Conditions leading to severe MIC of FPSO mooring chains

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Dedicated to the memory of Professor Dr Andrew Potts (deceased) former Chief Executive Officer and Founder of the AMOG Consulting group of companies, based in Melbourne, Australia and with offices world-wide.

Abstract: FPSO are the floating production storage and offloading vessels increasingly used in the offshore oil and gas industry for oil and gas production many miles offshore and in deep waters - currently up to about 3 km deep. The vessels are kept ‘on-station’ by a system of 8-12 mooring lines typically consisting of stud-less chain at the top (steel diameter 76mm minimum) and through the wave zone into the fully immersed zone, followed by steel mooring cables (typically 100mm diam.) and near the seafloor back into stud-less chain. Field experience at two quite different warm water locations showed some (but not all) chain links to have localized corrosion (pits) more than 20mm deep and of 30-50mm diameter after only 8 years exposure. This is very much more than typical for seawater tidal or immersion corrosion. Investigations showed unexpected high dissolved inorganic nitrogen (DIN) in the seawater local to the vessels. Consistent with previous findings for pitting corrosion in seawater, this indicates MIC was involved. The reasons for these conditions apparently so far removed from anthropological influences, and the practical implications, are discussed.

Keywords: Microbiologically Influenced Corrosion; Mooring chains; Nutrients.

Introduction

Floating production storage and offloading (FPSO) vessels are floating, steel platforms, similar to oil tankers, or are converted oil tankers, used in the oil and gas industry for offshore operations. Typically they have extensive topside equipment that includes, for production platforms, pipework, pumps, tanks etc. and equipment for handling the considerable length of pipe for production pipelines (risers) that extend to the seafloor, as well as associated equipment.

FPSOs are finding increasing application in deep waters, currently up to about 3km deep, often located many kilometres offshore. For safety, environmental and economic reasons it is important for the vessels to be kept ‘on-station’ to quite close tolerances, lessening the risk of riser failure and hence crude oil spills. Typically this is achieved by a system of 8-12 mooring lines. Typically the mooring lines consist of steel chain at the top and through the wave zone into the fully immersed zone, followed by steel mooring cables or synthetic hawsers and near the seafloor back into steel chain. Usually all the chains are stud-less to save weight and for improved fatigue performance. Mooring line tension due to self-weight of the mooring lines can be an issue and in some cases underwater buoys are employed to add buoyancy.

The anchorage point(s) for the mooring lines often is at a turret mounted on the bow of the vessel, although there also are systems where the turret is within the vessel hull, or the mooring lines connect directly to the vessel hull. Typically chain is used at the top of the mooring lines to connect to the vessel platform. This permits easier logistics for attaching the mooring lines to the platform and a more mechanically robust connection. While alternative systems have been considered and used in some instances, the use of chains is still the industry standard. Chain link sizes currently are often 76mm diameter but sizes up to 150mm and more also are employed. The steel cables are around 100mm diameter. Although non-metallic cables are being trialled, steel is still the predominant
material. Typically the cables are galvanized. Together with the grease used in their construction and remaining inside the multiple strands making up a cable, they are not particularly prone to corrosion, noting also that they are entirely in the immersion zone. Similarly the lower chains, while usually bare steel, normally are not prone to significant corrosion, at least no more than would be expected at depth. The most severe corrosion problem is for the upper chains and mainly in the intertidal / wave action zone [1]. Particularly in the Tropics some chains have been found to show severe, usually quite localized corrosion, even after only some 8-10 years continuous exposure (Fig. 1). This is of considerable practical interest as increasingly FPSOs are being deployed in Tropical waters.

![Corroded Chain Links](image1.png)

Figure 1. (a) Corroded chain links under immersion conditions, showing evidence of localized corrosion even with presence of rust layers (b) localized corrosion of immersed chain links in Tropical seawaters, after recovery and onshore high pressure water-blasting.

