Corrosion of Steel Shipwreck in the Marine Environment: USS *Arizona*—Part 1

Donald L. Johnson
National Park Service

Brent M. Wilson
Amsted

James D. Carr
University of Nebraska - Lincoln, jcarr1@unl.edu

Matthew A. Russell
National Park Service Submerged Resources

Larry E. Murphy
National Park Service Submerged Resources Center

See next page for additional authors

Authors
Donald L. Johnson, Brent M. Wilson, James D. Carr, Matthew A. Russell, Larry E. Murphy, and David L. Conlin

2006 Materials Performance 45(10), pp. 40-44

Corrosion of Steel Shipwreck in the Marine Environment: USS *Arizona*—Part 1

DONALD L. JOHNSON, BRENT M. WILSON, AND JAMES D. CARR,
University of Nebraska-Lincoln
MATTHEW A. RUSSELL, LARRY E. MURPHY, AND DAVID L. CONLIN,
Submerged Resources Center, National Park Service

The USS *Arizona* has remained submerged in Pearl Harbor, Hawaii, since the Japanese attack on December 7, 1941. The ship presents a potential hazard from fuel oil still present in the ship's hull. As an important factor in management decisions, the effect of corrosion after nearly 65 years is being studied to determine the integrity of the ship's structure. Coupon samples from the hull revealed decreasing corrosion rates from ~1 to 3 mpy (0.03 to 0.08 mm/y) from just below the water surface to the mudline. This is about one-third of that expected in the absence of biofouling or concretion. Methods of determining the corrosion rate, including correlation of chemistry and properties, are discussed.

The wreckage of USS *Arizona* has been submerged in shallow water since December 7, 1941, when Japanese forces sank USS *Arizona* (Figure 1) and eight other battleships during the Pearl Harbor attack in Hawaii. The remnants of the hull rest below water at a location that is now the USS *Arizona* Memorial (Figure 2). The hull, with a slight list to port, is submerged from the main deck to the keel in ~30 ft (9.1 m) of water and 25 ft (7.6 m) of mud. The mudline today is roughly equivalent to the original water line.

Steel corrosion in seawater is extensively documented in the professional literature.[1] Corrosion effects, however, are not comprehensively documented as related to the interaction between substrate steel and accumulated marine concretion (marine hard biofouling) when the steel is not cathodically protected, as in the case of USS *Arizona*.

The current USS *Arizona* Preservation Project builds upon pioneering site documentation and environmental research conducted by the National Park Service Submerged Resources Center (SRC) in the 1980s.[2] Several interdisciplinary steps, including corrosion analysis, were initiated by the SRC in 1999 to provide the scientific foundation for long-term preservation and management decisions for this immensely significant national shrine and National Historic Landmark.[3-4] A critical management issue is that an estimated 500,000 gal (1.89 million L) of Bunker C fuel oil remains on board and has been slowly escaping since 1941. Catastrophic oil release could pose a potentially serious environmental hazard. To deal effectively with this issue, memorial managers seek a scientific characterization of the rate and nature of the deterioration processes on the sunken ship.

Part 1 of this article presents the experimental approach and results of metal coupon corrosion rate measurements at the midship hull, and discusses minimal impact methods used to measure the corrosion rate. Part 2, to be published in the November 2006 issue of *MP*, continues with a characterization of hull concretion samples removed in support of studies reported in the literature.[5]

Literature Review

An initial corrosion study objective was a metallurgical evaluation of steels used to build the ship. This evaluation, published in 2000,[6] included brief statements concerning the ship's history, recovery efforts, and the 1980s underwater survey. The mild steels used to fabricate the ship during its original construction, and later during the 1930s reconstruction, were consistent with the best materials available. A typical analysis and comparison with the present-day ASTM A36 steel values are shown in Table 1. The differences in chemistry between USS *Arizona*-era steel and present-day ASTM A36 steel are not considered significant with regard to corrosion response.

A follow-on of the metallurgical study was focused on in-situ corrosion potential measurements at the interface between the hull metal and the encrustation or hard biofouling layer (concretion) that covers the entire submerged ship. This study, published in 2002,[7] primarily involved sequential drilling, corrosion potential, and pH measurements into the concretion from seaside (concretion/seawater interface) to shipside (concretion/hull metal interface). Data clearly confirm the crevice effect at shipside where the pH is the lowest, and gradually increased through the concretion to seaside. In addition, results indicated that the corrosion potential at both shipside and seaside decreases with water depth. These results are being incorporated into a finite element model, which is the primary predictive tool used to assess corrosion effects on hull structural elements for management purposes.

