Report for NERA-NDRI

Monitoring localised corrosion behaviour of decommissioned O & G metallic infrastructure in the ocean

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1. Introduction

The prediction of the corrosion behaviour and remaining life of decommissioned oil and gas metallic infrastructure in ocean conditions requires corrosion data. The acquisition of corrosion data can be achieved partly through extensive review of historical literature and survey of operators [1,2] and partly through in situ field corrosion monitoring using corrosion probes [3,4]. Corrosion data and models reported in the literature are mostly for predicting general corrosion over long term exposure in marine environmens. These models cannot be used directly for predicting localised forms of corrosion. Models for pitting corrosion [1,2] show much greater degrees of scatter in data, reflecting the various ways in which localized corrosion can initate and propagate. As a result, prediction of the initation of localised corrosion, its severity and its development with increased exposure duration remains difficult. It remains a critical knowledge gap in the corrosion literature. This is despite localised corrosion often being responsible for worst case scenario damages to marine structures and that could be responsible for damage to the structural integrity of decommissioned O&G metallic infrastructure. As noted, for the recovery of pipelines their structural strength potentially is important. In part this can be governed by the amount of corrosion loss over the surface of individual or groups of pipeline spools. It also may be affected by the integrity, and thus the structural capacity, of joints between spools, including welds and flanges. Such capacity is influenced by localised forms of corrosion.

Localised corrosion behaviour of decommissioned oil and gas metallic infrastructure in ocean conditions was identified as a knowledge gap at the commencement of this NDRI research project, specifically for (i) pitting corrosion at welds along spools, and between spools, (ii) crevice corrosion at bolts (heads, buts, washers) on flanges between spools, (iii) crevice corrosion between flanges bolted together and at end plates on parked pipelines. In order to acquire data to aid understanding of the behaviour of common localised corrosion of decommissioned O&G metallic infrastructure and to aid development of tools for predicting the degree of localised corrosion penetration, an extensive field corrosion monitoring program was considered essential. As reported further in the present report, this was done using innovatively designed corrosion probes [3,4]. These probes were designed to target the simulation and the monitoring of three types of localised corrosion that were considered could lead to localized damage of pipe joints and thus potentially to pipe breakup during any recovery process. Particular attention was paid on the severity of crevice corrosion for joints between spools soon after impressed current cathodic protection (ICCP) has been removed and where there was no protective coating in the joint region.

2. Field corrosion monitoring using corrosion probes

Two special field corrosion monitoring experiments were carried out using electrochemically integrated multi-electrode array corrosion probes. These were designed and made to acquire data on the initiation and propagation of localised corrosion. Figure 1 illustrates the electrode array based probe design concept.

