VARIABILITY OF CORROSION OF MILD STEEL COUPONS IN TIDAL, SPLASH AND ATMOSPHERIC MARINE ENVIRONMENTS

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SUMMARY: The corrosivity at a particular geographical location is often determined by material loss of mild steel coupons. It is known that there can be some variability with horizontal placement but little has been published on variability of corrosion losses for coupons in the horizontal direction. Herein results are presented for the corrosion loss of sets of nine mild steel coupons exposed for various periods up to 42 months in the mid-tide and marine atmospheric environments. Duplicate sets were exposed east-west and north-south. Generally, variability of coupon mass loss for those exposed in mid-tide conditions was less than 10%, whereas variability for those exposed in atmospheric conditions ranged from less than 5 % to greater than 50%. Possible reasons for such large variations are given. Additionally it was found that coupons exposed in the east-west orientation corroded slightly more than those exposed north-south.

Keywords: Variability, Steel, Corrosion, Tidal, Splash Zone.

1. INTRODUCTION

The corrosivity of a particular local environment is often determined by exposing metallic coupons and deriving the mass loss after a given period of exposure, such as days, months or years. Usually the corrosion loss results are given for one year exposure at a particular location or geographic zone. For this micro-climate the corrosivity is then given in microns loss of steel (or other material) per year. More generally, the characteristics of the corrosion process at a given location can be measured by means of coupons that are recovered on a regular or irregular basis. Normally the results are reported in a plot of corrosion loss as a function of time. It is now well established that corrosion loss with time is not linear (Melchers and Jeffrey 2008). It is also been established that season of exposure, angle of inclination, direction and height from ground level all influence corrosion loss in atmospheric corrosion (Roberge 2007). In tidal and immersed conditions factors such as water and air temperature, water velocity, distance from mean mid-tide and other factors also can influence corrosion loss. Typically, results are derived from the mass losses averaged from one, two or occasionally three coupons. What has not been well established is the overall variability of reported data from field testing. To this end, a trial was undertaken to elucidate how much corrosion losses can vary under nominally identical exposure conditions in the mid-tide, splash-zone and marine atmospheric zones. Additionally the effect of cardinal direction was investigated. Some results for the effect of orientation on the corrosion loss of mild steel coupons in atmospheric and splash zone have been reported previously (Jeffrey and Melchers 2008a,b). The present paper reports more detailed results from a specific investigation. The following outlines the experimental programme and reports the results obtained.

2. EXPERIMENTAL PROCEDURE

2.1 Test Sites

The majority of the present study was carried out at the NSW Department of Primary Industry's Fishing Research Facility at Taylors Beach, approximately 200 kilometres north of Sydney, in the sub-tropical tidal waters of a tributary of Port Stephens on the eastern Australian seaboard. Here the water is essentially the same as ocean water except that because of the shallow black mudflats on the further reaches of the tributary the diurnal water temperature range is slightly elevated, the reason for this phenomena has been explained previously (Jeffrey and Melchers 2006). During the present trial, the water temperature range was 8.8°C to 26.7°C with an average of 16.3°C. The maximum tidal range is 1.6 metres but in general varies from 0.8m to 1.2m. Water velocity varied with depth and time, the maximum measured being 0.20 m/s on the surface at full ebb flow.

Tests were also carried out in coastal seawater at Townsville using the jetty at the Australian Institute of Marine Sciences and at the Water Police depot, Hobart, Tasmania. Details of these sites have been described previously (Jeffrey and Melchers 2006).

2.2 Test Specimens

Mild steel coupons 100 mm x 50 mm x 3.0 mm thick were guillotined from the same sheet, drilled with individual identifying holes, acid cleaned and weighed to the nearest 0.1 mg prior to deployment, following procedures described previously (e.g. Jeffrey and Melchers 2006). The trial consisted of two experimental components:

a) establishment of corrosion profiles at atmospheric, mean-high- tide (MHT), mean mid-tide (MMT), mean-low-tide (MLT) and submerged levels, and

b) establishment of variability of corrosivity with direction (North and West) for mild steel coupons.

To achieve these objectives, 24 sets of nine coupons were bolted to aluminium channel cross bars using insulating plastic bolts and spacers. Six bars were attached in the atmospheric zone facing North and a further six bars attached facing West. Similarly six bars were attached in the mid-tide zone facing North and an additional six bars faced West. All the cross-bars were bolted to a 3.0m x 0.6m x 0.6m fibreglass frame that was itself suspended from a steel beam set on two timber pylons approximately 50m from shore. The sides of the frame were positioned so as to face the cardinal points. The test frame in position is shown in Figure 1.

