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Melchers, Robert E.; Jeffrey, Robert "Corrosion of long vertical steel strips in the marine tidal zone and implications for ALWC" Corrosion Science Vol. 65, p. 26-36 (2012)

Available from: http://dx.doi.org/10.1016/j.corsci.2012.07.025

Accessed from: http://hdl.handle.net/1959.13/1052858

Corrosion of long vertical steel strips in the marine tidal zone and implications for ALWC

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Abstract

The cause of the high corrosion losses below the low tide level on older steel piling (usually called Accelerated Low Water Corrosion - ALWC) is incompletely understood but usually linked to microbiological influences. Vertical 3-6 m long steel strips were exposed through the tidal zone at 13 different marine sites. After only 1-3 years good correlation was found between ALWC and local seawater average concentration of dissolved inorganic nitrogen, a necessary nutrient for microbiological activity. These results allow prediction of the likelihood of long-term ALWC through measurement of either short-term corrosion loss profiles or average nutrient levels.

Keywords: A. Mild steel; B. Weight loss; B. Modelling studies; C. Microbiological corrosion.

Introduction

The marine tidal zone is a severe corrosion environment for unprotected steel, such as sheet and other piling used in seawater harbours. Traditionally it does not have cathodic protection or protective coatings. The corrosion of bare steel sheet piling was of interest already during the late 1940's to mid-1950's with several field studies on the US East coast at Kure Beach [1,2]. These showed that for continuous vertical steel strips the most severe corrosion loss occurred at around the high water mark and the least in the mid tide zone, much less than in the fully immersed zone. In contrast, isolated coupons over the same vertical distance showed the highest high corrosion losses in the mid-tide zone. Some typical results are shown in Fig. 1.

Figure 1 - Some classical data and corrosion profiles for exposure of mild steel strips and coupons in the Atlantic Ocean at Kure Beach, USA. For strips the highest corrosion loss is in the splash zone.

The causative mechanism for these observations was attributed to differential aeration [2]. This followed the much earlier work in Cambridge by Agar, Bengough and Evans [3,4] that small (near-) vertical strips of steel and zinc partially immersed in pure water in laboratory beakers showed high levels of corrosion a short distance below (but not at) the water line. Recently, comparable field results were reported for steel strips of different lengths and for 1m long strips with different immersion/atmosphere exposure ratios exposed for 12 months in unpolluted Pacific Ocean coastal seawater [5,6].

Standard texts show the profiles in Fig. 1 as typical for corrosion through the tidal zone. However, during the 1980s alarm was expressed at the discovery of sheet piling showing corrosion sufficient to cause perforation, sometimes over extended areas, in the region just below the lowest astronomical tide (LAT) 7]. This is not predicted by the classical corrosion profiles such as Fig.1. Such damage has the potential to cause structural failure of the sheet piling, failure of docks and quays constructed with steel sheet or other steel piling and may cause severe disruption of port services. It appears first to have been observed in the UK in several coastal harbours but subsequently it was discovered also at a number of other ports in other parts of the world. The phenomenon was not understood, was given the name Accelerated Low Water Corrosion (ALWC) and was described at a UK Institution of Civil Engineers conference as 'a matter of national importance' [8]. Despite considerable research attention the mechanisms involved in ALWC and the influences on it are still not fully understood.

ALWC often is considered a relatively 'modern' phenomenon [8]. However, already in the 1910s cases of severe localized corrosion (pitting) of steel piling were reported for water depths ranging from 2-5m [9]. These depths are greater than typical for ALWC. High corrosion losses immediately below the waterline were reported during the 1950s for retired naval ships moored in San Diego harbor. Both differential aeration [10] and bacterial influence were considered possible mechanisms, the latter facilitated by the high levels of sewage pollution in the harbor at that time [11].

In 1963 Arup and Glantz [12] summarized an extensive survey of 20 Danish harbors. It reported perforation of steel sheet piling after 25-35 years service, and pitting corrosion rates estimated at 0.25-0.5 mm/year for piling 15-35 years old. The greatest corrosion losses were observed 0.3-0.6m below

mean low tide (MLT), which, for the small tidal range in Danish waters, corresponds closely to LAT. The authors made the almost casual observation that 'the highest corrosion rates have been found in harbors with fish industries'. Although not elaborated by the authors at the time, a more modern interpretation immediately suggests a link to microbiologically influenced corrosion (MIC) since waste from fish industries can act as nutrients for bacteria [13].