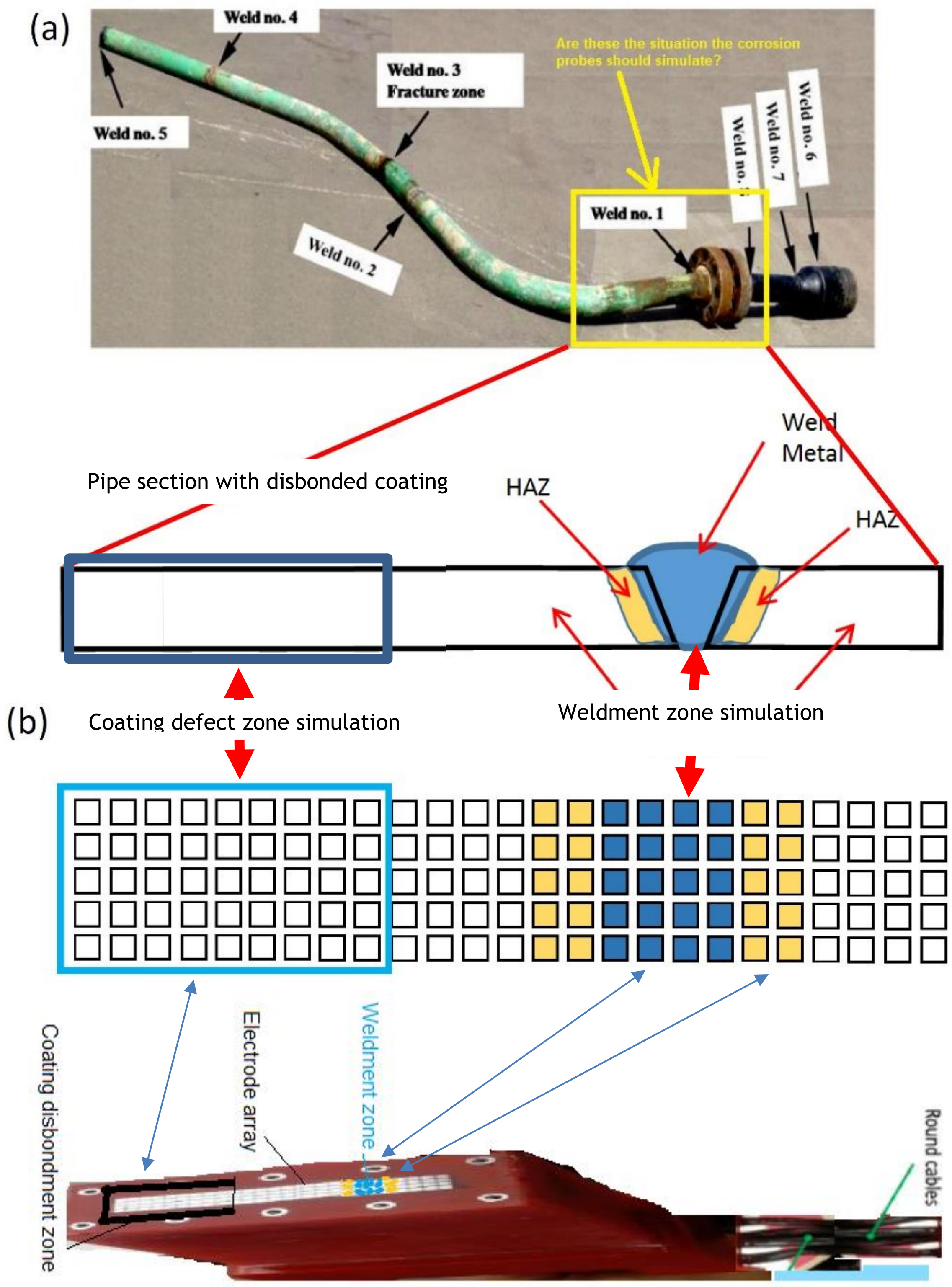


Figure 1. (a) Shows the corrosion at different regions of a pipeline. The region in yellow rectangle indicates the co-existence of three types of critical corrosion i.e. pitting corrosion at welds along spools (spools = segments of pipe), crevice corrosion at bolts on flanges between spools, and crevice corrosion between flanges bolted together. (b) The schematic representation of the designed electrode array probe to simulate the industry conditions shown in (a).

The electrode array probe in Figure 1 was designed and used to simulate and monitor the presence of three types of critical corrosion, i.e. pitting corrosion at welds along spools (i.e. individual segments of pipe), crevice corrosion at bolts on flanges between spools, and crevice corrosion between flanges bolted together. The electrode array probe consisted of one hundred 1.6mm diameter pipeline steel wires arranged in a 4 by 25 square array. The wires were mounted in epoxy resin and equally spaced at a distance of approximately 0.27mm. The array surface was abraded with silicon carbide papers to 1200 grit finished using water as a lubricant, and then rinsed with ethanol and acetone.

The electrode array probes were used for continuous field in-situ electrochemical monitoring, to obtain information about the initiation, propagation and mechanism of localised forms of metal corrosion, under simulated decommissioned oil and gas infrastructure conditions. The field corrosion monitoring tests were conducted by exposing corrosion probes in a marine environment laboratory at Deakin University; at the Deakin Centre for Marine Fisheries and Aquaculture Sciences at Queenscliff (Vic.) and at the University of Newcastle Taylors Beach (NSW) field test site. Figure 2 shows the field test locations and the field testing setup and measurements at the Queenscliff field testing site. Figure 3 shows the field testing setup and measurements at the Taylors Beach field testing site.

During exposure of the electrode array probe in the ocean, all 100 electrodes were coupled to simulate a continuous pipe surface under marine corrosion. When corrosion monitoring was carried out, the electrode connections were managed by an automatic switcher programed to maintain, at any time, one electrode connected to WE2 while the remaining 99 electrodes to WE1. A Zero Resistance Ammeter (ZRA1 in Fig. 2) was interposed between WE1 and WE2 to measure the net current flowing through this electrode, i.e. the local CP current flowing through the electrode. Local currents at different locations are measured by connecting a different electrode to the ZRA1 using the automatic switcher (switching once every 10 seconds). In this way, current distributions over the whole electrode array are measured by completing a scan. The currents obtained by ZRA1 was post-processed using a script designed for Matlab 2012b to build current density distribution maps of the array surface. Subsequently these current density distribution results were used to calculate metal losses using Faraday's law. More details on measurement procedures and data analysis methods can be found in references [3,4].

3. Corrosion data and observations

Figure 4(a) shows the corrosion measurement data obtained from the field-testing at the Queenscliff site. These are all at the same comparative scale. The longer term data (weeks 11-35) is shown in Figure 4(b) at a magnified scale in order to increase the visibility of weldment corrosion and cathodic activities inside the crevice area. Throughout, the corrosion currents (in µA) measured within and outside the crevice zone were translated to corrosion rates (in mm/y) based on using Faraday's law. The calculated corrosion rates are represented by colour coding in Figures 4(a) and (b). Evidently, for practical applications the highest corrosion rates within the crevice zone (or outside it) are of most interest because they indicate the worst case scenario damages to marine structures and that could be responsible for damage to the structural integrity of decommissioned O&G metallic infrastructure.

