THE EFFECT COUPON SIZE FOR THE DETERMINATION OF ATMOSPHERIC CORROSIVITY

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SUMMARY: The corrosivity of an atmospheric environment is often determined by exposing metal coupons and measuring mass loss over a certain time, typically one year. It has been shown previously that orientation of the coupon can affect the derived corrosion loss, particularly at severe atmospheric locations. It also has been shown that the season of exposure will influence corrosion loss and that, depending on weather conditions, corrosivity may vary from one year to the next. Typically mild steel has been used as a determining metal but zinc, copper and alloyed steels also have been employed. To date there has been no investigation regarding the size of coupons used for corrosion rate determination. Reported herein are the results of a one-year trial in which four different sized coupons (50 mm x 100 mm to 200 mm x 400 mm) were exposed to the atmosphere at eight different locations, ranging from sub-alpine conditions to a severe marine environment. In almost all locations the smaller coupons showed higher corrosion loss for the same exposure period and conditions. At the more benign sites the difference in corrosion loss was marginal but noticeable. The change in corrosion loss became more obvious as the environment became more aggressive. After only 6 months exposure at the severe marine site the corrosion loss for the 50 mm x 100 mm coupons was more than three times that of the 200 mm x 400 mm coupons. Copper-bearing steel coupons of 50 mm x 100 mm size corroded at a similar rate to the same-sized mild steel coupons in milder environments but at a much higher rate near ocean locations.

Keywords: Coupon size, Atmospheric corrosion, Mild Steel.

1. INTRODUCTION

The corrosivity of an environment usually is determined by exposing metal coupons and measuring mass loss over a particular time period, typically one year. Previously it has been shown that orientation of the coupon can have a significant effect on the derived corrosion loss, particularly at severe atmospheric locations (Jeffrey and Melchers 2008). A similar effect has been observed in tidal conditions (Jeffrey and Melchers 2007). The season of exposure also may influence corrosion loss and that corrosivity may vary from one year to the next, largely as a result of different climatic conditions (Jeffrey and Melchers 2008). Often coupons made from mild steel or zinc are used, but there has been a tendency to employ copper bearing steel because it tends to corrode more evenly, without pitting (King et al 1982).

Coupons of different sizes have been used or recommended. For example, in their classic extensive study of atmospheric tropical corrosion, Ambler and Bain (1955) used 2" x 2" (50 mm x 50 mm) panels. LaQue, in his classic tidal profile evaluation, used 300 mm x 300 mm specimens (LaQue 1975). Peterson and Lennox (1984) used 150 mm x 300 mm x 1.6 mm mild steel and zinc coupons when evaluating the effect of water velocity. Blekkenhorst et al. (1986) had the prepared sheets cut to 300 mm x 250 mm for his extensive research into marine corrosion of alloy steels. Morales et al. (2005) employed 40 mm x 100 mm x 3.0 mm coupons in an extensive atmospheric study on the Canary Islands.

In terms of shape, ISO 9226, the International Standard, recommends two types of coupons for evaluating corrosivity: flat plate specimens and open helix specimens. The Standard recommends that the preferable size for plate coupons is 100 mm x 150 mm and that they should be at least 50 mm x 100 mm. Similarly, ISO 4542 (testing coatings) specifies the surface area of the test specimen should be as large as possible and in any case not less than 50 mm x 100 mm. Further, ISO 8565 (general requirements for field testing) recommends rectangular flat sheets with a convenient specimen size of 150 mm x 100 mm, 1 mm to 3 mm thick. This standard also specifies that the minimum specimen size should be 50 mm x 100 mm.
Finally, the Australian building fasteners standard AS 3566.2 specifies 150 mm x 100 mm zinc coupons for corrosivity evaluation.

In summary, the coupon size most preferred as recommended by various standards is 150 mm x 100 mm, although it is clear that in field investigations a number of other sizes have been used. However, the Standards mentioned do not state on what basis the preferred size is recommended. Nor do they provide information about the influence of coupon size on corrosivity estimates. This matter is explored herein and it is shown surface area of atmospheric corrosion coupons is very important, particularly as the corrosivity of atmosphere increases.

2. TEST PROGRAMME

Four different sized coupons were deployed at eight locations. Coupon sizes were: 400 mm x 200 mm, 200 mm x 100 mm, 125 mm x 75 mm and 100 x 50 mm. The coupons were all cut from the same steel sheet. Their composition is given in Table 1.

