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In-situ Corrosion Studies on Wrecked Aircraft of the Imperial Japanese Navy in Chuuk Lagoon, Federated States of Micronesia

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A preliminary *in-situ* corrosion survey of the submerged Japanese WWII aircraft in Chuuk Lagoon, in the Federated States of Micronesia, has provided information on the way in which the wrecks interact with the marine environment. The aircraft are characterised by a lack of encrusting marine organisms and are clearly identifiable. The values of pH and the corrosion potentials vary with depth and the voltage depends on the composition of the underlying metal alloys. It is possible that with additional data from these non-destructive methods techniques it will be possible to provide marine archaeologists with appropriate diagnostic tools.

Key words: aluminium alloys, WWII aircraft wrecks, Chuuk Lagoon, corrosion, conservation.

During February 1944 the United States Navy conducted a bombing campaign known as 'Operation Hailstone' against the Chuuk (Truk) Lagoon base of the Imperial Japanese Navy in the Federated States of Micronesia. The loss of more than 64 vessels, merchant and naval, and a large number of aeroplanes crippled Japanese activities in the Pacific Ocean. The first corrosion survey of submerged wrecks in Chuuk Lagoon was conducted in 2002 to assess the state of deterioration of the submerged cultural resources.

Experimental

Previous *in-situ* corrosion studies on a number of submerged archaeological sites have demonstrated the efficacy of these techniques in providing an insight into the degradation processes that control the deterioration of shipwrecks (MacLeod *et al.*, 1986; MacLeod, 1989; MacLeod, 1995; MacLeod, 1997; Gregory, 1999; Gregory, 2000). The surfaces of the aeroplanes were normally covered with a mucilaginous layer less than 1 mm thick consisting of a combination of marine growth and corrosion-products with some areas of calcareous concretion. Measurement of pH on aluminium aircraft surfaces was made by gently abrading the surface with the blunt end of a diver's knife and immediately placing the flat-surface glass electrode against the exposed metal. Under such conditions the pH values on the aircraft are generally very conservative, that is the underlying acidity will be higher than was reported, since there is no significant reserve of acidic materials trapped under the protective layer that can buffer the immediate effect of the corroding surface being directly exposed to the alkaline seawater. After measuring the pH, corrosion-potentials (E_{corr}) were measured against $Ag/AgCl_{sea\ water}$ reference electrode using a platinum 2 mm diameter wire electrode. The reference electrode was calibrated against a platinum electrode at pH 4 in saturated quinhydrone solution at +0.268 volts vs. the Standard Hydrogen Electrode. The relationships between the E_{corr}, pH and water-depth were established by using linear regression analysis and the fit of the data is reported in terms of the R^2, the square of the correlation coefficient. It has been found that E_{corr} measurements are reproducible to within ±2 millivolts on sites over a number of years. This stability reflects periods of no change in the micro-environmental

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conditions, such as on the boiler of the SS *Xantho* (1871) site off Port Gregory in Western Australia (MacLeod, 1998). The precise water-depth at the point of measurement was recorded after reading the digital depth-meter attached to the meter-box and to the diver's arm. The depth readings are accurate to ±0.1 m.

Results and discussion

The locations of the five aircraft wreck-sites, four in open water and the other inside the number 2 hold of the *Fujikawa Maru*, are shown in Fig. 1. Marine fouling on aluminium tends to be dominated by bacteria, which form a biofilm that has similar properties to biologically-inert titanium metal (Kamimura and Araki, 1984). Marine organisms respond to the release of iron (II) and (III) ions from corroding iron wrecks since the availability of iron is a growth-limiting factor in the marine environment (MacLeod, 1988). The overall amount of marine growth found on the aircraft is very limited. The concentration of dissolved oxygen to the corroding metals is controlled by the salinity and temperature, which set the absolute values that can be obtained in saturated seawater. The supply or flux of dissolved oxygen is largely determined by the amount of water-movement across the surface of the object. Since the lagoon waters are essentially protected, the combination of currents and wave-action will control the flux of oxygen to the submerged objects. Since the aircraft were found over the range of 1–17 m and in the enclosed waters of the *Fujikawa Maru* at approximately 28 m, it is expected that the effect of water-movement in the lagoon will be able to be discerned through the measurements of corrosion-potentials (E_{corr}) and pH. Owing to the different nature of the wreck-sites each is described in turn and the overall results are summarised.