Microbiologically influenced corrosion (MIC) has a long history, particularly for buried steel and cast iron pipes [14]. By the early 1990 it had become linked also to the corrosion of sheet piling [15,16]. This was confirmed in several studies [17, 18, 19]. These reported high bacterial counts in seawaters adjacent to steel piling whenever ALWC was present and that the sulfate reducing bacteria (SRB) [20], usually associated with marine corrosion, were present. Other bacteria also were reported, including the sulfur oxidizing bacteria (SOB) known to enhance the metabolism of SRB [13] and iron oxidizing (IOB) and iron reducing bacteria (IRB). These bacteria are involved in the model for the localization of the ALWC effect as proposed by Gehrke and Sand [21]. While these observations and the model are important in gaining understanding, their relevance for long-term ALWC is less clear, particularly when considerable rusts have formed on the steel exterior surfaces as of older piling [16]. An example of the difficulty of relating bacterial observations to ALWC can be seen in a study of sheet piling corrosion at 22 different sites in harbors in Europe [17, 22]. No clear correlation could be established between bacterial counts and ALWC for piling some 30-40 years old and already considerably corroded. At 10 sites the sheet piling did not appear to have been affected by ALWC (as judged by sheet pile perforation), despite high bacterial counts. However, iron sulfide, the corrosion product normally associated with SRB activity (and usually considered the most common cause of MIC), was detected at all sites [23].

Since all experience to date associates ALWC only with long-term marine exposures, a detailed practical study of the contribution of MIC to ALWC and its relationship to nutrient availability would appear to require longer-term observations. Such a research program is unlikely to be feasible in a laboratory setting, more so since this can seldom replicate the precise conditions required for a realistic study of microbiological activity and its potential influence on seawater corrosion, including that of steel [24]. On the other hand, 30-40 year long field test programs to understand long-term behaviour also are unrealistic. A way forward, paralleling the recent work on the development of better understanding marine immersion corrosion of steel, is to employ mathematical models that are based both on field data and on corrosion science principles [25, 26]. Previous work in this area already has

shown the importance of the effect of MIC soon after initial exposure [27] and also the importance of MIC much later, when considerable amounts of rust have developed on the steel and the environmental conditions for microbiological activity within the rust layers became appropriate [25, 26]. The underlying hypothesis for the work described herein is that the same model for corrosion applies. This means that any microbiological involvement in ALWC should be evident both in short- and in long-term corrosion influences and thus in experimental observations. In particular, any microbiological involvement in producing an ALWC effect should be evident in short-term field studies.

Under suitable conditions, the rate of MIC of steel is controlled by the rate of bacterial metabolism. In turn this is influenced by the rate of supply of critical nutrients, provided the rate of energy supply, usually from electrochemical reaction kinetics, is sufficient [14, 23]. Of most interest for bacterial activity in seawater is its (dissolved inorganic) nitrogen content (i.e. its concentration), previously shown to be correlated both with early [28] and longer-term exposures in seawater [29]. If ALWC is indeed a function of MIC for steel then the influence of nutrients on the bacterial effect on corrosion can be expected to be reflected also in an effect on ALWC. That there is correlation between bulk seawater nutrient concentration and ALWC is the first working hypothesis.

Empirical data collected from a variety of natural seawater exposure experiments shows that the effect of MIC for exposures lasting days to weeks tends to be relatively less severe than for much longer exposures [26]. This suggests that any ALWC effect that can be attributed to MIC is not likely to be clearly discernible in very short-term experiments, particularly in colder waters. Conversely, experiments of one or more years duration could be sufficient to indicate proneness to ALWC. This is the second working hypothesis.

Two further aspects of ALWC are of interest [23]. Currently no explanations are available why sheet piling of different geometries corrodes in different ways. Larssen (U-shaped) sheet piling usually perforates first in the outer trough of the U shape while Frodingham (Z shaped) sheet piling typically corrodes more severely in the middle or at the folded edges of the Z shape [8]. Also, ALWC appears to be more severe on south-facing compared with north-facing sheet piling for quay walls in (Northern hemisphere) harbors [8]. Although these are important practical issues they are not discussed herein. The present paper is concerned only with the vertical distribution of corrosion on mild steel strips.

Experimental Program

For the reasons outlined above, a field exposure test program was chosen to ascertain whether evidence of ALWC could be detected within 12-24 months and whether there was a correlation with average dissolved inorganic nitrogen concentration in the surrounding seawater. The program consisted of immersing mild steel strips (Table 1), 3 and 6 m long, 50 x 3.03 mm in cross section, at 13 different locations along the East coast of Australia (Fig. 2) at sites selected, intuitively, on the expected average level of seawater nutrient pollution. For example, Ulladulla was chosen because it is a port with fish processing facilities and was expected to have elevated local seawater nutrient concentrations. Williamstown has naval docking and ship building facilities and environmental studies have shown the local seawater has high nutrient concentrations [30]. Conversely, the Townsville site is in a Marine National Park and was expected to have very low nutrient concentrations.