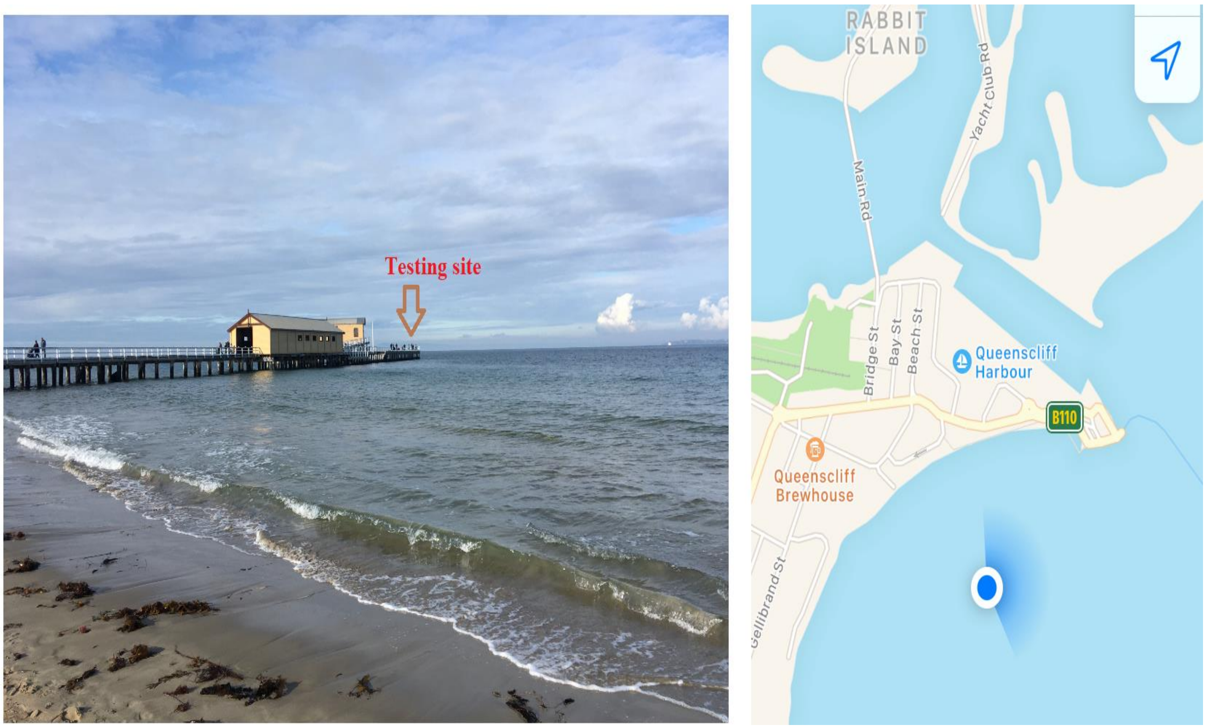
From Figure 4(a) it can be seen that at the very beginning of field exposure, corrosion initiated on the probe surface mainly within the crevice area. When cathodic protection (at -900mV vs $Cu/CuSO_4$ reference electrode) was applied, the corrosion in the crevice area reduced to almost zero. However, corrosion started again after the cathodic protection potential was switched off. In the first week the highest corrosion rates were observed at the bottom of the crevice area, at approximately 7mm/y, and later moved towards crevice mouth area. Corrosion was concentrated mainly at the crevice and at crevice-mouth areas. These observations are in agreement with industry experience that high crevice corrosion tends to occur at bolts (heads and washers) on flanges between spools, and between flanges bolted together, and at end plates on parked pipelines in ocean. In Figure 4(b), it can be seen that corrosion started to be active first at the heat-affected zone (i.e. acting as an anode with, presumably the rest of the weldment acting as the cathode). Figure 4(b) also shows that localised corrosion is visible at the heat-affected zone after 17 weeks and that major localised corrosion had occurred the same zone after 26 weeks. This is in agreement with erlier work on the corrosion of welds [6, 7]. Observation of the probe surface using an underwater camera showed that already after 35 weeks the crevice area was covered with corrosion products and marine growth, possibly causing separation of corrosion cells inside and outside the crevice.

In Figure 4(b), it is interesting to note the presence of corrosion inside the crevice area. Since the crevice area was covered with corrosion products and marine growth it would be expected that access of oxygen to the inside of the crevice would be limited. However, it is possible that the additional cathodic reaction associated with the observed corrosion is associated with the reduction in local pH (acidification) within the crevice and the development of corrosion with hydrogen evolution reaction as the cathodic reaction. This is in agreement with a theory proposed earlier [8] and further shown in detail in recent research results [9] for extended corrosion under corrosion deposits.

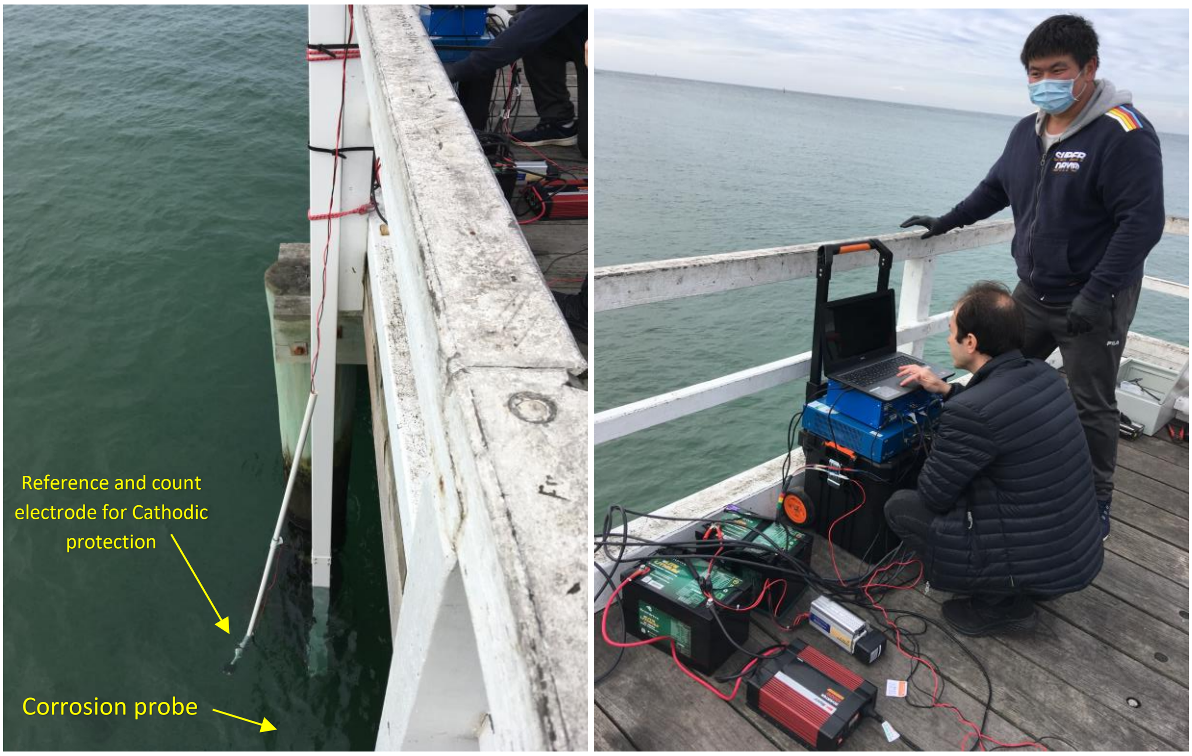
Figure 5 shows corrosion measurement data from field-testing at Taylors Beach. It can be seen that the corrosion rates measured at Taylors Beach are higher than those obtained at Queenscliff. Most likely this is the result of differences in ocean water conditions, noting that the seawater at Taylors Beach averages 20˚C compared to 13.7˚C at Queenscliff.

