

IMPLICATIONS OF THE MARINE AGGREGATE PROPOSAL ON  
THE DEGRADATION OF HISTORIC SHIPWRECKS SOUTH OF  
SYDNEY, NEW SOUTH WALES

by

Dr. Ian D. MacLeod

Department of Materials Conservation

Western Australian Maritime Museum

Fremantle, Western Australia 6160

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## **1.0 INTRODUCTION**

The marine aggregate proposal involves the underwater recovery of marine aggregate off the New South Wales coast by suction removal. A slurry of the aggregate and sea water will be deposited into hoppers on the extraction vessel and the excess water and fines will be returned to the sea. The details of the work and the measures that will be followed can be found in the supporting documents from the primary and secondary consultants. The purpose of this report is to provide comment on issues raised in the following consultants reports-

:GEOMARINE- *Appendix XI. Impacts on Shipwrecks*

:THE ECOLOGY LAB PTY. LTD.- *Marine Ecological Investigations ; Sections 6.0-6.5, Sections 10.0 -10.6 and sections 14.2.3 -14.3.4, as well as section 17.0 -17.6 .*

:MARITIME ARCHAEOLOGICAL STUDIES by *Rebecca Bower Preliminary Draft 4 (whole document)*

:POLLUTION RESEARCH PTY LTD - *Seawater and Sediment Chemistry*

The primary focus of this report is to assess the data in the above reports in terms of the possible affects of the proposals for the long-term viability of the resource that is to be found in the form of **Historic Shipwrecks**.

## **2.0 OBJECTIVES**

In order to assess the implications of the proposed operations it is necessary to have an understanding of the parameters that affect the deterioration of materials on shipwreck sites. The first section of this report deals with the phenomena that are associated with the deterioration of shipwrecks on the seabed. This section forms an essential component of the report.

Our assessment of the proposal on historic shipwrecks within and close to the proposed extraction areas took account of a series of other specialist reports relating to the nature of the marine environment. The evidence was considered and a series of residual impacts of the proposal on the shipwrecks, after all the relevant safeguards are adopted, has been formulated. Appropriate recommendations for procedures to be adopted during the life of the marine aggregate project, should it proceed, have been made.

**It is important to note that no detailed corrosion studies have been made on historic shipwrecks off the New South Wales coast. It has therefore been necessary to use data obtained elsewhere, principally from Western Australia, Norfolk Island and Port**

Philip Bay, to assess the likely impact of the proposed activities on the degradation rates of the shipwrecks. Although the corrosion mechanisms are believed to be common to all shipwreck sites the data refer to shallow water sites and to areas associated with significant sand movement.

It should be noted that the general rate of deterioration of metals on shipwreck sites is very dependent on the water depth and the flux of oxygenated sea water over the objects lying proud of the sea-bed. For organic materials such as wood, rope, textiles and leather the deterioration is largely dominated by the activity of marine organisms such as *Limnoria*, the wood-boring mollusc *teredo* and microflora. Once buried the organic materials continue to degrade but at a rate that will fall significantly with increasing amount of sediment cover.

Given that the water depth of the Providential Head shipwreck sites is approximately 45 metres, the wrecks of the SS *Tuggerah* (1919) and the SS *Undola* (1918) can be considered to be in an environment characterised by relatively slow rates of deterioration, compared with many other historic wrecks which lie in high energy-shallow water areas. In a similar fashion, the wreck of the SS *Woniora* (1882) lies in 60-64 metres of water and so it is not subject to massive amounts of water movement on a frequent basis. For both sets of sites, the wrecks are primarily influenced by the normal water movement associated with the effects of onshore and offshore currents and to the periodic intervention of major storms.

The wrecks of the SS *Hilda* (1893) and the SS *Kelloe* (1902) are also in the general vicinity of the Cape Banks proposed extraction area but that are in shallower waters, at 25 and 40-50 metres respectively, than the SS *Woniora*. The SS *Hilda* is more than one kilometre from the western boundary of the proposed extraction area and cannot be expected to come under any influence of the activity. The wave action on this reef site will be the dominant forces controlling the rate of degradation. The wreck of the SS *Kelloe* has been noted to have been damaged extensively by explosives and even at a depth of 40-50 metres it is subject to significant wave action associated with the reef.

### **3.0 CORROSION MECHANISMS AND SHIPWRECK DEGRADATION**

#### **3.1 CORROSION PHENOMENA AND IRON SHIPWRECKS**

The overall impression of an iron shipwreck site is often dominated by the remains of the boiler, the engine and the frames that once gave the vessel its form. In warm tropical to sub-tropical waters, corroding iron and steel in seawater rapidly becomes encapsulated by encrusting organisms such as coralline algae and bryozoa (North 1982). This encapsulation begins the process of separating the anodic and cathodic sites of the corrosion cell, with oxygen reduction generally occurring

on the outer surface and oxidation of the metal occurring underneath the marine growth (MacLeod 1989). Under such conditions the anodic, or oxidation, reaction is not the rate determining step in the overall corrosion process. The corrosion process results in the inward diffusion of chloride ions from the sea, through the marine growth to the corroding metal, and the outward diffusion of the metal ions towards the seaward surface.