<table>
<thead>
<tr>
<th>Table 1. Composition of mild steel used for corrosion coupons.</th>
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<tr>
<td>C</td>
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<tr>
<td>%</td>
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</table>

The mild steel coupons were acid cleaned and weighed to the nearest 0.01g prior to deployment. All coupons were individually identified using a drilled-hole template system. Upon recovery after exposure the coupons were cleaned and reweighed in accordance with ISO 8407 method C.3.5. Corrosion loss (μm) was derived from the change in mass loss. This was done for all coupons recovered from the eight exposure locations selected for the programme (see below). Results obtained at the severe marine site from two separate exposure trials are included in the following. The coupons were deployed vertically and faced north.

In addition to mild steel, copper bearing mild steel (0.25 % Cu) coupons also were exposed at the eight exposure locations. These coupons were from the same heat as those used by King el al. (1982) in their corrosivity study of Melbourne. The analysis of the low alloy copper bearing steel is given in Table 2.

<table>
<thead>
<tr>
<th>Table 2. Composition of low alloy copper bearing steel used for corrosion coupons.</th>
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<tr>
<td>C</td>
</tr>
<tr>
<td>%</td>
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</tbody>
</table>

The amount of airborne chemicals (that could be regarded as either pollutants or nutrients) was measured using salt wicks (also referred to as wet candles). These were exposed at all locations and treated as specified in ISO 9225 section 4. Usually the solution recovered after a month of exposure is analysed only for chlorides but in the present experimental trials it was analysed also for sulphates, nitrates and phosphates so as to estimate their deposition rates. Temperature, time-of-wetness and rainfall also have been monitored at all of test locations. These have been reported previously (Jeffrey and Melchers 2011).

3. EXPOSURE SITES

3.1 Sub-Alpine

Samples were deployed on a sheep and cattle property south of Walcha, NSW. The exposure site is situated on the southeastern edge of the Northern Tablelands, approximately 425 km north of Sydney, 130 km from the Tasman Sea and at an elevation of almost 1500m. Heavy snow falls are usual during most winters. No snow fell during the exposure period in 2011 but the temperature dropped to -11°C several times that winter. Rainfall is similar to other inland sites and airborne nutrients were found to be minimal.

3.2 Inland Rural

The inland rural site is located adjacent to Chichester Dam, which is part of the Hunter Valley domestic water supply catchment and storage infrastructure. Large tracts of State Forests and National Parks border the north and east of the site and the farmlands of the Williams River Valley flank it along the west and south. The Pacific Ocean is over 50 km to the south-east. Coupons were placed in the recreational area abutting the dam, an environment nominally with minimal SOx, NOx and chlorides.
3.3 Turf Farm
This exposure site is north of Newcastle on a turf farm. High levels of fertilizers with high nitrogen content are used to promote the growth of turf. The farm is irrigated from the nearby Hunter River but is far enough from the ocean that chloride deposition is minimal. There are no immediate sources of SOx to promote bacterial activity although there are dairy farms nearby.

3.4 Inland Industrial
This site is located at Lake Liddell, a man-made storage reservoir used for the holding cooling water for two large coal burning power stations. Corrosion coupons were placed in the recreational reserve on the opposite side of the lake to the power station, about 1 km away. Although exhaust gases are monitored and minimal SOx is vented to the atmosphere, earlier reports have identified plumes potentially containing nutrients emanating from these power stations (King et al. 1982, 1992). The lake is fresh water and the site is 80 km from the coast so the influence of chloride should be negligible.

3.5 Intense Agricultural
This site is positioned at a dairy farm. The coupons were placed between a milking bay holding pens and a sewage treatment facility. The coupons are subject to significant sulphur and nitrous product deposition. Because of local transportation of significant amounts of organic waste, it is possible that microbiological consortia are deposited on the coupons.

3.6 Coastal School
This is a secure exposure site adjacent to a school and is located approximately one kilometre inland from breaking surf on the east and a similar distance from Lake Macquarie on the west. The site is considered to represent one with corrosivity typical of many Australian suburbs. The site appears to be relatively free of SOx and NOx airborne compounds although it is noted that it was, at one time, the site of a coalmine. The known very sharp drop of salt deposition with distance from the ocean probably explains the relatively low chloride levels detected at this site.