The testing program remains ongoing, in an effort to extract data for extended exposures.

Data from both the literature and corrosion monitoring experiments have been used to fit to major corrosion models, in particular the bi-modal corrosion loss model [2], generating corrosion trend diagrams showing long-term seawater corrosion under the effect of major marine environmental conditions, producing a practical tool for quantifying the long-term trends and rates of degradation/corrosion of metallic infrastructure in the ocean.



(a). Field test locations at Queenscliff



(b). Field test setup at Queenscliff and measurement at the Queenscliff field testing site.

Figure 2. Field test locations and field testing setup and measurements at Queenscliff field testing site for acquiring localised corrosion data.

Figure 3. Field test locations and field testing setup and measurements at Taylors Beach NSW field testing site for acquiring localised corrosion data.

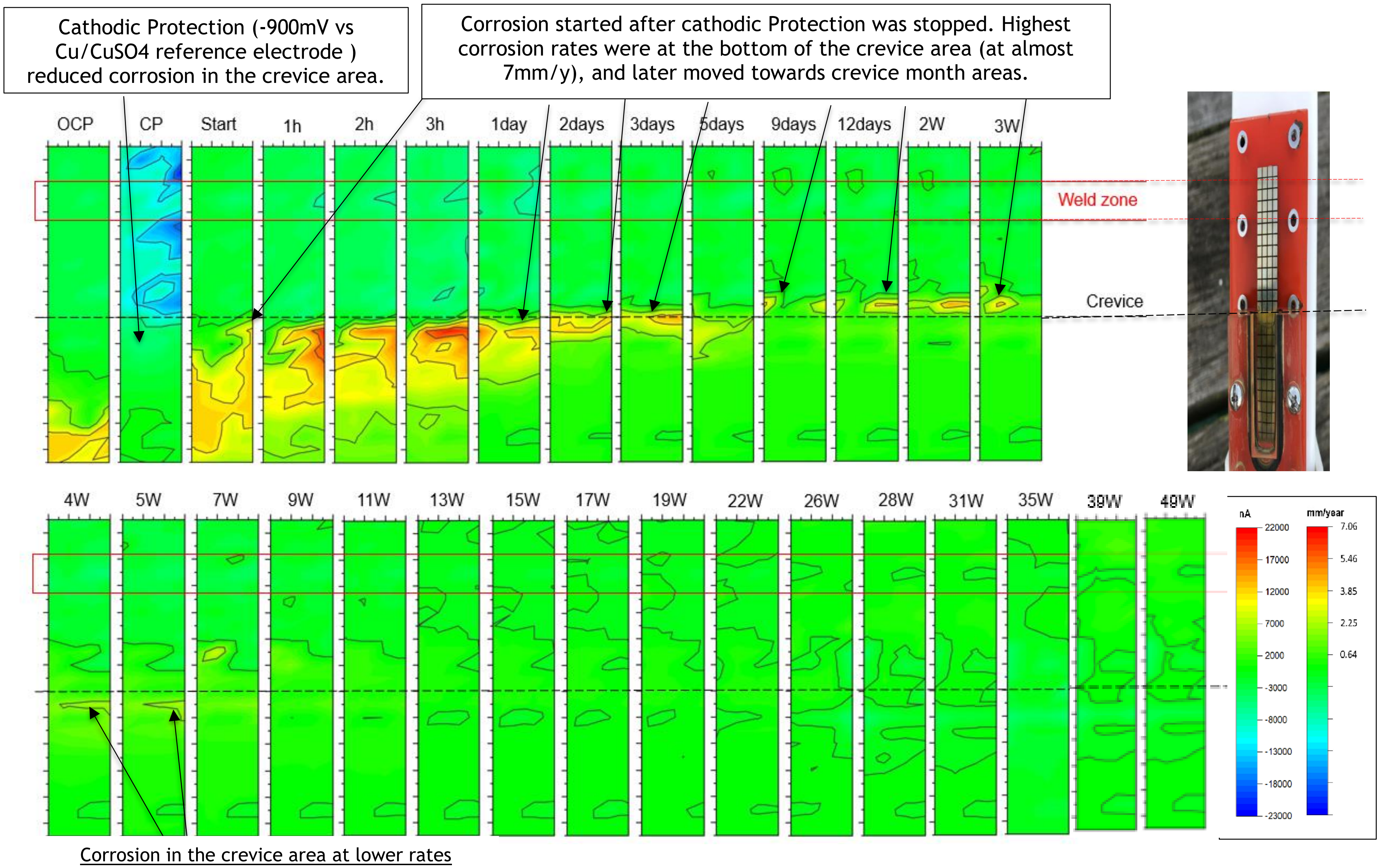


Figure 4(a). Queenscliff site long-term measurement data (showing corrosion rates in the same scale).