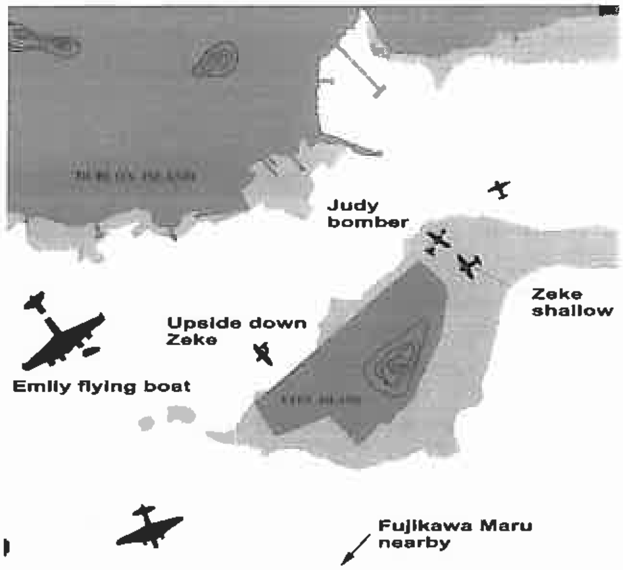

Figure 1. Locations of *Emily* flying-boat, *Judy* dive-bomber and *Zeke* fighters. (after Bailey, 2000, 480)

Emily *flying-boat*

The Kawanishi '*Emily*' H8K was a big shoulder-wing flying-boat, a well-armed and sturdy aircraft that flew long-range reconnaissance missions with a crew of ten. It had a wing-span of 38 m, was 28.13 m long and 9.15 m high, and was driven by four Mitsubishi MK4Q Kasei 22 14-cylinder air-cooled radials driving 4-bladed metal propellers. The aircraft crashed into the sea under power and lies several hundred yards off the south-west end of Dublon Island in three separate sections at depths varying from 12.6 to 16.7 m. The corrosion data is listed in Table 1. The E_{corr} of the anchor at –0.639 volts is very different from the 10 skin (external sheeting) measurements whose mean $^{\text{Emily skin}}E_{corr}$ was –0.749 ± 0.002 volts at an average depth of 14.4 ± 1.4 m, while the corresponding value for two propellers $^{\text{Emily props}}E_{corr}$ was –0.724 ± 0.005 volts. Since the skin or sheathing on the aircraft was manufactured by rolling, the frames by extrusion and the propellers by casting, the alloys used in the construction of the different parts of the plane will naturally have widely different compositions, which will be reflected in their electrochemical properties. The corrosion-potentials of aluminium alloys in synthetic oxidising sea-water (Table 2) demonstrate the sensitivity to compositional change (Dix and Binger, 1975). The E_{corr} of the anchor is within 40 mV of the E_{corr} of an α (Al-Fe) alloy with the composition $FeAl_3$ so it may well have a similar composition. The mean pH of the *Emily* aluminium alloys was 7.61 ± 0.26. Oxidation of aluminium alloys is largely controlled by the passage of electrons from the metal through defects in the passivating oxide coating to react with oxygen or other oxidising agents (Dexter, 1980). Owing to the nature of the passivating film less negative E_{corr} values, that is, less cathodic or more anodic, generally imply a lower corrosion-rate.

Table 1. In-situ *corrosion parameters for Chuuk Lagoon aircraft wrecks, April 2002*