Table 1. Typical composition of mild steel strips used in the study (wt %).

Figure 2. Map of eastern Australian coastline showing corrosion testing sites.

At the Jervis Bay site the steel strips were exposed about 15 m apart along a wooden jetty, so as to capture different tidal water velocities. The velocities were estimated from visual observations. Tidal water velocity effects also were investigated near the mouth of the seawater bay of Lake Macquarie, on the Pacific Ocean, at three sites (Swansea Heads, Pelican and Marks Point Marina), separated some 1.8 km but with very similar water quality. The peak tidal water velocities at these sites are known from a previous study [31].

Water quality monitoring was carried out periodically at all sites. Seawater samples were collected in sterile 1-litre bottles and immediately sent to a commercial water-quality testing laboratory for analysis (Table 2). Because nutrient concentration levels are known to vary throughout the year, with extremes occurring typically in Summer and Winter [32], water quality samples were taken at these times where possible as well as in Spring and Autumn. Table 2 shows the ranges of the readings at each site. Annual average seawater temperature was similarly recorded at each site or was known from previous mild steel seawater corrosion studies.

Table 2. Water Quality at the exposure sites

At all exposure sites the strips were placed in locally open conditions away from physical protection or sheltering and in one case well away from a impressed current protection system. In all cases the strips were attached to a timber jetty using one steel bolt at the top of the strip. In the more exposed locations the longer strips were also bolted to timber at lower levels so as to reduce vibration and bending due to tidal currents. The use only of timber jetties for the exposure of the steel strips was considered to provide sufficient electrical insulation from surrounding structures.

Because of the difficulty of preparing the surfaces of these long strips to conventional corrosion testing standards, all strips were exposed in the 'as-delivered' condition, apart from being degreased prior to exposure. All the strips had a uniform smooth grey surface mill-scale finish. Previous studies have shown that the presence of mill-scale has only a temporary, short-term effect on marine corrosion loss although it has a longer effect on pitting [3]. In most cases strips were recovered at 6, 12, 18, 24 and 36 month exposure periods, although because of practical and operational difficulties these timings were not always achieved exactly nor were recoveries always made for all planned periods. Also, some strips were lost in-service or could not be recovered. In each case only one strip was recovered at a time, approximately at every six months, rather than duplicate strips at 12 month intervals. This provides more information for the same amount of material and test space.

Immediately after recovery marine growth, fouling and loose rusts were removed from the strips. They were then repatriated to the laboratory where they were immediately guillotined sequentially into individual segments to a 100 mm gauge-length and number-punched sequentially as they were cut. This permitted subsequent re-assembly of each strip and the construction of plots of corrosion loss as described below. Each segment was cleaned to remove adherent rusts in accordance with ASTM G3.

The mass loss for each steel strip segment over the exposure period was calculated using the assumption that the original mass of each segment could be estimated from the density of the steel and the original dimensions (allowing where necessary for any fixing holes). The uncertainty in mass loss was estimated by considering the error in the cutting of the strips to segment lengths, the error in estimating the original mass as governed by permissible dimensional tolerances and the error in determining the mass of the cleaned corroded segments. The total uncertainty in mass loss was estimated at around 10% but because for each strip all segments were from the same steel profile and all segment lengths were governed by the same gauge length set on the guillotine, the between-segment mass loss uncertainty was estimated to be much lower, about 1%.

Experimental Results

The equivalent corrosion loss for each segment was calculated from the mass loss. For each site Fig. 3 shows the corrosion losses as a function of vertical elevation at 12 month exposure (where available). The individual corrosion mass loss is plotted at the mid-height elevation of each segment. From these data the corrosion loss profiles were constructed using a piecewise linear fitting routine. The mean high tide (MHT), mean tide (MT) and mean low tide (MLT) levels are as shown for all cases and the highest astronomical tide (HAT) level and the lowest astronomical tide (LAT) level in some cases.

Figure 3. Corrosion loss profiles at 12 months (where available) for all sites in the experimental program.