3.7 Fertilizer storage shed
At this large storage and blending facility on Kooragang Island, Newcastle, tonnes of various sulphates, nitrates, phosphates, urea and ammonium salts are trucked in daily, mixed as required, and shipped out to rural customers. Newcastle harbour, the Hunter River, coal loaders and chemical plants are all within one kilometre of the shed, making this location highly susceptible to airborne contaminants. The exposure test site is located immediately adjacent to the main building. It is likely that the coupons are exposed to high levels of airborne nitrates and sulphates from the blended material.

3.8 Severe Marine
This exposure site is at Belmont Beach, less than 200m from breaking surf. The atmospheric chloride content typically is >300 mg/m$^2$.day. Corrosion loss results obtained at this location have been published previously (Jeffrey and Melchers 2008). It was selected because of its close proximity to breaking surf and consequent high chloride deposition. Sulphur and nitrous products are minimal.

4. ENVIRONMENTAL RESULTS
Environmental monitoring was performed at all the sites. In addition, some observations of past environmental conditions are available in the literature for some of the sites. King et al. (1996) published sulphur and chloride contour maps of the Greater Newcastle region that correlated well with a previously published corrosivity map of the same area (King and Carberry 1992). In that work corrosivity was determined by exposing 142 low alloy steel coupons in a grid covering about 1000 square kilometres around Newcastle and Lake Macquarie region. Rust from the exposed low alloy steel was later analysed using an X-ray Energy Dispersive (XRD) spectrometer to semi-quantify the sulphur and chloride content. Results were transformed into sulphur and chloride contour maps. The results on the sulphur deposition map indicated that corrosion was closely associated with heavy industry. Sulphur deposition from this previous study is of limited relevance now because of the closure of the zinc smelter and the integrated steelworks. However, the chloride deposition map is likely to remain relevant. It also demonstrates the hyperbolic relationship between chloride deposition and distance from the ocean.

For the present study the ‘wet candle’ method was used to obtain estimates of deposition rates. The ‘wet candle’ method was developed by Ambler and Bain (1955) who conducted extensive atmospheric corrosion studies in which they correlating salinity levels with corrosion rates. The ‘wet candle’ subsequently was adopted as an ISO standard. Although this normally relates only to estimating salt deposition rates, the method also can be used to estimate deposition rates of other anions such as nitrates, sulphates and phosphates. This approach was adopted for the present study. The results from the wet candles placed at the test sites are shown in Table 3, expressed in mg/m$^2$.day.
Table 3. Deposition rate of anions at test locations (mg/m². day)

<table>
<thead>
<tr>
<th>Site</th>
<th>Chloride</th>
<th>Sulfate</th>
<th>Nitrate</th>
<th>Phosphates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Severe Marine</td>
<td>252</td>
<td>45.2</td>
<td>0.081</td>
<td>0.110</td>
</tr>
<tr>
<td>Fertilizer Shed</td>
<td>40</td>
<td>40.2</td>
<td>4.000</td>
<td>4.667</td>
</tr>
<tr>
<td>Turf Farm</td>
<td>44</td>
<td>0.8</td>
<td>50.000</td>
<td></td>
</tr>
<tr>
<td>Coastal School</td>
<td>16</td>
<td>19.4</td>
<td>0.048</td>
<td>0.042</td>
</tr>
<tr>
<td>Dairy</td>
<td>56</td>
<td>0.8</td>
<td>175.000</td>
<td></td>
</tr>
<tr>
<td>Power Stations</td>
<td>2</td>
<td>103.4</td>
<td>0.483</td>
<td>0.052</td>
</tr>
<tr>
<td>Rural Dam</td>
<td>6</td>
<td>32.3</td>
<td>0.013</td>
<td>0.016</td>
</tr>
<tr>
<td>Sub-Alpine</td>
<td>13</td>
<td>51.6</td>
<td>0.010</td>
<td>0.387</td>
</tr>
</tbody>
</table>

It is seen that the results are quite variable between the test sites, however certain, expected, trends can be observed. The highest chloride deposition was at the severe marine test site with much lower levels at the inland stations. Sulphate levels were highest at the power stations – probably because of SO₂ emissions and also unexpectedly high at the sub-alpine farm possibly caused by fertilizer application. Nitrates were highest at the intense agricultural farm and lowest at the remote locations. Deposition of phosphates was significantly the highest at the fertilizer blending shed, with only trace amounts elsewhere.

