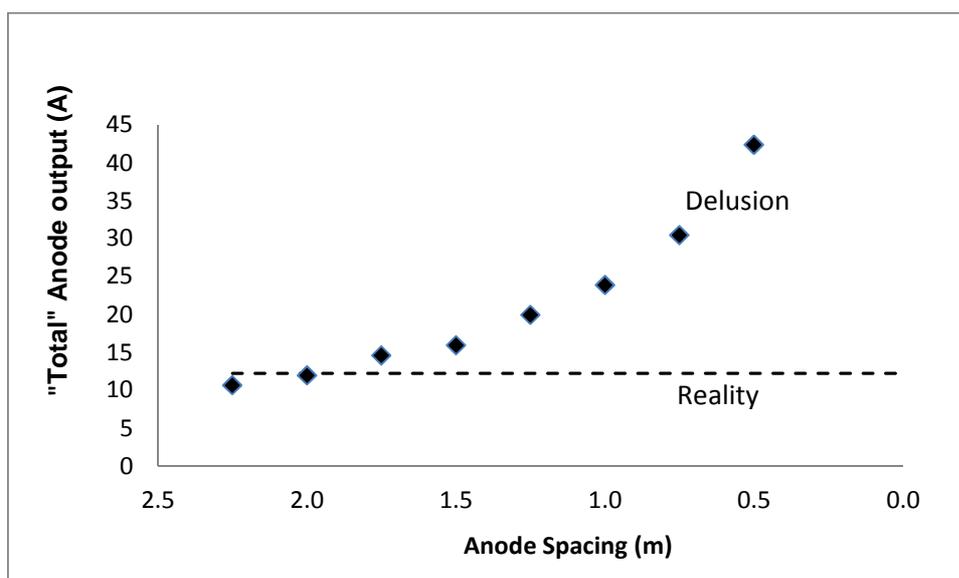
The codes lack clarity on how a designer should allow for this mutual suppression of anode current output. Section 7.11.3 of DNV tells us that, with the exception of very large anodes, shielding and interference effects become insignificant at a distance of about 0.5 m. This is potentially misleading. It suggests to a designer that installing anodes no less than 0.5 m apart will not compromise their outputs. To see the problem with this advice, it is convenient to move from a consideration of electrode kinetics, and to re-interpret the situation using the conventional CP design approach of calculating anode outputs according to their resistances to remote earth.

Let us consider an artificial, but not unrealistic situation, of attempting to provide CP to a large diameter driven pile of the type that might be used to support the tower of an offshore wind turbine. Because anode attachments would shear off due to the piling vibrations, it is not possible to place anodes on the pile itself. One obvious solution is to install anodes attached to a collar which is subsequently installed at the top of the driven pile. This practice is typically adopted in offshore wind farms, where the anodes are mounted on the transition piece which connects the pile to the tower.

If we base a design on a notional Al-Zn-In cylindrical stand-off anode 1 m long and 0.15 m diameter then, using the Dwight formula and taking the seawater resistivity as 0.3  $\Omega\text{m}$ , we estimate an anode resistance to remote earth of  $\sim 0.19 \Omega$ . Using the difference between the codes' values for protected steel potential ( $E_c$  -800 mV) and anode operating voltage ( $E_a$  -1050 mV) we see that our driving voltage is 0.25 V. Ohm's law then tells us that our anode has an instantaneous output of  $\sim 1.3$  A. Moreover, so long as we do not encroach on the 0.5 m limit on spacing suggested by DNV, we can simply add anodes around the circumference of the transition piece to increase the CP current output.

The process is illustrated by the solid markers in Figure 1. As the lateral anode spacing is reduced, more anodes can be fitted around the circumference, and the cumulative output increases. However, as noted in the figure, this approach is likely to lead to a "delusion". The problem is that by simply applying Ohm's law to the individual anodes, no account is taken of the mutual suppression of anode outputs. One way of providing a "reality check" is to adopt the view that the maximum output would be obtained if enough anodes were installed to produce a solid band around the circumference. This would constitute a bracelet, the resistance of which is most realistically estimated using the McCoy formula. The output of the equivalent solid bracelet is shown by the dotted line in the same figure, referred to on the figure as the "reality". Thus, we see that application of the Dwight equation to multiple

anodes could lead the CP designer to over-estimate the current output by a factor of up to four.