Discovery of the localized corrosion shown in Fig. 1 during routine inspections as part of a major research study (SCORCH-JIP) to ascertain the effect of operating in the Tropics [1] caused considerable alarm because of the potential implications for FPSO operational safety. This led the research project to investigate the potential reasons for such corrosion, noting that the FPSOs involved were many kilometres offshore and thus in what were assumed to be unpolluted ocean waters. However, water quality testing showed that this was not the case and that there were high concentrations of Dissolved Inorganic Nitrogen (DIN) in the seawaters, indicating that microbiologically influenced corrosion (MIC) was likely to be involved [2]. The next section reviews the background for the link between MIC and DIN in seawater, drawing on earlier work for accelerated low water corrosion (ALWC) and the correlation between DIN and MIC for corrosion loss. It also considers the potential role of other nutrients for microbiological metabolism and their potentially limiting function. The corrosion mechanism(s) likely to be involved are considered, including the most likely reason for the rather large but usually isolated areas of localized corrosion as seen in Fig. 1. Brief consideration is given to possible ameliorating strategies and also why MIC at depth appears to be unlikely.

**Background**

It has been established for some time that for field exposure conditions the concentration of critical nutrients in sea (or other) waters is likely to influence the activity of microorganisms and thus, potentially corrosion loss and pitting, provided other aspects such as shelter and energy sources are available [3]. The presence of bacteria and archaea alone is not sufficient. Microorganisms can multiply at very fast rates relative to the rate of marine corrosion [4]. It follows that the rate-limiting step for microorganism activity, and thus potentially for their effect on the rate of corrosion, is a function of the rate of supply, and thus of the availability,
of critical nutrients. For corrosion of steel in seawater, the critical nutrient has been shown to be dissolved inorganic nitrogen (DIN) [3, 5, 6]. Other nutrients critical for microorganism activity and metabolism typically are available to excess in seawater, including sulphates, phosphorous and organic carbon. For the corrosion of steels (and alloys containing some Fe component) the critical micro-nutrient, ferrous iron, is supplied by the corrosion process. That process also supplies the energy source in terms of electron flow, while biofilms and rusts can provide the necessary shelter.

For steel corrosion coupons exposed over several years in various seawaters the effect of DIN concentration in the seawater local to unprotected steel structures has been quantified using corrosion loss data obtained from a wide variety of field exposure sites and correlated with data about nutrient concentrations [2]. In terms of the bi-model model for the corrosion loss of steels in seawater over extended periods of exposure (years), the effect of bacterial activity stimulated by nutrient availability is most prominent at the beginning of the second mode (Fig. 2). The effect may be simplified for longer-term corrosion using the tangent line AC. It represents the long-term trend without nutrient availability. The effect of the present of nutrients is to raise the tangent AC as shown, roughly parallel to AC. The tangent is parameterized by the intercept $c_s$ and the slope $r_s$.

![Figure 2. Bi-modal corrosion model, long-term linear corrosion and effect of microbiologically influenced corrosion [2].](image)

In what is essentially an (environmental) input - (corrosion severity) output relationship, the relative increase in corrosion loss for waters with elevated concentration of DIN compared to corrosion in low DIN seawaters is approximately a linear function of nutrient concentration [6]. The change in the parameter $c_s$ with increased DIN is as shown in Fig. 3 [2] for moderate changes in DIN and for different average water temperatures. Similarly, Fig. 4 shows the changes with DIN and average water temperature in the long-term slope of the corrosion losses, defined by parameter $r_s$ [2].
These two figures may be used to construct, for a given average annual seawater temperature, the long-term trend AC but now with the inclusion of the possible microbiological corrosion effect (i.e. with MIC), defined through the concentration of the critical nutrient DIN. Fig. 5 shows the result for seawater at 25°C and various DIN concentrations. It is an extrapolation to DIN = 3.0mgN/l of the results in Figs. 3 and 4 applied to the long-term trend AC in Fig. 2. The validity of the extrapolation has not been proven but is plausible. Note that Figs. 2, 3 and 4 deal with corrosion loss defined as ‘uniform’ corrosion, as conventionally obtained from mass loss observations. It does not deal specifically with localized corrosion or pitting corrosion.
The fact that MIC usually is associated with significant localized corrosion and deeper pitting corrosion is well-known, even for laboratory observations under rather artificial conditions and for short-term exposure periods [4]. For longer-term exposures the effect of MIC for localized corrosion can be estimated from test results for steel strips suspended vertically in seawater through the immersion, tidal, splash and atmospheric zones. This experimental arrangement is similar to sheet piling in harbours. Under elevated DIN conditions these strips (and sheet piling) show accelerated low water corrosion (ALWC). From many experimental observations for steel strips [6], and from data recovered for sheet piling in various US harbours [7], the trend shown in Fig. 6 was obtained. It shows the localized corrosion in the low water zone (measured by $a$ - see inset) and the amount of corrosion in the immersion zone (shown as $b$). It also shows the ratio $R = a / b$ as a function of the total dissolved inorganic nitrogen (DIN) measured for the corresponding exposure sites. For most of these the data were reasonably precise, but for some, shown circled, there is considerable degree of uncertainty, mainly because of difficulty in obtaining reliable data for average DIN at or close to the sites where the corrosion losses were reported [1]. The US data alone give the linear trend shown, with $R = 1.055 + 4.5 N \ [r = 0.715]$. For the Australian data, covering a lower range of $N$, the trend line is very similar, with function $R = 0.98 + 4.49 N \ [r = 0.982]$.