Duplicate corrosion profile coupons and one variability bar from each of the four positions were recovered after 6, 12, 18, 24, 36 and 42 months. Once recovered coupons were cleaned in accordance with ASTM G3, reweighed and the corrosion loss (in microns) derived for each of the coupons. Sets of recovered coupons are shown in Figure 2.

Figure 1. Test rig in position at Taylors Beach at low tide. The overall tidal range can be gauged from the support pylons.

Figure 2. Sets of atmospheric and tidal coupons recovered after two years of exposure.

3. RESULTS

3.1 Tidal profile for isolated coupons

The mass losses of the two coupons recovered for profile determination were averaged and plotted against exposure time (Figure 3). The profile is similar in shape to that obtained at other locations (Larrabee 1958, Jeffrey and Melchers 2008a) with the greatest loss occurring in mean high tide zone.

The evolution of the corrosion profile for the individual coupons with increased exposure time generally is similar to that observed previously at other immersion locations (Melchers 2003a). Direct comparison of the magnitude of the corrosion losses for these coupons must allow for the effect of water temperature but it is clear from such comparisons that the maximum loss of 1500 microns in three to four years is consistent with expectations for the average water temperature at this site. Generally similar losses were observed at Townsville (water temp-average 26.5° C range 21.8-31.2 °C) after 2.5- 3 years (Figure 4) and a loss of 1000 microns was recorded at Hobart (water temp average 14.6 °C, range 7.6-22.4°C) after three years (Figure 5). All show only a gradual increase with time for the part of the profile below the mean low water level. However there is in all cases a more significant increase in corrosion loss at higher levels. For the present profiles derived from the coupons there is no evidence of high corrosion losses at low water levels, such as has been reported in some cases for continuous strips (Melchers and Jeffrey 2010).

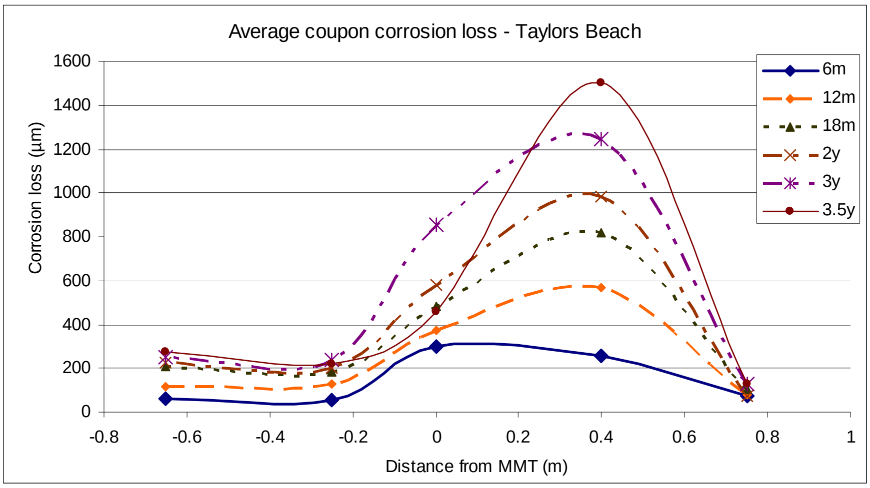

Figure 3. Plot of corrosion loss with time at different tidal positions at Taylors Beach.

Figure 3 shows very little increase in corrosion loss for the coupons above the splash zone, that is for the coupons in the atmospheric zone. This was observed also at Hobart, where the corrosion loss of the atmospheric corrosion coupons was less than 150 microns. For the atmospheric coupons at Townsville there was a gradual increase in corrosion loss with time, increasing from 80 microns after 6 months to almost 1400 microns after 3 years. The reason(s) for the difference in corrosion rates is the subject of further analyses.

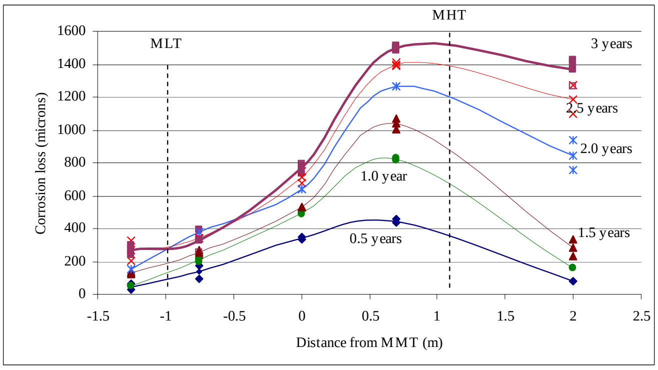

Figure 4. Plot of corrosion loss with time at different tidal positions at Townsville.

