A new corrosion mechanism for iron shipwrecks in seawater: a study of the *Fujikawa Maru* (1944) in Chuuk Lagoon, Federated States of Micronesia

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Abstract

Measurements of in situ corrosion on the wreck of the Japanese merchant vessel *Fujikawa Maru* formed part of a survey of the underwater cultural heritage resources of the island state in Chuuk Lagoon, Federated States of Micronesia. The vessel sits upright on its keel and is largely intact but has suffered from the repeated impact of dynamite fishing, which has caused loss of protective concretion and resulted in accelerated decay. The relation between the values of the corrosion potential and the pH of the corroding metal has been interpreted as reflecting the initial stages of decay of an iron shipwreck, which is the first time such information has been reported. The study has demonstrated that the vessel could probably be protected in situ and remain a premier diving attraction without any adverse environmental impact.

Keywords

corrosion mechanism, iron shipwrecks, Chuuk Lagoon, in situ protection, dynamite fishing

Introduction

Iron shipwrecks from the 19th and early 20th century are generally characterized by a series of scattered elements of boilers, engines, propeller shafts, winches and bollards among the residual structure of frames, ribs and steel plating. The remains of the Japanese merchant fleet that was sunk in February 1944 in Chuuk (Truk) Lagoon in the Federated States of Micronesia provide an opportunity to study the decay mechanisms of intact iron wrecks that lie in the relatively sheltered waters of the lagoon. The corrosion phenomena on the 65 wrecks provide a set of experiments that enable the impact of wreck orientation and location to be assessed, along with the effects of explosions and torpedo damage. The wreck of the *Fujikawa Maru* is largely structurally intact, apart from the damage caused by the explosion of a torpedo on the starboard bow, and the vessel sits upright on its keel on a flat sandy bottom of the atoll. The *Fujikawa Maru* contains several aeroplanes in the forward hold and is one of the most popular diving sites.

Method

Measurements of pH and corrosion potential were done on the wreck to determine the underlying nature of the corrosion processes. Electrical contact is made with the underlying metal by drilling through the marine growth with an air-powered masonry-tipped drill bit. Immediately after drilling, a BDH Gelplas flat-surface glass pH electrode is inserted into the drill hole and the minimum pH is recorded. Subsequently a platinum electrode is placed in electrical contact with the underlying metal and the corrosion potential is recorded, against a reference electrode lying immediately adjacent to the area of measurement. A shipwreck can also characterized by corrosion profiles of degraded cast-iron objects at a number of water depths. Depths of graphitization are obtained by drilling through the corroded (graphitized) layer with a 3 mm diameter high-speed metal drill until contact is made with sound cast iron. A small section of concretion adjacent to the measurement area is removed to facilitate the measurement of the corrosion depth, from the original surface, with a vernier calliper.

Results and discussion

The hull of the *Fujikawa Maru* sits horizontally on a flat seabed free of underwater obstructions such as ledges and cliffs. The vessel is located in the Fefan-Doublon channel, south of Eten Island, which offers some shelter from the prevailing winds, as seen in Figure 1. This vessel was chosen for detailed study owing to its fairly sound condition, its popularity as a dive site and the evidence of dynamite fishing on the concreted surfaces of the upper decks. The 31 sets of data were gained from a series of measurements from the seabed to the top of the masts and on the starboard side, where the torpedo had penetrated, and on the undamaged port side. The locations studied included hull plates, bollards, stanchions and a gun on the forward deck and the results are summarized in Table 1.

