In-situ conservation management of historic iron shipwrecks in Port Phillip Bay: a study of *J7* (1924), HMVS *Cerberus* (1926) and the *City of Launceston* (1865)

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Introduction

Heritage Victoria (HV) is the State government management agency for non-aboriginal heritage in the south-east Australian state of Victoria. The locations of 239 historic shipwrecks dating between 1831 and 1942 are known and of these 39% are steel or iron-hulled vessels. Approximately one third of all the Victorian shipwrecks lie within Port Phillip Bay, of which 20 (25%) are steel or iron-hulled vessels. This paper presents elements of the work being undertaken in Victoria that aims to establish the condition of iron and steel-hulled wrecks in Port Phillip Bay, and to determine the effectiveness and viability of *in-situ* conservation measures on this significant shipwreck resource.

Fieldwork was undertaken between 12 and 15 January 2010 by Heritage Victoria maritime archaeologists, Dr Ian MacLeod of the Western Australian Museum (WAM) and Maritime Archaeology Association of Victoria (MAAV) volunteers, Des Williams and Peter Taylor. The fieldwork consisted of a training exercise in the determination of *in-situ* corrosion measurements on the *J7* submarine and application of these methods to assessment of the state of deterioration–preservation of the shipwrecks HMVS *Cerberus* and *City of Launceston*.

Due to forecast poor weather conditions, the *J7* submarine was identified as an appropriate training site. The boat *J7* lies in shallow water in a marina, which enabled easier demonstration and discussion during training. In addition to the logistical suitability of *J7* as a training site, the opportunity to study one of the most accessible J Class submarines in terms of the naval architecture will make future assessments of the most visited and favourite wreck site *J4* significantly easier in terms of interpretation of structural continuity. The observations on *J7* were useful comparators for data obtained from the normally inaccessible *J3* at Swan Island which is in a restricted military reserve off Swan Island in Port Philip Bay. Data from *J7* is of value when reviewing data collected by the Get Under Dive Club who are investigating the potential for *in-situ* conservation for the very popular *J5* wreck which is experiencing noticeable collapse .

The conservation management of the wreck of HMVS *Cerberus* (1926) is perhaps one of the most challenging administrative processes in Australia since there are at least three bodies exerting influence on the decision making processes. The National Trust of Australia (Victoria) (NT-Vic) holds seed funding for expenditure on conservation measures for the *Cerberus* thus action plans involve discussions between Friends of the *Cerberus*, NT-Vic and HV about how the funding should be spent. The agreed programme identified that the placement of anodes on the *Cerberus* hull for cathodic protection could be appropriate, as part of the long-term management of the site. Part of the commitment of HV to the project was to undertake an electrical continuity survey of the hull of the *Cerberus* and this formed part of the fieldwork.

The four large guns were removed from the *Cerberus* gun turrets in 2005 and placed on the seabed in close proximity to the hull structure. The guns are currently being conserved *in situ* via cathodic protection using sacrificial zinc anodes. This technique not only prevents further corrosion, but also removes chloride ions, and the accumulated acidity which resulted from the previous corrosion history of the objects (MacLeod 1996a, 1998). This approach may be of great benefit if discussions for land based interpretation progress, as the guns could be expeditiously recovered and placed on display with minimal conservation works (i.e. removal of the concretion layer and application of a protective coating system). Measurements taken during this fieldwork continued the monitoring programme, which has been in place since the guns were placed on the seabed.

The corrosion and site deterioration of the *City of Launceston* has been monitored by MacLeod for the past 20 years (MacLeod 2002a and 2010) through pH and corrosion potential (E_{corr}) measurements. The late Terry Arnott performed a set of detailed corrosion potential and depth of graphitisation measurements of cast iron fittings on the *City of Launceston* in 1992. From these measurements, a site specific corrosion equation was developed, see equation 1, which converts E_{corr} measurements into corrosion rates which are expressed as mm of corrosion per year of immersion.The *City of Launceston* corrosion equation

$$\log d_g = 3.25\, E_{corr} + 0.202, \qquad (1)$$

provides a connection between the long-term corrosion rates and the present day measurements of the corrosion potentials.

In July 2009 Professional Diving Services were commissioned by HV to place five anodes on the *City of Launceston* hull and engine to slow the corrosion process and delay an expected catastrophic collapse of

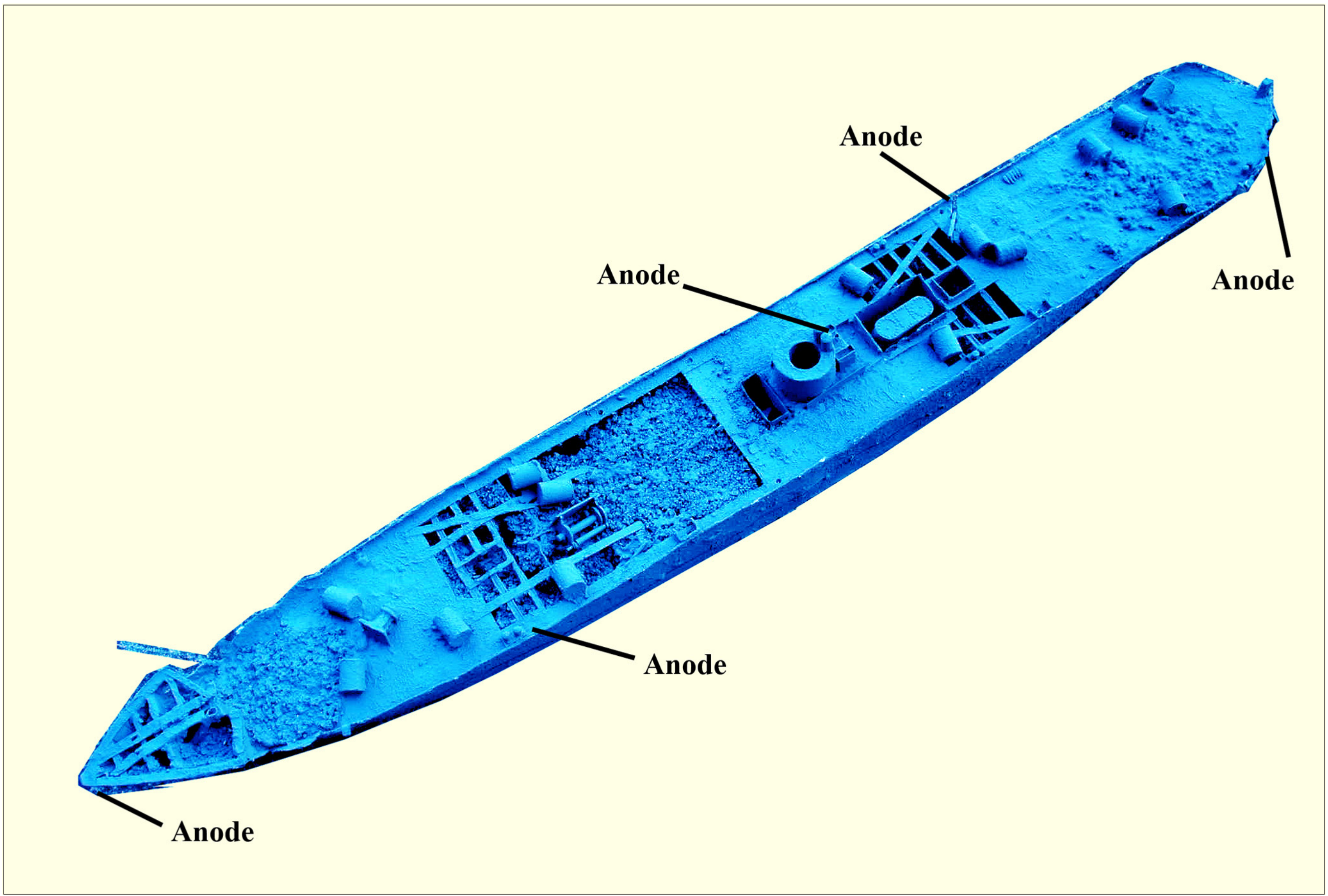

Figure 1. Site plan for *City of Launceston* showing location of anodes and the Macquay device.

the midships area. Measurements of E_{corr} during 1997 and 1998 showed an increasing number of hull plates whose voltages indicated that little or no solid metal remained in that section of the vessel. The implication of this observation was that a major storm crossing the site could provide enough energy to cause the collapse of this intact iconic historic iron shipwreck. Due to the fragile nature of the hull plates, 'G' clamps were used to attach the anodes, instead of drilled and tapped connections, at the positions shown in Figure 1. The anodes were placed in positions that would protect the hull, engine and the lower parts of the wreck attached to the engine bed.