**Figure 1 Notional Outputs: Multiple Stand-Off Anodes vs Single Bracelet**

Although we have used something of a sleight of hand, in so far as we have illustrated an issue of mutual anode output suppression by invoking resistance to earth formula, the point stands that literal interpretation of the codes in this type of anode arrangement could produce a non-conservative design.

## CATHODIC CURRENT DENSITY

### Carbon Steel

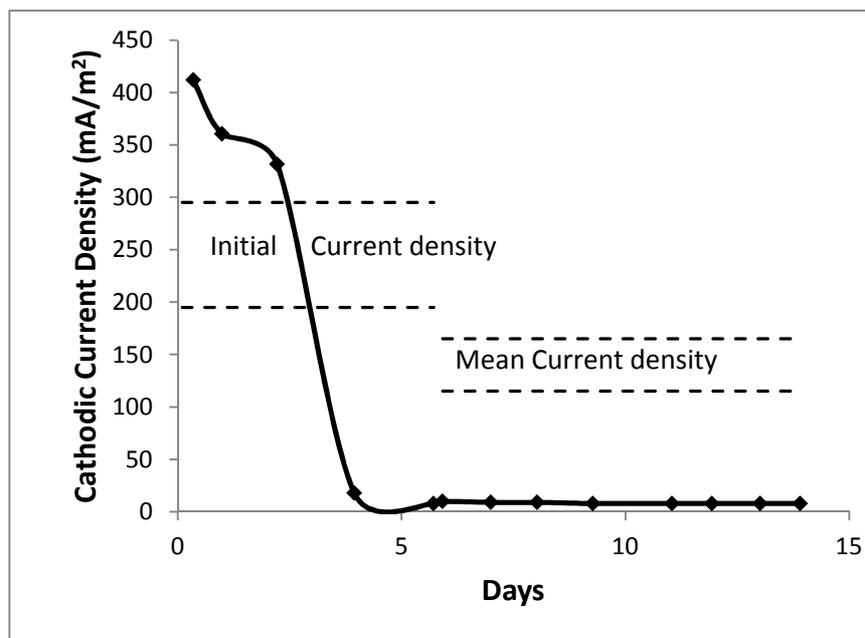
As well as giving guidance on the potential needed to ensure protection, most codes also offer advice on the current density needed to achieve and maintain that potential. The problem confronting the guideline drafting committees is that the current density is a much more difficult parameter to tie down than the potential. Whilst the latter can be fixed by thermodynamics, and is independent of the nature of the environment, the current demand varies in a complex manner depending upon the circumstances of exposure. Even if we set aside the major imponderable of predicting how a coating will perform, and we consider only bare metal, we find that the cathodic current density is influenced by many factors. These include: seawater temperature, oxygen content, flow rate and, moreover, by interactions between these parameters. The cathodic current demand also depends on the nature of the biofilm that forms on the metal surface; and, crucially, on the previous polarization history of the metal.

A consequence of this uncertainty is that guidelines err on the side of conservatism. This, of course, can have major CP cost implications. Only if the designer has access to a body of relevant data to justify less conservative selections can the guidelines be over-ruled. For example, one major operator [21] has been able to make use of historical data accumulated from a particular geographical location to permit the use of less conservative design values. On the other hand, such data are not available to many CP designers who, inevitably, follow the guideline to the letter.

One of the factors affecting the required cathodic current density is the temperature. There is a consensus among the codes that the design current density should be increased at elevated temperatures. This is intuitively reasonable since the rates of chemical, and electrochemical, processes generally increase with temperature. On further consideration, however, this might prompt a query, because the converse argument would suggest that the codes would advise lower current densities for colder waters. However, they do not; and for very sound reasons.

Section 6.3.9 of DNV is typical. In the case of hot piping it advises an increase in the cathodic current density of  $1 \text{ mA/m}^2$  for each degree above  $25^\circ\text{C}$  at the metal environment interface. It informs us that the additional current is to account for increased convective and diffusive mass transfer of oxygen induced by heat transfer. This is all very plausible. However, it ignores the influence of the elevated interfacial temperature on the formation of calcareous deposits. These deposits have a profound effect on the cathodic current density. Indeed, as observed by Evans [27], were it not for the formation of calcareous deposits, CP would be impracticable in many circumstances. Moreover, since these scales are primarily calcium carbonate, which exhibits an inverse temperature-solubility behaviour, there is a reasonable expectation that calcareous scale formation is made easier at elevated temperatures.