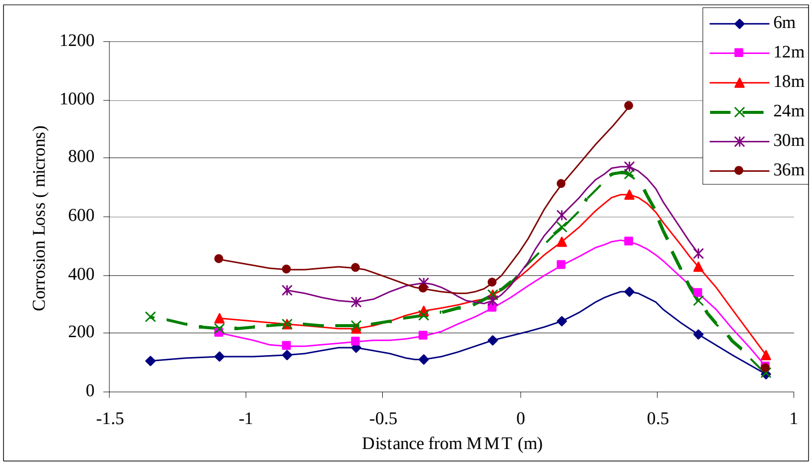

Figure 5. Plot of corrosion loss with time at different tidal positions at Hobart.

3.2 Effect of orientation

The effect of orientation was investigated for the tidal and the atmospheric zone environments using four racks each holding nine coupons. Coupons were recovered at regular intervals over a period of 42 months. As before, individual corrosion losses were obtained. In the present case averages were determined for coupons oriented in the N-S and E-W directions. The average losses are shown in Figure 6.

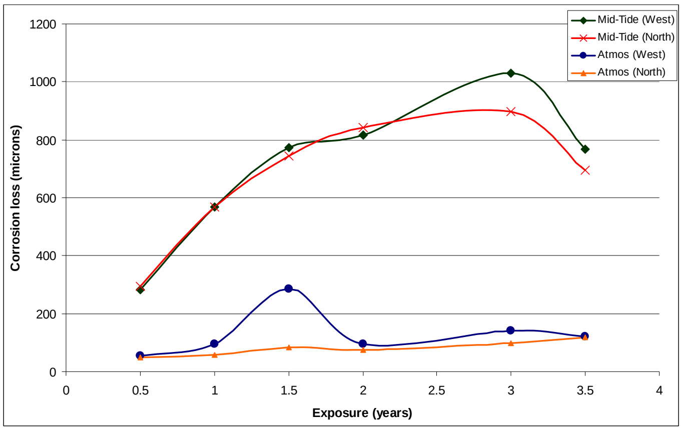

Figure 6. Average corrosion losses in tidal and atmospheric conditions.

A number of observations must be made regarding the plots in Figure 6. For the coupons in tidal exposure conditions no distinct difference is evident between the corrosion losses with respect to orientation. This is not unexpected as the water temperature and the time of wetness is highly likely to be similar, irrespective of orientation.

The lower corrosion loss at the final 3.5 year recovery compared with the corrosion loss for the previous 36 month recovery, was somewhat unexpected. Evidently, under identical conditions this is unusual, as corrosion loss must increase with time, although due to the use of individual coupons some variability might be expected. However, in this case the change is much greater than likely due to variability. More detailed examination of the exposure conditions revealed what is now recognized as an experimental oversight. In the trial, the mid-tide racks were arranged over two different elevations some 0.7m apart vertically, thereby being exposed to slightly different tidal ranges. In the recovery process they were recovered opportunistically, mainly as a function of accessibility rather than sequentially in ascending or descending order. At the time of recovery the importance of this in relation to the corrosion losses relative to the tidal profile was not fully appreciated. Attempts to adjust the corrosion loss with time and placement have proved inconclusive. The results presented here should therefore be considered as variability of the process rather than being considered to represent a definitive corrosion profile.

The corrosion loss results for the atmospheric coupons show a slight increase of corrosion loss with exposure time for both the E-W and the N-S facing coupons. This is in agreement with other results (Roberge 2007, Jeffrey and Melchers 2008a). However, it is evident that at 1.5 years exposure there is a very significantly higher corrosion loss observation for the atmospheric coupons facing west. A possible explanation for this is offered later in this paper. Overall, however, there is a slight increase over the north-facing coupons for the remainder of the exposure period.

3.3 Range of corrosion loss

Maximum and minimum corrosion losses for the mild steel coupons at different orientations are shown in Figures 7 and 8. Figure 7 shows that in tidal conditions there is generally a substantial overlap of corrosion losses for the coupons even though they face different directions. The reason for the decrease in corrosion loss at 3.5 years was already noted above in relation to Figure 6. Comparison to Figure 8 shows that the overlap is more apparent under tidal conditions than it is for atmospheric exposure where, for the first 2 years, all of the losses on the west-facing coupons are somewhat greater than any of the losses on the north-facing coupons. For the remainder of the exposure period there is only a slight overlap between west- and north-facing coupons. The reason for high corrosion loss also was noted already above and is explored more fully later in this paper.