Mitsubishi Zosensho built the ship in the port city of Nagasaki in 1938; the

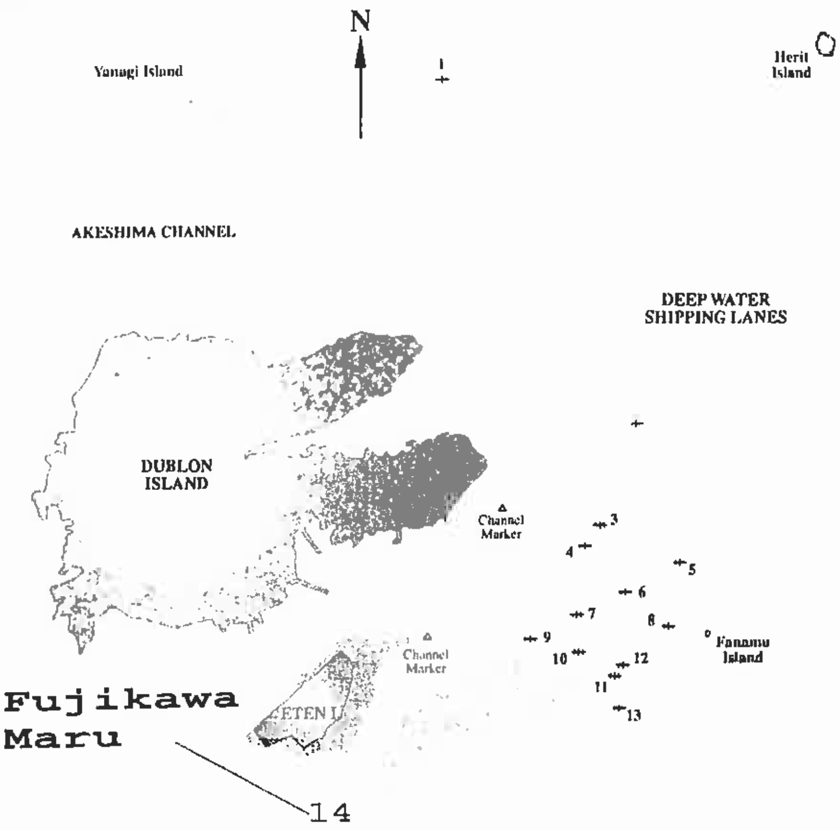

Figure 1. Location of the Fujikawa Maru (Bailey 2000)

Table 1. Corrosion potentials and pH measurements on the Fujikawa Maru

Distance from bow (m)	Water depth (m)	E_{corr} vs. $Ag/AgCl_{sea}$	pH	Corrosion profile (mm)	Observations
18	15.4	−0.612	5.75		Hull plate, port side
27	17.7	−0.607	6.78		Stanchion, port side
85	19.5	−0.568	6.90		Stanchion, port side
38	19.8	−0.615	6.16		Hull plate, port side
46	23.2	−0.614	6.18		Hull plate, port side
60	27.3	−0.606	7.19		Hull plate, weeping rust, port side
83	31.8	−0.604	6.94		Hull plate, port side
92	32.1	−0.602	7.66		Torpedo hole on starboard side; difficult surface with little concretion
98	27.2	−0.585	7.38		Folded back metal inside the hold
101	25.0	−0.594	7.69		Hatch cover grid aft of bridge
115	25.6	−0.614	7.38		Second cargo plates aft of bridge
124	20.7	−0.606	6.30		Base of aft gun emplacement, gas evolved
2	12.2	−0.610	6.63	6.5	Port bow bollard, forward
2	12.2	−0.610	6.46	6.6	Port bow bollard, rear
4	12.4	−0.614	7.36		Port side plate near bow
7	12.5	−0.608	6.54	11.6	Gun mounting
46	17.6	−0.601	7.32		Fallen mast
57	20.1	−0.613	7.15		Bridge wall near top
60	12.6	−0.526	6.44		Blasted area of iron stained wood
69	11.5	−0.603	6.09		Cylinder on top of bridge
72	8.5	−0.606	7.75		Tower platform, thin concretion regrowth
95	12.4	−0.610	6.16		King post
109	4.9	−0.614	7.36		Aft mast
10	12.9	−0.598	6.31		Blasted area of bow
8	12.6	−0.598	6.71		Brass plate overlocked by iron, gas evolved
1	12.4	−0.601	5.84		Cast-iron base of bridge telegraph, poor drill 2 mm
2	12.3	−0.596	6.18	8.4	Windlass main shaft, 8.4 mm
9	11.6	−0.608	n.a.		Stainless steel on gun plate