In Fig. 3 where an ALWC region appears to occur in the profile it is identified, together with the estimated corrosion loss in that region, marked A. Also shown are the mid-tide corrosion region and the corresponding corrosion loss (M) as well as the immersion corrosion region and its corresponding average corrosion loss (I). As in earlier work on immersed steel strips, there was some variation ('wobble') with depth [5]. In some cases there was a rather high corrosion loss at the end of the strip, similar to that noted both in classical studies [4] and in previous field studies [5, 6]. Both this and the 'wobble' effect were ignored. Table 3 gives a summary of the values of A, M and I estimates from the corrosion profiles for all sites at all the exposure periods for which data were collected. Inevitably, some degree of judgment was required in deciding on the locations of A and I in particular and in assigning values.

Table 3. Corrosion loss measures *A*, *I* and *M*, parameters R_1 and R_2 and average dissolved inorganic nitrogen concentrations [N] for the exposure sites.

Analysis

In analyzing the results the effect of seawater temperature and of possible nutrient load on corrosion profiles must be considered as well as the effect of higher water velocities. As there is insufficient data for a factorial analysis the approach adopted is to consider first the sites with lower water velocities. These constitute the majority. The next step is to attempt to eliminate or reduce the effect of water

temperature since this will be vary between the different geographical sites. This is done through the use of two parameters. The first is the ratio R_1 , defined as:

$$R_1 = A / I \tag{1}$$

where *A* is the corrosion loss estimated for the ALWC zone and *I* is the average corrosion loss estimated for the immersion zone, ignoring any end effect, as shown for each case in Fig. 3. The use of R_1 rather than the actual losses tends to by-pass the influence of water temperature in the following way. It is well known that higher water temperatures increase both the rate and the amount of immersion corrosion loss and also that water temperature varies with seasons. For longer-term corrosion losses the latter can be accounted for by considering only the annual mean seawater temperature as used in previous studies [26]. Also, it is reasonable to assume that water temperature has a similar effect on both the corrosion losses *A* and *I*. Thus, taking their ratio can be considered as a first approximation to eliminate the effect of water temperature between the different geographical sites. With this assumption, Fig. 4 shows the corrosion loss ratio R_1 plotted against the annual average dissolved inorganic nitrogen (DIN) load for all the results for each of the sites (Table 3). It might be noted for aerated seawaters the major component of DIN is nitrate since nitrites and ammonia rapidly oxidize to nitrate [14].

Figure 4. Correlation between the ratio R_1 for maximum low water and immersion corrosion losses and the average dissolved inorganic nitrogen concentration [N] in the local seawater.

The second parameter is the ratio R_2 defined as:

$$R_2 = A / M \tag{2}$$

where A is as before and M is the corrosion loss at the mid-tide level (MT) as shown in the cases given in Fig. 3. Table 3 summarizes the results for each of the data sets. Although the steel surface average temperatures were not ascertained at the locations where A and M are shown in Fig. 3, in this case, too, it may be assumed that the temperatures are similar, at least for longer-term exposures when rust layers have developed since these tend to retain seawater within the rusts under which corrosion occurs. For the shorter-term exposures of the present study there is likely to be a somewhat higher net water temperature for M during the summer months and perhaps a somewhat lower temperature during winter. These two effects are likely to balance out over one year of exposure. In any case there would be a broadly similar effect for all the test sites. The ratio R_2 is plotted in Fig. 5, again as a function of annual average dissolved inorganic nitrogen concentration in the local seawater (Table 3).

Figure 5. Correlation between the ratio R_2 for maximum and minimum corrosion losses and the average dissolved inorganic nitrogen concentration [N] in the local seawater.

The effect of water temperature can be seen in Fig. 6 in which the influence of nutrients is ignored. It shows that there is little effect of temperature on R_1 . An alternative measure *A*-*I* is shown in Fig. 7. Comparing it to Fig. 4 shows very similar relativity between the sites and the measure of the difference between corrosion measured by *A* and that measured by *I*. It follows that either R_1 or *A*-*I* can be used as a measure of the ALWC effect. In the following R_1 is used for further comparisons.

Figure 6. Effect of average seawater temperature T on parameters R_1 and R_2 .

Figure 7. Correlation between the difference between the maximum low water and the immersion corrosion losses (A - I) and the average dissolved inorganic nitrogen concentration [N] in the local seawater.

The progression of the corrosion profiles with period of exposure is evident in the data given in Table 3 and is shown in Figs. 8, 9 and 10 for Hobart, Queenscliff and Townsville, which, based on the usual climatic zone classifications in Australia, can be taken to represent cool, temperate and tropical water sites respectively. These cases also represent extremes in nitrogen concentrations – from high to very low respectively (Table 3). It is seen that at only 6 months and at one year exposure the evidence for the ALWC effect is not particularly clear but that it becomes more evident with somewhat longer exposures.

Figure 8. Progression of corrosion profile as a function of exposure period for strips exposed at the Hobart site.