To obtain a better appreciation of the degree of overlap of the data for the directional effect, the nine individual coupon losses for tidal and atmospheric conditions are shown in Tables 1 and 2 respectively, with the data arranged in increasing order of corrosion loss. The mean (μ), standard deviation (σ) and coefficient of variation (COV) are also shown.

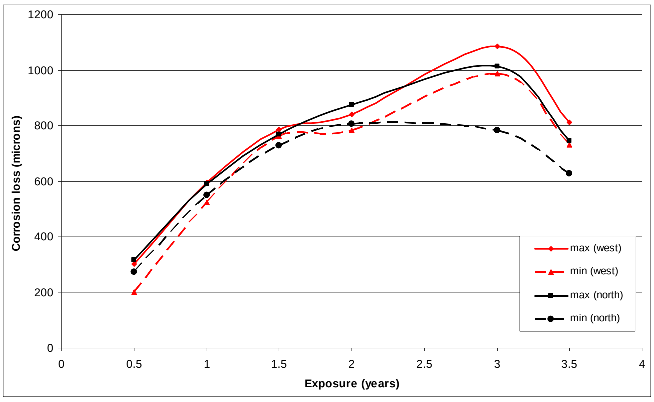

Figure 7. Plot of maximum and minimum mild steel loss in tidal conditions.

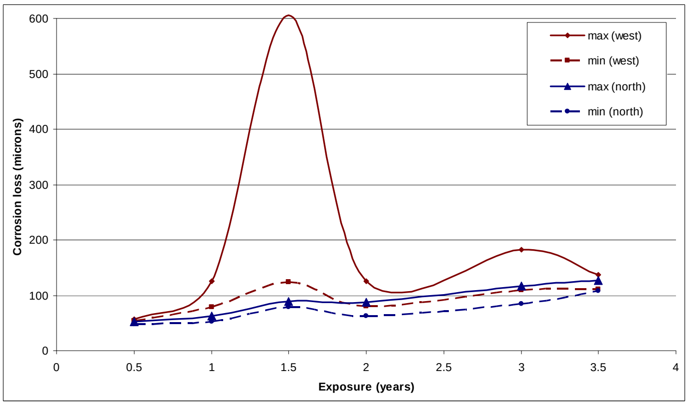

Figure 8. Plot of maximum and minimum mild steel loss in atmospheric conditions.

Table 1. Corrosion loss of mild steel coupons exposed in tidal conditions, arranged in ascending order of loss (microns)

	6 month		12 months		18 months		24 months		36 months		42 months	
	North	West	North	West	North	West	North	West	North	West	North	West
	273	201	550	525	729	762	805	784	782	988	627	731
	284	285	558	559	731	763	811	796	798	989	662	747
	287	286	559	561	738	767	821	813	851	1033	688	759
	287	292	561	563	742	767	841	819	909	1033	698	763
	291	296	565	570	743	770	853	824	911	1036	704	765
	295	298	568	578	744	775	855	824	929	1037	706	766
	299	298	577	580	749	779	857	825	934	1037	708	774
	306	300	580	589	765	781	859	829	940	1086	718	787
	316	301	590	597	769	786	875	839	1013		747	811
Mean μ	293	284	568	569	746	772	842	817	896	1030	695	767
Std. Devn σ	12.9	31.9	12.4	21.0	13.7	8.5	24.2	17.2	73.5	30.9	34.3	22.9
COV	4.4	11.2	2.2	3.7	1.8	1.1	2.9	2.1	8.2	3.0	4.9	3.0

Table 2. Corrosion loss of mild steel coupons exposed in atmospheric conditions, arranged in ascending order of loss (microns)

	6 month		12 months		18 months		24 months		36 months		42 months	
	North	West	North	West	North	West	North	West	North	West	North	West
	47.6	54.0	57.1	78.6	78.2	123.6	62.9	80.1	84.5	108.8	108.5	110.9
	48.3	54.3	57.6	83.0	78.3	139.4	65.7	81.1	90.8	116.5	110.6	113.9
	48.5	55.3	53.3	85.1	80.5	165.0	66.1	83.8	91.0	120.3	113.6	113.9
	49.0	55.4	52.4	85.6	83.0	213.8	66.8	84.1	93.7	123.4	116.4	117.9
	49.1	55.5	54.0	85.7	83.9	271.4	68.0	89.7	94.8	146.7	118.7	118.5
	51.8	55.9	58.6	90.0	85.3	289.7	79.7	98.2	96.3	148.2	122.8	120.2
	51.9	57.0	57.1	91.5	86.0	296.2	83.3	102.6	96.7	155.0	123.1	134.6
	52.2	57.0	61.1	120.3	89.5	469.1	86.4	110.8	109.6	160.1	127.3	137.0
	53.1	57.5	62.5	124.9	89.5	605.9	87.1	125.7	116.9	182.7		
Mean μ	50.2	55.8	57.0	93.8	83.8	286.0	73.99	95.13	97.1	140.2	117.6	120.9
Std. Devn σ	2.1	1.2	3.4	16.7	4.2	159.6	9.9	15.6	10.0	24.4	6.6	9.7
COV	4.1	2.1	6.0	17.9	5.1	55.8	13.4	16.4	10.3	17.4	5.6	8.0