The information in Fig. 6 is of interest because the corrosion in the low water zone is quite localized, noted already many years ago by Evans [8] for corrosion at the water-air interface for still water conditions. For tidal conditions that zone moves up and own, but it was quite evident in the experimental samples from actual seawater exposures over several years [5, 6]. Whereas the data for the US sites was opportunistic, extracted many years after the original observations were made, the Australian data are from controlled experimental work in which the local corrosion loss in the low water zone, and in fact the corrosion losses in all the zones was captured by cutting the long strips into short (100mm long) segments and determining the mass loss for each of these. This produced profiles of localized corrosion loss similar to that shown schematically in the inset in Fig. 6. The importance of this in the present context is that
the size of the segments so produced is of the same order of magnitude as the extent of the most severe localized corrosion observed for the chain links most affected by localized corrosion. This is now described.

Figure 6. Relationship between corrosion ratio $R$ and DIN, with $R$ defined as $R = a / b$, where $a$ is the local severity of corrosion for the lower water zone and $b$ the local severity of corrosion in the immersion zone, as defined in the inset. It shows, schematically, the different corrosion zones for seawater tidal conditions defined along the vertical axis, against the degree of corrosion along the horizontal axis. $R = 1$ indicates no accelerated low water corrosion and corresponds to $N = 0$.

**Observations**

The chain links considered herein were recovered from operational FPSO sites off West Africa, and in Indonesian and East Timor waters. There also is some information about corrosion of FPSO mooring chains in the Gulf of Mexico and in the North Sea. The (few) cases that were available for examination in the SCORCH-JIP project [1] are summarized in Table 1. In each case the mooring line became available as a result of field inspection and the decision by the platform operator to take the mooring line out of service. This decision is governed by a balance between the risk of mooring line failure and the considerable cost of a new mooring line and the cost of downtime. There was also the issue of whether the operator was willing to let the chains be examined in what was essentially a process that permitted access by competitors, consultants and academics. A number of the participants in the SCORCH project actively participated and provided in-kind support as well as the data summarized in Table 1.
Table 1. General corrosion losses (mm) and maximum corrosion penetration (all 76mm diam. chains)

<table>
<thead>
<tr>
<th>Location</th>
<th>Exposure Period (years)</th>
<th>Estimated DIN (mgN/l)</th>
<th>Average corrosion loss b (mm)</th>
<th>Maximum penetration a (mm)</th>
<th>$R = a / b$</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>East Timor</td>
<td>5</td>
<td>0.68</td>
<td></td>
<td></td>
<td></td>
<td>Unit 16</td>
</tr>
<tr>
<td>Gulf of Mexico</td>
<td>8</td>
<td>0.3-0.5</td>
<td>1.65</td>
<td>$4.3 \pm 0.9$</td>
<td>$\approx 3 - 4$</td>
<td>Unit 8</td>
</tr>
<tr>
<td>Brazil</td>
<td>11</td>
<td>?</td>
<td>1.7</td>
<td>?</td>
<td></td>
<td>Unit 9</td>
</tr>
<tr>
<td>Indonesia A</td>
<td>5</td>
<td>0.4-1.0</td>
<td>$1.13 \pm 0.6$</td>
<td></td>
<td></td>
<td>Unit 14</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td></td>
<td>1.5-2.0; 1.7; 4</td>
<td>10-20</td>
<td>4 - 5</td>
<td></td>
</tr>
<tr>
<td>Indonesia B</td>
<td>15</td>
<td>2 - 2.3</td>
<td>$11.5 \pm 0.45; 10.4$</td>
<td>15-20</td>
<td>$\approx 2$</td>
<td>Unit 14</td>
</tr>
<tr>
<td>West Africa</td>
<td>7</td>
<td>12.08 c (2.71)</td>
<td>5.5 - 7.8</td>
<td>14-28</td>
<td>3 - 5.1</td>
<td>Unit 16</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>12.08 c (2.71)</td>
<td>7</td>
<td>?</td>
<td></td>
<td>Unit 4</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>12.08 c (2.71)</td>
<td>8.48</td>
<td>20-30</td>
<td>2 - 4.5</td>
<td>Unit 3</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>12.08 c (2.71)</td>
<td>11.0</td>
<td>20-30</td>
<td>2 - 3</td>
<td>Unit 5</td>
</tr>
<tr>
<td>North Sea</td>
<td>?</td>
<td>0.2 - 0.3</td>
<td></td>
<td></td>
<td>$\approx 2^d$</td>
<td>-</td>
</tr>
</tbody>
</table>