Methodology

The methodology for drilling through the concretions and taking measurements on the underlying metal structures followed established procedures. This approach has been used for the past 20 years on sites across Australia (MacLeod 1997, 1998, 1989, 2006) and involves drilling holes using a pneumatic drill, powered by a dedicated scuba tank. The drill bit makes a hole 16 mm across, which is the slightly larger than the diameter of the flat surface pH electrode, allowing for measurements to be taken with minimal ingress of sea water into the hole. Holes are drilled until solid metal is reached, which can be estimated by the operator through changes in tension on the hand piece. The masonry bit normally prevents penetration into the solid metal. During the drilling process copious amounts of corrosion products are often released in a 'black cloud'.

The pH is determined by recording the minimum value of the pH meter connected to a flat surface, glass electrode which has pressure compensation to ensure equilibration of the internal reference solution. It takes roughly one minute to get a reliable reading of the acidity of the metal surface as the acidity from the immediate microenvironment overcomes the alkalinity of the sea water that inevitably penetrates during the drilling process. After recording the pH, the corrosion potential is measured using a platinum working electrode and a nearby calibrated $Ag/AgCl_{sea}$ reference electrode which are both connected to a high impedance digital multimeter housed in a waterproof housing. The voltage indicates the relative degree of reactivity of the underlying metal. For concreted marine iron the more negative values of E_{corr} reflect a lower corrosion rate while more anodic, or less negative data, means that the iron is corroding at a faster rate. Examination of Equation 1, the corrosion equation for the *City of Launceston,* demonstrates that there is a logarithmic relationship between the value of E_{corr} and the corrosion rate. The slope of the plot of the logarithm of the corrosion rate as a function of the corrosion potential is 3.25 which means that for every 308 mV (i.e. $^{1}/_{3.25}$) difference in the corrosion potential,

Position	Depth (m)	pH	E_{corr} vs Ag/AgCl (V)	E_{corr} vs NHEl (V)	Depth of concretion and corrosion (mm)	Observations
1	2	7.80	-0.557	-0.298	0.3	Thin concretion, poor pH contact and significant corrosion
2	1	5.85	-0.568	-0.309	6.0	Moderate concretion and corrosion layer
3	0.5	7.18	-0.579	-0.320	9.5	Plate has mainly corroded from this section of the vessel
4	0.8	6.95	-0.576	-0.317	21.5	Good thickness of concretion and good pH profile drilled
5	0.3	7.23	-0.584	-0.325	20.8	Similar concretion thickness but less corroding environment
6	0.4	8.32	-0.478	-0.219	2.0	Area had a very hard inorganic calcareous deposit on it and it was more alkaline than sea water
7	0.3	8.12	-0.574	-0.315	8.2	General plating, poor pH hole drilled?
8	0.5	6.90	-0.574	-0.315	12.5	Standard acidic concretion values, good black corrosion products into sea water
9	0.5	6.68	-0.568	-0.309	11.5	Possible site for interaction of the moorings of other vessels with the submarine
10	0.5	7.72	-0.575	-0.316	14.1	Site is very silty
11	0.5	7.10	-0.572	-0.313	8.7	Appears to be in a sound condition
12	0.2	8.05	-0.459	-0.200	3.5	Not in the calcareous zone

Table 1. Measurements taken on J7 submarine January 2010.

Depth (m)	Temp. °C	Dissolved oxygen (ppm)	Salinity (ppk)	* DO (ppm)	% saturation
0.5	29	3.88	37.3	6.25	62
1.0	29	4.46	37.4	6.25	71
1.5	28	6.10	38.6	6.29	97
2.0	28	6.27	38.6	6.29	100
2.5	28	6.34	38.6	6.29	101
3.0	28	5.96	38.6	6.29	95
3.3	28	0.18	38.4	6.30	2.9

Table 2. Dissolved oxygen at the HMAS *J7* submarine, Sandringham January 2010.
* Data taken from Riley, J.P. and Skirrow, G., (eds.), *Chemical Oceanography, Vol. 1.* Second Edition. Academic Press, London (1975).

the corrosion rate increases or decreases by ten times. This methodology was used to calculate the reduction in corrosion rate for various elements on the *City of Launceston* after the application of anodes.

Additional measurements taken at each drill point include the water depth at the drill hole point, the length of the drill hole from the surface of the concretion to the bare metal and the water temperature. If the object being measured is made of cast iron then the depth of graphitisation, that is, the corrosion profile beneath the concretion preserved in the residual structure, can be recorded after changing to a metal drill bit and penetrating the corrosion profile until solid metal is reached. This data provides additional information about the relationship between the pH and E_{corr} and the total coverage of the area by marine growth while the water temperature provides comparative measurements for wreck sites across Port Phillip Bay and in other waters.

Salinity and dissolved oxygen measurements are taken from a work station on board the diver support vessel at 0.5 m intervals down the water column from the surface to the seabed at each wreck site. These measurements are done in conjunction with water temperature, water depth and measurements described above, assists with the interpretation of corrosion data. This environmental information is essential to enable comparison of corrosion rates between different sites.

An electrical continuity survey was also conducted on the *Cerberus*, using a high impedance digital multimeter located in a separate 316 stainless steel housing connected

Distance from stern (m)	pH	Ecorr vs. Ag/AgCl (V)	Ecorr vs. NHE (V)	Corrosion & concretion thickness (mm)	Depth (m)	Resistance (kΩ)
0	8.07	-0.447	-0.188	21.5	2.1	
5	8.08	-0.582	-0.323	13.5	2.3	530
10	7.46	-0.575	-0.316	7.5	3.1	574
15	7.82	-0.573	-0.314	6.0	3.1	155
20	7.83	-0.585	-0.326	2.0	3.9	322
25	8.03	-0.583	-0.324	8.5	3.6	12
30	7.81	-0.580	-0.321	4.0	4.0	13
35	7.41	-0.579	-0.320	2.5	4.0	12
40	8.07	-0.506	-0.247	3.5	3.4	12
40	8.00	-0.563	-0.304	7.0	3.4	4800
45	8.02	-0.452	-0.193	4.0	3.2	4800
45	7.62	-0.557	-0.298	6.5	3.2	15600
50	7.12	-0.582	-0.323	2.0	3.3	5610
55	8.05	-0.374	-0.115	4.5	3.7	28
60	8.04	-0.558	-0.299	3.5	3.7	22
65	7.28	-0.586	-0.327	11.5	3.4	22
70	7.68	-0.582	-0.323	6.8	3.7	22

Table 3. *In-situ* corrosion data collected on the HMVS *Cerberus* January 2011.

Location	Barrel pH	E_{corr} vs. AgCl (V)	E_{corr} vs. NHE (V)	Depth (m)	pH Zn anode	E_{corr} Zn anode (V)
gun 1	n.d	-0.976	-0.717	3.9	7.24	-0.980
gun 2	n.d.	-0.820	-0.561	3.9	6.87	-0.820
gun 3	8.18	-0.934	-0.675	4.5	6.43	-0.920
gun 4	8.29	-0.861	-0.602	4.5	6.62	-0.912

Table 4. pH and E_{corr} measurements taken on anodes attached to each of the four guns.

Location	pH	E_{corr} volts vs. Ag/AgCl (V)	Delta E_{corr} volts	% fall in corrosion rate	%increase in corrosion rate
bow	7.52	-0.664	0.050	42	
frame amidships port side	8.04	-0.670	0.056	48	
starboard amidships	8.17	-0.718	0.104	107	
engine	7.32	-0.641	0.027	21	
stern	7.70	-0.673	0.059	51	
Mcquay device near engine	7.92	-0.337			20

Table 5. E_{corr} and pH measurements on the anodes and a Mcquay device Jan 2010, *City of Launceston* (1865).

to two waterproofed resistance probes. Resistance readings were taken at 5 m intervals, using the drill holes made for pH and E_{corr} measurements. The multimeter was set on the megohm (MΩ) range for the resistance readings.

