Metallurgical and Corrosion Assessment of Submerged Tanker S.S. *Montebello*

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The Union Oil Tanker S.S. Montebello *was torpedoed and sunk six miles (9.7 km) off the coast of Cambria, California by a Japanese submarine on December 23, 1941, two weeks after the attack on Pearl Harbor. With close proximity to the National Monterey Bay Marine Sanctuary, concern about possible crude oil contamination led to the most recent expedition to the site in October 2011. Assessment of the shell plate found that the average corrosion rate was very low and the structure will remain stable for many decades.*

"Yesterday, December 7, 1941, a date that will live in infamy, the United States of America was suddenly and deliberately attacked by naval and air forces of the Empire of Japan." This statement rang out in history as President Franklin D. Roosevelt declared war against Japan on December 8, 1941, the day after the Pearl Harbor attack. The attack was one of many planned for the same day at British and American military installations throughout the Pacific, including Guam, Wake Island, Singapore, British Malaya, Burma, Thailand, the Dutch East Indies, and the Philippine Islands.[1] On December 23, 1941, two weeks after the Pearl Harbor attack, Japanese submarine I-21 sighted and followed the tanker S.S. *Montebello*. The tanker had departed Port San Luis, California on December 22 and was on its way to Vancouver, British Columbia when it was fired on by two torpedoes. One struck and exploded midship, sinking the ship within an hour. The tanker contained 73,500 bbl (11.7 million L) of crude oil, 2,470 bbl (392,730 L) of Bunker-C fuel oil, and an unknown amount of lubricating oil.

For more than 72 years, the tanker has rested upright on the bottom in ~900 ft (275 m) of water, ~6 miles (9.7 km) off the coast of Cambria, California. Because of the ship's close proximity to the Monterey Bay National Marine Sanctuary, a marine habitat, discovery dives in 1996 and subsequent reconnaissance dives in 1996 and 2003 employed still photography and video taping to document the integrity of the hull and general site conditions for potential oil contamination.[2] In October 2011, an expedition to the site was conducted to assess corrosion directly from samples recovered robotically and to determine if crude oil remained on board. This article presents the results of the metallurgical/corrosion study and shows how the data are incorporated into a universal corrosion prediction model. Unexpected difficulties in robotic acquisition of metal and concretion samples from a comparatively deep sea environment are also discussed.[3]

The Ship

Structural

The shelter deck tanker was built in 1921 by the Southwest Shipbuilding Co. (San Pedro, California). Figure 1 shows a rare photograph.[4] Historic structural drawings could not be found; however, the original plate thickness (T_L) [Equation (1)] the basis for determining the corrosion rate, was evaluated from the American Bureau of Shipping Rules.[5] To properly interpret the rules for the shell steel plate used to construct the *Montebello,* Naval Architect Zachary Malinoski was consulted.[6] For a total ship length of 440 ft (134 m), and side shell stiffeners on 30-in (762-mm) spacing, plate thicknesses were variable depending upon horizontal positions as follows:

- Sides, midships section of length 0.4L (176 ft [53.6 m]): T_L = 0.68 in (17 mm)
- Ends extend inwards 0.1L (44 ft [13.4 m]) from bow and stern: T_L = 0.46 in (12 mm)
- Taper fore and aft extends 0.2L (88 ft [27 m]) from ends: T_L = 0.46 in; to sides: T_L = 0.68 in

A shear strake plate runs longitudinally at the shelter deck at the height of the summer tanks. The thickness is 0.16 to 0.25 in (4.0 to 6.35 mm) greater than the shell plate thickness. Whether the strake plate is an additional plate overlying the hull plate is unknown, although local doubling plates "can be fitted as necessary" according to the rules.

FIGURE 1 The S.S. *Montebello.* Photo courtesy of the Vancouver Maritime Museum.