Notes: sulphates equivalent to typical seawater, phosphorous detected.

a  Source: Chevron IndoAsia TS Lab. reported as NO$_3^-$ and converted to N.
b  Source: Duri Lab., Jakarta, at 5m depth.
c  Source: Chevron Nigeria Ltd Escravos Laboratory. Reported as 12.08 mg/l as N - more likely it is NO$_3^-$ as obtained from standard ion chromatography. This is equivalent to 2.71 mgN/l (see text).
d  Estimated from photographs.

Based on data in the Final Report for the SCORCH project [9].

The mooring lines available for the project were recovered at sea (Fig. 1a), usually high-pressure water blasted to remove marine growth and loose rusts, transported to land, the chain length of the upper part of the mooring line separated and then grit blasted to attempt to remove as much as possible of the rusts including as much as possible inside the pits inside the localized corrosion regions and elsewhere and thus to expose the remaining surface of the chain links (Fig. 1b). The links were then scanned using an infra-red scanner and from the data so produced 3D computer models could be developed [1, 10]. These were used together with the known nominal sizes of the chains to estimate the general or uniform corrosion losses over the surface of the links. In addition, the maximum depth of localized corrosion penetration was determined. This was also checked manually wherever possible.

As shown in the examples in Fig. 1, the regions of severe localized corrosion occur in relatively isolated locations on the chain links, typically surrounded by larger areas of apparently uniform corrosion. Not all chains in all Tropical seawaters show these severe localized regions of corrosion. Typically the regions of localized corrosion have a complex topography (Fig. 7).
Figure 7. Close-up views of regions of severe localized corrosion of 76mm diameter chain links after 8-15 years exposure in near-surface immersion conditions and subsequent water jet cleaning and grit-blasting to remove the corrosion products. Fig. 7(a) shows that the grit-blasted surface still has some remnants of corrosion products in the pits. Figs. 7(b and c) show evidence of pits within the localized corroded zones and Figs. 7(d and e) show plateaus of corroded surfaces within the larger localized regions of corrosion. These two latter cases show depth of penetration of 20-30mm.

The topographies shown in Fig. 7 may be interpreted as showing pits (Figs. 7a-c) formed on plateaus within the corroded regions. Such plateaus are most obvious in Figs. 7(d and e). These also show evidence of pitting on the lowest plateaus, that is, in the deepest overall part of the local corrosion region. Evidently the size of the localized region is comparable to or greater than the chain link diameter and the overall pit depths 20-30mm (Table 1). Much of the chain link surfaces show much more uniform corrosion (Fig. 1). Because these links were recovered from field operations the original link diameters were not known precisely at all points along the links, noting that because of the way the links are manufactured the actual original link diameters vary by several millimetres from the nominal. For the links of the Indonesia 5 year data set it was observed that these showed sizes outside the upper tolerances on dimensions.

At each of the sites from which mooring lines were recovered the water quality (WQ) of the seawater local to the mooring lines was determined. This was done in the standard manner of taking a sizeable amount of seawater from the site, immediately taking it (often by helicopter) to a certified water quality testing laboratory on-shore for testing. The water quality testing included salinity, pH, conductivity, temperature, dissolved oxygen, nitrites, nitrates, ammonia, sulphates, phosphate, total phosphorous and calcium. In Table 1 only the DIN
values are reported (i.e. the inorganic N content derived from nitrites, nitrates and ammonia). These values are quite high when compared to, say, coastal and harbour conditions (Fig. 6).