Three dives were undertaken on the *Cerberus* hull and the guns over two days. Measurements on the hull were taken by teams of four, with one diver operating the drill, one holding the far end of the resistivity meter, MacLeod taking pH, E_{corr} and resistivity measurements (Fig. 2) and the fourth member measuring 5 m intervals, holding extra equipment and taking photographs.

Fieldwork results

J7 *submarine, Sandringham Yacht Club.*

The *J7* was last inspected by Heritage Victoria staff in 2006, although this was a visual inspection from the surface. Work undertaken by Beringer-Pooley in 2005 was the last sub-water survey and the data appears to be

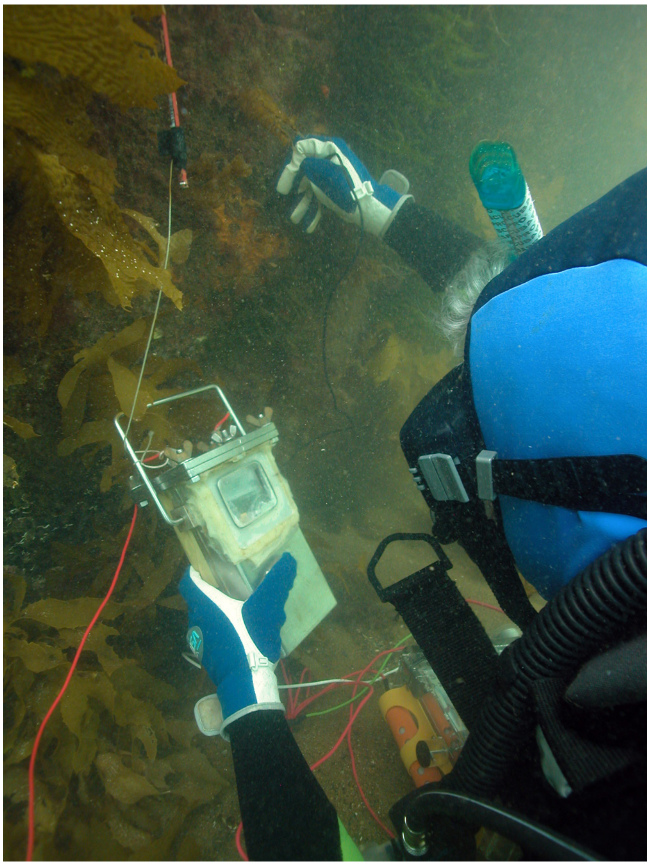

Figure 2. Divers undertaking resistance measurements on the hull of HMVS *Cerberus*.

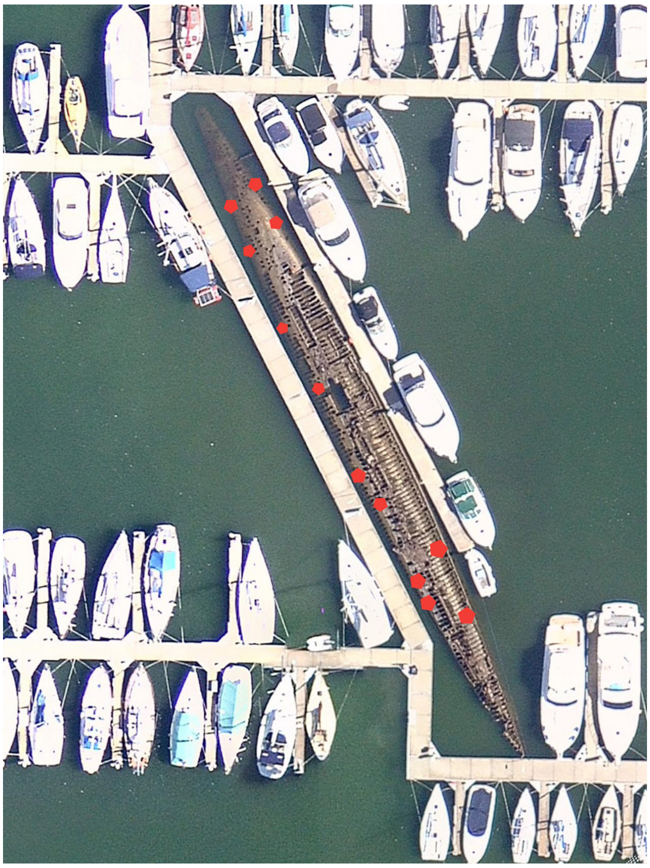

Figure 3. Location of the submarine *J7* in Sandringham Yacht Club showing measurement points.

non-representative owing to a combination of inadequate drilling through the hard concretion, recording of the pH after the E_{corr} measurements and associated systematic recording errors (Beringer-Pooley 2005), as such it was uncertain what condition the site would be in. However the indications were that the wreck was relatively sound.

The wreck lies within the central part of the Sandringham marina, with pontoons fully surrounding three sides and partly surrounding the fourth side (Fig. 3). As such, the wreck is not only protected from moored ships but also has minimal water movement around it. The wreck lies in approximately 3 m of water, with the upper sections fully exposed to the atmosphere, above the high water mark. The seabed is a fine, silty sediment and the lowest sections of hull are buried within the seabed.

Two dives were made on the site, with 12 drill holes for pH and E_{corr} measurements taken along both the port and starboard sides, as shown on Figure 3.

The sections of hull that were fully exposed above water had a much harder concretion layer in contrast to the softer and more easily penetrated marine concretions on the submerged sections. The concretion was thin (2–4 mm) in all measured areas. The pH and E_{corr} measurements taken around the hull, shown in Table 1, indicate that the hull is in moderate condition, given that corrosion rates are going to be at a maximum in the splash zone due to wind chop and water movement from passing boats. The data indicates that the corrosion potentials cannot be directly interpreted as is the case for fully immersed vessels. Caution needs to be exercised in interpreting this data without information about the residual metal thickness and conducting a calibration exercise that will establish the connection between metal loss and the present E_{corr} values.

Despite the number of years of immersion since the vessel was scuttled it is apparent that much of the structure is electrically connected and so corrosion of the exposed sections of the submarine is likely to provide some degree of protection for the sections that are fully immersed in the low levels of dissolved oxygen in the water, as a result of the minimal water movement around the site due to its protected position within the marina. The silty seabed provides an anaerobic environment that will protect the lower sections of hull from rapid aerobic corrosion but will naturally be subject to normal anaerobic corrosion mechanisms. It should be noted that there will be accelerated corrosion, due to the oxygenation profile changes, in the area of the hull near the interface of the oxygenated sea water and the anaerobic sediment.

It is instructive to compare the measurements of E_{corr} and pH on *J7* with those taken on the surface of *J3* at Swan Island in November 1998. The *J7* data at a mean water depth of 0.49±0.16 m had a mean E_{corr} of -0.316±0.005 (NHE) and a pH of 7.24±0.47 while the *J3* data gave a mean E_{corr} of -0.340±0.016 and the pH value was 8.01±0.14. The *J3* site had water cascading across the corroded structure