wreck site layout is shown in Figure 2 (Bailey 2000). The vessel lies upright and proud of the seabed and was originally 6938 tons, and 159.45 m long, 21.3 m wide and 9.48 m in depth. Because the wreck is in a natural channel between several islands, the currents associated with the diurnal tide variations of ±0.5 m may have some impact on the extent of corrosion. Because most of the measured points appear to operate as an electrically interconnected experiment the general trends normally observed on historic shipwrecks, of falling voltages with increasing water depth, are not readily discerned. There is no significant difference between the mean corrosion potential for cast-iron fittings, $^{\text{mean cast}}E_{\text{corr}} = -0.605 \pm 0.006$, and the mean value of the steel plates on the deck and hull at $^{\text{mean steel}}E_{\text{corr}} = -0.602 \pm 0.018$, which could be misinterpreted as implying that the sampled areas are all in the same corrosion microenvironment. An alternative approach is to study the variation in pH as a corrosion indicator because the pH is in dynamic equilibrium with the local corrosion rate because higher concentrations of ferrous ions and the concomitant higher acidity under the concretion are indicators of a higher corrosion rate. On the *Fujikawa Maru* site the localized corrosion rate is reflected in the pH with the mean value for cast-iron fittings, $^{\text{cast}}\text{pH}_{\text{mean}} = 6.33 \pm 0.29$, being more acidic that the mean for the steel plates on the deck and hull, $^{\text{steel}}\text{pH}_{\text{mean}} = 6.79 \pm 0.64$; the larger standard deviation of the mean value is associated with the greater range of water depths and the variations in concretion thickness.

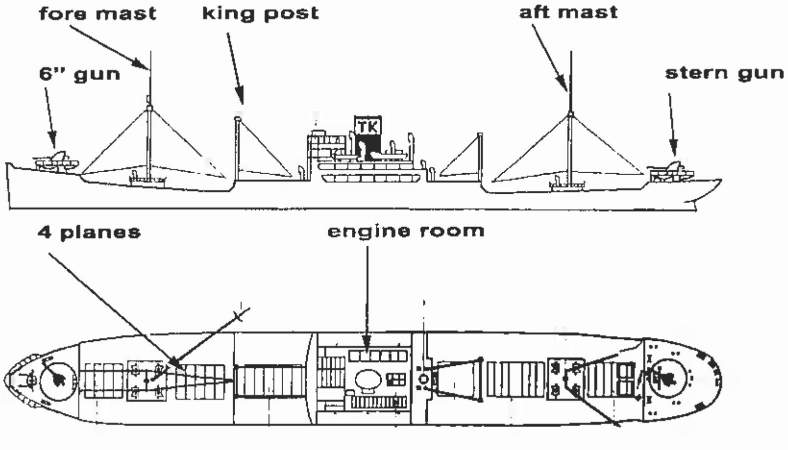

Figure 2. Site plan of the Fujikawa Maru, after Bailey (2000)

The similarity of most of the corrosion potentials seen in Table 1, which cover a depth range of 5–31.8 m, shows that this parameter is insensitive to the changing water depth owing to most of the wreck still functioning as an electrical entity. Some parts of the wreck site appear to be at least partly electrically isolated from the main vessel, for when the data from the portside deck stanchions, a piece of bent-back hull plate near where the torpedo entered, the torpedo hole and some hull plate in the midships, their values of E_{corr} fall with increasing depth. These sections of the vessel have either suffered stress or have a work history that means they are no longer in direct electrical contact with the rest of the vessel. All the E_{corr} and depth data are summarized in Figure 3, which illustrates how the values of the various measurement points vary as a function of water depth. For these six measurement sets there was a strong correlation between the E_{corr} and depth; the linear regression (Equation 1) had an R^2 value of 0.9762:

$$E_{\text{corr}} = -0.512 - 0.0028d \qquad (1)$$

where d is the water depth in metres. This move to more cathodic E_{corr} values of 2.8 mV/m is much less than the average values observed for open water wrecks where the voltage falls by 18±2 mV/m, such as on the largely intact iron wreck the *City of Launceston* (1876) where the E_{corr} fell by 16.5 mV/m (MacLeod 1988, 2002).