In one case initial WQ readings showed very low (background) values of DIN and when these were queried it became apparent that the samples had been taken some distance away from the FPSO vessel, and had measured, essentially, open sea levels of nutrients such as DIN. The values reported in Table 1 are those for water samples taken in the immediate vicinity of the mooring line, noting that discharges from FPSOs with poor housekeeping may be the critical agents for elevated DIN and other nutrients. A parallel situation has been reported for offshore fixed production platforms [11]. For the North Sea chains the DIN values shown in Table 1 were drawn from the OSPAR study of the North Atlantic and North Sea [12].

Analysis

The chain links in Fig. 1 and Fig. 7 show that the most severe corrosion is highly localized and that large areas of the chain links have experienced much less corrosion, mainly in a form that could classified as ‘uniform’ or ‘general’ corrosion. A parallel situation was found for the corrosion of vertical steel piling [6]. Particularly in seawaters with elevated DIN concentrations usually there is a contrast between the depth of highly localized corrosion, in the so-called accelerated low water corrosion (ALWC) immersion zone, compared with the corrosion for the remainder of the pile in the immersion zone (Fig. 6). For the present analysis it should be noted that the surface area extent of the localized corroded region for ALWC is comparable in size to the more severe cases of localized corrosion of the 76mm diameter chain links. In both exposure situations the concentration of DIN in the seawater appears to be an indicator of the severity of localized corrosion (Fig. 6 and Table 1).

To make progress in the analysis of the data for the chain links (Table 1), consider now the parameters $a$ and $b$ employed in Fig. 6. Let these be applied to the data in Table 1 for generalized corrosion and for the deepest penetrations respectively for the chain links (Fig. 8).

![Schematic of the rust layer and diffusion paths of inorganic nitrogenous nutrients](image)

**Figure 8.** Parameters $a$ and $b$ applied to the corrosion of the surfaces of chain links. A schematic of the rust layer and the diffusion paths of inorganic nitrogenous nutrients also are shown. The schematic rust layer thickness shown is based on the observation in Fig. 1(a) that the depressions caused by localized corrosion are visible on the outer rust layers.

As a first step, consider the overall ‘uniform’ corrosion losses (Table 1) and now described by parameter $b$. Using the corrosion loss trends for increasing values of DIN shown in Fig. 5, and extrapolated to higher DIN values, the data for $b$ are as shown in Fig. 9. Comparing to the DIN values in Table 1 for the cases of Indonesia B and West Africa at 15 years exposure it is apparent that the corrosion losses shown are considerably greater than would be expected, at least compared to the DIN values for the trends shown. For all the other data there is reasonable correspondence between the DIN values in Table 1 and the corrosion losses for the
trends for the different DIN values. The potential reasons for the apparent discrepancy for the higher DIN values is considered further below.

Figure 9. Average corrosion loss $b$ of chain links as a function of exposure period plotted on an extrapolated version of Fig. 5. Comparison to Table 1 shows some discrepancies in the DIN values recorded in the field and the expectations from extrapolations in Fig. 5.

The second comparison can be made for the ratio $R = a / b$ between the deepest localized corrosion values $a$ and the general corrosion losses $b$ using the ratios given in Table 1. The comparison can be made by adding the $R$ and $N$ values to Fig. 6. This produces the plot shown in Fig. 10. It is clear that the linear trend fitted to the data in Fig. 6 cannot be extrapolated ad infinitum for the chain link corrosion data. There is a clear limit on the value for $R$. The potential reasons for this are explored in the next section.
Figure 10. Plot of ratio $R$ against DIN $N$ for both the ALWC cases and the trend from Fig. 6, with extreme localized corrosion data from chain links added. The effect of longer exposure periods is shown.