Direct Experimental Measurement

In August 2002, the SRC partnered with the Naval Facilities Engineering Service Center–Ocean Construction Division, the Navy's Mobile Diving and Salvage Unit One, and Titan Maritime Industries, Inc. to collect external hull plate samples for metallurgical and microbiological analysis. Hull coupons were critical for establishing controls for the indirect hull corrosion-rate determination methods. A 4-in. (102-mm) hydraulic powered hole saw was used to collect eight hull metal samples, four on each side of the ship on vertical transects,

FIGURE 1

USS *Arizona* in the East River, New York City, circa 1916. Courtesy of the National Park Service.

FIGURE 2

USS *Arizona* Memorial at Pearl Harbor as it exists today. Courtesy of the National Park Service.

TABLE 1

CHEMISTRY OF TYPICAL USS *ARIZONA* STEEL COMPARED TO MODERN DAY ASTM A36 (ALL VALUES wt%)

	Carbon	Phosphorus	Sulfur	Silicon
USS *Arizona*	0.25	0.028	0.034	0.023
ASTM A36	0.20	0.012	0.037	0.007

FIGURE 3

Composite interior/exterior concretion with hull metal coupon from USS *Arizona*; sample taken from a water depth of 5 ft (1.5 m), port side.

FIGURE 4

Cross section of metal coupon from USS *Arizona*; sample taken from a water depth of 19.5 ft (5.9 m), port side.

near amidships frame 75 (each frame represents a 4-ft [1.2-m] section of the hull, beginning at the bow with frame 1), from near the water line to just below the mudline. The ship's blueprints were consulted to ensure that no compartments containing oil would be penetrated. Figure 3 is a picture of a core sample taken at a depth of 5 ft (1.5 m) with intact concretion on both sides. Samples from greater depths exhibited little concretion on the interior surfaces. Interior water in these locations was anaerobic. After removal, each location was plugged and sealed with marine epoxy. One location was plugged with a removable stopper to allow for the future retrieval of internal water samples as part of the long-term monitoring program.

Multiple optical metallographic measurements were made on each metal coupon at Rail Sciences Laboratory in Omaha, Nebraska. Figure 4 shows the cross section of a typical sample taken at 19.5 ft (5.9 m) below the water surface. General corrosion was evident in this macrophotograph, as it was on the other seven samples. For comparison, the sample in Figure 3 taken near the water's surface shows severe corrosion from wave action and corrosion from both sides. The bar graphs in Figure 5 (port) and 6 (starboard) are representations of the results of this analysis in terms of metal loss as a function of original plate thickness and water depth. The original nominal hull plate thickness was identified from original cross-section drawings, amidships, at frames 75 and 93. Thicknesses in the original blueprints were expressed in terms of weight per unit area (lb/ft^2). The magenta on each horizontal bar corresponds to metal lost during 61 years of seawater exposure. The direct corrosion rate is determined by subtracting the thickness of metal remaining from the original thickness, dividing the result by time (61 years), and multiplying by 1,000. The equation is given by:

$$icorr = \frac{T(o) - T(a)}{t} \cdot 1,000 \qquad (1)$$

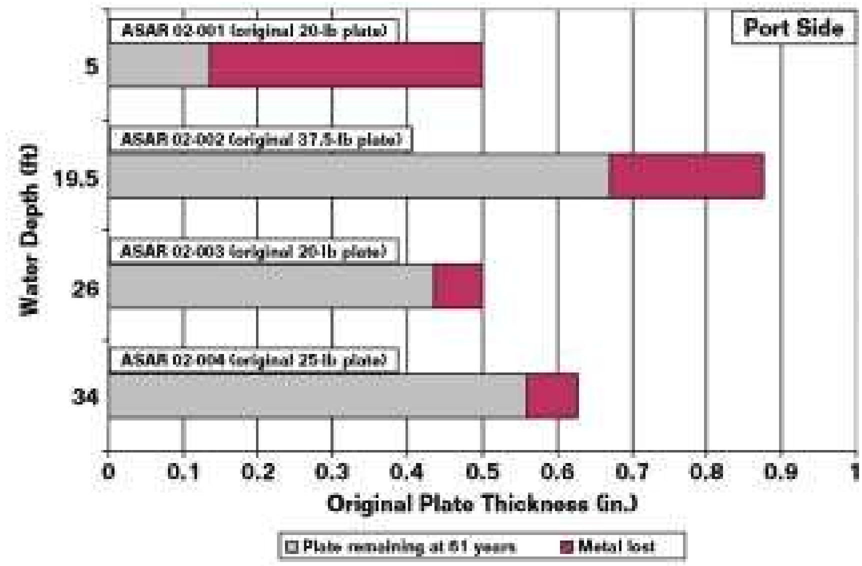
where icorr is the corrosion rate in mpy; T(o) is the original thickness, in.; T(a) is the actual thickness, in.; and t is time, year (1 mpy = 0.0254 mm/y).