By way of illustrating the profound effects of temperature, it is informative to consider an experiment carried out by the author in 1977 [22]. It formed part of an investigation into the intergranular corrosion of zinc anodes at elevated temperature. Incidental to the study, the potential-time and current-time behaviour of a zinc-steel galvanic couple (area ratio 1:10) in aerated, synthetic seawater at  $70^\circ\text{C}$  were recorded. The potential-time curve showed, unsurprisingly, that the steel reached fully protected potentials within minutes. The current-time curve is reproduced in Figure 2.



**Figure 2 Current-Time Curve – Steel in Aerated Synthetic Seawater at  $70^\circ\text{C}$**

Figure 2 also shows the range of initial and mean current densities offered by an assortment of CP guidelines for seawater at that temperature (dotted lines). Clearly, the situation is not

straightforward. Initially, currents much higher than suggested by the codes flow in this galvanic circuit; but soon the current demand drops to much lower values than the codes suggest.

These results are not offered with a view of refuting the guidelines. To do so on the basis of a single experiment, carried out under isothermal conditions, would be rash. However, they do serve to illustrate the point that considerable circumspection is required when applying any of the established guidelines to some CP design situations.

### **Corrosion Resistant Alloys**

The potentials needed to protect corrosion resistant alloys (CRAs) are generally less negative than the potential needed to protect carbon steel. In practice, however, this has little relevance. Most CRAs are found in multi-metal systems. Since it is necessary to protect the carbon steel component, the potential of the entire assembly needs to be shifted to the protection potential of the steel. This begs the question: what is the current density needed to bring about the required polarization of the CRA? This question is answered in section 6.3.10 of DNV, which advises us, without explanation, to use the same current density for CRAs as for carbon steel. This advice may seem counter-intuitive to an engineer, who might reason that, because the CRA naturally has a more positive potential than carbon steel then it will receive a greater potential shift when polarized to (say) -800 mV. It would then be easy to assume that a greater potential shift required a larger current. This line of reasoning reflects the implicit assumption that electrochemical systems obey Ohms's law. As already remarked, they do not.

As for carbon steel, the cathodic current density for a CRA is determined by the rate of reduction of dissolved oxygen on the metal's surface at the protection potential. In the case of stainless steels, for example, the evidence is that the passive oxide film restricts the rate of this reaction. For example, experiments conducted in artificial seawater [23] have confirmed that the kinetics of oxygen reduction:



are more sluggish on stainless steel than on carbon steel.

In contrast to the results in artificial seawater, the situation in natural seawater is not so straightforward. For example, Johnsen and Bardal [24] found that microbial slime layers, formed on various stainless steels after about a week of immersion in natural seawater, acted as cathodic depolarizers. This implies that there might be an increase in the required current density for polarization. This is indeed so. However, irrespective of changes in the cathodic activity of the surface, the current density needed to polarize the alloy to the protection potential of carbon steel will still be limited by the rate at which the oxygen, dissolved in the seawater, diffuses to the metals surface. Since the oxygen molecule carries no electrical charge, its rate of diffusion is not influenced by the electrolytic current flowing to the metal's surface; or by the electric field associated with the flow of that current. Thus, the advice offered by DNV to use the same current density for CRAs as for carbon steel has a sound scientific basis. More important, it is supported by test data [25].

## Open and Enclosed Compartments

The advice given in section 6.3.7 of DNV is to treat the internal surfaces of freely flooded compartments as if they were in open seawater; and that “closed and sealed flooded compartments do not normally need CP”. Both propositions represent sound advice; but it is worth considering the long term corrosion situation in a flooded and sealed compartment in the absence of CP.