**Discussion**

As noted, the data for general corrosion of the chain links as plotted on Fig. 9 show reasonable consistency what the extrapolated trends derived from Fig. 6 for the cases with lower concentrations of DIN. The cases with somewhat higher DIN have values for corrosion loss that align, on Fig. 9, with DIN values that are much higher than the actual field values for DIN. In part this may be because the general corrosion losses reported in Table 1 relate to $b$ as measured by the observed diameters compared with the original, but nominal diameters and these are not usually the actual localized diameters. For example, the corrosion losses for Indonesian chains at 5 years exposure were mostly calculated from observed diameters and nominal diameters to be negative, clearly indicating that the original, nominal diameters were not sound bases for comparisons. The other aspects is that the change in diameter is unlikely to be a sufficient measure of overall corrosion since that would not include the, in some cases significant, loss of metal occasioned by the presence of localized corrosion and pitting, such as seen, for example, in Fig. 1b. Overall, however, these aspects do not appear to offer an explanation for the very considerable differences seen for the 15 year Indonesia B and 15 year the West Africa data.

The most likely reason for the differences between the trend lines for different DIN concentrations and the concentrations of DIN recorded in Table 1 for the 15 year Indonesia B and the 15 year West Africa corrosion losses lies with the DIN values. Longer term corrosion can be considered to be related to average values of DIN. This is important because it is known that coastal region DIN values can vary considerably throughout the year. For example, for temperate zones such as the North Sea the DIN values are much higher in winter compared with summer [12]. This is owing to the variations in fresh water inflow and freshwater catchment fertilizer application between these seasons, with the winter months having the highest river waters inflow, corresponding to the higher DIN values in the offshore zones.

In the Tropics, such as would apply to Indonesia and West Africa, a parallel scenario might be expected, with the wet season (April-October) supplying both more river flow into the coastal zone ans also higher DIN, although information about the DIN aspects appear to be poor. The values recorded in Table 1 were obtained in the dry season, and thus are likely to be under-estimates of DIN for the Indonesia and West Africa offshore sites. It follows that the average DIN values could be considerably higher, not inconsistent with the DIN values corresponding to the corrosion loss values in Fig. 9. However, it is clear that this aspect requires further investigation. This is an area for further research.

Turning now to the severity of localized corrosion, it is clear from Figs. 7(a-c) that pitting is very much involved in the development of the regions of localized corrosion. The mechanism for this has been described [13] and discussed previously [14]. In brief pit depth is constrained by potential limitations and eventually any further corrosion within a pit can occur only sideways, permitting, for pits in close proximity (which is not uncommon, see Fig. 7b), the development of corrosion plateaus. On these new pitting can form (Fig. 7b) and the process can then repeat, a process that has been referred to as clustering of pit depths [15]. It follows that the processes inside corrosion pits [16, 17] are relevant to the pits themselves but not to the overall localized corrosion cavity - for these overall conditions almost certainly will
prevail, not unlike those for other areas of the corroding surface not affected by the localized corrosion scenario.

The most likely constraint on the depth of localized corrosion as measured by \( R \) is diffusion through the rust layers (Fig. 8). Unlike the rusts that form over pits (the rust ‘cap’) the rusts that from over the inner surfaces of the localized corrosion region are more likely to follow the contours of the depression as seen, for example, in Fig. 1(a). This is represented as shown in Fig. 8. Similar to the recognized concept that the build-up of rust layers in oxygen-rich environments limits inward diffusion of oxygen, they also will inhibit the inward diffusion of nitrates, nitrites and ammonium, and will do so more effectively than inhibiting oxygen diffusion because of their larger molecular size, assuming potential differences are comparable. Interestingly, because of the small molecular size of hydrogen, the thickness and permeability of the rusts are unlikely to have any significant effect on its outward diffusion, and thus on the rate of the hydrogen evolution cathodic reaction as is relevant under longer term exposures [18].

In the early stages of exposure both \( a \) and \( b \) are small and comparable, with \( a \) driven by the same considerations that cause pitting to be selective in location or by crevice corrosion initiation conditions [19, 20]. Once such differential corrosion has set in, the process is similar to that for other localized corrosion by differential aeration effects, except that there could be the contributing effect of microbiological metabolites contributing to lowering the pH inside the pits. Fundamentally this is no different to the processes involved in MIC, including its often localized nature, induced by local in-homogeneities in the steel or caused by deposits or localized microbiological, bacterial or algal marine growth [4]. For the present analysis the precise mechanisms involved in the initiation and the earlier stages are not of particular interest - what is important is the longer-term development of the resulting localized corrosion. This has now been shown to be, like MIC more generally, related directly to the DIN concentration in the seawater immediately to the corroding surfaces, although with an upper limit of about \( R = 4 - 5 \), as shown in Fig. 10. The dependence on \( N \) is less clear in view of the comments relating to Fig. 9 that the values for DIN in Table 1 may be underestimates for Indonesia and West Africa owing to the time of the year when the DIN in the seawater was measured. However, it should be clear that this does not affect the reasons for the limitation on \( R \).