TABLE 1. CHEMISTRY OF *MONTEBELLO* STEEL

Sample No.	%C	%P	%S	%Mn	%Si	%Cr	%Ni
MB-1	0.289	0.0147	0.0567	0.399	0.011	0.019	0.011
MB-3	0.216	0.0180	0.0820	0.329	0.012	0.011	0.024
MB-5	0.292	0.0460	0.1270	0.376	0.009	0.013	0.017
MB-8	0.235	0.0200	0.0650	0.368	0.013	0.013	0.009
Modern Grade A36	0.200	0.0120	0.0370	0.550	—	—	—

Coupon Analysis

Metal Coupon Chemistry

Samples MB-1, 3, 5, and 8 are typical of steel manufactured in 1921 when the *Montebello* was under construction. Table 1 indicates that %C, %P, and %S are somewhat higher for the *Montebello* than modern Grade A36 steel (UNS K02600). More precise control is the reason for the difference, although such differences have no measureable effect on corrosion of the *Montebello* hull.

Metallographic Examination

The samples were prepared by traditional metallographic techniques as described in ASTM E3-11.[7] The microstructures are dominant in ferrite (light, >99% iron) due to the low carbon content and heat-treatment history (Figure 2). The darker areas are pearlite a layered mixture of ferrite and iron carbide (Fe_3C), which is an intermediate compound of iron. Inclusions are in the form of manganese (II) sulfide (MnS) stringers, a form of sulfur common in carbon steels, particularly those manufactured early in the twentieth century. The average hardness of the coupons varied from 64 to 76 Rockwell B hardness. The hardness is slightly low compared to modern low-carbon steels but is not a significant issue with regard to corrosion performance.

Corrosion Rate Expressions

Equation (1) is an expression for the corrosion rate in terms of direct thickness measurement:[8]

$$i_{corr} = ½\,(T_L - T_m)/t \qquad (1)$$

where T_L is original shell plate thickness (1,000 × 25.4 = mil, mil × 25.4 = mm), T_m is measured post exposure thickness, t = 70 is submergence time (years), and i_{corr} is corrosion rate in mils per year (mpy) or mm (25.4 × in/y). Since corrosion occurs on both sides, a factor of one half is applied.

Equation (2) is an expression for corrosion rate in terms of data extracted from collected marine concretions, concretion equivalent corrosion rate (CECR):[8]

$$i_{corr} = i_{cecr} = 0.8\rho d\%Fe/t \qquad (2)$$

where: ρ is density (g/cm^3), d is concretion thickness (cm), %Fe is iron content in wt%, and t is defined above.

Equation (3) is an expression for the Weins number (Wn) given by:[9]

$$Wn = i_{corr}/i_{aocr} = k_0 \exp(-\Delta H^a/RT) \qquad (3)$$

where i_{aocr} (available oxygen corrosion rate) is calculated from the expression i_{aocr} =