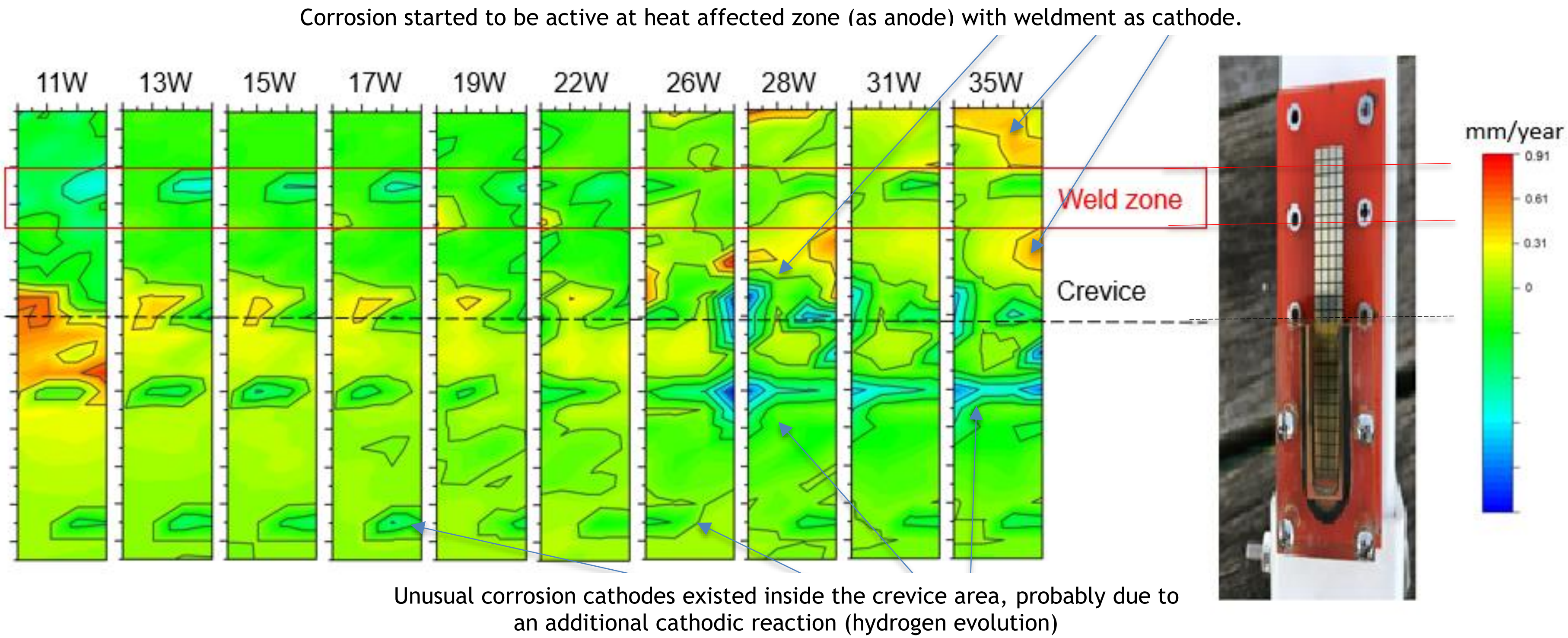


Figure 4(b). Queenscliff site long-term measurement data (showing details of corrosion rates in a different scale)