Wrecked aircraft	Depth metres	Ecorr volt vs. Ag/AgCl	pH	Detail
Fujikawa Maru	28.1	−0.751	7.65	*Zero* skin
Fujikawa Maru	27.5	−0.743	7.63	*Zero* cockpit
Fujikawa Maru	27.2	−0.710	7.62	*Claude* tail
Emily	15.3	−0.727	7.70	port propeller
Emily	16.7	−0.750	7.72	starboard wing float
Emily	16.4	−0.749	7.73	starboard wing frames
Emily	16.0	−0.750	6.89	starboard wing float
Emily	16.0	−0.753	7.49	bottom of hull on fuselage
Emily	15.5	−0.720	7.72	starboard inner prop
Emily	14.5	−0.639	7.75	anchor
Emily	14.1	−0.747	7.74	nacelle inner port engine
Emily	13.9	−0.748	7.72	port cockpit
Emily	13.9	−0.750	7.26	outer port engine cowl
Emily	13.5	−0.750	7.76	sticking up bit
Emily	13.6	−0.746	7.64	engine cowling, port
Emily	12.6	−0.750	7.75	starboard wing edge
Upside down *Zero*	9.1	−0.733	8.06	Skin near nose
Upside down *Zero*	9.0	−0.735	8.22	Skin port upper wing
Upside down *Zero*	8.5	−0.731	7.93	Skin port side of tail plane
Upside down *Zero*	8.4	−0.734	7.40	Engine
Upside down *Zero*	8.3	−0.732	8.65	Gun
Upside down *Zero*	8.3	−0.726	7.99	Skin starboard side near nose
Upside down *Zero*	8.0	−0.735	8.20	Gun
Upside down *Zero*	7.8	−0.735	8.04	Skin port side near nose
Upside down *Zero*	7.6	−0.736	8.01	Skin near undercarriage
Upside down *Zero*	7.6	−0.731	7.83	Skin port side aft of wing
Upside down *Zero*	7.5	−0.735	7.86	Skin leading edge starboard wing
Upside down *Zero*	7.0	−0.731	8.02	Skin starboard tail plane
Judy	2.8	−0.762	7.72	propeller
Judy	2.8	−0.721	7.72	tail
Judy	2.6	−0.766	6.62	starboard wing, concreted spot
Judy	2.2	−0.703	7.66	Engine housing
Judy	2.0	−0.765	7.64	cockpit, port leading edge
Zeke Eten	2.0	−0.700	7.77	buried wing, port
Zeke Eten	1.9	−0.701	7.69	tail
Zeke Eten	1.8	−0.790	7.72	landing gear, corroded
Zeke Eten	1.7	−0.724	8.22	gun
Zeke Eten	1.5	−0.723	7.72	starboard wing, skin
Zeke Eten	1.4	−0.707	7.71	propeller
Zeke Eten	1.4	−0.723	7.83	bomb rack, stainless steel nut
Zeke Eten	1.3	−0.707	7.71	engine, behind cowling
Zeke Eten	1.2	−0.777	7.79	port wing frame
Zeke Eten	1.0	−0.683	7.72	starboard wing, frame

Since aluminium alloys have widely different values it is important to group the data according to alloy functionality when reviewing the impact of parameters such as water-depth. The values for the 'Duralumin' type of skin-sheeting from the starboard wing, wing-float, fuselage and lightweight frame showed an anodic shift of 2.7 millivolts per metre of increasing depth but the scatter of the data (Fig. 2) gave an R^2 of only 0.2886. A similar slope was observed for the E_{corr} data from the cowling, cockpit and engine nacelle but more measurements are needed to improve the quality of data from this site.

Judy *dive-bomber*

The two-person *Judy* dive-bomber was carrier-based, built by Yokosuka as the D4Y Suisei in 1942 with a Kinsei 62 radial engine and a wingspan of 11.5 m, 10.22 m long and 3.675 m high. The wreck lies in 2.5 ± 0.4 m, and is broken into three sections lying off the north-eastern end of Eten Island

Table 2. *Corrosion potentials of aluminium alloys in oxidising chloride environments*[1]

Material type	Composition	E vs. 0.1 N calomel[1]	E vs. Ag/AgCl sea water
	Al+Zn+Mg (4% $MgZn_2$ solid solution)	−1.07	−1.11
	Al+Zn (4% Zn solid solution)	−1.05	−1.09
	β Zn-Mg ($MgZn_2$)	−1.05	−1.09
	Al+Zn (1% Zn solid solution)	−0.96	−1.00
frames	7072, Alclad 7075	−0.96	−1.00
	Al + Mg (7% Mg solid solution)	−0.89	−0.93
cast	220 Alloy 10% Mg	−0.89	−0.93
	Al + Mg (5% Mg solid solution)	−0.88	−0.92
	Al + Mg (3% Mg solid solution)	−0.87	−0.91
	α Al-Mn ($Mn\text{-}Al_6$)	−0.85	−0.89
	Al 99.95%	−0.85	−0.89
cast props	Al +Mg + Si (1% Mg_2Si solid solution)	−0.83	−0.87
	Al + Si (1% Si solid solution)	−0.81	−0.85
frames	7075-T6	−0.81	−0.85
skin	2024-T81, 3.8–4.9% Cu	−0.80	−0.84
skin	2014-T6, 3.9–5.0% Cu	−0.78	−0.82
cast	355 5% Si, 1.3% Cu, 0.5% Mg	−0.78	−0.82
cast	108 4% Cu, 3% Si	−0.77	−0.81
	4.4% Cu, 0.8% Si, 0.4% Mn	−0.75	−0.79
	(Al-Cu) ($Cu\text{-}Al_2$)	−0.73	−0.77
cast	B195 4.5% Cu, 2.5% Si	−0.71	−0.75
	Al + Cu (4% Cu solid solution)	−0.69	−0.73
	alpha (Al-Fe) ($Fe\text{-}Al_3$)	−0.56	−0.60

[1] Dix, Brown and Binger, 1975.