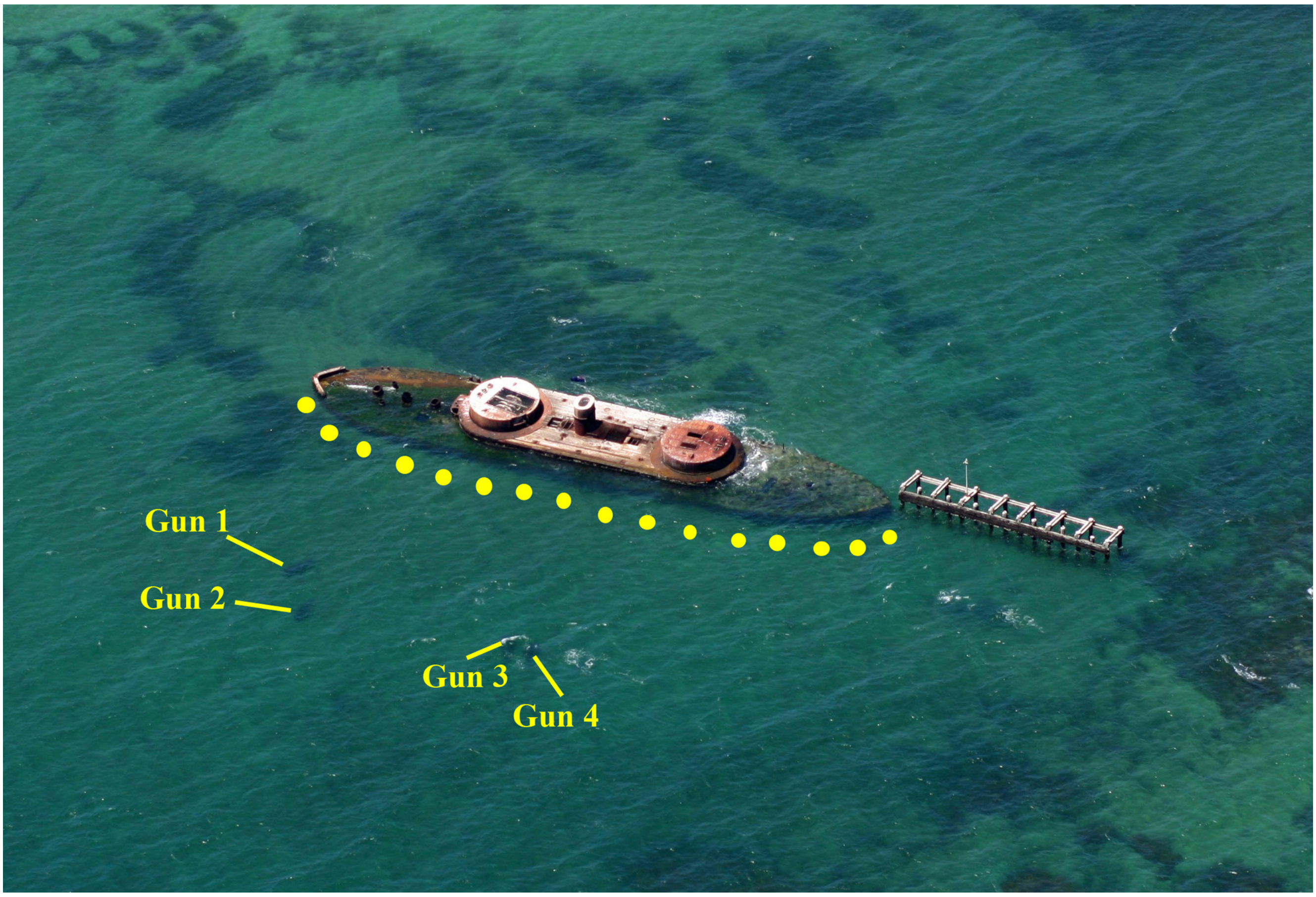

Figure 4. Aerial view of the *Cerberus* site showing location of the gun barrels undergoing *in-situ* treatment and the starboard measurement points.

which meant that the pH data was simply reflecting the pH of the local sea water which was 8.00—the shallow concretion profile precluded the development of a representative reading of the underlying acidity. The more negative mean E_{corr} value for *J3* compared with *J7* may be due to the fact that the former submarine lies lower in the water and so much less of the structure is fully exposed. During measurements in November 1998, which were taken at slack water at low tide, the upper works of the submarine rapidly began to flood as a strong current swept across the site that threatened to dislodge the author. The 24 millivolt difference in the mean E_{corr} values of *J3* and *J7* may indicate that the submarine off Swan Island is corroding at 20% slower rate than the vessel locked into the Sandringham Yacht Club marina.

It is noted that at the deepest part of the *J7* site the very low dissolved oxygen level is associated with the weighted probe penetrating the silt mound which is a region characterized by limited exchange with oxygenated sea water.

HMVS Cerberus

A series of corrosion measurements on the wreck of HMVS *Cerberus* have been undertaken by one of the authors over a period of 17 years and the fieldwork provided an opportunity of establishing the suitability of using *in-situ* cathodic protection for the hull structure. Measurements on the vessel itself, the gun barrels and their anodes were taken, at the locations shown in Figure 4. Measurements of the E_{corr} and the pH of the anodes provide data which also demonstrates that higher anode corrosion rates are associated with more acidic pH values—see data in Table 3. The acidic nature of the surface of the zinc anodes is due to the hydrolysis of the Zn^{2+} ions and the general observation is that the more acidic the anode the greater is its corrosion rate and the higher the current density being supplied to the cannon barrels. Measurements were also taken on the stainless steel connecting bolts that are tapped into threaded holes drilled into the barrels of the guns prior to them being removed from the gun turrets and placed on the seabed. Since the bolts are electrically connected to the gun barrels it is a less interventive procedure to measure the E_{corr} on the connecting bolts than to drill through the concretion and conduct the measurement on the gun itself.

Measurements were taken on the hull at 5 m intervals, along the starboard side measured from the stern with a tape measure, as shown in Figure 2. All drill holes were made approximately 1 m from the seabed, into the armour plating.

The drill holes varied in depth (i.e. the concretion on the armour plating varied in thickness) between 21.5 and 2.0 mm. The thin concretion measurements are indicators of areas that had been deconcreted during the major collapse of the *Cerberus* and have had insufficient

Figure 5. Zinc anode on the *City of Launceston* site showing voluminous corrosion products resulting from protecting the vessel.

time to allow them to develop concretion thicknesses that are commensurate with the underlying rate of decay. During the measurement period Melbourne had been subjected to unseasonable weather with air temperatures in excess of 40°C and so the sea-water temperatures recorded were high at 24°C. Full details of the measurements taken are shown in Table 3.

The four guns on the seabed (named as per Figure 4) had their E_{corr} values recorded and the pH values of guns 3 and 4 assisted the authors to establish the degree of cathodic protection being provided by the anodes. Measurements were also taken on the anodes attached to each gun, and results are presented in Table 4.

The dives along the armour belt confirmed that there is no longer a gap between the seabed and the wreck and that the armour belt is resting on the seabed, that is, the original hull structure has totally collapsed since 1997. A small gap of a few millimetres was noticed in the upper part of the armour belt, which may be a reflection of where differential corrosion rates have removed a joint between the original plating and that added later on (MacLeod 1996b). The seabed on the starboard side is littered with broken frames, bits of hull plating and other broken, deformed and displaced parts of the lower hull. It should be noted that the pH of the gun barrels is more alkaline than the surrounding sea water value of 8.08 and this provides evidence of the efficacy of the cathodic protective current being provided by the zinc anodes.

City of Launceston

One dive was undertaken on the *City of Launceston* which was sufficient to acquire the pH and E_{corr} readings of the areas of the vessel directly connected to the anodes. Measurements were taken on the hull and at the anodes at locations specified in Figure 1 to establish their effectiveness. An additional drill hole made for further measurements on a reference Maquay patent lifting device which had been used in the initial salvage attempts shortly after the accidental sinking due to the *City of Launceston* being rammed by the *Penola* steamship. The Maquay devices were large cast iron drums that contained zinc which, when reacted with sulphuric acid, generated hydrogen to provide buoyancy. The results are summarised in Table 5.

The anodes were noted to have a massive covering of zinc corrosion product, as seen in Figure 5, indicating that they were actively corroding.

The measurements (see Table 5) show a significant reduction in the corrosion rate in all areas attached to the anodes which indicates that the anodes are working. By way of comparison the Maquay device, which had no anodes attached to it, has seen a 20% increase in corrosion rate since 1991. The $Ag/AgCl_{sea}$ reference electrode was calibrated at +0.259 volts vs. the normal hydrogen electrode (NHE) to facilitate comparison of data over a number of years.