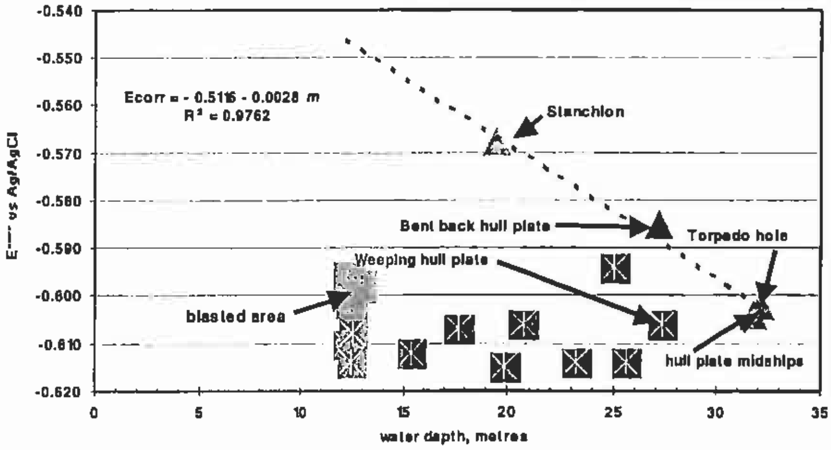

Figure 3. Plot of corrosion potentials vs. water depth on the Fujikawa Maru

The pH data exhibit a much greater degree of variation with water depth than the corrosion potential data. Because concretion layers act as a semi-permeable membrane that separate the anodic (metal oxidation) and cathodic (oxygen reduction) sites, the varying thickness of this layer will also be reflected in the absolute values of pH (North 1976). Recently deconcreted and recolonized areas tend to give pH values around 7.5 ± 0.3 whereas the fully matured sections of the vessel gave much more acidic values. Analysis of the pH data reveals two subgroups that have the same dependence on water depth but have different intercept values (Equations 2 and 3). The more acidic data set, which reflects the eight measurement points where there has been little disturbance of the site, is seen in diagrammatic form in Figure 4. A linear regression analysis on the 'older concretion data' gives a value of $R^2 = 0.837$ and Equation 2:

$$\mathrm{pH}_{\mathrm{old}} = 4.52 + 0.086d \tag{2}$$

where d is the water depth in metres. The second set of 17 data points for the hull and deck plates has an R^2 value of 0.914 for the regression and the resultant Equation (3) is:

$$\mathrm{pH}_{\mathrm{new}} = 5.35 + 0.084d. \tag{3}$$

Statistical analysis of the regression data for Equation 2 has an intercept error of ±0.37 and a value of ±0.016 for the error in the slope. The corresponding data for Equation 3 has an intercept error of ±0.12 and a slope error of ±0.007, which means that both equations have identical slopes and that the overall nature of the processes controlling corrosion is the same. The difference of 0.83 in the intercepts of Equations 2 and 3 simply means that the older concretion is nearly seven times more acidic than the newly formed material. The intercept value for Equation 2 is typical of the pH data recorded on marine iron in shallow waters (MacLeod 1989a). The average slope of 0.085 ± 0.001 pH unit per metre means that the acidity of the environment under the concretion decreases by approximately 22 per cent per metre of increased water depth. This in turn indicates that the corrosion rate is very sensitive to water depth.

The data listed in Table 1 and illustrated in Figure 3 are consistent with major damage to the *Fujikawa Maru* from the action of dynamite fishing. The impact of the explosions and the associated shock waves on the deck and hull plates were reflected in only very thin layers of concretion being present; and the deck had several sections where the masonry tipped drill bit went through the paper-thin residual metal. When the E_{corr} and pH data are plotted on an appropriate Pourbaix diagram (Pourbaix 1974) it becomes apparent that these two parameters are closely linked (North 1982). The electrically isolated parts of the wreck indicate an electrochemical process controls the pH and the E_{corr} on this wreck site. The linear regression for the six data points had an R^2 value of 0.8277 and their interrelationship is defined by Equation 4:

$$E_{corr} = -0.170 - 0.057 \text{ pH}. \qquad (4)$$

The standard deviation of the intercept was ±0.095 V and the error for the slope was ±0.013. The dependence of 57 ± 13 mV in the value of E_{corr} per pH unit is consistent with the following reaction controlling the acidity of the corroding surface:

$$Fe + 2Cl^- + 2H_2O \rightarrow Fe(OH)_2 + 2H^+ + 2Cl^- + 2e^-. \qquad (5)$$

This 59 mV fall in E_{corr} per pH unit is in marked contrast to the data found for older wrecks corroding in open seawater, where the dependence of E_{corr} on pH is half that observed on the *Fujikawa Maru* (MacLeod 1996b, 1998a, b). This relation represents the first major difference in apparent corrosion mechanism between the 60-year-old Japanese wrecks in the lagoon and those historic 18th and 19th century iron shipwrecks in open ocean seawater.