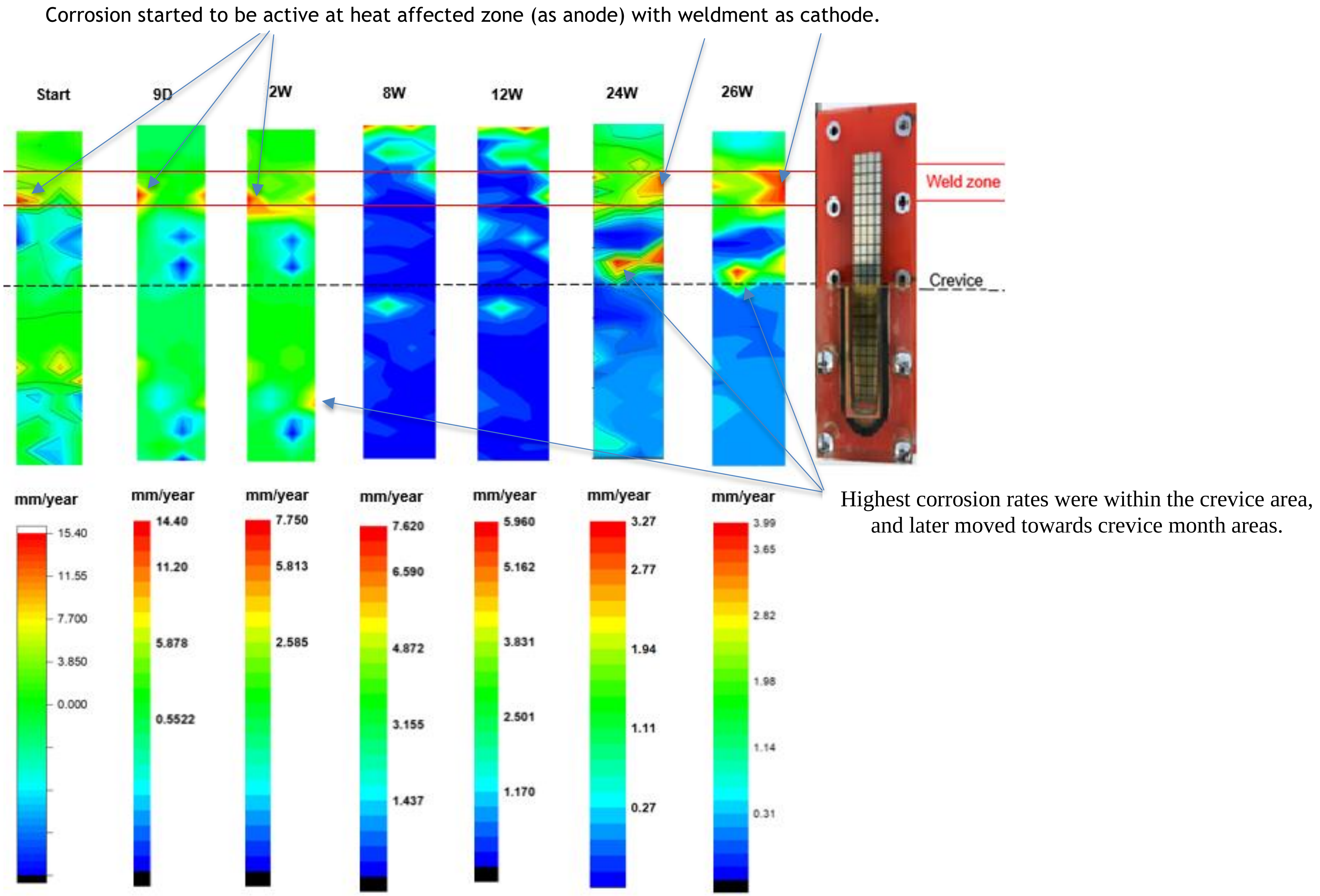


Figure 5. Initial measurement data from field-testing at Taylors beach testing site (See Appendix 3 for testing setup details).

4. Interpretation of observations

Figures 6 and 7 are diagrams developed to predict locaised corrosion based on the application of the bi-modal corrosion loss model [1,2] and in situ field corrosion monitoring data acquired as outlined above. The diagrams take the most common forms of localised corrosion (crevice and weldment pitting corrosion) into consideration by adding additional trend lines to the bi-modal corrosion loss model [1,2] to indicate localised corrosion loss with time. Figure 6 shows overall, crevice and weldment pitting corrosion trends at Queenscliff (average water temperature 13.7°C). The trends in this diagram are more closely relevant to south part of Australian climate conditions such as the Bass Strait, although at depth the water temperature will be considerably lower. Figure 7 shows overall, crevice and weldment pitting corrosion trends at Taylors Beach (average water temperature approximately 20°C). This diagram is more closely relevant to waters such as the Perth Basin. Tables 1 and 2 show the corrosion data used for plotting Figures 6 and 7, which are extracted from corrosion monitoring data shown in Figures 4 and 5.

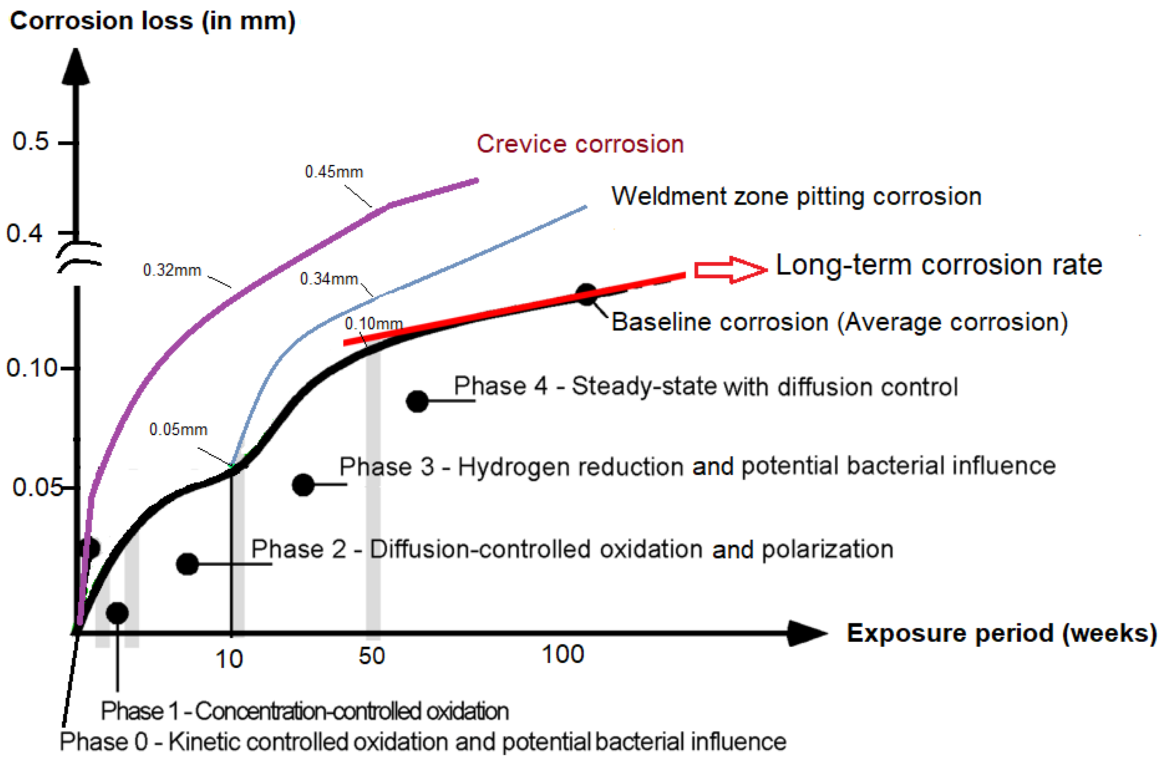


Figure 6. Localised corrosion trends diagram prepared based on the bi-modal corrosion loss model [1,2] using corrosion-monitoring data obtained at Queenscliff beach (see Tabel 1 below) by adding additional trend lines to indicate long-term corrosion loss and localised corrosion under the effects of crevice corrosion, weldment pitting corrosion.