In the absence of calcareous colonising organisms, a corroding iron wreck will generally be covered with a matrix of corrosion products and marine organisms such as algae, barnacles and tunicates. Wrecks such as the *City of Launceston* (1865) in Port Philip Bay are typical of historic iron vessels that are corroding in deep water (22 metres) in the absence of calcareous concreting organisms (MacLeod, 1991). In-situ corrosion measurements on this vessel and others in Port Philip Bay confirmed that the same corrosion mechanism operates for wrecks in this type of environment as for material that is concreted with a matrix of calcareous materials. More recently corrosion studies on submerged and riparian sites on the River Murray have confirmed that the cathodic reduction of dissolved oxygen is the dominant process in determining the overall rate of corrosion (MacLeod, 1992).

The rates of corrosion are naturally dependent on a range of microenvironmental parameters. For iron materials lying proud of or on the seabed, the primary cathodic reaction is the reduction of dissolved oxygen. For metal that is totally buried in the sediment and is not electrically connected to iron that is exposed to oxygenated waters, the major cathodic reaction will be the reduction of water and the associated evolution of hydrogen. Under such circumstances, the corrosion process is often dominated by microbiological activity (Fischer, 1983) since the presence of dehydrogenase enzymes will often control the rate of hydrogen evolution (Sequeira and Tiller, 1988 & Metals Society, 1983).

Since the concretion acts as a semi-permeable membrane, a hundred years of corrosion results in a substantially different micro-environment being established around the metal itself compared with the surrounding sea. For example, the chloride concentration can be increased by a factor of 3 above the mean seawater levels and the pH can fall from the normal value of 8.2 to as low as 4.2 (MacLeod 1989-2). If the matrix of corrosion products and calcareous deposits are accidentally removed the increased access to oxygen results in accelerated corrosion of iron in a chloride-rich, acidic micro-environment, and the loss of much of the archaeological values (MacLeod, 1981 & 1987).

On an iron wreck any non-ferrous materials that are electrically connected to metallic iron will be protected by galvanic coupling. One result of this interaction is that all the copper, brass and bronze fittings become covered with a thin, adherent white calcareous concretion (MacLeod 1982). Once the

concretion has formed, the surface is no longer biologically toxic and so it is then subject to the normal colonisation mechanisms associated with the particular marine ecology of the area.

A novel form of corrosion has been observed on historic shipwrecks where the deleterious effects of galvanic coupling on the corrosion of iron materials is observed where there has been no direct physical contact. This phenomena is now known as *PROXIMITY CORROSION* and has been observed on the historic shipwreck sites of the *Rapid* (1811) and the *Hadda* (1877). These wrecks are in shallow waters at depths of 7 metres and 4-6 metres respectively. The initial research into the nature of this type of corrosion and the implications for structures has been reported by North (1989).

### **3.2 DEGRADATION OF WOODEN SHIPWRECKS**

When wooden vessels become wrecked they are subjected to the normal forces of physical damage associated with being driven upon reefs and rocks. If they sink in open waters as a result of storm damage and general wave action they will fall to the sea bed in a much more intact form. Normally a vessel will lie to one side, as a result of cargo movement which is often associated with the sinking incident, and gradually as the timber is eaten by wood-boring marine organisms, the structure will tend to collapse onto itself. After a century or two in sea water very little of the original structure will remain proud of the sea bed. Biodeterioration of the timbers continues under the sand and general sediment cover and in the process the structural materials associated with cellulose will be lost and replaced by water.

The lignin fraction, consisting of polymers of aromatic /phenolic materials, is much more resistant to deterioration and so the general shape of the beams, planks and frames is retained. Water replaces the cellular material and the wood swells by about 3-5% on waterlogging. Based on the dry weight of material, waterlogged wood can easily contain up to 300-750 wt % water after more than two centuries in sea water (Grattan, 1987). If the timber is removed from this environment it will rapidly disintegrate unless appropriate conservation procedures are instigated.

### **3.3 BURIAL AND EXPOSURE PHENOMENA ON IRON WRECKS.**

The effects of the cyclical burial and exposure of wreck materials and the effects on corrosion mechanisms is best illustrated by analysis of the site of the *SS Xantho* which was an iron screw vessel that sank off Port Gregory, Western Australia in 1872.