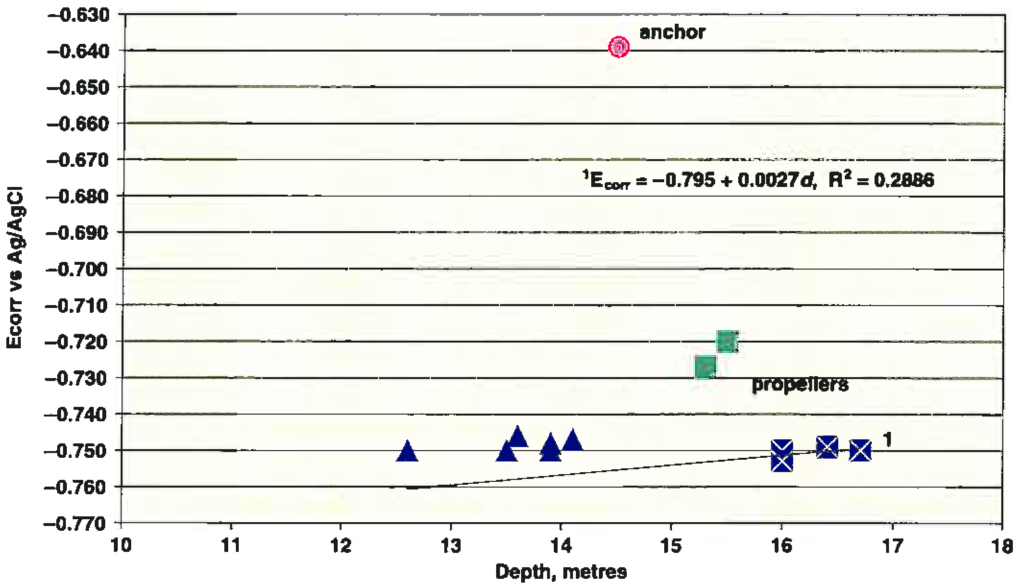

Figure 2. Plot of E_{corr} for the aluminium alloys on the *Emily* flying-boat as a function of water-depth.

(Table 1). The corrosion-potential for the engine-housing is −0.703 volts and a 63 mV difference between the engine and the skin for the starboard wing is possibly due to a higher copper concentration in the engine than in the skin (Table 2). The remaining three measurements have a low R^2 of 0.5460 for the linear regression shown in equation 1, where d is the water-depth in m.

$$^{Judy}E_{corr} = -0.784 + 0.0025\,d \qquad (1)$$

The intercept error of ±0.017 volts is small and the error in the slope was ±0.0023 volts per metre. The difference in E_{corr} of the propellers and the skin on the *Emily* was 25 mV while on the *Judy* dive-bomber they were within a few millivolts of each other. The 43 mV more anodic E_{corr} of the tail than other parts of the skin is likely to be due to a difference in alloy composition. One area of the wing had a lump of concretion on it and the underlying pH was greater than 11 times more acidic (δpH of -1.05) than the average. It is likely that the reason why the local E_{corr} of the wing section that had the lower pH under the concretion did not have a dissimilar potential to the other areas is that the pH reflects the microenvironment while the E_{corr} reflects the average voltage of the corrosion cell that consists of the areas that are electrically connected to the point of measurement. Similar behaviour has been noted on iron shipwrecks (MacLeod, 2002).