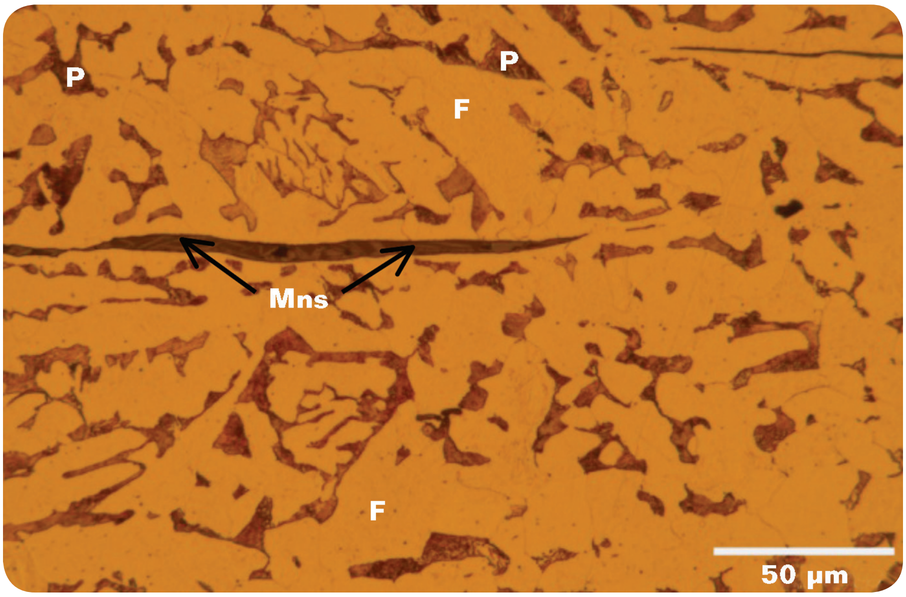

FIGURE 2 Microstructure consists of ferrite, F, pearlite, P, and inclusions (MnS). Etched with 2% nital.

FIGURE 3 Robert Schwemmer, NOAA/ONMS, recovers the hole saw aboard support vessel OSRV *Nanuq*. Photo courtesy of Kerry Walsh, Global Diving and Salvage.

$kC(O_2)/(100\ d)$, $C(O_2)$ is percent dissolved oxygen (DO), d is concretion thickness (cm), k_0 is preexponential constant, ΔH^a is activation energy (Kcal/mole/°K or KJ/mole/°K), R is the gas constant, and T is absolute temperature.

Corrosion Rate

Core metal thickness measurements were conducted on seven metal coupon samples at ESI laboratories (Omaha, Nebraska). From four to eight measurements were taken around the circumference of each sample in the "as-received" condition. Figure 3 shows the recovered robotic hole saw shipside core sample. Figure 4 shows the hole saw cutting into the hull. Figure 5 shows the sample "as received." Table 2[3] gives original thickness, average core thickness, and corresponding corrosion rates for each sample.

From Table 2, column 4, corrosion rate per side, average i_{corr} = 0.4 mpy (10.16 um/y) or 0.8 mpy (20.32 um/y) both sides. Neglecting Sample MB-3 because of uncertainty in original thickness at the strake, the average corrosion rate is given by Equation (4):

$$i_{corr} \approx 0.2 \text{ mpy } (5.08\ \mu m/y) \pm 0.15 \text{ mpy } (3.81\ \mu m/y) \quad (4)$$

From published data,[10] corrosion rates are reported to be significantly higher at ~2.5 mpy (63 um/y) per side at a depth of 1,000 ft (305 m) near Port Hueneme, California on the Pacific coast. With sample exposure times at Port Hueneme of three years or less, the difference between reported results at Port Hueneme and the *Montebello* is likely related to the protection afforded by concretion over a 70-year period. All of the *Montebello* samples were taken either above the summer tanks located just below the shelter deck or in boiler spaces. None of these spaces held oil before the attack.

Concretion Measurements

Concretion measurements on seven samples were completed in chemistry laboratories at the University of Nebraska-Lincoln. Enough material in small pieces was available to obtain the iron content of all the samples. Only one sample, MB-7c (c for concretion), however, was sufficient in size to measure density and thickness between shipside and seaside (the side exposed to the open water). Equation (5) applies criteria developed from environmental scanning electron microscopy (ESEM) characterization studies[11] and CECR Equation (2):

$$i_{cecr} = 0.7 \text{ mpy } (17.78\ \mu m) \quad (5)$$

where $\rho = 2.24\ g/cm^3$, %Fe = 45.3, and d = 0.6 cm. The average would likely have been lower if additional samples could have been acquired that provided continuity between the hull and seaside. Some loss of sample was encountered during acquisition, however, and concretion was broken up after removal from the hole saw.

Application of Weins Number Profile

The Wn was developed as a method to correlate long-term marine corrosion under widely variable environmental seawater conditions from 2 °C to >30 °C.[11] The Wn is defined by the ratio of the actual corrosion rate to a corrosion rate determined from environmental parameters including the thickness of the accumulated concretion (Equation [3]). Based on site percent DO, %DO = 17, temperature = 8 °C, salinity = 34 PSU, and corrosion rate from Equation (4), a new data point with point spread, is added to the Wn profile (Figure 6).