3.4 Variability of corrosion loss – Standard Deviation (σ)

For assessment of longer-term reliability of structures and other infrastructure, reliability estimates typically are required. These rely on the availability of estimates of the uncertainty associated with input parameters, such as the corrosion loss for given exposure periods (Melchers 2003b). One measure of uncertainty in data or experimental results is Standard Deviation. It gives an estimate of the degree of variation of data about the data mean. Figure 9 shows the progression of corrosion loss standard deviation for each of the two orientations and the two exposure zones. Apart from the obvious spike with the west-facing atmospheric samples at 1.5 years (see above), standard deviation is higher for coupons in the tidal zone than it is for those in the atmospheric zone.

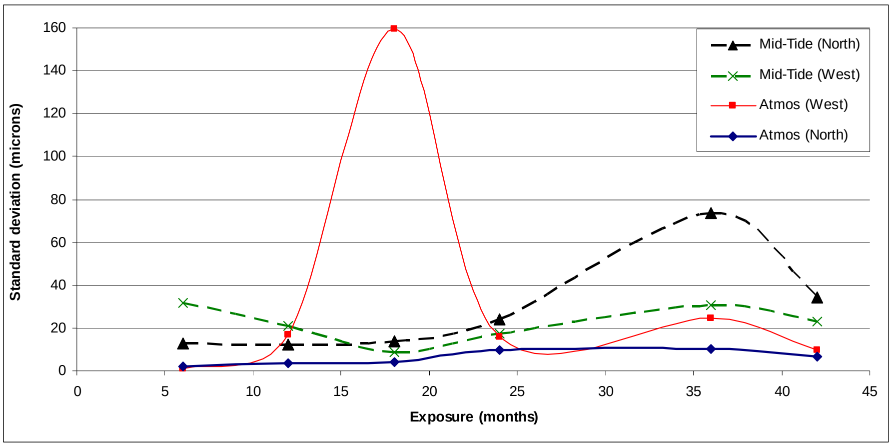

Figure 9. Standard deviation of corrosion loss for mild steel coupons as a function of exposure time and orientation.

3.5 Variability of corrosion loss – Coefficient of Variation (COV)

The coefficient of variation (COV) is a normalized measure of dispersion of probability distribution, defined as COV = (standard deviation / mean) or COV = σ/μ. It has the advantage that it permits more ready comparison of the variability of various data sets without reference to the mean. Evidently, COV is a dimensionless quantity. Figure 10 shows the derived COV for the data in Figure 9.

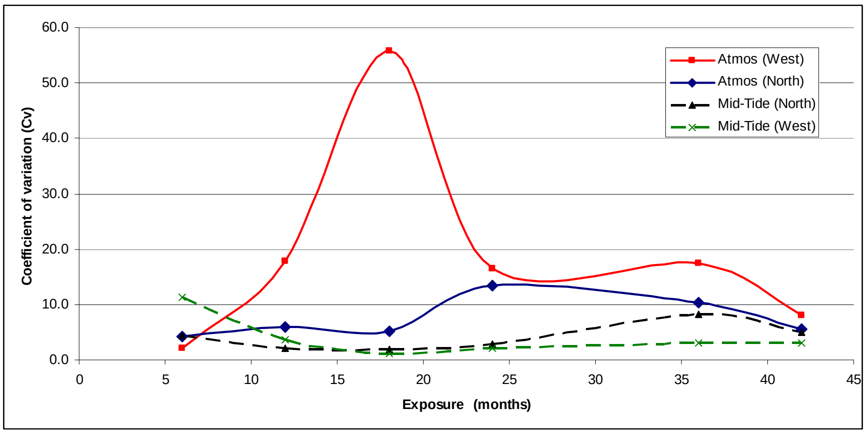

Figure 10. Plot of coefficient of variation (COV) of corrosion loss as a function of exposure time.