The extent of corrosion at any one part of the wreck can be gauged by the depth of graphitization of the nearby grey cast-iron objects. The corrosion profiles are obtained after the normal in situ data collection by drilling into the existing drill penetration into the corroded cast iron with a small diameter steel drill bit, approximately 3.5 mm diameter, until there is no further penetration, which occurs once the un-corroded alloy is reached. The depth of penetration was determined by measuring how far the micrometre probe penetrated beneath the original surface of the cast-iron object, which had been exposed by partial deconcreting of an area adjacent to the drill hole (MacLeod 1989b, 1996a). The depth of graphitization of the 6 inch gun base on the forward deck was very high at 11.6 mm, the windlass was corroded to a depth of 8.4 mm whereas the deck bollards near the bow were 6.5 and 6.6 mm. These corrosion depths can be expressed in terms of annualized rates of 0.199, 0.144, 0.112 and 0.113 mm/year at an average depth of 12.3 ± 0.14 m. No detailed examination of the corroded gun surface was conducted, as this would have involved excessive deconcretion. The two bollards have a low physical profile on the deck and are relatively sheltered by the splashguard and gunwale whereas the windlass sits in the middle of the foredeck and presents an impediment to the smooth passage of water over its surface. Because the 6 inch gun base sits on its elevated mounting and will have a different composition to the cast iron of the windlass and the bollards, so its corrosion rate is not directly comparable. Unless the profiled cast-iron objects are electrically isolated from the rest of the vessel there is little chance that the corrosion profiles will be reflected in the corrosion potential.

The *Fujikawa Maru* in situ data indicate that the pH more accurately reflects the corrosivity of the microenvironment of the metal. So when the annualized depth of graphitization is compared with the in situ pH values, a linear regression analysis gives Equation 6:

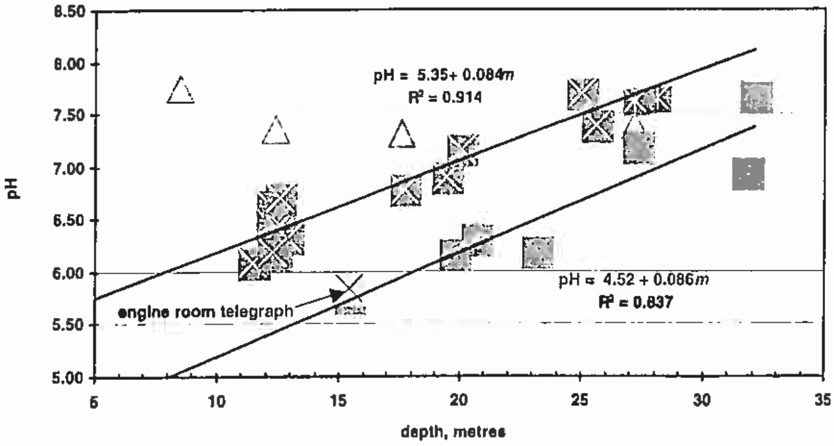

Figure 4. Plot of pH data on the Fujikawa Maru as a function of water depth

$$\log d_g = 0.758 - 0.2601 \text{ pH} \tag{6}$$

with an R^2 value of 0.8948 and where d_g is the annualized corrosion rate in millimetres of graphitization per year of immersion as a shipwreck. Although the data set is very limited, the relation indicates that the surface pH provides a guide to the local corrosion rates. When the pH data are plotted as a function of the distance from the bow, some interesting trends emerge (Figure 5). The more acidic values (circles) relate to areas of the vessel where there is less evidence of deconcretion activity, and the diamonds reflect areas of thinner concretion thickness. A pH minimum (circles) occurs around 18 m and again near 70 m from the bow. There appears to be a similar trend in the more recently concreted zones (diamonds) in that the zone of highest acidity is around 10 m from the bow then 60 m and again near 85 m. When the pH data that conform to either Equations 2 or 3 have the intercept value subtracted and the result is divided by water depth, the data for the steel plating show up similar zones of higher acidity at 18, 45, 80 and 120 m from the bow, as shown in Figure 6. Similar pH minima that relate to localized turbulence of water movement were observed on the *City of Launceston* (1856) wreck (MacLeod 2002). The data for cast iron from the bow (circles) relate directly to the observed corrosion profiles, with lower values of the normalized pH corresponding to greater corrosion depths. The bridge structure, aft and fallen-mast have more alkaline values owing to their recent history of having been deconcreted.