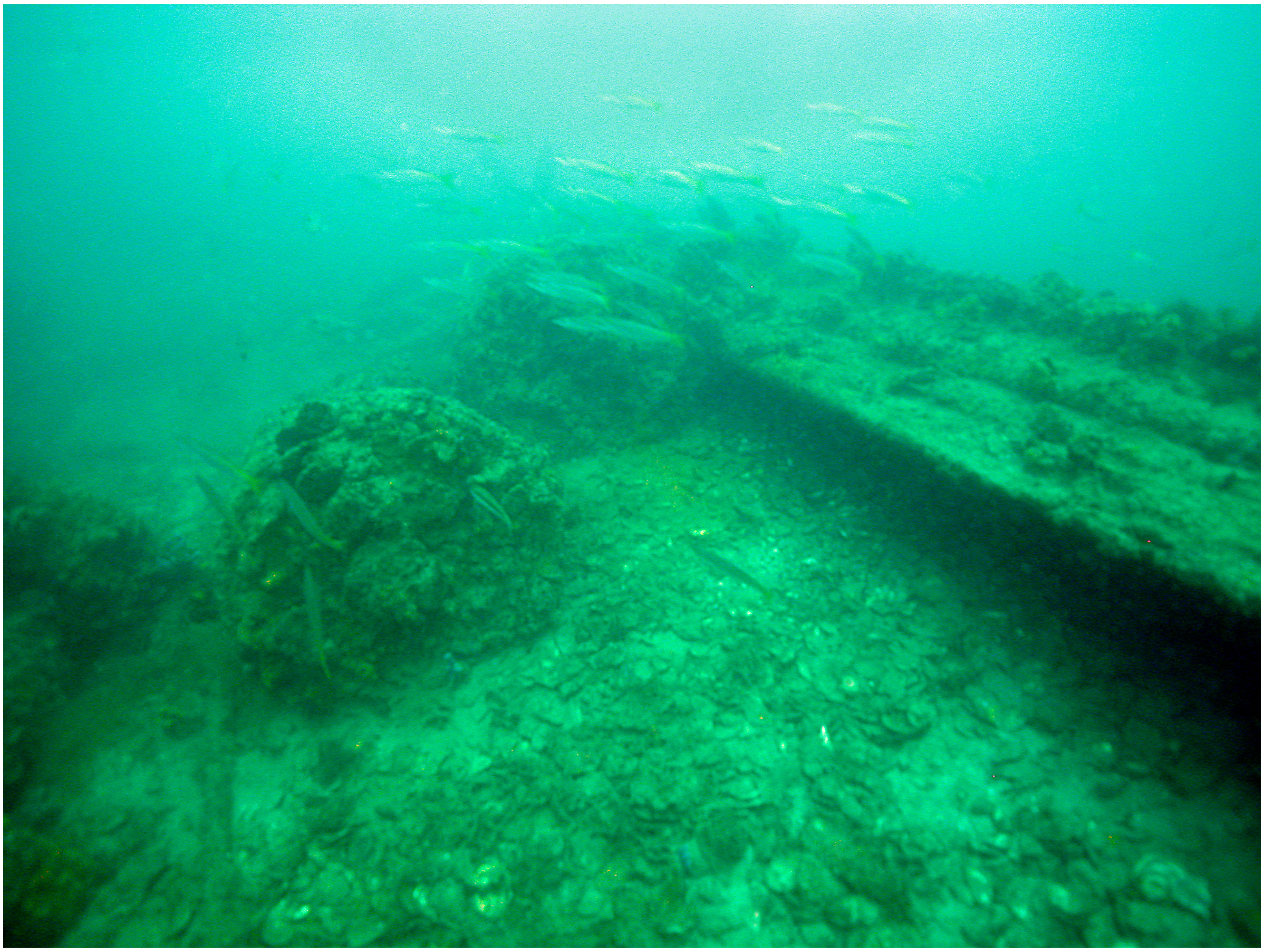

Figure 6. Changes in water flow leading to scouring on the *City of Launceston* site.

A second photographic recording dive on the *City of Launceston* two weeks after the training exercise revealed that the site is continuing to lose sediment, with the spiral staircase now well exposed, and a 'shelf' at the bow now well defined. It seems that either loss of sediment or collapse of some internal, buried feature (possibly a deck) has resulted in a slumping of the visible features (Figure 6). Further evidence of sediment loss comes from exposed features around the stern which have not been observed before.

Discussion

The J class submarine J7 *(1924)*

The *J7*'s apparently good condition is deceptive since the structure appears to be remarkably intact yet when drilled there was a significant crust of oxidized metal that had to be penetrated. If the exposed metal was deconcreted it is likely that there would be a lot less mechanical strength in the residual structure so this form of intervention should be actively discouraged. Given its sheltered position *J7* is unlikely to be subjected to significant physical stress and so it is likely to continue in its present form until the areas at and near the silt line at the bottom of the vessel collapse. Due to the soft silty nature of the seabed sediment, working at the seabed would have stirred up the sediment and created near black water conditions. The operational difficulties of working in these conditions meant that no measurements were taken on the lowest part of the hull at or near the sediment line. In order to properly assess the overall condition of *J7* it would be helpful to obtain residual metal thickness measurements on deconcreted elements at the seabed.

The work on *J7* revealed the value of collecting the standard parameters of temperature, salinity and dissolved oxygen. Data collected at the *J7* site showed that when the oxygen levels are plotted as a function of water depth they initially increase and then fall to essentially zero at the sediment interface, confirming that the bottom section of the submarine is corroding in an anaerobic microenvironment (Fig. 7).

The dissolved oxygen, salinity and temperature data for the *J7* site are listed in Table 2 where it can be seen that in the first metre of the site the higher temperature of 29˚C means that the total amount of dissolved oxygen available to the site is less than in the deeper parts of the site and that the amount of oxygen in the surface waters is significantly depleted, as seen in the plot in Figure 7. The data in this figure shows that the waters surrounding the upper parts of the grounded submarine amounts to 62% of the saturated level and that over the next metre

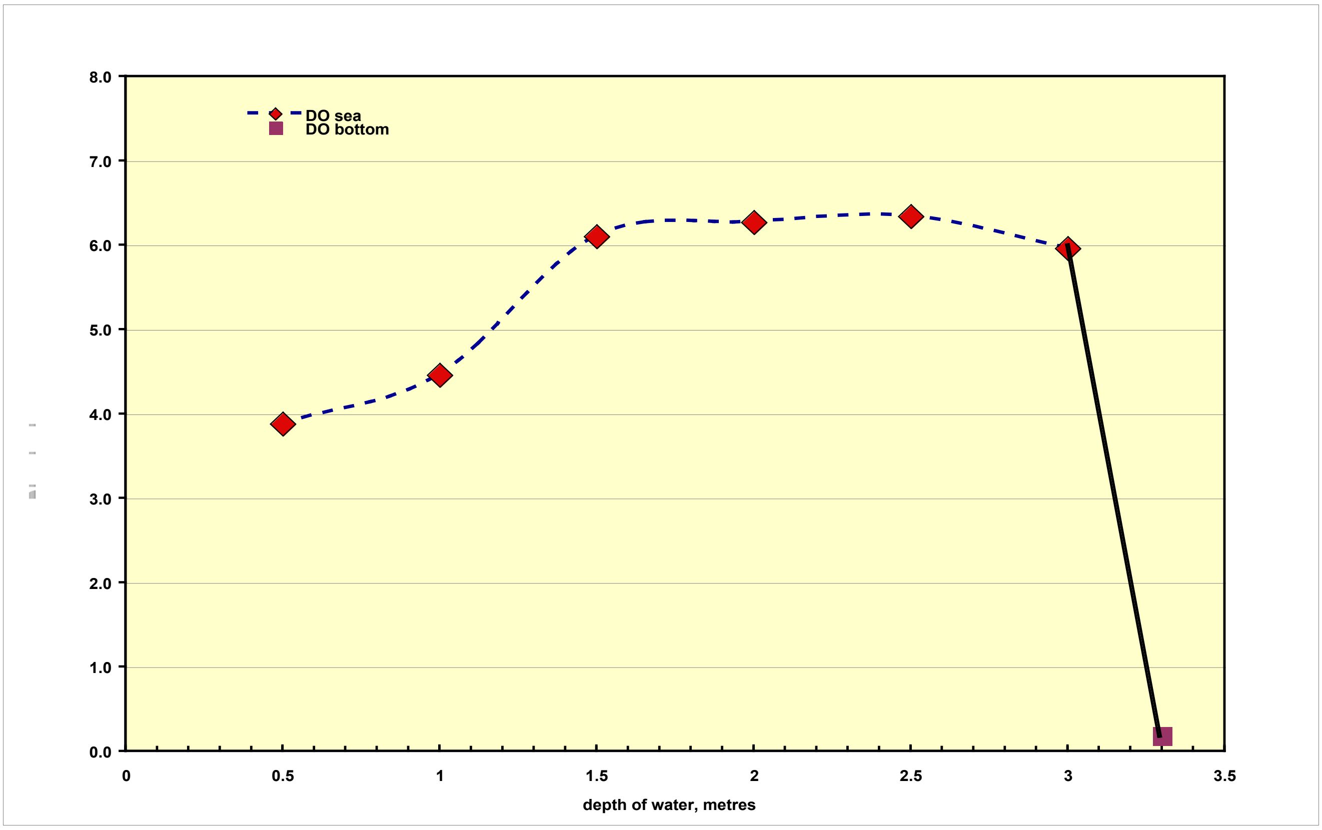

Figure 7. Plot of dissolved oxygen concentration on the *J7* site in Sandringham Yacht Club marine.