Figure 7 illustrates the corrosion rate as a function of water depth for all of the samples collected at frame 75.

Indirect Experimental Measurement

Several indirect methods for the determination of corrosion rate with minimal impact on the existing structure of USS *Arizona* are being studied. These methods include corrosion potential, potential gradient across concretion, ultrasonic thickness, electrochemical measurements, limiting current density, and concretion iron content analysis. None of these methods stand alone, however, and each must be correlated with actual metal loss. The method presently showing the most promise is the correlation between hull iron loss and concretion iron gain. X-ray and electron diffraction analysis, to be presented in Part 2, lends support to this method.[1]

FIGURE 5

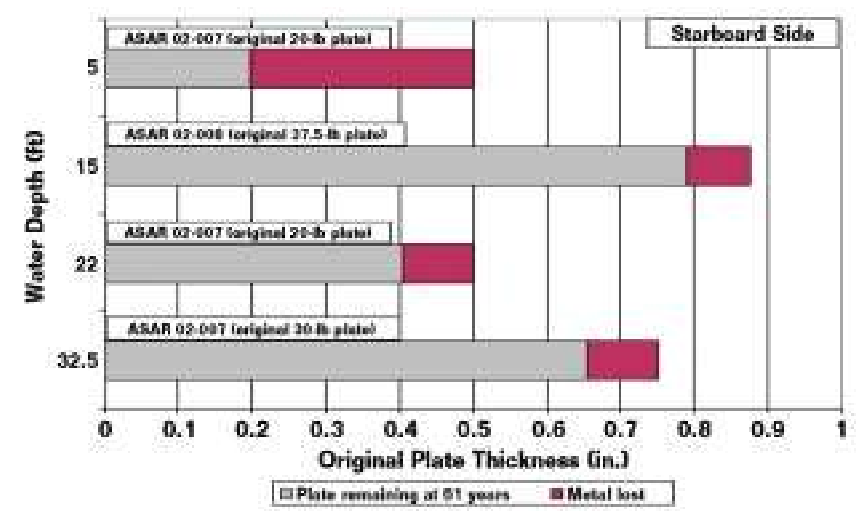


Metal loss (magenta) on USS *Arizona* as a function of water depth, port.

Conclusions

Based on metal coupon analysis at frame 75, the corrosion rate on USS *Arizona's* exterior hull is ~3 mpy (0.08 mm/y) near the surface and decreases by nearly one third to ~1 mpy (0.03 mm/y) just below the mudline. By comparison, corrosion rates for unconcreted steel in open seawater at the surface are reported to be in the 7 to 8 mpy (0.18 to 0.20 mm/y) range.[1] Lower-than-predicted corrosion rates are directly related to metal/concretion interaction and subsequently decreased oxygen availability. Studies are ongoing to evaluate the role of the concretion and its effect on corrosion in marine environments.

FIGURE 6



Metal loss (magenta) on USS *Arizona* as a function of water depth, starboard.

Acknowledgments

The following organizations contributed funding to this research: Legacy Resources Management Fund, Department of Defense, Submerged Resources Center, National Park Service, USS *Arizona* Memorial and *Arizona* Memorial Museum Association, University of Nebraska Foundation, Emeriti Association, and the Department of Mechanical Engineering at the University of Nebraska-Lincoln. Special thanks to Robert DeAngelis, Air Force Research Laboratory, Eglin Air Force Base, for x-ray diffraction; Richard Schalek, Michigan State University, for scanning electron microscopy analysis; John Makinson, Rail Sciences; Titan Maritime Industries, Dania Florida; and U.S. Navy, Pearl Harbor, all of whom are acknowledged for considerable contributions.

The following individuals are acknowledged for helpful advice and/or equipment loans: Gary Matlock, GMC Electrical; Steve West, Thermo Electron; and Jon Johnson, FilmTec Corporation. This article is dedicated to the memory of William N. Weins.

References

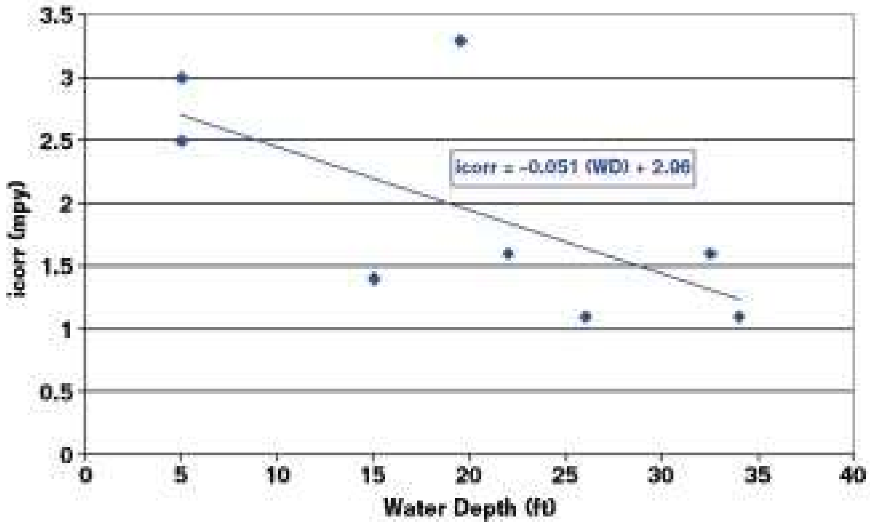
1. M. Schumacher, ed., Sea Water Corrosion Handbook (Park Ridge, NJ: Noyes Data Corp., 1979).