Analysis of the corrosion layers around a copper wire in a water cooling device from the engine room showed that there were a

number of corrosion layers. When the logarithm of the spacings between the layers was plotted against the number of **growth rings**, the linear relationships showed that the corrosion phenomena on that site can be described in terms of the liesegang phenomena, i.e. of periodic precipitation (MacLeod 1986-2). The precipitation of the copper sulphides as the corrosion products occurs with the change of the micro-environment from being aerobic, when the object was exposed to the strongly flowing seawater, to anaerobic when two metres of sand were deposited on the site.

During the periods of exposure to open seawater the fitting was in a passive corrosion state and suffered negligible corrosion. Under anaerobic conditions the passivating nature of the  $Cu_2O$  film was rendered inactive and so significant corrosion took place each time the site was reburied. This type of corrosion illustrates how the **corrosion mechanism of materials can change as a function of burial conditions. During the time interval associated with historic shipwrecks it is probable that significant changes have occurred on the site.**

The rapidly changing nature of the seabed was noted in 1864 when the *Zephyr* found a discrepancy of 2.1m in the charted water depth and grounded at Port Gregory (Henderson 1988). In the space of the last 110 years approximately 16 bands were found in the corrosion product layers on the artefact. These changes amount to approximately a seven year cycle and it seems not unlikely that the site has been buried and exposed at least that number of times. The "newness" of the biological environment on the wreck site compared with the surrounding reef is most probably due to the fact that the whole site is periodically buried under several metres of sand. It may be that such burials are due to the scouring of the upstream beaches during heavy winter storms.

**IT IS IMPORTANT TO REALISE THAT THE ACCUMULATION OF SAND AND MARINE DEBRIS IS PART OF THE NATURAL PHENOMENA ASSOCIATED WITH THE MOVEMENT OF MATERIALS ON THE SEA BED. REGULAR MONITORING OF A SITE OVER A PERIOD OF YEARS AND AT DIFFERENT SEASONAL INTERVALS CAN ESTABLISH THE SCOPE OF SUCH PHENOMENA.**

It should be noted that the situation in the proposed marine aggregate extraction areas south of Sydney is very different to that described above for the Port Gregory (Western Australia). Data on the carbon dated sediments in the proposed extraction areas indicates that there has been no major change in the nature of the sediments in the past one thousand years.

### 3.4 CONCRETION MICROENVIRONMENT

In order to properly assess the impact of changes in the site conditions, it is important to have an understanding of the phenomena that are taking place underneath the essentially protective layer of concretion. The following section deals

with the information that was gleaned from a study (MacLeod, 1988) of the gases that were trapped under the concretion and that were liberated during the corrosion survey of iron artefacts on the seabed.

The corrosion potentials ( $E_{\text{corr}}$ ) show that archaeological iron is often in strongly reducing conditions with Eh values at  $-0.290 \pm 0.015$  volts at pH 4.8, i.e. just below the hydrogen evolution potential for the same pH. Hydrogen has been identified as a major component of the gases released when concretions are penetrated for the first time in centuries (MacLeod 1988). Amongst the other gases were carbon dioxide (from acid dissolution of calcite and aragonite as a result of hydrolysis reactions) and methane. Analysis of the carbon isotope ratios of  $^{13}\text{C}/^{12}\text{C}$  in the methane gave an isotope shift of  $-4.7$  ppt which showed that the methane was inorganically derived via reactions such as 1



Since bacteria effectively fractionate carbon isotopes in favour of  $^{12}\text{C}$ , an isotope shift ( $\delta^{13}\text{C}$ ) with a value in the range of  $-55$  to  $-75$  ppt (relative to the standard limestone, PDB) would have been observed for bacterially produced methane (Hunt 1979). Inspection of the carbon Pourbaix diagram shows that methane is the thermodynamically stable form of carbon under the lower portion of the range of Eh and pH (Pourbaix 1974) that have been recorded on wreck sites at depths up to 22 metres.

### **3.5 CORROSION AND WATER MOVEMENT**

The effects of the movement of water, and with it the changing flux of dissolved oxygen, on the corrosion rate of the iron materials was clarified in studies associated principally with the wrecks of the SS *Xantho* (1872) and HMS *Sirius* (1790). The water depths of these site varies from 3.5-5.5 and from 1.5-3.5 metres respectively.

During the initial survey on the SS *Xantho* it was noted that the apparent extent of corrosion varied quite markedly. The windlass contained no solid metal and the  $E_{\text{corr}}$  values for the engine, boiler, etc. all seemed to be similar while the frames near the stern reflected lower corrosion rates. Subsequent work on the HMS *Sirius* showed systematic differences in  $E_{\text{corr}}$  between wrought and cast iron of approximately 70 mV for the same water depth (MacLeod 1989). The model also demonstrated that the corrosion rate is very dependent on water depth and the flux of dissolved oxygen.