Figure 9. Progression of corrosion profile as a function of exposure period for strips exposed at the Queenscliff site.

Figure 10. Progression of corrosion profile as a function of exposure period for strips exposed at the Townsville site.

The effect of water velocity is shown in Figs. 11 and 12 for Jervis Bay and the sites near the ocean entrance to the seawater bay Lake Macquarie, respectively. In all cases these are for one-year exposures. It is evident that the differentiation between the corrosion losses A and I is not particularly clear. As a result it is not possible to be definitive about the effect of water velocity on R_1 and R_2 . This is a matter for further investigation.

Figure 11. Effect of water velocity on the corrosion profile for steel strips exposed at Jervis Bay.

Figure 12. Effect of water velocity on the corrosion profile for steel strips exposed in Swansea Channel (Swansea Bridge, Pelican and Marks Point Marina respectively).

Discussion

The results given in Tables 2 and 3 and Figs. 4 and 5 are up-dated from preliminary results for strips with shorter exposure periods and for a small number of sites [33]. Comparing the present results and trends with the earlier results and trends shows that although the ordering for nitrogen concentration levels has changed somewhat, the overall outcomes are very similar. Both show a good correlation between the ALWC effect and the average dissolved inorganic nitrogen concentration of the seawater at the exposure location. This is despite the obvious scatter in the data shown in Figs. 4 and 5. Overall, the trends are consistent both with anecdotal historical observations and with what has been suspected but hitherto not demonstrated.

The trend line for R_1 in Fig.4 is seen to be a moderately good fit to the data, indicated also by the correlation coefficient R = 0.65. Extension of the data trend for R_1 shows it is approximately unity at zero nutrient concentration. This means that there is no ALWC effect and can be compared with the classical corrosion profile given by LaQue [2] for steel strip immersed for 151 days at Kure Beach (Fig, 1) at a time when water pollution and hence DIN concentration levels in the area would have been very low.

The trend line for R_2 in Fig 5 also is a moderately good fit to the data with a similar correlation coefficient R = 0.66. Extrapolating the trend to zero dissolved inorganic nitrogen concentration shows that at N = 0 parameter R_2 is approximately 1.5 which is much lower than the values that can be deduced for Kure Beach (Fig. 1). Obviously this is the result of the very low values (approaching zero) of corrosion loss in the mid-tide zone. The precise experimental conditions that existed at the time at Kure Beach cannot now be ascertained but for the present results it can be confirmed that none were sheltered and all were subject to moderate wave action in unprotected waters. Wave action and thus a more severe local environment may be the reason for the higher mid-tide corrosion, consistent with what was found in earlier studies at Jervis Bay [5, 6]. This also may be the reason for the high corrosion losses observed in the high tide region at Newcastle Harbour Entrance (Fig. 3).

The trends for R_1 and R_2 as functions of mean seawater temperature (Fig. 6) show that for R_1 there is little effect of temperature, as expected. If anything, the relative difference between A and I as measured by R_1 decreases with increasing temperature. This is considered the result of corrosion for both A and I increasing with water temperature. Using the values given in Table 3 it is found that the difference A-I also decreases with water temperature. Both these observations are important since they show that the ALWC effect is likely to be somewhat greater in lower water temperatures. This may explain why AWLC was first observed in the colder waters of the UK and of France.

Figs. 8, 9 and 10 show the progression of the corrosion profile with increased exposure period for three different sites. Typically, the ALWC phenomenon is seen already after only one year of exposure. This is considerably shorter than the detection time for ALWC reported in any previous investigation. These results contradict the notion that ALWC is a phenomenon that becomes evident only after long-term exposures [8].

The observations in Figs. 8, 9 and 10 that the ALWC effect is seen already after about one year of exposure is consistent with the hypothesis for the present work that if bacteria are involved in ALWC in long-term exposures then evidence of it should be available already soon after first exposure in seawater. Apart from artificial laboratory experiments, direct evidence that the bacteria or other micro-organisms associated with areas of corroding steel are actually involved in the corrosion process, and hence contribute to either pitting or corrosion loss or both of steel in in-situ situations, has been difficult to obtain [34]. In contrast the approach used herein is to side-step the identification of micro-organisms and instead to ascertain whether there is a relationship between critical nutrient availability

(in this case dissolved inorganic nitrogen) and corrosion loss or pitting, irrespective of precisely which bacteria or other micro-organisms are involved [26]. Such relationships are precisely what is shown in Figures 5 and 6.