Apart from the spike (see above), Figure 10 shows that the variability in the corrosion loss of steel coupons exposed to marine atmospheric conditions is rather greater than it is for similar coupons exposed to tidal conditions. The standard deviation σ and the coefficient of variation (COV) are each derived quantities. In the present case, they were derived from samples that are just 9 in number and this is rather small relative to the sample size commonly considered desirable for statistical purposes. For this reason both σ and COV themselves have a degree of uncertainty in their estimation (they are actually sample values). This is the most likely reason for the apparent inconsistency at 0.5 years (6 months) exposure relative to the remaining parts of the plots in Figure 10.

3.6 Probability distributions

For samples (such as the corrosion coupons used in the present study) exposed at locations that can be considered, asymptotically at least, to be independent, the most likely probability distribution for the data shown in Tables 1 and 2 is the Normal distribution. To test whether this is a reasonable assumption, the data for the North- and for the West-facing coupons were plotted on Normal (cumulative) probability paper. The results are shown in Figures 11 and 12. Straight (bold) lines have been plotted through the data. On a Normal probability plot these denote the form of the Normal distribution. It appears that in each case, at all exposure times (apart from the 4 year North data set which was ignored), the Normal distribution provides a good fit to the data. This information will be of immediate benefit in structural reliability calculations involving corrosion loss.

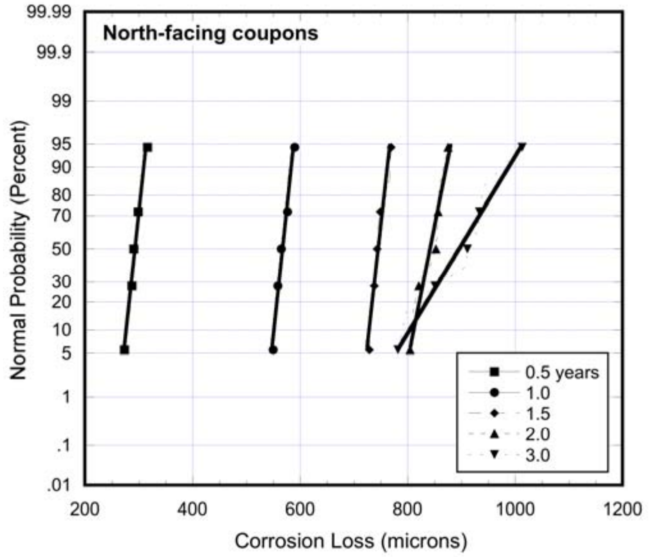

Figure 11. Normal probability plot for data for North-facing coupons.

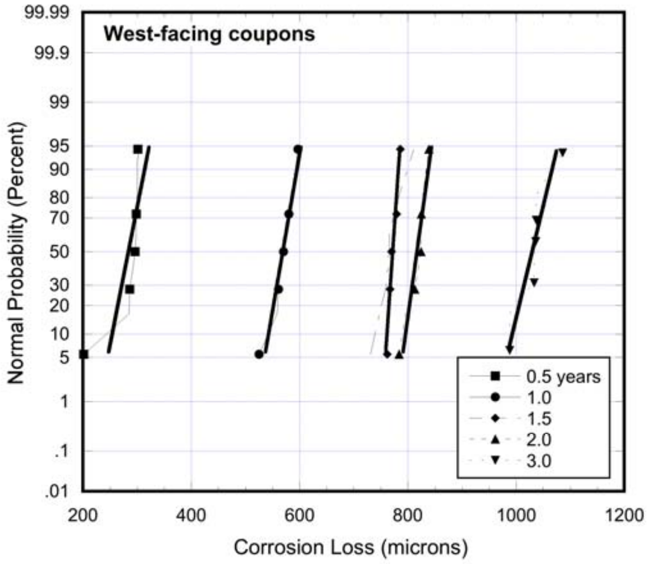

Figure 12. Normal probability plot for data for West-facing coupons.

3.7 Effect of position on corrosion loss – atmospheric exposures

To elucidate if any spatial conditions influenced the variability of corrosion, results for atmospheric conditions have been plotted for each coupon, as the coupons would have been deployed, right to left on the support bars (Figure 13).