When the SS *Xantho* on-site data is reviewed in the light of the new model it makes much more sense. The worst affected items such as the windlass were at a shallower depth and exposed to



localised eddying of current, while the engine was sheltered behind the boiler and was at a greater water depth. The corrosion potentials for the wrought iron objects such as the boiler and frames can be compared with cast iron materials on the engine if "corrected" by 70 mV for the ennobling effect of the carbon.

Armed with a knowledge of water depth and site profiles and the way in which water moves over a wreck, it is possible to interpret the corrosion potentials on iron shipwrecks and to develop appropriate management strategies.

The temperature effects on corrosion potentials have not been directly determined, but repeated measurements of the *Xantho* boiler at Port Gregory (MacLeod 1988) over a period of four years gave an  $E_{\text{corr}}$  of  $-0.274 \pm 0.003$  volts with the temperature at 4 metres depth ranging from 18.5-25.0°C. The small variation in  $E_{\text{corr}}$  values indicates that after more than 100 years immersion the objects are not as sensitive to temperature effects as objects at 30 days exposure (La Que 1975).

### **3.6 EFFECTS OF PARTIAL EXCAVATION ON CORROSION**

Provided that no concretion is removed from the surface of the corroded and concreted material, archaeological intervention on a site can have a minimal impact on the rate of deterioration of the remainder of the site. An example of this can be found on the site of the SS *Xantho* where the historic Penn's horizontal trunk steam engine was removed for the purposes of display and research (Kimpton & McCarthy, 1988). Prior to removal of the engine the  $E_{\text{corr}}$  values of the significant site features were recorded and the measurements have been repeated within 24 hours of the extraction and again after intervals of 13, 34 and 83 months. The  $E_{\text{corr}}$  value for the boiler showed no change over the entire period and had a steady value of  $-0.270 \pm 0.005$  mV vs. NHE (the Normal Hydrogen Electrode). Admittedly the boiler is upstream of the engine location but the results do indicate that provided that the integrity of the surface conditions of the concreted iron works is maintained, the corrosion rates are not going to be subject to major change. We cannot provide the same data set for sections of the site downstream of the engine room since the stern section has been subject to in-situ conservation treatment using sacrificial anodes (MacLeod, 1987)

### **3.7 CORROSION SURVEYS**

The routine measurement of electrochemical parameters such as the surface pH of degrading artefacts and the corrosion potential,  $E_{\text{corr}}$ , of metal objects on wreck sites has a very recent history (MacLeod, 1981 and North, 1982). Corrosion scientists have found that the knowledge obtained through these on-site measurements is an invaluable aid in understanding the corrosion mechanisms and the modes of deterioration of materials

on archaeological sites.

Corrosion potentials are measured by noting the voltage difference between a platinum electrode in contact with the corroding metal and an appropriate reference electrode. For practical reasons the digital multimeter is normally housed in a waterproof case. A suitable reference electrode for working in open sea water is a silver/silver chloride (Ag/AgCl). If working in sediments or in waters subject to sulphide contamination, it is important to have a double-junction Ag/AgCl electrode to prevent contamination of the electrode which would change the standard voltage. Platinum is used as the working electrode because it is electrochemically inert and therefore the measured voltages refer to the object itself and are not due in part to the nature of the electrode material.

Corrosion potential measurements are made by drilling through the marine growth and placing the platinum electrode into the hole with the reference electrode adjacent to the point of measurement, and reading the voltage. Correct determination of the corrosion potential is normally indicated by the obtaining of a very steady voltage, i.e. a reading that varies by only 1 to 2 millivolts over several minutes.

The significance of the corrosion potential ( $E_{\text{corr}}$ ) is that it is essentially a parameter that is sensitive to the rate of corrosion of the metal. The primary corrosion product occurring underneath the concretion is ferrous chloride ( $\text{FeCl}_2$ ). Ferrous chloride subsequently undergoes hydrolysis to  $\beta\{\text{Fe}(\text{OH})_2 \cdot \text{FeCl}_2\}$ . As the ferrous chloride solution diffuses out through the concretion matrix and undergoes hydrolysis the resultant increase in acidity causes the dissolution of the calcium carbonate in the marine organisms. Re-precipitation of iron carbonate follows with concomitant oxidation of the iron (II) corrosion products to iron (III).

#### **4.0 IMPACT OF PROPOSALS ON HISTORIC SHIPWRECKS**

##### **4.1 ELECTROCHEMICAL MODELLING OF EXTRACTION EXCLUSION ZONES**

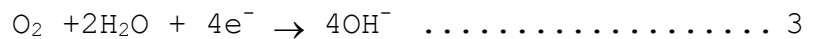
In order to make an assessment of how the proposed extraction process might affect the processes of deterioration on a wreck site, it is essential to have an understanding of the basic phenomena that are controlling the rates of deterioration. These parameters have been discussed in detail in section 3 of

this report. Since the corrosion reactions are essentially diffusion controlled it is possible to establish a simple model to act as a guide in determining to what extent a corroding iron vessel is interacting with the local environment.