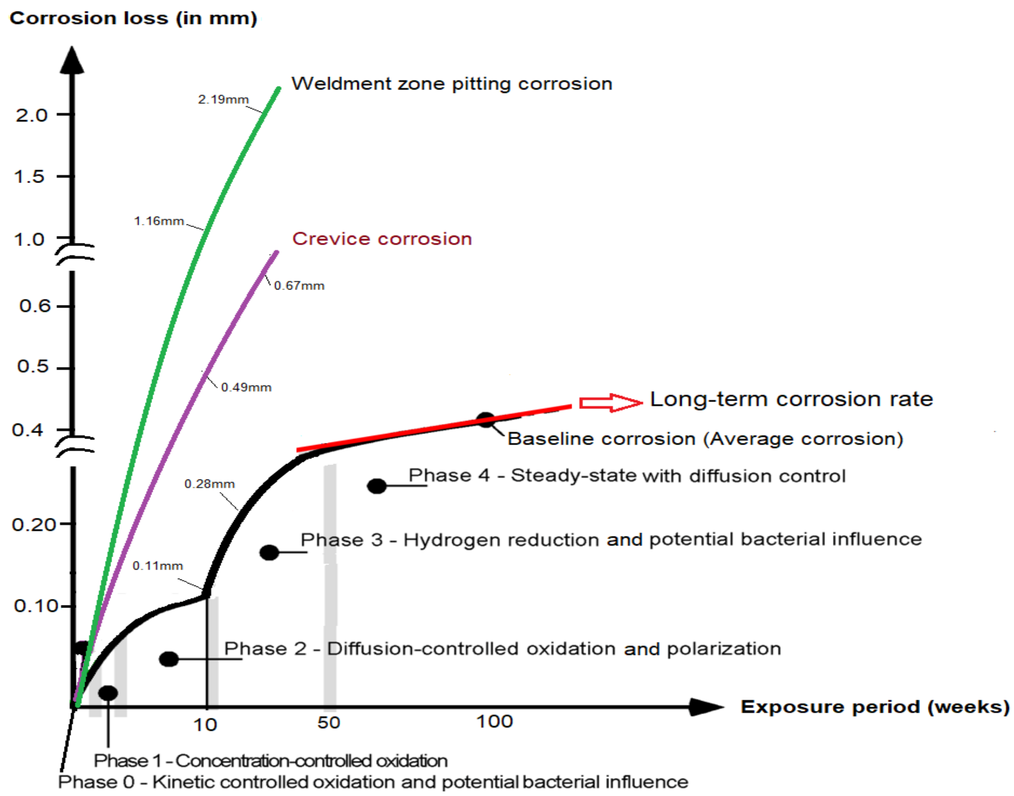


Figure 7. Localised corrosion trends diagram prepared based on the bi-modal corrosion loss model [1,2] using corrosion-monitoring data obtained at Taylors Beach (see Table 2) by adding additional trend lines to indicate long-term corrosion loss and localised corrosion under the effects of crevice corrosion, weldment pitting corrosion.

Figures 6 and 7 will assist in estimation of localized corrosion in the early stages of corrosion exposure for decommissioned marine structures. For instance, for offshore Bass Strait locations, Figure 6 indicates expected crevice corrosion penetration of approximately 0.45mm over the first year. This would apply wherever crevice corrosion could occur, such as at bolts (heads, buts, washers) on flanges between spools, and between flanges bolted together, and at end plates on parked pipelines. Similarly, pitting corrosion penetration of approximately 0.34mm is predicted over the first year in heat-affected zones of welds. Over the same period, as shown in Figure 6, only 0.10mm of general corrosion (i.e. depth of penetration) can be expected over the pipe surface if unprotected. These results suggest that localised corrosion penetration can be 3-5 times greater than general corrosion, at least for such short periods of exposure. Importantly, since the trends are highly non-linear, it cannot be concluded that *rates* of corrosion differ by such amounts. As is evident, there is no such thing as a 'corrosion rate' for non-linear trends as in Figures 6 and 7. Note Figures 6 and 7 show only preliminary trends using the relatively short-term monitoring data. An up-dated version of this report will provide additional data being collected and also up-dated trends.

Table 1. Queenscliff corrosion data

Test duration		1D	1W	2W	3W	4W	5W	7W	9W	11W	13W	15W	17W	19W	22W	26W	28W	31W	35W	39W	49W
Average corrosion rate (mm/y)																					
General	Rate	0.64	0.26	0.28	0.49	0.30	0.29	0.27	0.17	0.14	0.06	0.06	0.05	0.05	0.05	0.06	0.08	0.05	0.08	0.08	0.09
	Loss								0.05 mm												0.10 mm
Highest corrosion rate (mm/y)																					
Crevice	Rate	4.32	2.23	2.84	2.13	1.79	1.79	1.68	1.17	0.68	0.32	0.29	0.28	0.27	0.26	0.23	0.12	0.10	0.10	0.12	0.09
	Loss								0.32 mm					0.39 mm				0.42 mm			0.45 mm
Weld	Rate	0	0	0	0	0	0	0	0	0	0	0	0	0.14	0.28	0.44	0.53	0.35	0.48	0.69	0.50
	Loss																				0.34 mm