With the profile modified slightly after inclusion of the *Montebello* data points, Equation (6) illustrates how the Wn (from the definition of the Wn, Equation [3]) could be used to estimate the corrosion rate of the *Montebello* shell plate knowing three variables: 1) concretion thickness d = 0.6 cm, 2) temperature = 8 °C, and 3) %DO = 17. The temperature, 8 °C, converts to T = 8+273 = 281 °K. The reciprocal is 1/T (K-1) × 1,000 ≈ 3.56. In Figure 6, 3.56 on the x-axis intersection with the profile line corresponds to a y-axis reading of Wn = 0.4.

$$i_{corr} = 0.901\ Wn\ (\%DO)d/100 = 0.901(0.4)(17)(0.6)/100 \approx 0.05\ \text{mpy}\ (1.27\ \mu\text{m}) \quad (6)$$

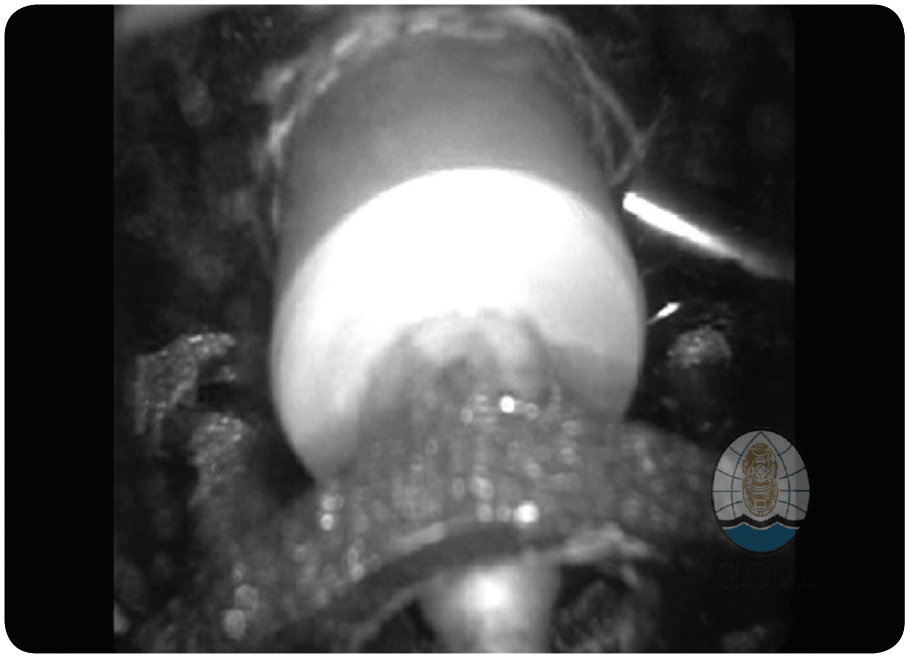

FIGURE 4 The robotic hole saw cutting into the hull. Photo courtesy of Kerry Walsh, Global Diving and Salvage.

Discussion

Based on metal core thickness difference, Equation (1), the corrosion rate was estimated to be i_{corr} = 0.2 ± 0.15 mpy (5.08 ± 3.8 um/y). Based on Equation (2), the CECR method estimated the corrosion rate to be i_{corr} = 0.70 mpy (17.78 um/y). As mentioned earlier, the latter would likely have been lower if sufficient concretion had been available. *Montebello* data are consistent with the existing Wn profile, supporting the conclusion that the Wn remains a potential methodology to correlate and predict long-term marine corrosion at widely diverse sites. This is especially important at deep-water sites where core samples are difficult or impossible to obtain.

Unofficial reports after the latest expedition indicate that no crude remains in the cargo tanks today although the smell of oil is noted on at least one of the core samples. The expertise of the research group does not include prediction of structural integrity; it is the collective opinion of the group, however, that the S.S. *Montebello* will maintain on-site integrity for many decades to come. In future operations, it is highly recommended that a metallurgist/corrosion scientist be on board to monitor sample acquisition.