An estimate of how long it will take before the *Fujikawa Maru* collapses and loses its current iconic status was made using the mean value determined from pH data (Equation 6) and from E_{corr} data. The mean rate ${}^{pH}i_{corr}$ was 0.124 ± 0.027 whereas the mean ${}^{Ecorr}i_{corr}$ was 0.119 ± 0.013 mm/year to which an additional 30

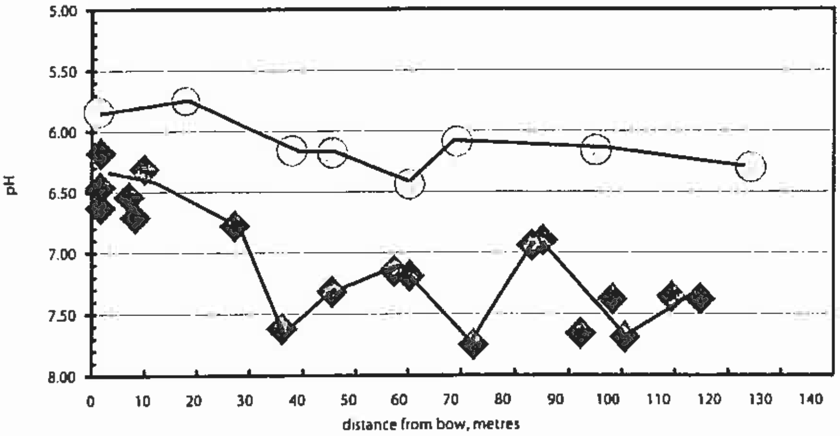

Figure 5. Surface pH on the Fujikawa Maru vs. distance from bow

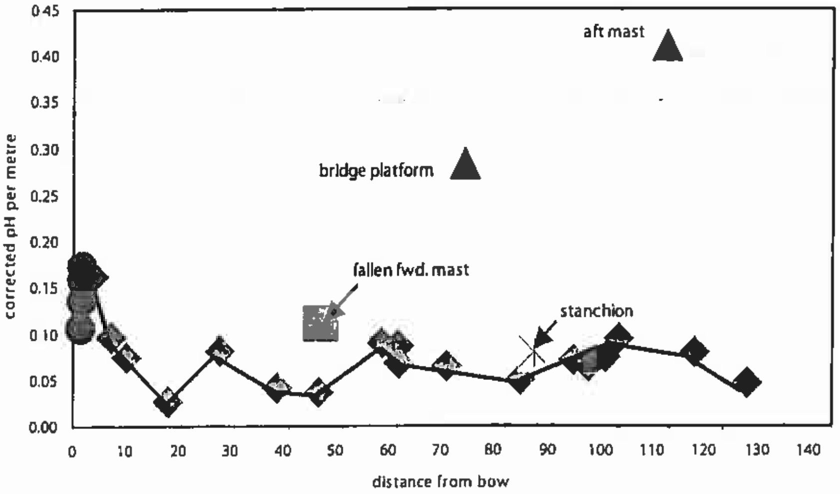

Figure 6. Plot of the depth-normalized pH as a function of distance from the bow

per cent was added to allow for internal corrosion. In the absence of data on the original thickness of the various sections of the vessel, estimates are based on the Lloyds specifications for ships of the same tonnage. The calculated times for the thinnest part of the ship, the deck plates, indicate that total loss should have occurred somewhere between 1993 and 2003, which agrees with the current areas of loss. The estimated lifetime for external hull plates ranges from 15 to 44 years, depending on the original thicknesses used from the range of data in the Lloyds tables. A way forward to extend the life of the ship is to protect it in situ with some form of cathodic protection.

Conclusion

The wreck of the *Fujikawa Maru* retains electrical continuity of the bulk of the structure and represents an historic iron shipwreck in the 'initial' stages of decay, with a different corrosion mechanism to that observed on historic 19th and 20th century shipwrecks. Dynamite fishing has increased the corrosion rate through the repeated loss of protective concretion cover. Further detailed corrosion surveys, including residual hull thickness, are needed to fully characterize the corrosion microenvironment and determine the feasibility of in situ conservation using renewable energy sources from solar panels to provide the direct cathodic current to the ship. Such treatment will preserve the iconic status of the vessel and provide an exemplar in conservation management of underwater cultural resources that will also prevent leakages of oil from corroding fuel tanks.

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