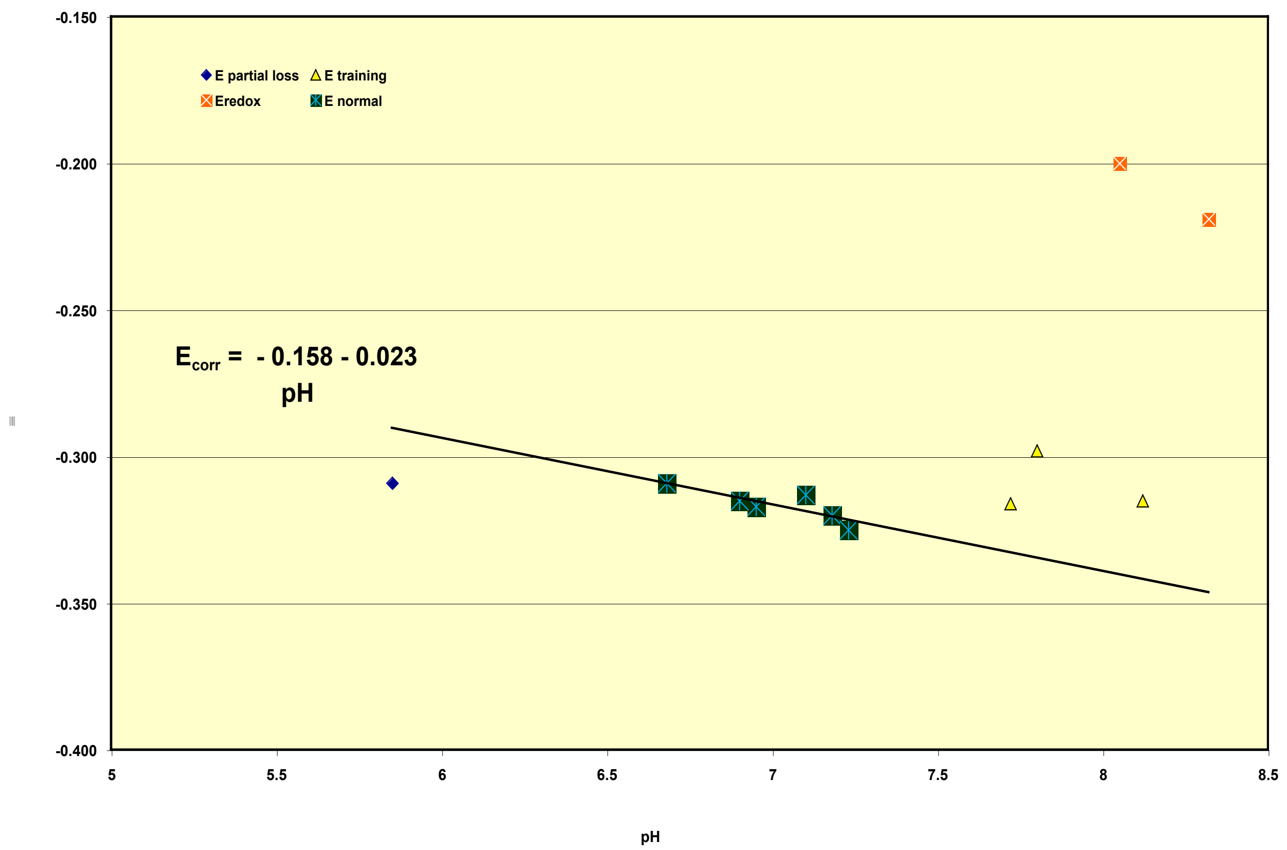

Figure 8. A modified Pourbaix diagram with *in-situ* corrosion data from *J7* illustrating good and bad data points.

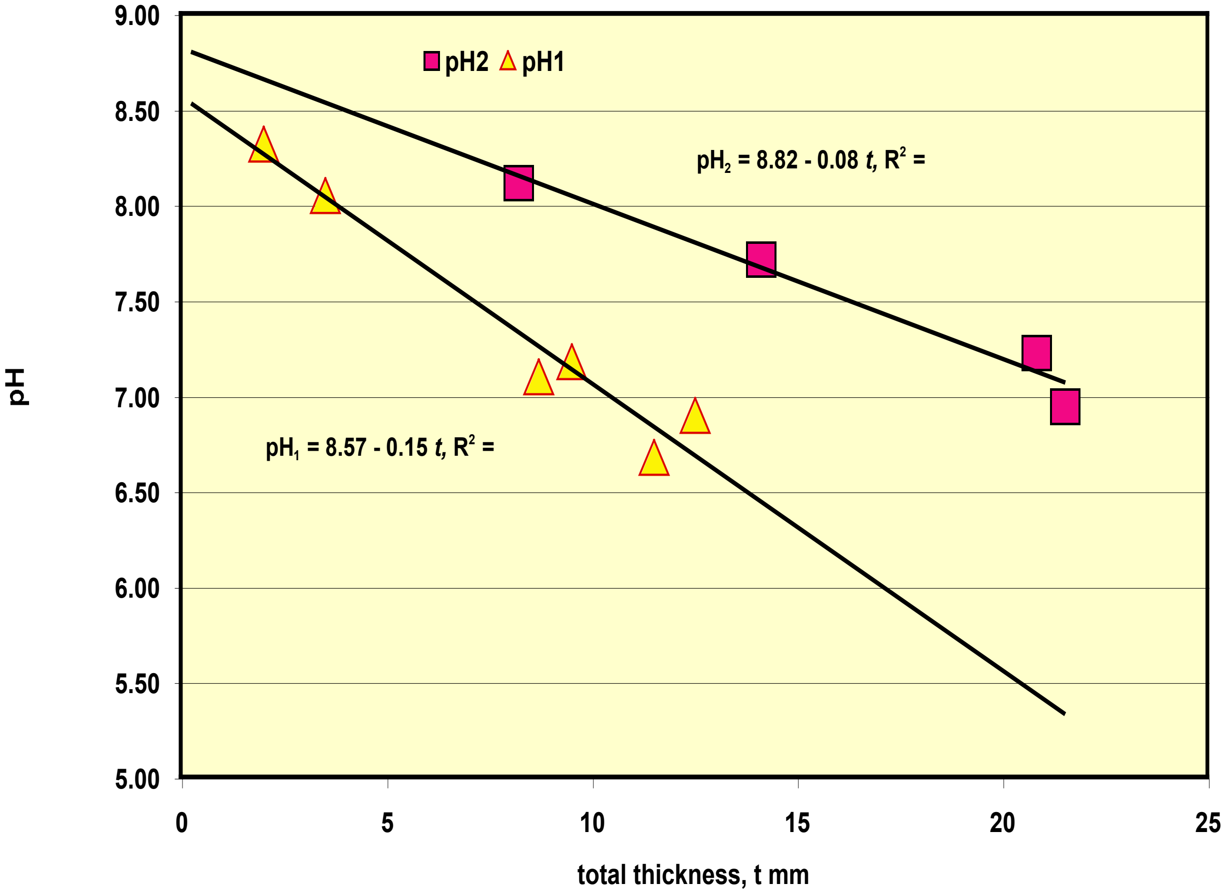

Figure 9. Effect of varying thickness *t* of corrosion products and concretion on the pH of the matrixes on *J7*.

of depth this percentage increases by 35% to approach the saturated value for that salinity and temperature. Thereafter the amount of dissolved oxygen in the water column remains high at 98.0 ± 2.7% saturation until the bottom waters are touched and the probe entered the upper silt layer where the value fell to almost zero. Thus it can be seen that although the actual salinity corrected values of the dissolved oxygen reported in Table 2 are a useful indicator of the general physical chemistry of the site it is often very instructive to compare the measured with the literature data for the same temperature and salinity to see how saturated the sea water is with respect to oxygen and its inherent power to corrode the historic iron structure.