5. CORROSION LOSS RESULTS

5.1 Sub-Alpine (Fig. 1)

Fig. 1 shows that the corrosion losses at this site are low, as would be expected for the exposure conditions this location. There is some variation in measured corrosion loss for both the 6 and 12 month exposures. Fig. 1 shows also that after 6 months the larger coupons had corroded slightly less than the smaller coupons. This is also the case after 12 months exposure. The copper bearing mild steel and the same sized mild steel corroded at almost the same rate. For the short exposure time shown in Fig. 1 the corrosion trend is approximately linear.

5.2 Inland Rural (Fig. 2)
The results for the inland rural site, which is in a national park, show a range of corrosion losses after six months and a noticeable difference after a year of exposure (Fig. 2a). The range varies by more than 100% for the 6 month exposures, depending on the size of the coupon. The 75 mm x 125 mm coupon showed a loss of 18 microns, whereas the largest coupon corroded at less than half that rate at 8 microns. The 12 month results show a smaller range for the corrosion loss and the larger coupons show noticeably less corrosion. The copper bearing coupons corroded at about the same rate as their mild steel counterparts. Fig. 2b shows that the corrosion rate trend varies between almost linear with time to quite nonlinear.

5.3 Turf Farm (Fig. 3)

At this site the corrosion losses were remarkably consistent between the coupons (Fig. 3). The larger plates show almost the same corrosion loss (20 and 21µm) after six months of exposure. Corrosion losses after one year show very little variation but there is a very slight decrease from the smallest plate, from 39µm to 36µm on the largest plate.

5.4 Inland Industrial (Fig. 4)

The maximum corrosion loss at this site, which is one kilometre from two large power stations, was similar to that observed at most of the inland locations despite airborne contaminants being the highest for any of the rural sites. There was however significant difference in corrosion loss depending on the plate size (Figure 4a), the 6 months exposure results show a moderately higher (40%) corrosion loss on the smaller coupons compared with the larger plates. After 12 months the smallest coupon corroded almost twice as much as the 75mm x 125mm plate (35µm as against 19µm). The larger plates

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show an approximately linear corrosion loss trend with time. However, corrosion losses on the smaller coupons tend to increase with exposure (Fig. 4b). The coppered steel specimen has a similar corrosion loss to that of the mild steel coupon.

5.5 Intense Agricultural (Fig. 5)

The intense agricultural site is at a dairy farm between the milking holding bay and the sewage treatment ponds. The general corrosion loss rate of 30µm/year to 40µm/year (Fig. 5a) is similar to that at the power stations and the turf farm. After six months of exposure there is a direct relationship between plate size and corrosion loss (Fig. 5a). This is less pronounced after one year, although care is required in interpretation as the largest plate was compromised. When the coupons were first deployed at this site it was closed-off from animal activity. However, during the second 6 months, cattle were able to gain access to the area and it appears that the largest coupon was used as a ‘back-scratcher’ and became dislodged from the cross-beam of the test rack. For this reason the result for the 12 month exposure of the largest plate is not shown. Fig. 5b shows an approximately linear relationship between loss and exposure period. The copper-bearing coupons show about the same corrosion loss as the mild steel plates.

5.6 Coastal School (Fig. 6)

At this site, located about one kilometre from breaking surf, corrosion losses are similar to those at a number of the inland locations, with a rate of about about 30 µm/year (Fig. 6a). The corrosion losses at this site show a high degree of consistency. The corrosion rate is similar for all sized coupons for both 6 and 12 month exposures although the largest plate shows the least loss for both recoveries. The copper steel corroded at almost the same rate as its mild steel counterpart. Figure 6b shows a very slight increase in corrosion loss with time for all but the 75 mm x 125 mm coupon.

5.7 Fertilizer Blending Shed (Fig. 7)
Except for the beach site, the 6 month corrosion losses at this site are the highest recorded. However, the coupons recovered from this site show unusual corrosion behaviour. There is little or no increase in corrosion for some of the coupon sizes after the first 6 months of exposure (Fig. 7a). This can be seen also in Fig. 7b, with corrosion loss trends in some cases slowing (or even apparently reversing) after the first six month of exposure. The smaller coupons appear to have stopped corroding after initially corroding at a very fast rate while the corrosion losses for the larger plates increased by only 50%. It would appear from these results that the airborne contaminants may have acted as inhibitors and slowed or stopped the corrosion process.