2. D.J. Lenihan, ed., "Submerged Resources Study—USS Arizona," Southwest Cultural Resources Center Professional Papers, no. 23, 2nd ed. (Santa Fe, NM: National Park Service, 1990).

3. M.A. Russell, L.E. Murphy, "Long-Term Management Strategies for USS Arizona: A Submerged Cultural Resource in Pearl Harbor, Hawaii," Legacy Resources Management Fund Project No. 03-170:2003 Annual Report, Submerged Resources Center Technical Report No. 15.

4. M.A. Russell, L.E. Murphy, D.L. Johnson, T.J. Foecke, P.J. Morris, R. Mitchell, "Science for Stewardship: Multidisciplinary Research on USS Arizona," Marine Technol. Soc. J. 38, 3 (2004): pp. 54-63.

FIGURE 7



Corrosion rate as a function of water depth for USS *Arizona*; data compiled from coupon results at Frame 75.

5. M.A. Russell, D.L. Johnson, B.M. Wilson, D.L. Conlin, L.E. Murphy, J.D. Carr, "A Minimum Impact Method for Measuring Corrosion Rate of Steel-Hulled Shipwrecks in Seawater," Int. J. of Nautical Archeology, 35.2 (September 2006): pp. 310-318.

6. D. L. Johnson, W.N. Weins, J.D. Makinson, D.A. Martinez, "Metallographic Studies on the USS Arizona," Microstructural Science, vol 27 (Materials Park, OH: ASM International, 2000), pp. 85-91.

7. J.D. Makinson, D.L. Johnson, M.A. Russell, D.L. Conlin, L.E. Murphy, "In Situ Corrosion Studies on the Battleship USS Arizona," MP 41, 9 (2002): pp. 56-60.

DONALD L. JOHNSON is a Professor Emeritus at the University of Nebraska-Lincoln, Dept. of Mechanical Engineering, 14709 W. Via Manana, Sun City West, AZ 85375. He has worked in the areas of teaching, research, and consulting since 1963 and has been a volunteer science and engineering consultant to the National Park Service since 1999. A 40-year member of NACE, Johnson has an M.S. degree in metallurgy from the Colorado School of Mines and a Ph.D. in chemical engineering and materials from the University of Nebraska-Lincoln. He received the George B. Hartzog National Park Service Volunteer of the Year Award in May 2006.

BRENT M. WILSON is an Assistant Professor of Research at the University of Nebraska-Lincoln, N104 Waller Scott Engineering Center, Lincoln, NE 68588-0656. He earned his Ph.D. in 2002 from the University of Nebraska in chemical and materials engineering. He serves as the facility specialist for the Metallurgical and Mechanical Characterization Facility as part of the Nebraska Center for Materials and Nanoscience at the university. His primary research is in the area of tapered roller bearings and wheels, which are used extensively in the railroad industry.

MATTHEW A. RUSSELL is an archeologist at the National Park Service Submerged Resources Center, PO Box 728, Santa Fe, NM 87504-0728. He is a maritime archeologist and project director for USS *Arizona* research. He was deputy field director for the recovery of Civil War submarine *H.L. Hunley* in 2000. He has been with the National Park Service's Submerged Resources Center since 1993.

LARRY E. MURPHY is chief of the National Park Service Submerged Resources Center. He has been a professional underwater archeologist for more than 30 years, and has been involved in USS *Arizona* documentation and research since the first project in 1983.

DAVID L. CONLIN is an underwater archeologist with the National Park Service Submerged Resources Center. He has worked on underwater archeology projects all over the world, including the recovery of the Confederate submarine *H.L. Hunley* and USS *Arizona*.

JAMES D. CARR is a professor of chemistry at the University of Nebraska-Lincoln. He has been a professor of analytical chemistry at the university since 1966. He has conducted research on several topics involving aqueous chemistry. He has a Ph.D. from Purdue University and is a member of the University of Nebraska Academy of Distinguished Teachers. MP