The thickness of the Nernst diffusion layer, where dissolved oxygen is consumed at the corroding interface between the shipwreck and the sea water, is in part determined by the concentration of dissolved oxygen and the diffusion coefficient of oxygen in sea water. The limiting current is given by the following relationship

$$i_L = nFAD_oC_o^b / \delta_N \dots\dots\dots 2$$

where A is the area of the electrode and  $\delta_N$  is the thickness of the diffusion layer (Adams,1969). The other parameters have their normal electrochemical values: n is the number of electrons involved in the rate determining step of the reduction reaction, F is the Faraday (96487 coulombs),  $D_o$  is the diffusion coefficient of the oxidised species,  $C_o^b$  is the bulk concentration of the oxidised species in solution and  $i_L$  is the limiting current of the reduction reaction. In this case we are looking at oxygen reduction being the cathodic reaction with the overall process being defined by equation 3,



Since oxygen reduction normally occurs by two sequential two-electron steps, the number of electrons n is equal to two. Using a value of  $2 \times 10^{-5} \text{ cm}^2 \cdot \text{sec}^{-1}$  for the diffusion coefficient for oxygen and a value of  $9 \text{ mg} \cdot \text{l}^{-1}$  for the concentration of dissolved oxygen at 100% saturation at 20°C ( $5.6 \times 10^{-7} \text{ moles} \cdot \text{cm}^{-3}$ ) and a limiting current of  $2.15 \text{ } \mu\text{A} \cdot \text{cm}^{-2}$ , the equivalent of a corrosion rate of  $0.05 \text{ mm} \cdot \text{yr}^{-1}$ , equation 2 can be rewritten as

$$\delta_N = 1.005 A \dots\dots\dots 4$$

where the diffusion layer thickness is measured in cm and the area of the electrode A is measured in  $\text{cm}^2$ .

One problem that arises is the calculation of the effective surface area of a concreted and corroded iron shipwreck since all parts of the vessel will contribute to the overall corrosion process. In the absence of detailed site records we can draw on data collected for an iron wreck in Port Phillip Bay. A detailed calculation of the surface area of the hull and the engine has been carried out for the wreck of the *City of Launceston* (1865). The wreck is of an essentially intact vessel of 54 m length, 7.43 m breadth and depth of 3.56 m. Calculations by Shaw (Shaw,1991) show that a total surface area of approximately  $2800 \text{ m}^2$  is needed to account for the frames, bulkheads, ribs, frames, plates, boiler etc. Given that the wreck of the SS *Woniora* is currently only 21 metres in length and that only 2-3 metres of material lies above the sea bed, the

effective surface area of the wreck may be of the order 250-500 m<sup>2</sup>. For this surface area equation 4 predicts a diffusion layer thickness of 2.5x10<sup>4</sup> metres or some 25 km for a still solution!

If some adjustment of the parameters is made the diffusion layer thickness falls significantly. For a dissolved oxygen concentration 30% of saturation and a corrosion rate of 0.005 mm.yr<sup>-1</sup>, the diffusion layer thickness would correspond to 750 m.

Solution movement reduces the boundary layer thickness but not always in a strictly linear fashion. The boundary layer thickness follows empirical relationships of the form

$$\delta_N = B/U^n \dots\dots\dots 5$$

where *B* is a constant for a set of conditions and *U* represents the velocity of the liquid flow. Experimental values of *n* usually fall between 0.4 and 1.0. Typically the change of water movement from still to "stirred" (in a laboratory situation) would decrease  $\delta_N$  from 0.05 to 0.001 cm. Thus water movement on a site will reduce the thickness of the boundary layer but the increase in the corrosion rate, as noted in the discussion section 3.5, will tend to compensate the effect of water movement and so maintain an approximately constant boundary layer. Without access to data obtainable from *in-situ* corrosion studies, dissolved oxygen concentrations and measurements of effective surface areas of the corroding wrecks, it is difficult to obtain more than an estimate of the diffusion zone or *halo* around the sites.

Given that water movement on the sites will lie somewhere between zero and turbulent flow, it can be seen that a boundary layer thickness of the order 300-500 metres is not an unreasonable estimate of the area that needs to be excluded from the proposed marine recovery operations to minimise the chance of altering the corrosion rate of materials on the site.