Fig. 10 shows that the limit on \( R \) depends on the period of exposure, with a lower value for 15 years exposure compared with 7 or 8 years exposure. This effect can be attributed to the gradual build-up of rusts, with those at 15 years being thicker and likely more dense than those for shorter-term exposures. In the localized corrosion region the rate of build-up will be faster as, inside the pits, more metal is lost and thus the rate of growth of the rusts in this region will be faster. As a result, inward diffusion of nutrients will be slowed. The difference will tend to level out with time, as \( a \) and \( b \) also come closer in value, with consequent reduction in \( R \geq 1 \). In addition, the thickness of the rust layer is controlled, in the classical model, by the balance between the inward build-up of rust layers utilizing the ferrous ions released at the anodic parts within pits and the external removal of the rusts to the external environment, through oxidation and perhaps erosion [21]. Erosion is less likely for depressed region of corrosion product, as can be seen for example already after a few years exposure under immersion conditions (e.g. Fig. 1a).

The cases considered herein are all for chain links exposed to near-surface immersion conditions, or in the splash zone. In both zones seawater soluble DIN can be available, even
some distance from shore if environmental and hydrodynamic conditions permit the transportation of the necessary nutrients. Since particularly the oxidized form of DIN, nitrate, undergoes degradation with time, and is highly soluble in water, it is unlikely to reach great depths. At depth, the temperature is also lower, which suppresses the rate of corrosion relative to the warmer surface waters, and therefore the rate of electron flow to support MIC is also reduced. This suggests that MIC of steel chain at depth, sometimes suspected [22], is unlikely, unless the presence of nutrients, particularly including DIN, can be verified. At depth there is also the issue of the ultimate electron acceptor - in surface waters this is still \( \text{O}_2 \) but at depth the concentration of \( \text{O}_2 \) is almost always extremely low [23].

Finally, the possibilities for avoiding MIC in nutrient polluted seawaters appear to be limited, largely through practical considerations. The most obvious is to select operational sites with low or negligible nutrient concentrations. But this is seldom an option. Impressed current cathodic protection (CP) would require the links to be electrically connected, either to each other or to a common point, and this is considered to be both expensive and infeasible under the usually exposed conditions to which most FPSOs are exposed. The present understanding is that direct electrical connectivity through the wearing surfaces between links is low to very low. For this reason, too, sacrificial anodes for CP would need to be applied to each link. This has the disadvantage of adding to bulk of the chain links and hence increasing drag on the chains. The anodes also would need to be replaced at regular intervals and this would be difficult below the water surface. And in any case CP is effective only for surfaces continuously immersed - others would need a protective coating of some type. Zinc or aluminium coatings of various forms have been considered and are sometimes used, but these have little wear resistance, important at the inter-link region, and also may cause hydrogen embrittlement issues. The use of biocides or microorganisms to oppose the effects of MIC has obvious practical and environmental limitations in what is often a hostile offshore environment. Clearly the avoidance, amelioration or elimination of MIC for offshore systems such as the mooring lines used for FPSOs and similar structures is an area ripe for innovative research.

**Conclusion**

The following conclusions may be drawn from the present observations of the corrosion of mooring chain links in seawaters with elevated concentrations of DIN:

1. The available observations from field conditions show that localized corrosion can be very severe reaching depths of 20 mm within 8 years and 30mm in 15 years. The field observations suggest that the localized corrosion is instigated by marine organisms, marine biofilm and deposits.

2. The effect of DIN on general corrosion of chain links is generally consistent with that found earlier for steel coupons in seawaters with DIN values less than about 0.5 mgN/l. The data indicate that the trend will continue for higher DIN values, provided these are average annual values.

3. The relatively greater depth of localized corrosion compared to more uniform corrosion increases with the concentration of DIN in the local seawater up to a relative ratio of depth of corrosion \( R \) of 4-5 for shorter term exposures (say < 8 years) and thereafter gradually becomes more comparable with uniform corrosion. This is largely independent of DIN concentrations greater than about 0.5 mgN/l, indicating that localized corrosion is more critical for earlier exposures.
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