The aluminium oxide coatings on the naval aircraft alloys were in a good state of preservation when the aircraft were wrecked, with highly-polished metal surfaces that do not appear to be readily colonised by encrusting organisms since the surface covering seems to be more of a proteinaceous and algal based layer. Owing to the inherent acidity of hydrated trivalent metal ions, a series of hydrolysis reactions will take place in the micro-environment of the pits or underlying a biofilm. Reactions of the form

$$Al(H_2O)_6^{3+} + H_2O \leftrightarrow Al(OH)(H_2O)_5^{2+} + H_3O^+ \quad (2)$$

show the relationship between metal ion concentrations and the acidity or pH of the microenvironment. The amount of aluminium corrosion-products will be in a dynamic equilibrium with the acidity arising from the hydrolysis reactions, thus higher Al^{3+} ions will be reflected in lower pH values. Since the pH is a measure of the underlying concentration of metal ions, the increased pH with depth, pH = 7.44 + 0.1 *d*, is consistent with a fall in corrosion-rate, as lower Al^{3+} concentrations will undergo less hydrolysis and produce less acid.

Zeke *fighters*

The carrier-borne *Zeke* (*Zero*) fighters were manufactured by Mitsubishi (A6M Reisen type) with a wingspan of 11 m, 9.121 m long and 3.509 m high. They were powered by a single Nakajima NK1F Sakae 21 14-cylinder radial engine, driving a 3-bladed propeller. The Eten *Zeke* is in less than 2 m of water and is subjected to a constant flux of fully-oxygenated seawater, which is reflected in the pH and E_{corr} seen in Table 1 and illustrated in Fig. 3. There is a difference of 107 mV between −0.790 volt for the starboard wing skin and the E_{corr} of −0.683 volts for the landing gear. Agitation of salt solutions has a marked effect on the E_{corr} of aluminium alloys (Sherif and

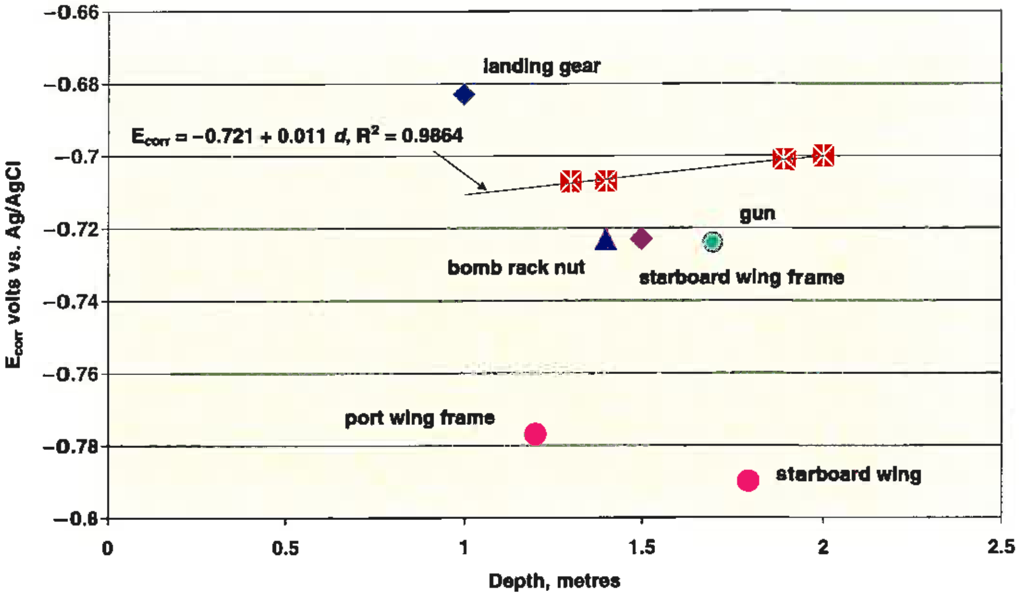

Figure 3. Corrosion potentials of the *Zeke* fighter plane off Eten Island.

Narayan, 1989). The difference of 77 mV in the corrosion-potentials on two sections of the port wing is probably a reflection of the different alloys that were used in its construction (Table 2). Most of the E_{corr} values fall into either that with a mean of −0.704 ± 0.004 V and the other at −0.723 ± 0.002 volts. When the E_{corr} data is plotted as a function of water-depth (Fig. 3) the linear regression had an R^2 value of 0.9864 and it gave equation 3

$$^{Eten\ Zeke}E_{corr} = -0.721 + 0.011\,d \qquad (3)$$

where d is the water-depth in metres. The intercept error was ±2 mV and the slope had an error of ±0.0009 volts per metre. The apparently greater sensitivity of E_{corr} on water-depth than observed on the *Emily* (14.4 ± 1.4 m) and *Judy* dive-bomber (2.5 ± 0.4 m) is not surprising as the Eten *Zeke* site (1.5 ± 0.3 m) will have strong surface mixing. Since the gun pH at 8.22 is more alkaline than the surrounding sea-water at pH 8.12 and is much more alkaline than the mean pH of 7.74 ± 0.05 for the rest of the wreck indicates that it is being cathodically protected by corroding aluminium alloys. The E_{corr} of the landing-gear reflects the differences in composition between cast-aluminium alloys and wrought and extruded alloys on other parts of the wreck.