#### 4.2-CAPE BANKS and the wrecks of the SS *Woniora* (1882), SS *Hilda* (1893) and SS *Kelloe* (1902)

In Bower's report the significance of the SS *Woniora* (1882) is noted in terms of the engine and the surrounding wreck structure that is still extant. It also notes that the site has a strong

association with the diving community and that it is also significant in terms of the fish and other biota that have colonised the site.

In the *Marine Ecological Investigations* report it was noted that the tidal effects of the water movements into and out of Botany Bay have little effect on the proposed Cape Banks extraction area. The influence of the Eastern Australian Current (EAC) is largely limited to the surface waters. Other currents do have a significant contribution at these depths - the direction of the flow is not constant and this variability should be noted. Wave action will have a major effect on the site of the SS *Woniora*. Even at a depth of 60 metres Geomarine have shown that mobilisation of the sites can occur about 25% of the time. Significant site disturbances are generally associated with high energy waves that are generated in severe storms.

It has been noted that the communities that exist around the shipwrecks are not those normally associated with the sandy bottom. This is a natural consequence of the wreck providing a different habitat for a wide variety of marine organisms. One effect of the formation of concretion on corroding iron materials is that the colonisation rate is strongly influenced by the iron. Recent work by this author (MacLeod, 1988) has shown that the average annual rate of colonisation by encrusting organisms is approximately doubled on iron substrates compared with inert wreck materials such as stone and ceramics. The anaerobic conditions that develop under the concretion result in the *activation* of microorganisms that convert inorganically bound phosphorus into a volatile phosphine (Microbial Corrosion, 1983). It appears that the encrusting organisms are able to capitalise on this source of phosphorus since there is a linear increase in the annual growth rate as the amount of phosphorus in the iron increases. An amount of 1.18 wt % phosphorus doubles the rate of concretion formation compared with the effects of iron by itself.

Given that the normal metallurgical procedures used at the time of the SS *Woniora* being built in 1863 were not totally efficient at removing the undesirable phosphorus content, it is highly probable that a significant amount of this element is "stored" in the remaining metal. In the event of significant sedimentation resulting in the death of the present colonising organisms, it is possible that the wreck can be recolonised at a better rate than would otherwise be anticipated on the basis of short term (1-2 years) marine ecological studies.

Since the level of dissolved oxygen in the surrounding sea water is unlikely to change as a result of the extraction process (Pollution Research, 1992) the only significant factor that can lead to an increased rate of deterioration of the site is an increase in the total water movement. The underlying rationale for these comments is given in the preceding discussion on the effects of water movement on the corrosion processes. The dissolved oxygen content of open sea water is not significantly

different at depths of 60 metres for the SS *Woniora* and the 45 metres associated with the wrecks of the SS *Tuggerah* and the SS *Undola* (Cresswell, 1989). Data obtained off Norfolk Island shows that the increased water depth generally causes an increase in the concentration of O<sub>2</sub> of about 4 % in ten metres (Strommel et al., 1973). Differences in the rate of deterioration of the iron will therefore be primarily dependent on the amount of water movement over the different sites.

Provided that discharge depths are varied in accordance with the recommendations made in the reports of *Geomarine* and *The Ecology Lab*, there is a small chance that the level of sedimentation at the SS *Woniora* site will be changed from that which is currently due to the combination of natural processes. Since electron transfer is a factor in the overall corrosion rate, it should be noted that anything that decreases the resistance of the pathway separating the oxidation of the metal and the seaward reduction of dissolved oxygen, will result in an increase in the overall corrosion rate. If significant sedimentation did result in the death of the colonies on the wreck the biodeterioration processes may have a small effect on the corrosion rate. It must be remembered that the sea water has a significant buffering capacity and so the net result of changes in the chemical microenvironment are minimised.

*Geomarine* have discussed the effect of a 5 metre deep depression on the movement of sediment from the vicinity of the wreck of the SS *Woniora* in terms of a 250 metre exclusion zone around the site. Translocation of the batter slopes towards the wreck is expected to occur at a rate of 0.13 metres per year, although the rate is expected to fall with time. In terms of the extant length of the vessel and the amount of exposed wreck, the proposed 250 metre zone is at the lower end of the estimates of diffusion layer thickness, as described above in section 4.1. If the sand movement associated with the proposed extraction rates is as predicted by *Geomarine*, the radius of the exclusion zone should be enough to protect the remains of the wreck. Once dissolved oxygen data and water movement measurements are known for the site it may be possible to recalculate a value of the exclusion zone.

The wrecks of the SS *Hilda* and the SS *Kelloe* are also in the general area of the proposed Cape Banks proposed extraction area. The SS *Hilda* lies in about 25 metres of water and the site mainly consists of scattered remains of the original 125 feet length of the vessel. It was noted by Bower (1992) that the degradation of the wreck is significant and generally associated with strong wave action associated with the reef on which the vessel was wrecked. Given that the SS *Hilda* is one kilometre from the limit of the proposed extraction area, it is most unlikely that the proposal will have any effect on the rate of deterioration of the remains. The rate of corrosion of the remaining structural materials on the site will be determined by the forces associated with water movement in the local area.