The use in the present analysis of bulk water nutrient concentration is entirely for practical reasons. The nutrient concentration of direct relevance for bacterial metabolism is that in the immediate vicinity of the organisms involved, that is within the biofilms or similar locations. However, to measure or estimate bacterial metabolism in such locations is clearly difficult and also raises the issue of interference by the experimental techniques in the very processes being studied. For this reason also, the bulk water nutrient content was used, despite its surrogate nature. Nevertheless, it might be expected from considerations of species diffusion that the nutrient concentration in the bulk water will be reflected, on average, in the local nutrient concentration adjacent to microorganisms, even though it will not be the same and may vary between locations and the microorganisms involved. Moreover, there is likely to be interaction between different microorganisms and between different levels of nutrients - the precise details of these interactions are, of course, of scientific interest but are unlikely to be directly relevant to practical assessment of risk of ALWC. Whether these localized effects have a significant influence on the longer-term corrosion processes remains to be elucidated through further research. Neglecting this aspect implies an additional degree of uncertainty in the data and in its interpretation and therefore is likely to be a part of the scatter seen in the data in Figs. 4 and 5. Nevertheless, both Figs. 4 and 5 show good correlation between nutrient load and corrosion loss profiles. It is this aspect that is of most direct practical interest.

There are three practical implications from the above findings. The first is that the likelihood of longterm ALWC problems can be estimated using observation(s) of the corrosion loss profile of steel strips similar to those reported here, within exposure periods of 1-3 years. The corrosion profile can be measured easily, after cleaning, with a micrometer or ultrasonically. This is a simple process.

The second practical implication follows from Figs. 5 and 6. Despite the scatter in the data, they show positive correlation between corrosion loss below the MLT region and dissolved inorganic N concentration in the bulk water. It follows directly that (i) waters with low or negligible concentrations of N are unlikely to lead to ALWC and (ii) that the likelihood of the occurrence of the ALWC phenomenon increases with higher N levels. In this sense corrosion loss and pitting are 'accelerated' in time over what would be expected in low nutrient waters and provides some justification for the

'accelerated' in ALWC. It also means that water quality data for a site can provide a simple means for assessing the likelihood of the occurrence of ALWC. If water quality data is not available at least one year of observation is required to obtain a suitable assessment of the average dissolved inorganic nitrogen concentration.

The third implication arises from the observations that while the severity of the ALWC phenomenon relative to immersion corrosion decreases with average seawater temperature (Fig. 6), the rate of corrosion under immersion conditions increases with average water temperature. The overall result is that higher water temperatures result in faster corrosion but with lower likelihood of ALWC. Conversely, it may explain why ALWC appears to have been observed first in colder seawater harbours (Copenhagen, Aberdeen).

As noted in the Introduction, ALWC is not a modern phenomenon as sometimes assumed, having been noted in Danish harbors already in the 1950's if not earlier [12]. Nevertheless, its relatively recent widespread appearance in ports along the North Sea and also in Atlantic Ocean ports, both in the UK and elsewhere, appears to have been quite unexpected [7]. A possible explanation for this can now be offered. For the North Sea and the North Atlantic, environmental studies have shown that water pollution, and thus nutrient loading had risen considerably in coastal zones since about the 1950s [35]. There is now evidence that this has peaked and may be declining [32]. However, long-term corrosion integrates the influences of environmental variables over many years of time and what is observed after many years perhaps is simply the legacy of earlier periods of high nutrient loadings (i.e. water pollution). This may be the simple explanation for the puzzle of the apparently modern nature of ALWC – that it is the outcome of earlier decades of high levels of water pollution and that it is a matter of time before that legacy is revealed. This proposition remains a matter for further investigation, perhaps through attempting a correlation study of the evolving nature of ALWC discoveries and the relevant local histories of nutrient pollution.

Conclusion

1. Despite the scatter in the available data for corrosion loss and for water quality, positive correlation was found between moderate levels of annual average dissolved inorganic nitrogen content in the bulk seawater and ALWC (as measured using the two parameters proposed herein). Since long-term

corrosion is related to short-term corrosion, this offers a practical indicator of the risk of long-term ALWC occurrence.

2. Comparison to earlier work demonstrates that the correlation is robust and not very sensitive to uncertainty in the available data, both for corrosion loss profiles and for water quality.

3. In nutrient rich waters steel tests strips show corrosion profiles with evidence of the ALWC effect already after short-term (1-3 year) periods of exposure. Thus the measurement of corrosion profiles after 1-3 years exposure offers a second practical approach for assessing the long-term risk of ALWC.

4. The experimental data presented herein do not support the notion that severity of ALWC is influenced by water velocity. The data do suggest that the severity of ALWC is reduced somewhat with average seawater temperature. This may explain why the first modern observations of ALWC occurred in colder UK and French waters.