Upside-down Zero

This *Zero* fighter lies in deeper water just to the north of the eastern end of the runway on Eten Island and the fuselage is broken just behind the wings into two pieces. The mean E_{corr} was −0.733 ± 0.003 V, which is nearly 30 mV more negative than the Eten *Zeke* (Table 1). The pH values of 8.20 and 8.65 for the two guns indicate that the surrounding aluminium alloys are actively protecting them. Its general micro-environment is best seen in a Pourbaix plot (Fig. 4) where the E_{corr} values are plotted against the pH of the objects. The two machine-guns and the concreted spot on the engine have atypical pH to other parts of the site that indicate a clear connectivity between E_{corr} and pH. Two sub-sets of data have a common slope of +64 ±8 millivolts which indicates that one proton is involved with each electron. The corresponding equations are

$$^{Upside\ down\ Zero}E_{corr\ 1} = -1.277 + 0.069\ \mathrm{pH} \qquad (4a)$$

$$^{Upside\ down\ Zero}E_{corr\ 2} = -1.200 + 0.058\ \mathrm{pH} \qquad (4b)$$

and the R^2 values are 0.9883 for equation 4a and 0.9098 for equation 4b. Examination of the Pourbaix diagram for aluminium (Pourbaix, 1974) shows that the above equations are consistent with the reaction

$$2Al + 3H_2O \rightarrow Al_2O_3 + 6H^+ + 6e^- \qquad (5)$$

The difference of 77 millivolts in the intercepts is due to compositional differences in the aircraft skin and frames since addition of an extra 2% copper in solid solution with aluminium results in a 60 mV difference in E_{corr} of the wrought alloys (Table 2). Despite the difficulties in gaining accurate pH data on submerged aircraft wrecks in Chuuk the variation in pH with E_{corr} for the *upside-down Zero* provides an insight into the

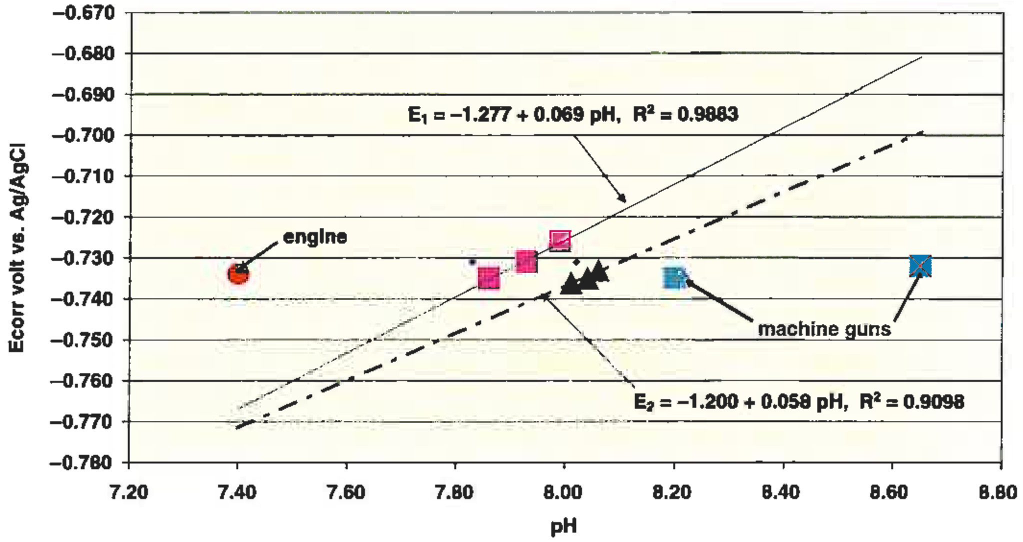

Figure 4. Plot of pH versus E_{corr} for the upside-down *Zero* off Eten Island.

corrosion mechanism. Thermodynamic data on aluminium complex ions shows that $Al(OH)_3$ is the dominant form at pH values above 7 at room temperatures, $Al(OH)_2^+$ in the range 7–6 and $Al(OH)^{2+}$ between 6–5.5 (Lowson, 1974). The gelatinous nature of the corrosion-products on the aluminium alloys is consistent with them being aluminium hydroxide gels mixed with algae.