Table 2. Taylors Beach corrosion data

Test duration		1D	1W	2W	3W	4W	5W	7W	9W	11W	13W	15W	17W	19W	22W	26W	28W	31W	35W
Average corrosion rate (mm/y)																	Corrosion monitoring in progress		
General	Rate	1.65	1.07	0.69	-	-	-	-	0.60	-	0.57	-	-	-	0.63	0.59			
	Loss								0.11mm					0.21mm		0.28mm			
Highest corrosion rate (mm/y)																			
Crevice	Rate	8.99	5.78	4.07					0.77		0.89				0.36				
	Loss								0.49mm							0.67mm			
Weld	Rate	33.40	9.96	5.86					5.67		4.25				2.90				
	Loss								1.16mm							2.19mm			

A comparison of localised corrosion trending, such as in Figure 6, with trending over 16 years exposure for general corrosion penetration is shown in Figure 8, in this case for pit depth and general corrosion for steel exposed in the warmer waters of the Panama Canal Zone (27˚C average). It is shown that localised corrosion penetration is approximately 0.5mm over over the first year while the general corrosion penetration is approximately 0.12mm.

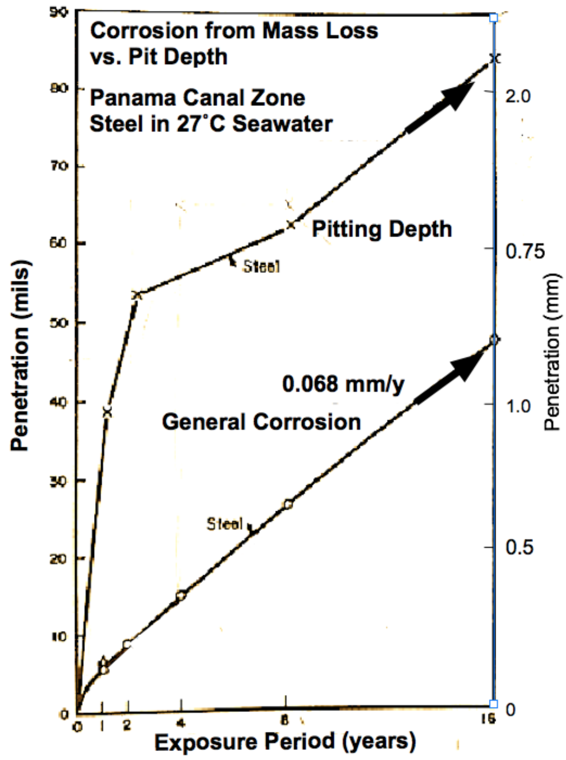


Figure 8. Plots of pit depth and of average depth of general corrosion of steel over 16 years of seawater exposure in the 27˚C seawaters of the Panama Canal Zone (1 mils =0.0254mm), showing the relationship (arrows added) between the two for extended exposures. Basic plots from Schumacher [8]. More details can be found in reference [10].

These data, although for only up to about 12 months exposure, show that the penetration of corrosion is greater at crevices than it is for general corrosion. They also show that the main effect of the crevices is to increase the early stages of corrosion (corrosion penetration) and that after about one year the longer term trend is similar to that for general corrosion. The first estimates of this increase are +0.4mm for waters averaging 12.5˚C and +0.85 mm for waters averaging 20˚C. This means that the trends in Figures 6 and 7 may be used for long-term effects of crevice corrosion with an increase depending on average water temperature. These tests did not consider variations in the size or width of opening of the crevices. However, those used are considered reasonable representations of likely crevices in actual joints. There are on-going studies on crevice corrosion of steel in seawater. Figure 9 shows overall trends that could be used to estimate crevice corrosion for joints between spools soon after ICCP has been removed and where there was no protective coating in the joint region.

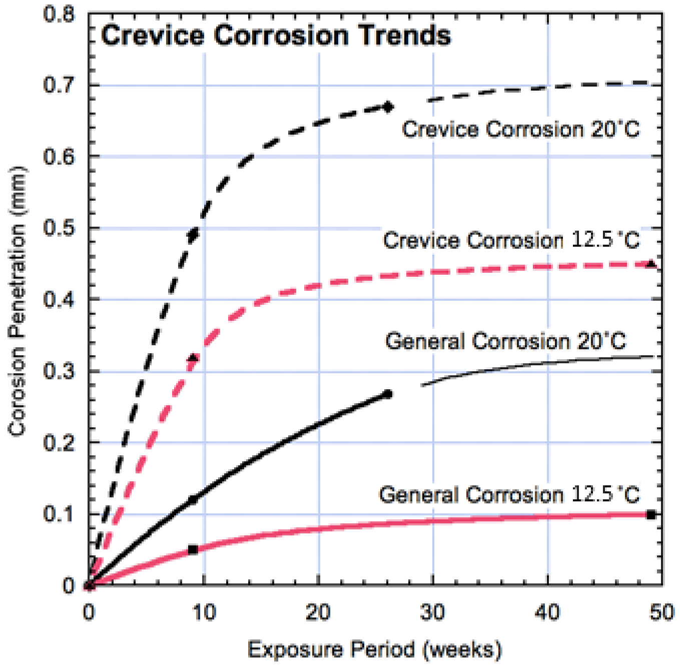


Figure 9. Trends for crevice corrosion and early general corrosion from field experiments at 20 and 12.5˚C (average) showing effect that crevice corrosion increases corrosion penetration in the early stages an that this carresi through to longer exposures.

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