Examination of the E_{corr} and pH data listed in Table 1 shows that the majority of the measurements on the *J7* submarine is the same as the relationship found on other historic iron shipwrecks, where the slope of the Pourbaix diagram is -29.5 ± 2.0 mV, consistent with the following simplified chemical reaction describing the overall corrosion process (Equation 2) as,

$$2\,Fe + 2\,Cl^- + 2\,H_2O \{Fe(OH)_2FeCl_2\} + 2\,H^+ + 4\,e^- \quad (2)$$

The E_{corr} and pH data from Table 1 is plotted in Figure 8 where it is noted that three data points, designated 'training' lie outside the line of best fit and this is due to the trainees taking too long to get the pH electrode inserted into the drill hole so the pH reading is too alkaline. The increased alkalinity is due to the influx of sea water as the trainees were becoming familiar with how to place the flat surface pH electrode into the custom drilled hole. Once some practical experience had been gained the volunteer divers were able to record meaningful data. The highest corrosion potential readings labelled E_{redox} had voltages more than 100 mV anodic (more positive) of the other values which is a strong indication that the metal is in a highly corroded state. Since there were only two redox data points there is insufficient data to make an informed comment on the apparent sensitivity of these corrosion cells with water depth. It had been previously reported that for highly degraded hull plates on the City of Launceston for the redox voltage fell by 114 mV per metre (MacLeod 2010). Typical sensitivity of the E_{corr} to water depth is of the order the 5-12 mV for most open water wreck sites. The much greater apparent sensitivity to depth is one way of discriminating real corrosion potentials from redox voltages of the corrosion matrix on highly degraded metal fittings. The two redox potentials are also associated with high pH values, greater than the surrounding sea water, and this is likely to be due to these sites being areas of cathodic reduction of oxygen, and reflects processes associated with the complex corrosion microenvironment of J7 lying in its present location in the Sandringham Yacht Club marina.

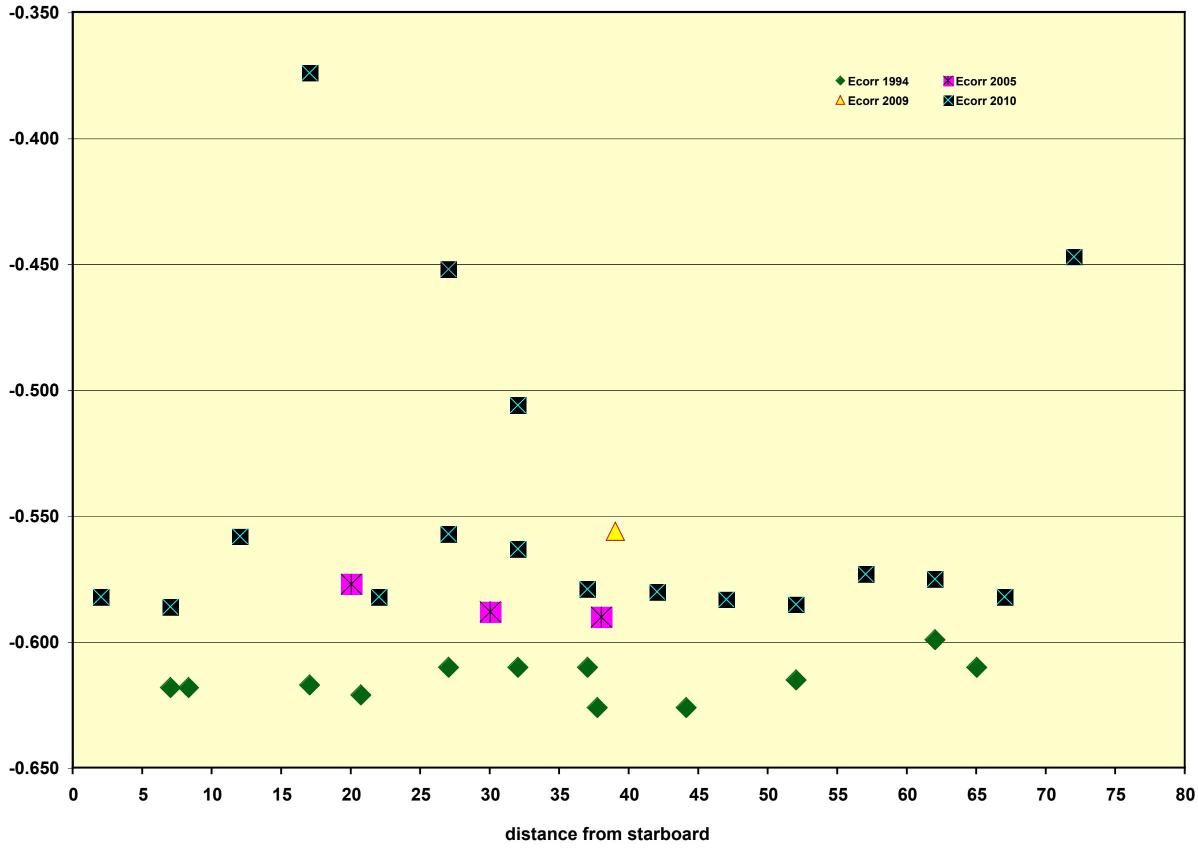

Figure 10. Plot of the corrosion potentials on the *Cerberus* as a function of time of measurement and distance from the bow.

It was previously noted that the concretion on the submarine was of varying thickness and anecdotal reports indicate that the public periodically remove corrosion products and concretion when visiting the site to satisfy their curiosity to see if there is any solid metal underneath the covering. When the combined thickness, t of concretion and corrosion products is plotted as a function of pH, the data in Figure 9 shows two groupings of data which is not surprising given the complex corrosion microenvironment of the submarine which is buried in silt, exposed to flowing sea water, has wet and dry areas all electrically connected to sections that are permanently out of water but in the zone of being saturated with sea spray. The data groupings reflect the different physical microenvironment of the submarine. The lower line, equation 3, shown in Figure 9 reflects data collected around 1 m below the water line which has thinner concretion,

$$pH_1 = 8.57 - 0.15\, t \qquad (3)$$

where t is the combined thickness of concretion and corrosion products and the tightness of the linear regression is shown in the high R^2 value for equation 3 which was 0.9539. The second regression line has an intercept value of 8.82 and has been derived from the thicker set of concretions associated with the test sites at or near the splash zone and is described by equation 4,

$$pH_2 = 8.82 - 0.08\, t \qquad (4)$$

for which the R^2 of the regression equation is 0.9649. It is likely that the differences in the slopes of equations 3 and 4 are reflections of the differences in the corrosion microenvironments since data points relating to equation 3 are continuously wet whereas data for equation 4 relates to areas that include wet and drying cycles.

From the data collected during this training exercise *J7* appears to be corroding at a slower rate than would be predicted on the basis of the nature of its exposed condition thus its low energy environment appears to be effective in providing a good scenario for its future survival. Despite evidence that some plates are completely corroded, *J7* is one of the best surviving examples of the J-class submarines, and the unusual location of the site presents a rare opportunity for on site education and interpretation about this class of ship and wreck. As a result of the *J7's* protected position in Sandringham marina the *J7* would be amenable to corrosion protection from a shore based impressed (direct) current system, rather than relying on a series of sacrificial anodes. Treatment of the exposed metal frames with a fish-oil based coating would significantly improve its viability to retain its present configuration.

HMVS Cerberus *(1926)*

Consecutive sets of measurements taken on the *Cerberus* hull since 1994 have demonstrated continually increasing