In this case also, the larger plates corroded less than the smaller ones. The copper bearing-steel corroded much less than the corresponding mild steel plates, suggesting that airborne particulates may have had a role in this through reacting with the copper. This effect is seen in Fig. 7b. The smaller coupons show no further corrosion after six months and the corrosion rate of the larger plates and copper-bearing steel diminishes.

### 5.8 Severe Marine (Fig. 8)

For this site, as expected, corrosion loss 200m from breaking surf proved to be the highest in the study. However, the dramatic effect of coupon size on corrosion loss was not expected (Fig. 8a). After six months corrosion loss on the smallest coupon is three times greater than that of the largest plate. After 12 months the 50 mm x 100 mm coupon had corroded almost six times as much as the 200 mm x 400 mm coupon. It appears that the corrosion loss for the coupons is roughly proportional to surface area.

Also unexpected was the very considerable increase in the rate of corrosion with time. Fig. 8b shows the substantial increase in corrosivity between the two recoveries. Corrosion on the largest plate increased about 250 % and on the small coupon about 430%.

The results also show the effect on corrosion loss of alloying with copper in reducing marine atmospheric corrosion (Fig. 8a). This effect has been known for a long time (Coburn et al. 1995).

### 5.9 Independent Trials

In addition to the main study reported herein, two other trials were undertaken at the severe marine test site for additional reasons. The results are available (Jeffrey and Melchers 2011, 2012).
The first trial involved recovery of 50 mm x 100 mm coupons on a monthly basis and the second employed 75 mm x 125 mm plates recovered in triplicate every three months. Both trials were initiated at about the same time. Corrosion losses for these two trials are compared in Fig. 9. It shows the corrosion losses extending over a period of 2.5 years. It is apparent, again, that the smaller coupons corrode at a faster rate than the larger coupons.

5.10 Copper-bearing steel

It has long been recognized that small additions of copper (0.25-0.5% by weight) increase the corrosion resistance of mild steel (Coburn et al. 1995). When used for structural applications these steels are reputed to have about three times the atmospheric corrosion resistance as mild steels. Lower amounts of copper are reported to encourage uniform corrosion and avoid pitting (King et al. 1982). This is seen also in the present results, summarized in Fig. 10.

Fig. 10 shows that after 6 months the copper-bearing steel had corroded marginally less than the non-alloyed steel at all locations. The difference ranged from 10% to 25% at rural sites but increased to almost twice that at the fertilizer shed and was greater than seven times at the severe marine site. The copper-bearing steel lost only 12 microns at the ocean beach site, about the same or less than at most of the rural exposure sites. After 12 months the difference between the two metals was less pronounced at most of the inland sites and in some cases the copper-bearing steel had corroded slightly more than the mild steel. The variability in corrosion loss of the copper-bearing steel coupons at the turf farm (41 µm and 50 µm) was greater than that of the mild steel coupons (38 µm and 39 µm) but as there were only two specimens in the trial no strong conclusions can be drawn.

After 12 months the difference between the two metals was less pronounced at most of the inland sites and in some cases the copper-bearing steel had corroded slightly more than the mild steel. The variability in corrosion loss of the copper-bearing steel coupons at the turf farm (41 µm and 50 µm) was greater than that of the mild steel coupons (38 µm and 39 µm) but as there were only two specimens in the trial no strong conclusions can be drawn.

At the fertilizer shed corrosion loss of the mild steel did not increase in the second six months but the alloy steel lost a further 50%. Possible reasons for this phenomenon are discussed below.

The most dramatic difference between the two metals occurred in severe marine conditions. After six months the copper-bearing coupons had corroded only one seventh that of the same-sized mild steel coupon and after twelve months the difference was about four times.

From these results it appears that the inhibiting effect of low copper alloying becomes significant at more severe exposure sites. It is apparent also that the influence of alloys at more benign environments is beneficial for six months or so but after a year the impact is minimal.
6. DISCUSSION

The primary aim of this study was to determine if the size of the coupon used to determine corrosivity was of significance. Additional conclusions can be drawn, not only showing some correlation between environmental influences and increased corrosivity, but also highlighting factors that appear to inhibit corrosion.