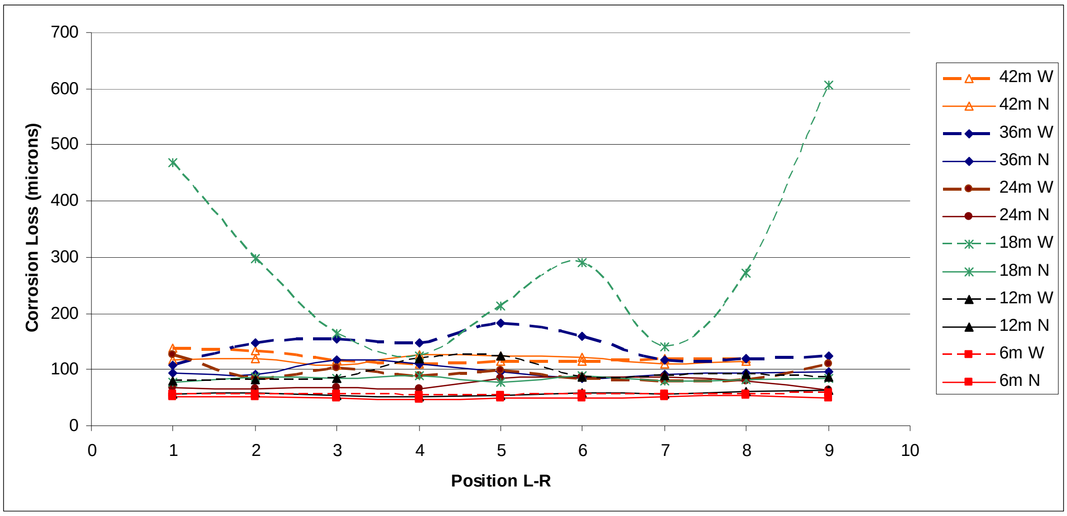

Figure 13. Plot of individual atmospheric coupons to determine any correlation between position and corrosion loss.

The corrosion loss from the 18 month West (18mW) set of coupons tends to overwhelm all other results but it is of interest that on this set the third coupon from each end recorded the lowest mass loss and the coupons closest to the ends recorded the greatest loss of any coupons for this trial. To see if this trend is evident in other atmospheric recoveries the 18mW results have been removed in the plot shown in Figure 14. It is also much easier to observe any trends if the plots are separated into West- (Figure 14) and North-facing sets of coupons (Figure 15).

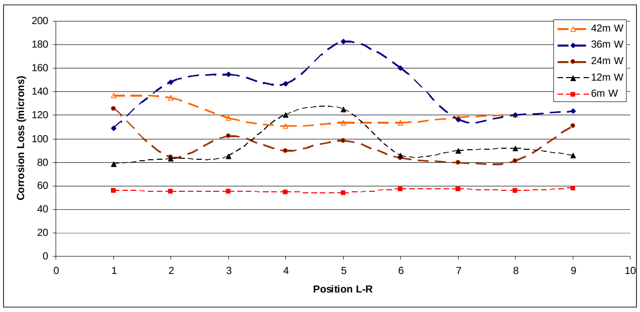

Figure 14. Corrosion loss for West-facing atmospheric coupons for different exposure periods, with the 18mW set removed.

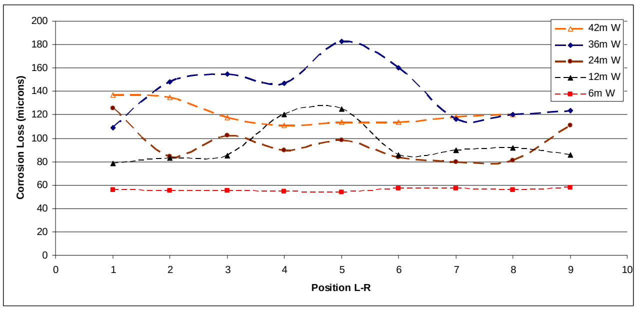

Figure 15. Corrosion loss for North-facing atmospheric coupons for different exposure periods.

With the dominant 18mW set removed and the other results divided according to facing direction, the plots become clearer. From both Figures 14 and 15 it is evident that there is no clear trend to correlate spatial placement with corrosion loss in atmospheric conditions.

3.8 Effect of position on corrosion loss – tidal conditions

To check if there was any spatial trend in the corrosion of coupons in the tidal zone in the horizontal direction, corrosion losses were obtained for coupons at various positions along the support bar (Figure 16).