The wreck of the SS *Kelloe* lies in water at depths between 40-50 metres - the topography of the site prohibits a more accurate measurement of the water depth. The wreck of this collier has been significantly damaged by explosives but despite this sections of the vessel such as the boiler, rudder post and propeller are still easily discernible. As such the site represents value as a diving recreation location and as an example of a nineteenth century collier (built in 1866). The wreck site is within 400 metres of the proposed limit of the extraction area and as such it could be anticipated to be subjected to some influence from the proposed activities. The original length of the vessel was 123 feet (37.49 m) and given the size of the remains, it is unlikely that the proposal will have any real impact on the nature of the forces of deterioration on the site.

**In view of the above information it is unlikely that the proposal will have any significant impact on the integrity of the sites of the SS *Woniora*, the SS *Hilda* or the SS *Kelloe*.**

#### **4.3 -PROVIDENTIAL HEAD and the wrecks of the SS *Tuggerah* (1919) and the SS *Undola* (1918)**

In assessing the impact of the proposed activities on the wrecks of the SS *Tuggerah* (1919) and the SS *Undola* (1918), it should be noted that both vessels lie in waters of the same depth at 45 metres. Under the conditions of intense storms and the associated wave action (see above discussion on the SS *Woniora*) these sites are going to be more disturbed than the deeper site of the SS *Woniora*. As noted in the discussions regarding the effects of the natural changes in the level of the seabed, the deterioration of historic shipwrecks is already subject to a range of forces.

The positioning of the shipwrecks on the sandy bottom has resulted in the entrapment of sediment and the formation of a different marine ecology to that of the surrounding environment. The effects of the iron metal and the phosphorus contained therein on the rate of growth of encrusting marine organisms has already been discussed for the case of the SS *Woniora* (1882). The report from *The Ecology Lab* highlights one of the problems associated with discussion of the impact of the extraction proposal. The problem is principally a dearth of information on the nature of the colonisation of the wrecks. The primary cause for this is the depth of the vessels. Reports indicate that all the historic vessels under consideration are covered with a "mosaic of sessile organisms, such as hydroids, anemones, sponges and, occasionally, corals".

In their report *Geomarine* noted a possible translocation rate for the top of the batter slopes towards the SS *Tuggerah* of approximately 0.06 metres per year. Although the extent of the wreck materials on the SS *Tuggerah* site has an effective

"radius" of 30 metres, the 250 metre exclusion zone would fall at the lower end of the range of diffusion layer thicknesses detailed in section 4.1 of this report. Recent data gives average currents of the order 0.1 metres per second - this would provide moderate mixing of the water and reduce the boundary layer thickness and so the 250 metre exclusion zone for the in *SS Tuggerah* is not unreasonable.

**In summary, we recommend an exclusion zone of 250 metres from the centre of the wreck of the *SS Tuggerah* (1919) in order to avoid any possible adverse impact that the proposal might have on the remains of the vessel. It is unlikely that the proposal will have any impact on the remains of the wreck of the *SS Undola* (1918) since it is more than five kilometres from the southern end of the proposed extraction zone in the Providential Head area.**

#### **4.4 CORROSION RATES AND SITE COLLAPSE**

In order to maintain the integrity of the historic shipwrecks *SS Woniora* (1882) and the *SS Tuggerah* (1919), it is essential that proper management schemes are implemented. One factor that needs to be remembered in framing such schemes is that the resource of historic iron shipwrecks is essentially a diminishing one. The wrecks will continue to corrode until no solid iron remains. If the vessels are surrounded by a matrix of corrosion products and encrusting organisms the structure can survive in a physical form that reflects the original shape and form of the vessel. Given the descriptions of the sites by Riley in Bower (1992), it is apparent that the natural degradative forces have already brought about major changes to the integrity of the vessels.

The wreck of the *SS Woniora* has the engines, the stern post and the boiler and associated superheater standing proud of the seabed. Large sections of the plating have collapsed and this is consistent with the thinner metal sections corroding to an extent where they can no longer bear the strain associated with the increased weight (due to incorporation of corrosion products and marine organisms) and the decreased mechanical strength. Data on the long-term corrosion rates of iron on historic shipwrecks is limited, but within one site the rate of deterioration can vary by a factor of between three and four fold (Carpenter and MacLeod, 1992). Using a rate of  $0.03 \text{ mm.y}^{-1}$  a 10 mm plate would be corroded through in 166 years. However if the corrosion rate is typical of shallow average open water rates, the plates would be perforated in 56 years. Assuming the lower corrosion rate for the *SS Woniora*, side plates would now have a residual thickness of 3.4 mm.