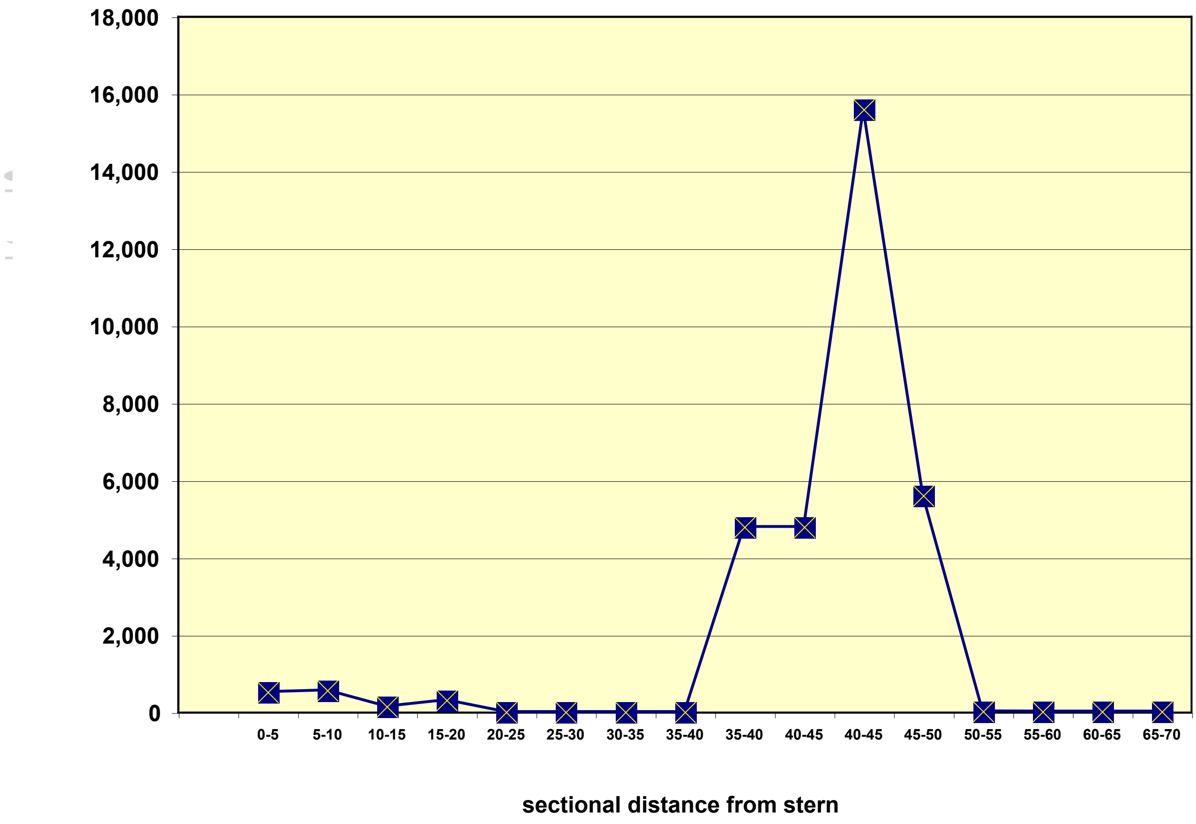

Figure 11. Plot of electrical resistance in kΩ on the *Cerberus* hull along the ship's starboard side.

rates of corrosion. This indicates that in addition to continued movement and settling on the seabed, the wreck has yet to achieve an environmental equilibrium since the collapse of the lower hull in 1993. The change in corrosion rate is indicated by the shifting values of the E_{corr}, thus the data in Figure 10 shows an incremental movement of the E_{corr} values towards more anodic (positive) potentials, an indicator of increased corrosion rates.

The measurements on the four off-site guns indicate that the anodes are working effectively so long as they remain attached. There have been ongoing issues with anodes becoming detached from the guns due to the large swells experienced on the site that causes case-hardening of the heavy gauge multi-strand insulated copper cables. This has been largely addressed by burying the anodes in the sediment and regular inspection by both HV and Professional Diving Services however it seems that occasionally this problem still occurs.

The resistance measurements are particularly significant in the way in which they vary considerably down the length of the wreck. The low resistance along the first eight 5-m sections indicates that there is still very good electrical conductivity and connection between elements of the submerged structures. Sections between 40 and 50 m exterior length indicated poor connection and the interval between 40 and 45 m shows that there is no connection. At this point the forward and aft parts of the vessel are in electrical isolation from each other (Fig. 11). Since the middle sections of the vessel are not electrically connected any cathodic or impressed current system would have to be independently connected at the bow and at the stern. Some bridging connection could be made if the upper sections of the wreck amidships were to be fully protected. When the linear dimensions along the outward curve of the starboard side of the *Cerberus* are corrected for the overall length derived from the Admiralty plans it can be seen that the midships of the wreck are in electrical isolation. It is likely that there is a break in the structure at this point, that is, in the middle of the wreck in the general vicinity of the conning tower. If corresponding measurements on the port side show the same discontinuity then the implications for any proposed jacking of the vessel or other form of lifting is most serious and profound.

This is supported by the engineering report by Gutteridge Haskins and Davey (GHD) (2000) which stated that surveys found that the turrets remained level and true, with no measurable sagging or twisting between them, suggesting that the structures which supported them were in fact intact, strong and true. However GHD went on to state that it was their expectation that the structures were in fact not solid and 'could be expected to collapse imminently'. The survey data presented here however, suggests that the structure remains in good solid condition both aft and forward of the section between 40 and 50 m from the stern.

The surveys undertaken in January 2010 show that *Cerberus* is much more solid, and intact internally than previously thought. The placement of anodes on the armour plating would be an easy and cost-effective way to begin *in-situ* conservation works to the hull, internal structure and turrets and would extend the life of the wreck in its current form for future research, public enjoyment and interpretation. The anodes on the four guns are working well, and will ensure that should there be a desire to recover them for interpretation purposes, the anodes will have minimised the complexity and the associated costs of the conservation works required.

City of Launceston *(1865)*

The E_{corr} measurements taken in 2010 have been compared with those taken on the hull in 2007 to establish the efficacy of the anodes at reducing corrosion rates. The anodes can be said to have reduced corrosion rates by between 69 and 79%, with a dramatic reduction of 130% for the anode positioned at starboard amidships (MacLeod 2010). The changes in E_{corr} and the pH of the frame on the starboard side amidships, compared with the other moves to more cathodic values, indicates that the frame is functioning as an electrically isolated unit.

The anodes placed on the *City of Launceston* in July 2009 have had a marked effect in slowing the corrosion rate of the hull and engine, and can be considered a success for *in-situ* conservation of an iron-hulled vessel. The anodes are corroding at a reasonably rapid rate and are likely to need replacing within the next 12–24 months. The anode attached to the engine appears not to be as effective as the others, in terms of the drop in the corrosion potential, but given that it is connected to a much larger amount of metal, it may take much longer to be able to reduce the corrosion activity to the same level as in other sections of the vessel. A second anode has since been attached to the engine to assist with reducing the corrosion rate of not only the engine block, but also the keelson, frames and hull structure to which it is likely to be attached.

Conclusions

The measurements taken as part of this fieldwork have provided important data which will enhance the management of these three important shipwreck sites. Whilst all three shipwrecks may appear, visually, to be similar in their condition, the data clearly indicates that the three vessels are in very different electrochemical environments. Data from the *J7* site indicates that the variations in the dissolved oxygen content and the exposure of significant hull sections to a changing microenvironment, as the time of wetness varies according to the prevailing winds and the splash zone associated with wave chop, demonstrate the need for more extensive documentation of the extent of deterioration of the exposed and wet-concreted sections of the vessel. Although there are similarities between the corrosion microenvironment of *J3* and *J7*, since both vessels have their upper sections fully exposed, their main sections immersed and the keel area buried in anaerobic sediments, additional studies would assist in the development of appropriate conservation management programmes.

The long-term corrosion studies undertaken on *Cerberus* and *City of Launceston* have provided baseline information against which the effectiveness of cathodic protection, through the attachment of zinc anodes, can be assessed.

Data from the *Cerberus* guns has demonstrated the value of *in-situ* or in-water cathodic protection for the conservation treatment of iron objects. These four items have effectively been 'treated' and can be seen as no longer corroding, so long as the anodes remain attached. The continued presence of anodes on the guns will ensure that should the removal of the guns from the water for display become a viable option, the required conservation treatment will be of short duration and minimal expense since they have been effectively desalinated whilst in sea water. Data collected from the hull of *Cerberus* has shown that large sections of the hull and internal structure are still electrically connected, however still corroding at a high rate. These results will facilitate the optimal location for anode placement that was planned for the winter of 2010. This work is a first step in the medium-term conservation plan for the site, which aims to maintain the current condition of the site with minimal visual and structural intervention.

Data collected from *City of Launceston* has demonstrated the dramatic effect the placement of cathodic protection on steel-hulled shipwreck sites can have in reducing the rates of corrosion. It is understood that the slowing of corrosion will help to maintain the current condition of the site, where the upright hull contains intact archaeological deposits. Once the initial corrosion rate has been checked and the chlorides removed, the continuing presence of cathodic current brings about a re-precipitation of the original calcareous binding minerals that had dissolved as a consequence of the acidity produced through the hydrolysis of the original iron objects. This process results in increased mechanical strength for the encapsulating concretions which in turn make the degraded vessel more resistant to the damaging effects of storm surge.

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