Fujikawa Maru *aircraft within the hold*

Diving conditions limited measurements inside the forward hold of the *Fujikawa Maru* to three aeroplanes. Subsequent historical analysis (Jeffery, 2004) showed that one of the planes was a Mitsubishi A5M (Type 96 Carrier Fighter) to which the USA gave the code-name *Claude*, the world's first mono-wing shipboard fighter (Fig. 5). The two *Zeros* had a mean E_{corr} of -0.747 ± 0.006 volts while the *Claude* was -0.710 volts and there was no real difference in the pH values which had a mean of 7.63 ± 0.02 (Table 1). The aircraft are clearly electrically isolated from the steel in the hold for otherwise they would have been selectively corroded to protect the surrounding iron ship. A Japanese aircraft-production worker reported that a layer of pure aluminium was bonded on the surface of the Duralumin type of alloys to improve the corrosion-performance of the alloys in the latter part of the war during which the two *Zeros* were made (pers. comm. Chiaki Ajioka, 2004).

Observations on aircraft corrosion

The variations in E_{corr} and pH of the individual aircraft wrecks in the lagoon and on board the *Fujikawa Maru* have been previously discussed but when all the E_{corr} data in Table 1 are plotted as a function of depth it was found that more than 38 measurements followed a similar dependence of E_{corr} on water-depth in the form of a linear relationship of the voltages becoming less cathodic with depth.

$$E_{corr} = k + 0.0034\, d \qquad (6)$$

For equation 6 the four intercepts (k) values ranged from -0.759 to -0.811 volts in increments of 14 ± 1 millivolt and the slope(s) had a standard deviation of ± 0.0002. The differences in intercept values are a reflection of slightly different compositions in the aluminium alloys used in the

Figure 5. Inside the hull of the *Fujikawa Maru* with the *Claude* in the foreground and one of the *Zeros* behind with the painted numerals '39' on the highlighted section. (Bill Jeffery)

manufacture of the aeroplanes. When the E_{corr} values for the *Judy* dive-bomber, *Emily*, *Zeke* and *Claude* skins are plotted against depth the intercept value of equation 6 is −0.811 volts and the R^2 is 0.9949 and the calculated E_{corr} for the two *Zeros* in the *Fujikawa Maru* hull are between 34 mV (wing section) and 44 mV (cockpit) more negative than expected. The observed E_{corr} values for the later model *Zeros* is consistent with an outer coating of pure aluminium having been sandwiched on the parent Duralumin alloys. It is likely that the *Emily* was made using similar alloys to both the *Judy* dive-bomber and the *Claude*, which were made in 1942. The intercept values of equation 6 are in effect measures of the E_{corr} at the surface of the lagoon and the range $-0.759 \leq E_{corr} \geq -0.811$ agree with literature values for the 2000 series of aluminium alloys which typically contain 3–6% copper, 0.2–1% manganese and 0.2–1.8% magnesium. Since all the aluminium alloys are corroding in a common oxidising saline environment, the different values of the corrosion-potentials are a very handy non-destructive guide to the underlying differences in alloy composition.

Conclusion

It is important that further work is conducted to provide a more extensive corrosion-map of each of the wrecked aeroplanes so that a unifying corrosion-model can be developed. In order to predict the life-time of the submerged aircraft, samples of corroded alloys should be recovered and subjected to full metallurgical analysis and corrosion-simulation/conservation treatments in a laboratory (Beccaria and Poggi, 1985). The results have shown that the use of *in-situ* studies on Second World War aircraft can provide the maritime archaeologists with a valuable non-destructive technique of assessing this unique heritage resource. Archival research on the alloys used in the manufacture of aircraft has the potential to be of great assistance in determining the corrosion-processes that are controlling the decay of the wrecked aeroplanes. The combination of *in-situ* and laboratory studies should lead to the development of sound conservation techniques to extend the life of the aircraft. Systematic trends in the behaviour of the aluminium alloys have been established through a comparison of the corrosion-potentials of the cast alloys, such as propellers, and the wrought alloys such as found on the skins of the aircraft. The corrosion-potentials of the aluminium alloys were found to be very sensitive to compositional variation associated with both the form and function of the fittings and with the known supply problems during the latter part of the Second World War.

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