However when consideration is given to the fact that the buried parts of the vessel are in a different microenvironment to the exposed sections, the exposed plates and fixtures are going to



be selectively corroded. In the light of this observation it is not surprising that the upper plating of the SS *Woniora* has essentially disappeared. It is only the greater initial thickness of the structure bearing engine beams etc. that has resulted in their apparent "preservation"

By way of comparison, the remains of the SS *Tuggerah* (1919) are much more extensive than those of the SS *Woniora*. Given that the latter vessel has been corroding for 110 years compared with only 73 years for the SS *Tuggerah*, it is normal that the observed differences in the sites are noted. If the original thickness of the major structural members has been recorded in the archives, it is possible to make estimates of how long the structures will survive. However, long before the metal is totally corroded collapse will occur owing to the loadings on the degraded structure. Apart from the weight of the corrosion products and concretion, the stress associated with storm induced water movement may be sufficient to cause partial collapse of extensively corroded structures.

## **5.0 ASSESSMENT OF RESIDUAL IMPACTS**

Provided the extraction vessel operates within the constraints delineated in the consultants reports relating to the marine ecology and the movements of sediments, it is our considered opinion that the extraction process would have a minor effect on the historic resource associated with shipwrecks in the area of concern. It is essential that in any proposal such as this, appropriate monitoring procedures are recommended. If the monitoring of the sites indicates that significant variations in local conditions are occurring then the work programmes should be altered until the details of the impact can be ascertained.

The degraded structures associated with wooden and iron shipwrecks are the remains of the vessels that once were integral units. In their degraded state the remains are often supported by the compressive forces associated with the sand levels on the seabed. At this stage no wooden historic shipwrecks have been located in the areas of the proposed activity. Given that Geomarine suggest that there will be negligible scouring, the problems associated with site collapse are unlikely to be a concern. The principal problem with scouring lies in the loss of physical support for the corroded structure and the increased flux of dissolved oxygen to the corroding metal surfaces. Provided that the following recommendations are followed the integrity of the historic shipwrecks should be able to be maintained.

Wooden shipwrecks are known to last for many centuries when protected under a sand deposit on the sea bed. Iron wrecks will degrade at a steady rate until no more solid metal remains. The nature of the remnant structure will depend on the extent and type of encapsulation by marine growth and on whether the iron is essentially unalloyed, in the form of steel and wrought iron,

or if it has been cast as an alloy with carbon. Provided the guidelines are followed, the wrecks in the proposed areas should last well into the twenty first century.

## 6.0 CONCLUSIONS AND RECOMMENDATIONS

The proposed extraction programme has been reviewed in terms of the possible impact on historic shipwrecks in the area. In order to properly assess the impact of the proposal the following recommendations are made.

(i) That appropriate biological surveys of the wrecks SS *Woniora* (1882) and the SS *Tuggerah* (1919) be undertaken prior to the extraction programme beginning.

(ii) That an electrochemical survey of significant residual structural sections of the vessels be made at the same time as the marine biological surveys. These two interdependent surveys will provide base-line data on the nature of the biological and the electrochemical microenvironments of the sites. Comparison of the pre-disturbance and subsequent surveys carried out during the term of the proposed activities will provide a sensitive indication of changes before any significant alteration occurs. The data should be communicated to appropriate consultants for interpretation who would then frame recommendations regarding any changes to work practices.

(iii) That appropriate exclusion zones be maintained around the wrecks for the duration of the extraction project and that a series of inspections of the sites be carried out to gauge any impact of the operations, as noted above. The proposed zone for the SS *Woniora* (1882) is 250 metres and that for the SS *Tuggerah* (1919) is 300 metres. Such inspections would need to be carried out at least on an annual basis until the impact of the extraction operations can be gauged.

(iv) That if any wrecks are accidentally uncovered in the region of the extraction zone appropriate authorities will be notified and an exclusion zone of 250 metres be established around the same.

(v) That the precise locations of historic shipwrecks in the proposed region of extraction be noted and the guidance systems and operational notes for the vessels take this data into account when aligning the extraction courses.

## 7.0 GLOSSARY

ppt Parts per thousand

PDB PeedeeBelemite. PDB is the acronym for the mineral which is a reference sample of a Cretaceous belemnite, *Belemnitella americana*, from the Peedee formation in South Carolina, in the United States of America. The carbon dioxide evolved from the reaction of the limestone with 100% phosphoric acid at 25.2°C is used as a standard in carbon isotope measurements for determining the  $^{13}\text{C}/^{12}\text{C}$  ratios. The details are found in Craig, 1957.

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