Overall corrosion loss was, as expected, greatest 200m from breaking surf and the least on the NSW Tablelands, 130 km from the ocean. It is clear that at all location larger plates corrode less than smaller plates. The largest test piece (200 mm x 400 mm) did not always corrode the least but on no occasion did it corrode more than any other. The difference in measured corrosivity using the different sized coupons was least at the turf farm and greatest at the beach. The reason for the size effect is not immediately apparent. Edge effect or the ratio of length of cut edge to surface area was investigated previously under marine immersion conditions (Jeffrey and Melchers 2002) and found to be negligible with these sized coupons. However, a crucial difference between the corrosion of immersed plates or coupons, the inland atmospheric coupons and the marine atmospheric coupons is that the latter tend to exfoliate when the corrosion losses are relatively high. Under these conditions it has been observed in the present experiment that moisture tends to accumulate within the rust layers and seep to the base of a vertical coupon. Presumably this is the cause of the differential thinning that is a feature of most of the coupons. It has been observed previously (Coburn et al. 1995). This phenomenon may explain, in part, the size-effect at the severe marine site after 12 months but at all other sites the corrosion product was well adhered with no evidence of corrosion laminations.

At seven of the eight sites, corrosion loss increased with time on all coupons, irrespective of size. In some cases, such as the school and the dairy farm the increase of corrosion loss with time was approximately linear. At the power station corrosion only slightly increased with time, possibly due to the higher sulphate deposition. Close proximity to breaking surf and consequent high chloride deposition correlated with a considerable increase in corrosion loss at the ocean site at Belmont Beach. At the inland dam and the dairy farm the mid-sized coupons (75 mm x 125 mm) exhibited a slight decrease of corrosion rate with time. However at the fertilizer shed coupons of all the sizes tested displayed a loss in corrosivity, with corrosion loss on the smaller mild steel coupons remaining unchanged between six and twelve months. It is of relevance that analysis of the solution recovered from the fertilizer shed showed, relative to all other sites, the highest phosphate deposition level by a significant factor (4.7 mg/m².day). All other sites yielded phosphate deposition levels of less than 1-10% of this deposition rate. It is relevant in this context to note that phosphates in the form of orthophosphates or polyphosphates are used as corrosion inhibitors in fresh water treatment systems.

Consistent with earlier work (Coburn et al. 1995, King et al. 1982) the present study showed that low alloy copper-bearing steel tended to corrode less than mild steel. This was the case throughout for the first 6 months exposures in rural exposure conditions. The effect was more to much more in the very aggressive environments. At 12 months exposure corrosion losses were varied for the rural sites and there was little difference between the copper-bearing and the mild steel. At the coastal marine site (Belmont Beach) the copper-bearing steel corroded significantly less than the mild steel for similar-sized coupons. Overall, these results emphasize the need to specify the grade of steel used for corrosivity assessment as the corrosion inhibiting effect of low levels of copper (and nickel) alloying is important particularly at highly corrosive locations.

7. CONCLUSIONS

The present study has shown that atmospheric corrosivity as defined in corrosion standards depends, in general, on the size of the coupon used to measure corrosion loss. The field experimental work showed that the larger coupons (200 mm x 400 mm) corroded at a slower rate than did the smaller coupons (50 mm x 100 mm) and this effect became more obvious with increased site corrosivity. This was confirmed by independent field trials conducted for completely different reasons over two years.

The present study confirmed earlier observations that the use of copper-bearing low alloy steel generally resulted in slightly lower corrosion losses and hence corrosivity compared with mild steel. The effect was minimal at low corrosivity sites but was quite apparent at highly aggressive severe marine environments. No distinct correlation could be made between corrosion loss on mild steel and low-alloy copper bearing steel.

The inhibiting effect of phosphates deposited on exposed steel coupons was demonstrated and a tentative explanation offered.

8. ACKNOWLEDGMENTS

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He co-authored a paper that won the prestigious T P Hoar Prize (Institute of Corrosion, UK) and has twice been presented with the ACA’s Marshal Fordham award (1999, 2002) and the AC Kennet award (2010) for corrosion research.

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He was awarded the Marshall Fordham prize (ACA) in 1999, 2002 and 2007, the 2004 TP Hoar Prize (Institute of Corrosion, UK) (with Robert Jeffrey), the 2007 Guy Bengough Award (Institute of Materials, Minerals and Mining, UK), the 2009 ACA Corrosion Medal and the 2012 Jin S Chung Award (International Society of Offshore and Polar Engineers).