As noted above, the dominant cathodic process in seawater is the reduction of dissolved oxygen which is usually present at levels of 8-10 mg/L. This oxygen will rapidly be consumed by the chemical and biological demand of the seawater, and also by some corrosion of the internal steel surface. Usually, a corrosion engineering assessment will ignore the rate of general corrosion in fully deaerated seawater. The only cathodic process available to drive the corrosion reaction is the reduction of hydrogen ions to form hydrogen gas:



This is the familiar cathodic process that causes the rapid corrosion of steel, and many other metals, in a mineral acid such as hydrochloric acid (HCl). It is not usually considered relevant to steel in deaerated seawater, because the pH of natural seawater is typically slightly above 8. This means that the hydrogen ion concentration in seawater is about  $10^8$  to  $10^9$  times lower than in HCl; so the “acid” corrosion rate would be proportionally lower.

We have not found any reports dealing with measurements of corrosion rates in oxygen-free seawater. However, a recent study by Noor and Al-Moubaraki [20], on the corrosion of steel in varying strengths of HCl, affords an opportunity to extrapolate to seawater pH values. The result of this extrapolation is shown as a log-log plot in Figure 3.

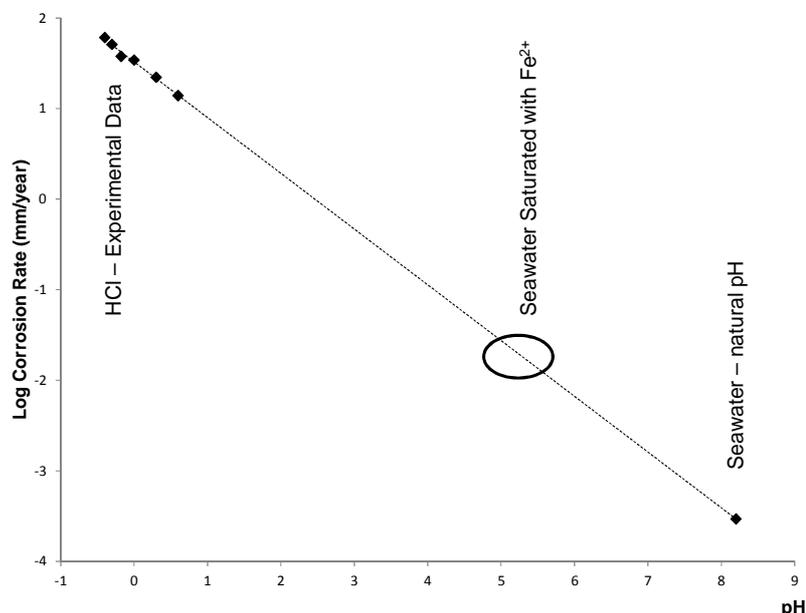
Caution must always be exercised in extrapolating data on a log-log plot. This is particularly the case when the experimental data are bunched at one end, and the extrapolation is required to span numerous orders of magnitude. It also adopts the untested assumption that the corrosion mechanism does not change; so the log-log plot remains linear. Nevertheless, the result obtained, which equates to a corrosion rate for steel of  $\sim 0.3 \mu\text{m}/\text{year}$  in deaerated seawater seems reasonable. It is too low to be of any practical engineering concern since it would require a period of time roughly equivalent to that which separates us from the Trojan wars to corrode through 1 mm of steel. However, it is worth noting that even this very low corrosion rate still means that over a hundred billion iron atoms per second are leaving every square centimetre of the steel surface. These react with the water in a hydrolysis reaction which produces hydrogen ions:



These  $\text{H}^+$  ions lower the pH; the final equilibrium value of which is determined by the solubility product of ferrous hydroxide and by the pH buffering capacity of the seawater. Based on considerations of chemical equilibria, we would expect the pH near the interface of steel corroding in seawater shifts from  $\sim 8$  to  $\sim 5$ .

Thus, the corrosion process of steel in deaerated seawater is, to some extent, autocatalytic. From Figure 3 we see that this shift in pH would be expected to increase the corrosion rate from  $\sim 0.3 \mu\text{m}/\text{year}$  by a factor of about 30; to  $\sim 0.01 \text{ mm}/\text{year}$ . Although higher than the rate

predicted in the absence of hydrolysis, it only amounts to about 1 mm per century. This is negligible from a practical corrosion engineering perspective. It justifies the view of the codes that the internals of structures filled with seawater and then sealed do not require CP.