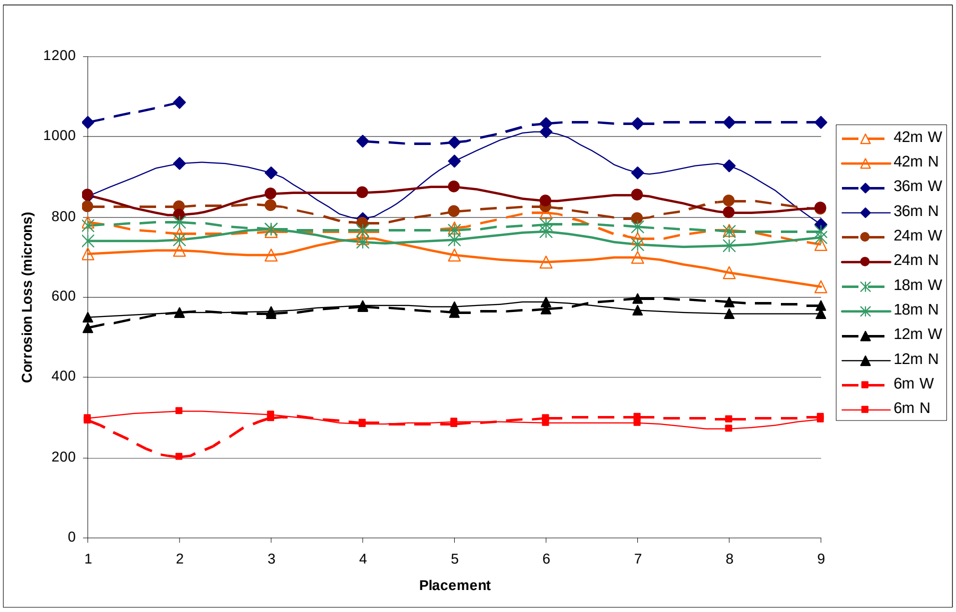

Figure 16. Corrosion loss of individual tidal coupons as a function of position (placement) along the support bars.

It is clear from Figure 16 that apart from the 36mN corrosion loss, there is little variation between North- and West-facing coupons (as detailed above). It is also evident that there in no clear correlation between position along the support bar and difference in corrosion loss.

4. DISCUSSION

The corrosion profiles obtained in the present test programme using discrete isolated coupons are closely similar to those observed at other marine immersion sites both by other investigators and in previous, shorter term tests at the three sites described above. In each case it was found that the greatest loss of steel occurred about midway between mean-mid tide and mean high tide levels. Somewhat unexpected, but now understandable as explained above, was the observation of a relatively small increase in loss in the atmospheric zone compared to coupons only some 0.4 m lower. As noted above, this means that the precise location, vertically, is very important in assessing likely corrosion loss as a function of time.

From the above data and analysis, it can be seen that in all circumstances there is some variation in the corrosion losses observed within given sets of coupons, even when these have been exposed to an environment that, for all practical purposes, is essentially identical for all the coupons. For inter-tidal conditions, where a considerable number of factors can influence corrosion loss (particularly the randomness of bacterial and other marine settlement) variability was generally less than 10%. This is somewhat less than variability under atmospheric conditions. Here the coefficient of variation ranged from 2% to greater than 50%. The latter is a very high value but is associated with low corrosion losses. Nevertheless, these results indicate that variability of likely corrosion loss should not be ignored.

The corrosion rate of mild steel coupons is often used to gauge the corrosivity of a macro-environment or a micro-environment. The present results show that there can be significant variability within sets of coupons exposed under nominally identical conditions (particularly atmospheric exposure conditions) and that any corrosivity readings quoted for a particular site should not rely on a single or even duplicate result. Ideally, the reported data should include the number of coupons used to make the corrosion loss assessment for the given exposure period and for the particular exposure site. Ideally also, the quoted result for corrosion (rate) should include a statement of the variability in that result.

5. CONCLUSIONS

The results from the present test program show

1. Consistent with classical results, the corrosion of mild steel coupons, for tropical and for temperate weather zones is greatest in the region around mean high tide,

2. Coupons exposed in different orientations showed little difference in corrosion loss for the tidal and splash zones, however even small variation in vertical direction can have a mrked effect on corrosion loss,

3. Consistent with earlier results, the variability (standard deviation, coefficent of variation) in corrosion loss observations increased with increased exposure period and this was greater for west-facing coupons than for north-facing coupons, an observation likely to be due to greater solar radiation effects,

4. The variability in corrosion losses can be represented by a Normal distribution,

5. As expected, both for atmospheric and for tidal exposures there is no significant effect for corrosion loss of horizontal placement of coupons on exposure rack.

6. ACKNOWLEDGMENTS

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8. AUTHOR DETAILS

Robert Jeffrey is a research scientist at The University of Newcastle, Australia where for the last ten years he has been investigating corrosion in marine, tidal and atmospheric conditions. Robert is also principal consultant for Pacific Testing Pty Ltd, a company specializing in corrosion problems. He is a past president of the ACA and has been on the committee of the Newcastle branch for twenty years. 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 for corrosion research.

Robert E Melchers is Professor of Civil Engineering and Australian Research Council Professorial Fellow at The University of Newcastle, Australia. He has a BE and MEngSc from Monash University and a PhD from the University of Cambridge, UK. He was awarded the 2004 TP Hoar Prize (Institute of Corrosion, UK) (with Robert Jeffrey), the 2007 Guy Bengough Award (Institute of Materials, Minerals and Mining, UK) and the Marshall Fordham prize (Australasian Corrosion Association) in 1999, 2002 and 2007. He received the ACA's 2009 Corrosion Medal. His research interests include structural reliability and marine corrosion.