FIGURE 5 Sample received at ESI Omaha. The sample is ~4 in (100 mm) in diameter.

Acknowledgments

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TABLE 2. CORROSION RATE AND SUPPORTING THICKNESS MEASUREMENTS

Sample Location	Average Final Thickness (in)	Original Thickness (in)	Corrosion Rate per Side (i_{corr}) (mpy) Equation (1)
MB-1m (Port) Taper region[A]	0.674	0.680 – 0.080 = 0.600 Taper correction = –0.08	(0.600 – 0.674) × (1,000/70) × 0.5 ≈ 0.0
MB-2m (Stbd) End	0.460	0.460 + 0.052 = 0.512 Taper correction = 0.052	(0.512 – 0.460) × (1,000/70) × 0.5 ≈ 0.4
MB-3m (Stbd) Strake plate	0.550	0.680 + 0.160 = 0.840 Taper correction = 0.16	(0.840 – 0.550) × (1,000/70) × 0.5 ≈ 2.0
MB-4m (Port) Taper[A]	0.620	0.680 – 0.090 = 0.590 Taper correction = –0.09	(0.590 – 0.620) × (1,000/70) × 0.5 ≈ 0.0
MB-5m (Port) Side	0.677	0.680	(0.680 – 0.677) × (1,000/70) × 0.5 ≈ 0.02
MB-6m (Port) Side	0.673	0.680	(0.680 – 0.673) × (1,000/70) × 0.5 ≈ 0.05
MB-7c	——Concretion Only——		
MB-8m (Stbd) Taper[A]	0.543	0.680 – 0.080 = 0.600 Taper correction = –0.08	(0.600 – 0.543) × (1,000/70) × 0.5 ≈ 0.4

[A]Taper shell plate thickness determined by linear extrapolation between 0.46 and 0.68 in.

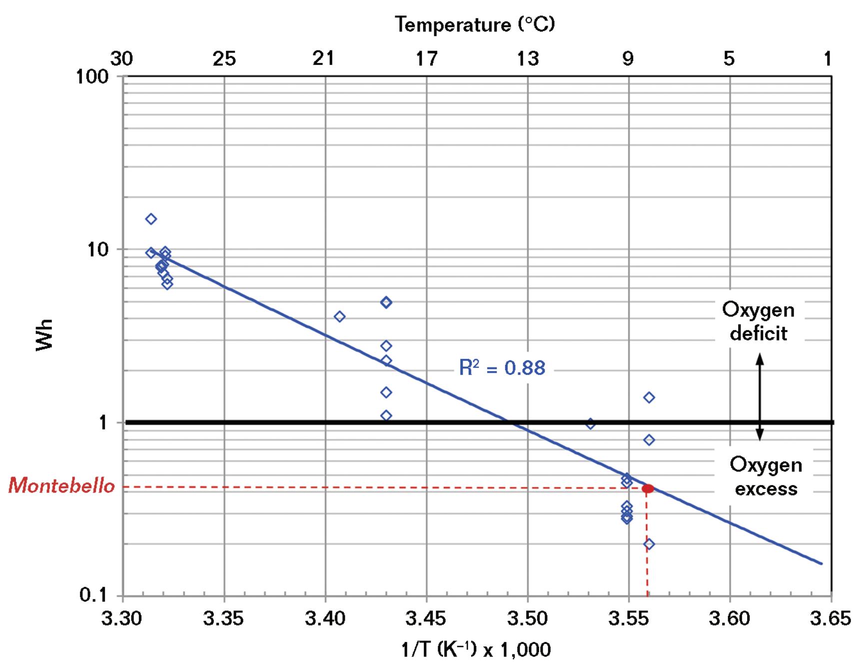

FIGURE 6 Wn plot as a function of reciprocal absolute temperature. The *Montebello* estimate is depicted in red.

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