**Figure 3 Corrosion Rate of Carbon Steel as a Function of pH**

### Partially Enclosed Spaces

There are, however, circumstances whereby flooded structures are neither fully open nor fully sealed. At present, there are no codes to give guidelines on this; although there is a draft CEN document in preparation [19].

An example of such a situation would be a sub-sea oil storage tank working on an oil-over-water basis. These contain seawater which is displaced as the stored volume of produced oil accumulates. Periodically, the oil cargo is displaced by fresh seawater as it is loaded into a shuttle tanker. The cycle is then repeated.

A first principle corrosion engineering approach would indicate that the need to defend against oxygen induced corrosion of the steel is very low. This is because the amount of oxygen that could be introduced over the operating life is limited by the finite volume of seawater that will enter the tank over its lifetime. This is almost exactly equal to the cumulative volume of oil production.

By way of an example, a recent study for a tank produced the results summarized in Table 2. This shows that, even if all of the oxygen took part in the corrosion reaction at the steel surface, the average corrosion penetration would be in the order of 0.2 mm over the operating life of the tank.

Parameter	Value	Comment
Operating Life	20 years	
Seawater passing through tank	$7.2 \times 10^6 \text{ m}^3$	Used to displace a predicted oil production of $45.2 \times 10^6$ standard barrels
Oxygen concentration in seawater	8 mg/L	Typical value at that location.
Mass of oxygen entering tank	57.5 tonnes	
Mass of steel corroded	151 tonnes	From laws of chemical equivalence. (Conservatively assumes that all of the oxygen reacts with the steel surface.)
Volume of steel corroded	$18.9 \text{ m}^3$	Based on steel density of $7.89 \text{ tonnes/m}^3$
Internal surface area of steelwork	$87\,147 \text{ m}^2$	From preliminary drawings
Average steel section loss	0.2 mm	

**Table 2 Example of Predicted O<sub>2</sub> corrosion in Oil-over-Water Subsea Tank**

However, this figure is an exaggeration because, most of the oxygen would be consumed due to the biological and chemical oxygen demand of the bulk seawater, before it could diffuse to the surface of the steel and participate in the cathodic corrosion process. For example, Lee et al. [26] have reported that, when a body of natural seawater is sealed in a container, the dissolved oxygen level drops to a matter of parts per billion within a few days. This implies that the average life-time corrosion penetration due to oxygen will be a small fraction of the 0.2 mm estimated in Table 2.

Interestingly, the data in Table 2 permit a first-pass electrochemistry-based assessment of what the appropriate mean, or maintenance, design current density should be for the subject tank. The worst-case maximum predicted steel corrosion due to oxygen diffusion is 0.2 mm in 20 years; or an average of 0.01 mm per year. Applying Faraday's laws of electrochemical equivalence tell us that this corrosion is equivalent to an anodic current density of  $\sim 8.5 \text{ mA/m}^2$ . Furthermore, since design current densities in seawater systems equate to the estimated diffusion controlled cathodic current densities, this suggests that, in this example, the appropriate figure would also be  $8.5 \text{ mA/m}^2$ ; a figure very much lower than that being considered in the draft guidelines [19].

Happily for the corrosion enthusiast, albeit not for the tank owner, the reality of the situation is not quite so straightforward. In the first place, unlike the general case of offshore CP design, we should not ignore the contribution to the corrosion of the hydrogen evolution reaction, which will also contribute about 0.01 mm/year to the average corrosion rate. Unfortunately, even though the predicted cumulative life-time corrosion due to oxygen reduction and hydrogen evolution is probably tolerable, we cannot eschew corrosion control in storage tanks of this type. The combination of anaerobic conditions and the steady replenishments of nutrients, from the oil and the seawater entering the tank, means that, over time, MIC becomes the dominant corrosion threat. This is particularly so for the tank floor plating where sediments accumulate.

Thus, any CP system design will need either to be tailored to the specific circumstances of the tank or else will end up being designed according to the existing, or soon to be published codes. The latter will, inevitably incur a substantial measure of over-provision of anodes.

## SUMMARY

Although it is perfectly permissible to design CP systems by mechanically following the published guidelines there are, inevitably, situations where the guidelines fall short of providing authoritative advice. In those instances a little knowledge of electrochemistry may not be absolutely essential; but it will invariably be helpful.

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