5. The increased occurrence of ALWC reported in recent years most likely is the result of elevated levels of nutrient concentration in the waters to which the steel piling has been exposed over its lifetime, irrespective of the current nutrient levels.

Acknowledgements

The authors acknowledge with gratitude the continued financial support of the Australian Research Council. They also acknowledge the very helpful support of a number of people and organizations in facilitating the exposure tests reported here. They include: Royal Australian Navy (Jervis Bay), Australian Institute of Marine Sciences (Townsville), Port Stephens Fisheries Centre, Taylors Beach (NSW Department of Primary Industries), Tasmanian Police (Hobart), Tasmanian Department of Conservation and Infrastructure (Port Arthur), Queenscliff Cruising Yacht Club, Defence Science Technology Organization (Williamstown), Newcastle Port Corporation and Marks Point Marina.

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Corrosion of long vertical steel strips in the marine tidal zone and implications for ALWC





Figure 1 - Some classical data and corrosion profiles for exposure of mild steel strips (and coupons) in the Atlantic Ocean at Kure Beach, USA. For strips the highest corrosion loss is in the splash zone.



Figure 2 - Map of eastern Australian coastline showing corrosion testing sites.









Figure 3. Corrosion loss profiles at 12 months (where available) for all sites in the experimental program.



Average Dissolved Inorganic Nitrogen Concentration [N] (mg N / I)

Figure 4. Correlation between the ratio R_1 for maximum low water and immersion corrosion losses and the average dissolved inorganic nitrogen concentration [N] in the local seawater.



Figure 5. Correlation between the ratio R_2 for maximum and minimum corrosion losses and the average dissolved inorganic nitrogen concentration [N] in the local seawater.



Figure 6. Effect of average seawater temperature T on parameters R_1 and R_2 .



Average Dissolved Inorganic Nitrogen Concentration [N] (mg N / I)

Figure 7. Correlation between the difference between the maximum low water and the immersion corrosion losses (A - I) and the average dissolved nitrogen concentration [N] in the bulk seawater.



Figure 8. Progression of corrosion profile as a function of exposure period for strips exposed at the Hobart site.



Figure 9. Progression of corrosion profile as a function of exposure period for strips exposed at the Queenscliff site.



Figure 10. Progression of corrosion profile as a function of exposure period for strips exposed at the Townsville site.



Figure 11. Effect of water velocity on the corrosion profile for steel strips exposed at Jervis Bay.



Figure 12. Effect of water velocity on the corrosion profile for steel strips exposed in Swansea Channel (Swansea Bridge, Pelican and Marks Point Marina respectively).

Table 1. Typical composition of mild steel strips used in the study (wt %).

С	Р	Mn	Si	S	Ni	Cr	Mo	Cu	Al	V	Ti	Sn	Pb	Fe
0.13	0.019	0.04	0.106	0.033	0.01	0.03	<0.01	0.03	< 0.005	0.002	0.001	0.006	<0.01	Bal.

Table 2 Water Quality at the exposure sites

Parameter	Units	Townsville	Coffs Harbour	Taylors Beach	Newcastle Harbor	Swansea Bridge	Pelican	Marks Point
Mean Water Temp	°C	26.5	21	20	20	20	20	20
No. of samples		3	3	6	2	3	4	4
Salinity	g/kg	32.5	33.1-35	31.3	29.4-31.8	26.7-35.2	24-35.3	26.1-29.8
pН		7.5-8.2	8.2	??	9.4-9.6	8.1-8.3	8.2-8.3	8.1-8.2
D.O.	mg/l					7.0-7.5	7.3-7.9	7.1-7.8
D.O. % saturation				>90		92-		92-
Conductivity	µS/cm		47300			47500	42200-47600	47300
Nitrates	mg N /l	<0.005-0.016	< 0.01	0.017-0.05	0.05-0.07	0.005-0.01	0.005-<0.01	< 0.01
Nitrites	mg N /l	0.002-0.005	< 0.01	0.003-0.11	0.01	0.005	0.005	< 0.01
Sulphates	mg S /l	2400-2720	2650	1600-2750		2200-2650	2500-2700	2000-2400
Ammonia	mg N /l	0.014-0.19	<0.02-0.12	0.05-0.08	0.06	0.02-0.03	0.01-<0.02	< 0.02
Ortho-Phosphates	mg P /1	0.003-0.017	0.006	< 0.001	0.01-0.02	< 0.01	0.005-<0.01	0.006-0.01
Total Phosphorous	mg P /1	0.003-0/074	0.012-0.013	0.003-0.07	0.04-0.05	0.005-0.02	0.007-0.02	0/007
Calcium	mg/l	228-286	416-425	409		362-497	376-428	316-428

Parameter	Units	Jervis Bay	Ulladulla	Williamstown	Queenscliff	Port Arthur	Hobart
Mean Water Temp	°C	19	19	16	16	15	15
No. of samples		3	4	3	5	4	4
Salinity	g/kg	29.0	30.2-36.0	30.9-34.1	30.3-36.3	29,1-34.0	23.4-30.0
pН		8.2	8.0-8.1	8.1	8.2	8.0	8.0
D.O.	mg/l						
D.O. % saturation							
Conductivity	µS/cm						
Nitrates	mg N /l	< 0.005 - 0.022	0.005-0.14	<0.003-0.05	0.005-0.16	0.005-0.18	0.005-0.05
Nitrites	mg N /l	< 0.003 - 0.036	0.003-0.007	<0.003-0.01	< 0.01	0.003-0.76	0.003-0.074
Sulphates	mg S /l	2300 - 2800	2250-2800	2490-2760	2689-2960	2615-2984	1888-2700
Ammonia	mg N /l	0.009 - 0.045	0.011-0.14	0.071-0.14	0.005-0.14	0.027-0.044	0.005-0.081
Ortho-Phosphorous	mg P /l		< 0.001-0.06	0.063-0.078	0.001-0.003	0.006-0.011	0.004-0.02
Total Phosphorous	mg P /1	0.007-0.008	0.008-0.11	0.072-0.09	0.005-0.05	0.005-0.05	0.013-0.05
Calcium	mg/l		402-445	400	356-389	352-378	323-374

D.O. = Dissolved oxygen concentration.

Table 3. Corrosion loss measures A, I and M, parameters R1 and R2 and average dissolved inorganic nitrogen concentrations [N] for the exposure sites

Column (1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Site (increasing S latitude)	Exposure	ALWC	Immersion	Mid-tide	Rl = A/I	R2 = A/M	Estimated
	Period	(A)	(I)	(M)	=(3)/(4)	=(5)/(4)	average N ^a
Units	Months	μm	μm	μm			mg N /l
Townsville	6	350	350	200	1.00	1.75	0.02
	12	380	350	240	1.09	2.6	0.02
	18	540	500	260	1.08	2.1	0.02
	24	500	480	420	1.04	1.2	0.02
Coffs	6	420	300	200	1.40	2.1	0.06
Harbour	12	630	500	300	1.26	2.15	0.06
Taylors Beach Wharf	12	560	380	250	1.47	2.24	0.065
	18	550	400	200	1.38	2.75	0.065
	24	590	410	200	1.44	2.95	0.065
Newcastle	6	250	220	100	1.14	2.5	0.05
Harbour	12	290	220	70	1.32	4.14	0.05
Swansea Channel ^b							
Swansea bridge – high	12	470	350	200	1.34	2.35	0.04
Pelican - medium	12	250	210	140	1.20	1.8	0.04
Marks Point - low	12	280	250	140	1.12	2.0	0.04
Jervis Bay ^b - high	12	520	440	170	1.18	3.1	0.045
Jervis Bay - medium	12	480	350	200	1.37	2.4	0.045
Jervis Bay - low	12	460	370	120	1.24	3.8	0.045
Ulladulla	12	420	300	80	1.43	5.3	0.11
Williamstown	6	220	?	?			0.125
	12	60	40	?	1.5		0.125
	18	660	350	110	1.88	6.0	0.125
Queenscliff	8	320	250	120	1.28	2.67	0.095
	13	570	420	200	1.36	2.85	0.095
	18	470	400	200	1.18	2.35	0.095
	24	620	450	220	1.38	2.82	0.095
	30	740	550	220	1.34	3.36	0.095
	38	760	550	230	1.38	3.30	0.095
Hobart	6	450	300	150	1.50	3.00	0.09
	12	550	350	180	1.57	3.06	0.09
	18	750	500	175	1.50	4.3	0.09
	24	640	460	190	1.39	3.37	0.09
	30	840	670	200	1.25	4.2	0.09
	36	790	700	200	1.14	3.95	0.09
Port Arthur	7	390	250	140	1.56	2.78	0.10
	13	540	300	150	1.80	3.60	0.10
	18	580	400	150	1.45	3.90	0.10
	26	520	400	150	1.30	3.47	0.10

Notes: ^a Based on average between summer and winter levels or best estimate. ^b High, medium and low refer to relative water velocities at sample locations.